MUNI BUDHU

Soil Mechanics & Foundations

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MUNI BUDHU
Professor, Department of Civil Engineering & Engineering Mechanics
University of Arizona

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PREFACE

This textbook is written for an undergraduate course in soil mechanics and foundations. It has three primary objectives. First, to present basic concepts and fundamental principles of soil mechanics and foundations in a simple pedagogy using the students' background in mechanics, physics, and mathematics. Second, to integrate modern learning principles, teaching techniques and learning aids to assist students in understanding the various topics in soil mechanics and foundations. Third, to provide a solid background knowledge to hopefully launch students in life-long learning of geotechnical engineering issues.

Topics are presented thoroughly and systematically to elucidate the basic concepts and fundamental principles without diluting technical rigor. The intention is to provide the student with a firm grounding in the principles behind the practice. Example problems have been solved to demonstrate or to provide further insights into the basic concepts and applications of fundamental principles. The solution of each example is preceded by a strategy, which is intended to teach students to think about possible solutions to a problem before they begin to solve it. Each solution provides a step by step procedure to guide the student in problem solving. Each chapter in the book is structured on modern teaching themes of gaining attention (reception), learning objectives (expectancy), recollecting of prior knowledge (working memory), presenting the information (selective perception), providing guidance (semantic encoding), key points (reinforcement), eliciting performance on key concepts through an interactive quiz on CD-ROM (retrieval and reinforcement), summarizing (retrieval and generalization), and assessing performance through problem solving. The text is written in colloquial English to try to engage students and make them feel that they are active participants in the learning process. The emphasis in this book is on the delivery and retention of the fundamental principles and concepts.

Today's students are surrounded by visual media and obtain much of their information from them. This book is accompanied by an interactive multimedia CD-ROM in which many of the concepts are animated. The author hopes that this would capture the visual learners and enhance learning. Various interactive tools such as interactive problem solving, virtual laboratories, quizzes, etc., are included to facilitate learning, retention, evaluation, and assessment.

With the proliferation and accessibility of computers, programmable calculators, and software, students will likely use these tools in their practice. Consequently, generalized equations which the students can program into their calculators, and computer program utilities are provided rather than charts.

I am grateful to the following reviewers who offered many valuable suggestions for improving this textbook:

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Additional resources are available online at *www.wiley.com/college/budhu*.

NOTES for Instructors

I would like to present some guidance to assist you in using this book in undergraduate geotechnical engineering courses.

DESCRIPTION OF CHAPTERS

The philosophy behind each chapter is to seek coherence and group topics that are directly related to each other. This is a rather difficult task in geotechnical engineering because topics are intertwined. Attempts have been made to group topics based on whether they relate directly to the physical characteristics of soils or mechanical behavior or are applications of concepts to analysis of geotechnical systems. The sequencing of the chapters is such that the preknowledge required in a chapter is covered in previous chapters.

Chapter 1 sets the introductory stage of informing the students of the importance of geotechnical engineering. Most of the topics related to the physical characteristics of soils are grouped in Chapter 2. Description of soils, soil constituents, index properties, soils classification, soil compaction, permeability, and soil investigations form the core.

Chapter 3 deals with stresses, strains, and elastic deformation of soils. Most of the material in this chapter builds on course materials that students would have encountered in their courses in statics and strength of materials. Often, elasticity is used in preliminary calculations in analyses and design of geotechnical systems. The use of elasticity to find stresses and settlement of soils is presented and discussed. Stress increases due to applied surface loads common to geotechnical problems are described. Students are introduced to stress and strain states and stress and strain invariants. The importance of effective stresses and seepage in soil mechanics is emphasized. Stress paths are introduced not only because of their importance in understanding the performance of a geotechnical structure but because they are connected to the presentation of stresses—stress paths being a graphical representation or vector representation of stresses. Drained and undrained conditions are introduced within the context of elasticity.

One-dimensional consolidation of soils is considered in Chapter 4. Here the basic concepts of consolidation are presented with methods to calculate consolidation settlement. The theory of one-dimensional consolidation is developed to show the students the theoretical framework from which soil consolidation settlement is interpreted and the parameter required to determine time rate of settlement. The oedometer test is described and procedures to determine the various parameters for settlement calculations are presented.

Chapter 5 deals with the shear strength of soils and the tests (laboratory and field) required for its determination. The Mohr–Coulomb failure criterion is discussed using the student's background in strength of materials (Mohr's circle) and in statics (dry friction). Soils are treated as a dilatant-frictional material rather than the conventional cohesive-frictional material. Typical stress–strain responses of sand and clay are presented and discussed. The implications of drained and undrained conditions on the shear strength of soils are discussed. Laboratory and field tests to determine the shear strength of soils are described.

Chapter 6 deviates from traditional undergraduate textbook topics by dealing with soil consolidation and strength as separate issues. In this chapter, deformation and strength are integrated within the framework of critical state soil mechanics using a simplified version of the modified cam-clay model. The emphasis is on understanding the mechanical behavior of soils rather than presenting the mathematical formulation of critical state soil mechanics and the modified cam-clay model. The amount of mathematics is kept to the minimum needed for understanding and clarification of important concepts. Projection geometry is used to illustrate the different responses of soils when the loading changes under drained and undrained loading. Although this chapter deals with a simplification and an idealization of real soils, the real benefit is a simple framework, which allows the student to think about possible soil responses if conditions change from those originally conceived, as is usual in engineering practice. It also allows them to better interpret soil test results.

Chapter 7 deals with bearing capacity and settlement of footings. Here bearing capacity and settlement are treated as a single topic. In the design of foundations, the geotechnical engineer must be satisfied that the bearing capacity is sufficient and the settlement at working load is tolerable. Indeed, for most shallow footings, it is settlement that governs the design, not bearing capacity. Limit equilibrium analysis is introduced to illustrate the method that has been used to find the popular bearing capacity equations and to make use of the student's background in statics (equilibrium) to introduce a simple but powerful analytical tool. Three sets of bearing capacity equations (Terzaghi as modified by Vesic, Meyerhof, and Skempton), the influence of groundwater level, and eccentric loads on bearing capacity are discussed. These equations are simplified by breaking them down into two categories—one relating to drained conditions, the other to undrained conditions. Elastic, one-dimensional consolidation, and Skempton and Bjerrum's method of determining settlement are presented. The elastic method of finding settlement is based on work done by Gazettas (1985), who described problems associated with the Janbu, Bjerrum, and Kjaernali (1956) method that is conventionally quoted in textbooks.

Pile foundations are described and discussed in Chapter 8. Methods for finding bearing capacity and settlement of single and group piles are presented.

Chapter 9 is about two-dimensional steady state flow through soils. Solutions to two-dimensional flow using flow nets and the finite difference technique are discussed. Emphases are placed on seepage, pore water pressure, and instability. This chapter normally comes early in most current textbooks. The reason for placing this chapter here is because two-dimensional flow influences the stability of earth structures (retaining walls and slopes), discussion of which follows in Chapters 10 and 11. A student would then be able to make the practical connection of two-dimensional flow and stability of geotechnical systems readily.

Lateral earth pressures and their use in the analysis of earth retaining systems and excavations are presented in Chapter 10. Gravity and flexible retaining walls, in addition to reinforced soil walls, are discussed. Guidance is provided as to what strength parameters to use in drained and undrained conditions.

Chapter 11 is about slope stability. Here stability conditions are described based on drained or undrained conditions.

An appendix (Appendix A) allows easy access to frequently used typical soil parameters and correlations.

CHAPTER LAYOUT

The ***Introduction*** of each chapter attempts to capture the student's attention, to present the learning objectives, and to inform the student on what prior knowledge is needed to master the material. At the end of the introduction, a ***Sample Practical Situation*** is described. The intention is to give the student a feel for the kind of problem that he/she should be able to solve on completion of the chapter. At the end of the chapter, a problem similar to the sample practical situation is solved. This provides closure to the chapter.

Definitions of Key Terms are presented to alert and introduce the students to new terms in the topics to be covered. A section on ***Questions to Guide Your Reading*** is intended to advise the students on key information that they should grasp and absorb. These questions form the core of the quiz on the CD-ROM.

Each topic is presented thoroughly with the intention of engaging the students and making them feel involved in the process of learning. At various stages, ***Key Points*** are summarized for reinforcement. ***Examples*** are solved at the end of each major topic to illustrate problem-solving techniques, to reinforce and to apply the basic concepts. A ***What's Next*** section serves as a link between articles and informs students about this connection. This prepares them for the next topic and serves as a break point for your lectures. A ***Summary*** at the end of each chapter reminds students, in a general way, of key information. The ***Exercises*** or problems are divided into three sections. The first section contains problems that are theoretically based, the second section contains problems suitable for problem solving, and the third section contains problems biased toward application. This gives you flexibility in setting problems based on the objectives of the course.

CD ROM

With the advent of personal computers, learning has become more visual. Some studies have reported that visual images have improved learning by as much as 400%. This textbook is accompanied by a CD ROM that contains text, interactive animation, images, a glossary, notation, quizzes, notepads, and interactive problem solving. It should appeal, particularly, to visual learners.

A quiz is included in appropriate chapters on the CD ROM to elicit performance and provide feedback on key concepts. Interactive problem solving is used to help students solve problems similar to the problem-solving exercises. When an interactive problem is repeated, new values are automatically generated. Sounds are used to a limited extent. The CD ROM contains a virtual soils laboratory for the students to conduct geotechnical tests. These virtual tests are not intended to replace the necessary hands-on experience in a soil laboratory. Rather, they complement the hands-on experience, prepare the students for the real experience, test relevant prior knowledge of basic concepts for the interpretation of the test results, guide them through the evaluation and interpretation of the results, allow them to conduct tests that cannot otherwise be done during laboratory sessions, and allow them to use the results of their tests in practical applications.

ABET REQUIREMENTS

The United States Accreditation Board for Engineering and Technology (ABET) has introduced new criteria for accreditation purposes. Each chapter in this book has the author's judgment on how it satisfies ABET's engineering science (ES) and engineering design (ED) criteria. You may adjust the recommended percentages allocated to ES and ED based on your own judgment.

COURSE MATERIAL

I have used this book and CD ROM for teaching two undergraduate courses. One course is on soil mechanics in which I cover Chapters 1 through 6. The other course is an introduction to foundation engineering in which I cover Chapters 7 through 11. If you wish, you may consider Chapter 9, which deals with two-dimensional flow through porous media, in your first course in soil mechanics or geotechnical engineering. Visual learners may find the CD ROM more helpful than the textbook. However, the CD ROM does not cover the full range of topics in the textbook. In addition, the textbook contains a lot more detail.

COURSE DELIVERY

I have used the CD ROM exclusively in my classroom to deliver my course. This significantly cuts down on lecture preparation time. Moreover, the interactivities and animations coded in the CD ROM make it easier for students to understand difficult topics. Before a new topic is introduced, I used the quiz on the CD ROM to evaluate how much of the content of the previous topic was retained. The interactive problem solving on the CD ROM is used to illustrate problem solving to the students.

NOTES for Students and Instructors

PURPOSES OF THIS BOOK

This book is intended to present the principles of soil mechanics and its application to foundation analyses. It will provide you with an understanding of the properties and behavior of soils, albeit not a perfect understanding. The design of safe and economical geotechnical structures or systems requires considerable experience and judgment, which cannot be obtained by reading this or any other textbook. It is hoped that the fundamental principles and guidance provided in this textbook will be a base for lifelong learning in the science and art of geotechnical engineering.

The goals of this textbook in a course on soil mechanics and foundation are as follows:

1. To understand the physical and mechanical properties of soils.
2. To determine parameters from soil testing to characterize soil properties, soil strength, and soil deformations.
3. To apply the principles of soil mechanics to analyze and design simple geotechnical systems.

LEARNING OUTCOMES

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

- Describe soils and determine their physical characteristics such as, grain size, water content, and void ratio
- Classify soils
- Determine compaction of soils
- Understand the importance of soil investigations and be able to plan a soil investigation
- Understand the concept of effective stress
- Determine total and effective stresses and pore water pressures
- Determine soil permeability
- Determine how surface stresses are distributed within a soil mass
- Specify, conduct, and interpret soil tests to characterize soils

- Determine soil strength and deformation parameters from soil tests, for example, Young's modulus, friction angle and undrained shear strength
- Discriminate between "drained" and "undrained" conditions
- Understand the effects of seepage on the stability of structures
- Estimate the bearing capacity and settlement of structures founded on soils
- Analyze and design simple foundations
- Determine the stability of earth structures, for example, retaining walls and slopes

Certain topics are ubiquitous. The table below provides a guide to the distribution of the major topics in this textbook. A solid circle denotes significant coverage of the topic while an open circle denotes some coverage of the topic or the use of it in the chapter. For example, total and effective stresses and pore water pressures are introduced and significantly covered in Chapter 3. However, they are used in every chapter thereafter. You should pay particular attention to the topics that have wide distributions in this textbook. Chapters 2 and 6 cover the fundamentals of soil mechanics, Chapters 7 and 11 cover analysis of foundations and earth structures.

Distribution of Main Topics in This Textbook

	Chapter										
	Soil mechanics						Foundation and earth structures				
Description	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Physical characteristics and properties	I	●		○	○	○	○	○	○	○	○
Compaction	N	●					○				
Soil investigation	T	●		○	○	○	○	○	○	○	○
Total and effective stresses and pore water pressure	R		●	○	○	○	○	○	○	○	○
Permeability	O	●		○					○		
Stresses in soils	D		●	○	○	○	○	○	○	○	○
Drained and undrained conditions	U		●		●	●	○	○		○	○
Settlement and deformation	C		○	●		○	●	●		○	
Shear strength	T				●	●	○	○	○	○	○
Seepage	I	●							●	○	○
Bearing capacity and settlement of foundations	O						●	●		○	
Stability of earth structures	N								○	●	●

ASSESSMENT

You will be assessed on how well you absorb and use the fundamentals of soil mechanics. Three areas of assessment are incorporated in the Exercise sections of this textbook. The first area called "Theory" is intended for you to demonstrate your knowledge of the theory and extend it to uncover new relationships. The questions under "Theory" will help you later in your career to address unconventional issues using fundamental principles. The second area called "Problem Solving" requires you to apply the fundamental principles and concepts to a wide variety of problems. These problems will test your understanding and use of the fundamental principles and concepts. The third area called "Practical" is intended to create practical scenarios for you to use not only the subject matter in the specific chapter but prior materials that you have encountered. These problems try to mimic some aspects of real situations and give you a feel for how the materials you have studied so far can be applied in practice. Communications are, at least, as important as the technical details. In many of these "Practical" problems you are placed in a situation to convince stakeholders of your technical competence. A quiz (multiple choice) on each chapter is included in the CD to test your general knowledge of the subject matter in that chapter. The questions on the quiz are related to the section "Questions to Guide Your Reading," included in each chapter.

SUGGESTIONS FOR PROBLEM SOLVING

Engineering is, foremost, about problem solving. For most engineering problems, there is no unique method or procedure for finding solutions. Often, there is no unique solution to an engineering problem. A suggested problem-solving procedure is outlined below.

1. Read the problem carefully; note or write down what is given and what you are required to find.
2. Draw clear diagrams or sketches wherever possible.
3. Devise a strategy to find the solution. Determine what principles, concepts, and equations are needed to solve the problem.
4. Perform calculations making sure that you are using the correct units.
5. Check whether your results are reasonable.

The units of measurement used in this textbook follow the SI system. Engineering calculations are approximations and do not result in exact numbers. All calculations in this book are rounded, at the most, to two decimal places except in some exceptional cases, for example, void ratio.

SUGGESTIONS FOR USING TEXTBOOK AND CD-ROM

This textbook is accompanied by and integrated with a CD-ROM. Not all sections of the textbook are covered in the CD-ROM. The textbook provides significantly more details on the subject matter than the CD-ROM. The CD-ROM provides animations, interactive problem solving, quizzes, virtual laboratories, special modules (for example, a computer program to find stresses within a soil), spreadsheets, videos, a notepad, a glossary, a list of notations, and a calculator.

CD icons in the textbook have inset numbers that are intended to alert you to special features present on the CD-ROM. The numbers have the following meaning:

1. Interactive animation
2. Virtual lab
3. Interactive problem solving
4. Spreadsheet
5. Video
6. Computer program utility

PRESENTATION

Few engineering projects involve design and construction only. Often, you have to present your work, orally or in writing, to clients who do not have the technical knowledge to grasp technical lingo. In oral presentations, you are normally given a very short time to present your project to your client. On many projects, the awarding of a contract depends on those precious few minutes. Your task is to make the best, easily understood presentation in the shortest possible time. Because of the importance of communicating your ideas and solutions, problems are included in several chapters in this book in which you will have to make a short presentation of your solution to stakeholders.

The key to a good presentation is to tell your audience what you are going to say, say it (body of presentation), and then tell them what you told them (conclusion). There are several media available for making visual presentations. These include a computer-aided presentation using a laptop computer connected to an LCD projector, overhead transparencies, and slides. You should use one (or more) of these media that best suit your audience and the message you want to transmit. Your visuals should have a reasonable font size (24 points), should not be busy, and should have simple language and clear graphics. The visuals should highlight what you are going to present and you should not normally read from them.

A sample page of a presentation is shown below. Here the central idea is "Shear Strength of Soils" (font size: 30 points). In this visual, you would be defining shear strength and inform your audience that Coulomb's law is used to interpret the shear strength of soils.

SHEAR STRENGTH OF SOILS

- Resistance to shear forces
- Coulomb's law

Now, let us start our study of soil mechanics and foundations.

Notation

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

A	Area
B	Width
c_o	Cohesion
C_c	Compression index
C_r	Recompression index
C_h	Horizontal coefficient of consolidation
C_v	Vertical coefficient of consolidation
C_α	Secondary compression index
CC	Coefficient of curvature
CSM	Critical state model
D	Diameter
D_f	Embedment depth
D_r	Relative density
D_{10}	Effective particle size
D_{50}	Average particle diameter
e	Void ratio
E	Modulus of elasticity
E_i	Initial tangent modulus
E_p	Modulus of elasticity of pile
E_s	Secant modulus
E_{so}	Modulus of elasticity of soil
E_t	Tangent modulus
f_b	Ending bearing stress
f_s	Skin friction
FS	Factor of safety
F_ϕ	Mobilization factor for ϕ
F_u	Mobilization factor for s_u
G	Shear modulus
G_s	Specific gravity
h_p	Pressure head
h_z	Elevation head
H	Head
H_o	Height
H_{dr}	Drainage path
i	Hydraulic gradient
I	Influence factor
I_s	Settlement influence factor
I_L	Liquidity index
I_p	Plasticity index
k	Hydraulic conductivity or coefficient of permeability
K_a	Active lateral earth pressure coefficient
K_p	Passive lateral earth pressure coefficient
K_0	Lateral earth pressure coefficient at rest
L	Length
m_v	Modulus of volume compressibility
N	Standard penetration number
N_c, N_q, N_γ	Bearing capacity factors
n	Porosity
NCL	Normal consolidation line
OCR	Overconsolidation ratio
p	Mean stress
q	Deviatoric stress or shear stress
q_a	Allowable bearing capacity
q_s	Surface stress
q_{ult}	Ultimate bearing capacity
q_v	Flow rate
Q	Flow, quantity of flow
Q_b	End bearing or point resistance
Q_f	Skin or shaft friction
Q_p	Point bearing resistance
Q_{ult}	Ultimate load capacity
$(Q_{ult})_g$	Ultimate group load capacity

R_T	Temperature correction factor
R_x	Resultant lateral force
R_o	Overconsolidation ratio with respect to stress invariants
s_u	Undrained shear strength
S	Degree of saturation
S_t	Sensitivity
SPT	Standard penetration test
T	Sliding force or resistance
T_v	Time factor
u	Pore water pressure
U	Average degree of consolidation
UC	Uniformity coefficient
URL	Unloading/reloading line
v	Velocity
v_s	Seepage velocity
v_{sh}	Shear wave 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_{LL}	Liquid limit
w_{opt}	Optimum water content
w_{PL}	Plastic limit
w_{SL}	Shrinkage limit
W	Weight
W_a	Weight of air
W_s	Weight of solid
W_w	Weight of water
z	Depth
α	Dilation angle
α_s	Slope angle
α_u	Adhesion factor
β	Skin friction coefficient for drained condition
δ	Deflection or settlement
ε	Normal strain
ε_p	Volumetric strain
ε_q	Deviatoric 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_{sat}	Saturated unit weight
γ_d	Dry unit weight
$\gamma_{d(\mathrm{max})}$	Maximum dry unit weight
γ_w	Unit weight of water
γ_{zx}	Shear strain
κ	Recompression index
λ	Compression index
μ	Viscosity
μ_s	Shape coefficient
μ_{emb}	Embedment coefficient
μ_{wall}	Wall friction coefficient
ν	Poisson's ratio
ρ_e	Elastic settlement
ρ_{pc}	Primary consolidation
ρ_{sc}	Secondary consolidation 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	Velocity potential
ψ	Rotation of principal plane to the horizontal
ψ_p	Plastification angle for piles
ψ_s	Stream potential

CONTENTS