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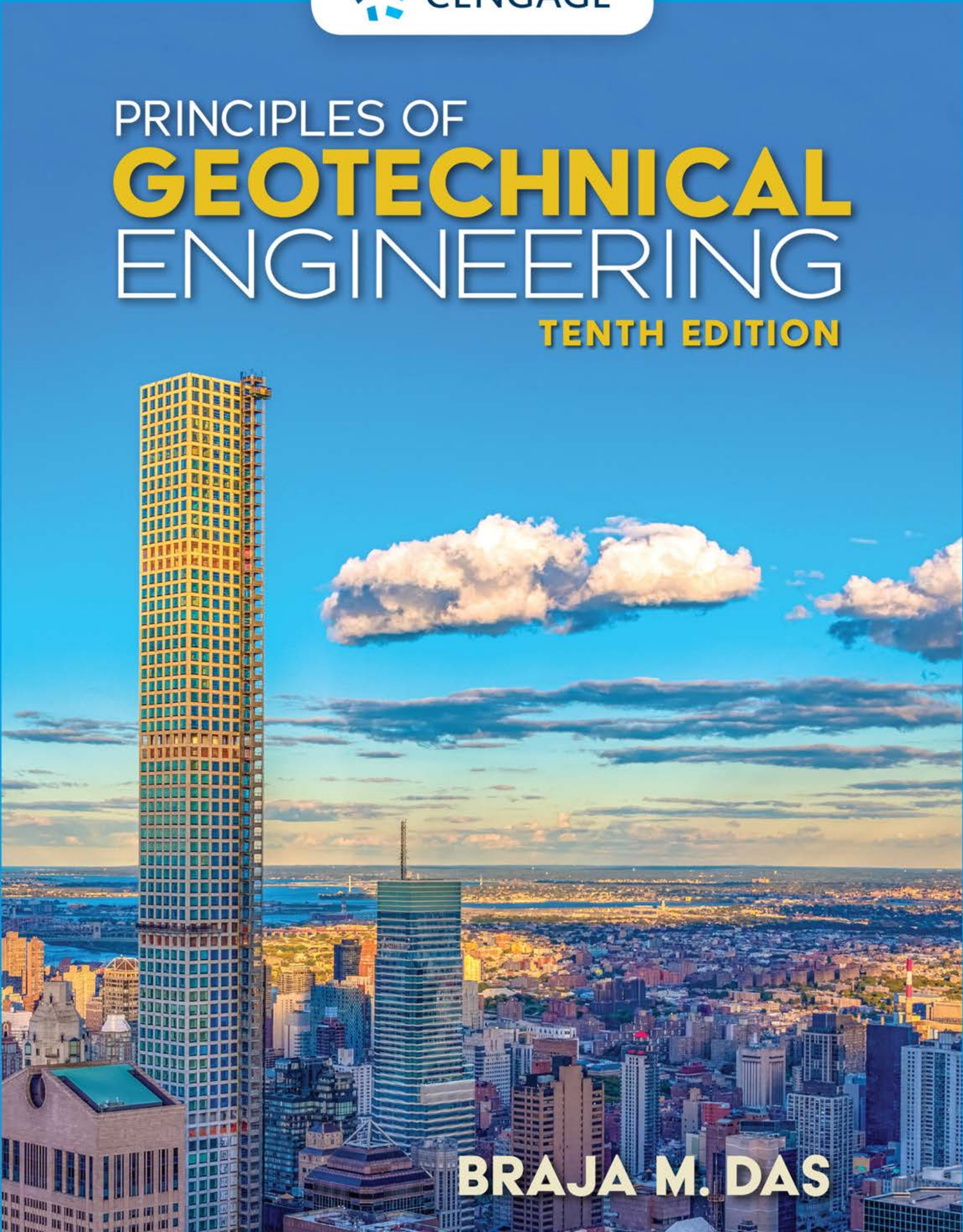
TENTH EDITION



BRAJA M. DAS

Principles of Geotechnical Engineering

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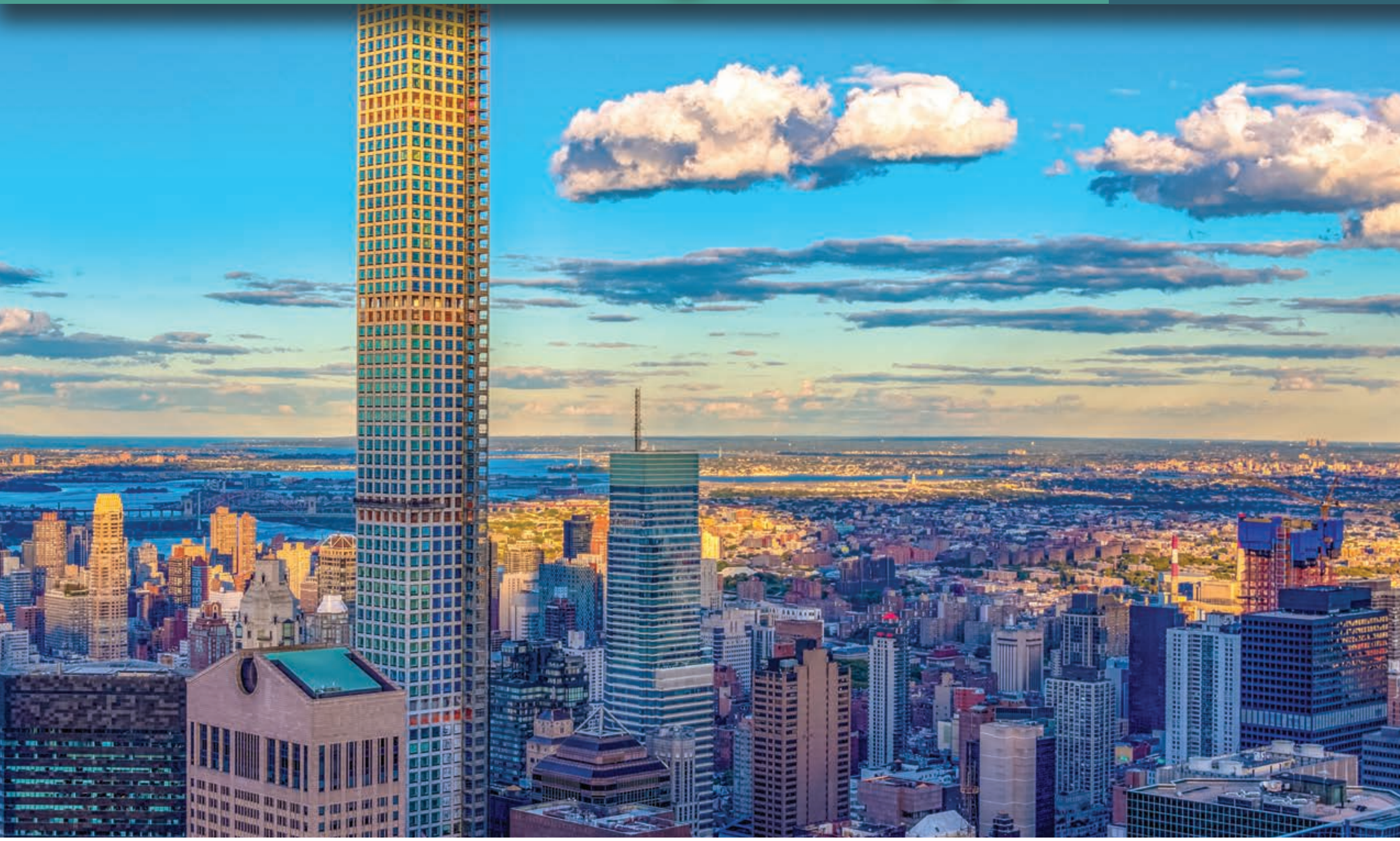

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Principles of Geotechnical Engineering,
Tenth Edition
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To our daughter, Valerie Jean

Contents

Preface

Principles of Geotechnical Engineering is intended for use as a text for the introductory course in geotechnical engineering taken by most civil engineering students, as well as a reference book for practicing engineers. The original version of this text was entitled *Introduction to Soil Mechanics* and was published by Iowa State University in 1979. The original text was thoroughly revised and then published as *Principles of Geotechnical Engineering, 1st Edition* in 1984. It was then revised in 1989, 1993, 1997, 2001, 2005, 2009, 2013, and 2017. As in the previous editions of the book, this new tenth edition offers a valuable overview of soil properties and mechanics together with coverage of field practices and basic engineering procedures. The properties of soil include weight-volume relationship, plasticity, classification for engineering use, permeability, seepage, compactibility, and shear strength. The mechanics component includes evaluation of stress in the soil media using the theory of elasticity, soil compressibility (elastic and consolidation), evaluation of lateral earth pressure for design of retaining walls and braced cuts, stability of slope, and behavior of shallow foundations under various types of loading. A brief overview of various geosynthetic-related products is also included. It is not the intent of this book to conform to any design codes. The author appreciates the overwhelming adoptions of this text in various classrooms and is gratified that it has become the market-leading textbook for this course of study.

NEW t O t HE tEN t H Ed It ION

- The tenth edition includes many new examples as well as revisions to existing examples. It now offers more than 194 examples to help students understand the content. The author has also added to and updated the book's end-of-chapter practice problems throughout. A total of 275 end-of-chapter practice problems are presented in the book.
- In Chapter 1 on "Geotechnical Engineering—A Historical Perspective," a new section entitled "Geosynthetics and Civil Engineering Construction" has been added. The ISSMGE Technical Committees list has been updated. Photographs of several pioneers in the era of modern geotechnical engineering have been added. They are Sir Alec Skempton (Imperial College, London), John Burland (Imperial College, London), J. P. Giroud (Paris, France), and Robert M. Koerner (Drexel University, Philadelphia).
- In Chapter 2 on "Origin of Soil and Grain Size," a brief description of the type and nature of lava from volcanic eruptions that form igneous rocks has been added.
- In Chapter 3 on "Weight-Volume Relationships," Section 3.5 provides a summary table for various forms of relationships for moist, dry, and saturated unit weights of soil.
- In Chapter 4 on "Plasticity and Structure of Soil," an approximate relationship based on Casagrande's suggestion to obtain the shrinkage limit from a plasticity chart has been provided. This was necessary since, at this time, the ASTM does not provide any test procedure for obtaining the shrinkage limit of soil. Empirical relationships to obtain the plastic limit and plasticity index from the liquid limit and clay-size fraction (< 2 mm) provided by Polidori (2007) also have been added.

- In Chapter 6 on "Soil Compaction," many of the plots involving the dry unit weight of soil (γ_d) have been replotted in a nondimensional form as γ_d/γ_w (γ_w = unit weight of water). Compaction of organic soil and waste materials are presented in Section 6.13.
- In Chapter 8 on "Seepage," Section 8.3 gives an example of solving simple flow problems using the equation of continuity. The procedure for the plotting of phreatic line for seepage through earth dams has also been added (Section 8.12).
- In Chapter 10 on "Stresses in a Soil Mass," the following sections were added to estimate vertical stress increases due to

  – Horizontal point load (Section 10.5)
  – Symmetrical vertical triangular strip load (Section 10.11)
  – Parabolic and conical loading on a flexible circular area (Section 10.15)

- Elastic settlement of shallow foundations is now presented in a separate chapter (Chapter 11, "Compressibility of Soil—Elastic Settlement"). Section 11.1 provides a sequential theoretical development of elastic settlement relationships provided by Schleicher (1926), Steinbrenner (1934), and Fox (1948). Settlement of foundations on saturated clay [Janbu, et al. (1956); Christian and Carrier (1978)] is discussed in Section 11.5.
- In Chapter 12 on "Consolidation," Section 12.5 gives procedures for obtaining preconsolidation pressure using the log–log method (Jose, et al., 1989) and Oikawa's method (1987). Section 12.6 provides some general comments on conventional consolidation test results. Several published correlations for estimation of the swell index have been added to Section 12.10. Precompression is discussed in Section 12.16. A case history of settlement observation due to preload fill is given in Section 12.17.
- In Chapter 13 on "Shear Strength of Soil," some correlations for the shear strength parameters of overconsolidated clay obtained from Denmark have been added to Section 13.6. Discussion on the friction angle of granular soil at critical void ratio state is presented in Section 13.11. The effect of the rate of rotation of vane on the magnitude of the undrained cohesion of clay has been added to Section 13.17. Sections 13.19 and 13.20 provide an overview of the stress path and shear strength of unsaturated soil.
- In Chapter 14 on "Lateral Earth Pressure: At-Rest, Rankine, and Coulomb," a closed form solution for the active pressure on a retaining wall with a $c'-\phi'$ backfill considering earthquake forces is added in a new section (Section 14.13).
- In Chapter 15 on "Lateral Earth Pressure: Curved Failure Surface," a new section (Section 15.7) on the passive force on walls with seepage has been added.
- In Chapter 16 on "Slope Stability," a new section on the stability of a saturated clay slope with earthquake forces (Section 16.9) has been added. Section 16.11 has a discussion on using Taylor's slope stability chart combined with earthquake effects for $c'-\phi'$ soils. Section 16.15 provides the case history of a slope failure. Morgenstern's (1963) method of slices for rapid drawdown condition is presented in Section 16.17.
- In Chapter 17 on "Soil Bearing Capacity for a Shallow Foundation," Meyerhof's bearing capacity, shape, and depth factor are discussed in Section 17.7. Section 17.8 provides a case history for the bearing capacity of shallow foundations. Prakash and Saran's theory (1971) for ultimate bearing capacity of shallow foundations with eccentric loading has been added in Section 17.7.
- In Chapter 18 on "Subsoil Exploration," additional correlations for the unconfined compression strength, preconsolidation pressure, and overconsolidation ratio of clay soil (Section 18.6) have been added. Additional correlations for the friction angle on granular soils with standard penetration resistance are provided in Section 18.7.

SUPPLEMENTS FOR THE INSTRUCTOR

Supplements to the text include a Solution and Answer Guide that provides complete solutions to all practice problems, Lecture Note PowerPoint™ slides, and an image library of all figures in the book. These can be found on the password-protected Instructor's Resources website for the book at login.cengage.com.

ACKNOWLEDGMENTS

- I am deeply grateful to Janice Das for her assistance in completing this revision. She has been the driving force behind this textbook since the preparation of the first edition.
- Thanks are due to all of the reviewers and instructors who, over approximately the last 40 years, have made suggestions that improved the quality and readability of the book.
- Thanks are also due to the Global Engineering team at Cengage Learning for their dedication to this new book: Timothy Anderson, Senior Product Manager; MariCarmen Constable, Learning Designer; Alexander Sham, Associate Content Manager; and Anna Goulart, Senior Product Assistant.
- Thanks are due to Rose P. Kernan of RPK Editorial Services. You have been instrumental in the development of several aspects for this edition and several past editions.

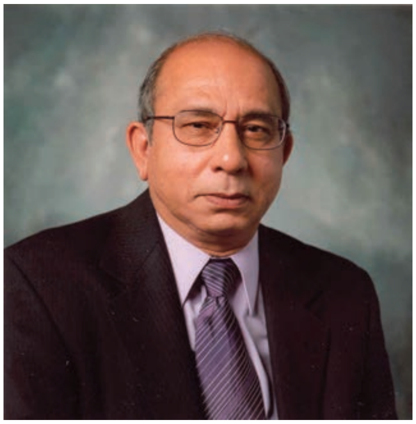
  All of the individuals mentioned here have skillfully guided every aspect of this text's development and production to successful completion. I am truly grateful to all of them.

A FINAL NOTE

The preparation of the original manuscript began in June, 1976. My wife, Janice, typed the original manuscript on a manual typewriter. That was a time-consuming affair. At the time, our daughter was two years old. She missed a lot of quality time with her parents due to their serious commitment to the preparation of the manuscript. Since this tenth edition is a milestone, it is only fitting that it be dedicated to our daughter, Valerie Jean.

Braja M. Das
Henderson, Nevada

About the Author



Professor Braja Das is Dean Emeritus of the College of Engineering and Computer Science at California State University, Sacramento. He received his M.S. in Civil Engineering from the University of Iowa and his Ph.D. in the area of Geotechnical Engineering from the University of Wisconsin. He is the author of several geotechnical engineering texts and reference books and has authored more than 300 technical papers in the area of geotechnical engineering. His primary areas of research include shallow foundations, earth anchors, and geosynthetics. He is a Fellow and Life Member of the American Society of Civil Engineers, Life Member of the American Society for Engineering Education, and an Emeritus Member of the Stabilization of Geomaterials and Recycled Materials Committee of the Transportation Research Board of the National Research Council (Washington, D.C.). He has previously served as a member of the editorial board of the *Journal of Geotechnical Engineering* of ASCE, a member of the *Lowland Technology International* journal (Japan), associate editor of the *International Journal of Offshore and Polar Engineering* (ISOPE), and co-editor of the *Journal of Geotechnical and Geological Engineering* (Springer, The Netherlands). He was also the editor-in-chief of the *International Journal of Geotechnical Engineering* (Taylor and Francis, UK) from 2007 through 2019, and he has been named as the Founding Editor of this journal.

Dr. Das has received numerous awards for teaching excellence, including the AMOCO Foundation Award, AT&T Award for Teaching Excellence from the American Society for Engineering Education, the Ralph Teetor Award from the Society of Automotive Engineers, and the Distinguished Achievement Award for Teaching Excellence from the University of Texas at El Paso.

Some of Dr. Das's textbooks have been translated into several languages. The Spanish translations of his books are highly popular in Mexico, Central America, and South America. He is frequently invited to that region as a speaker. In 2016, he gave the inaugural Eulalio Juarez Badillo Honor Lecture during the biennial meeting of the Mexican Society for Geotechnical Engineering [Sociedad Mexicana de Ingenieria Geotecnica, AC (SMIG)] at the National Meeting of the Mexican Society of the Professors of Geotechnical Engineering of Mexico. Dr. Badillo was one of the founding members of SMIG. In 2018, Dr. Das also delivered the keynote lecture for the celebration of their 60th anniversary in Mexico City. The Soil-Structure Interaction Group of Egypt (SSIGE) initiated an honor lecture in the name of Dr. Das in 2017. The Braja Das Honor Lecture is given annually by a distinguished geotechnical engineer during the Geo-Middle East Conference in Egypt.

In 2018, his *Principles of Geotechnical Engineering* 9e received the McGuffey Longevity Award from the Textbook and Academic Authors Association (TAA) of the USA. The ninth edition of his *Principles of Foundation Engineering* was awarded the McGuffey Longevity Award by the TAA in 2020.

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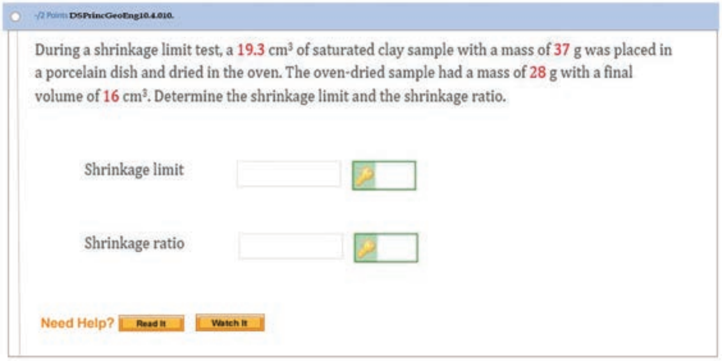

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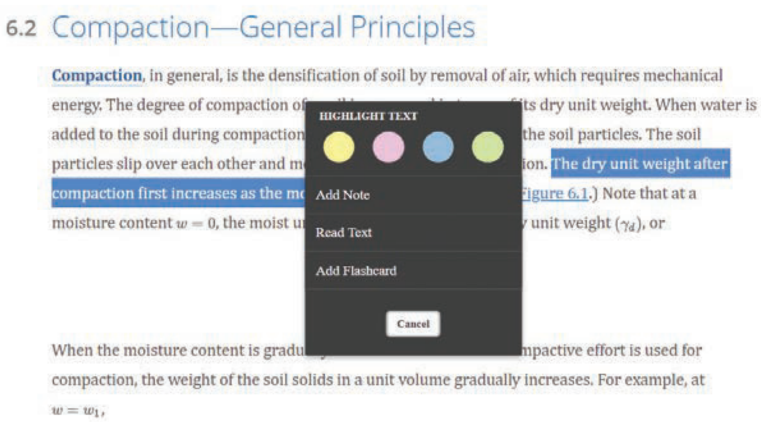

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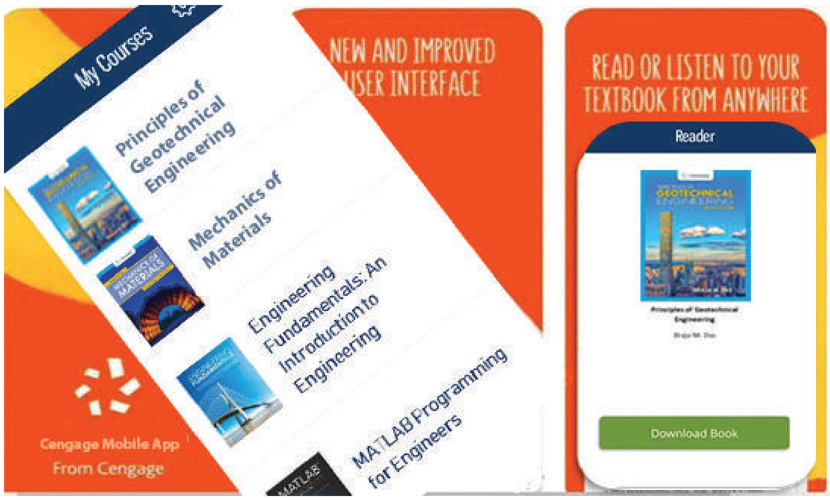

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Chapter 1

Geotechnical Engineering—A Historical Perspective

Learning Objectives

Upon completion of Chapter 1, you will be able to:

1.1 Explain the scopes of soil mechanics, soil engineering, and geotechnical engineering.

1.2 Discuss the history of geotechnical engineering prior to the 18th century.

1.3 Recognize the advances made in soil mechanics in the preclassical period.

1.4 Identify the developments made in the area of geotechnical engineering during the classical soil mechanics phase I.

1.5 Identify the developments made in the area of geotechnical engineering during the classical soil mechanics phase II.

1.6 Recognize the importance of the research conducted on clay during the modern soil mechanics era.

1.7 Explain the importance of the developments made in soil mechanics after 1927.

1.8 Relate the relevance of the use of geosynthetics in civil engineering construction since the 1970s.

1.9 Recognize the contributions made by pioneers of the field.

1.1 Introduction

For engineering purposes, *soil* is defined as the uncemented aggregate of mineral grains and decayed organic matter (solid particles) with liquid and gas in the empty spaces between the solid particles. Soil is used as a construction material in various civil engineering projects, and it supports structural foundations. Thus, civil engineers must study the properties of soil, such as its origin, grain-size distribution, ability to drain water, compressibility, strength, and its ability to support structures and resist deformation. *Soil mechanics* is the branch of science that deals with the study of the physical properties of soil and the behavior of soil masses subjected to various types of forces. *Soils engineering* is the application of the principles of soil mechanics to practical problems. *Geotechnical engineering* is the subdiscipline of civil engineering that involves natural materials found close to the surface of the earth. It includes the application of the principles of soil mechanics and rock mechanics to the design of foundations, retaining structures, and earth structures.

1.2 Geotechnical Engineering Prior to the 18th Century

Soil has been used as a construction material since the start of human civilization. In true engineering terms, the understanding of geotechnical engineering as it is known today began early in the 18th century (Skempton, 1985). For years, the art of geotechnical engineering was based on only past experiences through a succession of experimentation without any real scientific character. Based on those experimentations, many structures were built—some of which have crumbled, while others are still standing.

Recorded history tells us that ancient civilizations flourished along the banks of rivers, such as the Nile (Egypt), the Tigris and Euphrates (Mesopotamia), the Huang He (Yellow River, China), and the Indus (India). Dykes dating back to about 2000 B.C. were built in the basin of the Indus to protect the town of Mohenjo Dara (in what became Pakistan after 1947). During the Chan dynasty in China (1120 B.C. to 249 B.C.)

TABLE 1.1 Major Pyramids in Egypt

Pyramid/Pharaoh	Location	Reign of Pharaoh
Djoser	Saqqara	2630–2612 B.C.
Sneferu	Dashur (North)	2612–2589 B.C.
Sneferu	Dashur (South)	2612–2589 B.C.
Sneferu	Meidum	2612–2589 B.C.
Khufu	Giza	2589–2566 B.C.
Djedefre	Abu Rawash	2566–2558 B.C.
Khafre	Giza	2558–2532 B.C.
Menkaure	Giza	2532–2504 B.C.

many dykes were built for irrigation purposes. There is no evidence that measures were taken to stabilize the foundations or check erosion caused by floods (Kerisel, 1985). Ancient Greek civilization used isolated pad footings and strip-and-raft foundations for building structures. Beginning around 2700 B.C., several pyramids were built in Egypt, most of which were built as tombs for the country's Pharaohs and their consorts during the Old and Middle Kingdom periods. Table 1.1 lists some of the major pyramids identified through the Pharaoh who ordered it built. As of 2008, a total of 138 pyramids have been discovered in Egypt. Figure 1.1 shows a view of the three pyramids at Giza. The construction of the pyramids posed formidable challenges regarding foundations, stability of slopes, and construction of underground chambers. With the arrival of Buddhism in China during the Eastern Han dynasty in 68 A.D., thousands of pagodas were built. Many of these structures were constructed on silt and soft clay layers. In some cases the foundation pressure exceeded the load-bearing capacity of the soil and thereby caused extensive structural damage.

One of the most famous examples of problems related to soil-bearing capacity in the construction of structures prior to the 18th century is the Leaning Tower of Pisa in Italy (See Figure 1.2). Construction of the tower began in 1173 A.D. when the Republic of Pisa was flourishing and continued in various stages for over 200 years. The structure weighs about 15,700 metric tons and is supported by a circular base having a diameter of 20 m ($\approx$ 66 ft). The tower has tilted in the past to the east, north, west, and, finally, to the south. Recent investigations showed that a weak clay layer existed at a depth of about 11 m ($\approx$ 36 ft) below the ground surface compression of which caused the tower to tilt. It became more than 5 m ($\approx$ 16.5 ft) out of

FIGURE 1.1 A view of the pyramids at Giza (Joe Solic/Shutterstock.com)

FIGURE 1.2 Leaning Tower of Pisa, Italy (FilippoPH/Shutterstock.com)

plumb with the 54 m (≈ 179 ft) height (about a 5.5 degree tilt). The tower was closed in 1990 because it was feared that it would either fall over or collapse. It recently has been stabilized by excavating soil from under the north side of the tower. About 70 metric tons of earth were removed in 41 separate extractions that spanned the width of the tower. As the ground gradually settled to fill the resulting space, the tilt of the tower eased. The tower now leans 5 degrees. The half-degree change is not noticeable, but it makes the structure considerably more stable. The stabilization plan was overseen by a commission of thirteen members hired by the "Opera della Primaziale Pisana." This commission of thirteen included Professor John B. Burland (UK), Professor Michele Jamiolkowski (Poland), and Professor Salvatore Settis (Italy). John Burland (Figure 1.3) took the lead in this 30 million Euro project to its successful completion.

Figure 1.4 is an example of a similar problem. The towers shown in Figure 1.4 are located in Bologna, Italy, and they were built in the 12th century. The tower on the left is usually referred to as the *Garisenda Tower*. It is 48 m (≈ 157 ft) in height and weighs about 4210 metric tons. It has tilted about 4 degrees. The tower on the right is the Asinelli Tower, which is 97 m high and weighs 7300 metric tons. It has tilted about 1.3 degrees.

After encountering several foundation-related problems during construction over centuries past, engineers and scientists began to address the properties and behaviors of soils in a more methodical manner starting in the early part of the 18th century. Based on the emphasis and the nature of study in the area of geotechnical

FIGURE 1.3 John B. Burland (Courtesy of John B. Burland, Imperial College, London)

FIGURE 1.4 Tilting of Garisenda Tower (left) and Asinelli Tower (right) in Bologna, Italy (Courtesy of Braja M. Das, Henderson, Nevada)

engineering, the time span extending from 1700 to 1927 can be divided into four major periods (Skempton, 1985):

1. Preclassical (1700 to 1776 A.D.)
2. Classical soil mechanics—Phase I (1776 to 1856 A.D.)
3. Classical soil mechanics—Phase II (1856 to 1910 A.D.)
4. Modern soil mechanics (1910 to 1927 A.D.)

Brief descriptions of some significant developments during each of these four periods are presented below.

1.3 Preclassical Period of Soil Mechanics (1700–1776)

This period concentrated on studies relating to natural slope and unit weights of various types of soils, as well as the semiempirical earth pressure theories. In 1717, a French royal engineer, Henri Gautier (1660–1737), studied the natural slopes of soils when tipped in a heap for formulating the design procedures of retaining walls. The *natural slope* is what we now refer to as the *angle of repose*. According to this study, the natural slope of *clean dry sand* and *ordinary earth* were 31° and 45°, respectively. Also, the unit weight of clean dry sand and ordinary earth were recommended to be 18.1 kN/m^3 (115 lb/ft^3) and 13.4 kN/m^3 (85 lb/ft^3), respectively. No test results on clay were reported. In 1729, Bernard Forest de Belidor (1671–1761) published a textbook for military and civil engineers in France. In the book, he proposed a theory for lateral earth pressure on retaining walls that was a follow-up to Gautier's (1717) original study. He also specified a soil classification system in the manner shown in the following table.

	Unit weight	
Classification	**kN/m^3**	**lb/ft^3**
Rock	—	—
Firm or hard sand, compressible sand	16.7 to 18.4	106 to 117
Ordinary earth (as found in dry locations)	13.4	85
Soft earth (primarily silt)	16.0	102
Clay	18.9	120
Peat	—	—

The first laboratory model test results on a 76 mm high (≈ 3 in.) retaining wall built with sand backfill were reported in 1746 by a French engineer, Francois Gadroy (1705–1759), who observed the existence of slip planes in the soil at failure. Gadroy's study was later summarized by J. J. Mayniel in 1808. Another notable contribution during this period is that of the French engineer Jean Rodolphe Perronet (1708–1794), who studied slope stability around 1769 and distinguished between intact ground and fills.

1.4 Classical Soil Mechanics—Phase I (1776–1856)

During this period, most of the developments in the area of geotechnical engineering came from engineers and scientists in France. In the preclassical period, practically all theoretical considerations used in calculating lateral earth pressure on retaining walls were based on an arbitrarily based failure surface in soil. In his famous paper presented in 1776, French scientist Charles Augustin Coulomb (1736–1806) used the principles of calculus for maxima and minima to determine the true position of the sliding surface in soil behind a retaining wall. In this analysis, Coulomb used the laws of friction and cohesion for solid bodies. In 1790, the distinguished French civil engineer Gaspard Clair Marie Riche de Prony (1755–1839) included Coulomb's theory in his leading textbook, *Nouvelle Architecture Hydraulique* (Vol. 1). In 1820, special cases of Coulomb's work were studied by French engineer Jacques Frederic Francais (1775–1833) and by French applied mechanics professor Claude Louis Marie Henri Navier (1785–1836). These special cases related to inclined backfills and backfills supporting surcharge. In 1840, Jean Victor Poncelet (1788–1867), an army engineer and professor of mechanics, extended Coulomb's theory by providing a graphical method for determining the magnitude of lateral earth pressure on vertical and inclined retaining walls with arbitrarily broken polygonal ground surfaces. Poncelet was also the first to use the symbol ϕ for soil friction angle. He also provided the first ultimate bearing-capacity theory for shallow foundations. In 1846, Alexandre Collin (1808–1890), an engineer, provided the details for deep slips in clay slopes, cutting, and embankments. Collin theorized that in all cases the failure takes place when the mobilized cohesion exceeds the existing cohesion of the soil. He also observed that the actual failure surfaces could be approximated as arcs of cycloids.

The end of Phase I of the classical soil mechanics period is generally marked by the year (1857) of the first publication by William John Macquorn Rankine (1820–1872), a professor of civil engineering at the University of Glasgow. This study provided a notable theory on earth pressure and equilibrium of earth masses. Rankine's theory is a simplification of Coulomb's theory.

1.5 Classical Soil Mechanics—Phase II (1856–1910)

Several experimental results from laboratory tests on sand appeared in the literature in this phase. One of the earliest and most important publications is one by French engineer Henri Philibert Gaspard Darcy (1803–1858). In 1856, he published a study on the permeability of sand filters. Based on those tests, Darcy defined the term *coefficient of permeability* (or hydraulic conductivity) of soil, a very useful parameter in geotechnical engineering to this day.

Sir George Howard Darwin (1845–1912), a professor of astronomy, conducted laboratory tests to determine the overturning moment on a hinged wall retaining sand in loose and dense states of compaction. Another noteworthy contribution, which was published in 1885 by Joseph Valentin Boussinesq (1842–1929), was the development of the theory of stress distribution under load-bearing areas in a homogeneous, semiinfinite, elastic, and isotropic medium. In 1887, Osborne Reynolds (1842–1912) demonstrated the phenomenon of dilatancy in sand. Other notable studies during this period are those by John Clibborn (1847–1938) and John Stuart Beresford (1845–1925) relating to the flow of water through sand bed and uplift pressure. Clibborn's study was published in the *Treatise on Civil Engineering, Vol. 2: Irrigation Work in India,* Roorkee, 1901 and also in *Technical Paper No. 97*, Government of India, 1902. Beresford's 1898 study on uplift pressure on the Narora Weir on the Ganges River has been documented in *Technical Paper No. 97*, Government of India, 1902.

1.6 Modern Soil Mechanics (1910–1927)

In this period, results of research conducted on clays were published in which the fundamental properties and parameters of clay were established. The most notable publications are described next.

Around 1908, Albert Mauritz Atterberg (1846–1916), a Swedish chemist and soil scientist, defined *clay-size fractions* as the percentage by weight of particles smaller than 2 microns in size. He realized the important role of clay particles in a soil and the plasticity thereof. In 1911, he explained the consistency of cohesive soils by defining liquid, plastic, and shrinkage limits. He also defined the plasticity index as the difference between liquid limit and plastic limit (see Atterberg, 1911).

In October 1909, the 17 m (56 ft) high earth dam at Charmes, France, failed. It was built between 1902 and 1906. A French engineer, Jean Fontard (1884–1962), carried out investigations to determine the cause of failure. In that context, he conducted undrained double-shear tests on clay specimens (0.77 m^2 in area and 200 mm thick) under constant vertical stress to determine their shear strength parameters (see Frontard, 1914). The times for failure of these specimens were between 10 to 20 minutes.

Arthur Langley Bell (1874–1956), a civil engineer from England, worked on the design and construction of the outer seawall at Rosyth Dockyard. Based on his work, he developed relationships for lateral pressure and resistance in clay as well as bearing capacity of shallow foundations in clay (see Bell, 1915). He also used shear-box tests to measure the undrained shear strength of undisturbed clay specimens.

Wolmar Fellenius (1876–1957), an engineer from Sweden, developed the stability analysis of undrained saturated clay slopes (that is, $\phi = 0$ condition) with the assumption that the critical surface of sliding is the arc of a circle. These were elaborated upon in his papers published in 1918 and 1926. The paper published in 1926 gave correct numerical solutions for the *stability numbers* of circular slip surfaces passing through the toe of the slope.

Karl Terzaghi (1883–1963) of Austria (Figure 1.5) developed the theory of consolidation for clays as we know it today. The theory was developed when Terzaghi was teaching at the American Robert College in Istanbul, Turkey. His study spanned a five-year period from 1919 to 1924. Five different clay soils were used. The liquid limit of those soils ranged between 36 and 67, and the plasticity index was in the range of 18 to 38. The consolidation theory was published in Terzaghi's celebrated book *Erdbaumechanik* in 1925.

FIGURE 1.5 Karl Terzaghi (1883–1963) (SSPL via Getty Images)

1.7 Geotechnical Engineering after 1927

The publication of *Erdbaumechanik auf Bodenphysikalisher Grundlage* by Karl Terzaghi in 1925 gave birth to a new era in the development of soil mechanics. Karl Terzaghi is known as the father of modern soil mechanics, and rightfully so. Terzaghi was born on October 2, 1883 in Prague, which was then the capital of the Austrian province of Bohemia. In 1904 he graduated from the Technische Hochschule in Graz, Austria, with an undergraduate degree in mechanical engineering. After graduation he served one year in the Austrian army. Following his army service, Terzaghi studied one more year, concentrating on geological subjects. In January 1912, he received the degree of Doctor of Technical Sciences from his alma mater in Graz. In 1916, he accepted a teaching position at the Imperial School of Engineers in Istanbul. After the end of World War I, he accepted a lectureship at the American Robert College in Istanbul (1918–1925). There he began his research work on the behavior of soil and settlement of clay and on the failure due to piping in sand under dams. The publication *Erdbaumechanik* is primarily the result of this research.

In 1925, Terzaghi accepted a visiting lectureship at Massachusetts Institute of Technology, where he worked until 1929. During that time, he became recognized as the leader of the new branch of civil engineering called soil mechanics. In October 1929, he returned to Europe to accept a professorship at the Technical University of Vienna, which soon became the nucleus for civil engineers interested in soil mechanics. In 1939, he returned to the United States to become a professor at Harvard University.

The first conference of the International Society of Soil Mechanics and Foundation Engineering (ISSMFE) was held at Harvard University in 1936 with Karl Terzaghi presiding. The conference was possible due to the conviction and efforts of Professor Arthur Casagrande of Harvard University. About 200 individuals representing 21 countries attended this conference. It was through the inspiration and guidance of Terzaghi over the preceding quarter-century that papers were brought to that conference covering a wide range of topics, such as

- Effective stress
- Shear strength
- Testing with Dutch cone penetrometer
- Consolidation
- Centrifuge testing
- Elastic theory and stress distribution
- Preloading for settlement control
- Swelling clays
- Frost action
- Earthquake and soil liquefaction
- Machine vibration
- Arching theory of earth pressure

For the next quarter-century, Terzaghi was the guiding spirit in the development of soil mechanics and geotechnical engineering throughout the world. To that effect, in 1985, Ralph Peck wrote that "few people during Terzaghi's lifetime would have disagreed that he was not only the guiding spirit in soil mechanics, but that he was the clearing house for research and application throughout the world. Within the next few years he would be engaged on projects on every continent save Australia and Antarctica." Peck continued with, "Hence, even today, one can hardly improve on his contemporary assessments of the state of soil mechanics as expressed in his summary papers and presidential addresses." In 1939, Terzaghi delivered the 45th James Forrest Lecture at the Institution of Civil Engineers, London. His lecture was entitled "Soil Mechanics—A New Chapter in Engineering Science." In it, he proclaimed that most of the foundation failures that occurred were no longer "acts of God."

Following are some highlights in the development of soil mechanics and geotechnical engineering that evolved after the first conference of the ISSMFE in 1936:

- Publication of the book *Theoretical Soil Mechanics* by Karl Terzaghi in 1943 (Wiley, New York)
- Publication of the book *Soil Mechanics in Engineering Practice* by Karl Terzaghi and Ralph Peck in 1948 (Wiley, New York)
- Publication of the book *Fundamentals of Soil Mechanics* by Donald W. Taylor in 1948 (Wiley, New York)
- Start of the publication of *Geotechnique,* the international journal of soil mechanics, in 1948 in England

After a brief interruption for World War II, the second conference of ISSMFE was held in Rotterdam, The Netherlands, in 1948. There were about 600 participants, and seven volumes of proceedings were published. In this conference, A. W. Skempton (1914–2001) of Imperial College, London (Figure 1.6) presented the landmark paper on $\phi = 0$ concept for clays. Following Rotterdam, ISSMFE conferences have been organized about every four years in different parts of the world. The aftermath of the Rotterdam conference saw the growth of regional conferences on geotechnical engineering, such as

- European Regional Conference on Stability of Earth Slopes, Stockholm (1954)
- First Australia–New Zealand Conference on Shear Characteristics of Soils (1952)
- First Pan American Conference, Mexico City (1960)
- Research conference on Shear Strength of Cohesive Soils, Boulder, Colorado, (1960)

Two other important milestones between 1948 and 1960 are (1) the publication of A. W. Skempton's paper on *A* and *B* pore pressure parameters, which made effective

FIGURE 1.6 Sir Alec Skempton (1914–2001), Imperial College, London (Courtesy Judith Niechcial, Petts Wood, Orpington, UK)

stress calculations more practical for various engineering works, and (2) publication of the book entitled *The Measurement of Soil Properties in the Triaxial Text* by A. W. Bishop and B. J. Henkel (Arnold, London) in 1957. Dr. Bishop (1920–1988) was a geotechnical engineer and academic working at Imperial College, London.

By the early 1950s, computer-aided finite difference and finite element solutions were applied to various types of geotechnical engineering problems. When the projects become more sophisticated with complex boundary conditions, it is no longer possible to apply closed-form solutions. Numerical modeling, using a finite element (e.g., Abaqus, Plaxis) or finite difference (e.g., Flac) software, is becoming increasingly popular in the profession. The dominance of numerical modeling in geotechnical engineering will continue in the next few decades due to new challenges and advances in the modeling techniques. Since the early days, the profession of geotechnical engineering has come a long way and has matured. It is now an established branch of civil engineering, and thousands of civil engineers declare geotechnical engineering to be their preferred area of speciality.

In 1997, the ISSMFE was changed to ISSMGE (International Society of Soil Mechanics and Geotechnical Engineering) to reflect its true scope. These international conferences have been instrumental for exchange of information regarding new developments and ongoing research activities in geotechnical engineering. Table 1.2 gives the location and year in which each conference of ISSMFE/ISSMGE was held.

In 1960, Bishop, Alpan, Blight, and Donald provided early guidelines and experimental results for the factors controlling the strength of partially saturated cohesive soils. Since that time advances have been made in the study of the behavior of unsaturated soils as related to strength and compressibility and other factors affecting construction of earth-supported and earth-retaining structures.

ISSMGE has several technical committees, and these committees organize or co-sponsor several conferences around the world. A list of these technical committees (2017–2021) is given in Table 1.3. ISSMGE also conducts International Seminars (formerly known as Touring Lectures), which have proven to be an important activity; these seminars bring together practitioners, contractors, and academics, both on

TABLE 1.2 Details of ISSMFE (1936–1997) and ISSMGE (1997–present) Conferences

Conference	Location	Year
I	Harvard University, Boston, USA	1936
II	Rotterdam, the Netherlands	1948
III	Zurich, Switzerland	1953
IV	London, England	1957
V	Paris, France	1961
VI	Montreal, Canada	1965
VII	Mexico City, Mexico	1969
VIII	Moscow, USSR	1973
IX	Tokyo, Japan	1977
X	Stockholm, Sweden	1981
XI	San Francisco, USA	1985
XII	Rio de Janeiro, Brazil	1989
XIII	New Delhi, India	1994
XIV	Hamburg, Germany	1997
XV	Istanbul, Turkey	2001
XVI	Osaka, Japan	2005
XVII	Alexandria, Egypt	2009
XVIII	Paris, France	2013
XIX	Seoul, Korea	2017
XX	Sydney, Australia	2021 (scheduled)

TABLE 1.3 List of ISSMGE Technical Committees (November, 2017)

Category	Technical committee number	Technical committee name
Fundamentals	TC101	Laboratory Testing
	TC102	In-Situ Testing
	TC103	Numerical Methods in Geomechanics
	TC104	Physical Modeling in Geotechnics
	TC105	Geo-Mechanics from Micro to Macro
	TC106	Unsaturated Soils
	TC107	Lateritic Soils
Applications	TC201	Geotechnical Aspects of Dykes and Levees, and Shore Protection
	TC202	Transportation Geotechnics
	TC203	Earthquake Geotechnical Engineering and Associated Problems
	TC204	Underground Construction in Soft Ground
	TC205	Safety and Serviceability in Geotechnical Design
	TC206	Interactive Geotechnical Design
	TC207	Soil-Structure Interaction and Retaining Walls
	TC208	Slope Stability in Engineering Practice
	TC209	Offshore Geotechnics
	TC210	Embankment Dams
	TC211	Ground Improvement
	TC212	Deep Foundations
	TC213	Scour and Erosion
	TC215	Environmental Geotechnics
	TC216	Frost Geotechnics
	TC217	Land Reclamation
	TC218	Reinforced Fill Structures
Impact on Society	TC301	Preservation of Historic Sites
	TC302	Forensic Geotechnical Engineering
	TC303	Coastal and River Disaster Mitigation and Rehabilitation
	TC304	Engineering Practice of Risk Assessment and Management
	TC305	Geotechnical Infrastructure for Megacities and New Capitals
	TC306	Geo-engineering Education
	TC307	Sustainability in Geotechnical Engineering
	TC308	Energy Geotechnics
	TC309	Machine Learning and Big Data

stage and in the audience, to their own benefit irrespective of the region, size, or wealth of the Member Society, thus fostering a sense of belonging to the ISSMGE.

Soils are heterogeneous materials that can have substantial variability within a few meters. The design parameters for all geotechnical projects have to come from a site investigation exercise that includes field tests, collecting soil samples at various locations and depths, and carrying out laboratory tests on these samples. The laboratory and field tests on soils, as for any other materials, are carried out as per standard methods specified by ASTM International (known as American Society for Testing and Materials before 2001). ASTM standards (www.astm.org) cover a wide range of materials in more than 80 volumes. The test methods for soils, rocks, and aggregates are bundled into the two volumes—04.08 and 04.09.

Geotechnical engineering is a relatively young discipline that has witnessed substantial developments in the past few decades, and it is still growing. These new developments and most cutting-edge research findings are published in peer reviewed international journals before they find their way into textbooks. Some of these geotechnical journals are (in alphabetical order):

- Canadian Geotechnical Journal (NRC Research Press in cooperation with the Canadian Geotechnical Society)
- Geotechnical and Geoenvironmental Engineering (American Society of Civil Engineers)
- Geotechnical and Geological Engineering (Springer, Germany)
- Geotechnical Testing Journal (ASTM International, USA)
- Geotechnique (Institute of Civil Engineers, UK)
- International Journal of Geomechanics (American Society of Civil Engineers)
- International Journal of Geotechnical Engineering (Taylor and Francis, UK)
- Soils and Foundations (Elsevier on behalf of the Japanese Geotechnical Society)

For a thorough literature review on a research topic, these journals and the proceedings of international conferences (e.g., ICSMGE, see Table 1.2) would be very valuable. The references cited in each chapter in this book are listed at the end of the chapter.

1.8 Geosynthetics and Civil Engineering Construction

The early 1970s saw the use of geosynthetics in various civil engineering construction projects. Since then, it has grown very rapidly in practically all countries around the world. Geosynthetic products that are non-biodegradable are made from polymers such as polypropylene, polyester, polyethylene, and polyamide. Major geosynthetic products that are available commercially are classified under categories such as geotextile, geogrid, geomembrane, geonet, and geosynthetic clay liner. The properties of these products are described briefly in Chapter 19. Depending on the product, the major function of geosynthetics may involve one or more of the following: separation, reinforcement, filtration, drainage, and moisture barriers.

As an organized activity, an international conference on the use of fabrics in geotechnical engineering was held in 1977 in Paris, France. This event is now referred to as the First International Conference on Geotextiles. In that conference, J. P. Giroud presented a paper on the Valeros Dam in France in which he coined the words "geotextiles" and "geomembranes." The Second International Conference on Geotextiles was held in Las Vegas, USA, in 1982. Following that conference, the International Geotextile Society (IGS) was formed in November 1983 with Charles Schaerer (Switzerland) as its President. In 1986, J. P. Giroud (Figure 1.7) was elected President of the IGS (1986–1990) by direct vote of the society members. Dr. Giroud is presently the Chairman Emeritus of Geosyntec Consultants (USA) and lives in Paris, France. In September 1994, a name change occurred for the IGS, and it became known as the International Geosynthetics Society.

The IGS has grown substantially and has several international chapters in various countries with a membership of over 3000.

In 1986, Robert M. Koerner (Figure 1.8) authored the first comprehensive book on geosynthetics entitled *Designing with Geosynthetics*. He was an Emeritus Professor of Drexel University and Director Emeritus of the Geosynthetic Institute (USA). Professor Koerner delivered the first Mercer Lecture in 1992 and the first Giroud Lecture in 1998. The Mercer Lecture is named after Frank Brian Mercer of

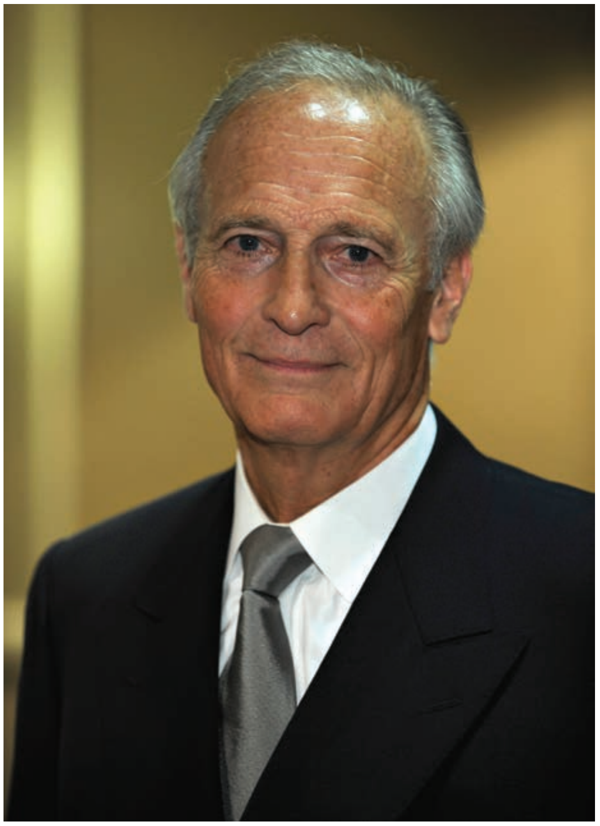

FIGURE 1.7 J. P. Giroud, Geosynthetics and Geotechnical Engineering Consultant, J. P. Giroud, Inc. (Courtesy of J. P. Giroud, Paris, France)

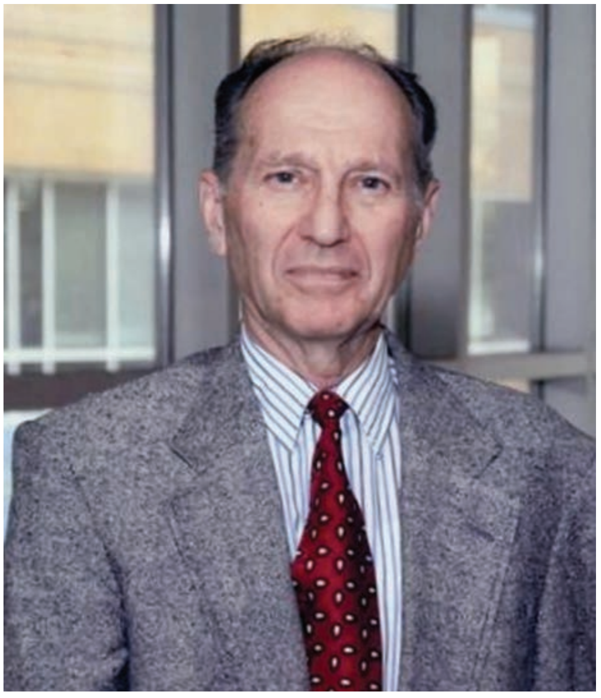

FIGURE 1.8 Robert M. Koerner, Director Emeritus of the Geosynthetic Institute and Professor Emeritus of Drexel University (1933–2019) (Courtesy of Robert M. Koerner, Emeritus Professor, Drexel University)

the UK. In 1956, he invented the Netlon process in which he made a net by molding heated plastic into mesh structures. This led to the development and production of extruded geogrids in the late 1970s and early 1980s.

Geosynthetics are probably the most important civil engineering products developed and used in the twentieth century. They are an indispensable part of many construction projects throughout the world.

1.9 End of an Era

In Section 1.7, a brief outline of the contributions made to modern soil mechanics by pioneers such as Karl Terzaghi, Arthur Casagrande, Donald W. Taylor, Alec W. Skempton, and Ralph B. Peck was presented. The last of the early giants of the profession, Ralph B. Peck, passed away on February 18, 2008, at the age of 95.

Professor Ralph B. Peck (Figure 1.9) was born in Winnipeg, Canada to American parents Orwin K. and Ethel H. Peck on June 23, 1912. He received B.S. and Ph.D. degrees in 1934 and 1937, respectively, from Rensselaer Polytechnic Institute, Troy, New York. During the period from 1938 to 1939, he took courses from Arthur Casagrande at Harvard University in a new subject called "soil mechanics." From 1939 to 1943, Dr. Peck worked as an assistant to Karl Terzaghi, the "father" of modern soil mechanics, on the Chicago Subway Project. In 1943, he joined the University of Illinois at Champaign–Urbana and was a professor of foundation engineering from 1948 until he retired in 1974. After retirement, he was active in consulting, which

FIGURE 1.9 Ralph B. Peck (1912–2008) (Photo courtesy of Ralph B. Peck)

included major geotechnical projects in 44 states in the United States and 28 other countries on five continents. Some examples of his major consulting projects include

- Rapid transit systems in Chicago, San Francisco, and Washington, D.C.
- Alaskan pipeline system
- James Bay Project in Quebec, Canada
- Heathrow Express Rail Project (UK)
- Dead Sea dikes

His last project was the Rion-Antirion Bridge in Greece. On March 13, 2008, *The Times* of the United Kingdom wrote, "Ralph B. Peck was an American civil engineer who invented a controversial construction technique that would be used on some of the modern engineering wonders of the world, including the Channel Tunnel. Known as 'the godfather of soil mechanics,' he was directly responsible for a succession of celebrated tunneling and earth dam projects that pushed the boundaries of what was believed to be possible."

Dr. Peck authored more than 250 highly distinguished technical publications. He was the president of the ISSMGE from 1969 to 1973. In 1974, he received the National Medal of Science from President Gerald R. Ford. Professor Peck was a teacher, mentor, friend, and counselor to generations of geotechnical engineers in every country in the world. The 16th ISSMGE Conference in Osaka, Japan (2005) was the last major conference of its type that he would attend.

This is truly the end of an era.

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Chapter 2

Origin of Soil and Grain Size

Learning Objectives Upon completion of Chapter 2, you will be able to:

2.1 Recognize that soils are formed by the weathering of rock and that the physical properties of soils are dictated by the minerals that constitute the soil particles.

2.2 Discuss the formation of various types of rock and identify their origins from the solidification of molten magma in the mantle of the earth as well as the formation of soil by the mechanical and chemical weathering of rock.

2.3 Identify rock-forming minerals and rock structures.

2.4 Estimate the distribution of particle sizes in a given soil mass.

2.5 Recognize the composition of clay minerals and how they provide the plastic properties of a soil mass.

2.6 Identify how specific gravity is used in calculations in soil mechanics.

2.7 Use mechanical analysis to find the particle-size distribution of soil.

2.8 Apply the particle-size distribution curve to determine the parameters of a given soil (i.e., effective size, uniformity coefficient, coefficient of gradation).

2.9 Identify the shape of various particles in soil mass.

2.1 Introduction

In general, soils are formed by weathering of rocks. The physical properties of soil are dictated primarily by the minerals that constitute the soil particles and, hence, the rock from which it is derived. In this chapter, we will discuss the following:

- The formation of various types of rocks, the origins of which are the solidification of molten magma in the mantle of the earth
- Formation of soil by mechanical and chemical weathering of rock
- Determination of the distribution of particle sizes in a given soil mass
- Composition of the clay minerals. The clay minerals provide the plastic properties of a soil mass
- The shape of various particles in a soil mass

2.2 Rock Cycle and the Origin of Soil

The mineral grains that form the solid phase of a soil aggregate are the product of rock weathering. The size of the individual grains varies over a wide range. Many of the physical properties of soil are dictated by the size, shape, and chemical composition of the grains. To better understand these factors, one must be familiar with the basic types of rock that form the earth's crust, the rock-forming minerals, and the weathering process.

On the basis of their mode of origin, rocks can be divided into three basic types: *igneous, sedimentary*, and *metamorphic*. Figure 2.1 shows a diagram of the formation cycle of different types of rock and the processes associated with them. This is called the *rock cycle*. Brief discussions of each element of the rock cycle follow.

IGNEOUS ROCK

Igneous rocks are the result of the *fissure eruption* or *volcanic eruption* of a large, deep-seated reservoir of molten rock. They are also referred to as magma chambers. Most of those known are close to the surface—between 1 km and 10 km down. Below

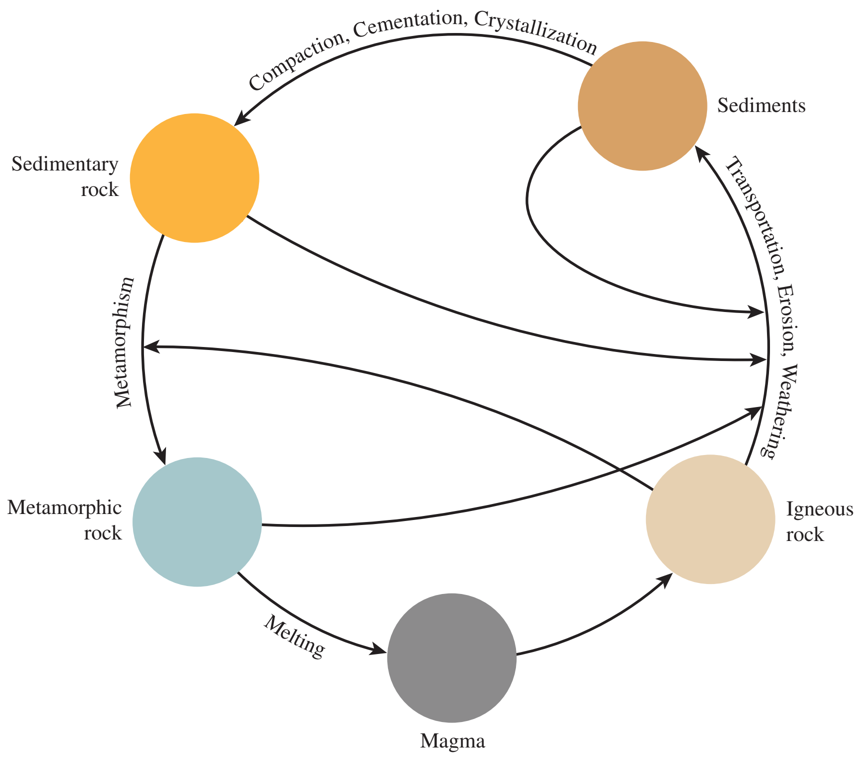


FIGURE 2.1 Rock cycle

the ground's surface, the molten rock is called *magma.* When the magma is extruded to the surface, it is called *lava*. Magma cools down slowly on the surface after ejection. When exposed to the air on the surface, the crystallization of lava consisting of nonferromagnesian at about 1100°C and having a thickness of 1 m may take about 12 days. It may take up to three years if the thickness is about 10 m (Leet and Judson, 1971). Lava can be classified into three major categories, i.e., acidic lava, intermediate lava, and basic lava. Acidic lava has about 70% or more silicia, and basic lava has generally less than 50% silicia. The viscosity of lava increases when it becomes acidic.

After ejection by either *fissure eruption* or *volcanic eruption,* some of the molten lava cools on the surface of the earth. Sometimes magma ceases its mobility below the earth's surface and cools to form intrusive igneous rocks that are called *plutons.* The plutons can be classified into two major categories: *tabular plutons* and *massive plutons.* A tabular pluton will have a smaller thickness compared to its other dimensions. Intrusive rocks formed in the past may be exposed at the surface as a result of the continuous process of erosion of the materials that once covered them.

The types of igneous rock formed by the cooling of magma depend on factors such as the composition of the magma and the rate of cooling associated with it. After conducting several laboratory tests, Bowen (1922) was able to explain the relation of the rate of magma cooling to the formation of different types of rock. This explanation—known as *Bowen's reaction principle*—describes the sequence by which new minerals are formed as magma cools. The mineral crystals grow larger and some of them settle. The crystals that remain suspended in the liquid react with the remaining melt to form a new mineral at a lower temperature. This process continues until the entire body of melt is solidified. Bowen classified these reactions into two groups: (1) *discontinuous ferromagnesian reaction series*, in which the minerals formed are different in their chemical composition and crystalline structure, and (2) *continuous plagioclase feldspar reaction series*, in which the minerals formed have different chemical compositions with similar crystalline structures. Figure 2.2 shows Bowen's reaction series. The chemical compositions of the minerals are given in Table 2.1. Figure 2.3 is a scanning electron micrograph of a fractured surface of

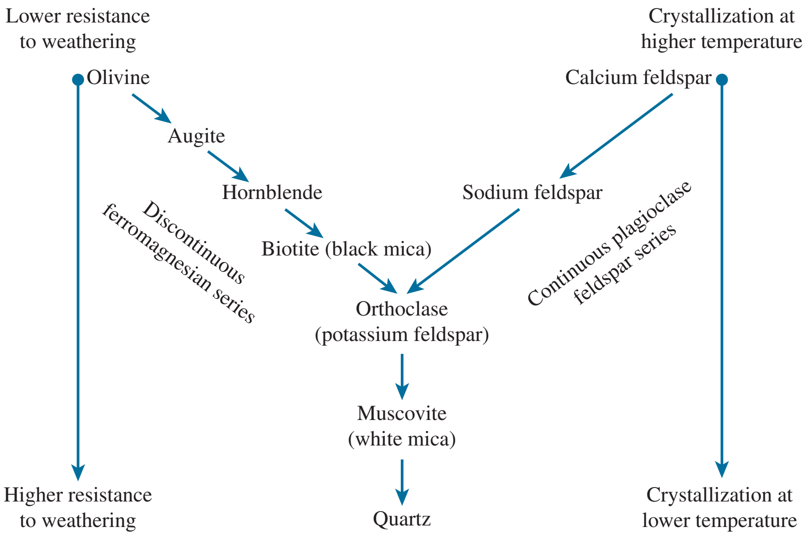


FIGURE 2.2 Bowen's reaction series

TABLE 2.1 Composition of Minerals Shown in Bowen's Reaction Series

Mineral	Composition
Olivine	$(Mg, Fe)_2SiO_4$
Augite	$Ca, Na(Mg, Fe, Al)(Al, Si_2O_6)$
Hornblende	Complex ferromagnesian silicate of Ca, Na, Mg, Ti, and Al
Biotite (black mica)	$K(Mg, Fe)_3AlSi_3O_{10}(OH)_2$
Plagioclase: calcium feldspar	$Ca(Al_2Si_2O_8)$
Plagioclase: sodium feldspar	$Na(AlSi_3O_8)$
Orthoclase (potassium feldspar)	$K(AlSi_3O_8)$
Muscovite (white mica)	$KAl_3Si_3O_{10}(OH)_2$
Quartz	SiO_2

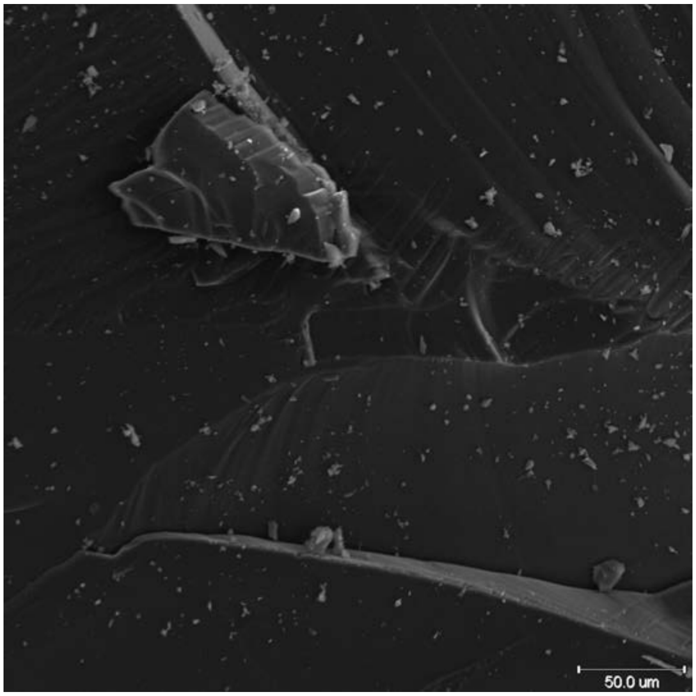


FIGURE 2.3 Scanning electron micrograph of fractured surface of quartz showing glass-like fractures with no discrete planar surface (Courtesy of David J. White, Iowa State University, Ames, Iowa)

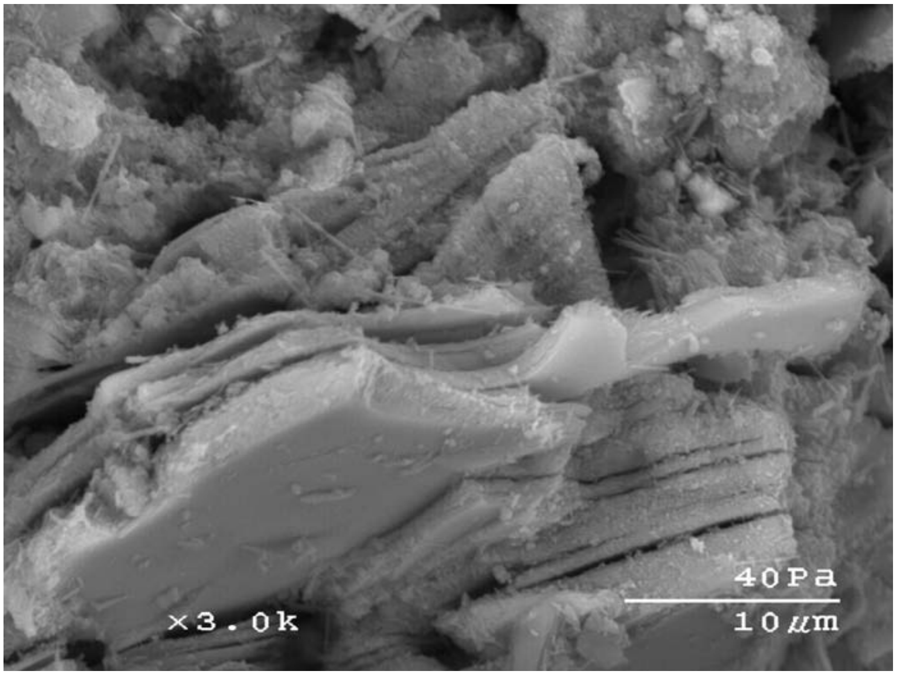


FIGURE 2.4 Scanning electron micrograph showing basal cleavage of individual mica grains (Courtesy of David J. White, Iowa State University, Ames, Iowa)

quartz showing glass-like fractures with no discrete planar cleavage. Figure 2.4 is a scanning electron micrograph that shows basal cleavage of individual mica grains.

Thus, depending on the proportions of minerals available, different types of igneous rock are formed. Depending on the mineral content, the rocks may be light colored, transitional, or dark colored. The light-colored rocks are sometimes referred to *sialic rocks*, and the dark-colored rocks are called *simatic rocks*. For example, *granite* is a sialic rock, *andesite* is a transitional rock, and *basalt* is a simatic rock. Table 2.2 shows the general composition of some igneous rocks.

In Table 2.2, the modes of occurrence of various rocks are classified as *intrusive* or *extrusive*. The intrusive rocks are those formed by the cooling of lava beneath the surface. Since the cooling process is very slow, intrusive rocks have very large crystals that can be seen by the naked eye. These are called rocks with *granular texture.* When the lava cools on the surface (extrusive rocks), the process is fast. Grains are fine; thus they are difficult to identify by the naked eye. Thus, the igneous rocks that result have *aphanitic texture*. If the magma is suddenly ejected and cools very rapidly, the resulting rock may have a glassy texture.

WEATHERING

Weathering is the process of breaking down rocks by *mechanical* and *chemical processes* into smaller pieces. Mechanical weathering may be caused by the expansion and contraction of rocks from the continuous gain and loss of heat, which results in

TABLE 2.2 Composition of Some Igneous Rocks

Name of rock	Mode of occurrence	Texture	Abundant minerals	Less abundant minerals
Granite	Intrusive	Coarse	Quartz, sodium feldspar, potassium feldspar	Biotite, muscovite, hornblende
Rhyolite	Extrusive	Fine		
Gabbro	Intrusive	Coarse	Plagioclase, pyroxines, olivine	Hornblende, biotite, magnetite
Basalt	Extrusive	Fine		
Diorite	Intrusive	Coarse	Plagioclase, hornblende	Biotite, pyroxenes (quartz usually absent)
Andesite	Extrusive	Fine		
Syenite	Intrusive	Coarse	Potassium feldspar	Sodium feldspar, biotite, hornblende
Trachyte	Extrusive	Fine		
Peridotite	Intrusive	Coarse	Olivine, pyroxenes	Oxides of iron

ultimate disintegration. Frequently, water seeps into the pores and existing cracks in rocks. As the temperature drops, the water freezes and expands. The pressure exerted by ice because of volume expansion is strong enough to break down even large rocks. Other physical agents that help disintegrate rocks are glacier ice, wind, the running water of streams and rivers, and ocean waves. It is important to realize that, in mechanical weathering, large rocks are broken down into smaller pieces without any change in the chemical composition. Figure 2.5 shows several examples

(text continues on page 25)

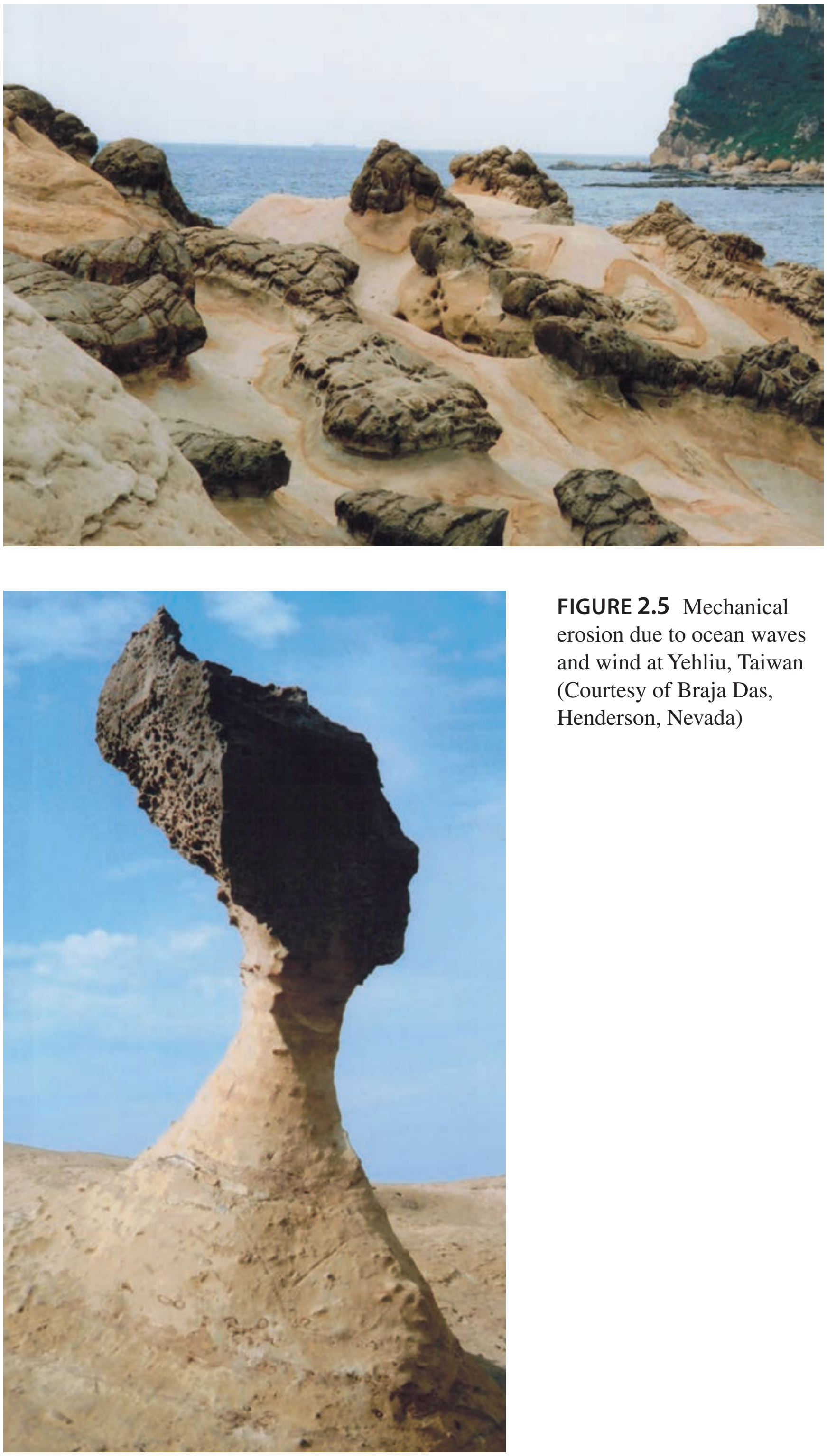


FIGURE 2.5 Mechanical erosion due to ocean waves and wind at Yehliu, Taiwan (Courtesy of Braja Das, Henderson, Nevada)

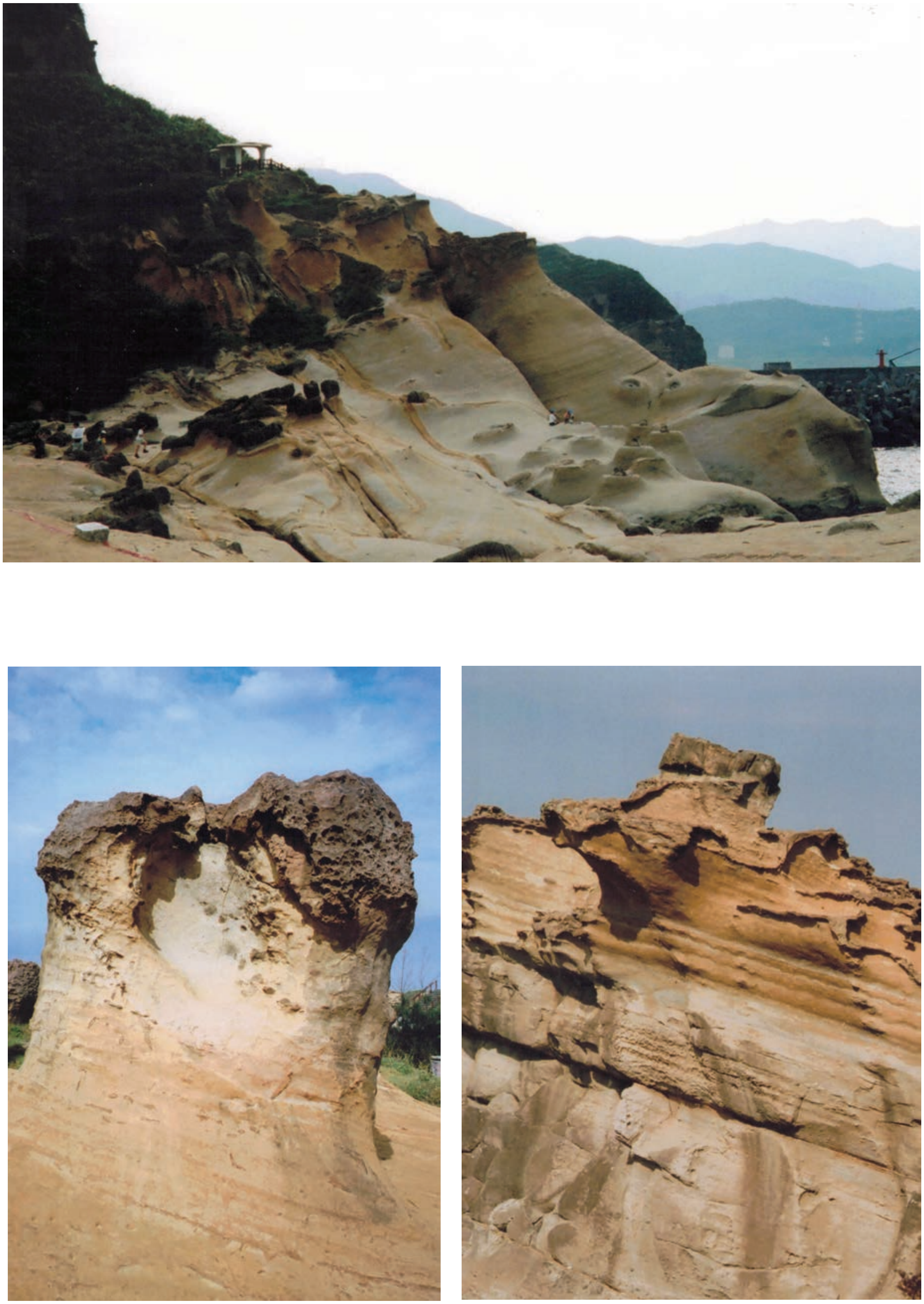
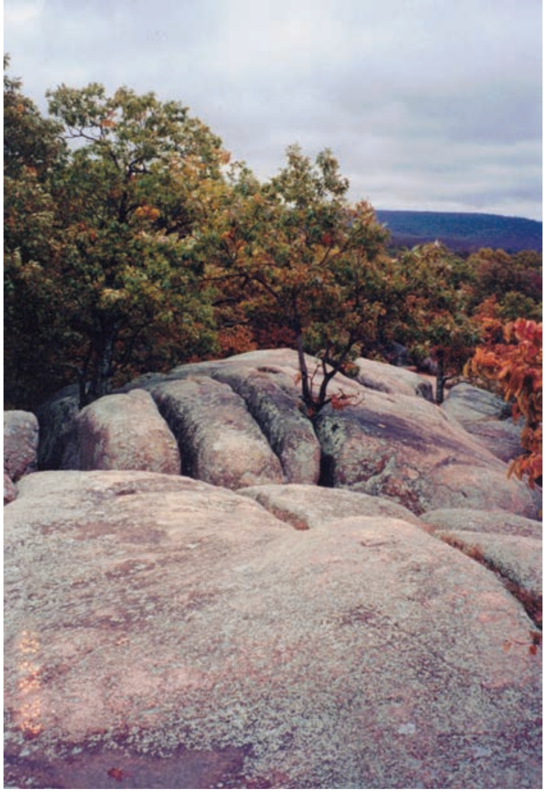
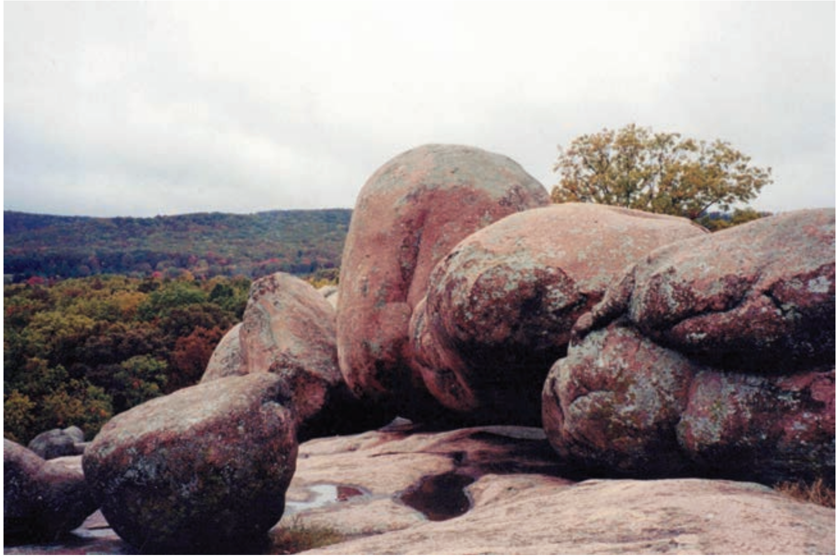


FIGURE 2.5 (*Continued*)

of mechanical erosion due to ocean waves and wind at Yehliu in Taiwan. This area is located at a long and narrow sea cape at the northwest side of Keelung, about 15 kilometers between the north coast of Chin Shan and Wanli. Figure 2.6 shows another example of mechanical weathering in the Precambrian granite outcrop in the Elephant Rocks State Park in southeast Missouri. The freezing and thawing action of water on the surface fractures the rock and creates large cracks and a drainage pattern in the rock (Figure 2.6a). Over a period of time, unweathered rock is transformed into large boulders (Figure 2.6b). Figure 2.7 shows another photograph of *in situ* weathering of granite.



(a)



(b)

FIGURE 2.6 Mechanical weathering of granite: (a) development of large cracks due to freezing and thawing followed by a drainage pattern, (b) transformation of unweathered rock into large boulders (Courtesy of Janice Das, Henderson, Nevada)

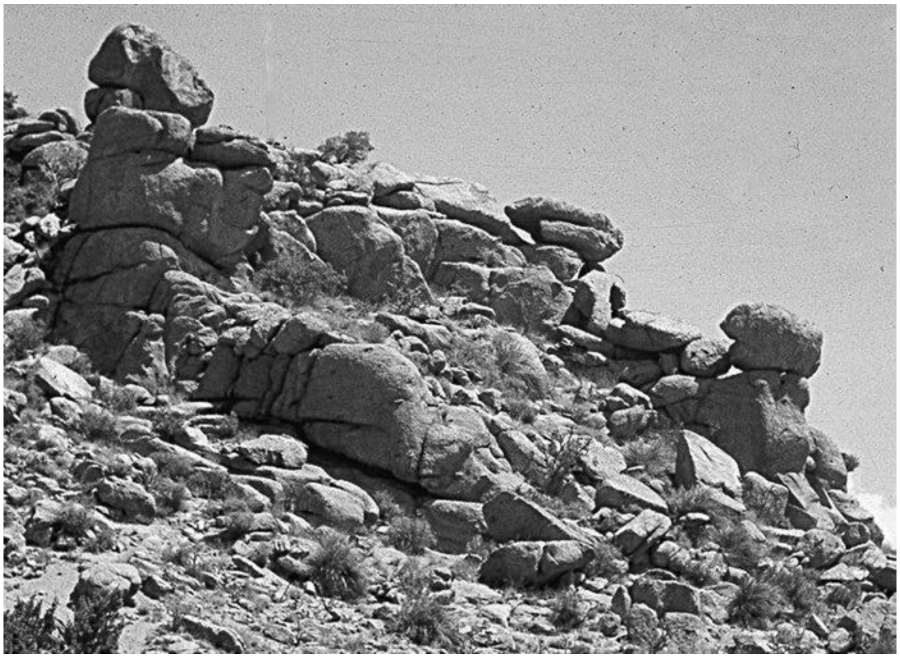


FIGURE 2.7 *In situ* mechanical weathering of granite (Courtesy of Richard L. Handy, Iowa State University, Ames, Iowa)

In chemical weathering, the original rock minerals are transformed into new minerals by chemical reaction. Water and carbon dioxide from the atmosphere form carbonic acid, which reacts with the existing rock minerals to form new minerals and soluble salts. Soluble salts present in the groundwater and organic acids formed from decayed organic matter also cause chemical weathering. An example of the chemical weathering of orthoclase to form clay minerals, silica, and soluble potassium carbonate follows:

$$H_2O + CO_2 \rightarrow \underset{\text{Carbonic acid}}{H_2CO_3} \rightarrow H^+ + (HCO_3)^-$$

$$\underset{\text{Orthoclase}}{2K(AlSi_3O_8)} + 2H^+ + H_2O \rightarrow 2K^+ + \underset{\text{Silica}}{4SiO_2} + \underset{\substack{\text{Kaolinite}\\\text{(Clay mineral)}}}{Al_2Si_2O_5(OH)_4}$$

Most of the potassium ions released are carried away in solution as potassium carbonate is taken up by plants.

The chemical weathering of plagioclase feldspars is similar to that of orthoclase in that it produces clay minerals, silica, and different soluble salts. Ferromagnesian minerals also form the decomposition products of clay minerals, silica, and soluble salts. Additionally, the iron and magnesium in ferromagnesian minerals result in other products such as hematite and limonite. Quartz is highly resistant to weathering and only slightly soluble in water. Figure 2.2 shows the susceptibility of rock-forming minerals to weathering. The minerals formed at higher temperatures in Bowen's reaction series are less resistant to weathering than those formed at lower temperatures.

The weathering process is not limited to igneous rocks. As shown in the rock cycle (Figure 2.1), sedimentary and metamorphic rocks also weather in a similar manner.

Thus, from the preceding brief discussion, we can see how the weathering process changes solid rock masses into smaller fragments of various sizes that can range from large boulders to very small clay particles. Uncemented aggregates of these small grains in various proportions form different types of soil. The clay minerals, which are a product of chemical weathering of feldspars, ferromagnesians, and micas, give the plastic property to soils. There are three important clay minerals: (1) *kaolinite*, (2) *illite*, and (3) *montmorillonite*. (We discuss these clay minerals later in this chapter.)

TRANSPORTATION OF WEATHERING PRODUCTS

The products of weathering may stay in the same place or may be moved to other places by ice, water, wind, and gravity.

The soils formed by the weathered products at their place of origin are called *residual soils*. An important characteristic of residual soil is the gradation of particle size. Fine-grained soil is found at the surface, and the grain size increases with depth. At greater depths, angular rock fragments may also be found.

The transported soils may be classified into several groups, depending on their mode of transportation and deposition:

1. *Glacial soils*—formed by transportation and deposition of glaciers
2. *Alluvial soils*—transported by running water and deposited along streams
3. *Lacustrine soils*—formed by deposition in quiet lakes
4. *Marine soils*—formed by deposition in the seas
5. *Aeolian soils*—transported and deposited by wind
6. *Colluvial soils*—formed by movement of soil from its original place by gravity, such as during landslides

SEDIMENTARY ROCK

The deposits of gravel, sand, silt, and clay formed by weathering may become compacted by overburden pressure and cemented by agents like iron oxide, calcite, dolomite, and quartz. Cementing agents are generally carried in solution by groundwater. They fill the spaces between particles and form sedimentary rock. Rocks formed in this way are called *detrital sedimentary* rocks.

All detrital rocks have a *clastic* texture. The following are some examples of detrital rocks with clastic texture.

Particle size	Sedimentary rock
Granular or larger (grain size 2 mm–4 mm or larger)	Conglomerate
Sand	Sandstone
Silt and clay	Mudstone and shale

In the case of conglomerates, if the particles are more angular, the rock is called *breccia*. In sandstone, the particle sizes may vary between $\frac{1}{16}$ mm and 2 mm. When the grains in sandstone are practically all quartz, the rock is referred to as *orthoquartzite*. In mudstone and shale, the size of the particles are generally less than $\frac{1}{16}$ mm. Mudstone has a blocky aspect, whereas, in the case of shale, the rock is split into platy slabs.

Sedimentary rock also can be formed by chemical processes. Rocks of this type are classified as *chemical sedimentary rock*. These rocks can have *clastic* or *nonclastic texture*. The following are some examples of chemical sedimentary rock.

Composition	Rock
Calcite ($CaCO_3$)	Limestone
Halite (NaCl)	Rock salt
Dolomite [$CaMg(CO_3)$]	Dolomite
Gypsum ($CaSO_4 \cdot 2H_2O$)	Gypsum

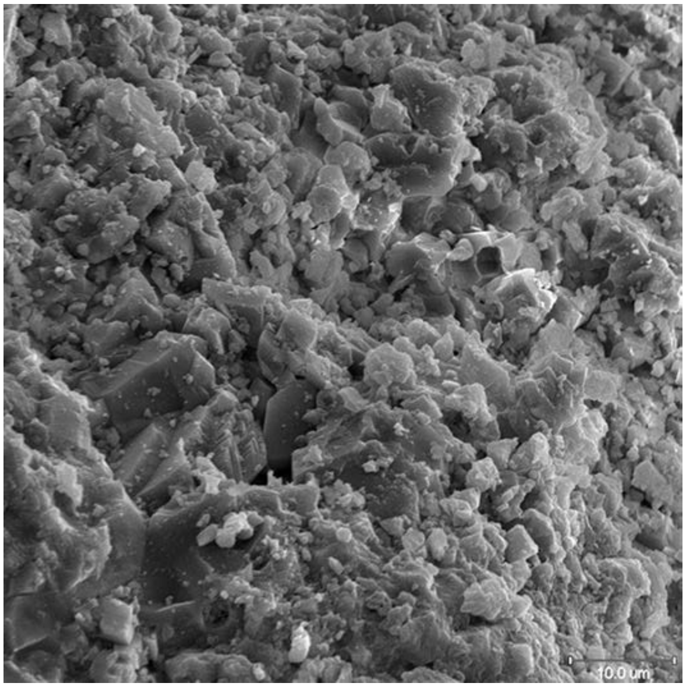


FIGURE 2.8 Scanning electron micrograph of the fractured surface of limestone (Courtesy of David J. White, Iowa State University, Ames, Iowa)

Limestone is formed mostly of calcium carbonate deposited either by organisms or by an inorganic process. Most limestones have a clastic texture; however, nonclastic textures also are found commonly. Figure 2.8 shows the scanning electron micrograph of a fractured surface of limestone. Individual grains of calcite show rhombohedral cleavage. Chalk is a sedimentary rock made in part from biochemically derived calcite, which are skeletal fragments of microscopic plants and animals. Dolomite is formed either by chemical deposition of mixed carbonates or by the reaction of magnesium in water with limestone. Gypsum and anhydrite result from the precipitation of soluble $CaSO_4$ due to evaporation of ocean water. They belong to a class of rocks generally referred to as *evaporites*. Rock salt (NaCl) is another example of an evaporite that originates from the salt deposits of seawater.

Sedimentary rock may undergo weathering to form sediments or may be subjected to the process of *metamorphism* to become metamorphic rock.

METAMORPHIC ROCK

Metamorphism is the process of changing the composition and texture of rocks (without melting) by heat and pressure. During metamorphism, new minerals are formed, and mineral grains are sheared to give a foliated texture to metamorphic rock. Gneiss is a metamorphic rock derived from high-grade regional metamorphism of igneous rocks, such as granite, gabbro, and diorite. Low-grade metamorphism of shales and mudstones results in slate. The clay minerals in the shale become chlorite and mica by heat; hence, slate is composed primarily of mica flakes and chlorite. Phyllite is a metamorphic rock, which is derived from slate with further metamorphism being subjected to heat greater than 250 to 300°C. Schist is a type of metamorphic rock derived from several igneous, sedimentary, and low-grade metamorphic rocks with a well-foliated texture and visible flakes of platy and micaceous minerals. Metamorphic rock generally contains large quantities of quartz and feldspar as well.

Marble is formed from calcite and dolomite by recrystallization. The mineral grains in marble are larger than those present in the original rock. Green marbles are colored by hornblendes, serpentine, or talc. Black marbles contain bituminous material, and brown marbles contain iron oxide and limonite. Quartzite is a metamorphic rock formed from quartz-rich sandstones. Silica enters into the void spaces between the quartz and sand grains and acts as a cementing agent. Quartzite is one of the hardest rocks. Under extreme heat and pressure, metamorphic rocks may melt to form magma, and the cycle is repeated.

2.3 Rock-Forming Minerals, Rock, and Rock Structures

In the preceding section, we were introduced to the process of the formation of igneous rocks from rock-forming minerals, weathering and formation of sedimentary rocks, and metamorphism and formation of metamorphic rocks. Figure 2.9 shows

(a) (b) (c) (d)

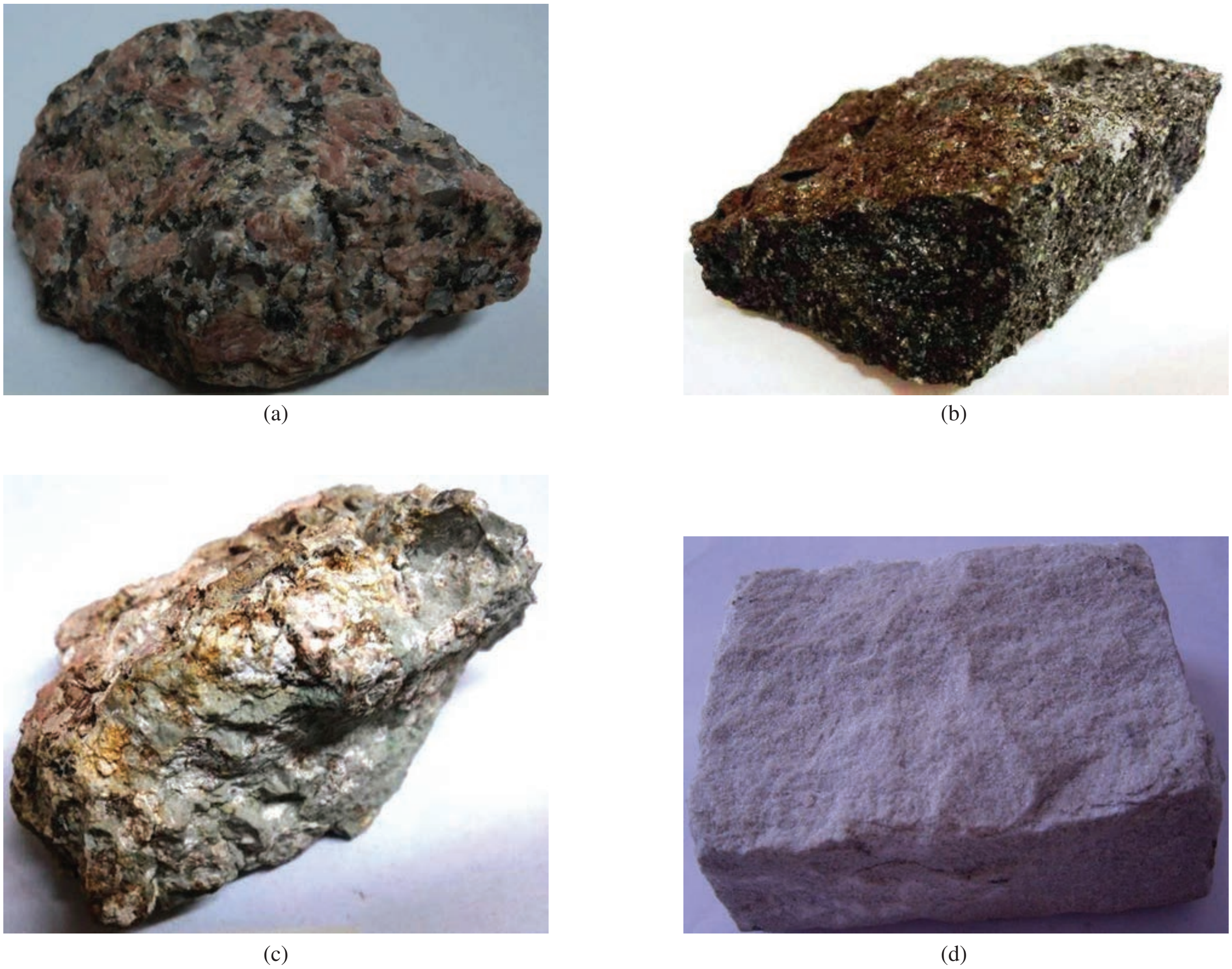
FIGURE 2.9 Some typical rock-forming minerals: (a) quartz; (b) orthoclase; (c) plagioclase; (d) muscovite (Courtesy of Dr. Sanjay K. Shukla, Edith Cowan University, Perth, Australia)

FIGURE 2.9 (*Continued*) Some typical rock-forming minerals: (e) biotite; (f) andradite garnet; (g) calcite; (h) dolomite; (i) chlorite (Courtesy of Dr. Sanjay K. Shukla, Edith Cowan University, Perth, Australia)

some common rock-forming minerals, such as quartz, orthoclase, plagioclase, muscovite, biotite, andradite, garnet, calcite, dolomite, and chlorite. Some common types of rocks that geotechnical engineers may encounter in the field, such as granite, basalt, rhyolite, sandstone, limestone, conglomerate, marble, slate, and schist, are shown in Figure 2.10. Figure 2.10j shows an example of *folded schist* from the James Cook University Rock Garden on its campus in Townsville, Australia. Shear stresses and metamorphism involving high temperature and pressure caused the layers to buckle and fold. Figure 2.11 shows some structures constructed on rock.

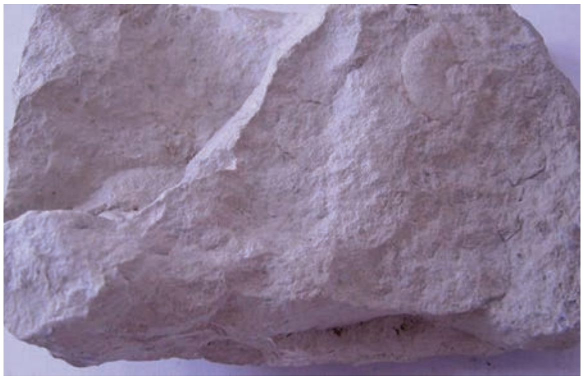
There are large structures built several centuries ago around the world with, or in/on rock, that are still intact and undergoing partial weathering. The Parthenon (Figure 2.11a), built on the Acropolis in Athens, Greece, in the second half of the 5th century B.C., is made of marble and built on a limestone hill underlain by phyllite, a fine-grained metamorphic rock containing large quantities of mica and resembling slate or schist.

Figure 2.11b shows the Corinth Canal in Greece. The Corinth Canal crosses the Isthmus of Corinth, a narrow strip of land that connects Peloponnesus to the mainland of Greece, thus linking the Saronic Gulf in the Aegean Sea (eastern part of Greece) with the Gulf of Corinth (a deep inlet of the Ionian Sea in western Greece). The canal was completed in 1893. The canal consists of a single channel

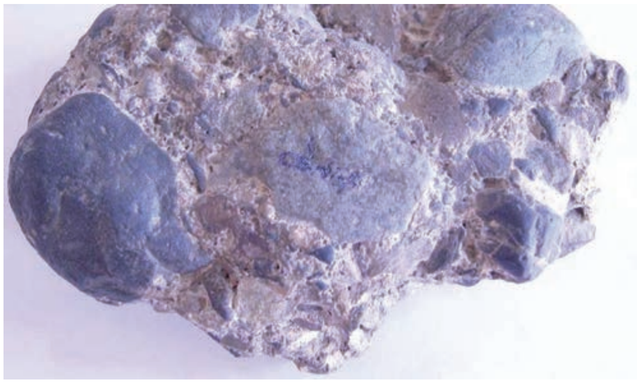


(a) (b) (c) (d)

FIGURE 2.10 Some typical rocks: (a) granite; (b) basalt; (c) rhyolite; (d) sandstone (Figures (a) through (d) Courtesy of Dr. Sanjay K. Shukla, Edith Cowan University, Perth, Australia)



(e)



(f)

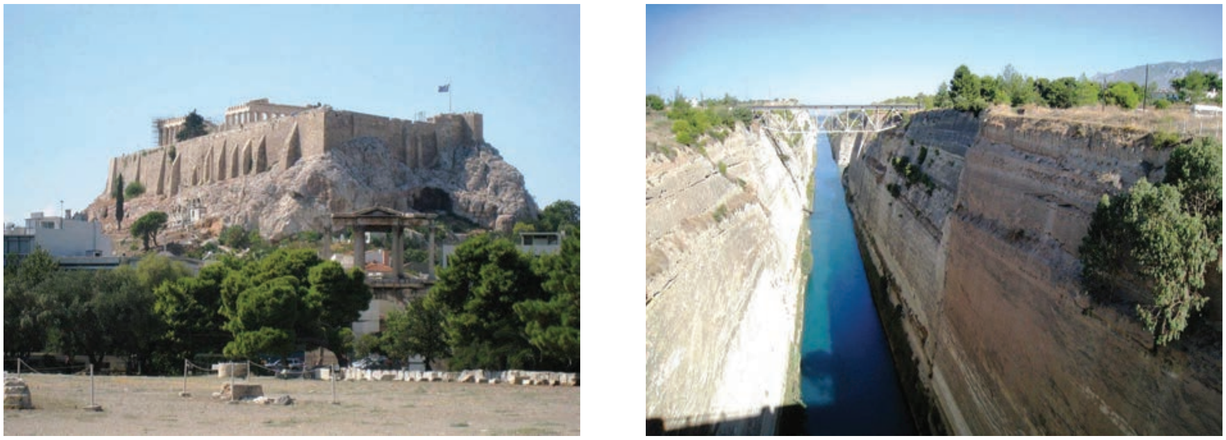
(g)

(h)

(i)

(j)

FIGURE 2.10 (*Continued*) Some typical rocks: (e) limestone; (f) conglomerate; (g) marble; (h) slate; (i) mica schist; (j) folded schist (Figures (e) through (i) Courtesy of Dr. Sanjay K. Shukla, Edith Cowan University, Perth, Australia; (j) Courtesy of Dr. Nagaratnam Sivakugan, James Cook University, Townsville, Australia)



(a) (b)

FIGURE 2.11 (a) The Parthenon on the Acropolis in Athens, Greece; (b) Corinth Canal in Greece (Courtesy of Dr. Nagaratnam Sivakugan, James Cook University, Townsville, Australia)

8 m deep excavated at sea level (thus requiring no locks) measuring 6346 m long and is 24.6 m wide at the top and 21.3 m wide at the bottom. The canal slopes have an inclination of 3V:1H to 5V:1H. The central part of the canal, where the excavated slopes are highest, consists of Plio-Pleistocene marls with thin interlayers of marly sands and marly limestone. The marls in the upper part of the slopes are whitish yellow to light brown, while those in the middle and lower parts are yellow gray to bluish gray.

2.4 Soil-Particle Size

As discussed in the preceding section, the sizes of particles that make up soil vary over a wide range. Soils generally are called *gravel, sand, silt,* or *clay,* depending on the predominant size of particles within the soil. To describe soils by their particle size, several organizations have developed particle-size classifications. Table 2.3 shows the particle-size classifications developed by the Massachusetts Institute of Technology, the US Department of Agriculture, the American Association of State Highway and Transportation Officials, and the US Army Corps of Engineers and US Bureau of Reclamation. In this table, the MIT system is presented for illustration

TABLE 2.3 Particle-Size Classifications

	Grain size (mm)			
Name of organization	**Gravel**	**Sand**	**Silt**	**Clay**
Massachusetts Institute of Technology (MIT)	>2	2 to 0.06	0.06 to 0.002	<0.002
US Department of Agriculture (USDA)	>2	2 to 0.05	0.05 to 0.002	<0.002
American Association of State Highway and Transportation Officials (AASHTO)	76.2 to 2	2 to 0.075	0.075 to 0.002	<0.002
Unified Soil Classification System (US Army Corps of Engineers, US Bureau of Reclamation, and American Society for Testing and Materials)	76.2 to 4.75	4.75 to 0.075	Fines (i.e., silts and clays) <0.075	

Note: Sieve openings of 4.75 mm are found on a US No. 4 sieve; 2 mm openings on a US No. 10 sieve; 0.075 mm openings on a US No. 200 sieve. See Table 2.5.