Mechanics of Unsaturated Geomaterials

This book is dedicated to the memory of our dear colleague,
Dr. Olivier Coussy, who tragically passed away
while working on a chapter for this book

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Edited by
Lyesse Laloui

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Preface

An understanding of the mechanics of unsaturated geomaterials has become an important component of the background for a geo-engineer operating in various fields of geomechanics.

Several geotechnical operations, such as compaction and excavation processes, are linked to the mechanics of unsaturated geomaterials. As more than one-third of the Earth's surface is arid or semi-arid, in addition to the less extreme cases of seasonal droughts and diurnal variations of the water table in soils, it is obvious that most soils and rocks are in a general state of partial water saturation. In other words, the pore space within geomaterials (e.g. soil, rock, and concrete) is generally filled with water and air. It means that the mechanics and physics of the considered material are those of a three-phase material: solid mineral and two immiscible fluid phases.

Even though most natural and engineered geomaterials are only partially saturated with water, a persistent assumption made in geomechanics and geotechnical engineering over the past decades has been the assumption of complete saturation. The study of the mechanics of unsaturated geomaterials was initiated approximately 50 years ago as a natural extension of the knowledge developed in the conventional areas of the mechanics of (saturated) soils and rocks. The mechanics of saturated geomaterials is primarily based on the concept of effective stress and on the consolidation theory. In the hydromechanical frameworks for saturated materials that have been developed, the pore fluid (water) pressure mainly contributes to the mechanical behavior through the field equations (consolidation theory). Its contribution to the constitutive behavior of the solid skeleton is considered “neutral” (no effect of the pore fluid pressure on the effective material compressibility or strength, for instance). When this particular assumption about materials saturated with a fluid under compression was no longer considered valid, the conventional theories needed to be revised. This was the first major development in defining the mechanics of unsaturated materials. The field equations were found to need an extension to address the effect of the degree of saturation on water permeability and compressibility; the gas flow also had to be considered in some situations. The solid skeleton constitutive behavior must incorporate the effect of the gas pressure, or more specifically, its difference with respect to the liquid pressure, known as suction. In addition, the extension of the effective stress concept to the unsaturated conditions revealed a need to take into account the important contribution of the water retention behavior, linking the degree of saturation to suction.

In the past decade, the advancement of knowledge regarding the mechanics of unsaturated geomaterials has been significant. Some fundamental issues were solved, and important achievements were made in certain areas, including application of the effective stress concept and measurement of volume variations. The multiphysical interactions were then extended to non-isothermal conditions. This spectacular progress in the field also included engineering applications. In many cases, new tools were developed and advanced analysis became possible.

The objective of this book is to supply the reader with an exhaustive overview on new trends in the field of the mechanics of unsaturated geomaterials, starting from the basic issues and covering the most recent theories and applications (i.e. natural disasters and nuclear waste disposal). The presentation of the fundamental concepts is based on an interdisciplinary approach and includes chapters on the topics of soil-, rock-, and cement-based mechanics.

The book begins with the introduction of several fundamental notions concerning the mechanics of unsaturated materials. Basic concepts about the state of water in soils are presented in Chapter 1, and Chapter 2 introduces the concepts of mechanics in unsaturated geomaterials. Chapter 3 reviews the phenomenon of soil cracking during soil desaturation. Part II of the book is devoted to experimental techniques that allow testing of soils and rocks in unsaturated conditions. Chapter 4 reviews the techniques for controlling and measuring suction and presents mechanical testing devices.

The characterization of highly overconsolidated clayey unsaturated materials is presented in Chapter 5. Field measurement techniques (of suction, water content, and water permeability) are presented in Chapter 6. In Part III of the book, the main theoretical concepts are established. The numerical treatment of the field equations is emphasized, with special attention devoted to the analysis of the strain localization in coupled transient phenomena. The conservation laws in unsaturated porous materials are discussed in Chapter 7, while the hydromechanical coupling theory and its numerical integration methods are presented in Chapter 8. Strain localization in coupled transient phenomena is the topic of Chapter 9. Part IV of the book presents engineering applications that show the importance of the mechanics of unsaturated geomaterials in many fields of practical interest. Numerical modeling of landslides is investigated in Chapter 10. Moisture transport and pore pressure generation in nearly saturated geomaterials are the main topics of Chapter 11. Chapter 12 deals with application to nuclear waste storage. Chapter 13 reviews experimental results and modeling of soil–pipeline interactions. The engineering behaviors of different unsaturated zones are described in Chapter 14, where the modeling of consolidation and swelling in fine soils is also considered. River embankments are geomechanically analyzed in Chapter 15.

This book was written for postgraduate students, researchers and practitioners in the fields where unsaturated conditions play a fundamental role, such as soil mechanics, soil physics, rock mechanics, petroleum engineering, hydrology, and nuclear waste engineering.

I would like to express my appreciation to all of my colleagues who chose to contribute to this book. Special thanks are due to Prof. Tomasz Hueckel and Prof. Félix Darve for their encouragement, which made the book possible. My thanks are also directed to the Alert Geomaterials network that supported this initiative.

Lyesse LALOUI
June 2010

PART I

Fundamental Concepts

Chapter 1

Basic Concepts in the Mechanics and Hydraulics of Unsaturated Geomaterials

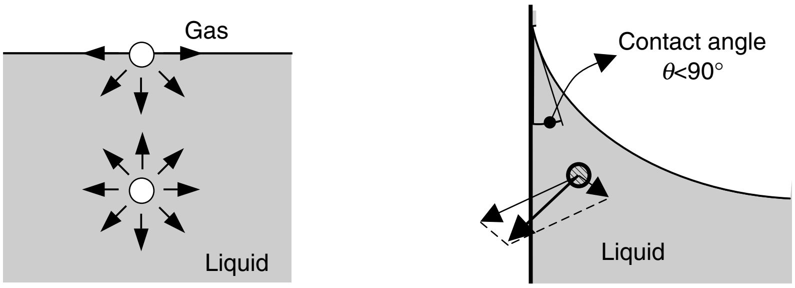
Unsaturated geomaterials are geomaterials with void spaces partially filled with liquid and partially with gas. The liquid (wetting) phase is an aqueous solution, generically referred to as *water*, whereas, the gaseous (non-wetting) phase is a mixture of air and water vapor, generically referred to as *air*. The mutual interaction between these two phases and their interaction with the solid phase plays a key role in the mechanical and hydraulic response of unsaturated geomaterials. The basic mechanisms and thermodynamics of the interaction between the liquid, gaseous, and solid phases are not commonly covered in undergraduate and graduate courses. As a result, students and engineers with geotechnical background may find it difficult to approach the mechanics and hydraulics of unsaturated soils. The purpose of this chapter is to fill this gap and to illustrate the basic elementary mechanisms behind water retention, water flow, and mechanical behavior of unsaturated geomaterials. Special emphasis has been given to capillary mechanisms arising from surface tension at the air–water interface and from the angle formed by the air–water interface at the solid–liquid–gas junction (contact angle). Capillary actions play a major role in the response of unsaturated geomaterials and can conveniently serve as a basis to introduce the most distinctive features of the hydraulic and mechanical response of unsaturated geomaterials.

Chapter written by Alessandro TARANTINO.

1.1. Water retention mechanisms in capillary systems

1.1.1. *Surface tension, contact angle, and water tension*

Liquid surfaces act as if they are in tension as a result of an imbalance between intermolecular attractions at a surface. In bulk liquid, the forces acting on a molecule are effectively equal in all directions and the molecule feels no net force. As a molecule moves to the surface, it loses some nearest neighbors, thus leaving it with unbalanced attractive forces with a downward resultant force (Figure 1.1(a)). For a molecule to stay in the surface region, it must gain excess energy (and entropy) over those in the bulk liquid. This excess energy (surface free energy) is the surface tension and causes the surface to act like a membrane in tension. When in contact with a solid surface, the interface will curve near that surface to form a *meniscus*. If adhesive forces between solid and liquid prevail on cohesive forces in the liquid, the interface will curve up and will form an angle lower than 90° with the solid surface (Figure 1.1(b)). Contact angles, which are measured *through* the liquid, lower than 90° are typical for soil water on soil minerals.



(a) (b)

Figure 1.1. *(a) Development of surface tension at the gas–liquid interface and (b) curvature of the gas–liquid interface in proximity of a solid surface*

Menisci concave on the air side generate water pressures lower than the air pressure. Let us consider a meniscus in a capillary tube of diameter d (Figure 1.2). The water pressure at the back of the meniscus can be calculated by considering the vertical force equilibrium of the air–water interface:

$$u_w - u_a = -\frac{4T\cos\theta}{d} = -\frac{2T}{R}, \qquad [1.1]$$

where u_w is the water pressure at the back of the meniscus, u_a the air pressure, T the surface tension, θ the contact angle, and R the radius of curvature of the interface. If the contact angle is lower than 90°, the gauge water pressure u_w–u_a becomes negative.

Using equation [1.1], it is instructive to calculate the gauge and the absolute water pressure for capillary tubes having diameters of the same order of magnitude as the size of pores in clay, silt, and sand. For the sake of simplicity, let us assume that pore size is about 1/10 of the grain size and contact angle is $\theta = 0$. As shown in Table 1.1, if the pore size is sufficiently small, as in the case of clays, *absolute* water pressure may be negative. Water can, therefore, be held in tension (i.e. it is being stretched) in unsaturated geomaterials.

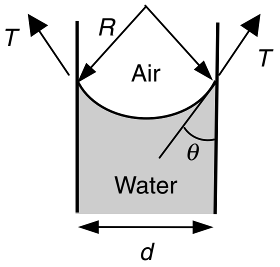


Figure 1.2. *Negative water pressure generated by meniscus concave on the air side*

Water can indeed sustain high tensile stresses as recognized earlier by Berthelot [BER 50] and confirmed by several experiments carried out using metal and glass Berthelot-type systems (see [MAR 95]). The magnitude of negative pressure and the duration over which the negative pressure can be sustained is limited by the phase relationships of the pore fluid and the phenomenon of heterogenous cavitation [MAR 08]. Heterogenous cavitation of water typically occurs at negative gauge pressures close to –100 kPa, but this pressure should not be mistaken for the tensile strength of water.