

FIFTH EDITION

FUNDAMENTALS OF GEOTECHNICAL ENGINEERING



BRAJA M. DAS | NAGARATNAM SIVAKUGAN



Fundamentals of Geotechnical Engineering

Fifth Edition



Fundamentals of Geotechnical Engineering

Fifth Edition

Braja M. Das

Dean Emeritus, California State University
Sacramento, California, USA

Nagaratnam Sivakugan

Associate Professor, College of Science, Technology & Engineering
James Cook University, Queensland, Australia



CENGAGE
Learning®

Australia • Brazil • Mexico • Singapore • 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.

Important Notice: Media content referenced within the product description or the product text may not be available in the eBook version.

**Fundamentals of Geotechnical
Engineering, Fifth Edition**
Braja M. Das and Nagaratnam Sivakugan

Product Director, Global Engineering:
Timothy L. Anderson

Senior Content Developer: Mona Zeftel

Media Assistant: Ashley Kaupert

Product Assistant: Alexander Sham

Marketing Manager: Kristin Stine

Director, Content and Media Production:
Sharon L. Smith

Senior Content Project Manager:
Kim Kusnerak

Production Service: RPK Editorial
Services, Inc.

Copyeditor: Harlan James

Proofreader: Martha McMaster

Indexer: Braja Das

Compositor: MPS Limited

Senior Art Director: Michelle Kunkler

Internal Designer: Carmela Pereira

Cover Designer: Tin Box Studios

Cover Image: Rohini Sivakugan

Intellectual Property

Analyst: Christine Myaskovsky

Project Manager: Sarah Shainwald

Text and Image Permissions Researcher:
Kristiina Paul

Senior Manufacturing Planner: Doug Wilke

© 2017, 2013 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: 2015937334

ISBN-13: 978-1-305-63518-0

Cengage Learning

20 Channel Center Street
Boston, MA 02210
USA

Cengage Learning is a leading provider of customized learning solutions with employees residing in nearly 40 different countries and sales in more than 125 countries around the world. Find your local representative at www.cengage.com

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

To learn more about Cengage 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.

The cover photograph by Rohini Sivakugan is of the Shin-Meishin Expressway construction near Kyoto, Japan. This section connects Kobe and Takatsuki. The construction site is closer to Takatsuki.

Printed in the United States of America
Print Number: 01 Print Year: 2015

To Janice, Rohini, Joe,
Valerie and Elizabeth



Contents

1	GEOTECHNICAL ENGINEERING— FROM THE BEGINNING	1
1.1	Introduction	1
1.2	Geotechnical Engineering Prior to the 18th Century	2
1.3	Preclassical Period of Soil Mechanics (1700–1776)	5
1.4	Classical Soil Mechanics—Phase I (1776–1856)	6
1.5	Classical Soil Mechanics—Phase II (1856–1910)	6
1.6	Modern Soil Mechanics (1910–1927)	7
1.7	Geotechnical Engineering after 1927	8
1.8	End of an Era	14
	References	15
2	SOIL DEPOSITS—ORIGIN, GRAIN-SIZE, AND SHAPE	17
2.1	Introduction	17
2.2	Rock Cycle and the Origin of Soil	17
2.3	Soil Deposits—General	25
2.4	Residual Soil	25
2.5	Gravity-Transported Soil	25
2.6	Alluvial Deposits	26
2.7	Lacustrine Deposits	28

2.8	Glacial Deposits	28
2.9	Aeolian Soil Deposits	29
2.10	Organic Soil	30
2.11	Soil-Grain Size	30
2.12	Clay Minerals	32
2.13	Specific Gravity (G_s)	36
2.14	Mechanical Analysis of Soil	37
2.15	Sieve Analysis	37
2.16	Hydrometer Analysis	40
2.17	Effective Size, Uniformity Coefficient, and Coefficient of Gradation	44
2.18	Grain Shape	50
2.19	Summary	51
	Problems	51
	Critical Thinking Problem	54
	References	55

3 WEIGHT–VOLUME RELATIONSHIPS AND PLASTICITY 56

3.1	Introduction	56
3.2	Weight–Volume Relationships	56
3.3	Relationships among Unit Weight, Void Ratio, Moisture Content, and Specific Gravity	60
3.4	Relationships among Unit Weight, Porosity, and Moisture Content	62
3.5	Various Unit Weight Relationships	64
3.6	Relative Density	70
3.7	Consistency of Soil	73
3.8	Activity	81
3.9	Liquidity Index	82
3.10	Plasticity Chart	83
3.11	Summary	84
	Problems	84
	Critical Thinking Problems	87
	References	87

4 SOIL CLASSIFICATION 89

4.1	Introduction	89
4.2	AASHTO Classification System	89
4.3	Unified Soil Classification System (USCS)	93
4.4	Visual Identification of Soils	100
4.5	Summary	101
	Problems	101
	Critical Thinking Problems	103
	References	103

5 SOIL COMPACTION 104

- 5.1 Introduction 104
- 5.2 Compaction—General Principles 104
- 5.3 Standard Proctor Test 105
- 5.4 Factors Affecting Compaction 109
- 5.5 Modified Proctor Test 111
- 5.6 Empirical Relationships 115
- 5.7 Field Compaction 118
- 5.8 Specifications for Field Compaction 120
- 5.9 Determination of Field Unit Weight after Compaction 122
- 5.10 Effect of Compaction on Cohesive Soil Properties 124
- 5.11 Other Ground Improvement Methods 126
- 5.12 Summary 128
 - Problems 128
 - Critical Thinking Problem 132
 - References 133

6 HYDRAULIC CONDUCTIVITY 135

- 6.1 Introduction 135
- 6.2 Bernoulli's Equation 135
- 6.3 Darcy's Law 138
- 6.4 Hydraulic Conductivity 139
- 6.5 Laboratory Determination of Hydraulic Conductivity 141
- 6.6 Empirical Relations for Hydraulic Conductivity 146
- 6.7 Equivalent Hydraulic Conductivity in Stratified Soil 152
- 6.8 Permeability Test in the Field by Pumping from Wells 155
- 6.9 Summary 157
 - Problems 157
 - Critical Thinking Problem 161
 - References 162

7 SEEPAGE 163

- 7.1 Introduction 163
- 7.2 Laplace's Equation of Continuity 163
- 7.3 Flow Nets 165
- 7.4 Seepage Calculation from a Flow Net 167
- 7.5 Flow Nets in Anisotropic Soil 171
- 7.6 Summary 175
 - Problems 175
 - Critical Thinking Problem 178

8 STRESSES IN A SOIL MASS 179

- 8.1 Introduction 179
- Effective Stress Concept* 180
- 8.2 Stresses in Saturated Soil without Seepage 180
- 8.3 Stresses in Saturated Soil with Seepage 183
- 8.4 Seepage Force 189
- 8.5 Heaving in Soil Due to Flow Around Sheet Piles 191
- Vertical Stress Increase Due to Various Types of Loading* 194
- 8.6 Stress Caused by a Point Load 194
- 8.7 Vertical Stress Caused by a Line Load 195
- 8.8 Vertical Stress Below a Uniformly Loaded Circular Area 196
- 8.9 Vertical Stress Caused by a Rectangularly Loaded Area 199
- 8.10 Summary 203
 - Problems 204
 - Critical Thinking Problems 208
 - References 210

9 CONSOLIDATION 211

- 9.1 Introduction 211
- 9.2 Fundamentals of Consolidation 212
- 9.3 One-Dimensional Laboratory Consolidation Test 215
- 9.4 Void Ratio–Pressure Plots 218
- 9.5 Normally Consolidated and Overconsolidated Clays 220
- 9.6 Effect of Disturbance on Void Ratio–Pressure Relationship 222
- 9.7 Calculation of Settlement from One-Dimensional Primary Consolidation 223
- 9.8 Compression Index (C_c) and Swell Index (C_s) 225
- 9.9 Settlement from Secondary Consolidation 233
- 9.10 Time Rate of Consolidation 236
- 9.11 Coefficient of Consolidation 241
- 9.12 Calculation of Primary Consolidation Settlement under a Foundation 248
- 9.13 Skempton-Bjerrum Modification for Consolidation Settlement 251
- 9.14 Effects of Initial Excess Pore Pressure Distribution of U - T_v Relationship 255
- 9.15 Construction Time Correction of Consolidation Settlement 257
- 9.16 Summary 260
 - Problems 260
 - Critical Thinking Problems 266
 - References 266

10 SHEAR STRENGTH OF SOIL 268

- 10.1 Introduction 268
- 10.2 Mohr–Coulomb Failure Criteria 268
- 10.3 Inclination of the Plane of Failure Caused by Shear 271
- Laboratory Determination of Shear Strength Parameters* 273
- 10.4 Direct Shear Test 273
- 10.5 Triaxial Shear Test 280
- 10.6 Consolidated-Drained Test 282
- 10.7 Consolidated-Undrained Test 291
- 10.8 Unconsolidated-Undrained Test 296
- 10.9 Unconfined Compression Test on Saturated Clay 299
- 10.10 Selection of Shear Strength Parameters 301
- 10.11 Sensitivity and Thixotropy of Clay 302
- 10.12 Anisotropy in Undrained Shear Strength 304
- 10.13 Summary 305
 - Problems 306
 - Critical Thinking Problems 310
 - References 310

11 GROUND IMPROVEMENT 312

- 11.1 Introduction 312
- Chemical Stabilization* 313
- 11.2 Lime Stabilization 313
- 11.3 Cement Stabilization 315
- 11.4 Fly-Ash Stabilization 316
- Mechanical Stabilization* 317
- 11.5 Vibroflotation 317
- 11.6 Dynamic Compaction 320
- 11.7 Blasting 322
- 11.8 Precompression 322
- 11.9 Sand Drains 327
- 11.10 Summary 332
 - Problems 333
 - Critical Thinking Problem 334
 - References 335

12 SUBSURFACE EXPLORATION 336

- 12.1 Introduction 336
- 12.2 Subsurface Exploration Program 337
- 12.3 Exploratory Borings in the Field 340
- 12.4 Procedures for Sampling Soil 344

12.5	Split-Spoon Sampling and Standard Penetration Test	344
12.6	Sampling with Thin Wall Tube	351
12.7	Observation of Water Levels	352
12.8	Vane Shear Test	353
12.9	Cone Penetration Test	358
12.10	Pressuremeter Test (PMT)	364
12.11	Dilatometer Test	366
12.12	Coring of Rocks	368
12.13	Preparation of Boring Logs	370
12.14	Geophysical Exploration	372
12.15	Soil Exploration Report	379
12.16	Field Instrumentation	380
12.17	Summary	382
	Problems	383
	Critical Thinking Problem	387
	References	388

13 SLOPE STABILITY 390

13.1	Introduction	390
13.2	Factor of Safety	391
13.3	Stability of Infinite Slopes	392
13.4	Finite Slopes	396
13.5	Analysis of Finite Slope with Cylindrical Failure Surface—General	400
13.6	Mass Procedure of Stability Analysis (Circularly Cylindrical Failure Surface)	402
13.7	Method of Slices	423
13.8	Bishop's Simplified Method of Slices	426
13.9	Analysis of Simple Slopes with Steady-State Seepage	430
13.10	Mass Procedure for Stability of Clay Slope with Earthquake Forces	435
13.11	Summary	439
	Problems	440
	Critical Thinking Problems	444
	References	445

14 LATERAL EARTH PRESSURE 446

14.1	Introduction	446
14.2	Earth Pressure at Rest	446
14.3	Rankine's Theory of Active and Passive Earth Pressures	451
14.4	Diagrams for Lateral Earth Pressure Distribution against Retaining Walls	458
14.5	Rankine Active Pressure with Sloping Granular Backfill	471

- 14.6 Coulomb's Earth Pressure Theory—Retaining Walls with Friction 472
- 14.7 Passive Pressure Assuming Curved Failure Surface in Soil 481
- 14.8 Summary 483
 - Problems 484
 - Critical Thinking Problems 488
 - References 489

15 RETAINING WALLS, BRACED CUTS, AND SHEET PILE WALLS

490

-
- 15.1 Introduction 490
 - Retaining Walls* 491
 - 15.2 Retaining Walls—General 491
 - 15.3 Proportioning Retaining Walls 493
 - 15.4 Application of Lateral Earth Pressure Theories to Design 494
 - 15.5 Check for Overturning 496
 - 15.6 Check for Sliding along the Base 498
 - 15.7 Check for Bearing Capacity Failure 500
 - Mechanically Stabilized Earth Retaining Walls* 508
 - 15.8 Mechanically Stabilized Earth 508
 - 15.9 General Design Considerations 509
 - 15.10 Retaining Walls with Metallic Strip Reinforcement 509
 - 15.11 Step-by-Step-Design Procedure Using Metallic Strip Reinforcement 512
 - 15.12 Retaining Walls with Geotextile Reinforcement 518
 - 15.13 Retaining Walls with Geogrid Reinforcement 523
 - Braced Cuts* 528
 - 15.14 Braced Cuts—General 528
 - 15.15 Lateral Earth Pressure in Braced Cuts 532
 - 15.16 Soil Parameters for Cuts in Layered Soil 534
 - 15.17 Design of Various Components of a Braced Cut 535
 - 15.18 Heave of the Bottom of a Cut in Clay 541
 - 15.19 Lateral Yielding of Sheet Piles and Ground Settlement 543
 - Sheet Pile Walls* 545
 - 15.20 Cantilever Sheet Pile Wall in Granular Soils ($c' = 0$) 545
 - 15.21 Cantilever Sheet Piles in Cohesive Soils 552
 - 15.22 Anchored Sheet Pile Wall 554
 - 15.23 Deadman Anchor—A Simplified Approach 557
 - 15.24 Summary 558
 - Problems 559
 - Critical Thinking Problems 565
 - References 567

16 SHALLOW FOUNDATIONS— BEARING CAPACITY

568

-
- 16.1 Introduction 568
 - 16.2 Ultimate Bearing Capacity of Shallow Foundations—
General Concepts 569
 - 16.3 Terzaghi's Ultimate Bearing Capacity Theory 571
 - 16.4 Modification to Terzaghi's Bearing Capacity Equation 573
 - 16.5 Modification of Bearing Capacity Equations
for Water Table 577
 - 16.6 The Factor of Safety 578
 - 16.7 Eccentrically Loaded Foundations (One-Way Eccentricity) 581
 - 16.8 Reduction Factor Method for Eccentrically Loaded Strip Foundation
on Granular Soil 584
 - 16.9 Strip Foundation Under Eccentrically Inclined Load 586
 - 16.10 Foundations with Two-Way Eccentricity 591
 - 16.11 Ultimate Bearing Capacity with Earthquake Condition 599
 - 16.12 Mat Foundations—Common Types 601
 - 16.13 Bearing Capacity of Mat Foundations 604
 - 16.14 Compensated Foundations 605
 - 16.15 Summary 607
 - Problems 607
 - Critical Thinking Problems 610
 - References 611

17 SETTLEMENT OF SHALLOW FOUNDATIONS

612

-
- 17.1 Introduction 612
 - 17.2 Elastic Settlement of Foundations on Saturated Clay Soils
($\mu_s = 0.5$) 613
 - 17.3 Elastic Settlement Based on Theory of Elasticity (Drained Soil) 615
 - 17.4 Range of Material Parameters for Computing
Elastic Settlement 623
 - 17.5 Improved Method for Settlement Calculation
in Granular Soil 623
 - 17.6 Settlement of Sandy Soil: Use of Strain Influence Factor 629
 - 17.7 Allowable Bearing Pressure for Spread Footing
in Sand Based on Settlement Consideration 634
 - 17.8 Allowable Bearing Pressure of Mat Foundation in Sand 635
 - 17.9 Effects of Water Table Rise on Elastic Settlement
in Granular Soils 636
 - 17.10 Summary 638
 - Problems 638
 - Critical Thinking Problems 641
 - References 641

18 PILE FOUNDATIONS

643

- 18.1 Introduction 643
- 18.2 Need for Pile Foundations 643
- 18.3 Types of Piles and Their Structural Characteristics 645
- 18.4 Estimation of Pile Length 653
- 18.5 Installation of Piles 654
- 18.6 Load Transfer Mechanism 656
- 18.7 Equations for Estimation of Pile Capacity 659
- 18.8 Load Carrying Capacity of Pile Point, Q_p 660
- 18.9 Frictional Resistance, Q_s 662
- 18.10 Allowable Pile Capacity 668
- 18.11 Load-Carrying Capacity of Pile Point Resting on Rock 669
- 18.12 Elastic Settlement of Piles 679
- 18.13 Pile Load Tests 682
- 18.14 Pile-Driving Formulas 687
- 18.15 Negative Skin Friction 691
- 18.16 Group Piles—Efficiency 693
- 18.17 Elastic Settlement of Group Piles 698
- 18.18 Consolidation Settlement of Group Piles 698
- 18.19 Summary 702
 - Problems 703
 - Critical Thinking Problem 710
 - References 711

19 DRILLED SHAFT

712

- 19.1 Introduction 712
- 19.2 Types of Drilled Shafts 713
- 19.3 Construction Procedures 714
- 19.4 Estimation of Load-Bearing Capacity 718
- 19.5 Drilled Shafts in Sand—Net Ultimate Load 720
- 19.6 Drilled Shafts in Clay—Net Ultimate Load 723
- 19.7 Settlement of Drilled Shafts at Working Load 728
- 19.8 Load-Bearing Capacity Based on Settlement 728
- 19.9 Summary 736
 - Problems 736
 - Critical Thinking Problem 739
 - References 740

20 LOAD AND RESISTANCE FACTOR DESIGN (LRFD)

741

- 20.1 Introduction 741
- 20.2 Design Philosophy 742
- 20.3 Allowable Stress Design (ASD) 744

20.4	Limit State Design (LSD) and Partial Safety Factors	745
20.5	Summary	750
	Problems	750
	References	750

Appendix A: Geosynthetics	752
Answers to Selected Problems	758
Index	767



Preface

Principles of Foundation Engineering and *Principles of Geotechnical Engineering* were originally published with 1984 and 1985 copyrights, respectively. These texts were well received by instructors, students, and practitioners alike. Depending on the needs of the users, the texts were revised and are presently in their eighth editions. These texts have also been translated in several languages.

Toward the latter part of 1998, there were several requests to prepare a single volume that was concise in nature but combined the essential components of *Principles of Foundation Engineering* and *Principles of Geotechnical Engineering*. In response to those requests, the first edition of *Fundamentals of Geotechnical Engineering* was published in 2000. This text includes the fundamental concepts of soil mechanics as well as foundation engineering, including bearing capacity and settlement of shallow foundations (spread footings and mats), retaining walls, braced cuts, piles, and drilled shafts.

New to This Edition

This fifth edition has been revised and prepared based on comments received from several reviewers and users without changing the philosophy on which the text was originally prepared. Professor Nagaratnam Sivakugan of James Cook University, Australia, has joined as a co-author of this edition. As in the previous editions, SI units are used throughout the text. This edition consists of 20 chapters and an appendix. The major changes from the fourth edition include the following:

- About forty additional photographs have been added.
- A number of additional example problems and homework problems have been added in each chapter.
- Each chapter has some critical thinking problem(s) added to the homework problem set.

- An interactive digital version of this text is now available. Please see the MindTap description on page xix.
- In Chapter 2 on “Soil Deposits—Origin, Grain-Size, and Shape” a discussion has been added for the U.S. sieve size designations. Details for the British standard sieves and the Australian standard sieves have also been added.
- In Chapter 3 on “Weight-Volume Relationships and Plasticity,” a table for various unit-weight relationships has been added.
- Chapter 4 on “Soil Classification” has a new section on visual identification of soils.
- In Chapter 5 on “Soil Compaction,” some recently published correlations for maximum dry unit weight and optimum moisture content has been added. Also added in this chapter is a brief description on various ground improvement methods.
- Chapter 9 on “Consolidation” now has a new section on the effects of initial excess pore water pressure distribution on $U-T_v$ relationships. Also added to this chapter is a discussion on the construction time correction of consolidation settlement.
- A number of recently published correlations for effective stress friction angle (ϕ') and cohesion (c') for cohesive soils has been added to Chapter 10 on “Shear Strength of Soils.” Also included in this chapter are several correlations for the undrained shear strength of remolded clays with liquidity index.
- Chapter 12 on “Subsurface Exploration” now has a section on field instrumentation.
- In Chapter 13 on “Slope Stability,” an analysis to evaluate the factor of safety of clay slopes with the undrained cohesion increasing with depth has been added. This chapter now also has a discussion on the mass procedure for stability analysis of homogeneous clay slopes ($\phi = 0$) with earthquake forces.
- Chapter 15 has been renamed as “Retaining Walls, Braced Cuts, and Sheet Pile Walls.” Analyses of cantilever sheet pile walls and anchored sheet pile walls have been added to this chapter.
- The bearing capacity of strip foundation under eccentrically inclined load has been discussed in greater detail in Chapter 16 on “Shallow Foundations—Bearing Capacity.”
- An improved method for elastic settlement calculation of shallow foundations on granular soil taking into consideration the variation of soil stiffness with stress level has been added to Chapter 17 on “Settlement of Shallow Foundations.”
- A new chapter (Chapter 20) on “Load and Resistance Factor Design (LRFD)” has been added to the text.

Instructor Resource Materials

A detailed *Instructor's Solutions Manual* and Lecture Note PowerPoint slides are available for instructors through a password-protected Web site at www.cengagebrain.com.

MindTap Online Course and Reader

This textbook is also available online through Cengage Learning's MindTap, a personalized learning program. Students who purchase the MindTap have access to the book's multimedia-rich electronic Reader and are able to complete homework and assessment material online, on their desktops, laptops, or iPads. Instructors who use a Learning Management System (such as Blackboard, Canvas, or Moodle) for tracking course content, assignments, and grading, can seamlessly access the MindTap suite of content and assessments for this course.

With MindTap, instructors can:

- Personalize the Learning Path to match their course syllabus by rearranging content or appending original material to the online content
- Connect a Learning Management System portal to the online course and Reader
- Customize online assessments and assignments
- Track student engagement, progress and comprehension
- Promote student success through interactivity, and exercises

Additionally, students can listen to the text through ReadSpeaker, take notes in the digital Reader, study from or create their own Flashcards, highlight content for easy reference, and check their understanding of the material through practice quizzes and automatically-graded homework. The MindTap for *Fundamentals of Geotechnical Engineering* also includes algorithmically generated problems, providing an endless pool for student practice and assessment.

Acknowledgments

Thanks are due to:

The following reviewers for their comments and constructive suggestions:

- Alierza Bayat, University of Alberta
- Raymond Haddad, California State University, Northridge
- Anne Lemnitzer, University of California, Irvine
- Matthew Sleep, Oregon Institute of Technology
- Kamal Tawfiq, Florida A&M University
- Alexandria Wayllace, Colorado School of Mines
- Attila Michael Zsaki, Concordia University, Canada

Several individuals in Cengage Learning, for their assistance and advice in the final development of the text—namely:

- Tim Anderson, Product Director
- Mona ZefTEL, Senior Content Developer

Thanks are also due to Janice Das for her continuous help in the development of the original text and its subsequent four editions.

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 *Fundamentals of Geotechnical Engineering* as well as all previous editions.

Braja M. Das
Henderson, Nevada, USA

Nagaratnam Sivakugan
Townsville, Queensland, Australia



CHAPTER

1

Geotechnical Engineering—From the Beginning

1.1 Introduction

For engineering purposes, **soil** is defined as the uncemented aggregate of mineral grains and decayed organic matter (solid particles) with liquid and gas in 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, strength, and its ability to support structures and resist deformations. **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. **Soil engineering** is the application of the principles of soil mechanics to practical problems. **Geotechnical engineering** is the subdiscipline of civil engineering that involves natural materials found close to the surface of the earth. It includes the application of the principles of soil mechanics and rock mechanics to the design of foundations, retaining structures, and earth structures.

This chapter is a historical overview of geotechnical engineering and its challenges, with some mention of the great contributions by two eminent scholars, Dr. Karl Terzaghi (1883–1963) and Dr. Ralph Peck (1912–2008), and others.

1.2 Geotechnical Engineering Prior to the 18th Century

The record of a person’s first use of soil as a construction material is lost in antiquity. In true engineering terms, the understanding of geotechnical engineering as it is known today began early in the 18th century (Skempton, 1985). For years the art of geotechnical engineering was based on only past experiences through a succession of experimentation without any real scientific character. Based on those experimentations, many structures were built—some of which have crumbled, while others are still standing.

Recorded history tells us that ancient civilizations flourished along the banks of rivers, such as the Nile (Egypt), the Tigris and Euphrates (Mesopotamia), the Huang Ho (Yellow River, China), and the Indus (India). Dykes dating back to about 2000 B.C. were built in the basin of the Indus to protect the town of Mohenjo Dara (in what became Pakistan after 1947). During the Chan dynasty in China (1120 B.C. to 249 B.C.), many dikes were built for irrigation purposes. There is no evidence that measures were taken to stabilize the foundations or check erosion caused by floods (Kerisel, 1985). The ancient Greek civilization used isolated pad footings and strip-and-raft foundations for building structures. Beginning around 2700 B.C., several pyramids were built in Egypt, most of which were built as tombs for the country’s Pharaohs and their consorts during the old and Middle Kingdom periods. Table 1.1 lists some of the major pyramids identified through the Pharaoh who ordered it built. As of 2008, a total of 138 pyramids have been discovered in Egypt. Figure 1.1 shows a view of the three pyramids at Giza. The construction of the pyramids posed formidable challenges regarding foundations, stability of slopes, and construction of underground chambers. With the arrival of Buddhism in China during the Eastern Han dynasty in 68 A.D., thousands of pagodas were built. Many of these structures were constructed on silt and soft clay layers. In some cases the foundation pressure exceeded the load-bearing capacity of the soil and thereby caused extensive structural damage.

One of the most famous examples of problems related to soil-bearing capacity in the construction of structures prior to the 18th century is the Leaning Tower of Pisa in Italy (Figure 1.2). Construction of the tower began in 1173 A.D.

Table 1.1 Major Pyramids in Egypt

Pyramid/Pharaoh	Location	Reign of Pharaoh
Djoser	Saqqara	2630–2612 B.C.
Sneferu	Dashur (North)	2612–2589 B.C.
Sneferu	Dashur (South)	2612–2589 B.C.
Sneferu	Meidum	2612–2589 B.C.
Khufu	Giza	2589–2566 B.C.
Djedefre	Abu Rawash	2566–2558 B.C.
Khafre	Giza	2558–2532 B.C.
Menkaure	Giza	2532–2504 B.C.



FIG. 1.1 A view of the pyramids at Giza (Courtesy of Braja M. Das, Henderson, Nevada)

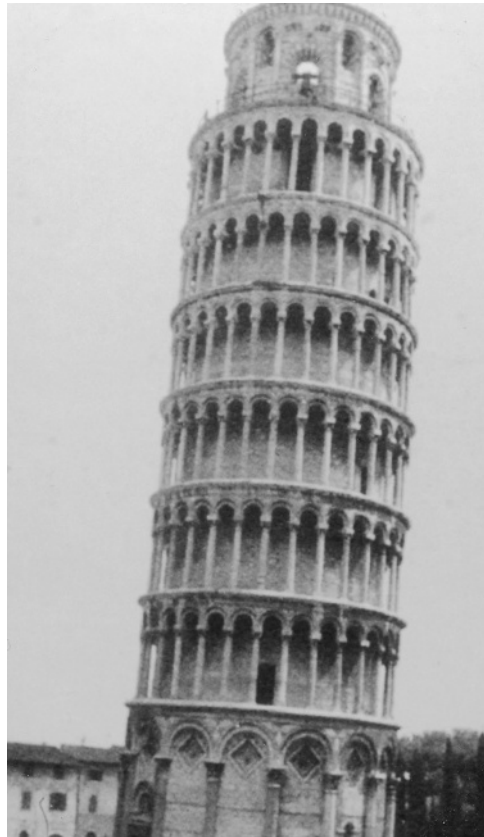


FIG. 1.2 Leaning Tower of Pisa, Italy (Courtesy of Braja M. Das, Henderson, Nevada)

when the Republic of Pisa was flourishing and continued in various stages for over 200 years. The structure weighs about 15,700 metric tons and is supported by a circular base having a diameter of 20 m. The tower has tilted in the past to the east, north, west and, finally, to the south. Recent investigations showed that a weak clay layer exists at a depth of about 11 m below the ground surface, compression of which caused the tower to tilt. It became more than 5 m out of plumb with the 54 m height (about 5.5 degree tilt). The tower was closed in 1990 because it was feared that it would either fall over or collapse. It has recently been stabilized by excavating soil from under the north side of the tower. About 70 metric tons of earth were removed in 41 separate extractions that spanned the width of the tower. As the ground gradually settled to fill the resulting space, the tilt of the tower eased. The tower now leans 5 degrees. The half-degree change is not noticeable, but it makes the structure considerably more stable. Figure 1.3 is an example of a similar problem. The towers shown in Figure 1.3 are located in



FIG. 1.3 Tilting of Garisenda Tower (left) and Asinelli Tower (right) in Bologna, Italy (Courtesy of Braja M. Das, Henderson, Nevada)

Bologna, Italy, and they were built in the 12th century. The tower on the left is the Garisenda Tower. It is 48 m high and weighs about 4210 metric tons. It has tilted about 4 degrees. The tower on the right is the Asinelli Tower, which is 97 m high and weighs 7300 metric tons. It has tilted about 1.3 degrees.

After encountering several foundation-related problems during construction over centuries past, engineers and scientists began to address the properties and behavior of soils in a more methodical manner starting in the early part of the 18th century. Based on the emphasis and the nature of study in the area of geotechnical engineering, the time span extending from 1700 to 1927 can be divided into four major periods (Skempton, 1985):

1. Preclassical (1700 to 1776)
2. Classical soil mechanics—Phase I (1776 to 1856)
3. Classical soil mechanics—Phase II (1856 to 1910)
4. Modern soil mechanics (1910 to 1927)

Brief descriptions of some significant developments during each of these four periods are discussed below.

1.3 Preclassical Period of Soil Mechanics (1700–1776)

This period concentrated on studies relating to natural slope and unit weights of various types of soils as well as the semiempirical earth pressure theories. In 1717 a French royal engineer, Henri Gautier (1660–1737), studied the natural slopes of soils when tipped in a heap for formulating the design procedures of retaining walls. The **natural slope** is what we now refer to as the **angle of repose**. According to this study, the natural slopes of **clean dry sand** and **ordinary earth** were 31° and 45°, respectively. Also, the unit weights of clean dry sand and ordinary earth were recommended to be 18.1 kN/m³ and 13.4 kN/m³, respectively. No test results on clay were reported. In 1729, Bernard Forest de Belidor (1694–1761) published a textbook for military and civil engineers in France. In the book, he proposed a theory for lateral earth pressure on retaining walls that was a follow-up to Gautier's (1717) original study. He also specified a soil classification system in the manner shown in the following table.

Classification	Unit weight kN/m ³
Rock	—
Firm or hard sand, compressible sand	16.7 to 18.4
Ordinary earth (as found in dry locations)	13.4
Soft earth (primarily silt)	16.0
Clay	18.9
Peat	—

The first laboratory model test results on a 76 mm high retaining wall built with sand backfill were reported in 1746 by a French engineer, Francois Gadroy

(1705–1759), who observed the existence of slip planes in the soil at failure. Gadroy's study was later summarized by J. J. Mayniel in 1808. Another notable contribution during this period is that by the French engineer Jean Rodolphe Perronet (1708–1794), who studied slope stability around 1769 and distinguished between intact ground and fills.

1.4 Classical Soil Mechanics—Phase I (1776–1856)

During this period, most of the developments in the area of geotechnical engineering came from engineers and scientists in France. In the preclassical period, practically all theoretical considerations used in calculating lateral earth pressure on retaining walls were based on an arbitrarily based failure surface in soil. In his famous paper presented in 1776, French scientist Charles Augustin Coulomb (1736–1806) used the principles of calculus for maxima and minima to determine the true position of the sliding surface in soil behind a retaining wall. In this analysis, Coulomb used the laws of friction and cohesion for solid bodies. In 1790, the distinguished French civil engineer, Gaspard Claire Marie Riche de Brony (1755–1839) included Coulomb's theory in his leading textbook, *Nouvelle Architecture Hydraulique* (Vol. 1). In 1820, special cases of Coulomb's work were studied by French engineer Jacques Frédéric Français (1775–1833) and by French applied-mechanics professor Claude Louis Marie Henri Navier (1785–1836). These special cases related to inclined backfills and backfills supporting surcharge. In 1840, Jean Victor Poncelet (1788–1867), an army engineer and professor of mechanics, extended Coulomb's theory by providing a graphical method for determining the magnitude of lateral earth pressure on vertical and inclined retaining walls with arbitrarily broken polygonal ground surfaces. Poncelet was also the first to use the symbol ϕ for soil friction angle. He also provided the first ultimate bearing-capacity theory for shallow foundations. In 1846, Alexandre Collin (1808–1890), an engineer, provided the details for deep slips in clay slopes, cutting, and embankments. Collin theorized that, in all cases, the failure takes place when the mobilized cohesion exceeds the existing cohesion of the soil. He also observed that the actual failure surfaces could be approximated as arcs of cycloids.

The end of Phase I of the classical soil mechanics period is generally marked by the year (1857) of the first publication by William John Macquorn Rankine (1820–1872), a professor of civil engineering at the University of Glasgow. This study provided a notable theory on earth pressure and equilibrium of earth masses. Rankine's theory is a simplification of Coulomb's theory.

1.5 Classical Soil Mechanics—Phase II (1856–1910)

Several experimental results from laboratory tests on sand appeared in the literature in this phase. One of the earliest and most important publications is by French engineer Henri Philibert Gaspard Darcy (1803–1858). In 1856, he

published a study on the permeability of sand filters. Based on those tests, Darcy defined the term **coefficient of permeability** (or **hydraulic conductivity**) of soil, a very useful parameter in geotechnical engineering to this day.

Sir George Howard Darwin (1845–1912), a professor of astronomy, conducted laboratory tests to determine the overturning moment on a hinged wall retaining sand in loose and dense states of compaction. Another noteworthy contribution, which was published in 1885 by Joseph Valentin Boussinesq (1842–1929), was the development of the theory of stress distribution under load-bearing areas in a homogeneous, semi-infinite, elastic, and isotropic medium. In 1887, Osborne Reynolds (1842–1912) demonstrated the phenomenon of dilatancy in sand. Other notable studies during this period are those by John Clibborn (1847–1938) and John Stuart Beresford (1845–1925), relating to the flow of water through sand bed and uplift pressure. Clibborn's study was published in the *Treatise on Civil Engineering, Vol. 2: Irrigation Work in India*, Roorkee, 1901, and also in *Technical Paper No. 97*, Government of India, 1902. Beresford's 1898 study on uplift pressure on the Narora Weir on the Ganges River has been documented in *Technical Paper No. 97*, Government of India, 1902.

1.6 Modern Soil Mechanics (1910–1927)

In this period, results of research conducted on clays were published in which the fundamental properties and parameters of clay were established. The most notable publications are described next.

Around 1908, Albert Mauritz Atterberg (1846–1916), a Swedish chemist and soil scientist, defined **clay-sized fractions** as the percentage by weight of particles smaller than 2 microns in size. He realized the important role of clay particles in a soil and the plasticity thereof. In 1911, he explained the consistency of cohesive soils by defining liquid, plastic, and shrinkage limits. He also defined the plasticity index as the difference between liquid limit and plastic limit (see Atterberg, 1911).

In October 1909, the 17 m high earth dam at Charmes, France, failed. It was built between 1902–1906. A French engineer, Jean Fontard (1884–1962), carried out investigations to determine the cause of failure. In that context, he conducted undrained double-shear tests on clay specimens (0.77 m² in area and 200 mm thick) under constant vertical stress to determine their shear strength parameters (see Fontard, 1914). The times for failure of these specimens were between 10 to 20 minutes.

Arthur Langley Bell (1874–1956), a civil engineer from England, worked on the design and construction of the outer seawall at Rosyth Dockyard. Based on his work, he developed relationships for lateral pressure and resistance in clay as well as bearing capacity of shallow foundations in clay (see Bell, 1915). He also used shear-box tests to measure the undrained shear strength of undisturbed clay specimens.

Wolmar Fellenius (1876–1957), an engineer from Sweden, developed the stability analysis of undrained saturated clay slopes (that is, $\phi = 0$ condition) with the assumption that the critical surface of sliding is the arc of a circle. These were elaborated upon in his papers published in 1918 and 1926. The paper published in 1926 gave correct numerical solutions for the **stability numbers** of circular slip surfaces passing through the toe of the slope.



FIG. 1.4 Karl Terzaghi (1883–1963) (SSPL via Getty Images)

Karl Terzaghi (1883–1963) of Austria (Figure 1.4) developed the theory of consolidation for clays as we know today. The theory was developed when Terzaghi was teaching at the American Robert College in Istanbul, Turkey. His study spanned a five-year period from 1919 to 1924. Five different clay soils were used. The liquid limit of those soils ranged between 36 to 67, and the plasticity index was in the range of 18 to 38. The consolidation theory was published in Terzaghi's celebrated book *Erdbaumechnik* in 1925.

1.7 Geotechnical Engineering after 1927

The publication of *Erdbaumechnik auf Bodenphysikalischer Grundlage* by Karl Terzaghi in 1925 gave birth to a new era in the development of soil mechanics. Karl Terzaghi is known as the father of modern soil mechanics, and rightfully so. Terzaghi (Figure 1.4) was born on October 2, 1883 in Prague, which was then the capital of the Austrian province of Bohemia. In 1904, he graduated from the Technische Hochschule in Graz, Austria, with an undergraduate degree in

mechanical engineering. After graduation he served one year in the Austrian army. Following his army service, Terzaghi studied one more year, concentrating on geological subjects. In January 1912, he received the degree of Doctor of Technical Sciences from his alma mater in Graz. In 1916, he accepted a teaching position at the Imperial School of Engineers in Istanbul. After the end of World War I, he accepted a lectureship at the American Robert College in Istanbul (1918–1925). There he began his research work on the behavior of soils and settlement of clays and on the failure due to piping in sand under dams. The publication *Erdbaumechanik* is primarily the result of this research.

In 1925, Terzaghi accepted a visiting lectureship at Massachusetts Institute of Technology, where he worked until 1929. During that time, he became recognized as the leader of the new branch of civil engineering called soil mechanics. In October 1929, he returned to Europe to accept a professorship at the Technical University of Vienna, which soon became the nucleus for civil engineers interested in soil mechanics. In 1939, he returned to the United States to become a professor at Harvard University.

The first conference of the International Society of Soil Mechanics and Foundation Engineering (ISSMFE) was held at Harvard University in 1936 with Karl Terzaghi presiding. The conference was possible due to the conviction and efforts of Professor Arthur Casagrande of Harvard University. About 200 individuals representing 21 countries attended this conference. It was through the inspiration and guidance of Terzaghi over the preceding quarter-century that papers were brought to that conference covering a wide range of topics, such as

- Effective stress
- Shear strength
- Testing with Dutch cone penetrometer
- Consolidation
- Centrifuge testing
- Elastic theory and stress distribution
- Preloading for settlement control
- Swelling clays
- Frost action
- Earthquake and soil liquefaction
- Machine vibration
- Arching theory of earth pressure

For the next quarter-century, Terzaghi was the guiding spirit in the development of soil mechanics and geotechnical engineering throughout the world. To that effect, in 1985, Ralph Peck (Figure 1.5) wrote that “few people during Terzaghi’s lifetime would have disagreed that he was not only the guiding spirit in soil mechanics, but that he was the clearing house for research and application throughout the world. Within the next few years he would be engaged on projects on every continent save Australia and Antarctica.” Peck continued with, “Hence, even today, one can hardly improve on his contemporary assessments of the state of soil mechanics as expressed in his summary papers and



FIG. 1.5 Ralph B. Peck (Photo courtesy of Ralph B. Peck)

presidential addresses.” In 1939, Terzaghi delivered the 45th James Forrest Lecture at the Institution of Civil Engineers, London. His lecture was entitled “Soil Mechanics—A New Chapter in Engineering Science.” In it, he proclaimed that most of the foundation failures that occurred were no longer “acts of God.”

Following are some highlights in the development of soil mechanics and geotechnical engineering that evolved after the first conference of the ISSMFE in 1936:

- Publication of the book *Theoretical Soil Mechanics* by Karl Terzaghi in 1943 (Wiley, New York);
- Publication of the book *Soil Mechanics in Engineering Practice* by Karl Terzaghi and Ralph Peck in 1948 (Wiley, New York);
- Publication of the book *Fundamentals of Soil Mechanics* by Donald W. Taylor in 1948 (Wiley, New York); and
- Start of the publication of *Geotechnique*, the international journal of soil mechanics in 1948 in England.

After a brief interruption for World War II, the second conference of ISSMFE was held in Rotterdam, The Netherlands, in 1948. There were about

600 participants, and seven volumes of proceedings were published. In this conference, A. W. Skempton presented the landmark paper on $\phi = 0$ concept for clays. Following Rotterdam, ISSMFE conferences have been organized about every four years in different parts of the world. The aftermath of the Rotterdam conference saw the growth of regional conferences on geotechnical engineering, such as

- European Regional Conference on Stability of Earth Slopes, Stockholm (1954)
- First Australia-New Zealand Conference on Shear Characteristics of Soils (1952)
- First Pan American Conference, Mexico City (1960)
- Research conference on Shear Strength of Cohesive Soils, Boulder, Colorado (1960)

Two other important milestones between 1948 and 1960 are (1) the publication of A. W. Skempton's paper on A and B pore pressure parameters which made effective stress calculations more practical for various engineering works and (2) publication of the book entitled *The Measurement of Soil Properties in the Triaxial Test* by A. W. Bishop and B. J. Henkel (Arnold, London) in 1957.

By the early 1950s, computer-aided finite difference and finite element solutions were applied to various types of geotechnical engineering problems. When the projects become more sophisticated with complex boundary conditions, it is no longer possible to apply closed form solutions. Numerical modeling, using a finite element (e.g., Abaqus, Plaxis) or finite difference (e.g., Flac) software, is increasingly becoming popular in the profession. The dominance of numerical modeling in geotechnical engineering will continue in the next few decades, due to new challenges and advances in the modeling techniques. Since the early days, the profession of geotechnical engineering has come a long way and has matured. It is now an established branch of civil engineering, and thousands of civil engineers declare geotechnical engineering to be their preferred area of speciality.

In 1997, the ISSMFE was changed to ISSMGE (International Society of Soil Mechanics and Geotechnical Engineering) to reflect its true scope. These international conferences have been instrumental for exchange of information regarding new developments and ongoing research activities in geotechnical engineering. Table 1.2 gives the location and year in which each conference of ISSMFE/ISSMGE was held.

In 1960, Bishop, Alpan, Blight, and Donald provided early guidelines and experimental results for the factors controlling the strength of partially saturated cohesive soils. Since that time advances have been made in the study of the behavior of unsaturated soils as related to strength and compressibility and other factors affecting construction of earth-supported and earth-retaining structures.

ISSMGE has several technical committees, and these committees organize or cosponsor several conferences around the world. A list of these technical