

Principles of

FOUNDATION ENGINEERING

Eighth Edition

Braja M. Das





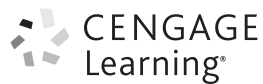
Principles of Foundation Engineering



Principles of Foundation Engineering

Eighth Edition

Braja M. Das



Australia • Brazil • Japan • Korea • Mexico • Singapore • Spain • United Kingdom • United States

This is an electronic version of the print textbook. Due to electronic rights restrictions, some third party content may be suppressed. Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. The publisher reserves the right to remove content from this title at any time if subsequent rights restrictions require it. For valuable information on pricing, previous editions, changes to current editions, and alternate formats, please visit www.cengage.com/highered to search by ISBN#, author, title, or keyword for materials in your areas of interest.

**Principles of Foundation Engineering,
Eighth Edition****Braja M. Das**Publisher, Global Engineering:
Timothy L. AndersonSenior Developmental Editors:
Hilda Gowans

Development Editor: Eavan Cully

Media Assistant: Ashley Kaupert

Team Assistant: Sam Roth

Marketing Manager: Kristin Stine

Director Content and Media Production:
Sharon SmithSenior Content Project Manager:
Kim Kusnerak

Marketing Manager: Kristin Stine

Production Service: RPK Editorial
Services, Inc.

Compositor: MPS Limited

IP Analyst: Christine Myaskovsky

IP Project Manager: Sarah Shainwald

Text and Image Permissions Researcher:
Kristiina Paul

Manufacturing Planner: Doug Wilke

Senior Art Director: Michelle Kunkler

Cover Designer: Tin Box Studio

Internal Designer: RPK Editorial
Services, Inc.

Copyeditor: Shelly Gerger-Knechtl

Proofreader: Martha McMaster

Indexer: Braja M. Das

Cover Image: The Reinforced Earth
Company (RECo). Photo taken by
Chris Clements (RECo).

© 2016, 2012 Cengage Learning

WCN: 02-200-203

ALL RIGHTS RESERVED. No part of this work covered by the copyright herein may be reproduced, transmitted, stored, or used in any form or by any means graphic, electronic, or mechanical, including but not limited to photocopying, recording, scanning, digitizing, taping, web distribution, information networks, or information storage and retrieval systems, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without the prior written permission of the publisher.

For product information and technology assistance, contact us at
Cengage Learning Customer & Sales Support, 1-800-354-9706.

For permission to use material from this text or product,
submit all requests online at www.cengage.com/permissions.
Further permissions questions can be emailed to
permissionrequest@cengage.com.

Library of Congress Control Number: 2014947850

ISBN-13: 978-1-305-08155-0

Cengage Learning20 Channel Center Street,
Boston, MA 02210
USA

Cengage Learning is a leading provider of customized learning solutions with office locations around the globe, including Singapore, the United Kingdom, Australia, Mexico, Brazil, and Japan. Locate your local office at: www.cengage.com/global.

Cengage Learning products are represented in Canada by
Nelson Education Ltd.

For your course and learning solutions, visit
www.cengage.com/engineering.

Purchase any of our products at your local college store or at our
preferred online store www.cengagebrain.com

Unless otherwise noted, all items © Cengage Learning.

Unless otherwise stated, all photos © Braja M. Das.

Printed in the United States of America

Print Number: 01 Print Year: 2014

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



Contents

Preface xvii

7

Introduction 1

- 1.1 Geotechnical Engineering 1
- 1.2 Foundation Engineering 1
- 1.3 General Format of the Text 2
- 1.4 Design Methods 2
- 1.5 Numerical Methods in Geotechnical Engineering 4
- References 4

PART 1 Geotechnical Properties and Exploration of Soil 5

2

Geotechnical Properties of Soil 7

- 2.1 Introduction 7
- 2.2 Grain-Size Distribution 8
- 2.3 Size Limits for Soils 11
- 2.4 Weight–Volume Relationships 11
- 2.5 Relative Density 16
- 2.6 Atterberg Limits 22
- 2.7 Liquidity Index 23
- 2.8 Activity 23
- 2.9 Soil Classification Systems 24
- 2.10 Hydraulic Conductivity of Soil 32
- 2.11 Steady-State Seepage 37
- 2.12 Effective Stress 39
- 2.13 Consolidation 41

2.14	Calculation of Primary Consolidation Settlement	47
2.15	Time Rate of Consolidation	48
2.16	Degree of Consolidation Under Ramp Loading	55
2.17	Shear Strength	57
2.18	Unconfined Compression Test	63
2.19	Comments on Friction Angle, ϕ'	64
2.20	Correlations for Undrained Shear Strength, c_u	67
2.21	Sensitivity	68
	Problems	69
	References	74

3 Natural Soil Deposits and Subsoil Exploration 76

3.1 Introduction 76

Natural Soil Deposits 76

- 3.2 Soil Origin 76
- 3.3 Residual Soil 78
- 3.4 Gravity Transported Soil 79
- 3.5 Alluvial Deposits 80
- 3.6 Lacustrine Deposits 82
- 3.7 Glacial Deposits 82
- 3.8 Aeolian Soil Deposits 83
- 3.9 Organic Soil 85
- 3.10 Some Local Terms for Soils 85

Subsurface Exploration 86

- 3.11 Purpose of Subsurface Exploration 86
- 3.12 Subsurface Exploration Program 86
- 3.13 Exploratory Borings in the Field 89
- 3.14 Procedures for Sampling Soil 93
- 3.15 Split-Spoon Sampling 93
- 3.16 Sampling with a Scraper Bucket 103
- 3.17 Sampling with a Thin-Walled Tube 104
- 3.18 Sampling with a Piston Sampler 106
- 3.19 Observation of Water Tables 106
- 3.20 Vane Shear Test 108
- 3.21 Cone Penetration Test 113
- 3.22 Pressuremeter Test (PMT) 122
- 3.23 Dilatometer Test 125
- 3.24 Iowa Borehole Shear Test 129
- 3.25 K_0 Stepped-Blade Test 131

3.26	Coring of Rocks	132
3.27	Preparation of Boring Logs	136
3.28	Geophysical Exploration	136
3.29	Subsoil Exploration Report	145
	Problems	145
	References	150

PART 2 Foundation Analysis 153

4

Shallow Foundations: Ultimate Bearing Capacity 155

4.1	Introduction	155
4.2	General Concept	155
4.3	Terzaghi's Bearing Capacity Theory	160
4.4	Factor of Safety	165
4.5	Modification of Bearing Capacity Equations for Water Table	167
4.6	The General Bearing Capacity Equation	168
4.7	Other Solutions for Bearing Capacity $N\gamma$, Shape, and Depth Factors	175
4.8	Case Studies on Ultimate Bearing Capacity	178
4.9	Effect of Soil Compressibility	184
4.10	Eccentrically Loaded Foundations	188
4.11	Ultimate Bearing Capacity under Eccentric Loading—One-Way Eccentricity	189
4.12	Bearing Capacity—Two-Way Eccentricity	196
4.13	Bearing Capacity of a Continuous Foundation Subjected to Eccentrically Inclined Loading	205
	Problems	208
	References	211

5

Ultimate Bearing Capacity of Shallow Foundations: Special Cases 213

5.1	Introduction	213
5.2	Foundation Supported by a Soil with a Rigid Base at Shallow Depth	213
5.3	Foundations on Layered Clay	221
5.4	Bearing Capacity of Layered Soils: Stronger Soil Underlain by Weaker Soil ($c' - \phi'$ soil)	225
5.5	Bearing Capacity of Layered Soil: Weaker Soil Underlain by Stronger Soil	233
5.6	Continuous Foundation on Weak Clay with a Granular Trench	236

5.7	Closely Spaced Foundations—Effect on Ultimate Bearing Capacity	239
5.8	Bearing Capacity of Foundations on Top of a Slope	240
5.9	Bearing Capacity of Foundations on a Slope	245
5.10	Seismic Bearing Capacity and Settlement in Granular Soil	247
5.11	Foundations on Rock	251
5.12	Uplift Capacity of Foundations	253
	Problems	259
	References	261

6

Vertical Stress Increase in Soil 263

6.1	Introduction	263
6.2	Stress Due to a Concentrated Load	264
6.3	Stress Due to a Circularly Loaded Area	264
6.4	Stress Due to a Line Load	266
6.5	Stress below a Vertical Strip Load (Finite Width and Infinite Length)	267
6.6	Stress below a Rectangular Area	272
6.7	Stress Isobars	277
6.8	Average Vertical Stress Increase Due to a Rectangularly Loaded Area	278
6.9	Average Vertical Stress Increase below the Center of a Circularly Loaded Area	284
6.10	Stress Increase under an Embankment	287
6.11	Westergaard's Solution for Vertical Stress Due to a Point Load	291
6.12	Stress Distribution for Westergaard Material	293
	Problems	295
	References	298

7

Settlement of Shallow Foundations 299

7.1	Introduction	299
7.2	Elastic Settlement of Shallow Foundation on Saturated Clay ($\mu_s = 0.5$)	299
	<i>Elastic Settlement in Granular Soil</i>	302
7.3	Settlement Based on the Theory of Elasticity	302
7.4	Improved Equation for Elastic Settlement	310
7.5	Settlement of Sandy Soil: Use of Strain Influence Factor	315

- 7.6 Settlement of Foundation on Sand Based on Standard Penetration Resistance 324
- 7.7 Settlement in Granular Soil Based on Pressuremeter Test (PMT) 328
- 7.8 Effect of the Rise of Water Table on Elastic Settlement 334

Consolidation Settlement 336

- 7.9 Primary Consolidation Settlement Relationships 336
- 7.10 Three-Dimensional Effect on Primary Consolidation Settlement 337
- 7.11 Settlement Due to Secondary Consolidation 342
- 7.12 Field Load Test 344
- 7.13 Presumptive Bearing Capacity 346
- 7.14 Tolerable Settlement of Buildings 347
- Problems 349
- References 351

8

Mat Foundations 353

- 8.1 Introduction 353
- 8.2 Combined Footings 353
- 8.3 Common Types of Mat Foundations 358
- 8.4 Bearing Capacity of Mat Foundations 360
- 8.5 Differential Settlement of Mats 364
- 8.6 Field Settlement Observations for Mat Foundations 364
- 8.7 Compensated Foundation 366
- 8.8 Structural Design of Mat Foundations 369
- Problems 388
- References 390

9

Pile Foundations 391

- 9.1 Introduction 391
- 9.2 Types of Piles and Their Structural Characteristics 393
- 9.3 Continuous Flight Auger (CFA) Piles 402
- 9.4 Estimating Pile Length 403
- 9.5 Installation of Piles 404
- 9.6 Load Transfer Mechanism 407
- 9.7 Equations for Estimating Pile Capacity 411
- 9.8 Meyerhof's Method for Estimating Q_p 414
- 9.9 Vesic's Method for Estimating Q_p 417
- 9.10 Coyle and Castello's Method for Estimating Q_p in Sand 421

9.11	Correlations for Calculating Q_p with SPT and CPT Results in Granular Soil	424
9.12	Frictional Resistance (Q_s) in Sand	426
9.13	Frictional (Skin) Resistance in Clay	433
9.14	Ultimate Capacity of Continuous Flight Auger Pile	438
9.15	Point Bearing Capacity of Piles Resting on Rock	441
9.16	Pile Load Tests	448
9.17	Elastic Settlement of Piles	453
9.18	Laterally Loaded Piles	456
9.19	Pile-Driving Formulas	470
9.20	Pile Capacity For Vibration-Driven Piles	476
9.21	Wave Equation Analysis	477
9.22	Negative Skin Friction	481
<hr/>		
	<i>Group Piles</i>	485
9.23	Group Efficiency	485
9.24	Ultimate Capacity of Group Piles in Saturated Clay	488
9.25	Elastic Settlement of Group Piles	491
9.26	Consolidation Settlement of Group Piles	493
9.27	Piles in Rock	496
	Problems	496
	References	502

10

Drilled-Shaft Foundations 505

10.1	Introduction	505
10.2	Types of Drilled Shafts	506
10.3	Construction Procedures	507
10.4	Other Design Considerations	513
10.5	Load Transfer Mechanism	514
10.6	Estimation of Load-Bearing Capacity	514
10.7	Drilled Shafts in Granular Soil: Load-Bearing Capacity	516
10.8	Load-Bearing Capacity Based on Settlement	520
10.9	Drilled Shafts in Clay: Load-Bearing Capacity	529
10.10	Load-Bearing Capacity Based on Settlement	531
10.11	Settlement of Drilled Shafts at Working Load	536
10.12	Lateral Load-Carrying Capacity—Characteristic Load and Moment Method	538
10.13	Drilled Shafts Extending into Rock	547
	Problems	552
	References	556

11**Foundations on Difficult Soils 557****11.1 Introduction 557***Collapsible Soil 557***11.2 Definition and Types of Collapsible Soil 557****11.3 Physical Parameters for Identification 558****11.4 Procedure for Calculating Collapse Settlement 562****11.5 Foundation Design in Soils Not Susceptible to Wetting 563****11.6 Foundation Design in Soils Susceptible to Wetting 565***Expansive Soils 566***11.7 General Nature of Expansive Soils 566****11.8 Unrestrained Swell Test 570****11.9 Swelling Pressure Test 571****11.10 Classification of Expansive Soil on the Basis of Index Tests 576****11.11 Foundation Considerations for Expansive Soils 580****11.12 Construction on Expansive Soils 582***Sanitary Landfills 587***11.13 General Nature of Sanitary Landfills 587****11.14 Settlement of Sanitary Landfills 588**

Problems 590

References 591

PART 3 Lateral Earth Pressure and Earth-Retaining Structures 593**12****Lateral Earth Pressure 595****12.1 Introduction 595****12.2 Lateral Earth Pressure at Rest 596***Active Pressure 600***12.3 Rankine Active Earth Pressure 600****12.4 A Generalized Case for Rankine Active Pressure—Granular Backfill 605****12.5 Rankine Active Pressure with Vertical Wall Backface and Inclined $c' - \phi'$ Soil Backfill 610****12.6 Coulomb's Active Earth Pressure 614****12.7 Lateral Earth Pressure Due to Surcharge 621**

12.8 Active Earth Pressure for Earthquake Conditions—Granular Backfill 625

12.9 Active Earth Pressure for Earthquake Condition (Vertical Backface of Wall and $c' - \phi'$ Backfill) 629

Passive Pressure 634

12.10 Rankine Passive Earth Pressure 634

12.11 Rankine Passive Earth Pressure—Vertical Backface and Inclined Backfill 637

12.12 Coulomb's Passive Earth Pressure 639

12.13 Comments on the Failure Surface Assumption for Coulomb's Pressure Calculations 641

12.14 Caquot and Kerisel Solution for Passive Earth Pressure (Granular Backfill) 642

12.15 Passive Pressure under Earthquake Conditions 645

Problems 647

References 648

13 Retaining Walls 650

13.1 Introduction 650

Gravity and Cantilever Walls 652

13.2 Proportioning Retaining Walls 652

13.3 Application of Lateral Earth Pressure Theories to Design 653

13.4 Stability of Retaining Walls 655

13.5 Check for Overturning 657

13.6 Check for Sliding along the Base 659

13.7 Check for Bearing Capacity Failure 663

13.8 Construction Joints and Drainage from Backfill 671

13.9 Comments on Design of Retaining Walls and a Case Study 674

Mechanically Stabilized Retaining Walls 677

13.10 Soil Reinforcement 677

13.11 Considerations in Soil Reinforcement 678

13.12 General Design Considerations 680

13.13 Retaining Walls with Metallic Strip Reinforcement 681

13.14 Step-by-Step-Design Procedure Using Metallic Strip Reinforcement 688

13.15 Retaining Walls with Geotextile Reinforcement 693

- 13.16 Retaining Walls with Geogrid Reinforcement—General 700
- 13.17 Design Procedure for Geogrid-Reinforced Retaining Wall 700
- Problems 705
- References 707

14**Sheet-Pile Walls 709**

- 14.1 Introduction 709
- 14.2 Construction Methods 712
- 14.3 Cantilever Sheet-Pile Walls 714
- 14.4 Cantilever Sheet Piling Penetrating Sandy Soils 715
- 14.5 Special Cases for Cantilever Walls Penetrating a Sandy Soil 721
- 14.6 Cantilever Sheet Piling Penetrating Clay 725
- 14.7 Special Cases for Cantilever Walls Penetrating Clay 730
- 14.8 Anchored Sheet-Pile Walls 734
- 14.9 Free Earth Support Method for Penetration of Sandy Soil 735
- 14.10 Design Charts for Free Earth Support Method (Penetration into Sandy Soil) 739
- 14.11 Moment Reduction for Anchored Sheet-Pile Walls Penetrating into Sand 743
- 14.12 Computational Pressure Diagram Method for Penetration into Sandy Soil 746
- 14.13 Field Observations for Anchor Sheet-Pile Walls 750
- 14.14 Free Earth Support Method for Penetration of Clay 752
- 14.15 Anchors 759
- 14.16 Holding Capacity of Anchor Plates in Sand 759
- 14.17 Holding Capacity of Anchor Plates in Clay ($\phi = 0$ Condition) 768
- 14.18 Ultimate Resistance of Tiebacks 769
- Problems 770
- References 773

15**Braced Cuts 774**

- 15.1 Introduction 774
- 15.2 Braced Cut Analysis Based on General Wedge Theory 775
- 15.3 Pressure Envelope for Braced-Cut Design 780
- 15.4 Pressure Envelope for Cuts in Layered Soil 782
- 15.5 Design of Various Components of a Braced Cut 783
- 15.6 Case Studies of Braced Cuts 793
- 15.7 Bottom Heave of a Cut in Clay 798

15.8	Stability of the Bottom of a Cut in Sand	802
15.9	Lateral Yielding of Sheet Piles and Ground Settlement	807
	Problems	809
	References	811

PART 4 Soil Improvement 813

16 Soil Improvement and Ground Modification 815

16.1	Introduction	815
16.2	General Principles of Compaction	816
16.3	Empirical Relationships for Compaction	819
16.4	Field Compaction	822
16.5	Compaction Control for Clay Hydraulic Barriers	825
16.6	Vibroflotation	828
16.7	Blasting	834
16.8	Precompression	836
16.9	Sand Drains	840
16.10	Prefabricated Vertical Drains	851
16.11	Lime Stabilization	857
16.12	Cement Stabilization	859
16.13	Fly-Ash Stabilization	861
16.14	Stone Columns	862
16.15	Sand Compaction Piles	867
16.16	Dynamic Compaction	869
16.17	Jet Grouting	871
16.18	Deep Mixing	873
	Problems	876
	References	878

Appendix 881

Answers to Problems 900

Index 912



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 significant 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.

- Personalize the Learning Path to match the course syllabus by rearranging content, hiding sections, or appending original material to the textbook content

- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student progress and comprehension with the Progress app
- 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.

Acknowledgements

Thanks are due to:

- The following reviewers for their comments and constructive suggestions:

Mohamed Sherif Aggour, University of Maryland, College Park

Paul J. Cosentino, Florida Institute of Technology

Jinyuan Liu, Ryerson University

Zhe Luo, Clemson University

Robert Mokwa, Montana State University

Krishna R. Reddy, University of Illinois at Chicago

Cumaraswamy Vipulanandan, University of Houston

- Henry Ng of hkn Engineers, El Paso, Texas, for his help and advice in completing the reinforced concrete design examples given in Appendix A.
- Dr. Richard L. Handy, Distinguished Professor Emeritus in the Department of Civil, Construction, and Environmental Engineering at Iowa State University, for his continuous encouragement and for providing several photographs used in this edition.
- Dr. Nagaratnam Sivakugan of James Cook University, Australia, and Dr. Khaled Sobhan of Florida Atlantic University, for help and advice in the development of the revision outline.
- Several individuals in Cengage Learning, for their assistance and advice in the final development of the book—namely:

Tim Anderson, Publisher

Hilda Gowans, Senior Development Editor

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 generally 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

$$Q_{all} = \frac{Q_u}{FS} \quad (1.1)$$

According to ASD,

$$Q_{design} \leq Q_{all} \quad (1.2)$$

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

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

where

Q_u = factored nominal load

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

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

$$Q_u \leq \phi Q_n \quad (1.4)$$

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,

$$Q_n = q_u(A) = q_u B^2 \quad (1.5)$$

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,

$$Q_u \leq \phi q_u B^2 \quad (1.6)$$

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.

References

- AASHTO (1994). *LRFD Bridge Design Specifications*, 1st Ed., American Association of State Highway and Transportation Officials, Washington, D.C.
- AASHTO (1998). *LRFD Bridge Design Specifications*, 2nd Ed., American Association of State Highway and Transportation Officials, Washington, D.C.
- ACI (2002). *Building Code Requirements for Structural Concrete (318-02) and Commentary (318R-02)*, American Concrete Institute, Detroit, Michigan.
- API (1993). *Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms—Working Stress Design, APR RP 2A*, 20th Ed., American Petroleum Institute, Washington, D.C.



PART 1

Geotechnical Properties and Exploration of Soil



Chapter 2: Geotechnical Properties of Soil

Chapter 3: Natural Soil Deposits and Subsoil Exploration



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

$$C_u = \frac{D_{60}}{D_{10}} \quad (2.1)$$

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

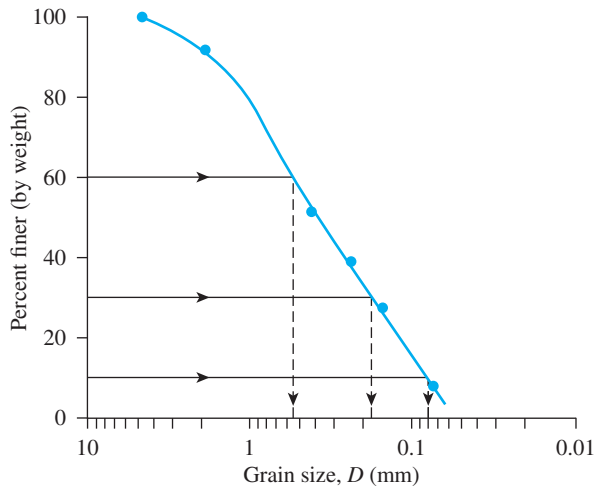


Figure 2.1 Grain-size distribution curve of a coarse-grained soil obtained from sieve analysis

and

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

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