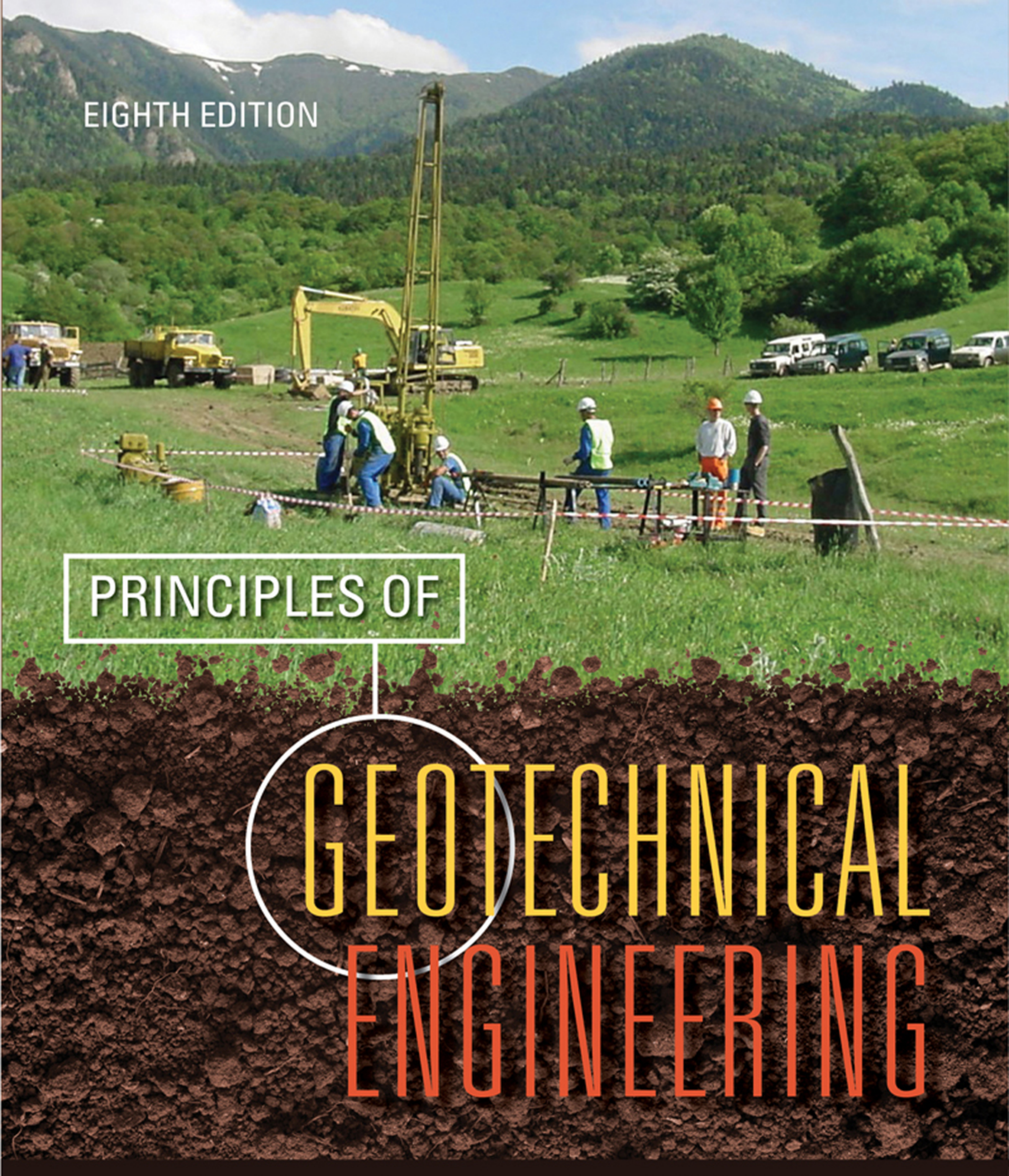

EIGHTH EDITION

PRINCIPLES OF GEOTECHNICAL ENGINEERING

BRAJA M. DAS | KHALED SOBHAN

CONVERSION FACTORS FROM ENGLISH TO SI UNITS

Length:	1 ft	= 0.3048 m
	1 ft	= 30.48 cm
	1 ft	= 304.8 mm
	1 in.	= 0.0254 m
	1 in.	= 2.54 cm
	1 in.	= 25.4 mm
Area:	1 ft^2	= 929.03 $\times$ 10^{-4} m^2
	1 ft^2	= 929.03 cm^2
	1 ft^2	= 929.03 $\times$ 10^2 mm^2
	1 in.^{2}	= 6.452 $\times$ 10^{-4} m^2
	1 in.^{2}	= 6.452 cm^2
	1 in.^{2}	= 645.16 mm^2
Volume:	1 ft^3	= 28.317 $\times$ 10^{-3} m^3
	1 ft^3	= 28.317 $\times$ 10^3 cm^3
	1 in.^{3}	= 16.387 $\times$ 10^{-6} m^3
	1 in.^{3}	= 16.387 cm^3
Section modulus:	1 in.^{3}	= 0.16387 $\times$ 10^5 mm^3
	1 in.^{3}	= 0.16387 $\times$ 10^{-4} m^3
Hydraulic conductivity:	1 ft/min	= 0.3048 m/min
	1 ft/min	= 30.48 cm/min
	1 ft/min	= 304.8 mm/min
	1 ft/sec	= 0.3048 m/sec
	1 ft/sec	= 304.8 mm/sec
	1 in./min	= 0.0254 m/min
	1 in./sec	= 2.54 cm/sec
	1 in./sec	= 25.4 mm/sec

Coefficient of consolidation:	1 in.^{2}/sec	= 6.452 cm^2/sec
	1 in.^{2}/sec	= 20.346 $\times$ 10^3 m^2/yr
	1 ft^2/sec	= 929.03 cm^2/sec
Force:	1 lb	= 4.448 N
	1 lb	= 4.448 $\times$ 10^{-3} kN
	1 lb	= 0.4536 kgf
	1 kip	= 4.448 kN
	1 U.S. ton	= 8.896 kN
	1 lb	= 0.4536 $\times$ 10^{-3} metric ton
	1 lb/ft	= 14.593 N/m
Stress:	1 lb/ft^2	= 47.88 N/m^2
	1 lb/ft^2	= 0.04788 kN/m^2
	1 U.S. ton/ft^2	= 95.76 kN/m^2
	1 kip/ft^2	= 47.88 kN/m^2
	1 lb/in.^{2}	= 6.895 kN/m^2
Unit weight:	1 lb/ft^3	= 0.1572 kN/m^3
	1 lb/in.^{3}	= 271.43 kN/m^3
Moment:	1 lb-ft	= 1.3558 N $\cdot$ m
	1 lb-in.	= 0.11298 N $\cdot$ m
Energy:	1 ft-lb	= 1.3558 J
Moment of inertia:	1 in.^{4}	= 0.4162 $\times$ 10^6 mm^4
	1 in.^{4}	= 0.4162 $\times$ 10^{-6} m^4

CONVERSION FACTORS FROM SI TO ENGLISH UNITS

Length:	1 m	= 3.281 ft
	1 cm	= 3.281×10^{-2} ft
	1 mm	= 3.281×10^{-3} ft
	1 m	= 39.37 in.
	1 cm	= 0.3937 in.
	1 mm	= 0.03937 in.
Area:	1 m^2	= 10.764 ft^2
	1 cm^2	= 10.764×10^{-4} ft^2
	1 mm^2	= 10.764×10^{-6} ft^2
	1 m^2	= 1550 in.^{2}
	1 cm^2	= 0.155 in.^{2}
	1 mm^2	= 0.155×10^{-2} in.^{2}
Volume:	1 m^3	= 35.32 ft^3
	1 cm^3	= 35.32×10^{-4} ft^3
	1 m^3	= 61,023.4 in.^{3}
	1 cm^3	= 0.061023 in.^{3}
Force:	1 N	= 0.2248 lb
	1 kN	= 224.8 lb
	1 kgf	= 2.2046 lb
	1 kN	= 0.2248 kip
	1 kN	= 0.1124 U.S. ton
	1 metric ton	= 2204.6 lb
	1 N/m	= 0.0685 lb/ft

Stress:	1 N/m^2	= 20.885×10^{-3} lb/ft^2
	1 kN/m^2	= 20.885 lb/ft^2
	1 kN/m^2	= 0.01044 U.S. ton/ft^2
	1 kN/m^2	= 20.885×10^{-3} kip/ft^2
	1 kN/m^2	= 0.145 lb/in.^{2}
Unit weight:	1 kN/m^3	= 6.361 lb/ft^3
	1 kN/m^3	= 0.003682 lb/in.^{3}
Moment:	1 N · m	= 0.7375 lb-ft
	1 N · m	= 8.851 lb-in.
Energy:	1 J	= 0.7375 ft-lb
Moment of inertia:	1 mm^4	= 2.402×10^{-6} in.^{4}
	1 m^4	= 2.402×10^{6} in.^{4}
Section modulus:	1 mm^3	= 6.102×10^{-5} in.^{3}
	1 m^3	= 6.102×10^{4} in.^{3}
Hydraulic conductivity:	1 m/min	= 3.281 ft/min
	1 cm/min	= 0.03281 ft/min
	1 mm/min	= 0.003281 ft/min
	1 m/sec	= 3.281 ft/sec
	1 mm/sec	= 0.03281 ft/sec
	1 m/min	= 39.37 in./min
	1 cm/sec	= 0.3937 in./sec
	1 mm/sec	= 0.03937 in./sec
Coefficient of consolidation:	1 cm^2/sec	= 0.155 in.^{2}/sec
	1 m^2/yr	= 4.915×10^{-5} in.^{2}/sec
	1 cm^2/sec	= 1.0764×10^{-3} ft^2/sec

Principles of Geotechnical Engineering

Eighth Edition

Principles of Geotechnical Engineering

Eighth Edition

BRAJA M. DAS, Dean Emeritus
California State University, Sacramento

KHALED SOBHAN
Florida Atlantic University

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Braja M. Das and Khaled Sobhan

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To Elizabeth Madison, Armaan, and Shaiza

Preface

Principles of Geotechnical Engineering was originally published with a 1985 copyright and was intended for use as a text for the introductory course in geotechnical engineering taken by practically all civil engineering students, as well as for use as a reference book for practicing engineers. The book was revised in 1990, 1994, 1998, 2002, 2006, and 2010. This eighth edition has a coauthor, Khaled Sobhan, of Florida Atlantic University. As in the previous editions of the book, this new edition offers an overview of soil properties and mechanics, together with coverage of field practices and basic engineering procedures, without changing the basic philosophy of the original text. It is not the intent of this book to conform to any design codes.

Unlike the seventh edition, which had 18 chapters, this edition has 17 chapters. The chapter on Landfill Liners and Geosynthetics has been deleted from this edition since the subject has grown and matured over the years and is offered as a separate course in many civil engineering programs.

Most of the example problems and homework problems have been changed and/or modified. One or two critical thinking problems have been added to the homework problems in most chapters to challenge and enhance the thought process and understanding of students on the subject(s) covered in a given chapter.

Since geotechnical engineering is a practical and application-oriented subject, a few actual case histories have also been included. These case histories are presented in Chapters 11, 15, and 16 with the primary intention being to familiarize students with the unpredictable variability of soil in the field compared to the idealized situation in classroom teaching and learning. New photographs have also been added throughout.

Other noteworthy changes in the eighth edition include the following:

- An expanded section of the introduction at the beginning and a summary section at the end of each chapter have been provided.
- In Chapter 2, on Origin of Soil and Grain Size, several photographs of common rock-forming minerals, rocks, and structures built with or in rock have been added (Section 2.3). To help students in future field identification of rocks and rock-forming minerals, they are presented in color as well as in black and white.

- In Chapter 3, on Weight–Volume Relationships, the section on maximum and minimum void ratio of granular soil has been expanded.
- The procedure for determination of shrinkage limit of cohesive soils using the wax method (ASTM Test Designation 4943) has been described in detail in Chapter 4 (Plasticity and Structure of Soil).
- In Chapter 5, on Classification of Soil, line diagrams have been added in example problems to determine the *group names of soils* from *group symbols* (Unified Soil Classification System). These line diagrams will help the readers follow a step-by-step procedure in arriving at the proper group name of soil during soil classification.
- The chapter on Soil Compaction (Chapter 6) now includes several recent empirical correlations to estimate maximum dry unit weight and optimum moisture content based on the energy of compaction. A section on evaluation of soils as compaction material has been added.
- In Chapter 9, on *In Situ* Stresses, a mathematical derivation for a general case to obtain the seepage force per unit volume of soil is added. Also in this chapter, Harza's chart to obtain the exit gradient of flow under a hydraulic structure is provided. This chart is helpful in estimating the factor of safety against heaving. An example to show the use of a filter on the downstream side of a hydraulic structure to increase the factor of safety against heaving is given.
- A section on the vertical stress increase at a certain point and depth below the ground surface due to a linearly increasing vertical loading on a infinite strip has been added in Chapter 10, on Stresses in a Soil Mass.
- An improved explanation of the fundamentals of consolidation is given in Chapter 11, on Compressibility of Soil. This chapter also provides a general discussion on the effect of load duration on the $e - \log \sigma'$ plot.
- Chapter 12, on Shear Strength of Soils, updates the calculation procedure of undrained cohesion for tests conducted with a tapered vane based on ASTM (2010).
- The procedure for estimation of active earth pressure in a $c' - \phi'$ soil under earthquake conditions has been updated in Chapter 13 (Lateral Earth Pressure: At-Rest, Rankine, and Coulomb).
- The Caquot and Kerisel theory for estimation of passive earth pressure with granular backfill (inclined back face of wall and horizontal backfill, and vertical back face of wall and inclined backfill) has now been included in Chapter 14, on Lateral Earth Pressure: Curved Failure Surface.
- In Chapter 15, on Slope Stability, a detailed derivation on the factor of safety of infinite slopes with seepage is now included. Results of some recent studies on the critical circles of failure for slopes in clay ($\phi = 0$ condition) and $c' - \phi'$ soil is added in this chapter.
- A generalized case for Rankine active and passive pressure with granular backfill is provided in Appendix A.

In the preparation of an engineering text of this type, it is tempting to include many recent developments relating to the behavior of natural soil deposits found in various parts of the world that are available in journals and conference proceedings with the hope that they will prove to be useful to the students in their future practice. However, based on many years of teaching, the authors feel that clarity in explaining the fundamentals of soil mechanics is more important in a first course in this area without cluttering the book with too many details and alternatives. Many of the intricate details can be left to an advanced course in the area of geotechnical engineering. This approach will most likely help in developing students' interest and appreciation in the geotechnical engineering profession at large.

Instructor Resource Materials

A detailed *Instructor's Solutions Manual* and PowerPoint slides of both figures and tables and equations and examples from the book are available for instructors through a password-protected Web site at www.cengagebrain.com.

Student Resource Materials

Self-Evaluation Multiple Choice Questions with Answers for each chapter are available for students on the book Web site. The students may also benefit from these questions as a practice tool in preparation for examinations.

To access additional course materials, please visit www.cengagebrain.com. At the cengagebrain.com home page, search for the ISBN of your title (from the back cover of your book) using the search box at the top of the page. This will take you to the product page where these resources can be found. If you require a password, follow directions for Instructor Resources.

The authors would not have been able to complete this revised manuscript without the support and encouragement of their wives, Janice and Samira, and their families. Janice Das was most helpful in getting the manuscript ready for publication. Professor Sanjay K. Shukla of Edith Cowan University, Australia, provided many valuable suggestions during the revision process. Finally, many thanks are due to Christoper Shortt, Publisher; Randall Adams, Senior Acquisitions Editor; Hilda Gowans, Senior Development Editor; and Lauren Betsos, Marketing Manager of Cengage Learning (Engineering) for their assistance and advice in the final development of the book. It is fitting also 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 *Principles of Geotechnical Engineering* as well as several previous editions.

Thanks are due to the following reviewers for their comments and constructive suggestions:

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BRAJA DAS AND KHALED SOBHAN

About the Authors

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 lowa 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 250 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 Chemical and Mechanical Stabilization 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). Presently he is the editor-in-chief of the *International Journal of Geotechnical Engineering* (J. Ross, Ft. Lauderdale, FL). 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.

Professor Khaled Sobhan is an Associate Professor of Civil Engineering at Florida Atlantic University. He received his M.S. degree from The Johns Hopkins University and his Ph.D. degree from Northwestern University, both in the area of Geotechnical Engineering. His primary research areas include ground improvement, geotechnology of soft soils, experimental soil mechanics, and geotechnical aspects of pavement engineering. He served as the Chair of the Chemical and Mechanical Stabilization committee (AFS90) of the Transportation Research Board (2005–2011) and coauthored the TRB Circular titled *Evaluation of Chemical Stabilizers: State-of-the-Practice Report* (E-C086). He is currently serving as an Associate Editor of ASCE *Journal of Materials in Civil*

Engineering, and on the editorial board of *the* ASTM *Geotechnical Testing Journal, Geotechnical and Geological Engineering* (Springer, The Netherlands) and *International Journal of Geotechnical Engineering* (J. Ross, Ft. Lauderdale, FL). He is a recipient of the distinguished Award for Excellence and Innovation in Undergraduate Teaching (2006) and the Excellence in Graduate Mentoring Award (2009) from Florida Atlantic University. He has published more than 75 technical articles and reports in the area of Geotechnical Engineering.

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CHAPTER

Geotechnical Engineering—A Historical Perspective

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, shear strength, and load-bearing capacity. *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

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

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.

Pakistan after 1947). During the Chan dynasty in China (1120 B.C. to 249 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 pyramids at Giza. The construction of the pyramids posed formidable challenges regarding foundations, stability of slopes,

Figure 1.1 A view of the pyramids at Giza. (*Courtesy of Janice Das, Henderson, Nevada*)

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 plumb with the 54 m ($\approx$ 179 ft) height.

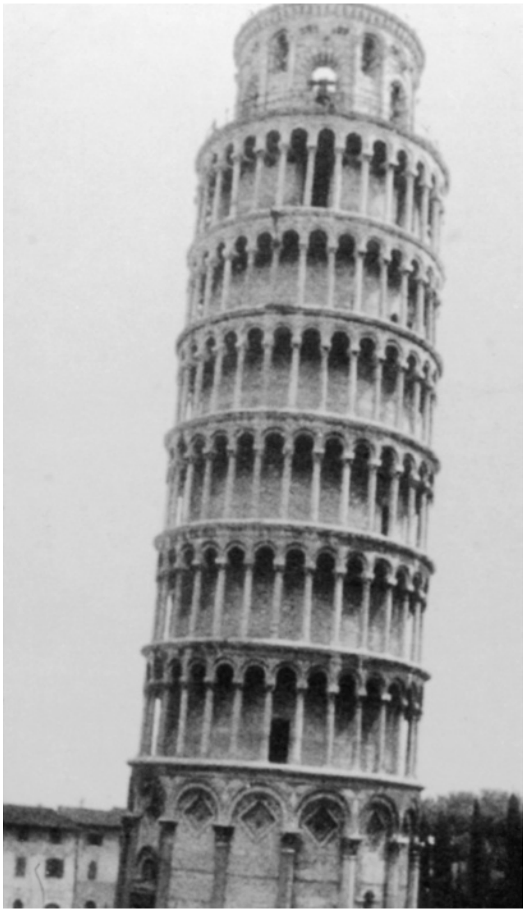

Figure 1.2 Leaning Tower of Pisa, Italy (*Courtesy of Braja M. Das, Henderson, Nevada*)

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. Figure 1.3 is an example of a similar problem. The towers shown in Figure 1.3 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.

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

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 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	16.7 to	106 to
Compressible sand	18.4	117
Ordinary earth (as found in dry locations)	13.4	85
Soft earth (primarily silt)	16.0	102
Clay	18.9	120
Peat	—	—

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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 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 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 loaded 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 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 1.4) 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 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 1.4 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 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 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