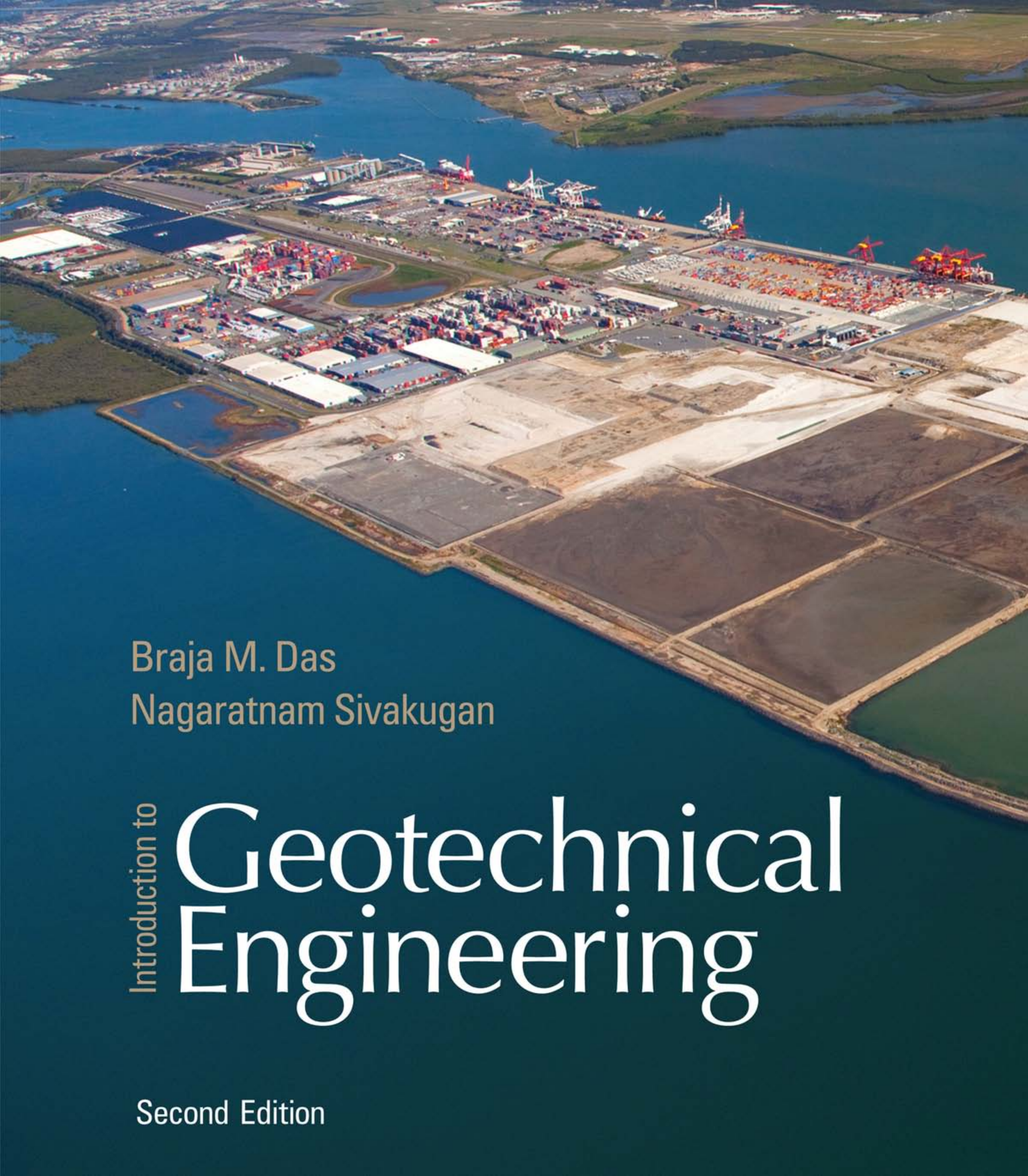
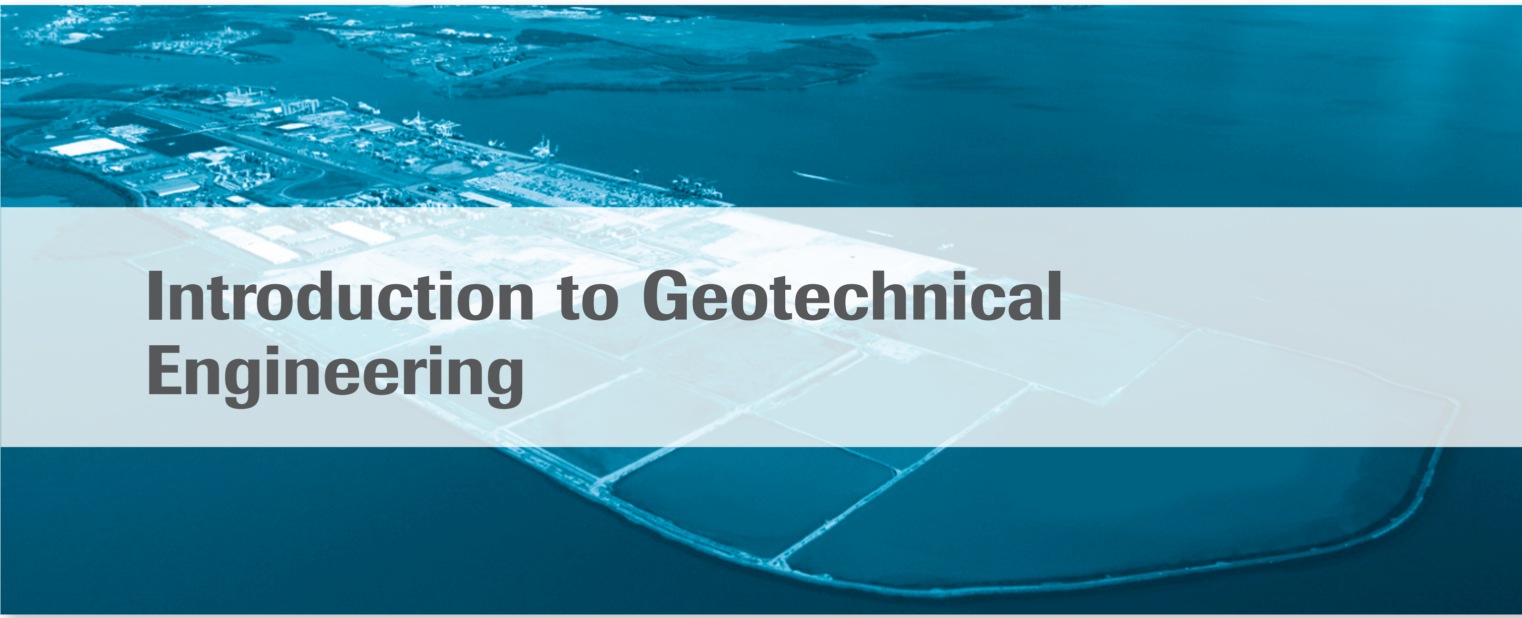


Braja M. Das

Nagaratnam Sivakugan

Introduction to Geotechnical Engineering

Second Edition



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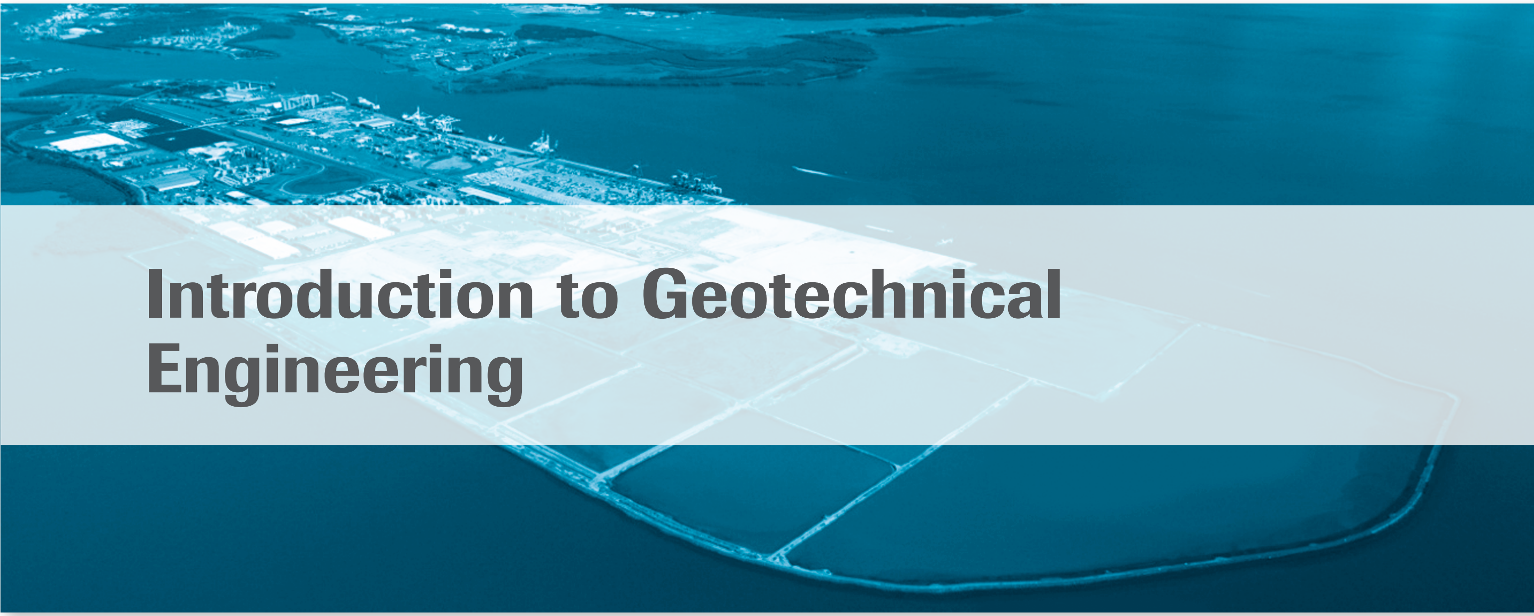

Introduction to Geotechnical Engineering

Second Edition

Braja M. Das

Dean Emeritus,
California State University,
Sacramento, USA

Nagaratnam Sivakugan

Associate Professor and Head,
Discipline of Civil Engineering,
James Cook University,
Australia

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Braja M. Das and Nagaratnam Sivakugan

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To Janice, Rohini, Joe,
Valerie, and Elizabeth

Contents

Preface

During the past half century, geotechnical engineering—soil mechanics and foundation engineering—have developed rapidly. Intensive research and observation in the field and laboratory have refined and improved the science of foundation design. *Introduction to Geotechnical Engineering, Second Edition,* uses those materials, and they are presented in a simple and concise form. This book is designed primarily for classroom instruction in Civil Engineering Technology and Construction Management programs. It is non-calculus based. It will be a useful reference book for civil engineering practitioners. It also can be used as a text for students in Civil Engineering programs where soil mechanics and foundations are combined into one course and covered in one semester. However, some supplemental material may be necessary.

The first edition of this text was published in 2008. The majority of the materials in the first edition of the text were drawn from *Principles of Foundation Engineering* and *Principles of Geotechnical Engineering*, which were originally published with 1984 and 1985 copyrights, respectively. These books are now in their eighth editions.

The present edition of the text has added a co-author—Dr. Nagaratnam Sivakugan, Associate Professor and Head of Civil Engineering at James Cook University, Townsville, Australia. In this edition, the following changes and additions have been incorporated.

- Since several users of the first edition preferred SI units, dual units (English and SI) have been used in the text.
- Several additional examples and homework problems have been added. These problems are approximately 50/50 in English and SI units. There are 113 example problems and 246 homework problems.
- Several new photographs have been added to help students visualize the material under discussion.
- Chapter 1, entitled "Geotechnical Engineering," is new and explains what geotechnical engineering is in general terms.
- Chapter 2 presents a general description of soil grain-size and grain-size analysis.
- Soil compaction has now been moved to Chapter 5.
- Based on the review comments, several additions and clarifications have been incorporated into the text.

Instructors must emphasize the difference between soil mechanics and foundation engineering in the classroom. Soil mechanics is the branch of engineering that involves the student of the properties of soils and their behavior under stress and strain under idealized conditions. Foundation engineering is the application of the principles of soil mechanics and geology in the planning, design, and construction of foundations for buildings, highways, dams, and so forth. Approximations and deviations from idealized conditions of soil mechanics become necessary for proper foundation design, because natural soil deposits are not homogeneous in most cases. However, if a structure is to function properly, these approximations only can be made by an engineer with a good background in soil mechanics. This book provides that background.

Instructor Resource Materials

A detailed *Instructor's Solutions Manual* is available for instructors.

MindTap Online Course and Reader

In addition to the print version, this textbook also will be available online through MindTap, which is a personalized learning program. Students who purchase the MindTap version will have access to the book's MindTap Reader and will be able to complete homework and assessment material online, through their desktop, laptop, or iPad. If your class is using a Learning Management System (such as Blackboard, Moodle, or Angel) for tracking course content, assignments, and grading, you can seamlessly access the MindTap suite of content and assessments for this course.

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Additionally, students can listen to the text through ReadSpeaker, take notes and highlight content for easy reference, and check their understanding of the material.

Acknowledgements

Thanks are given to the following for their contributions.

- The three reviewers, including Professor Saeed Daniali of the University of Washington, for their comments and helpful suggestions.
- Janice F. Das, in helping to complete the Instructor's Solution Manual and providing other suggestions and advice in the preparation of the revision.

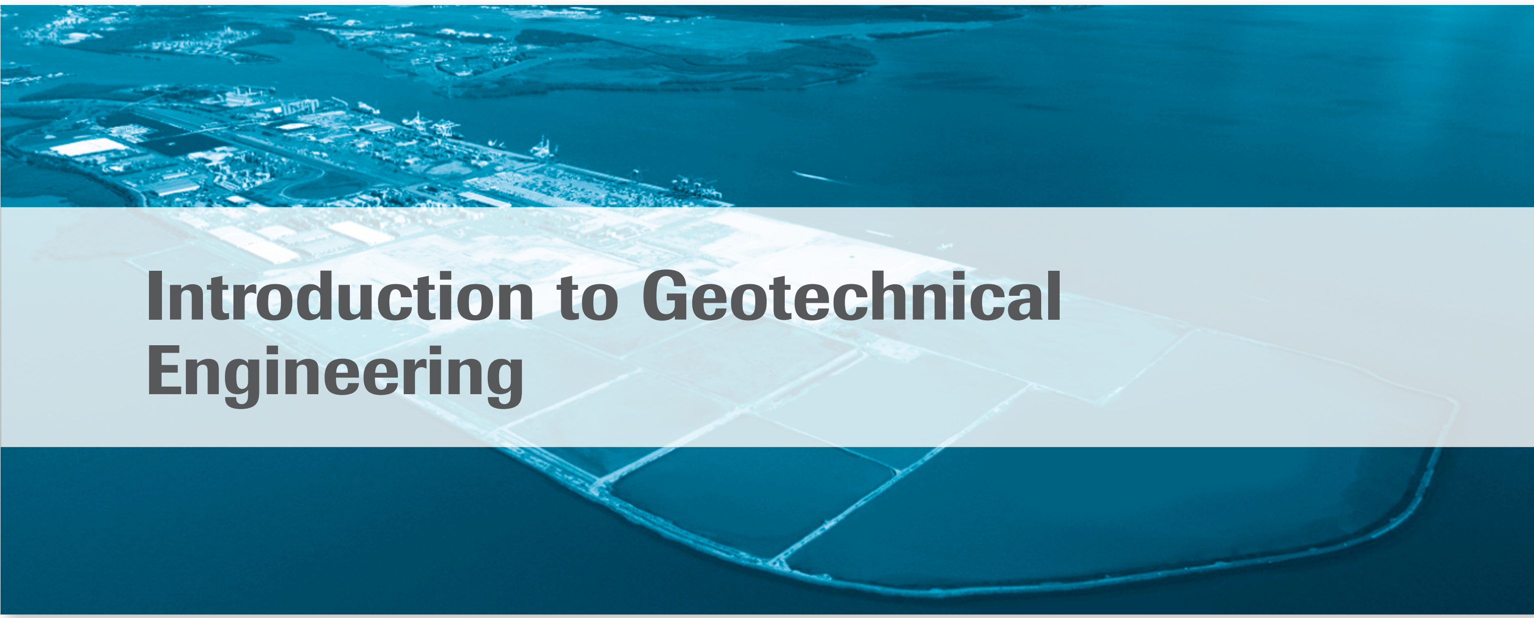
- Several individuals at Cengage Learning, for their assistance and advice in the final development of the book—namely:

  Tim Anderson, Publisher
  Hilda Gowans, formerly Senior Development Editor, Cengage
  Eavan Cully, Development Editor, Cengage

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 *Introduction to Geotechnical Engineering* as well as the first edition.

Braja M. Das

Nagaratnam Sivakugan



Introduction to Geotechnical Engineering

1 Geotechnical Engineering

Geotechnical engineering is defined as the sub-discipline of civil engineering that involves natural materials found close to the surface of the earth. This text is designed for use as an introduction to the fundamental principles of geotechnical engineering for students enrolled in civil engineering technology and construction management programs. This chapter provides a broad overview of the following topics.

- What is geotechnical engineering?
- An appreciation of different types of geotechnical problems.
- The role of soil testing as a means of determining the design parameters.

1.1 Geotechnical Engineering

Soils, rocks, and aggregates are natural materials of geologic origin derived from the earth. Sometimes, they are known as *geomaterials.* They are the most abundant materials on Earth. Rocks can break down into aggregates and soils. Soils and aggregates can turn into rocks through geologic processes over thousands of years. The mineralogy of the three is similar.

The term "geo" means earth. Geotechnical engineering deals with the engineering aspects of soils, rocks, and aggregates. It is a relatively young branch of civil engineering. With the growth of science and technology, the need for better and more economical structural design and construction became critical. During the early part of the twentieth century, this need led to a detailed study of the nature and properties of soil as they related to engineering. The publication of *Erdbaumechanik* by Karl Terzaghi in 1925 gave birth to modern soil mechanics as we know it today. Being a young discipline, there has been substantial new developments in the past two decades, and there will be more in the next few decades. *Environmental geotechnology* is one of the growing areas that is related to geotechnical engineering.

All buildings, structures, facilities, and infrastructure have to be placed on the ground. To ensure that they perform satisfactorily during their design lives, it is necessary to ensure that there are no excessive settlements or deformations and, worse, any failures in the underlying soils. This requires a thorough understanding of soil behaviour and its response to the structures or facilities built on them.

Geotechnical engineering includes *soil mechanics* and *foundation engineering.* Some exposure to *rock mechanics* and *geology* will strengthen your geotechnical engineering skills. *Mechanics* is the physical science that deals with forces, stresses, moments, displacements, strains, and equilibrium. Soil mechanics is a subject where the principles of mechanics are applied to soils, treating them as *continuous media* or *continuum* for simplicity. Geotechnical engineering is sometimes called *geomechanics* or *geo-engineering* in different parts of the world.

1.2 Geotechnical Engineering Applications

There is a wide range of geotechnical applications. The list keeps growing with new challenges such as hazardous waste disposal. The major applications are

a. *Foundations:* Footings, piles, and piers supporting buildings
b. *Retaining walls:* Concrete or masonry walls preventing lateral spread of soils
c. *Sheet piles:* Water-tight steel walls to prevent lateral spread of soils and retain soils and/or water
d. *Dams:* Large structures made of concrete or geomaterials for impounding water in reservoirs
e. *Earthworks:* Site preparation work prior to building a structure
f. *Slope stability:* Stability of the slope of an embankment or excavation
g. *Geosynthetics:* Natural or synthetic materials used to improve the soil behavior

As an example of geotechnical engineering work, Figure 1.1 shows the land reclamation at a port, where the dredged spoils are pumped (see inset) into the containment paddocks in the form of slurry.

Figure 1.1 Land reclamation containment paddocks (Inset: Dredge spoil pumped into the containment paddock) (*Courtesy of N. Sivakugan, James Cook University, Australia*)

(a) (b)

Figure 1.2 Earthwork: (a) during a site preparation; (b) after completion of the site preparation (*Courtesy of N. Sivakugan, James Cook University, Australia*)

The slurry settles and forms the reclaimed land for future developments. Similarly, Figure 1.2 shows the earthworks during a site preparation using a range of earthmoving equipment such as excavators, spreaders, and different types of rollers to carry out the compaction. Figure 1.3 shows the Leaning Tower of Pisa in Italy. The serviceability limit state is well and truly violated here, and the tower has become a world wonder and a major tourist attraction. In March 1990, the tower was closed to the

Figure 1.3 Leaning tower of Pisa (*Courtesy of Briony Rankine, Golder Associates, Australia*)

public for safety reasons, and after some years of remedial measures, it was reopened in 2001. After the recent foundation restoration work, the 56 m high tower is still leaning 4° to the vertical. The top of the tower is displaced horizontally by about 3.9 m.

1.3 Soil Parameters

All of the geotechnical applications discussed in Section 1.2 involve *design and analysis* that have to be carried out prior to the *construction.* To carry out proper design and analysis, it is necessary to have the *soil properties*, which are known as *design parameters.* The soil properties are generally determined from field (in situ) tests and laboratory tests on samples collected from the field.

References

Terzaghi, K. (1926). *Erdbaumechanik auf Bodenphysikalisher Grundlage*, Deuticke, Vienna.

2 Grain-Size Analysis

2.1 Introduction

For engineering purposes, *soil* is defined as an 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. This chapter relates to a general overview of grain sizes and their distribution in soils.

The study of grain sizes present in a given soil is an important and integral part of geotechnical engineering. The grain-size distribution in soil influences its physical properties, such as compressibility and shear strength. This chapter discusses the different types of soils on the basis of grain size and the means of quantifying the grain sizes. At the end of this chapter, you will have learned the following.

- What are the size ranges for gravels, sands and fines?
- How are soils formed?
- Some special names for specific soil types.
- Developing the grain-size distribution curve.

2.2 Soil-Grain Size

The sizes of grains that make up soil may 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 2.1 shows the soil-separate-size limits developed by the Massachusetts Institute of Technology, the U.S. Department of Agriculture, the American Association of State Highway and Transportation Officials, and the U.S. Army Corps of Engineers and U.S. Bureau of Reclamation. In this table, the MIT system has been presented for illustration purposes only. This system is important in the history of the development of soil-separate-size limits. However, presently, the Unified System is almost universally accepted. The

Table 2.1 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)	76.2 to 4.75	4.75 to 0.075	Fines (i.e., silts and clays) <0.075	

Unified Soil Classification System has now been adopted by the American Society for Testing and Materials. Figure 2.1 shows size limits in a graphical form.

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

Sand grains are mostly made of 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 2.1, clays are generally defined as grains less than 0.002 mm in size. However, in some cases, grains between 0.002 mm and 0.005 mm in size are also referred to as clay. Grains are classified as *clay* on the basis of their size; they do not necessarily contain clay minerals. Clays have been defined as those particles "which develop plasticity when mixed with a limited amount of water" (Grim, 1953). (Plasticity is the putty-like property of clays when they contain

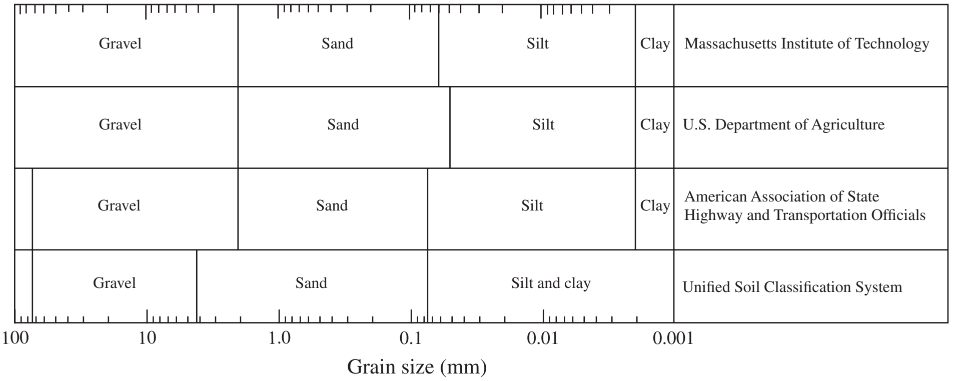
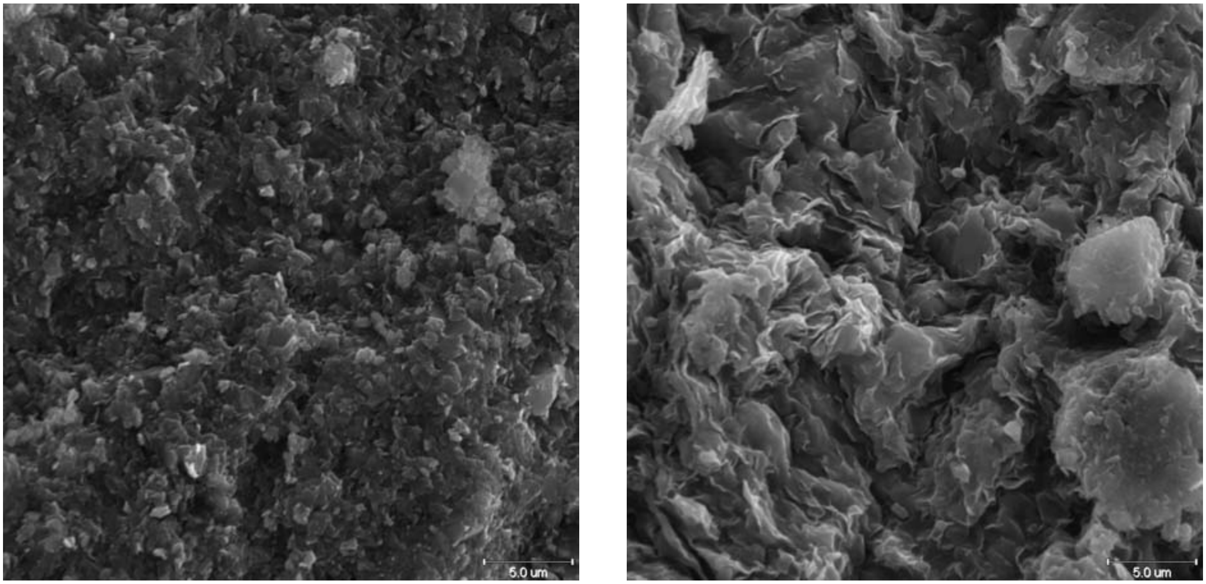


Figure 2.1 Soil-separate-size limits by various systems



(a) (b)

Figure 2.2 Scanning electron micrographs of clay fabric: (a) kaolinite; (b) montmorillonite (*Courtesy: David White, Iowa State University, Ames, Iowa*)

a certain amount of water.) Non-clay soils can contain grains of quartz, feldspar, or mica that are small enough to be within the clay classification. Hence, it is appropriate for soil grains smaller than 0.002 mm, or 0.005 mm as defined under different systems, to be called "clay-sized" grains rather than "clay." Clay grains are mostly of colloidal size range ($<$0.001 mm), and 0.002 mm appears to be the upper limit. The clay minerals, which are a product of chemical weathering of feldspars, ferromagnesians, and micas, are the minerals whose presence gives the plastic property to soils. There are three major types of clay mineral: (1) *kaolinite,* (2) *illite,* and (3) *montmorillonite*.

Individual grains of clay cannot be seen by the naked eye. It requires a microscope to see them. Figure 2.2 shows the scanning electron micrographs (same scale) of kaolinite and montmorillonite clays. Unlike the gravels, sands and silts, grains of clay are flaky with very large surface areas, as seen in the micrographs. It can be seen that montmorillonite grains have a much larger surface area than kaolinite. Their mineralogy, flakiness, and the large surface areas make the clays plastic and cohesive. Montmorillonite clays can swell in the presence of water, which enters between the layers. Such clays are known as expansive clays and cause billions of dollars worth of damage annually to roads and low-rise buildings.

2.3 General Soil Deposits

Most of the soils that cover the earth are formed by the weathering of various rocks. There are two general types of weathering: (1) *mechanical weathering*, and (2) *chemical weathering*.

Mechanical weathering is the process by which rocks are broken down into smaller and smaller pieces by physical forces. These physical forces may be running water, wind, ocean waves, glacier ice, frost action, and expansion and contraction caused by gain and loss of heat.

Chemical weathering is the process of chemical decomposition of the original rock. In the case of mechanical weathering, the rock breaks down into smaller pieces without a change of chemical composition. However, in chemical weathering, the original material may be changed to something entirely different. For example, the chemical weathering of feldspar can produce clay minerals.

The soil that is produced by the weathering process of rocks can be transported by physical agents to other places. These soil deposits are called *transported soils*. In contrast, some soils stay in the place of their formation and cover the rock surface from which they derive. These soils are referred to as *residual soils*.

Based on the *transporting agent*, transported soils can be subdivided into three major categories:

1. *Alluvial*, or *fluvial*: deposited by running water
2. *Glacial*: deposited by glacier action
3. *Aeolian*: deposited by wind action

In addition to transported and residual soils, there are *peats* and *organic soils*, which derive from the decomposition of organic materials. Organic soils are usually found in low-lying areas where the ground water table is near or above the ground surface. The presence of a high ground 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. The 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.

2.4 Some Local Terms for Soils

Soils are sometimes referred to by local terms. Following are a few of these terms with a brief description of each.

1. *Caliche*: a Spanish word derived from the Latin word *calix*, meaning *lime*. It is mostly found in the desert southwest of the United States. It is a mixture of sand, silt, and gravel bonded together by *calcareous deposits*. The calcareous deposits are brought to the surface by a net upward migration of water. The water evaporates in the high local temperature. Because of the sparse rainfall, the carbonates are not washed out of the top layer of soil.
2. *Gumbo*: a highly plastic, clayey soil.
3. *Adobe*: a highly plastic, clayey soil found in the southwestern United States.
4. *Terra Rossa*: residual soil deposits that are red in color and derive from limestone and dolomite.
5. *Muck*: organic soil with a very high moisture content.
6. *Muskeg*: organic soil deposit.
7. *Saprolite*: residual soil deposit derived from mostly insoluble rock.
8. *Loam*: a mixture of soil grains of various sizes, such as sand, silt, and clay.
9. *Laterite*: characterized by the accumulation of iron oxide (Fe_2O_3) and aluminum oxide (Al_2O_3) near the surface, and the leaching of silica. Lateritic soils in Central America contain about 80–90% of clay and silt-size grains. In the United States, lateritic soils can be found in the southeastern states, such as Alabama, Georgia, and the Carolinas.

2.5 Grain-Size Analysis

In a natural soil deposit, the size of grains may vary over a wide range. Determining the nature of distribution of the grain size in a given soil mass is important for all design and construction purposes. At the same time, the degree of plasticity of soils due to the presence of clay minerals dictates the physical behavior and properties of soil as they relate to the design of various civil engineering structures. If the grain-size distribution and the plasticity of soil are known, they can be used for engineering classification (Chapter 4).

Grain-size analysis for grain sizes larger than 0.075 mm is done by sieve analysis. Sieve analysis consists of shaking the soil sample through a set of sieves that have progressively smaller openings. U.S. standard sieve numbers and the sizes of openings are given in Table 2.2.

The sieves used for soil analysis are generally 8 in. (203 mm) in diameter. To conduct a sieve analysis, one must first oven-dry the soil and then break all lumps into small grains. The soil then is shaken through a stack of sieves with openings of decreasing size from top to bottom (a pan is placed below the stack). Figure 2.3 shows a set of sieves in a shaker used for conducting the test in the laboratory. The smallest-sized sieve that should be used for this type of test is the U.S. No. 200 sieve. After the soil is shaken, the mass of soil retained on each sieve is determined. When cohesive soils are analyzed, breaking the lumps into individual grains may be difficult. In this case, the soil may be mixed with water to make a slurry and then washed through the sieves. Portions retained on each sieve are collected separately and oven-dried before the mass retained on each sieve is measured.

Referring to Figure 2.4, we can step through the calculation procedure for a sieve analysis:

1. Determine the mass of soil retained on each sieve (i.e., $M_1, M_2, \ldots M_n$) and in the pan (i.e., M_p) (Figure 2.4a and 2.4b).
2. Determine the total mass of the soil: $M_1 + M_2 + \cdots + M_i + \cdots + M_n + M_p = \Sigma M$.

Table 2.2 U.S. Standard Sieve Sizes

Sieve no.	Opening (mm)	Sieve no.	Opening (mm)
4	4.75	35	0.500
5	4.00	40	0.425
6	3.35	50	0.355
7	2.80	60	0.250
8	2.36	70	0.212
10	2.00	80	0.180
12	1.70	100	0.150
14	1.40	120	0.125
16	1.18	140	0.106
18	1.00	170	0.090
20	0.850	200	0.075
25	0.710	270	0.053
30	0.600		