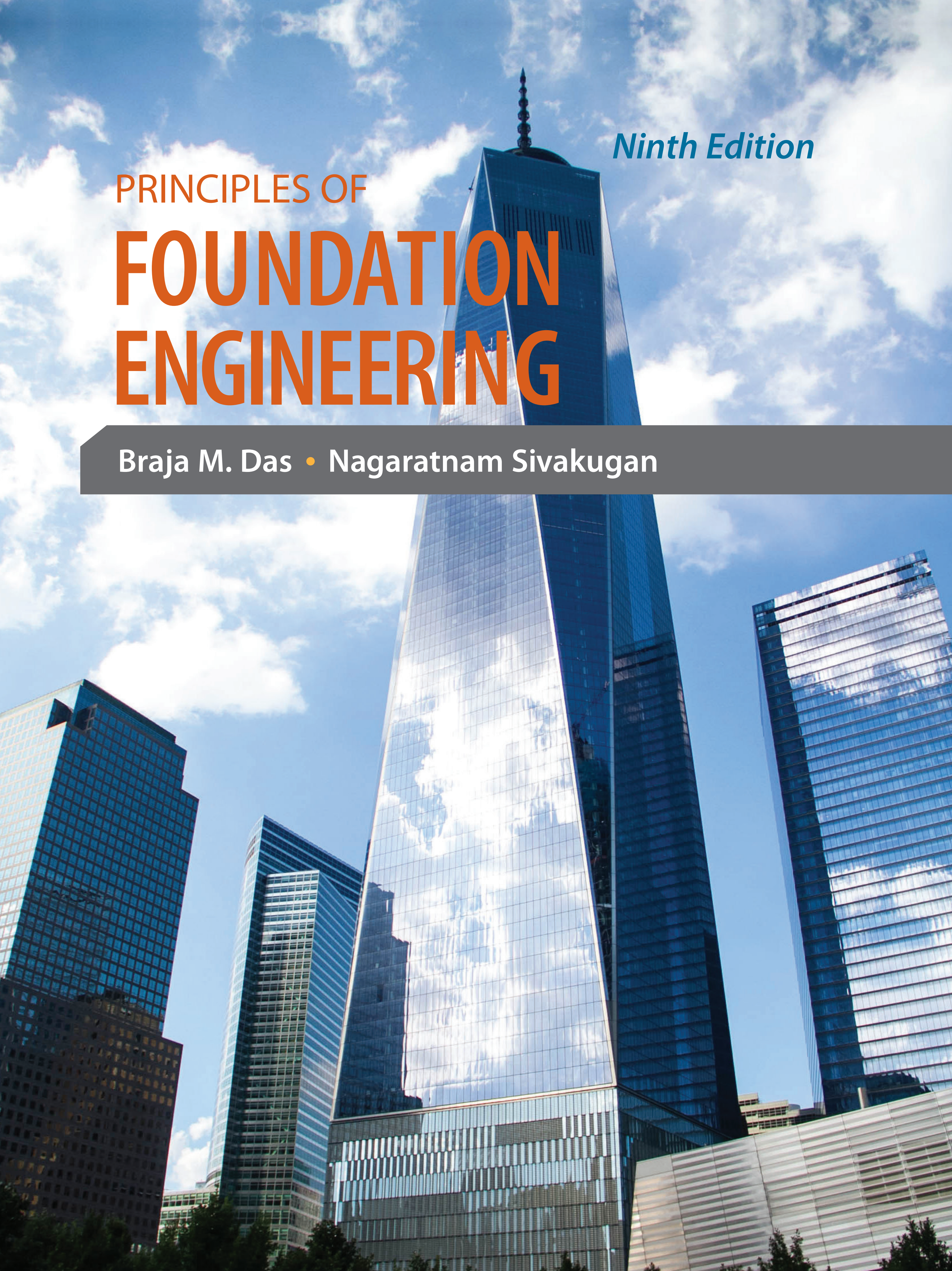
Ninth Edition

PRINCIPLES OF FOUNDATION ENGINEERING

Braja M. Das • Nagaratnam Sivakugan



CONVERSION FACTORS FROM SI TO ENGLISH UNITS

Length:	1 m	= 3.281 ft
	1 cm	= 3.281×10^{-2} ft
	1 mm	= 3.281×10^{-3} ft
	1 m	= 39.37 in.
	1 cm	= 0.3937 in.
	1 mm	= 0.03937 in.
Area:	1 m^2	= 10.764 ft^2
	1 cm^2	= 10.764×10^{-4} ft^2
	1 mm^2	= 10.764×10^{-6} ft^2
	1 m^2	= 1550 in^2
	1 cm^2	= 0.155 in^2
	1 mm^2	= 0.155×10^{-2} in^2
Volume:	1 m^3	= 35.32 ft^3
	1 cm^3	= 35.32×10^{-4} ft^3
	1 m^3	= 61,023.4 in^3
	1 cm^3	= 0.061023 in^3
Force:	1 N	= 0.2248 lb
	1 kN	= 224.8 lb
	1 kgf	= 2.2046 lb
	1 kN	= 0.2248 kip
	1 kN	= 0.1124 U.S. ton
	1 metric ton	= 2204.6 lb
	1 N/m	= 0.0685 lb/ft

Stress:	1 N/m^2	= 20.885×10^{-3} lb/ft^2
	1 kN/m^2	= 20.885 lb/ft^2
	1 kN/m^2	= 0.01044 U.S. ton/ft^2
	1 kN/m^2	= 20.885×10^{-3} kip/ft^2
	1 kN/m^2	= 0.145 lb/in^2
Unit weight:	1 kN/m^3	= 6.361 lb/ft^3
	1 kN/m^3	= 0.003682 lb/in^3
Moment:	1 N·m	= 0.7375 lb-ft
	1 N·m	= 8.851 lb-in.
Energy:	1 J	= 0.7375 ft-lb
Moment of inertia:	1 mm^4	= 2.402×10^{-6} in^4
	1 m^4	= 2.402×10^{6} in^4
Section modulus:	1 mm^3	= 6.102×10^{-5} in^3
	1 m^3	= 6.102×10^{4} in^3
Hydraulic conductivity:	1 m/min	= 3.281 ft/min
	1 cm/min	= 0.03281 ft/min
	1 mm/min	= 0.003281 ft/min
	1 m/sec	= 3.281 ft/sec
	1 mm/sec	= 0.03281 ft/sec
	1 m/min	= 39.37 in./min
	1 cm/sec	= 0.3937 in./sec
	1 mm/sec	= 0.03937 in./sec
Coefficient of consolidation:	1 cm^2/sec	= 0.155 in^2/sec
	1 m^2/yr	= 4.915×10^{-5} in^2/sec
	1 cm^2/sec	= 1.0764×10^{-3} ft^2/sec

CONVERSION FACTORS FROM ENGLISH TO SI UNITS

Length:	1 ft	= 0.3048 m
	1 ft	= 30.48 cm
	1 ft	= 304.8 mm
	1 in.	= 0.0254 m
	1 in.	= 2.54 cm
	1 in.	= 25.4 mm
Area:	1 ft^2	= 929.03×10^{-4} m^2
	1 ft^2	= 929.03 cm^2
	1 ft^2	= 929.03×10^{2} mm^2
	1 in^2	= 6.452×10^{-4} m^2
	1 in^2	= 6.452 cm^2
	1 in^2	= 645.16 mm^2
Volume:	1 ft^3	= 28.317×10^{-3} m^3
	1 ft^3	= 28.317×10^{3} cm^3
	1 in^3	= 16.387×10^{-6} m^3
	1 in^3	= 16.387 cm^3
Force:	1 lb	= 4.448 N
	1 lb	= 4.448×10^{-3} kN
	1 lb	= 0.4536 kgf
	1 kip	= 4.448 kN
	1 U.S. ton	= 8.896 kN
	1 lb	= 0.4536×10^{-3} metric ton
	1 lb/ft	= 14.593 N/m

Stress:	1 lb/ft^2	= 47.88 N/m^2
	1 lb/ft^2	= 0.04788 kN/m^2
	1 U.S. ton/ft^2	= 95.76 kN/m^2
	1 kip/ft^2	= 47.88 kN/m^2
	1 lb/in^2	= 6.895 kN/m^2
Unit weight:	1 lb/ft^3	= 0.1572 kN/m^3
	1 lb/in^3	= 271.43 kN/m^3
Moment:	1 lb-ft	= 1.3558 N·m
	1 lb-in.	= 0.11298 N·m
Energy:	1 ft-lb	= 1.3558 J
Moment of inertia:	1 in^4	= 0.4162×10^{6} mm^4
	1 in^4	= 0.4162×10^{-6} m^4
Section modulus:	1 in^3	= 0.16387×10^{5} mm^3
	1 in^3	= 0.16387×10^{-4} m^3
Hydraulic conductivity:	1 ft/min	= 0.3048 m/min
	1 ft/min	= 30.48 cm/min
	1 ft/min	= 304.8 mm/min
	1 ft/sec	= 0.3048 m/sec
	1 ft/sec	= 304.8 mm/sec
	1 in./min	= 0.0254 m/min
	1 in./sec	= 2.54 cm/sec
	1 in./sec	= 25.4 mm/sec
Coefficient of consolidation:	1 in^2/sec	= 6.452 cm^2/sec
	1 in^2/sec	= 20.346×10^{3} m^2/yr
	1 ft^2/sec	= 929.03 cm^2/sec

9E

Principles of Foundation Engineering

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To Janice, Rohini, Joe, Valerie, and Elizabeth.

Contents

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3 Natural Soil Deposits and Subsoil Exploration 67

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4 Instrumentation and Monitoring in Geotechnical Engineering 134

7 Ultimate Bearing Capacity of Shallow Foundations: Special Cases 258

8 Vertical Stress Increase in Soil 302

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Part 4 Lateral Earth Pressure and Earth Retaining Structures 637


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Preface

Soil mechanics and foundation engineering have developed rapidly during the last seventy years. Intensive research and observation in the field and the laboratory have refined and improved the science of foundation design. Originally published in the fall of 1983, *Principles of Foundation Engineering* is now in the ninth 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, consistent with the level of understanding of the intended users, have been incorporated into each edition of the text.

NEW TO THIS EDITION

Based on the increased developments in the field of geotechnical engineering, the authors have added three new chapters to this edition. The ninth edition of *Principles of Foundation Engineering* contains a total of 19 chapters. Listed here is a summary of the major revisions from the eighth edition and new additions to this edition.

- Numerous new photographs in full color have been included in various chapters as needed.
- The **Introduction** Chapter (Chapter 1) has been entirely revised and expanded with sections on geotechnical engineering, foundation engineering, soil exploration, ground improvement, solution methods, numerical modeling, empiricism, and literature.
- Chapter 2 on **Geotechnical Properties of Soil** includes new sections on the range of coefficient of consolidation and selection of shear strength parameters for design. All of the end-of-chapter problems are new.
- Chapter 3 on **Natural Soil Deposits and Subsoil Exploration** has an improved figure on soil behavior type chart based on cone penetration test. Approximately half of the end-of-chapter problems are new.
- Chapter 4 on **Instrumentation and Monitoring in Geotechnical Engineering** is a new chapter that describes the use of instruments in geotechnical projects, such as piezometer, earth pressure cell, load cell, inclinometer, settlement plate, strain gauge, and others.
- **Soil Improvement** (Chapter 5) has some details on typical compaction requirements as well as improved figures in the section of precompression. About half of the problems at the end of the chapter are new.
- Chapter 6 on **Shallow Foundations: Ultimate Bearing Capacity** has new sections on a simple approach for bearing capacity with two-way eccentricities, and plane strain correction of friction angle.
- Chapter 7 on **Ultimate Bearing Capacity on Shallow Foundation: Special Cases** has a section on ultimate bearing capacity of a wedge-shaped foundation. About half of the end-of-chapter problems are new.
- Chapter 8 on **Vertical Stress Increase in Soil** has a new section on stress below a horizontal strip load of finite width and infinite length. The majority of the end-of-chapter problems are new.

- In Chapter 9 on **Settlement of Shallow Foundations**, Section 9.3 on settlement based on the theory of elasticity has been thoroughly revised with the addition of the results of the studies of Poulos and Davis (1974) and Giroud (1968). In Section 9.6, which discusses the topic of settlement of foundation on sand based on standard penetration resistance, Terzaghi and Peck's method (1967) has been added. Elastic settlement considering soil stiffness variation with stress level is given in a new section (Section 9.7). Other additions include settlement estimation using the $L_1 - L_2$ method (Section 9.9) (Akbas and Kulhawy, 2009) and Shahriar et al.'s (2014) method to estimate elastic settlement in granular soil due to the rise of ground water table (Section 9.10). The section on tolerable settlement of buildings has been fully revised. More than half of the end-of-chapter problems are new.
- In Chapter 10 on **Mat Foundations**, the reinforcement design portion for the mats was removed to concentrate more on the geotechnical portion. All end-of-chapter problems are new.
- Chapter 11 on **Load and Resistance Factor Design (LRFD)** is a new chapter. It provides the design philosophies of the allowable stress design (ASD) and load and resistance factor design in a simple way.
- Chapter 12 on **Pile Foundations** has a new section defining point bearing and friction piles (Section 12.5). Section 12.5 on installation of piles has been thoroughly revised. Factor of safety for axially loaded piles suggested by USACE (1991) has been incorporated in Section 12.8 on equations for estimating pile capacity. The analysis by Poulos and Davis (1974) for estimation of elastic settlement of piles has been included in Section 9.17. About half of the end-of-chapter problems are new.
- In Chapter 13 on **Drilled Shaft Foundations**, several figures have been improved to aid in better interpolation for solving problems. More than half of the end-of-chapter problems are new.
- Chapter 14 on **Piled Rafts—An Overview** is a new chapter. It describes optimizations of the advantages of pile foundations and raft foundations for construction of very tall buildings.
- In Chapter 15 on **Foundations on Difficult Soil**, all but two of end-of-chapter problems are new.
- Chapter 16 on **Lateral Earth Pressure** has two new sections on (a) generalized case for Rankine seismic active pressure—granular backfill (Section 16.5), and (b) solution for passive earth pressure by lower bound theorem of plasticity (Section 16.15). The section on passive force on walls with earthquake forces (Section 16.7) has been expanded. All end-of-chapter problems are new.
- In Chapter 17 on **Retaining Walls**, a new section (Section 17.10) on gravity retaining wall design for earthquake conditions has been added. Discussion on the properties of geotextile has been expanded along with some new geotextile photographs. More than half of the end-of-chapter problems are new.
- Chapter 18 on S**heet-Pile Walls** has three new sections added: (a) cantilever sheet piles penetrating sandy soil—a simplified approach (Section 18.8); (b) free earth support method for penetration of sandy soil—a simplified approach (Section 18.10); and (c) holding capacity of deadman anchors (Section 18.18). All end-of-chapter problems are new.
- In Chapter 19 on **Braced Cuts**, all end-of-chapter problems are new.
- Each chapter now includes a **Summary** section. New and revised example problems are presented in various chapters as needed.

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A detailed **Instructor's Solutions Manual** containing solutions to all end-of-chapter problems, an **image bank** with figures and tables in the book, and **Lecture Note PowerPoint Slides** are available via a secure, password-protected Instructor Resource Center at https://login.cengage.com.

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ACKNOWLEDGMENTS

- We are deeply grateful to Janice Das for her assistance in completing the revision. She has been the driving force behind this textbook since the preparation of the first edition.
- Special thanks are due to Rohini Sivakugan for her help during the preparation of the manuscript for this edition.
- It is 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.
- We also wish to thank the Global Engineering team at Cengage who worked in the development of this edition. Especially, we would like to extend our thanks to Timothy Anderson, Product Director; Angie Rubino, Associate Content Developer; Kristin Stine, Marketing Manager; and Alexander Sham, Product Assistant.

Braja M. Das

Nagaratnam Sivakugan

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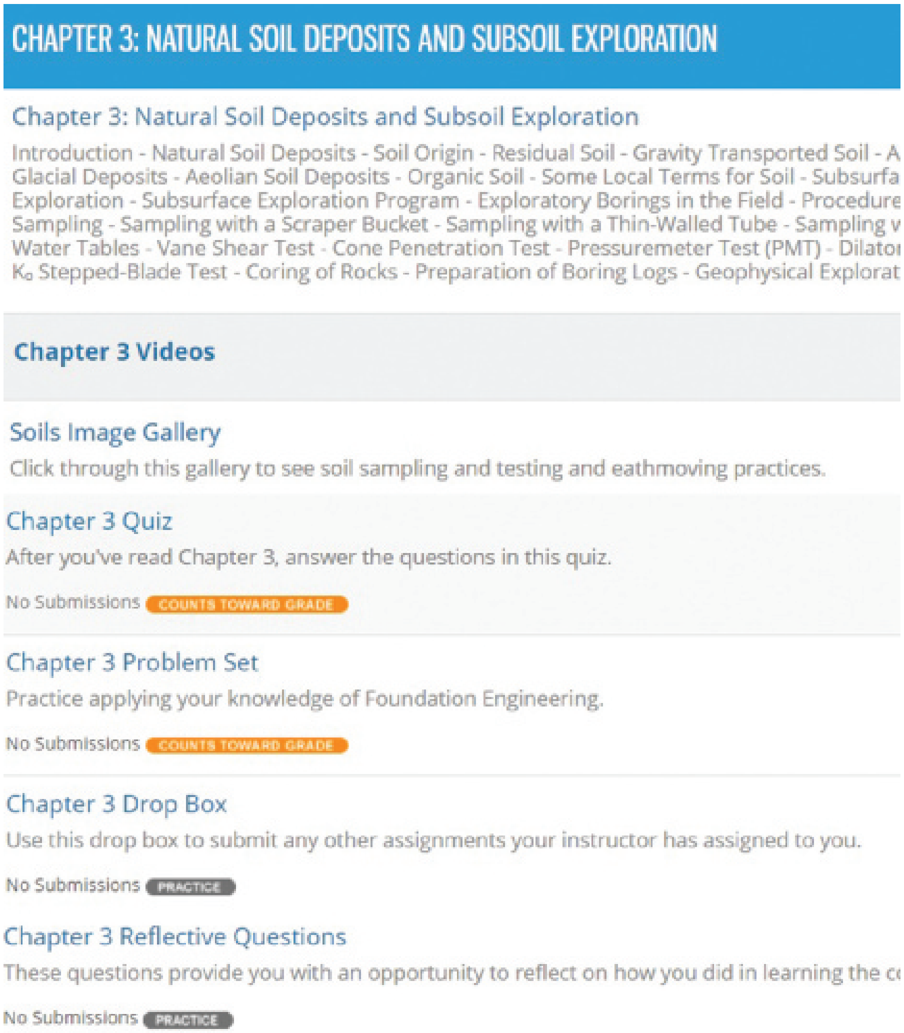

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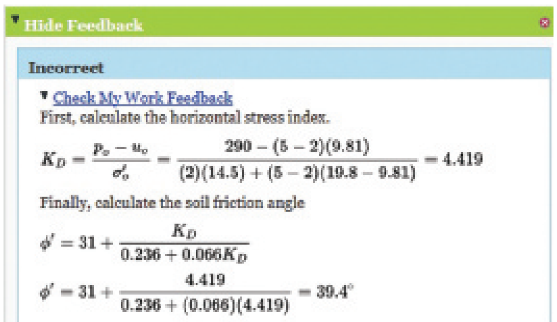

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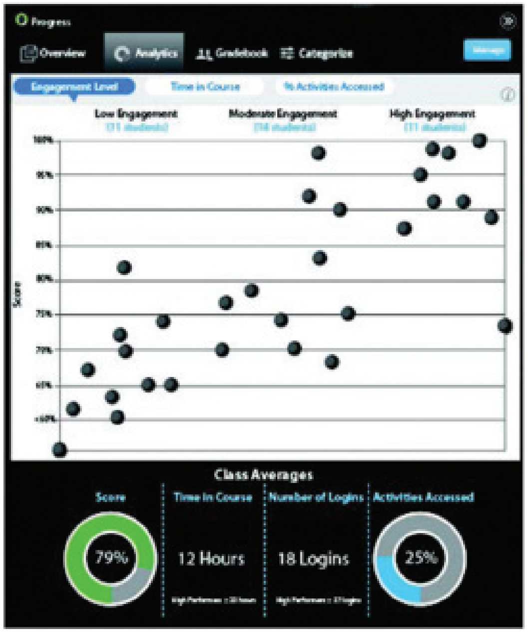

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About the Authors

Dr. Braja Das is Dean Emeritus of the College of Engineering and Computer Science at California State University, Sacramento. He received his B.Sc. degree with honors in Physics and B.Sc. degree in Civil Engineering from Utkal University, India; his M.S. in Civil Engineering from the University of Iowa, Iowa City; and his Ph.D. in Geotechnical Engineering from the University of Wisconsin at Madison. He is the author of a number of geotechnical engineering texts and reference books and more than 300 technical papers. His primary areas of research include shallow foundations, earth anchors, and geosynthetics.

Dr. Das is a Fellow and Life Member of the American Society of Civil Engineers, a Life Member of the American Society for Engineering Education, and an Emeritus Member of the Stabilization of Geomaterials and Recycled Materials Committee of the Transportation Research Board of the National Research Council (Washington DC). He has previously served as a member on the editorial board of the Journal of Geotechnical Engineering of ASCE, a member of the editorial board of Lowland Technology International Journal (Japan), as associate editor of the International Journal of Offshore and Polar Engineering (ISOPE), and as co-editor of the Journal of Geotechnical and Geological Engineering (Springer, The Netherlands). Presently he is the editor-in-chief of the International Journal of Geotechnical Engineering (Taylor & Francis, U.K.). He has received numerous awards for teaching excellence, including the AMOCO Foundation Award, the AT&T Award for Teaching Excellence from the American Society for Engineering Education, the Ralph Teetor Award from the Society of Automotive Engineers, and the Distinguished Achievement Award for Teaching Excellence from the University of Texas at El Paso.

Dr. Das is widely recognized in his field and has been invited as a keynote speaker to multiple conferences worldwide. His prolific career has taken him to Australia, Mexico, the Dominican Republic, Costa Rica, El Salvador, Peru, Colombia, Ecuador, India, Korea, Bolivia, Venezuela, Turkey, the Turkish Republic of North Cyprus, United Arab Emirates, Tunisia, and the United Kingdom. He has also been named as the first Eulalio Juárez Badillo Lecturer by the Mexican Society of Geotechnical Engineers. The Soil-Structure Interaction Group of Egypt established an honor lecture series that takes place once every two years in Egypt. The first lecture was delivered during the Geo-Middle-East Conference in July 2017.

Dr. Nagaratnam Sivakugan received his Bachelor's degree in Civil Engineering from the University of Peradeniya, Sri Lanka, with First Class Honors. He earned his MSCE and Ph.D. from Purdue University, West Lafayette, USA Dr. Sivakugan's writings include eight books, 140 refereed international journal papers, 100 refereed international conference papers, and more than 100 consulting reports. As a registered professional engineer of Queensland and a chartered professional engineer, Dr. Sivakugan does substantial consulting work for the geotechnical and mining industry in Australia and overseas, including the World Bank. He is a Fellow of the American Society of Civil Engineers and Engineers Australia. He has supervised 14 Ph.D. students to completion at James Cook University, Queensland, Australia, where he was the Head of Civil Engineering from 2003 to 2014. He is an Associate Editor for three international journals and serves on the editorial boards of the Canadian Geotechnical Journal and the Indian Geotechnical Journal.

1

Introduction

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1.1 Geotechnical Engineering

Geotechnical engineering, also known as *geomechanics*, is an emerging area in civil engineering. It deals with soil mechanics, with some emphasis on rock mechanics, where we apply engineering principles, such as the theory of elasticity, Mohr's circle, and continuum mechanics, to develop simple solutions that can be applied to geotechnical and foundation engineering problems. When dealing with problems related to *geomaterials*, which include soil, aggregates, and rocks, some knowledge of geology is always an advantage.

A thorough understanding of the geotechnical engineering fundamentals is a prerequisite for studying foundation engineering. These include phase relations, soil classification, compaction, permeability, seepage, consolidation, shear strength, slope stability, and soil exploration. These areas are covered in *Principles of Geotechnical Engineering* (9th Edition) in good detail. The main points are discussed very briefly in Chapters 2 and 3 in Part 1 of this text.

A new chapter on *geotechnical instrumentation* is included in this edition as Chapter 4 in Part 1. When projects become complex or the design or construction methods are nonstandard, it is often advisable to use instruments and measure the loads, stresses, deformations, and strains at critical locations and monitor them over a certain period to ensure the performance of the structure is satisfactory. This new chapter gives an overview of the major instruments used in geotechnical engineering.

1.2 Foundation Engineering

Every civil engineering project has some geotechnical or foundation engineering component. This includes all earth and earth-supported structures, namely, *foundations* and *earth-retaining structures*, the two broad categories discussed in this book. The related chapters are bundled into Parts 3 and 4, respectively. Under foundations (Part 3), shallow foundations and deep foundations are discussed. In this edition, a new chapter is introduced on the *load and resistance factor design* (LRFD) method, which is quite different compared to the traditional *allowable stress design* (ASD) method that has been used by geotechnical engineers for decades. The LRFD was initially brought into practice by the American Concrete Institute (ACI) in the 1960s. It is widely used in structural engineering and is becoming popular in foundation engineering applications such as footings, piles, and retaining walls. The main difference between LRFD and ASD is the way the safety factor is applied.

A new introductory chapter on piled-raft foundations is included in this edition (Chapter 14). Piled rafts exploit the advantages of piles and rafts, two different types of foundations. For tall buildings, they appear to give economical solutions compared to those given by rafts or piles alone.

Retaining walls, sheet piles, and braced cuts are covered under earth-retaining structures in Part 4.

1.3 Soil Exploration

All geotechnical designs require knowledge of the soil and rock properties in the vicinity of the structure. These are determined through a *soil exploration* (also known as *site investigation*) program that consists of (a) *in situ* tests, (b) sampling at the

FIGURE 1.1 Soil exploration program (Courtesy of N. Sivakugan, James Cook University, Australia)

site, and (c) laboratory tests on the samples taken from the site. Based on the soil exploration data, a simplified soil profile can be developed, which can be the basis for geotechnical designs. Figure 1.1 shows drilling in progress as part of a subsoil investigation.

The heterogeneous nature of the ground conditions and the spatial variability in the soil properties make it difficult to assign the design parameters to a simplified soil model. Every borehole and its associated tests can cost thousands of dollars to the client, and it is often the case that our wish list is longer than what the budget permits. Therefore, it is prudent to plan the soil exploration program to extract the maximum possible data from the ground that is relevant to the project at a reasonable cost.

Due to budgetary constraints, it is sometimes necessary to strike a balance between laboratory and *in situ* tests. The same parameters can be determined by laboratory or *in situ* tests. Some good geotechnical judgment is required here to select the right tests. Laboratory and *in situ* tests must complement each other. One should never be chosen at the expense of the other. They have their own advantages and disadvantages.

1.4 Ground Improvement

When designing a beam or a bridge, an engineer has the luxury of specifying the strength of concrete. The same thing applies to most engineering materials. When it comes to soil, the situation is different. Once the site is identified, one has to design the structure to suit the soil conditions. Any attempt to replace the soil with a better-performing soil can be an expensive option. However, the existing ground can be improved through one of the many ground improvement techniques.

Very often, the soil conditions at a site do not meet the design requirements in their present form. The soil may be too weak, undergo excessive deformations, and/or lead to possible failure. Even if the soil at the surface is suitable, the subsoil conditions may be unfavorable. Designing the structure or facility to suit the existing soil conditions is not necessarily the best option. Instead, improving the ground and looking for more economical alternatives can save millions of dollars.

Compaction is a simple and inexpensive ground improvement technique that works on all types of soil. Figure 1.2 shows some soil compaction in progress for a highway construction project. The other ground improvement techniques include

FIGURE 1.2 Soil compaction for a highway construction project (Courtesy of N. Sivakugan, James Cook University, Australia)

vibroflotation, dynamic compaction, blasting, preloading, vertical drains, lime/cement stabilization, stone columns, jet grouting, and deep mixing. They are discussed briefly in Chapter 5 (Part 2).

1.5 Solution Methods

In geotechnical or foundation engineering, there are three ways of solving a problem. They are:

- analytical methods
- physical modeling
- numerical modeling

For simple problems, similar to those discussed in textbooks, it is possible to apply the geotechnical engineering principles and the closed form solutions available in the literature. This applies to situations where the soil conditions are relatively uniform and the boundary conditions are well defined. In some instances, it is also possible to build a small scale model that can be tested in the laboratory to investigate the different scenarios. This is known as physical modeling. In larger projects, where the soil conditions and the boundary conditions are complex, it is difficult to apply the geotechnical theories and arrive at closed form solutions. Here, numerical modeling becomes a valuable tool. Once the model is developed, it can be used to carry out a thorough sensitivity analysis, exploring the effects of different parameters on the performance of the structure.

1.6 Numerical Modeling

Soil is a *particulate* medium. For simplicity it is treated as a *continuum*, which is assumed to follow one of the many *constitutive models* such as Mohr–Coulomb, linear elastic, nonlinear elastic, Cam Clay, or Drucker–Prager. These constitutive models define how the soil behaves. The *boundary conditions* define the loadings and displacements at the boundaries of the region of interest.

In large projects, the boundary conditions 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 can be carried out on foundations, retaining walls, dams, and other earth-supported structures. This 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 are specified to the problem domain, and equations are developed for the nodes/elements. By solving these equations, the variables at the nodes/elements are determined.

There are people who write their own finite element program to solve a specific 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 programs tailored for geotechnical applications, such as those developed by GEO-SLOPE International Ltd. (http://www.geo-slope.com), Soil Vision Systems Ltd. (http://www.soilvision.com), and GGU-Software (http://www.ggu-software.com). In addition, some of the more powerful software packages developed for structural, material, and concrete engineering also have the ability to model geotechnical problems. *Abaqus*® and *Ansys*® are two such finite element packages that are widely used in universities for teaching and research.

1.7 Empiricism

Experience, intuition, and judgment play a major role in geotechnical engineering. In addition to what has been developed through rational theories in soil and rock mechanics, there are many lessons learned through decades of experience, which help in fine-tuning these theoretical developments that may have been oversimplified. Empiricism is knowledge developed through experience, intuition, and judgment, often backed by reliable data.

There are literally hundreds of empirical correlations in the form of equations or charts that can be used in deriving soil properties. They were developed from large databases and are very valuable in the preliminary design stages, when limited soil data are available. These are derived based on laboratory or field data, past experience, and good judgment.

Geotechnical data, whether from the field or laboratory, can be quite expensive. We often have access to very limited field data [e.g., Standard Penetration Test (SPT)] from a limited number of boreholes, along with some laboratory test data on samples obtained from these boreholes and/or trial pits. We use the empirical correlations sensibly to complement the site investigation program and, hence, extract the maximum possible information from the limited laboratory and field data.

1.8 Literature

There are times when one is expected to go beyond what is covered in textbooks. When you are carrying out research on a new topic or trying to learn more about something covered only briefly in the textbook, a thorough literature review is necessary. A Web search can be a good start in locating some literature. There are also specialized geotechnical journals and conference proceedings that discuss the latest developments.

The U.S. Army, Navy, and Air Force do excellent engineering work and invest significantly in research and development. Their design guides, empirical equations, and charts are well proven and tested. They are generally conservative, which is desirable in engineering practice. Most of these manuals are available for free download. They (e.g., NAVFAC 7.1) are valuable additions to your professional libraries. The *Canadian Foundation Engineering Manual* (Canadian Geotechnical Society 2006), Kulhawy and Mayne (1990), and Ameratunga et al. (2016) have collated and critically reviewed the empirical correlations relating the soil and rock properties derived from laboratory and *in situ* tests.

REFERENCES

Ameratunga, J., Sivakugan, N., and Das, B. M. (2016). *Correlations of Soil and Rock Properties in Geotechnical Engineering*, Springer, New Delhi, India.

Canadian Geotechnical Society (2006). *Canadian Foundation Engineering Manual*, 4th ed., BiTech Publisher Ltd., British Columbia, Canada.

Kulhawy, F. H. and Mayne, P. W. (1990). *Manual on Estimating Soil Properties for Foundation Design*, Final Report 1493-6, ET-6800, Electric Power Research Institute (EPRI), Palo Alto, CA.

PART 1

Geotechnical Properties and Soil Exploration