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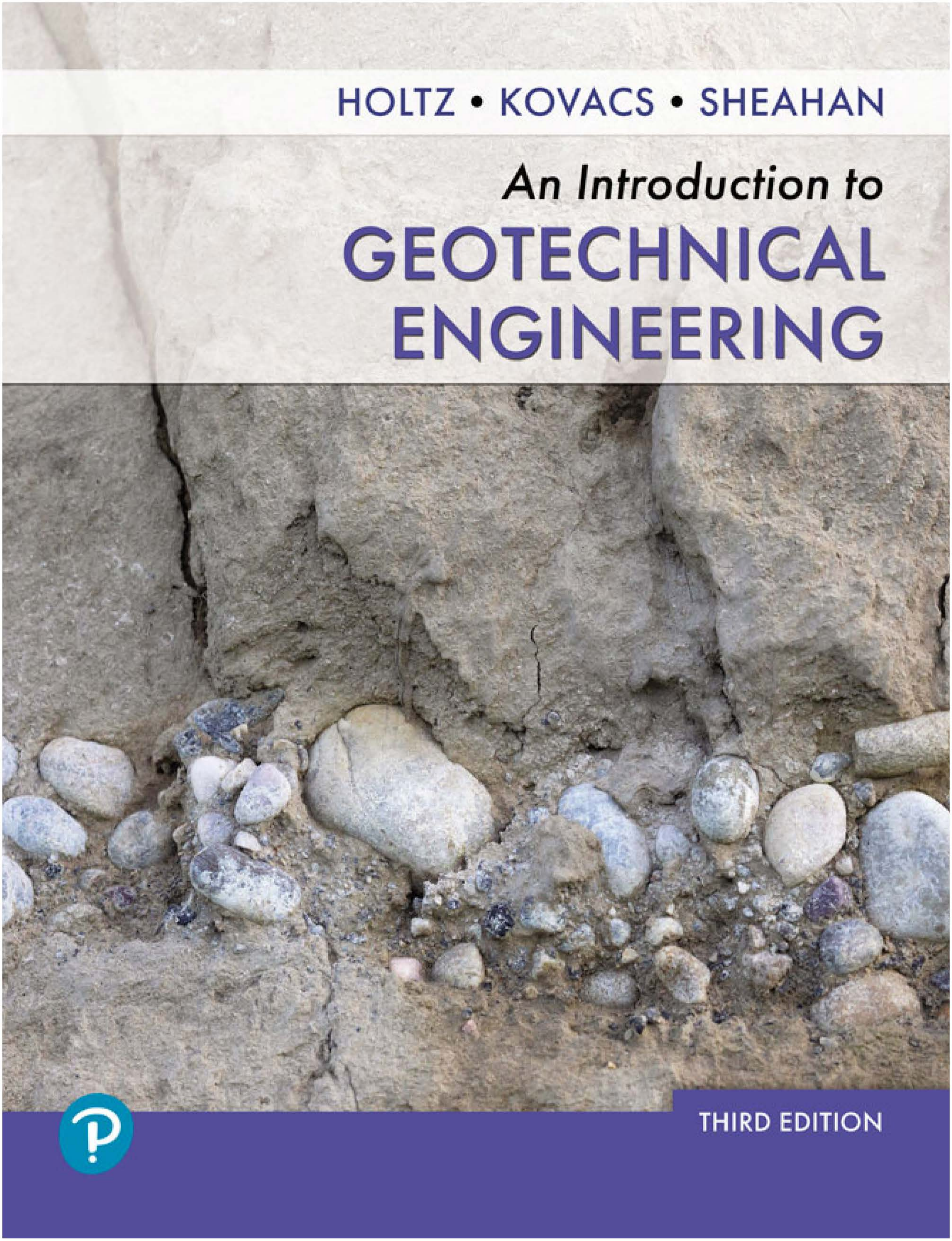
An Introduction to GEOTECHNICAL ENGINEERING



THIRD EDITION

AN INTRODUCTION TO GEOTECHNICAL ENGINEERING

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Preface

It has been over a decade since the publication of the second edition of *An Introduction to Geotechnical Engineering.* The impetus for this edition comes from a frequently heard need from faculty and students for a textbook that covers both the fundamentals of soil mechanics and soil properties, and also the basics of foundation engineering. As we noted in the preface to the second edition, technical content in engineering degree programs continues to be reduced, and these three areas of geotechnical engineering are often covered in a single undergraduate course. However, we continue to believe that even in such a compressed course, a textbook that is sophisticated and carries appropriate rigor is an ongoing necessity.

We still believe that there is a need for more detailed and modern coverage of the engineering properties of geo-materials than is found in most undergraduate texts. This applies to students who concentrate in geotechnical engineering as well as the general civil engineering undergraduate student. Our students will be involved in increasingly more complex projects, especially those in transportation, structural, construction, and environmental engineering. Those projects will increasingly involve environmental, economic, and political constraints that will demand innovative solutions to civil engineering problems. Modern analytical techniques using digital computers have had a revolutionary effect on engineering design practice, allowing multiple what-if design scenarios to be produced and graphically depicted. However, the validity of the results from these computational procedures is highly dependent on the quality of the geotechnical engineering design parameters as well as the geology and site conditions.

This edition is intended for use in either a stand-alone soil mechanics course or, as noted above, a geotechnical engineering course that includes fundamental foundation engineering, both usually taught to third- and fourth-year undergraduate civil engineering students. It might also be used in an introductory graduate school soils mechanics class. We assume the students have a working knowledge of undergraduate mechanics, especially statics and mechanics of materials, including fluids. In the first part of the book, we introduce the "language" of geotechnical engineering—that is, the classification and engineering properties of soils and rocks. Once the student has a working knowledge of the behavior of geo-materials, he/she can begin to predict soil behavior, and then carry out the design of simple foundations and earth structures.

We have tried to make the text easily readable by the average undergraduate. To this end, *An Introduction to Geotechnical Engineering* is written at a rather elementary level, although the material covered may at times be quite sophisticated and complex.

The emphasis throughout is on the practical, and admittedly empirical, knowledge of soil and rock behavior required by geotechnical engineers for the design and construction of foundations, embankments, earth retaining structures, and underground works. To strengthen this connection between the fundamental and applied, we have tried to indicate wherever possible the engineering significance of the property being discussed, why the property is needed, how it is determined or measured, and, to some extent, how it is actually used in specific design applications. We illustrate some simple geotechnical designs—for example, determining the flow, uplift pressures, and exit gradients in 2-D seepage problems, and estimating the settlement of shallow foundations on sands and saturated clays.

One thing that has not changed over the years is that units remain a problem with U.S. geotechnical engineers. While this edition continues to use both the British and Système International (SI) sets of units, we have chosen to abandon seldom used units in the SI system such as megagrams (Mg), but continue to have examples and problems that use kilograms (kg) and kilonewtons (kN). We continue to be careful to use the correct definitions of density (mass/unit volume) and unit weight (force or weight/unit volume) in phase relationships as well as in geostatic and hydrostatic pressure computations.

If you have a laboratory component with your course, we consider this to be an important part of the student's experience with soils as a unique engineering material. This is where you begin to develop a "feel" for soils and soil behavior, so essential for the successful practice of geotechnical engineering. An emphasis on laboratory and field testing is found throughout the text. The organization and development of the material in the text are traditional and generally follow the order of a typical laboratory portion of many courses. The early chapters introduce the discipline of geotechnical engineering, phase relationships, index, and classification properties of soils and rocks, geology, landforms, and the origin of geo-materials, clay minerals, soil and rock structures, and rock classification. These chapters provide the background and terminology for the remainder of the text.

Following a very practical discussion of compaction in Chapter 4, Chapters 5 and 6 describe how water influences and affects soil behavior. Topics presented in Chapter 5 include groundwater and vadose water, capillarity, shrinkage, swelling, and collapsing soils, frost action, and effective stress. Chapter 6 discusses permeability, seepage, and seepage control.

Chapters 7 through 9 deal with the compressibility and shear strength of soils and rocks. Chapter 7 covers both compressibility behavior of natural and compacted soils and rock masses and basic time-rate consolidation of soils. Chapter 8 begins with the theoretical underpinnings of stresses in a soil mass, followed by a description of laboratory and field tests that attempt to model those conditions in order to measure stress-strain-strength properties. Chapter 9 is an introduction to shear strength of soils and rock and is suitable for undergraduate students if the course schedule permits, and can be covered more extensively in a first soil mechanics course in graduate school.

Chapters 10 through 12 are new chapters in this edition, covering three fundamental areas of foundation engineering: shallow foundations, lateral earth pressures and earth retaining structures, and deep foundations. Chapter 10 introduces bearing capacity theory, followed by its application to bearing capacity in sands and clays, and approaches to determining settlement of shallow foundations. Chapter 11 covers the two theories of lateral earth pressure, Rankine and Coulomb, and then how these are used for the design of retaining structures. Chapter 12 describes the estimation methods for deep foundation bearing capacity, how we compute the tensile and lateral load capacity of piles, and advanced topics in deep foundations that are often the source of significant field performance issues.

Chapter 13 first covers advanced applications of stress paths, and also includes sections on critical-state soil mechanics and an introduction to constitutive models. We then discuss some advanced topics on the shear strength of sands that start with the fundamental basis of their drained, undrained, and plane-strain strengths. The residual shear strength of sands and clays provides a transition into the stress-deformation and shear strength of clays, where we discuss failure definitions, Hvorslev strength parameters, stress history, the Jürgenson–Rutledge hypothesis, consolidation methods to overcome sample disturbance, anisotropy, plane-strain strength, and strain-rate effects. We end Chapter 13 with sections on the strength of unsaturated soils, properties of soils under dynamic loading, and failure theories for rock.

Even though it is primarily for the beginning student in geotechnical engineering, advanced students in other disciplines and engineers desiring a refresher in engineering properties may find the book helpful. Advanced students, researchers, and practitioners will also likely make use of the advanced topical coverage in Chapter 13.

Because of the many fully worked example problems, students and others learning from this book can follow the solution steps for various types of geotechnical engineering problems, and assess their understanding of the material. From the previous two editions, we know that many practicing geotechnical engineers will find this book useful as a refresher and for the typical values given for classification and engineering properties for a wide variety of soils; we have found such a compendium very useful in our own engineering practice. We hope that the new chapters on foundation engineering will provide further value in this regard.

RESOURCES FOR INSTRUCTORS

The solutions manual and test manual as well as PowerPoint figures of all images and tables from this book can be downloaded electronically from our Instructor's Resource Center located at www.pearsonhighered.com. The material available through the Instructor Resource Center is provided solely for the use of instructors in teaching their courses and assessing student learning. If you are in need of a login and password for this site, please contact your local sales representative for additional assistance or support.

ACKNOWLEDGMENTS

To acknowledge all who have contributed to this edition and previous editions is a formidable task. We have continued the practice of trying whenever possible to indicate by references or quotations, concepts and ideas originating in the literature or with our former teachers, especially Profs. B. B. Broms, A. Casagrande, R. J. Krizek, C. C. Ladd, J. K. Mitchell, J. O. Osterberg, and H. B. Seed. Others have made helpful suggestions or reviewed portions of the text, resulting in improvements to the final product, including Prof. Mal Hill from Northeastern. We are indebted to Prof. Alan Lutenegger, who provided considerable editing contributions to the foundation engineering chapters, and Prof. Aaron Gallant and Danilo Botero Lopez were instrumental in revising the worked examples and end-of-chapter problems. Molly Liddell provided invaluable administrative assistance in preparing the final versions of chapters for copyediting.

Thank you to the reviewers of this edition: Andrew Assadollahi, Ph.D., P.E. (Christian Brothers University), Ghada Ellithy, Ph.D. (Embry-Riddle Aeronautical University), Evert Lawton, Ph.D., P.E. (University of Utah), Anne Lemnitzer, Ph.D., M.Sc. (University of California, Irvine).

IN MEMORIAM

We are saddened by the loss of our dear friend and colleague, Bill Kovacs, who passed away in March 2020 at the age of 84. Bill was devoted to his family, especially to his wife Eileen. Besides his wife, he is survived by his 7 children and 19 grandchildren. Bill will be remembered as a dedicated educator who also loved being a geotechnical engineer. In his lectures he regularly drew on lessons learned from his days in practice or his consulting experiences, and his delivery was peppered with deadpan humor, clever puns, and subtle jokes. He was a remarkable mentor who was very generous with his time for students and younger colleagues, never said an unkind word about anyone, and was a true friend to many of us. His contributions to the three editions are inestimable in both their technical content and overall presentation of the material. And, while we never divulge the source or even acknowledge the existence of humor in the book, we do hope students and others using this book will think fondly of Bill when they discover something to smile about in its pages.

R. D. HOLTZ
SEATTLE, WASHINGTON

W. D. KOVACS
(DECEASED)

T. C. SHEAHAN
BOSTON, MASSACHUSETTS

CHAPTER 1

Introduction to Geotechnical Engineering

1.1 GEOTECHNICAL ENGINEERING

Geotechnical engineering is concerned with the application of civil engineering technology to some aspect of the earth, usually the natural materials found on or near the earth's surface. Civil engineers call these materials *soil* and *rock*. *Soil*, in an engineering sense, is the relatively loose agglomerate of mineral and organic materials and sediments found above the bedrock. Soils can be relatively easily broken down into their constituent mineral or organic particles. *Rock*, on the other hand, has very strong internal cohesive and molecular forces which hold its constituent mineral grains together. This is true for massive bedrock as well as for a piece of gravel found in a clay soil. The dividing line between soil and rock is arbitrary, and many natural materials encountered in engineering practice cannot be easily classified. They may be either a "very soft rock" or a "very hard soil."

Other scientific disciplines have different meanings for the terms soil and rock. In geology, for example, *rock* means all the materials found in the earth's crust, including what most of us would call soil. Soils to a geologist are just decomposed and disintegrated rocks found in the very thin upper part of the crust and usually capable of supporting plant life. Similarly, pedology (soil science) and agronomy are concerned with only the very uppermost layers of soil—that is, those materials important to agriculture and forestry. Geotechnical engineers can learn much from both geology and pedology. Geotechnical engineering has considerable overlap with these fields, especially with engineering geology and geological engineering. But beginning students should remember that these fields may have different terminology, approaches, and objectives than geotechnical engineering.

Geotechnical engineering has several different aspects or emphases. *Soil mechanics* is concerned with the engineering mechanics and properties of soil, whereas *rock mechanics* is concerned with the engineering mechanics and properties of rock—usually, but not limited to, the bedrock. Soil mechanics applies to soils the basic principles of mechanics including kinematics, dynamics, fluid mechanics, and the mechanics of materials. In other words, soil—rather than water, steel, or concrete, for example—is the engineering material whose properties and behavior we must understand in order to build with it or upon it. A similar statement could also be made for rock mechanics. However, because in significant ways soil masses behave differently from rock masses, in practice, there is not much overlap between the two disciplines. This divergence is unfortunate from the viewpoint of the practicing civil engineer. Inconveniently, the world does not consist only of soft or loose soils and hard rock, but rather, most geo-materials fall somewhere between those extremes. In your professional practice you will have to learn to deal with a wide range of material properties and behaviors.

Foundation engineering applies engineering geology, soil mechanics, rock mechanics, and structural engineering to the design and construction of foundations for civil engineering and other structures. The foundation engineer must be able to predict the performance or response of the foundation soil or rock to the loads the structure imposes. Examples include foundations for industrial, commercial, and residential buildings, bridges, towers, and retaining walls, as well as foundations for oil and other kinds of storage tanks and offshore structures. Ships must have a drydock during construction or repairs, and the drydock must have a foundation. During construction and launch, rockets and appurtenant structures must be safely supported. Related geotechnical engineering problems that the foundation engineer faces are the stability of natural and excavated slopes, the stability of permanent and temporary earth-retaining structures, problems of construction, control of water movement and water pressures, and even the maintenance and rehabilitation of old buildings. Not only must the foundation safely support static structural and construction loads, but it must also adequately resist dynamic loads due to wind, blasting, earthquakes, and the like.

If you think about it, we cannot design or construct *any* civil engineering structure, whether built on the earth or extraterrestrial, without ultimately considering the foundation soils and rocks. The performance, economy, and safety of any civil engineering structure ultimately are affected or even controlled by its foundation.

Earth materials are often used as a construction material because they are the cheapest possible building material. However, their engineering properties such as strength and compressibility are often naturally poor, and measures must be taken to densify, strengthen, or otherwise stabilize and reinforce soils so that they will perform satisfactorily. Highway and railway embankments, airfields, earth and rock dams, levees, and aqueducts are examples of earth structures, and the geotechnical engineer is responsible for their design and construction. Dam safety and rehabilitation of old dams are important aspects of this phase of geotechnical engineering. A related consideration, especially for highway and airfield engineers, is the design of the surface layer on the earth structure—the pavement. Here the overlap between the transportation and geotechnical disciplines is apparent.

Rock engineering, analogous to foundation engineering for soils, is concerned with rock as a foundation and construction material. Because most of the earth's surface is covered with soil (or water), rock engineering usually occurs underground (tunnels, underground power houses, petroleum storage rooms, mines, yours, and so on). But some rock engineering problems occur at the surface, such as in the case of building and dam foundations carried to bedrock, deep excavations to bedrock, stability of rock slopes, and the like.

In recent years, geotechnical engineers have become increasingly involved in the solution of environmental problems involving soil and rock. This interdisciplinary field is called *geoenvironmental engineering* or *environmental geotechnics*. Especially challenging are problems of polluted groundwater, proper disposal and containment of municipal and industrial wastes, design and construction of nuclear waste repositories, and remediation of hazardous waste repositories and other contaminated sites. Although all these problems have a major geotechnical engineering component, they are interdisciplinary in nature, and their solutions require that geotechnical engineers work together with environmental and chemical engineers, environmental and public health specialists, geohydrologists, and regulatory agency personnel.

In presenting some of the typical problems facing the geotechnical engineer, we wanted you to see, first, how broad the field is and, second, how important it is to the design and construction of civil engineering structures, as well as to the basic health and safety of society. In a very real sense, geotechnical engineering combines the basic physical and mathematical sciences, geology, and pedology, with environmental, hydraulic, structural, transportation, construction, and mining engineering. It truly is an exciting and challenging field.

1.2 THE UNIQUE NATURE OF SOIL AND ROCK MATERIALS

We mentioned earlier that soil—from a civil engineering point of view—is the relatively loose agglomeration of mineral and organic materials found above the bedrock. In a broader sense, of course, even shallow bedrock is of interest to geotechnical engineers, as illustrated by examples given earlier.

The nature and behavior of soil and rock are discussed in greater detail throughout this text. For now, we want just to set the stage for what you are about to study. We assume you understand that rock refers to any hard solid aggregate or mass of mineral matter found in the earth's crust. You also already have a layperson's idea about soil. At least you know in general what *sand* and *gravel* are, and perhaps you even have an idea about fine-grained soils such as *silts* and *clays*. These terms have quite precise engineering definitions, as we shall later see, but for now the general concept that soils are particles will suffice.

Soils are particles of what? Well, soils are usually particles of mineral matter or, more simply, broken-up pieces of rock that result from weathering and other geologic processes (described in Chapter 3) acting on massive rock deposits and layers. If we talk for the moment about the size of the particles, gravels are small pieces of rock and typically contain several minerals, whereas sands are even smaller pieces, and each grain usually consists of only a single mineral. If you cannot *see* each individual grain of a soil, then the soil is either a silt or a clay or a mixture of each. In fact, natural soils generally are a mixture of several different particle sizes and may even contain organic matter. Some soils, such as *peat*, may be almost entirely organic. Furthermore, because soils are a particulate material, they have voids, and the voids are usually filled with water and air. The physical and chemical interaction of the water and air in the voids with the particles of soil, as well as the interaction of the particles themselves, makes soil's behavior complicated and leads to some of its unique properties. It is also what makes it a very interesting and challenging engineering material to study and understand.

Because of the nature of soil and rock materials and the complexity of the geological environment, geotechnical engineering is highly empirical, and requires both fundamental knowledge and experience. Soils and rocks are often highly variable, even within a distance of a few millimeters. In other words, soils and rocks are *heterogeneous* rather than *homogeneous* materials. That is, their material or engineering properties may vary widely from point to point within a soil or rock mass. Furthermore, these materials in general are *nonlinear*; their stress-strain curves are not straight lines. To further complicate things, soils in particular "remember" their previous loading history, and this fact strongly affects their subsequent engineering behavior. It means that the geotechnical engineer must have knowledge of the geologic history of a soil deposit. Instead of being *isotropic*, soils and rocks are typically *anisotropic*, which means that their material or engineering properties are not the same in all directions.

Most of our theories about the mechanical behavior of engineering materials assume that they are homogeneous and isotropic and obey linear stress-strain laws. Common engineering materials such as steel and concrete do not deviate too significantly from these ideals, so we can use, with discretion, simple linear theories to predict the response of these materials to engineering loads. With soils and rock, we are not so fortunate. We may assume a linear stress-strain response, but then we must apply large empirical correction or "safety" factors to our designs to account for the real materials' behavior. Furthermore, the behavior of soil and rock materials in situ is often controlled by joints (just don't inhale), fractures, weak layers and zones, and other "defects" in the material, which our laboratory tests and simplified methods of analysis often do not or are unable to take into account. That is why the practice of geotechnical engineering is sometimes seen as more an "art" than a science. Successful practice depends on the good judgment and experience of the designer, constructor, or consultant. Put another way, the successful geotechnical engineer must develop a "feel" for soil and rock behavior before a safe and economic foundation or tunnel design can be made, an earth structure can be safely built, or an environmentally sound waste containment and disposal system or a site remediation plan can be developed.

In summary, because of their nonlinear, nonconservative, and anisotropic mechanical behavior, plus the variability and heterogeneity of natural deposits due to the capriciousness of nature, soils and rocks are indeed complex engineering and construction materials. Helping you find some order in this potential chaos is our primary objective in this book.

1.3 SCOPE OF THIS BOOK

In this revised introductory text, the emphasis is on the *classification and engineering behavior of soil and rock materials*, followed by an introduction to the most important aspects of foundation engineering. Successful practice of geotechnical engineering requires a thorough knowledge and understanding of the engineering properties and behavior of soils and rocks in situ—that is, when they are subjected to engineering loads and environmental conditions. Therefore, the beginning student must first develop an appreciation for the engineering properties of geo-materials as distinct from other common civil engineering materials before learning how to analyze and design foundations, earthworks, tunnels, and the like.

Actually, this first part is the hard part. Most engineering students (and engineers) are very good at analysis and performing design calculations. But in geotechnical engineering, these calculations alone cannot tell the whole picture. If an incorrect picture of the site geology has been assumed or the wrong engineering properties assumed for the design, significant errors can result.

Since much of the practice of geotechnical engineering depends on the site geology, landforms, and the nature of the soil and rock deposits at a site, we have included a portion of Chapter 3 on geology and landforms. If you have had such a course, that portion of the chapter will serve as a good review. If you haven't, you are strongly encouraged to take a physical geology or an engineering geology course in connection with your studies of geotechnical engineering, and this chapter can provide initial, basic information.

In the early chapters, we introduce some of the basic definitions, index properties, and classification schemes for geo-materials that are used throughout the book. *Classification* of soils and rocks is important because it is the "language" engineers use to communicate certain general knowledge about the engineering behavior of the materials at a particular site.

The greatest portion of the book is concerned with the *engineering properties* of soils and rocks—properties that are necessary for the design of foundations, earth and underground structures, and geoenvironmental systems. We describe how water affects soil and rock behavior, including hydraulic conductivity and seepage characteristics. Then we get into compressibility, the important engineering property we need to understand in order to predict the settlement of structures constructed on soil and rock masses. We then describe some elementary strength characteristics of both soils and rocks. Strength is very important for the stability of, for example, foundations, retaining walls, slopes, tunnels, and waste containment systems.

The later part of the book introduces key concepts and design methods for the most basic parts of foundation engineering: shallow and deep foundations, and retaining structures. This is by no means meant to serve as an exhaustive reference on all foundation engineering topics. However, as more civil engineering programs offer a "merged" geotechnical engineering course with both soil mechanics and foundation engineering, these later chapters provide foundation engineering fundamentals.

Finally, we have included a chapter on advanced topics in the shear strength of soil and rock that is meant primarily for graduate study or for those who wish to extend their knowledge beyond the coverage in earlier chapters on these topics.

Consistent with this emphasis on fundamentals, keep in mind that this is an elementary text that emphasizes such basics, but with an eye toward the practical applications that you as a civil engineer are likely to encounter. Having studied this text, you will be well prepared for any follow-up, more specialized studies in foundations and earthwork engineering, environmental geotechnics, rock mechanics, and engineering geology. You should have a fairly good idea of what to look for at a site and how to obtain the soil and rock properties required for most designs. If you are able to accurately classify the materials, you will know the probable range of physical and engineering values for a given soil or rock property. You will have some idea of how to estimate foundation capacity and the stresses on an earth support structure. Finally, we hope you will learn enough about soils and rocks to be aware of your own limitations, and to avoid costly and dangerous mistakes in those aspects of your professional career that involve soils and rocks as engineering materials.

1.4 HISTORICAL DEVELOPMENT OF GEOTECHNICAL ENGINEERING

As long as people have been building things, they have used soils and rocks as a foundation or construction material. The ancient Egyptians, Babylonians, Chinese, and Indians knew about constructing dikes and levees out of the soils found in river flood plains. Ancient temples and monuments built all around the world involved soil and rock in some way. The Aztecs constructed temples and cities on the very poor soils in the Valley of Mexico long before the Spaniards arrived in the so-called New World. European architects and builders during the Middle Ages learned about the problems of settlements of cathedrals and large buildings. The most noteworthy example is, of course, the Leaning Tower of Pisa. Vikings in Scandinavia used timber piles to support houses and wharf structures on their soft clays. The "design" of foundations and other constructions involving soil and rock was by rule of thumb, and very little theory as such was developed until the mid-1700s.

Coulomb is the most famous engineering name of that era. He investigated the problems of earth pressures against retaining walls, and some of his calculation procedures are still in use today. The most common theory for the shear strength of soils is named after him (Coulomb, 1776). During the next century, the French engineers Collin and Darcy and the Scotsman Rankine made important discoveries. Collin (1846) was the first engineer to systematically examine failures in clay slopes as well as the measurement of the shear strength of clays. Darcy (1856) established his law for the flow of water through sands. Rankine (1857) developed a method for estimating the earth pressure against retaining walls. In England, Gregory (1844) utilized horizontal subdrains and compacted earth-fill buttresses to stabilize railroad cut slopes.

By the turn of the century, important developments in the field were occurring in Scandinavia, primarily in Sweden. Atterberg (1911) defined consistency limits for clays that are still in use today. During the period 1914–1922, in connection with investigations of failures in harbors and railroads, the Geotechnical Commission of the Swedish State Railways (Statens Järnvägers Geotekniska Kommission, 1922) developed many important concepts and apparatuses in geotechnical engineering. They developed methods for calculating the stability of slopes as well as subsurface investigation techniques such as weight sounding and piston and other types of samplers. They understood important concepts such as sensitivity of clays and consolidation, which is the squeezing of water out of the pores of the clay. At that time, clays were thought to be absolutely impervious, but the Swedes made field measurements to show they weren't. The Commission was the first to use the word *geotechnical* (Swedish: *geotekniska*) in today's sense: the combination of geology and civil engineering technology.

Even with these early developments in Sweden, the true father of modern soil mechanics is an Austrian, Prof. Karl Terzaghi. He published the first modern textbook on soil mechanics in 1925, and in fact the name "soil mechanics" is a translation of the German word *Erdbaumechanik*, which was part of the title of that book (Terzaghi, 1925). Terzaghi was an outstanding and very creative engineer. He wrote several other important books (for example, Terzaghi, 1943; Terzaghi and Peck, 1967; and Terzaghi, Peck, and Mesri, 1996) and over 250 technical papers and articles. His name will appear often in this book. He was a professor at Robert College in Istanbul, at Technische Hochschule in Vienna, at MIT, and at Harvard University from 1938 until his retirement in 1956. He continued to be active as a consultant until his death in 1963 at the age of 80. An excellent reference about his life and engineering career is that of Goodman (1999) and is well worth reading.

Another important figure is Prof. Arthur Casagrande, who was at Harvard University from 1932 until 1969. You will see his name often in this book, because he made many important contributions to the art and science of soil mechanics and foundation engineering. Since the 1950s, the field has grown substantially, and many people have been responsible for its rapid advancement. Important contributors to the field include Taylor, Peck, Tschebotarioff, Skempton, Bjerrum, Seed, Ladd, and Leonards.

Both Terzaghi and Casagrande began the teaching of soil mechanics and engineering geology in North America. Before the Second World War, the subject was offered only at a very few universities, mostly as a graduate course. After the war, it became common for at least one course in the subject to be required in most civil engineering curricula. Graduate programs in geotechnical engineering were implemented at many universities. Finally, there has been a real information explosion in the number of conferences, technical journals, and textbooks published on this subject during the past four decades.

In terms of foundation engineering, we have already mentioned the important role that Coulomb and Rankine played in the development of limit state analyses of lateral earth pressures for retaining structures. It should come as no surprise that Terzaghi was a pioneer in this area as well, offering some of the first rational methods for estimating soil capacity to support shallow foundations. In the 1950s, George Meyerhof and Aleksandr Vesic and others similarly began to formulate more fundamentals-based methods for deep foundations. A number of advances in this area of geotechnical engineering were often driven by contractors, innovating to build in difficult soils or use familiar materials in more efficient ways.

Important recent developments you should know about include soil dynamics and geotechnical earthquake engineering, the use of computer modeling for the solution of complex engineering problems, deformation-based analyses and designs, the introduction of probability and statistics into geotechnical engineering analysis and design, and geo-environmental engineering and technology.

1.5 SUGGESTED APPROACH TO THE STUDY OF GEOTECHNICAL ENGINEERING

Because of the nature of soil and rock materials, both laboratory and field testing are very important in geotechnical engineering. Student engineers can begin to develop a feel for soil and rock behavior in the laboratory by performing the standard tests for classification and engineering properties on many different types of soils and rocks. In this way, the novice can begin building up a "mental data bank" of how certain soils and rocks actually look, how they might behave with varying amounts of water in them and under different types of engineering loads, and the range of probable numerical values for the different tests. This is sort of a self-calibration process, so that when you are faced with a new soil deposit or rock type, you will in advance have some idea as to the engineering problems you will encounter at that site. You can also begin to judge, at least qualitatively, the validity of laboratory and field test results for the materials at that site.

Also important is a knowledge of geology. Geology is, of course, the "geo" part of geotechnical engineering, and you should get as much exposure to it as you can during your academic career. After a basic course in physical geology, courses in geomorphology and engineering geology are recommended. Geomorphology is concerned with landforms, which are important to geotechnical engineers because the soils and rocks at a site (and therefore the engineering problems) are strongly related to the particular landform. Engineering geology is concerned with the applications of geology to primarily civil engineering and has considerable interaction and overlap with geotechnical engineering.

The theoretical and analytical aspects of geotechnical engineering design also require a sound knowledge of engineering mechanics, including strength of materials and fluid mechanics. It also helps if you are familiar to some extent with basic structural analysis, reinforced concrete and steel design, hydraulic engineering and hydrology, surveying and engineering measurements, basic environmental engineering, and civil engineering construction—in other words, just about all the courses in a typical undergraduate civil engineering curriculum.

1.6 NOTES ON SYMBOLS, UNITS, AND STANDARDS

As with most disciplines, a standard notation is not universal in geotechnical engineering, so we have tried to adopt the symbols most commonly used. For example, the American Society for Testing and Materials has a list of Standard Definitions of Terms and Symbols Relating to Soil, Rock, and Contained Fluids, standard designation D 653. The International Society for Soil Mechanics and Foundation Engineering

(ISSMFE, 1977) published an extensive list of symbols. Although we sometimes deviate from these recommendations because of our personal preference, we have generally tried to follow them.

Units used in geotechnical engineering can be politely called a mess, and, less politely, several worse things. There has developed in practice, at least in the United States, a jumbled mixture of cgs-metric, Imperial or British Engineering units, and hybrid European metric units. With the introduction of the universal and consistent system of units, "Le Système International d'Unités" (SI) in the United States and Canada, the profession had a wonderful opportunity to bring some coherence to units in geotechnical engineering practice. However, since British Engineering units are still rather commonly used in the United States, students need to be familiar with the typical values in both sets of units. This edition of the book could be characterized as less tolerant of SI units than previous editions since efforts to use SI units more in the United States have largely failed. There are a number of excellent, open source units conversions sites on the web, and we recommend you find and bookmark one that suits your purposes.

We referred earlier to the American Society for Testing and Materials, commonly known as ASTM, which develops and publishes technical standards for a multitude of materials, products, systems, and services through a highly organized volunteer committee structure. These committees arrive at consensus to determine these standards. Throughout the text, we cite only active ASTM, AASHTO, and British standards without associated years. In the case of ASTM standard, complete ASTM standards do have a date (e.g., D 2216-19), which indicates the year of last revision (in this case, 2019). Standards remain in the system for 8 years, and if not reapproved through the balloting process within that period, are withdrawn from active status. AASHTO standards are generally reviewed every 4 years, and if a standard is no longer used, it may be discontinued and then ultimately deleted from the book of standards. We have cited only those standards that were active at the time of publication and have excluded the year in the citation.

1.7 SOME COMMENTS ON HOW TO STUDY IN GENERAL

It takes a while to learn how to study most effectively. You are probably using the study habits that you got by with in grade school and high school. As you progress professionally, things are going to get harder, starting in your third year of university or college, when you take mostly preprofessional courses. We have all used the following methods to do homework assignments. (1) Just read the assignment to satisfy the moral obligation to do so. (2) Go further by underlining or highlighting passages to emphasize the main points. Consider what you are doing physically: the information goes through the eyes, down your neck and arm into the writing fingers, completely bypassing the brain! Both (1) and (2) are pretty much a waste of time unless you have a photographic memory. If we are really going to learn anything, most of us need to study a third way: (3) Read a few pages and then *close* the book. Write down in your *own words* what the main concepts are; a "bullet" format is OK, and you could also use index cards to capture details of a particular topic on each card. You may have to cheat occasionally and look back at the book to create your own notes, but you will have started the process of having the material in the *brain*. Yes, this will take more time than "studying" using methods (1) and (2), but you will not be wasting your time.

A useful argument for doing it the recommended way is that you will have already started preparing for the exams, because now you *know* the material. The rest of the time, you are brushing up or *reviewing* the material, so you won't need to cram.

One big problem is that there may not be enough time in the week to use method (3) when you are taking three or four other courses. However, follow it as much as you can. You have invested a lot in your education. Don't waste time with methods (1) and (2).

Don't ask us to tell you how long it took for *us* to learn the correct way to study (it's too embarrassing).

Our suggested approach will help you prepare for the Fundamentals of Engineering (FE or EIT) exam and later the PE or PEng (professional engineer's exam). We *strongly* encourage you to take (and pass) the FE exam before you graduate and receive your engineering degree.

SUGGESTED ACTIVITIES

1.1 Attend a lecture with a geotechnical engineering topic, either through your department's research seminar series, your student chapter of the American Society of Civil Engineers, your local professional chapter, or other organizing group in your area. Not only will you learn something about an engineering topic or project, you may also be able to meet the speaker to build your professional network and learn why they became interested in geotechnical practitioner or researcher.

1.2 Visit a local project site where the geotechnical phase is still underway. Ideally, an engineer or contractor may be able to host you and other students, and explain the project and any details related to the geotechnical design and construction.

1.3 Speak to one of your geotechnical faculty members about research and/or consulting they are doing, and if you are interested, see if there are opportunities to participate in the research.

REFERENCES

Atterberg, A. (1911). "Lerornas Förhållande till Vatten, deras Plasticitetsgränser och Plasticitets- grader," ("The Behavior of Clays with Water, Their Limits of Plasticity and Their Degrees of Plasticity"), *Kungliga Lantbruksakademiens Handlingar och Tidskrift*, Vol. 50, No. 2, pp. 132–158; also in *Internationale Mitteilungen für Bodenkunde*, Vol. 1, pp. 10–43 ("Über die Physikalische Bodenuntersuchung und über die Plastizität der Tone").

Collin, A. (1846). Recherches Expérimentales sur les Glissements Spontanés des Terrains Argileux, Accompagnées de Considerations sur Quelques Principes de la Méchanicque Terrestre, Carilian-Goeury and Dalmont, Paris. Translated by W.R. Schriever under the title "Landslides in Clays by Alexandre Collin 1846," University of Toronto Press, Canada, 1956, 161 p. (21 plates).

Coulomb, C.A. (1776). "Essai sur une application des règles de Maximus et Minimis à Quelques Problèmes de Statique, Relatifs à l'Architecture," *Mémoires de Mathématique et de Physique, Présentés a l' Académie Royale des Sciences, par Divers Savans, et lûs dans ses Assemblées*, Paris, Vol. 7 (Vol. for 1773 published in 1776), pp. 343–382.

Darcy, H. (1856). *Les Fontaines Publiques de la Ville de Dijon*, Dalmont, Paris.

Goodman, R.E. (1999). *Karl Terzaghi: The Engineer as Artist*, ASCE Press, 340 p.

Gregory, C.H. (1844). "On Railway Cuttings and Embankments with an Account of Some Slips in London Clay, on the Line of the London and Croydon Railway," *Minutes and Proceedings of the Institution of Civil Engineers*, Vol. 3, pp. 135–145. Reprinted in *A Century of Soil Mechanics*, Institution of Civil Engineers, London, 1969, 482 p.

International Society for Soil Mechanics and Foundation Engineering (1977). "List of Symbols, Units, and Definitions," Subcommittee on Symbols, Units, and Definitions, *Proceedings of the Ninth International Conference on Soil Mechanics and Foundation Engineering*, Tokyo, Vol. 3, pp. 156–170.

Rankine, W.J.M. (1857). "On the Stability of Loose Earth," Abstracts of the Papers Communicated to the Royal Society of London, *Proceedings of the Royal Society*, London, Vol. VIII, pp. 185–187.

Statens Järnvägers Geotekniska Kommission (1922). *1914–1922 Slutbetänkande*, (*1914–1922 Final Report*), Presented to the Board of the Royal Swedish Railroads, Stockholm, 180 p. (42 plates).

Stokoe, K.H., II and Lodde, P.F. (1978). "Dynamic Response of San Francisco Bay Mud," *Proceedings of the Earthquake Engineering and Soil Dynamics Conference*, Los Angeles, ASCE, Vol. II, pp. 940–959.

Terzaghi, K. (1925). *Erdbaumechanik auf Bodenphysikalischer Grundlage*, Franz Deuticke, Leipzig und Wein, 399 p.

Terzaghi, K. (1943). *Theoretical Soil Mechanics*, Wiley, New York, 510 p.

Terzaghi, K. and Peck, R.B. (1967). *Soil Mechanics in Engineering Practice*, 2nd ed., Wiley, New York, 729 p.

Terzaghi, K., Peck, R.B., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice*, 3rd ed., Wiley, New York, 549 p.

CHAPTER 2

Index and Classification Properties of Soils

2.1 INTRODUCTION

In this chapter, we introduce the basic terms and definitions used by geotechnical engineers to index and classify soils. We need to establish a common language around how these properties are defined so that when different engineers refer to and use property values, it means the same thing to all. Some of these properties will have actual physical meaning (like density), while others may be so-called "index" properties that only make sense relative to some comparative scale. Additionally, as in many sciences, we want to be able to classify soils in some sort of commonly understood *taxonomy*. You may be familiar with this term from biology, where biological organisms have a genus and species. We shall define a relatively rigorous classification system for soils as well. The determination of physical, index, and classification properties is typically the first step in understanding how the soils in question are then used as engineering materials.

2.2 BASIC DEFINITIONS AND PHASE RELATIONS FOR SOILS

In general, any assemblage of soil consists of solid particles with voids in between. The solids are small grains of different minerals, whereas the voids can be filled with either water or other fluid (for example, a contaminant) or with air (or other gas), or filled partly with some of each (Fig. 2.1).

So, the total volume V_t of the soil mass consists of the volume of soil solids V_s and the volume of voids V_v. The volume of voids is in general made up of the volume of water V_w and the volume of air V_a.

A *phase diagram* (Fig. 2.2) shows the three phases separately. It's as if we could "melt down" all the solids into a single layer at the bottom, then have the water sit on top of that, and finally have the air in a single layer at the top. The phase diagram helps us solve problems involving soil phase relationships. On the left side we usually indicate the volumes of the three phases; on the right side we show the corresponding masses or weights. Even though the diagram is two-dimensional, it is understood that the volume shown is in units of L^3, such as cm^3 or ft^3. Also, since we're not chemists or physicists, we assume that the mass of air is zero.

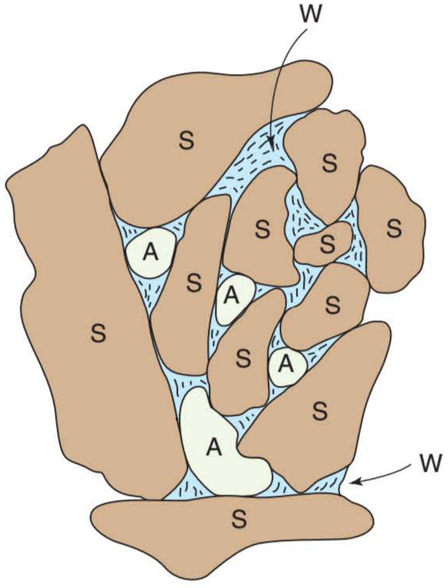

FIGURE 2.1 Soil skeleton containing solid particles (S) and voids with air (A) and water (W).

In engineering practice, we usually measure the total volume V_t, the mass of water M_w, and the mass of dry solids M_s. Then we calculate the rest of the values and the mass-volume relationships that we need. Most of these relationships are independent of sample size, and they are often dimensionless. They are very simple and easy to remember, especially if you draw the phase diagram.

Three volumetric ratios that are very useful in geotechnical engineering can be determined directly from the phase diagram (Fig. 2.2).

1. The *void ratio* e is defined as

$$e = \frac{V_v}{V_s} \tag{2.1}$$

where V_v = volume of the voids, and
V_s = volume of the solids.

The void ratio e is normally expressed as a *decimal* rather than a *percentage*. The maximum possible range of e is between 0 and ∞. However, typical values of void ratios for sands may range from 0.4 to about 1.0; typical values for clays vary from 0.3 to 1.5 and even higher for some organic soils.

2. The *porosity* n is defined as

$$n = \frac{V_v}{V_t} \times 100(\%) \tag{2.2}$$

where V_v = volume of voids, and
V_t = total volume of soil sample.

Porosity is traditionally expressed as a *percentage*. The maximum range of n is between 0 and 100%. From Fig. 2.2 and Eqs. (2.1) and (2.2), it can be shown that

$$n = \frac{e}{1 + e} \tag{2.3a}$$

and

$$e = \frac{n}{1 - n} \tag{2.3b}$$

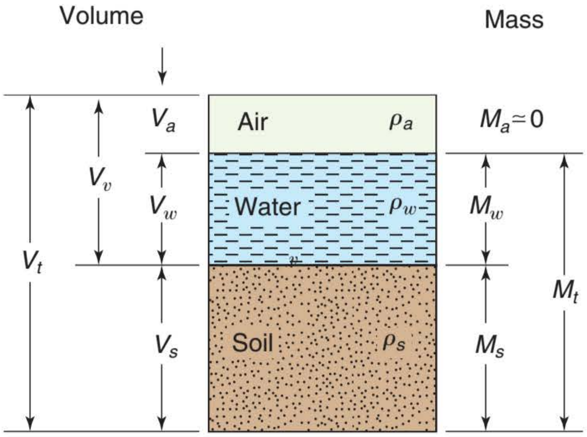

FIGURE 2.2 Volumetric and mass relationships for a soil shown in a phase diagram. Note: Weights, *W*, may also be used on the right side.

3. The *degree of saturation S* is defined as

$$S = \frac{V_w}{V_v} \times 100(\%) \tag{2.4}$$

The degree of saturation tells us what *percentage* of the total void space contains water. If the soil is completely dry, then $S = 0\%$, and if the pores are completely full of water, then the soil is fully saturated and $S = 100\%$.

Now let us look at the other side, the mass or weight side, of the phase diagram in Fig. 2.2. First, we will define a mass or weight ratio that is probably the single most important thing we need to know about a soil—its *water content* w. It is also the only strictly mass- or weight-based parameter that we'll define for phase relationships. The water content tells us how much water is present in the voids relative to the amount of solids in the soil, as follows:

$$w = \frac{M_w}{M_s} \times 100(\%) \tag{2.5a}$$

where M_w = mass of water, and
M_s = mass of soil solids.

or in terms of weights,

$$w = \frac{W_w}{W_s} \times 100(\%) \tag{2.5b}$$

where W_w = weight of water, and
W_s = weight of soil solids.

The ratio of the amount of water present in a soil volume to the amount of soil grains is based on the *dry mass* or *weight* of the soil and not on the total mass or weight. The water content, which is usually expressed as a *percentage*, can range from zero (dry soil) to several hundred percent. The natural water content for most soils is well under 100%, although in some marine and organic soils it can range up to 500% or higher.

The water content is easily determined in the laboratory. The standard procedure is detailed in ASTM standard D 2216. A representative sample of soil is selected and its total or wet mass or weight is determined. Then it is dried to constant mass or weight in a convection oven at 110°C. Normally, a constant mass or weight is obtained after the sample is left in the oven overnight. The mass or weight of the drying dish must, of course, be subtracted from both the wet and dry masses or weights. Then the water content is calculated according to Eq. (2.5a) or (2.5b). Example 2.1 illustrates how the calculations for water content are actually done in practice.

Example 2.1

Given:

A specimen of wet soil in a drying dish has a mass of 388 g. After drying in an oven at 110°C overnight, the sample and dish have a mass of 335 g. The mass of the dish alone is 39 g.

Required:

Determine the water content of the soil.

Solution: Set up the following calculation scheme; fill in the "given" or measured quantities **a**, **b**, and **d**, and make the calculations as indicated for **c**, **e**, and **f**.

a. Mass of total (wet) sample + dish = 388 g
b. Mass of dry sample + dish = 335 g
c. Mass of water (**a** − **b**) = 53 g
d. Mass of dish = 39 g
e. Mass of dry soil (**b** − **d**) = 296 g
f. Water content (**c**/**e**) × 100% = 17.9%

In the laboratory, masses are usually determined in grams (g) on an ordinary balance. The required sensitivity of the balance depends on the size of the specimen, and ASTM D 2216 gives some recommendations.

The water content may also be determined using an ordinary microwave oven. ASTM standard D 4643 explains the procedure. To avoid overheating the soil specimen, microwave energy is applied for only brief intervals and repeated until the mass becomes nearly constant. A heat sink, such as a glass beaker filled with water, helps to prevent overheating of the soil by absorbing microwave energy after water has been removed from the soil pores. Otherwise, the water content is determined exactly as indicated in Example 2.1. Note that the microwave water content is not a replacement for the oven dry water content but is used when the water content is needed quickly. Other methods sometimes used in the field for water content determination are described in Sec. 4.7.

Another very useful concept in geotechnical engineering is *density*. You know from physics that density is mass per unit volume, so its units are kg/m^3. The density is the ratio that connects the volumetric side of the phase diagram with the mass side. Several densities are commonly used in geotechnical engineering practice. First, we define the total, wet, or moist density ρ; the density of the particles, solid density ρ_s; and the density of water ρ_w. We also give the corresponding unit weights, γ, which are obtained by substituting M with the corresponding weight, W.

$$\rho = \frac{M_t}{V_t} = \frac{M_s + M_w}{V_t} \tag{2.6a}$$

$$\gamma = \frac{W_t}{V_t} = \frac{W_s + W_w}{V_t} \tag{2.6b}$$

$$\rho_s = \frac{M_s}{V_s} \tag{2.7a}$$

$$\gamma_s = \frac{W_s}{V_s} \tag{2.7b}$$

$$\rho_w = \frac{M_w}{V_w} \tag{2.8a}$$

$$\gamma_w = \frac{W_w}{V_w} \tag{2.8b}$$

In natural soils, the magnitude of the total density ρ will depend on how much water happens to be in the voids as well as the density of the mineral grains themselves. Thus, ρ can range from slightly above 1000 kg/m^3 to as high as 2400 kg/m^3, with corresponding units weights of 9.81 kN/m^3 (62.4 lb/ft^3) to 23.4 kN/m^3 (150 lb/ft^3). The high end of this range would be essentially solid mineral, with a corresponding density/unit weight close to that of concrete.

Typical values of ρ_s for most soils range from 2500 to 2800 kg/m^3 (156 to 175 pcf). Most sands have ρ_s values ranging between 2600 and 2700 kg/m^3 (162 to 169 pcf). For example, a common mineral in sands is quartz; its $\rho_s = 2650$ kg/m^3. Most clay soils have a value of ρ_s between 2650 and 2800 kg/m^3, depending on the predominant mineral in the soil, whereas organic soils may have a ρ_s as low as 2500 kg/m^3. Consequently, for most phase problems, unless a specific value of ρ_s is given, it is usually close enough for geotechnical work to *assume* a ρ_s of 2650 or 2700 kg/m^3. The density of water varies slightly, depending on the temperature. At 4°C, when water is at its densest, ρ_w exactly equals 1000 kg/m^3 (1 g/cm^3), and this density is sometimes designated by the symbol ρ_o. For ordinary engineering work, it is sufficiently accurate to take $\rho_w \approx \rho_o = 1000$ kg/m^3.

Three other densities very useful in soils engineering are the *dry density* ρ_d, the *saturated density* ρ_{sat}, and the *submerged* or *buoyant density* ρ' or ρ_b, and their corresponding unit weights.

$$\rho_d = \frac{M_s}{V_t} \tag{2.9a}$$

$$\gamma_d = \frac{W_s}{V_t} \tag{2.9b}$$

$$\rho_{\text{sat}} = \frac{M_s + M_w}{V_t}(V_a = 0,\ S = 100\%) \tag{2.10a}$$

$$\gamma_{\text{sat}} = \frac{W_s + W_w}{V_t}(V_a = 0,\ S = 100\%) \tag{2.10b}$$

$$\rho' = \rho_{\text{sat}} - \rho_w \tag{2.11a}$$

$$\gamma' = \gamma_{\text{sat}} - \gamma_w \tag{2.11b}$$

Among other uses, the dry density ρ_d is a common basis for judging a soil's degree of compaction after we have applied some mechanical energy to it, for example by using a roller or vibratory plate (Chapter 4). The saturated density ρ_{sat}, as the name implies, is the total density of the soil when 100% of its pores are filled with water; in this special case, $\rho = \rho_{\text{sat}}$. The concept of submerged or buoyant density ρ' is often difficult for students to understand, so it is discussed later after we have done a few example problems. However, you may be familiar with this concept from studying aggregates, where a "basket" of aggregate is weighed while it is submerged under water. Typical values of ρ_d, ρ_{sat}, and ρ' for several soil types are shown in Table 2.1, and Table 2.2 shows typical unit weights in terms of kN/m^3 and pcf.

From the basic definitions provided in this section, other useful relationships can be derived, as we show in the examples that follow.

TABLE 2.1 Some Typical Values for Different Densities of Some Common Soil Materials

	Density (kg/m^3)		
Soil Type	ρ_{sat}	ρ_d	ρ'
Sands and gravels	1900–2400	1500–2300	900–1400
Silts and clays	1400–2100	600–1800	400–1100
Glacial tills	2100–2400	1700–2300	1100–1400
Crushed rock	1900–2200	1500–2000	900–1200
Peats	1000–1100	100–300	0–100
Organic silts and clays	1300–1800	500–1500	300–800

Modified after Hansbo (1975).