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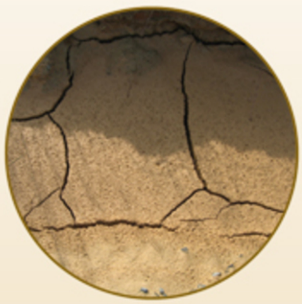
Soil Mechanics Fundamentals



Muni Budhu

with website

WILEY Blackwell

SOIL MECHANICS FUNDAMENTALS

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WILEY Blackwell

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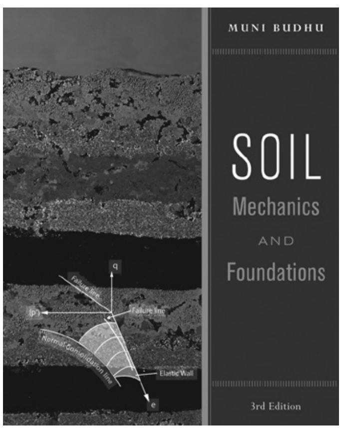
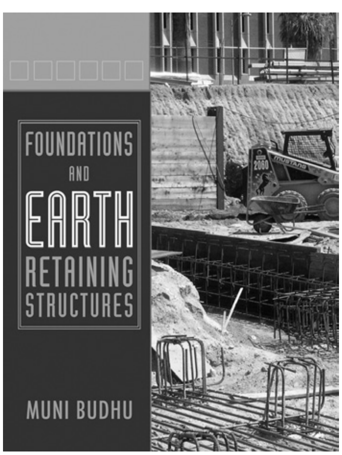
About the Author

MUNIRAM (Muni) BUDHU is Professor of Civil Engineering and Engineering Mechanics at the University of Arizona, Tucson. He received his BSc (First Class Honors) in Civil Engineering from the University of the West Indies and his PhD in Soil Mechanics from Cambridge University, England. Prior to joining the University of Arizona, Dr. Budhu served on the faculty at the University of Guyana, Guyana; McMaster University, Canada; and the State University of New York at Buffalo. He spent sabbaticals as Visiting Professor at St. Catherine's College, Oxford University; Eidgenössische Technische Hochschule Zürich (Swiss Federal Institute of Technology, Zurich); and the University of Western Australia. He authored and co-authored many technical papers on various civil engineering and engineering mechanics topics including soil mechanics, foundation engineering, numerical modeling, hydraulic engineering, and engineering education. Dr. Budhu has developed interactive animations for learning various topics in soil mechanics and foundation engineering, fluid mechanics, statics, and interactive virtual labs. He is the co-founder of YourLabs, developer of a knowledge evaluation system (www.yourlabs.com). Dr. Budhu has authored two other textbooks, *Soil Mechanics and Foundations* and *Foundations and Earth Retaining Structures*. Both books are available from John Wiley & Sons (www.wiley.com).

Other Books by this Author



Soil Mechanics and Foundations,
3rd Edition
by Muni Budhu
ISBN: 978-0471-43117-6
An in-depth look at soil mechanics, including content for both an introductory soil mechanics and a foundations course. For students and other readers who wish to study the detailed mechanics connected with the fundamental concepts and principles. This textbbook includes critical state soils mechanics to provide a link between soil settlement and soil shear strength.



Foundations and Earth Retaining Structures
by Muni Budhu
ISBN: 978-0471-47012-0
Introduction to foundations and earth retaining structures, with fundamentals and practical applications of soil mechanics principles to the analysis and design of shallow and deep foundations, and earth retaining structures. In addition to a review of important soil mechanics concepts, this textbook discusses the uncertainties in geotechnical analysis and design, design philosophy and methodology, and design issues.

Website: www.wiley.com\go\budhu\soilmechanicsfundamentals

Preface

GOAL AND MOTIVATION

My intent in writing this textbook is to present accessible, clear, concise, and contemporary course content for a first course in soil mechanics to meet the needs of undergraduates not only in civil engineering but also in construction, mining, geological engineering, and related disciplines.

However, this textbook is not meant to be an engineering design manual nor a cookbook. It is structured to provide the user with a learning outcome that is a solid foundation on key soil mechanics principles for application in a later foundation engineering course and in engineering practice.

By studying with this textbook, students will acquire a contemporary understanding of the physical and mechanical properties of soils. They will be engaged in the presentation of these properties, in discussions and guidance on the fundamentals of soil mechanics. They will attain the problem-solving skills and background knowledge that will prepare them to think critically, make good decisions, and engage in lifelong learning.

PREREQUISITES

Students using this textbook are expected to have some background knowledge in Geology, Engineering Mechanics (Statics), and Mechanics of Materials.

UNITS

The primary unit of measure used in this textbook is the US customary system of units. However, ASTM standards require certain tests, for example, for particle sizes of soils, to be conducted using SI units (International System of units). Therefore, wherever necessary, SI units are used. An SI version of this textbook is also available.

HALLMARK FEATURES

Contemporary methods: The text presents, discusses, and demonstrates contemporary ideas and methods of interpreting the physical and mechanical properties of soils that students will encounter as practicing engineers. In order to strike a balance between theory and practical applications for an introductory course in soil mechanics, the mechanics is kept to a minimum so that students can appreciate the background, assumptions, and limitations of the theories in use in the field.

The *implications of the key ideas* are discussed to provide students with an understanding of the context for the applications of these ideas.

A modern explanation of soil behavior is presented particularly in soil settlement and soil strength. These are foremost topics in the practice of geotechnical engineering. One-dimensional consolidation is presented in the context of soil settlement rather than as a separate topic (Chapter 7). The shear strength of soils is presented using contemporary thinking and approach. In particular, three popular failure criteria—Coulomb, Mohr-Coulomb, and Tresca—are discussed with regard to their applications and limitations. Students will be able to understand how to use these criteria to properly interpret soil test results and understand the differences between drained and undrained shear strength.

Some common applications of soil mechanics principles are presented to introduce students to and to inform them on the practical importance of studying soil mechanics.

Pedagogy and design directed by modern learning theory: The content and presentation of the chapters are informed by modern theories of how students learn, especially with regard to metacognition.

Learning outcomes listed at the beginning of each chapter inform students what knowledge and skills they are expected to gain from the chapter. These form the bases for the problems at the end of each chapter. By measuring students' performance on the problems, an instructor can evaluate whether the learning outcomes have been satisfied.

Definitions of key terms at the beginning of each chapter define key terms and variables that will be used in the chapter.

Key points summaries throughout each chapter emphasize for students the most important points in the material they have just read.

Practical examples at the end of some chapters give students an opportunity to see how the prior and current principles are integrated to solve "real world type" problems. The students will learn how to find solutions for a "system" rather than a solution for a "component" of the system.

Consistent problem-solving strategy: Students generally have difficulty in translating a word problem into the steps and equations they need to use to solve it. They typically can't read a problem and understand what they need to do to solve it. This text provides and models consistent strategies to help students approach, analyze, and solve any problem. Example problems are solved by first developing a strategy and then stepping through the solution, identifying equations, and checking whether the results are reasonable as appropriate.

Three categories—***conceptual understanding, problem solving, and critical thinking and decision making***—of problems are delineated at the end of the chapter to assess students' knowledge mastery. These are not strict categories. In fact, the skills required in each category are intermixed. Problems within the ***conceptual understanding*** category are intended to assess understanding of key concepts and may contain problems to engage lateral thinking. It is expected that the instructor may add additional problems as needed. Problems within the ***problem-solving*** category are intended to assess problem-solving skills and procedural fluency in the applications of the concepts and principles in the chapter. Problems within the ***critical thinking and decision-making*** category are intended to assess the student's analytical skills, lateral thinking, and ability to make good decisions. These problems have practical biases and require understanding of the fundamentals. Engineers are required to make decisions, often with limited data. Practical experience is a key contributor to good decisions. Because students will invariably not have the practical experience, they will have to use the fundamentals of soil mechanics, typical ranges of values for soils, and their cognitive skills to address problems within the ***critical thinking and decision-making*** category. The instructors can include additional materials to help the students develop critical thinking and decision-making skills.

Knowledge mastery assessment software. This textbook is integrated with YourLabs™ Knowledge Evaluation System (KES) (www.yourlabs.com). This system automatically grades students' solutions to the end of chapter problems. It allows students to answer the problems anywhere on any mobile device (smartphone, iPad, etc.) or any desktop computing device (PC, MAC, etc.). After answering each question in an assignment set by the instructor on KES, the student's answer (or answers to multi-parts problems) is compared to the correct answer (or answers in multi-parts problems) and scored. The student must step through the solution for each problem and answer preset queries to assess concept understanding, critical thinking, problem-solving skills, and procedural fluency. KES then analyzes the feedback from students immediately after submitting their responses and displays the analytics to the students and the instructor. The analytics inform the instructor what the students know and don't know, at what steps, and the types of mistakes made during problem solving. The instructor can re-teach what the students did not know in a timely manner and identify at-risks students. The analytics are also displayed to the student to self-reflect on his/her performance and take corrective action. Relevant instructional materials are linked to each problem, so the student can self-learn the materials either before or upon completion of the problem. Instructors can modify the questions and assets (links or embedded videos, images, customized instructional materials, etc.) and, at each step of the solution, add or delete solution steps or create a customized question. Each problem can be tagged with any standard required by academic or professional organizations. The analytics as well as students' scores are aggregated from the problem to assignment and to class or course levels.

GENESIS OF THIS BOOK

This textbook is an abridged version of the author's other textbook *Soil Mechanics and Foundations* (3rd ed., Wiley, 2011). The *Soil Mechanics and Foundations* textbook provides a more in-depth look at soil mechanics and includes content for both an introductory soil mechanics and a foundations course. For students and other readers who wish to study the detailed mechanics connected with the fundamental concepts and principles, they should consult the author's *Soil Mechanics and Foundations* textbook.

The present textbook, *Soil Mechanics Fundamentals*, arose from feedback from instructors' for a textbook similar to *Soil Mechanics and Foundations* that would cover just the essentials and appeal to a broad section of undergraduate students.

Acknowledgments

I am grateful to the many anonymous reviewers who offered valuable suggestions for improving this textbook. Ibrahim Adiyaman, my former graduate student at University of Arizona, Tucson, worked tirelessly on the Solutions Manual.

Madeleine Metcalfe and Harriet Konishi of John Wiley & Sons were especially helpful in getting this book completed.

Notes for Students and Instructors

WHAT IS SOIL MECHANICS AND WHY IS IT IMPORTANT?

Soil mechanics is the study of the response of soils to loads. These loads may come from human-made structures (e.g., buildings), gravity (earth pressures), and natural phenomena (e.g., earthquake). Soils are natural, complex materials consisting of solids, liquids, and gases. To study soil behavior, we have to couple concepts in solid mechanics (e.g., statics) and fluid mechanics. However, these mechanics are insufficient to obtain a complete understanding of soil behavior because of the uncertainties of the applied loads, the vagaries of natural forces, and the intricate, natural distribution of different soil types. We have to utilize these mechanics with simplifying assumptions and call on experience to make decisions (judgment) on soil behavior.

A good understanding of soil behavior is necessary for us to analyze and design support systems (foundations) for infrastructures (e.g., roads and highways, pipelines, bridges, tunnels, embankments), energy systems (e.g., hydroelectric power stations, wind turbines, solar supports, geothermal and nuclear plants) and environmental systems (e.g., solid waste disposal, reservoirs, water treatment and water distribution systems, flood protection systems). The stability and life of any of these systems depend on the stability, strength, and deformation of soils. If the soil fails, these systems founded on or within it will fail or be impaired, regardless of how well these systems are designed. Thus, successful civil engineering projects are heavily dependent on our understanding of soil behavior. The iconic structures shown in Figure 1 would not exist if soil mechanics was not applied successfully.

PURPOSES OF THIS BOOK

This book is intended to provide the reader with a prefatory understanding of the properties and behavior of soils for later applications to foundation analysis and design.

LEARNING OUTCOMES

When you complete studying this textbook you should be able to:

(a) (b) (c)

Figure 1 (a) Willis tower (formerly the Sears Tower) in Chicago, (b) Empire State Building in New York City, and (c) Hoover Dam at the border of Arizona and Nevada.

- Describe soils and determine their physical characteristics such as grain size, water content, void ratio, and unit weight.
- Classify soils.
- Determine the compaction of soils and be able to specify and monitor field compaction.
- Understand the importance of soil investigations and be able to plan and conduct a soil investigation.
- Understand one- and two-dimensional flow of water through soils and be able to determine hydraulic conductivity, porewater pressures, and seepage stresses.
- Understand how stresses are distributed within soils from surface loads and the limitations in calculating these stresses.
- Understand the concept of effective stress and be able to calculate total and effective stresses, and porewater pressures.
- Be able to determine consolidation parameters and calculate one-dimensional consolidation settlement.
- Be able to discriminate between "drained" and "undrained" conditions.
- Understand the stress–strain response of soils.
- Determine soil strength parameters from soil tests, for example, the friction angle and undrained shear strength.

ASSESSMENT

Students will be assessed on how well they absorb and use the fundamentals of soil mechanics through problems at the end of the chapter. These problems assess concept understanding, critical thinking, and problem-solving skills. The problems in this textbook are coordinated with the YourLabs™ Knowledge Evaluation System (see the Preface for more detail).

WEBSITE

Additional materials are available at www.wiley.com\go\budhu\soilmechanicsfundamentals.

Additional support materials are available on the book's companion website at www.wiley.com\go\budhu\soilmechanicsfundamentals.

DESCRIPTION OF CHAPTERS

The sequencing of the chapters is such that the pre-knowledge required in a chapter is covered in previous chapters. This is difficult for soil mechanics because many of the concepts covered in the chapters are linked. Wherever necessary, identification is given of the later chapter in which a concept is discussed more fully.

Chapter 1 covers soil composition and particle sizes. It describes soil types and explains the differences between fine-grained and coarse-grained soils.

Chapter 2 introduces the physical soil parameters, and explains how these parameters are determined from standard tests and their usage in soil classification.

Chapter 3 discusses the purpose, planning, and execution of a soils investigation. It describes the types of common in situ testing devices and laboratory tests to determine physical and mechanical soil parameters.

Chapter 4 discusses both the one-dimensional and two-dimensional flows of water through soils. It shows how water flows through soil can be analyzed using Darcy's law and Laplace's equation. Procedures for drawing flownets and interpreting flowrate, porewater pressures, and seepage condition are covered.

Chapter 5 describes soil compaction and explains why it is important to specify and monitor soil compaction in the field.

Chapter 6 is about the amount and distribution of stresses in soils from surface loads. Boussinesq's solutions for common surface loads on a semi-infinite soil mass are presented and limitations of their use are described. The concept of effective stress is explained with and without the influence of seepage stresses.

Chapter 7 discusses soil settlement. It explains how to estimate the settlement of coarse-grained soils based on the assumption of elastic behavior. It covers the limitations of using elasticity and the difficulties of making reliable predictions of settlement. Also, the discussion covers the basic concept of soil consolidation, the determination of consolidation parameters, and methods to calculate primary consolidation settlement and secondary compression.

Chapter 8 brings the discussion to the shear strength of soils. Soils are treated using the contemporary idealization of them as dilatant-frictional materials rather than their conventional idealization as cohesive-frictional materials. Typical stress–strain responses of coarse-grained and fine-grained soils are presented and discussed. The chapter discusses the implications of drained and undrained conditions, cohesion, soil suction, and cementation on the shear resistance of soils. Interpretations and limitations of using the Coulomb, Mohr–Coulomb, and Tresca failure criteria are considered as well.

Appendix A presents the derivation of a solution for the one-dimensional consolidation theory as proposed by Karl Terzaghi (1925).

Appendix B describes the procedure to determine the stress state using Mohr's circle. It is intended as a brief review in order to assist the student in drawing Mohr's circles to interpret soil failure using the Mohr–Coulomb failure criterion.

Appendix C provides a collection of frequently used tables taken from the various chapters to allow for easy access to tables listing values of typical soil parameters and with information summaries.

Appendix D provides a collection of equations used in this textbook. It can be copied and used for assignments and examinations.

For instructors who wish to introduce additional materials in their lectures or examinations, a special chapter (Chapter 9) is available at www.wiley.com\go\budhu\soilmechanicsfundamentals. Chapter 9 presents some common applications of soil mechanics. It is intended for students who will not move forward to a course in Foundation Engineering. These applications include simple shallow and deep foundations, lateral earth pressures on simple retaining walls, and the stability of infinite slopes. Simple soil profiles are used in these applications to satisfy a key assumption (homogeneous soil) in the interpretation of shear strength.

Notation, Abbreviations, Unit Notation, and Conversion Factors

NOTATION

Note: A prime (′) after notation for stress denotes effective stress.

A	Area
B	Width
c_{cm}	Cementation strength
c_o	Cohesion or shear strength from intermolecular forces
c_t	Soil tension
C	Apparent undrained shear strength or apparent cohesion
C_c	Compression index
C_r	Recompression index
C_v	Vertical coefficient of consolidation
C_α	Secondary compression index
CC	Coefficient of curvature
CI	Consistency index
CPT	Cone penetrometer test
CSL	Critical state line
Cu	Uniformity coefficient
D	Diameter
D_r	Relative density
D_{10}	Effective particle size
D_{50}	Average particle diameter
e	Void ratio
E	Modulus of elasticity
E_{sec}	Secant modulus
G_s	Specific gravity
h_p	Pressure head
h_z	Elevation head
H	Height
H_{dr}	Drainage path
H_o	Height
i	Hydraulic gradient

I_d	Density index
k	Hydraulic conductivity for saturated soils
k_z	Hydraulic conductivity in vertical direction for saturated soils
K_a	Active lateral earth pressure coefficient
K_o	Lateral earth pressure coefficient at rest
K_p	Passive lateral earth pressure coefficient
kips	1000 pounds
ksf	kips per square foot (1000 psf)
L	Length
LI	Liquidity index
LL	Liquid limit
LS	Linear shrinkage
m_v	Modulus of volume compressibility
n	Porosity
N	Standard penetration number
NCL	Normal consolidation line
OCR	Overconsolidation ratio with respect to vertical effective stress
pcf	Pounds per cubic foot
psf	Pounds per square foot
q	Flow rate
q_s	Surface stress
q_z	Flow rate in vertical direction
Q	Flow, quantity of flow, and also vertical load
R_d	Unit weight ratio or density ratio
R_T	Temperature correction factor
s_u	Undrained shear strength
S	Degree of saturation
SF	Swell factor
SI	Shrinkage index
SL	Shrinkage limit
SPT	Standard penetration test
SR	Shrinkage ratio
S_t	Sensitivity
u	Porewater pressure
u_a	Pore air pressure
U	Average degree of consolidation
URL	Unloading/reloading line
v	Velocity
v_s	Seepage velocity
V	Volume
V'	Specific volume
V_a	Volume of air
V_s	Volume of solid
V_w	Volume of water
w	Water content
w_{opt}	Optimum water content
W	Weight
W_a	Weight of air
W_s	Weight of solid
W_w	Weight of water
z	Depth

α	Dilation angle
α_p	Peak dilation angle
ε_p	Volumetric strain
ε_z	Normal strain
ϕ'	Generic friction angle
ϕ'_{cs}	Critical state friction angle
ϕ'_p	Peak friction angle
ϕ'_r	Residual friction angle
γ	Bulk unit weight
γ'	Effective unit weight
γ_d	Dry unit weight
$\gamma_{d(max)}$	Maximum dry unit weight
γ_{sat}	Saturated unit weight
γ_w	Unit weight of water
γ_{zx}	Shear strain
μ	Viscosity
ν	Poisson's ratio
ρ_e	Elastic settlement
ρ_{pc}	Primary consolidation
ρ_{sc}	Secondary consolidation settlement
ρ_t	Total settlement
σ	Normal stress
τ	Shear stress
τ_{cs}	Critical state shear strength
τ_f	Shear strength at failure
τ_p	Peak shear strength
τ_r	Residual shear strength
ξ_o	Apparent friction angle

ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
USCS	Unified Soil Classification System
USGS	United States Geological Service

UNIT NOTATION AND CONVERSION FACTORS

in.	inch
ksf	kips per square foot
lb	pounds
pcf	pounds per cubic foot
psf	pounds per square foot

1.00 kip = 1000 pounds (lb)
1.00 ksf = 1000 pounds per square foot (psf)

US Customary Units		SI Units
Length		
1.00 in.	=	2.54 cm
1.00 ft	=	30.5 cm
Mass and Weight		
1.00 lb	=	454 g
1.00 lb	=	4.46 N
1 kip	=	1000 lb
Area		
1.00 in.^{2}	=	6.45 cm^2
1.00 ft^2	=	0.0929 m^2
Volume		
1.00 mL	=	1.00 cm^3
1.00 L	=	1000 cm^3
1.00 ft^3	=	0.0283 m^3
1.00 in.^{3}	=	16.4 cm^3
Temperature		
°F	=	1.8(°C) + 32
°C	=	(°F − 32)/1.8
Pressure		
1.00 psi	=	6.895 kPa
1.00 psi	=	144 psf
1.00 ksi	=	1000 psi
Unit Weight and Mass Density		
1.00 pcf	=	16.0 kg/m^3
1.00 pcf	=	0.157 kN/m^3
Universal Constants		
g	=	9.81 m/s^2
g	=	32.2 ft/s^2

Unit weight of fresh water = 62.4 pounds per cubic foot (pcf)
Unit weight of salted water = 64 pounds per cubic foot (pcf)