INTRODUCTION

CHAPTER 1

STATE OF UNSATURATED SOIL

1.1 UNSATURATED SOIL PHENOMENA

1.1.1 Definition of Unsaturated Soil Mechanics

To provide and agree upon a precise definition of unsaturated soil mechanics is an academic challenge in itself. Perhaps one can draw some areas and boundaries by revisiting the classical definition of soil mechanics posed by Karl Terzaghi some 60 years ago. In his seminal book of 1943, *Theoretical Soil Mechanics,* Terzaghi defined soil mechanics as ‘‘the application of the laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles produced by the mechanical and chemical disintegration of rocks, regardless of whether or not they contain an admixture of organic constituents.’’ In drawing this silhouette of soil mechanics, Terzaghi refers to three basic requirements: (1) earthen materials, (2) the principles of mechanics and hydraulics, and (3) engineering problems.

The emerging appreciation of unsaturated soil in geotechnical engineering practice and education requires refinement of Terzaghi’s basic definition. The earthen materials dealt with in problems of unsaturated soil mechanics are arguably the same as in Terzaghi’s soil mechanics, referred to as ‘‘soils,’’ but under a very specific ‘‘unsaturated’’ condition. The qualifier ‘‘unsaturated’’ bears the same meaning as its alternative ‘‘partially saturated’’ and simply indicates that the degree of pore water saturation is any value less than unity or, more specifically, that a third phase of matter is introduced into the two-phase, saturated soil system. In the modern educational and professional geotechnical engineering environment, where the emphasis has historically been limited to the arena of saturated cohesive materials and completely dry or completely saturated cohesionless materials, the “unsaturated” qualifier is indeed significant.

In dealing with unsaturated soil, one requires not only the principles of mechanics and hydraulics but also of fundamental interfacial physics. Physics in this regard refers primarily to the thermodynamic principles describing equilibrium among gas, solid, and liquid phases, the transition of matter from one phase to another, and the adsorption or desorption of one phase of matter onto or from an adjacent phase of different matter. The forces and energies associated with these multiphase interactions by their very nature separate unsaturated soil behavior from saturated soil behavior. In many practical problems, where the hydrologic and stress-strain behavior of natural or engineered systems comprised of soil is strongly influenced by the presence, absence, or changes in these interfacial interactions, the traditional saturated soil mechanics framework often fails to satisfactorily describe or predict the behavior of the system.

Terzaghi’s reference to engineering problems was developed in the wake of a period of great uncertainty in the basic understanding of soil behavior. His formalization of soil mechanics provided a rational basis for tackling many of the pressing engineering problems of the day, most notably bearing capacity, consolidation and settlement, slope stability, lateral earth pressure, and seepage-related problems. In addition to these traditional geotechnical engineering problems, the practical problems of interest today might also include geo-environmental, seismic, land reclamation, and other challenges that have come to light over the past 30 years or so. These emerging problems have created important subdisciplines within the more general field of geotechnical engineering, which often benefit from a thorough understanding of the physical and thermodynamic principles governing unsaturated soil behavior.

Extending Terzaghi’s classical definition, therefore, unsaturated soil mechanics might be defined as “the application of the laws of mechanics, hydraulics, and interfacial physics to engineering problems dealing with partially saturated soils.” The spirit of this definition and the laws, concepts, and problems that characterize it will be addressed throughout this book. Of course, as new technical discoveries are made, as new and unforeseen types of problems emerge, and as the once distinct boundaries between the traditional engineering and science disciplines continue to blur, there is no doubt that this definition may one day also require refinement.

1.1.2 Interdisciplinary Nature of Unsaturated Soil Mechanics

The history of unsaturated soil mechanics is embedded in the history of hydrology, soil mechanics, and soil physics. Engineering problems involving unsaturated soil span numerous subdisciplines and practices within the general field of civil engineering. Hydrologists, for example, have long recognized that modeling of regional or local surface water and groundwater systems and cycles must consider infiltration, evaporation, and transpiration processes occurring in the near-surface unsaturated soil zone. Quantitative evaluation of moisture flux at the atmosphere-subsurface boundary requires not only knowledge of the relevant soil and pore water properties but also the predominant environmental conditions at the soil-atmosphere interface. Unsaturated soil often comprises cover or barrier materials for landfills and hazardous waste storage facilities of interest to the geo-environmental community. Contaminant transport and leaching processes are often strictly unsaturated fluid transport phenomena, occurring in many cases as multiphase transport problems. As national and international policy with regard to the health of the natural environment is becoming increasingly more regulated, recognition of these types of geo-enviromental issues and development of solutions from an unsaturated soil mechanics framework is becoming more and more common.

Many of the more traditional geotechnical engineering problems also fall wholly or partly into the category of unsaturated soil mechanics problems. Compaction, for example, a classical application involving unsaturated soil, has been routine practice for improving the mechanical and hydraulic properties of soil since far before the formation of civil engineering as a formal discipline in the mid-nineteenth century. Compacted soil comprising the many earthworks constructed all over the world is most appropriately considered from an unsaturated soils framework. It has long been recognized that expansive soils pose a severe threat to civil engineering infrastructure such as roads, housing, and transportation facilities nationally and internationally. Expansive soil formations in the United States alone are responsible for billions of dollars in damage costs each year, an amount exceeding that of all other natural hazards combined, including earthquakes, floods, fires, and tornados (Jones and Holtz, 1973). Expansive soils have been the subject, if not the driving force, of unsaturated soil research since the early stages in the formulation of unsaturated soil mechanics principles. Collapsing soils also pose a significant threat in many areas of the world. These problematic soils, which are typified by the massive loess deposits of the central United States, are marked by a structurally sensitive fabric weakly cemented by a small clay fraction. Upon wetting, usually occurring either as a sudden precipitation event or gradual process associated with urbanization and development, the cementation bonds are weakened and the inititally loose fabric collapses and densifies, often resulting in dramatic and damaging settlement. Any fundamental approach to mitigating collapsing soil hazards requires insight into the role of pore water interactions on the microscopic scale of the solid-liquid-air interface, a hallmark of unsaturated soil mechanics.

Reconsideration of the traditional saturated soil mechanics approach in light of these types of problems began to emerge during the late 1970s and continues today. In the authors' opinion, the soil mechanics community is far from achieving a comprehensive and satisfactory framework for approaching these and other unsaturated soil mechanics problems, but new insights and technical advances are continuously being made.

1.1.3 Classification of Unsaturated Soil Phenomena

While the development of theory and techniques in unsaturated soil mechanics requires principles drawn from mechanics, hydraulics, and interfacial physics, it is convenient to classify the various geotechnical engineering problems involving unsaturated soil into three general phenomena, specifically, flow phenomena, stress phenomena, and deformation phenomena. It should be noted, however, that generalization in this manner is mainly for understanding purposes and for convenience of presenting the principles, not to set up boundaries among different geotechnical problems. The majority of practical engineering problems generally involve all three phenomena concurrently and in coupled fashion. An effective theory describing the deformation behavior of expansive soil, for example, could well require application of the principles of stress, strain, and flow in highly deformable porous media.

Flow Phenomena *Flow phenomena* require mainly the application of hydraulics and interfacial physics principles. One well-known example falling into this class is capillary flow. The search for the driving force for capillary flow had once been the subject of research for many years. As early as the 1900s, Buckingham (1907) systematically studied capillary rise and drainage in laboratory soil columns such as that illustrated in Fig. 1.1. Early data provided evidence of the important effects of soil type, grain size, and pore size properties on capillary rise and pore water retention in unsaturated soil. As part of this early work, the terms *capillary potential* and *capillary conductivity* were introduced as the driving force and controlling material variable, respectively, for capillary fluid flow. Later, others recalled the more

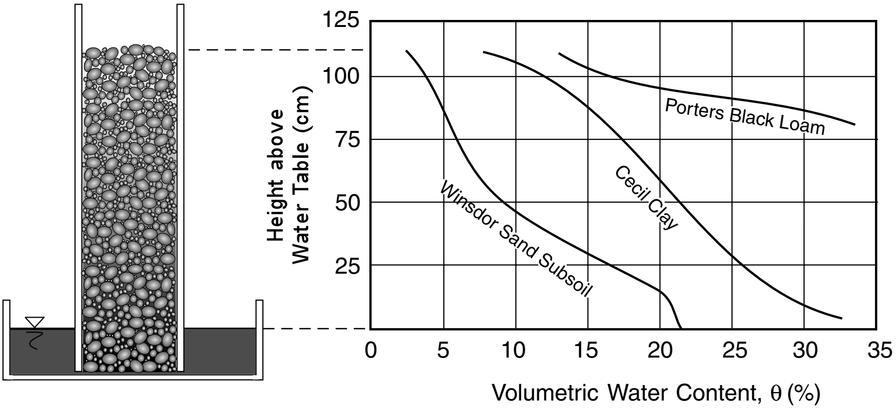

Figure 1.1 Capillary rise and equilibrium moisture content distribution in vertically oriented soil column (data from Buckingham, 1907). The curves shown, which describe the relationship between suction head and moisture content, are commonly called soil-water characteristic curves.

general term *chemical potential,* to include components of the pore water potential resulting from dissolved chemical species, gravity, capillarity, and short-range physicochemical effects occurring at the solid-liquid phase interface (e.g., Gardner and Widstoe, 1921; Richards, 1928; Russell, 1942; Edlefsen and Anderson, 1943). The chemical potential, or free energy, concept for soil pore water has been generalized by Sposito (1981) and others to include the mass of all three phases (gas, solid, and liquid), together with temperature and pressure as independent state variables. As a result, many seepage-related problems in unsaturated soil mechanics may be effectively treated through the application of thermodynamic potential theory with little or no involvement of solid mechanics.

Stress Phenomena Problems requiring consideration of both mechanical and chemical equilibrium are classified as *stress phenomena.* These include traditional geotechnical engineering problems such as lateral earth pressure, bearing capacity, and slope stability analysis. For each of these problems, the strength of the soil at its limit state is the primary concern. Analysis of the stress distribution within the soil mass and the corresponding bulk strength becomes critically important. Limit analysis developed extensively since the 1930s for saturated soil applications formed the basis for solving most of these types of problems. Developing elastoplastic theories for soil became the focus of much of the geomechanics research activity during the 1970s and 1980s. Powerful numerical methods to solve the governing partial differential equations for stress equilibrium under static or dynamic conditions have been developed and applied to many difficult foundation problems in the past 20 years or so.

It has become clear in recent years that improved solutions of many stress-related geotechnical engineering problems require not only sustained activities along the continuum-based solid mechanics approach but also new theories along a microscopic discontinuous approach for describing effective stress under multiphase conditions. Terzaghi's effective stress, which is the cornerstone of soil mechanics under saturated conditions, becomes either ineffective or inappropriate for fully describing the stress distributions or failure conditions in unsaturated soil. It has been recognized that theories for describing the states of stress and failure in unsaturated soil require consideration of the thermodynamic properties of the pore water in terms of soil suction, material variables such as grain size and grain size distribution, state variables such as the degree of saturation, and the consequent interparticle forces such as suction-induced effective stress or suction stress.

Deformation Phenomena Physical processes characterized by large deformations or strains are classified as *deformation phenomena.* In unsaturated soils, these deformations are very often caused or governed by changes in the moisture condition of the soil. Important deformation phenomena include compaction, multiphase consolidation and compressibility, and collapsing soil behavior. Arguably, the most notorious unsaturated soil deformation phenomenon is that of swelling or shrinking (i.e., expansive) soil. Figure 1.2, for example, illustrates several important mechanisms commonly occurring in near-surface deposits of expansive soil. Many of these mechanisms, such as heave or subsidence of the ground surface, swelling pressure generation under pavements or foundations, and tension cracking, fall into the general category of deformation phenomena. Others shown in the figure, such as infiltration, evaporation, and the corresponding seasonal fluctuation in the subsurface moisture profile, fall into the general category of unsaturated flow phenomena. The inherent coupling between volume change, pressure generation, and moisture transport in expansive soil demonstrates the importance of the combined roles of deformation, stress, and fluid flow phenomena in this and numerous other types of unsaturated soil mechanics problems.

1.2 SCOPE AND ORGANIZATION OF BOOK

1.2.1 Chapter Structure

Unsaturated Soil Mechanics is organized into four divisible but interrelated parts. The intent of this separation is to provide the reader with a format

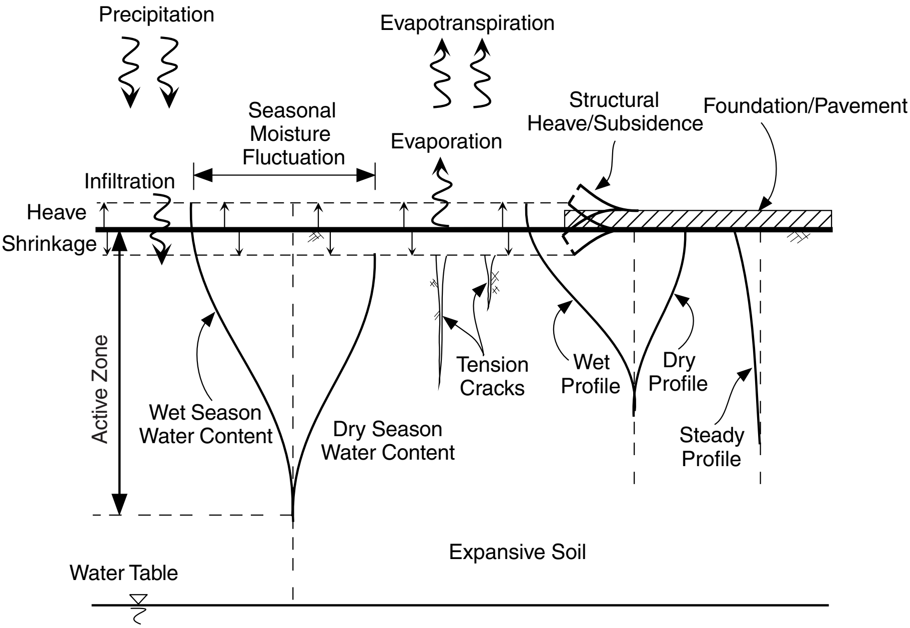

Figure 1.2 Deformation and fluid flow phenomena in a near-surface deposit of unsaturated expansive soil.

where particular concepts, theories, phenomena, or practical applications of interest may be directly accessed in a focused and concise manner. Each chapter concludes with a series of qualitative and/or quantitative problems. The 12 chapters of the book are organized as follows:

Introduction: Chapter 1
Part I: Fundamental Principles, Chapters 2 to 4
Part II: Stress Phenomena, Chapters 5 to 7
Part III: Flow Phenomena, Chapters 8 and 9
Part IV: Material Variable Measurement and Modeling, Chapters 10 to 12

Chapter 1, State of Unsaturated Soil, provides a general introduction to unsaturated soil mechanics. The relevant state variables, material variables, and constitutive laws for describing flow, stress, and deformation phenomena in three-phase unsaturated soil systems are introduced. The important differences between saturated and unsaturated soil systems in terms of subsurface moisture, pore pressure, and stress profiles are described. Common types of practical engineering applications that warrant an unsaturated soil mechanics approach are introduced. The important role of unsaturated soil in terms of naturally occurring phenomena such as the hydrologic cycle, global climatic changes, and soil formation is described. Finally, the important concepts of pore water potential, soil suction, and the constitutive relationship between soil suction and water content, the soil-water characteristic curve, are introduced.

Part I, Fundamental Principles, provides the necessary background for the remainder of the book. Chapter 2, Material Variables, introduces the relevant physical properties of air, water, and water vapor and evaluates their dependency on the state variables that are used to describe multiphase unsaturated soil systems. Relative humidity and surface tension are introduced and described with respect to their roles in the behavior and analysis of unsaturated soil systems. Cavitation phenomena are systematically described. Chapter 3, Interfacial Equilibrium, describes several fundamental concepts within the general realm of interfacial physics. Mechanical and chemical equilibrium for air-water-solid interfaces are described with the introduction of Kelvin's law. Associated interfacial phenomena including vapor pressure lowering, capillary condensation, and the solubility of air in water are described and illustrated through a series of thought experiments and quantitative examples. Finally, the soil-water characteristic curve is introduced from a micromechanical perspective by considering mechanical and chemical equilibrium for idealized systems of unsaturated soil grains. Chapter 4, Capillarity, introduces the Young-Laplace equation for describing equilibrium at an air-water interface, the height and rate of capillary rise, and the estimation of pore size distribution using capillary theory. The concept of suction stress is formulated from a micromechanical perspective to serve as a link between the preceding interfacial equilibrium concepts and the associated interparticle stresses in unsaturated soil systems.

Part II, Stress Phenomena, contains three chapters. Chapter 5, State of Stress, complements the interfacial equilibrium concepts introduced in Chapter 4 by providing a derivation of effective stress among idealized unsaturated soil particles. Mechanisms for hysteresis in the soil-water characteristic curve and suction stress characteristic curve are introduced and evaluated. Tensor notation and graphical representation for the independent stress state variable approach and the effective stress approach to describing the state of stress in unsaturated soil are introduced and explained using example problems. The concept of axis translation for controlling the stress state variables relevant to unsaturated soil is presented. Chapter 6, Shear Strength, describes several alternative theories for interpreting and analyzing shear strength in unsaturated soil. The extended Mohr-Coulomb failure criterion, the shear strength parameters describing it, and its advantages and limitations are introduced. Bishop's effective stress parameter χ and its role in effective stress for unsaturated soil is described. Finally, a unified framework for interpreting and measuring shear strength characteristics in unsaturated soil is suggested. Chapter 7, Suction and Earth Pressure Profiles, includes theoretical development of subsurface suction stress and water content profiles under steady-state infiltration, hydrostatic, and evaporation conditions. Corresponding lateral earth pressure profiles are derived for conditions at rest and under active and passive conditions. These new theories serve as an instructional vehicle to provide insight into the fundamental differences between the states of stress in saturated and unsaturated soil.

Part III, Flow Phenomena, is divided into Chapter 8, Steady Flows, and Chapter 9, Transient Flows. Together, these chapters provide an introduction to the governing principles and solutions for both liquid and gas flow in unsaturated soil systems. Governing flow equations are solved analytically and numerically and illustrated graphically through simple one-dimensional example problems. Capillary barriers for geo-environmental applications are described along with vapor phase transport and diffusion processes. Practical examples involving transient pore airflow by barometric pumping are provided to highlight the important impact of variations in the governing state variables (e.g., temperature and pressure) on pore fluid transport processes in unsaturated soil.

Part IV, Material Variable Measurement and Modeling, provides the practicing and research community with a reference source pertaining to suction and hydraulic conductivity measurement and modeling alternatives. Chapter 10, Suction Measurement, describes the general principles, technical aspects, and performance of many of the more common suction and soil-water characteristic curve measurement techniques. Chapter 11, Hydraulic Conductivity Measurement, describes several common steady-state and transient techniques for measuring the unsaturated hydraulic conductivity function. Finally, chapter 12, Suction and Hydraulic Conductivity Models, describes numerous methodologies by which the soil-water characteristic curve and hydraulic conductivity function may be either modeled, estimated, or predicted from more readily available material properties.

1.2.2 Geomechanics and Geo-environmental Tracks

Unsaturated Soil Mechanics contains sufficient material for a one-semester course tailored to follow either a geomechanics or geo-environmental track. Figure 1.3 illustrates two suggested paths through the chapters of the book corresponding to a geomechanics track, which emphasizes the stress and

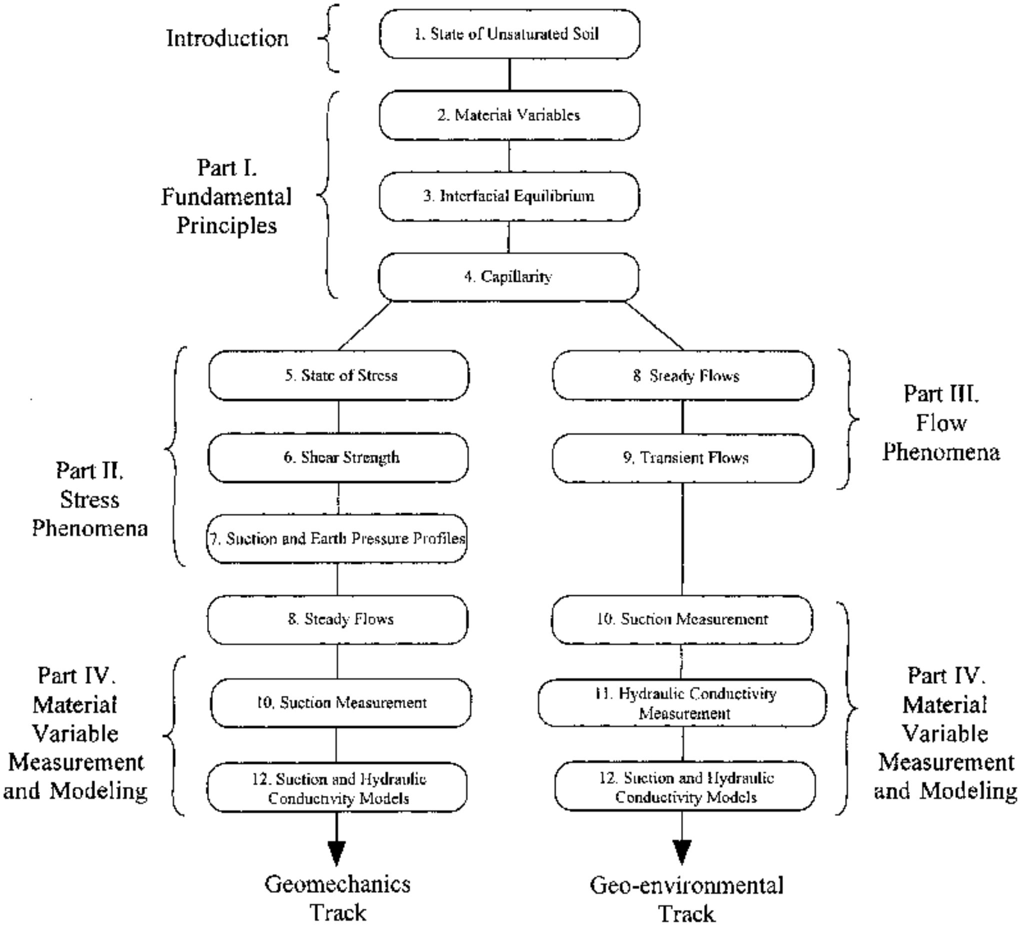

Figure 1.3 Recommended chapter sequences for geomechanics and geo-environmental learning tracks.

strength concepts described in Part II, and a geo-environmental track, which emphasizes the hydrology concepts described in Part III. Content along each track has been included such that each may generally stand on its own.

1.3 UNSATURATED SOIL IN NATURE AND PRACTICE

1.3.1 Unsaturated Soil in Hydrologic Cycle

Figure 1.4 shows a schematic diagram of the unsaturated soil environment and its role in the natural hydrologic cycle. The steady-state position of the water table is controlled by the general topography of the system, the soil properties, and the balance achieved among the natural mechanisms that act to either add or remove water to or from the subsurface. The scale of the corresponding hydrologic cycle could be either local or regional, extending from as small as a local engineering work site to as large as the continental or global scale. Globally, the amount of water in the unsaturated zone located between the water table and the ground surface represents only a small portion of the total water involved in the hydrologic cycle (less than 0.01%). However, because the unsaturated zone forms the necessary transition between the atmosphere and larger groundwater aquifers at depth, the movement of water within this small portion of the cycle is indeed significant.

1.3.2 Global Extent of Climatic Factors

The size and extent of the near-surface unsaturated soil zone are highly sensitive to perturbations in local or regional climate. Precipitation, evaporation,

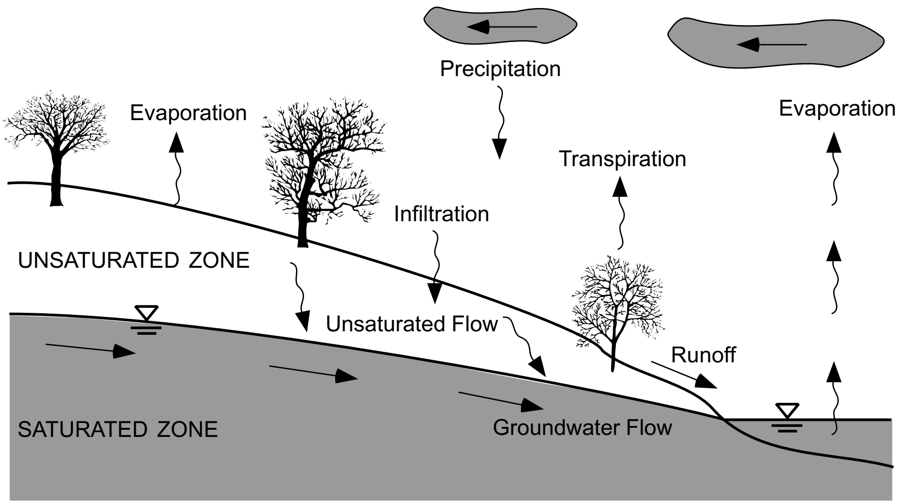

Figure 1.4 Role of the unsaturated zone in the natural hydrologic cycle.