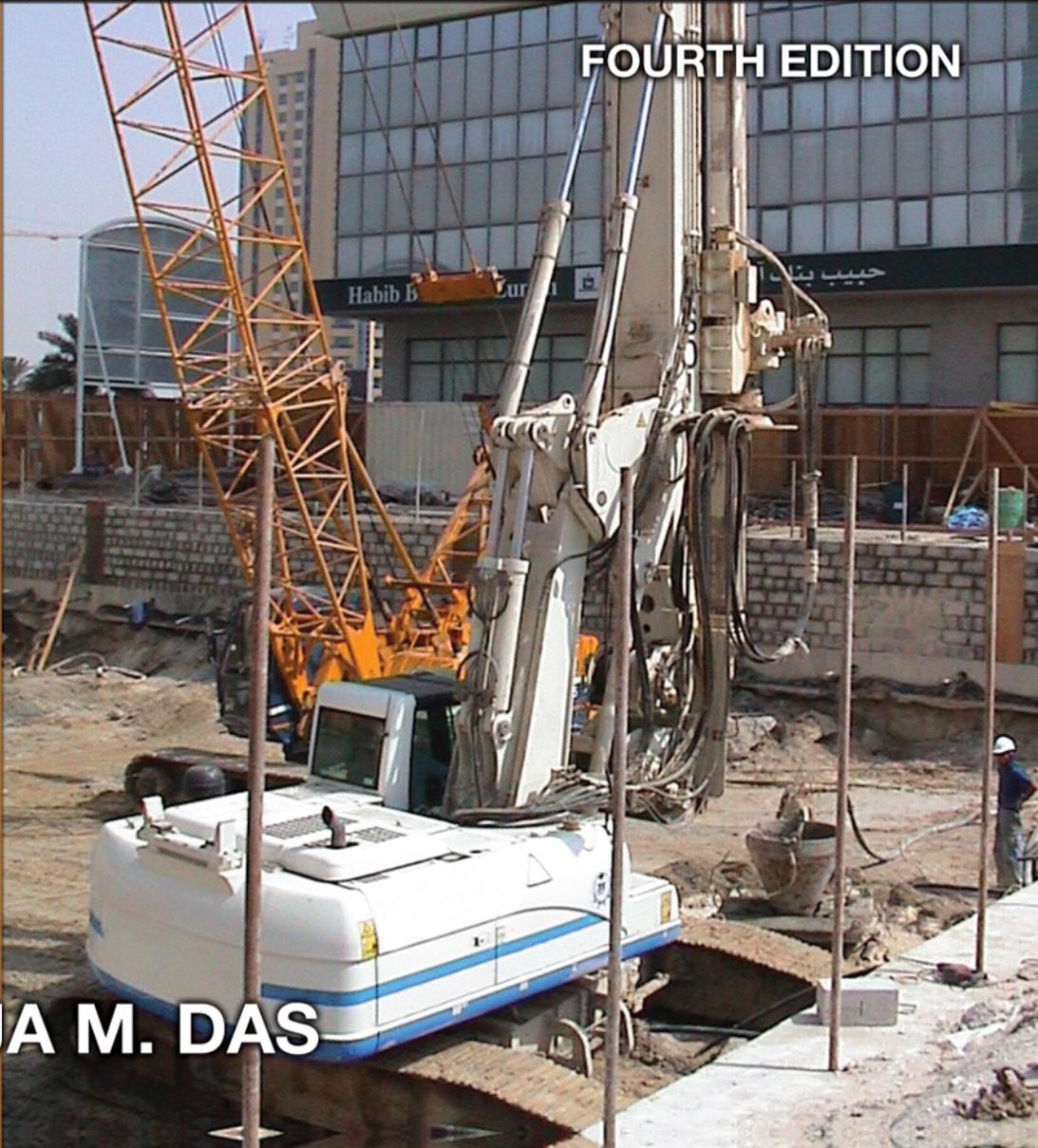


FUNDAMENTALS OF GEOTECHNICAL ENGINEERING

FOURTH EDITION

BRAJA M. DAS



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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, 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. *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.

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). Ancient Greek civilization used isolated pad footings and strip-and-raft foundations for building structures. Beginning around 2700 B.C.,

Table 1.1 Major Pyramids in Egypt

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

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



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

(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. 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. 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



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

are located in 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. Pre-classical (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 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	16.7 to
Compressible sand	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 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 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 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 m² in area and 200 mm thick) under constant vertical stress to determine their shear strength parameters (see Fontard, 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 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 Bodenphysikalischer 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



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

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 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



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

have been organized about every four years in different parts of the world. The aftermath of the Rotterdam conference saw the growth of regional conferences on geotechnical engineering, such as

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

Two other important milestones between 1948 and 1960 are (1) the publication of A. W. Skempton's paper on A and B pore pressure parameters which made effective stress calculations more practical for various engineering works and (2) publication of the book entitled *The Measurement of Soil Properties in the Triaxial Test* by A. W. Bishop and B. J. Henkel (Arnold, London) in 1957.

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

Conference	Location	Year
I	Harvard University, Boston, U.S.A.	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, U.S.S.R.	1973
IX	Tokyo, Japan	1977
X	Stockholm, Sweden	1981
XI	San Francisco, U.S.A.	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 (scheduled)

By the early 1950's, computer-aided finite difference and finite element solutions were applied to various types of geotechnical engineering problems. They still remain an important and useful computation tool in our profession. 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 sponsor several conferences around the world. A list of these technical 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.

Table 1.3 List of ISSMGE Technical Committees (2010–2013)

Category	Technical Committee Number	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	Limit State Design in Geotechnical Engineering
	TC206	Interactive Geotechnical Design
	TC207	Soil-Structure Interaction and Retaining Walls
	TC208	Stability of Natural Slopes
	TC209	Offshore Geotechnics
	TC210	Dams and Embankments
	TC211	Ground Improvement
	TC212	Deep Foundations
	TC213	Geotechnics of Soil 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

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 B.S. and Ph.D. degrees in 1934 and 1937, respectively, from Rensselaer Polytechnic Institute, Troy, New York. During the period from 1938 to 1939, he took courses from Arthur Casagrande at Harvard University in a new subject called “soil mechanics.” From 1939 to 1943, Dr. Peck worked as an assistant to Karl Terzaghi, the “father” of modern soil mechanics, on the Chicago Subway Project. In 1943, he joined the University of Illinois at Champaign-Urbana and was a professor of foundation engineering from 1948 until he retired in 1974. After retirement, he was active in consulting,



Figure 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)

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) would be the last major conference of its type that he would attend.

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.

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