FIFTH EDITION

FUNDAMENTALS OF GEOTECHNICAL ENGINEERING

BRAJA M. DAS | NAGARATNAM SIVAKUGAN

Fundamentals of Geotechnical Engineering

Fifth Edition

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Braja M. Das
Dean Emeritus, California State University
Sacramento, California, USA

Nagaratnam Sivakugan
Associate Professor, College of Science, Technology & Engineering
James Cook University, Queensland, Australia

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Braja M. Das and Nagaratnam Sivakugan

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To Janice, Rohini, Joe,
Valerie and Elizabeth

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Preface

Principles of Foundation Engineering and *Principles of Geotechnical Engineering* were originally published with 1984 and 1985 copyrights, respectively. These texts were well received by instructors, students, and practitioners alike. Depending on the needs of the users, the texts were revised and are presently in their eighth editions. These texts have also been translated in several languages.

Toward the latter part of 1998, there were several requests to prepare a single volume that was concise in nature but combined the essential components of *Principles of Foundation Engineering* and *Principles of Geotechnical Engineering*. In response to those requests, the first edition of *Fundamentals of Geotechnical Engineering* was published in 2000. This text includes the fundamental concepts of soil mechanics as well as foundation engineering, including bearing capacity and settlement of shallow foundations (spread footings and mats), retaining walls, braced cuts, piles, and drilled shafts.

New to This Edition

This fifth edition has been revised and prepared based on comments received from several reviewers and users without changing the philosophy on which the text was originally prepared. Professor Nagaratnam Sivakugan of James Cook University, Australia, has joined as a co-author of this edition. As in the previous editions, SI units are used throughout the text. This edition consists of 20 chapters and an appendix. The major changes from the fourth edition include the following:

- About forty additional photographs have been added.
- A number of additional example problems and homework problems have been added in each chapter.
- Each chapter has some critical thinking problem(s) added to the homework problem set.

- An interactive digital version of this text is now available. Please see the MindTap description on page xix.
- In Chapter 2 on "Soil Deposits—Origin, Grain-Size, and Shape" a discussion has been added for the U.S. sieve size designations. Details for the British standard sieves and the Australian standard sieves have also been added.
- In Chapter 3 on "Weight-Volume Relationships and Plasticity," a table for various unit-weight relationships has been added.
- Chapter 4 on "Soil Classification" has a new section on visual identification of soils.
- In Chapter 5 on "Soil Compaction," some recently published correlations for maximum dry unit weight and optimum moisture content has been added. Also added in this chapter is a brief description on various ground improvement methods.
- Chapter 9 on "Consolidation" now has a new section on the effects of initial excess pore water pressure distribution on U–T_v relationships. Also added to this chapter is a discussion on the construction time correction of consolidation settlement.
- A number of recently published correlations for effective stress friction angle (ϕ') and cohesion (c') for cohesive soils has been added to Chapter 10 on "Shear Strength of Soils." Also included in this chapter are several correlations for the undrained shear strength of remolded clays with liquidity index.
- Chapter 12 on "Subsurface Exploration" now has a section on field instrumentation.
- In Chapter 13 on "Slope Stability," an analysis to evaluate the factor of safety of clay slopes with the undrained cohesion increasing with depth has been added. This chapter now also has a discussion on the mass procedure for stability analysis of homogeneous clay slopes ($\phi = 0$) with earthquake forces.
- Chapter 15 has been renamed as "Retaining Walls, Braced Cuts, and Sheet Pile Walls." Analyses of cantilever sheet pile walls and anchored sheet pile walls have been added to this chapter.
- The bearing capacity of strip foundation under eccentrically inclined load has been discussed in greater detail in Chapter 16 on "Shallow Foundations—Bearing Capacity."
- An improved method for elastic settlement calculation of shallow foundations on granular soil taking into consideration the variation of soil stiffness with stress level has been added to Chapter 17 on "Settlement of Shallow Foundations."
- A new chapter (Chapter 20) on "Load and Resistance Factor Design (LRFD)" has been added to the text.

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- Tim Anderson, Product Director
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Thanks are also due to Janice Das for her continuous help in the development of the original text and its subsequent four editions.

It is also fitting to thank Rose P. Kernan of RPK Editorial Services. She has been instrumental in shaping the style and overseeing the production of this edition of *Fundamentals of Geotechnical Engineering* as well as all previous editions.

Braja M. Das
Henderson, Nevada, USA

Nagaratnam Sivakugan
Townsville, Queensland, Australia


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CHAPTER 1

Geotechnical Engineering—From the Beginning

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 deformations. **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. **Soil 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.

This chapter is a historical overview of geotechnical engineering and its challenges, with some mention of the great contributions by two eminent scholars, Dr. Karl Terzaghi (1883–1963) and Dr. Ralph Peck (1912–2008), and others.

1.2 Geotechnical Engineering Prior to the 18th Century

The record of a person's first use of soil as a construction material is lost in antiquity. 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 Ho (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.), many dikes 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). The 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 (Figure 1.2). Construction of the tower began in 1173 A.D.

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.

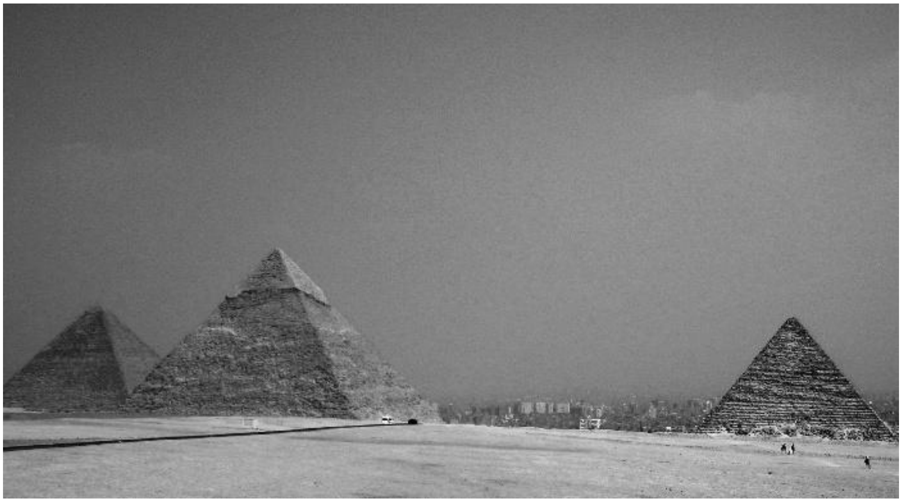

FIG. 1.1 A view of the pyramids at Giza (Courtesy of Braja M. Das, Henderson, Nevada)

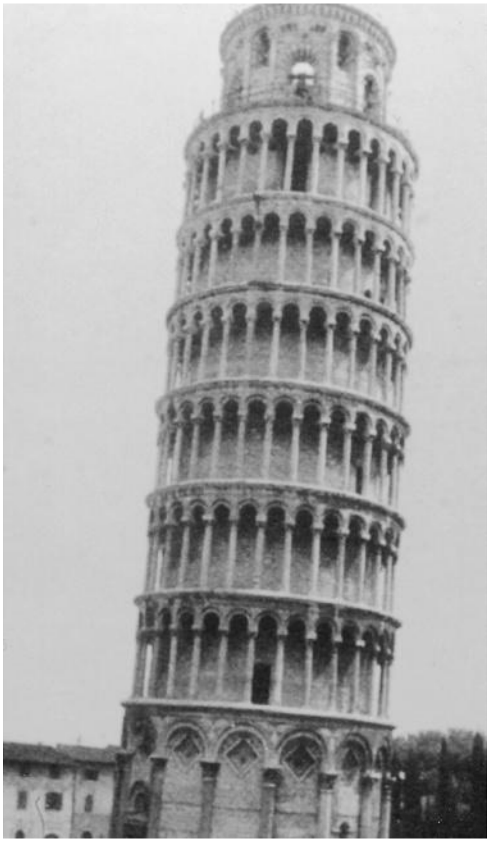

FIG. 1.2 Leaning Tower of Pisa, Italy (Courtesy of Braja M. Das, Henderson, Nevada)

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. 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 exists at a depth of about 11 m below the ground surface, compression of which caused the tower to tilt. It became more than 5 m out of plumb with the 54 m height (about 5.5 degree tilt). The tower was closed in 1990 because it was feared that it would either fall over or collapse. It has recently 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. Figure 1.3 is an example of a similar problem. The towers shown in Figure 1.3 are located in

FIG. 1.3 Tilting of Garisenda Tower (left) and Asinelli Tower (right) in Bologna, Italy (Courtesy of Braja M. Das, Henderson, Nevada)

Bologna, Italy, and they were built in the 12th century. The tower on the left is the Garisenda Tower. It is 48 m high 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 behavior 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 engineering, the time span extending from 1700 to 1927 can be divided into four major periods (Skempton, 1985):

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

Brief descriptions of some significant developments during each of these four periods are discussed 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 slopes of **clean dry sand** and **ordinary earth** were 31° and 45°, respectively. Also, the unit weights of clean dry sand and ordinary earth were recommended to be 18.1 kN/m^3 and 13.4 kN/m^3, respectively. No test results on clay were reported. In 1729, Bernard Forest de Belidor (1694–1761) 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.

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

The first laboratory model test results on a 76 mm high 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 by 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 Claire Marie Riche de Brony (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 Fredéric 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 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, semi-infinite, elastic, and isotropic medium. In 1887, Osborne Reynolds (1842–1912) demonstrated the phenomenon of dilatency 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-sized 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 high earth dam at Charmes, France, failed. It was built between 1902–1906. 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.

FIG. 1.4 Karl Terzaghi (1883–1963) (SSPL via Getty Images)

Karl Terzaghi (1883–1963) of Austria (Figure 1.4) developed the theory of consolidation for clays as we know 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 to 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.

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 (Figure 1.4) 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 soils and settlement of clays 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 (Figure 1.5) 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

FIG. 1.5 Ralph B. Peck (Photo courtesy of Ralph B. Peck)

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); and
- 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 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 (l) the publication of A. W. Skempton's paper on A and B pore pressure parameters which made effective 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.

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 increasingly becoming 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 cosponsor several conferences around the world. A list of these technical

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

Conference	Location	Year
I	Harvard University, Boston, United States of America	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, Russia	1973
IX	Tokyo, Japan	1977
X	Stockholm, Sweden	1981
XI	San Francisco, United States of America	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, South Korea	2017 (scheduled)

committees (2010–2013) is given in Table 1.3. ISSMGE also conducts International Seminars (formerly known as Touring Lectures), and they have proved to be an important activity, bringing together practitioners, contractors, and academics, both on stage and in the audience, to their own benefit irrespective of the region, size, or wealth of the Member Society, thus fostering the sense of belonging to the International Society for Soil Mechanics and Geotechnical Engineering.

Soils are heterogeneous materials, which can have substantial variability within a few meters. The design parameters for all geotechnical projects have to come from a site investigation exercise which includes field tests, collection of 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 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* (Maney Publishing, 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

Table 1.3 List of ISSMGE Technical Committees (November, 2013)

Category	Technical Number Committee	Technical Committee Name
Fundamentals	TC101	Laboratory Stress Strength Testing of Geomaterials
	TC102	Ground Property Characterization from In-Situ Tests
	TC103	Numerical Methods in Geomechanics
	TC104	Physical Modelling in Geotechnics
	TC105	Geo-Mechanics from Micro to Macro
	TC106	Unsaturated Soils
Applications	TC201	Geotechnical Aspects of Dykes and Levees, Shore Protection and Land Reclamation
	TC202	Transportation Geotechnics
	TC203	Earthquake Geotechnical Engineering and Associated Problems
	TC204	Underground Construction in Soft Ground
	TC205	Safety and Survivability in Geotechnical Engineering
	TC206	Interactive Geotechnical Design
	TC207	Soil-Structure Interaction and Retaining Walls
	TC208	Slope Stability in Engineering Practice
	TC209	Offshore Geotechnics
	TC210	Dams and Embankments
	TC211	Ground Improvement
	TC212	Deep Foundations
	TC213	Scour and Erosion
	TC214	Foundation Engineering for Difficult Soft Soil Conditions
	TC215	Environmental Geotechnics
	TC216	Frost Geotechnics
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

very valuable. The references cited in each chapter in this book are listed at the end of the chapter.

1.8 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, 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 was born in Winnipeg, Canada to American parents Orwin K. and Ethel H. Peck on June 23, 1912. He received BS and PhD 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 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 (U.K.)
- 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 attended.

Figure 1.6 shows a photograph of Dr. Peck during a visit to the Karl Terzaghi Park in Boğaziçi University (formerly American Robert College) during the XV ISSMGE Conference in Istanbul.

This is truly the end of an era.

FIG. 1.6 Dr. Ralph Peck in Karl Terzaghi Park in Boğaziçi University, Istanbul, Turkey, during the 2001 ISSMGE conference (Courtesy of Braja M. Das, Henderson, Nevada)

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Courtesy of Janice Das, Henderson, Nevada

CHAPTER 2

Soil Deposits—Origin, Grain-Size, and Shape

2.1 Introduction

During the planning, design and construction of foundations, embankments, and earth retaining structures, engineers find it helpful to know the origin of the soil deposit over which the proposed structure is to be built since each soil deposit has its own unique physical attributes. Most of the soils that cover the surface of the earth 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 is it derived.

In this chapter, we will discuss the following.

- The processes by which the three major rock types are formed
- Weathering of rocks and the different processes that contribute to the formation of different types of soil deposits.
- Grain size distribution of soils and grain shapes
- Clay mineralogy

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.

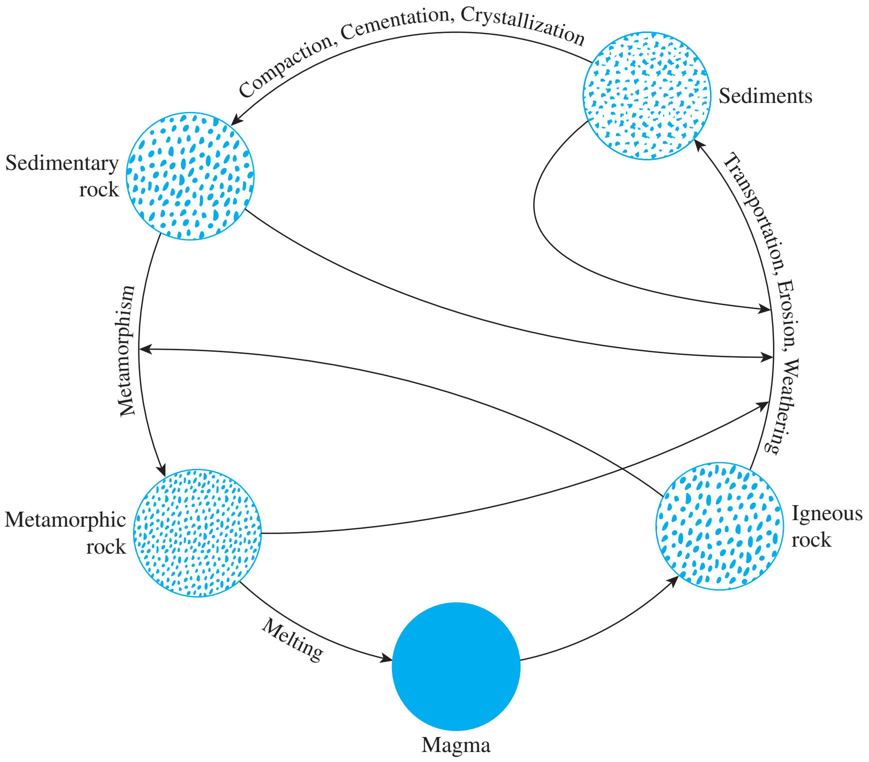

FIG. 2.1 Rock cycle

On the basis of their mode of origin, rocks can be divided into three basic types: **igneous**, **sedimentary**, and **metamorphic**. The earth's crust consists of approximately 65% igneous rocks, 27% metamorphic rocks, and only 8% sedimentary rocks. 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

It gets very hot inside the earth, where the temperature can exceed 1000°C. Molten rock beneath the surface is called **magma**, and when it comes above the surface through volcanic eruption, it is known as **lava**. Magma and lava are literally the same in composition. Magma/lava consists of elements such as Si, Fe, Na, K, and so forth. When it cools below the surface, the cooling is rather a slow process, taking thousands of years, and the grains are coarse that can be seen by the naked eye and hence easier to identify. Such rocks are known as **intrusive** or **plutonic**. Some examples of intrusive rocks are granite, diorite, gabbro, and peridotite. When the lava cools on the surface, the process is rather fast, taking from a few days to weeks, not giving much time for the grains to grow. Here, the grains fine and are difficult to identify by the naked eye. These rocks are known as **extrusive** or **volcanic**. Some examples of extrusive

FIG. 2.2 Granite intruded by black basalt dyke (Courtesy of N. Sivakugan, James Cook University, Australia)

rocks are rhyolite, andesite, basalt, and komatite. Figure 2.2 shows a granite rock that was intruded by black basalt dyke. The granite appears to be grainy, which is not the case with the basalt. 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 2.3 shows Bowen's reaction series. The chemical compositions of the minerals are given in Table 2.1.

Thus, depending on the proportions of minerals available, different types of igneous rock are formed. Granite, gabbro, and basalt are some of the common types of igneous rock generally encountered in the field. Table 2.2 shows the general composition of some igneous rocks.

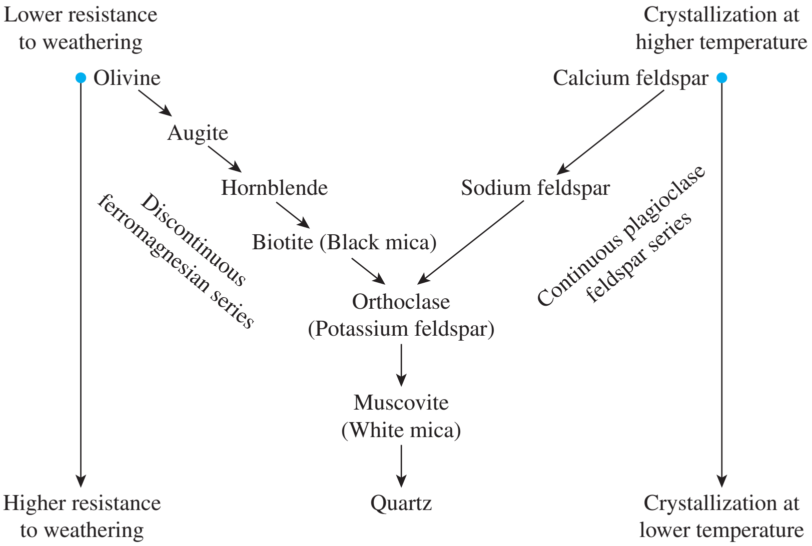

FIG. 2.3 Bowen's reaction series

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 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

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	$Ca(Al_2Si_2O_8)$
	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

Table 2.2 Composition of Some Igneous Rocks

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

composition. Figure 2.4 shows an example 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.

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 and are taken up by plants.

FIG. 2.4 Mechanical erosion due to ocean waves and wind at Yehliu, Taiwan (Courtesy of Braja M. Das, Henderson, Nevada)

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 2.3 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**—transported and deposited by gravity

Sedimentary Rock

While sedimentary rocks make up only about 8% of the earth's crust, their presence on the surface of the earth is substantial. 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 1/16 mm and 2 mm. When the grains in sandstone are practically all quartz, the rock is referred to as *ortho-quartzite*. In mudstone and shale, the size of the particles are generally less than 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
Dolomite [$CaMg(CO_3)$]	Dolomite
Gypsum ($CaSO_4 \cdot 2H_2O$)	Gypsum
Halite (NaCl)	Rock salt

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. 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 hornblends, 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 Soil Deposits—General

We have discussed briefly the weathering process of rocks and the formation of soil in the preceding section. After weathering, the soil formed can stay in place (residual soil) or be transported by natural agents such as glaciers, running water, streams, and air. In addition to transported and residual soils, there are **peats** and **organic soils** which are derived from the decomposition of organic materials.

A general overview of various types of soils described above is given in Sections 2.4 through 2.10.

2.4 Residual Soil

Residual soils are found in areas where the rate of weathering is more than the rate at which the weathered materials are carried away by transporting agents. The rate of weathering is higher in warm and humid regions compared to cooler and drier regions and, depending on the climatic conditions, the effect of weathering may vary widely.

Residual soil deposits are common in the tropics. The nature of a residual soil deposit will generally depend on the parent rock. When hard rocks, such as granite and gneiss, undergo weathering, most of the materials are likely to remain in place. These soil deposits generally have a top layer of clayey or silty clay material, below which are silty or sandy soil layers. These layers in turn, are generally underlain by a partially weathered rock, and then sound bedrock. The depth of the sound bedrock may vary widely, even within a distance of a few meters.

In contrast to hard rocks, there are some chemical rocks, such as limestone, that are chiefly made up of calcite ($CaCO_3$) mineral. Chalk and dolomite have large concentrations of dolomite minerals [$Ca\,Mg(CO_3)_2$]. These rocks have large amounts of soluble materials, some of which are removed by groundwater, leaving behind the insoluble fraction of the rock. Residual soils that derive from chemical rocks do not possess a gradual transition zone to the bedrock. The residual soils derived from the weathering of limestone-like rocks are mostly red in color. Although uniform in kind, the depth of weathering may vary greatly. The residual soils immediately above the bedrock may be normally consolidated. Large foundations with heavy loads may be susceptible to large consolidation settlements on these soils.

2.5 Gravity-Transported Soil

Residual soils on a steep natural slope can move slowly downward, and this is usually referred to as **creep**. When the downward soil movement is sudden and rapid, it is called a **landslide**. The soil deposits formed by landslides are **colluvium**. **Mud flows** are one type of gravity-transported soil. In this case, highly saturated, loose sandy residual soils, on relatively flat slopes, move downward like a viscous liquid and come to rest in a more dense condition. The soil deposits derived from past mud flows are highly heterogeneous in composition.

2.6 Alluvial Deposits

Alluvial soil deposits derive from the action of streams and rivers and can be divided into two major categories: (1) **braided-stream deposits**, and (2) **meander belt deposit**, deposits caused by the meandering belt of streams.

Deposits from Braided Streams

Braided streams are high-gradient, rapidly flowing streams that are highly erosive and carry large amounts of sediment. Because of the high bed load, a minor change in the velocity of flow will cause sediments to deposit. By this process, these streams may build up a complex tangle of converging and diverging channels, separated by sandbars and islands.

The deposits formed from braided streams are highly irregular in stratification and have a wide range of grain sizes. Figure 2.5 shows a cross section of such a deposit. These deposits share several characteristics:

1. The grain sizes usually range from gravel to silt. Clay-sized particles are generally *not* found in deposits from braided streams.
2. Although grain size varies widely, the soil in a given pocket or lens is rather uniform.
3. At any given depth, the void ratio and unit weight may vary over a wide range within a lateral distance of only a few meters.

Meander Belt Deposits

The term *meander* is derived from the Greek work *maiandros*, after the Maiandros (now Menderes) River in Asia, famous for its winding course. Mature streams in a valley curve back and forth. The valley floor in which a river meanders is referred to as the **meander belt**. In a meandering river, the soil from the bank is continually eroded from the points where it is concave in shape and is deposited at points where the bank is convex in shape, as shown in Figure 2.6. These deposits are called **point bar deposits**, and they usually consist of sand and silt-sized

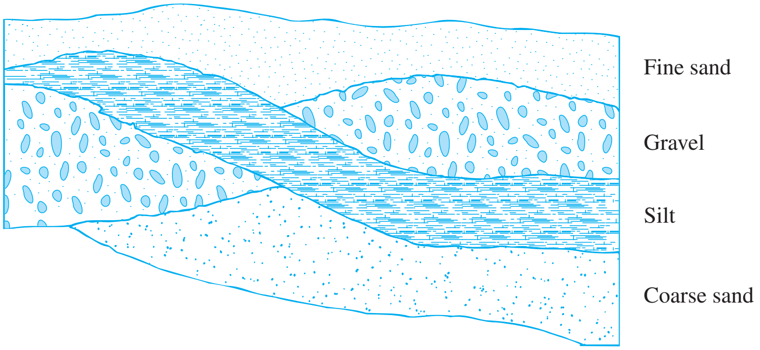

FIG. 2.5 Cross section of a braided-stream deposit

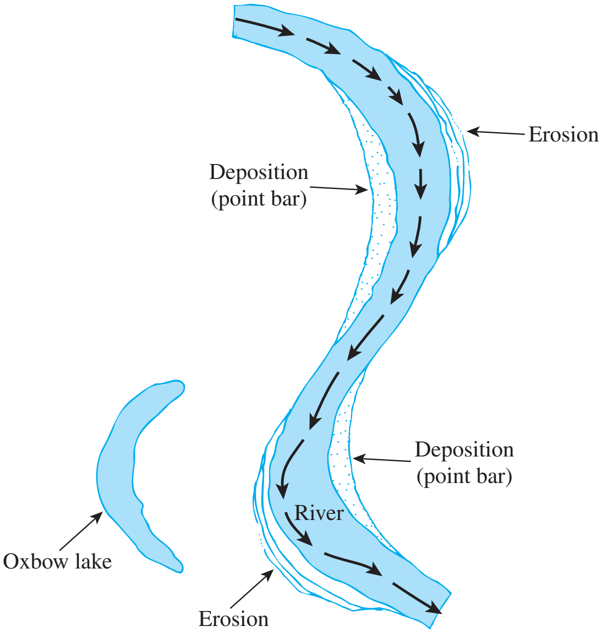

FIG. 2.6 Formation of point bar deposits and Oxbow lake in a meandering stream

particles. Sometimes, during the process of erosion and deposition, the river abandons a meander and cuts a shorter path. The abandoned meander, when filled with water, is called an **oxbow lake**. (See Figure 2.6.)

During floods, rivers overflow low-lying areas. The sand and silt-size grains carried by the river are deposited along the banks to form ridges known as **natural levees** (Figure 2.7). Finer soil particles consisting of silts and clays are

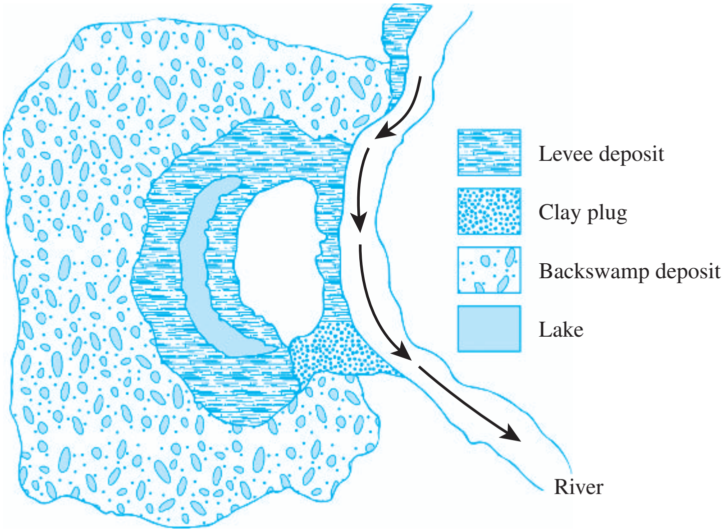

FIG. 2.7 Levee and backswamp deposit

carried by the water farther onto the floodplains. These particles settle at different rates to form **backswamp deposits** (Figure 2.7), often highly plastic clays.

2.7 Lacustrine Deposits

Water from rivers and springs flows into lakes. In arid regions, streams carry large amounts of suspended solids. Where the stream enters the lake, soil grains are deposited in the area forming a delta. Some coarser grains and the finer grains; that is, silt and clay, that are carried into the lake are deposited onto the lake bottom in alternate layers of with coarse and fine grains. The deltas formed in humid regions usually have finer grained soil deposits compared to those in arid regions.

2.8 Glacial Deposits

During the Pleistocene Ice Age, glaciers covered large areas of the earth. The glaciers advanced and retreated with time. During their advance, the glaciers carried large amounts of sand, silt, clay, gravel, and boulders. **Drift** is a general term usually applied to the deposits laid down by glaciers. Unstratified deposits laid down by melting glaciers are referred to as **till**. The physical characteristics of till may vary from glacier to glacier.

The landforms that developed from the deposits of till are called **moraines**. A *terminal moraine* (Figure 2.8) is a ridge of till that marks the maximum limit of a glacier's advance. *Recessional moraines* are ridges of till developed behind the terminal moraine at varying distances apart. They are the result of temporary stabilization of the glacier during the recessional period. The till deposited by the glacier between the moraines is referred to as a *ground moraine* (Figure 2.8). Ground moraines constitute large areas of the central United States and are called **till plains**.

The sand, silt, and gravel that are carried by the melting water from the front of a glacier are called **outwash**. In a pattern similar to that of braided-stream

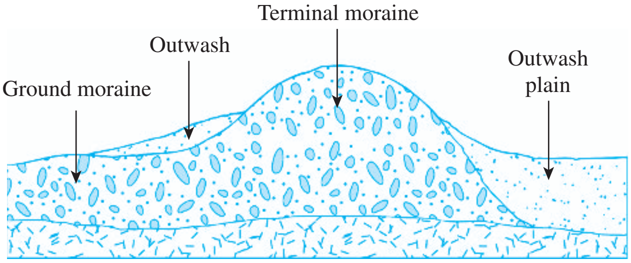

FIG. 2.8 Terminal moraine, ground moraine, and outwash plain

deposits, the melted water deposits the outwash, forming *outwash plains* (Figure 2.8), also called **glaciofluvial deposits**. The range of grain sizes present in a given till varies greatly.

2.9 Aeolian Soil Deposits

Wind is also a major transporting agent leading to the formation of soil deposits. When large areas of sand lie exposed, wind can blow the sand away and redeposit it elsewhere. Deposits of windblown sand generally take the shape of **dunes** (Figure 2.9). Figure 2.10 shows some sand dunes in the Sahara desert in Egypt. As dunes are formed, the sand is blown over the crest by the wind. Beyond the crest, the sand grains roll down the slope. The process tends to form a **compact**

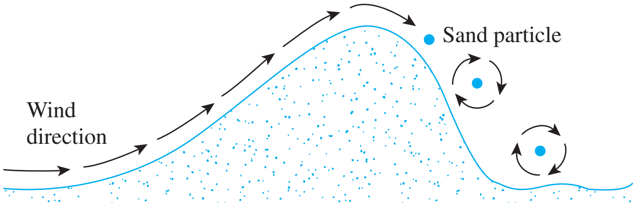

FIG. 2.9 Sand dune

FIG. 2.10 Sand dunes in the Sahara Desert in Egypt (Courtesy of Braja M. Das, Henderson, Nevada)

sand deposit on the *windward side*, and a rather **loose deposit** on the *leeward side*, of the dune. Following are some of the typical properties of **dune sand**:

1. The grain-size distribution of the sand at any particular location is surprisingly uniform. This uniformity can be attributed to the sorting action of the wind.
2. The general grain size decreases with distance from the source, because the wind carries the small particles farther than the large ones.
3. The relative density of sand deposited on the windward side of dunes may be as high as 50 to 65%, decreasing to about 0 to 15% on the leeward side.

Loess is an aeolian deposit consisting of silt and silt-sized grains. The grain-size distribution of loess is rather uniform. The cohesion of loess is generally derived from a clay coating over the silt-sized grains, which contributes to a stable soil structure in an unsaturated state. The cohesion may also be the result of the precipitation of chemicals leached by rainwater. Loess is a **collapsing** soil, because when the soil becomes saturated, it loses its binding strength between grains. Special precautions need to be taken for the construction of foundations over loessial deposits.

Volcanic ash (with grain sizes between 0.25 to 4 mm), and volcanic dust (with grain sizes less than 0.25 mm), may be classified as wind-transported soil. Volcanic ash is a lightweight sand or sandy gravel. Decomposition of volcanic ash results in highly plastic and compressible clays.

2.10 Organic Soil

Organic soils are usually found in low-lying areas where the water table is near or above the ground surface. The presence of a high water table helps in the growth of aquatic plants that, when decomposed, form organic soil. This type of soil deposit is usually encountered in coastal areas and in glaciated regions. Organic soils show the following characteristics:

1. Their natural moisture content may range from 200 to 300%.
2. They are highly compressible.
3. Laboratory tests have shown that, under loads, a large amount of settlement is derived from secondary consolidation.

2.11 Soil-Grain Size

Irrespective of the origin of soil, the sizes of grains, in general, that make up soil vary over a wide range. Soils are generally called **gravel**, **sand**, **silt**, or **clay**, depending on the predominant size of grains within the soil. To describe soils by their grain size, several organizations have developed **soil-separate-size limits**. Table 2.3 and Figure 2.11 show the soil-separate-size limits 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 purposes only, because it plays an important role in the

Table 2.3 Soil-Separate-Size Limits

	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
U.S. 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 (U.S. Army Corps of Engineers; U.S Bureau of Reclamation; American Society for Testing and Materials)	76.2 to 4.75	4.75 to 0.075	Fines (i.e., silts and clays) <0.075	

history of the development of soil-separate-size limits. Presently, however, the Unified System is almost universally accepted. The Unified Soil Classification System (USCS) has now been adopted by the American Society for Testing and Materials.

Gravels are pieces of rocks with occasional grains of quartz, feldspar, and other minerals.

Sand grains are made of mostly quartz and feldspar. Other mineral grains may also be present at times.

Silts are the microscopic soil fractions that consist of very fine quartz grains and some flake-shaped grains that are fragments of micaceous minerals.

Clays are mostly flake-shaped microscopic and submicroscopic grains of mica, clay minerals, and other minerals. As shown in Table 2.3 and Figure 2.11, clays are generally defined as grains smaller than 0.002 mm. In some cases, grains between 0.002 and 0.005 mm in size are also referred to as clay. Grains are classified as *clay* on the basis of their size; they may not necessarily contain clay minerals. Clays are defined as those grains "which develop plasticity when mixed with a limited amount of water" (Grim, 1953). (Plasticity is the puttylike property of clays when they contain a certain

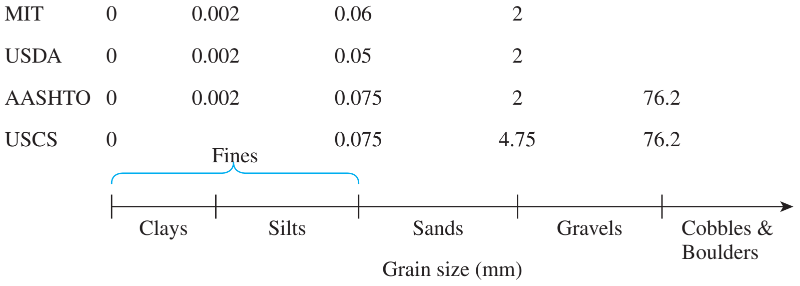

FIG. 2.11 Soil-separate-size limits

amount of water.) Non-clay soils can contain grains of quartz, feldspar, or mica that are small enough to be within the clay size classification. Hence, it is appropriate for soil grains smaller than 2 μm, or 5 μm (Note: 1 $\mu\text{m} = 10^{-6}$ m) as defined under different systems, to be called clay-sized grains rather than clay. Clay grains are mostly of colloidal size range (<1 μm), and 2 μm appears to be the upper limit.

2.12 Clay Minerals

Clay minerals are complex aluminum silicates composed of one of two basic units: (1) **silica tetrahedron** and (2) **alumina octahedron**. Each tetrahedron unit consists of four oxygen atoms surrounding a silicon atom (Figure 2.12a). The combination of tetrahedral silica units gives a **silica sheet** (Figure 2.12b). Three oxygen atoms at the base of each tetrahedron are shared by neighboring tetrahedra. The octahedral units consist of six hydroxyls surrounding an aluminum atom (Figure 2.12c), and the combination of the octahedral aluminum hydroxyl units gives an **octahedral sheet**. (This is also called a **gibbsite sheet**; Figure 2.12d.) Sometimes magnesium replaces the aluminum atoms in the octahedral units; in that case, the octahedral sheet is called a **brucite sheet**.

In a silica sheet, each silicon atom with a positive valence of four, is linked to four oxygen atoms, with a total negative valence of eight. But each oxygen atom at the base of the tetrahedron is linked to two silicon atoms. This means that the top oxygen atom of each tetrahedral unit has a negative valence charge of one to be counterbalanced. When the silica sheet is stacked over the octahedral sheet, as shown in Figure 2.12e, these oxygen atoms replace the hydroxyls to satisfy their valence bonds.

Kaolinite consists of repeating layers of elemental silica-gibbsite sheets, as shown in Figure 2.13a. Each layer is about 7.2 Å (Å $= 10^{-10}$ m) thick. The layers are held together by hydrogen bonding. Kaolinite occurs as platelets, each with a lateral dimension of 1000 to 20,000 Å and a thickness of 100 to 1000 Å. The surface area of the kaolinite grains per unit mass is about 15 m^2/g. The surface area per unit mass is defined as **specific surface**.

Illite consists of a gibbsite sheet bonded to two silica sheets—one at the top, and another at the bottom (Figure 2.13b). It is sometimes called **clay mica**. The illite layers are bonded together by potassium ions. The negative charge to balance the potassium ions comes from the substitution of aluminum for some silicon in the tetrahedral sheets. Substitution of one element for another with no change in the crystalline form is known as **isomorphous substitution**. Illite grains generally have lateral dimensions ranging from 1000 to 5000 Å, and thicknesses from 50 to 500 Å. The specific surface of the grains is about 80 m^2/g.

Montmorillonite has a similar structure to illite—that is, one gibbsite sheet sandwiched between two silica sheets (Figure 2.13c). In montmorillonite, there is isomorphous substitution of magnesium and iron for aluminum in the octahedral sheets. Potassium ions are not present between the layers as in the case of illite, and a large amount of water is attracted into the space between the layers. The layers are held together by weak van der Waal's force and can be separated easily. Grains of montmorillonite have lateral dimensions of 1000 to 5000 Å and thicknesses of 10 to 50 Å. The specific surface is about 800 m^2/g. Figure 2.14 is a scanning electron micrograph showing the fabric of montmorillonite.

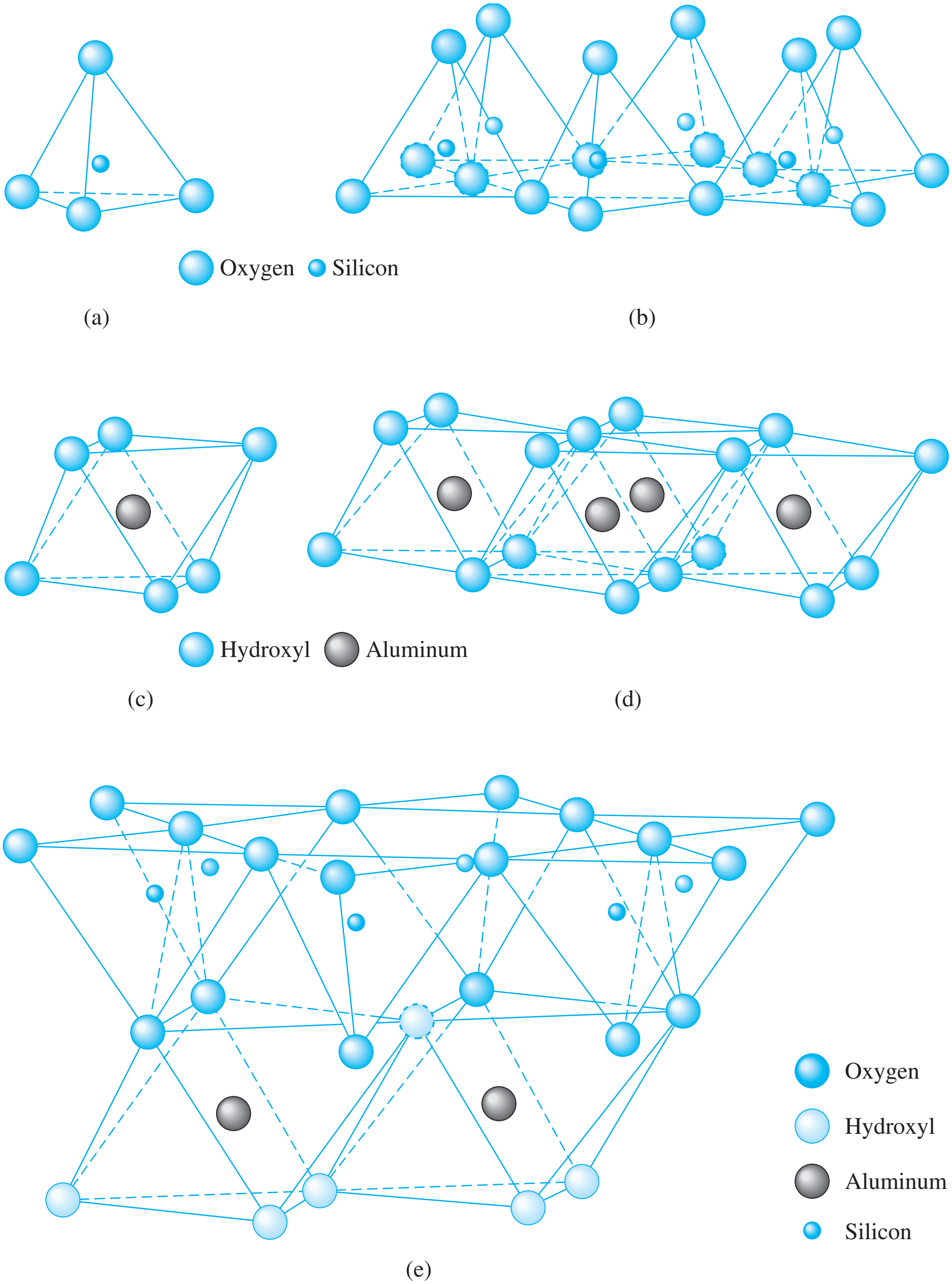

FIG. 2.12 (a) Silica tetrahedron; (b) silica sheet; (c) alumina octahedron; (d) octahedral (gibbsite) sheet; (e) elemental silica-gibbsite sheet (After Grim, 1959) (From Grim, "Physico-Chemical Properties of Soils: Clay Minerals," *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 85, No. SM2, 1959, pp. 1–17. With permission from ASCE.)