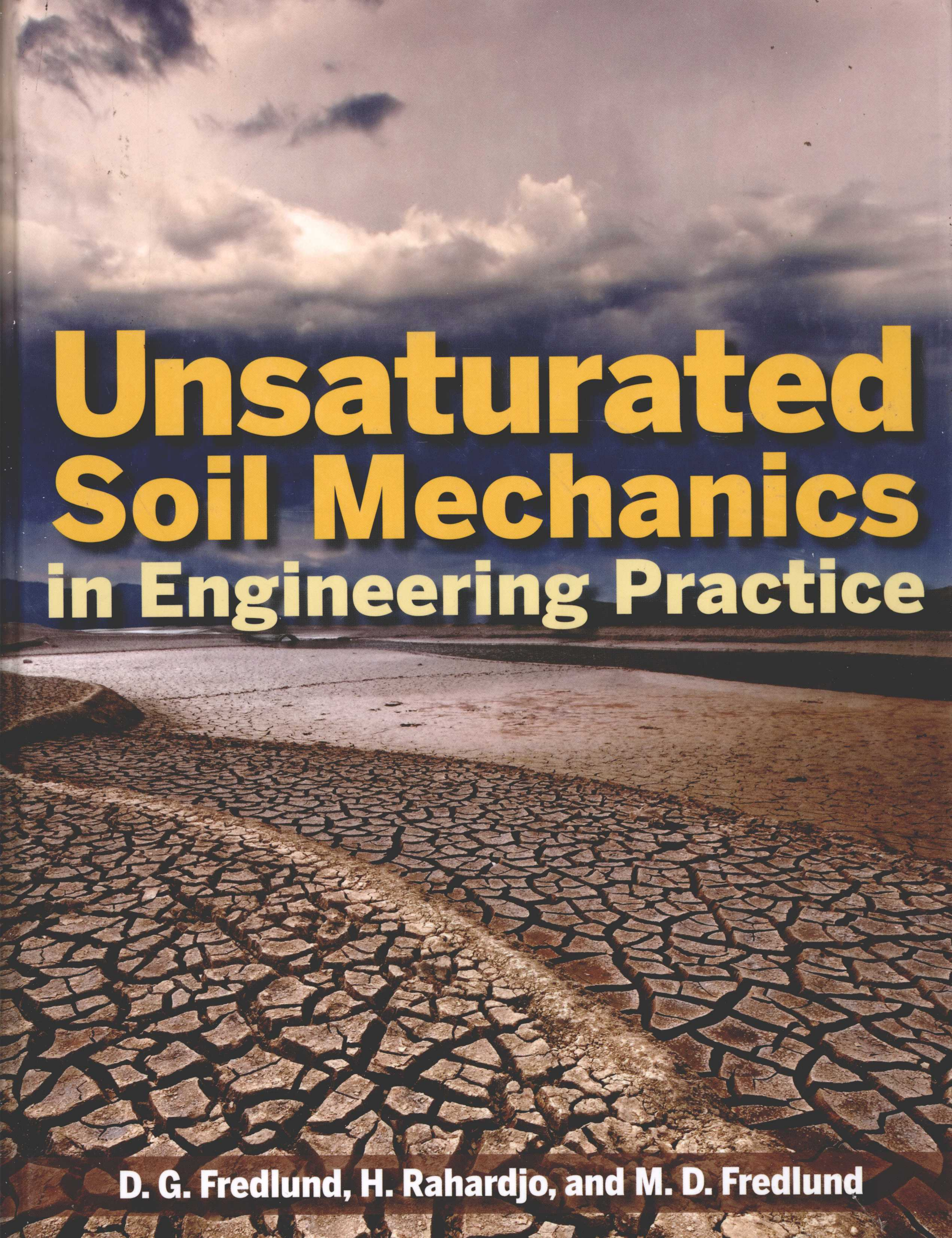

Unsaturated Soil Mechanics in Engineering Practice

D. G. Fredlund, H. Rahardjo, and M. D. Fredlund

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To our wives and families for their patience, tolerance, and enduring appreciation of our dedication to the development of the science for unsaturated soil behavior in engineering practice.

FOREWORD

In 1993, Professors Fredlund and Rahardjo published the first textbook solely concerned with the behavior of unsaturated soils: *Soil Mechanics for Unsaturated Soils*. That volume maintained the framework of classical soil mechanics, but extended it to incorporate the soil suction phenomenon as an independent variable that is amenable to measurement and calculation. It marked a major milestone in the evolution of unsaturated soil mechanics.

Professors Fredlund and Rahardjo have now collaborated with Murray Fredlund to publish their successor volume, *Unsaturated Soil Mechanics in Engineering Practice*. Murray Fredlund adds computational skills to the team and, in the view of the authors, these are essential to meet their objectives of presenting a volume that not only covers our present knowledge of unsaturated soil behavior, but also provides guidance on the manner in which practical problems involving unsaturated soil behavior are formulated and solved. Many flux-related problems in unsaturated soil behavior require the solution of nonlinear partial differential equations with associated boundary conditions and the volume adds guidance on these computational issues as applied to the formulation of water, air, and heat flow through unsaturated soils. Separate chapters concentrate on the shear strength of unsaturated soils and its application to earth pressure, bearing capacity, and stability problems, as well as the formulation of stress-deformation behavior and its application to heave- and stiffness-related problems.

A fundamental distinction between saturated and unsaturated soil behavior is the need to express the relationship in the latter between water content and soil suction, that is, the soil-water characteristic curve. Since 1993, there has been an explosion of studies into the measurement of soil suction and the development of soil-water characteristic curves. A particular effort has been made here to synthesize these developments in a manner that facilitates applications.

While most readers will concentrate on the technical contents of this book, I urge students of the subject to also reflect on the contents of Chapter 1 related to the emergence of unsaturated soil mechanics in a coherent form and the assessment of challenges to its implementation. The guiding spirit of this welcome volume is to give the reader confidence that all of these challenges can be addressed in a consistent and rational manner.

Understandably, given current research efforts in the field of unsaturated soil mechanics, not all researchers and practitioners will accept the total contents of this book in an uncritical manner. Science is the search for truth, predominantly by hypothetico-deductive methods, which drive its progression. However, engineering is the pursuit of functionality and it progresses by incremental improvements to enhance intended function. It is particularly in the latter context that the authors have made an important contribution to geotechnical engineering. I expect that *Unsaturated Soil Mechanics in Engineering Practice* will remain an essential reference for educators, researchers, and practitioners for a long time to come.

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of Civil Engineering

and

Past President, International Society of Soil
Mechanics and Geotechnical Engineering (1989–1994)

University of Alberta
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PREFACE

Soil mechanics is a relatively young applied science. Karl Terzaghi published his English version of *Theoretical Soil Mechanics* in 1943. The book provided a science-based context for analyzing the physical behavior of saturated soils.

Geotechnical engineering has changed in many ways since the 1940s. The procedures for performing subsurface investigations have undergone some changes, but the investigative procedures remain quite similar. Boreholes are still drilled with disturbed and undisturbed soil samples taken at intervals for later laboratory testing. However, the manner in which we obtain our geotechnical engineering solutions has changed dramatically. Terzaghi and his contemporaries assembled the context for soil mechanics at a time when the tools for solving mathematical problems were significantly different from the tools that are available today.

In the 1940s, the writers of soil mechanics textbooks attempted to take complex three-dimensional, real-world problems and reduce them to simplified, closed-form solutions. *Flownets* provided a graphical solution for the movement of water through an isotropic, homogeneous, two-dimensional porous continuum. *Methods of (vertical) slices* provided a solution for calculating the factor of safety of a two-dimensional slope. *Methods of (horizontal) layers* provided a solution for the calculation of settlement of a one-dimensional, compressible clay soil. The soil mechanics world contained a series of soil property constants (e.g., k, c', and ϕ'), and those soil properties that were not constants were converted to a linear form to be represented as constants (e.g., C_c and C_s).

It became clear in the 1960s and 1970s that unsaturated soil properties would need to be defined as nonlinear *unsaturated soil property functions* (USPFs). *Unsaturated soil mechanics* became a vibrant area of geotechnical research, and it was apparent that we were entering a new era that required a new paradigm for solving saturated-unsaturated soil mechanics problems. If unsaturated soil mechanics was to find its way into geotechnical engineering practice there needed to be reliable methodologies for obtaining the unsaturated soil property functions at reasonable cost and effort. Consequently, a wide variety of *estimation procedures* emerged from research in many countries. The estimation procedures relied heavily on the saturated soil properties and an understanding of the *soil-water characteristic curve* (SWCC), that is, the relationship between water content and soil suction.

The 1960s and 1970s were decades that witnessed rapid growth in our ability to solve complex mathematical formulations. The computer could be used to solve new mathematical formulations that described the physical behavior of saturated-unsaturated soil mechanics problems. Numerical methods of solution emerged for all areas of material behavior, areas that spanned well beyond classical soil mechanics. Soil mechanics problems were visualized as *boundary value problems* with the following conditions defined: (i) geometry and stratigraphy, (ii) initial conditions and boundary conditions, (iii) soil properties, and (iv) solution techniques. The physics of soil behavior was defined for a *referential elemental volume* (REV) of the saturated-unsaturated soil continuum and the mathematical formulation describing the physics of soil behavior took on the form of a *partial differential equation* (PDE). Generally the PDEs were found to be nonlinear because of the nonlinear unsaturated soil property functions required as part of the formulation. The type of equations that many of us disliked as undergraduate students became the heart of unsaturated soil problem solving. Fortunately, we were able to hide the PDE solver in advanced computer software tools.

Geotechnical engineers have benefited from research undertaken in two primary areas: (i) soil physics and agronomy and (ii) computer technology and mathematics. In particular, it was the rapid growth in computing capability (i.e., computer hardware and software) that made the solution of unsaturated soil problems possible. The stage was set for solving saturated-unsaturated soil mechanics problems within a boundary value context through use of numerical modeling techniques.

It is an understatement to say that the digital computer has revolutionized the way that soil mechanics is now implemented in engineering practice. It is safe to say that it would not be possible to model and solve saturated-unsaturated soil mechanics problems within a science framework without the power of the digital computer. Geotechnical engineering has moved into a *new paradigm*, a problem-solving environment involving SWCCs, USPFs, and PDEs. It is a world in which the challenge becomes the *convergence* and the *uniqueness* of the soil mechanics solution. It is a world in which computer software is no longer a luxury but a necessity for sound engineering practice.

During the course of writing this book, numerous example problems were analyzed using the SVOffice geotechnical software suite. The examples in this book are freely distributed as resources related to the learning process associated with unsaturated soil mechanics. Instructions for obtaining these examples may be found at www.soilvision.com/usmep. The examples include seepage (SVFLUX™), slope stability (SVSLOPE®), freeze/thaw (SVHEAT™), and stress/deformation (SVSOLID™) finite element numerical models for which the setup and solution information can be examined.

Eduardo Alonso and Antonio Gens (2011) put it well in the Preface to the Fifth International Conference on Unsaturated Soils, Barcelona, Spain, when they wrote, "The development of unsaturated soil mechanics in recent decades has been remarkable and it has resulted in momentous advances in fundamental knowledge, testing methods, computational procedures, prediction methodologies and geotechnical practice." As authors, we trust that the book *Unsaturated Soil Mechanics in Engineering Practice* will further advance the usage of the science of unsaturated soil behavior in engineering practice.

Unsaturated Soil Mechanics in Engineering Practice constitutes a substantial addition and reorganization of information from what was synthesized in the book *Soil Mechanics for Unsaturated Soils* by D. G. Fredlund and H. Rahardjo. *Unsaturated Soil Mechanics in Engineering Practice* more thoroughly covers our present knowledge of unsaturated soil behavior and better reflects the manner in which practical unsaturated soil engineering problems are solved. The fundamental physics of unsaturated soil behavior presented in *Soil Mechanics for Unsaturated Soils* has been retained in the present edition while greater emphasis has been placed on the importance of using the SWCC when solving engineering problems. Greater emphasis has also been placed on the quantification of thermal and moisture boundary conditions based on the use of weather data. In the end, the reader should find *Unsaturated Soil Mechanics in Engineering Practice* to be a practical book leading geotechnical engineers through to the implementation of unsaturated soil mechanics into engineering practice.

DELWYN G. FREDLUND

ACKNOWLEDGMENTS

Many persons have contributed to the synthesis of information presented in *Unsaturated Soil Mechanics in Engineering Practice*. Graduate students and research fellows have contributed much as they have researched a wide range of topics associated with unsaturated soil mechanics. The graduate students have sifted through past research and attempted to assemble a coherent synthesis of the findings of many researchers worldwide. The theses and research papers of many persons have been used in the synthesis of information required for the development of the science for unsaturated soil mechanics.

A number of researchers in unsaturated soil mechanics have volunteered to review various chapters of the book. The authors are grateful for their comments, edits and suggestions. In particular, the authors wish to acknowledge the contributions from the following persons: J. Côté, G. Gitirana, S. G. Goh, S. Houston, E. C. Leong, G. Newman, M. Padilla, H. Pham, A. Satyanaga, J. Stianson, S. Vanapalli, H. Vu, M. Yuan, C. Zapata, Q. Zhai, J. Zhang, and L. M. Zhang. The ongoing mentorship of Dr. N. R. Morgenstern and Dr. R. L. Lytton is also acknowledged and greatly appreciated.

A number of manufacturers of unsaturated soil testing equipment and monitoring devices have generously made information available for this book. The contributions from Campbell Scientific Corporation, Logan, Utah; Decagon Devices, Pullman, Washington; GCTS, Geotechnical Consulting and Testing Services, Tempe, Arizona; GDS Instruments, London; SoilMoisture Equipment Corporation, Santa Barbara, California; UPC, Barcelona, Spain, and Wille Geotechnik, Germany, are acknowledged. The initiatives on the part of many soil testing companies have done much to promote the practice of unsaturated soil mechanics. Their initiatives to develop soil testing and monitoring equipment contributes significantly to the practice of unsaturated soil mechanics.

Others have contributed greatly to the preparation of the manuscript and the figures for this book. Their diligence and willingness to assist have been greatly appreciated. The authors would like to acknowledge the following persons: Esther McAleer, Felicitas Egunyu, Patti Sawchuk, Marilyn D'Souza, Maki Ito, and O. Zapata.

Behind each of the authors there has been a company or institution that has been supportive of the venture to write a new book that embraces more of the recent research findings and engineering protocols for engineering practice. Dr. Del Fredlund has been employed by Golder Associates after his retirement from the University of Saskatchewan, Saskatoon. Golder Associates have been supportive and promoted the development of the Golder Unsaturated Soils Group (GUSG) under the direction of Greg Misfeldt. The GUSG has functioned as a loosely knit Web-based organization of the Golder office with the intent of addressing unsaturated soil problems worldwide. The GUSG has provided a valuable platform for the implementation of practical engineering protocols for a wide range of unsaturated soil problems.

Dr. Harianto Rahardjo has been employed at Nanyang Technological University (NTU), Singapore, since 1990. NTU has shown strong support for unsaturated soils research over many years. The result has been the establishment of a world-class unsaturated soil research laboratory containing most of the latest equipment for testing unsaturated soils. The research program has been complimented with numerous field instrumentation studies on residual soils. There has also been an ongoing series of unsaturated soil studies that have resulted in numerous journal, conference, and research reports.

Dr. Murray Fredlund started the software computing company called SoilVision Systems in 1997. The vision of the company was to provide computer software capable of solving problems involving unsaturated soils as well as saturated soils. This meant that it was necessary to develop and use solvers capable of solving highly nonlinear partial differential equations. SoilVision has not only provided engineering practitioners with software capable of solving a wide range of unsaturated soils problems but has also embarked on numerous research studies in an attempt to determine the most satisfactory solutions to unsaturated soil problems.

The support of Golder Associates, Nanyang Technological University, and SoilVision Systems has provided a framework for developing high-level engineering protocols for unsaturated soil mechanics. The authors want to express their appreciation for the support received through their places of employment. A platform for a vision has been developed for the promotion of unsaturated soil mechanics in geotechnical practice, and the authors are grateful for the opportunities afforded to them.

Delwyn G. Fredlund
Harianto Rahardjo
Murray D. Fredlund

CONTENTS

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CHAPTER 1

Theory to Practice of Unsaturated Soil Mechanics

1.1 INTRODUCTION

Soil mechanics involves a combination of engineering mechanics, soil behavior, and the properties of soils. This description is broad and can encompass a wide range of soil types. These soils could either be saturated with water or have other fluids in the voids (e.g., air). The development of classical soil mechanics has led to an emphasis on particular types of soils. The common soil types are saturated sands, silts and clays, and dry sands. These materials have formed the primary emphasis in numerous soil mechanics textbooks. More and more, it is realized that attention must be given to a broader spectrum of soil materials.

There are numerous soil materials encountered in engineering practice whose behavior is not consistent with the principles and concepts of classical, saturated soil mechanics. The presence of more than one fluid phase, for example, results in material behavior that is challenging to engineering practice. Soils that are unsaturated (i.e., water and air in the voids) form the largest category of soils which do not adhere in behavior to classical saturated soil mechanics.

The general field of soil mechanics can be subdivided into the portion dealing with saturated soils and the portion dealing with unsaturated soils. The differentiation between saturated soils and unsaturated soils becomes necessary due to basic differences in the material nature and engineering response. An unsaturated soil has more than two phases, and the pore-water pressure is negative relative to pore-air pressure. Any soil near the ground surface, present in an environment where the water table is below the ground surface, will be subjected to negative pore-water pressures and possible reduction in degree of saturation.

The process of excavating, remolding, and compacting a soil requires that the material be unsaturated. It has been difficult to predict the behavior of compacted soils within the framework of classical soil mechanics.

Natural surficial deposits of soil are found to have relatively low water contents over a large portion of the earth. Highly plastic clays subjected to a changing environment have produced the category of materials known as swelling or expansive soils. The shrinkage of these soils may pose an equally severe situation. Loose silt soils often undergo collapse when subjected to wetting and possibly a change in the loading environment. The pore-water pressures in both of the above-mentioned cases are initially negative, and volume changes occur as a result of increases in the pore-water pressure. Residual soils have also been of particular concern since their engineering behavior appears to deviate from classical soil mechanics principles. Once again, the primary factor contributing to the unusual behavior of residual soils is negative pore-water pressures.

Unsaturated soil mechanics is herein presented in the context of having a limited number of physical areas of application, namely, water flow (and storage), air flow (storage and compressibility), heat flow (and storage), shear strength, and volume-mass change (including swelling and collapse). The unsaturated soil theories are applied to real-world problems and solutions are illustrated in the context of a "boundary value problem." The physical behavior of unsaturated soil is formulated as a partial differential equation(s) that must be solved using a numerical technique. The partial differential equations are generally slightly too highly nonlinear in character and as a result computer analyses play an important role in solving practical engineering problems.

1.1.1 Application of Unsaturated Soil Mechanics in Engineering Practice

The content of this book takes into consideration the history of classical soil mechanics and the significant impact that the computer has had on the practice of geotechnical engineering. It is fair to say that the computer has resulted in a paradigm shift in how geotechnical engineering problems in general and specifically unsaturated soils problems are analyzed. The significant role that the computer has played has also been taken into consideration in assembling the content for this book. The nature of unsaturated soil problems makes it essentially imperative to use numerical methods when solving geotechnical engineering problems.

Terzaghi (1943) contributed significantly toward our understanding of unsaturated soil behavior in two chapters of his textbook *Theoretical Soil Mechanics*. Chapter 14 on "Capillary Forces" and Chapter 15 on "Mechanics of Drainage" (with special attention to drainage by desiccation) illustrate the importance of unsaturated soils. These chapters emphasize the importance of the unsaturated portion of the soil profile and in particular provide insight into the fundamental nature and importance of the air-water interface [i.e., the contractile skin (Fredlund and Rahardjo, 1993a)]. Considerable discussion was directed toward soils with negative pore-water pressures. Figure 1.1 shows an earth dam illustrating the manner in which water flows above the phreatic line through the capillary zone (Terzaghi, 1943). The contributions of Karl Terzaghi toward unsaturated soil behavior were truly commendable and are still worthy of consideration.

Terzaghi (1943) stated that "the theories of soil mechanics provide us only with the working hypothesis, because our knowledge of the average physical soil properties of the subsoil and the orientation of the boundaries between the individual strata is always incomplete and often utterly inadequate." Terzaghi emphasized the importance of clearly stating all assumptions upon which the theories were based and pointed out that "almost every alleged contradiction between theory and practice can be traced back to some misconception regarding the conditions for the validity of the theory." Terzaghi's advice from the early days of soil mechanics is extremely relevant as the theories for unsaturated soil behavior are being brought to the "implementation" stage in geotechnical engineering. With such an early emphasis on unsaturated soil behavior, one might ask the question, "Why did unsaturated soil mechanics not emerge simultaneously with saturated soil mechanics?" Pondering this question leads to the realization that there were several theoretical and practical challenges associated with unsaturated soil behavior that needed further research before unsaturated soil mechanics could be implemented into engineering practice. In fact, unsaturated soil mechanics would need to wait several decades before it would take on the character of a science that could be used in routine geotechnical engineering practice.

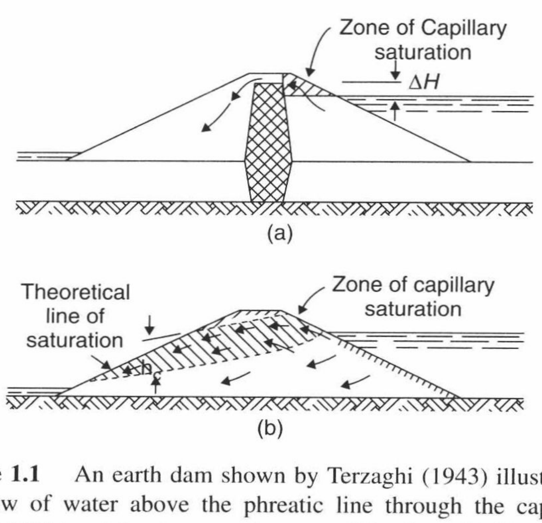

Figure 1.1 An earth dam shown by Terzaghi (1943) illustrating the flow of water above the phreatic line through the capillary zone. (a) Water siphoning over the core of the dam. (b) Water flow across the phreatic line.

Research within the agriculture-related disciplines strongly influenced the physical and hydraulic models that would later need to be brought into unsaturated soil mechanics (Baver, 1940). With time, numerous significant contributions have come from the agriculture-related disciplines (i.e., soil science, soil physics, and agronomy) into geotechnical engineering. It can be said that historically geotechnical engineers tended to test soils by applying total stresses to soils through the use of an oedometer or triaxial cell. On the other hand, agriculture-related counterparts tended to apply stresses to the water phase (i.e., tensions) through the use of pressure plate cells. Eventually, geotechnical engineers would realize that the information accumulated in agriculture-related disciplines was what was needed in geotechnical engineering with unsaturated soils. Careful consideration needed to be given to each of the test procedures and testing techniques when transferring the technology from agriculture into geotechnical engineering.

1.1.2 Scope of the Book

The scope of this book is limited to the field of unsaturated soil mechanics. An attempt is made to cover all aspects normally associated with soil mechanics. When the term "unsaturated soil mechanics" is used, the authors are referring to soils which have negative pore-water pressures.

The aspects of interest to geotechnical engineering fall into three main categories. These can be listed as problems related to (1) flow of fluids (i.e., air and water in liquid and vapor form) through porous media, (2) shear strength, and (3) volume-mass change behavior of unsaturated soils. An entire chapter is devoted to understanding the soil-water characteristic curve. A chapter is also devoted to heat flow through soils and another chapter is devoted to the establishment of boundary conditions. In particular, emphasis is placed on the quantification of the ground surface moisture flux boundary condition. Either moisture is falling to the ground, for example, in the form of rain or snow, or moisture is moving upward through evaporation and evapotranspiration. The quantification of both downward and upward moisture flow is pivotal to solving unsaturated soil mechanics problems. While this topic was largely absent from classical saturated soil mechanics, it has become an essential component related to solving unsaturated soil problems.

No attempt is made to duplicate or redevelop information already available in classical saturated soil mechanics books. This book should be used to assist the geotechnical engineer in understanding soil mechanics concepts unique to unsaturated soils. At the same time, these concepts have been developed and organized to appear as logical and relatively simple extensions of classical saturated soil mechanics concepts. Subjects such as clay mineralogy and physicochemical properties of soils are vitally important to understanding why soils behave in a certain manner. However, the readers are referred to other references for coverage of these subjects (Mitchell, 1993).

Most soil mechanics problems can be linked to a few key soil properties that are related to important processes. These properties relate to (1) the ease of flow through the multiphase material (e.g., liquid water, air, and heat), (2) the ability of the material to store (e.g., water storage, air storage and compression, and heat storage), (3) the shear strength characteristics, and (4) the volume-mass change soil properties (i.e., including the soil-water characteristic curve). The chapters in this book describe (1) theory related to each process and relevant soil properties, (2) measurement of each soil property, (3) estimation of each soil property (and soil property functions), and (4) application of the theory and soil properties to one or more soil mechanics problems.

The main objective of this book is to synthesize theories associated with the behavior of unsaturated soils and show how the theories can be applied in geotechnical engineering practice. The theoretical derivations are presented in considerable detail because unsaturated soil behavior is a relatively new area of study and many of the derivations are not readily available to engineers in a familiar context. The theory, measurement, and estimation of the soil-water characteristic curve are pivotal to the implementation of unsaturated soil mechanics. For this reason, they have been given special attention throughout the book. There is ongoing need for case histories, and it is anticipated that these will become more commonly reported in future decades. Hopefully, as the analyses illustrated in this book are put into engineering practice, case histories will emerge that verify the consistent theoretical context provided within this book.

1.1.3 Gradual Emergence of Unsaturated Soil Mechanics

Unsaturated soil mechanics did not emerge simultaneously with saturated soil mechanics. Rather, there were a number of important experimental findings and theoretical developments that led to the gradual emergence of a science for unsaturated soil mechanics. These developments took place over a period of several decades, and by the late 1970s it became clear that unsaturated soil mechanics would take the form of a natural extension of saturated soil mechanics. A few key findings that contributed significantly to the emergence of unsaturated soil mechanics are listed below.

Experimental laboratory studies in the late 1950s (Bishop et al., 1960) showed that it was possible to independently measure (or control) pore-water and pore-air pressures through the use of high-air-entry ceramic disks. Laboratory studies were reported over the next decade that revealed fundamental differences between the behavior of saturated and unsaturated soils. The studies also revealed that there were significant challenges that still needed to be addressed. The laboratory testing of unsaturated soils proved to be time consuming and demanding from a technique standpoint. The usual focus on soil property constants was diverted toward the study of nonlinear unsaturated soil property functions. Soil-water characteristic curves (SWCCs) were found to hold an important relationship to each of the unsaturated soil property functions (Croney and Coleman, 1954; Fredlund and Rahardjo, 1993a). The increased complexity of unsaturated soil behavior extended from the laboratory to theoretical formulations and solutions.

Originally, there had been a search for a single-valued effective stress equation for unsaturated soils, but by the late 1960s, there was increasing awareness that the use of two independent stress state variables would provide an approach more consistent with the principles of continuum mechanics (Fredlund and Morgenstern, 1977).

The 1970 decade was a period when constitutive relations for the classical areas of soil mechanics were proposed and studied with respect to uniqueness (Fredlund and Rahardjo, 1993a). Initially, constitutive behavior focused primarily on the study of seepage, shear strength, and volume change problems. Gradually it became apparent that the behavior of unsaturated soils could be viewed as a natural extension of saturated soil behavior (Fredlund and Morgenstern, 1976). Numerous studies attempted to combine volume change and shear strength in the form of elastoplastic models that were an extension from research on saturated soils (Alonso et al., 1990; Wheeler and Sivakumar, 1995; Blatz and Graham, 2003). The study of contaminant transport properties, thermal soil properties, and air flow properties for unsaturated soils also took on the form of nonlinear soil property functions (Newman, 1995; Lim et al., 1998; Pentland et al., 2001; Ba-Te et al., 2005).

The 1980 decade was a period when boundary value problems were solved using numerical, finite element and finite difference modeling methods. Computers were required and iterative, numerical solutions became the norm. The challenge was to find techniques that would ensure convergence of highly nonlinear partial differential equations on a routine basis (Thieu et al., 2001; Fredlund et al., 2002b). Saturated-unsaturated seepage modeling became the first of the unsaturated soil problems to come into common engineering practice. Concern for stewardship toward the environment further promoted interest in seepage and geoenvironmental, advection-dispersion modeling.

The 1990 decade and beyond have become a period when the emphasis has been on the implementation of unsaturated soil mechanics into routine geotechnical engineering practice. A series of international conferences have been dedicated to the exchange of information on the engineering behavior of unsaturated soils and it has become apparent that the time has come for increased application of unsaturated soil mechanics in engineering practice. Implementation

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