ICE Core Concepts

Soil Mechanics

Second edition

Sanjay Kumar Shukla

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Second Edition

Sanjay Kumar Shukla
School of Engineering, Edith Cowan University, Joondalup,
Perth, Australia

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Preface

Soil mechanics is the study of how soil masses respond to various loads, such as those from structures, gravity and natural events like earthquakes. Composed of solid, liquid and gas phases, soil exhibits complex behaviour that requires integrating principles from solid and fluid mechanics. However, due to natural variability and uncertainties, simplifying assumptions and sound judgement are often necessary. Understanding soil behaviour is important for designing stable foundations and other ground structures in infrastructure, energy and environmental systems. The performance and durability of these systems depend heavily on the strength and stability of the supporting soil mass, making soil mechanics a critical field not only in civil engineering but also in disciplines such as mining, agriculture and aquaculture.

As a fundamental subject in civil engineering undergraduate programmes worldwide, soil mechanics introduces students to the physical properties of soils and the behaviour of soil masses under various load conditions. Its principles are not limited to natural soils but extend to soil-like materials such as coal ash and mine tailings, which are increasingly utilised in engineering applications. By applying these concepts, engineers can design sustainable and efficient solutions for a range of projects, ensuring the safety and reliability of structures built on or within the ground.

Over the years, many books on soil mechanics have been written, covering both fundamental and advanced concepts. Each is tailored to meet the needs of students and practising engineers. This textbook, as its title indicates, emphasises the core principles and concepts of soil mechanics. It comprises nine chapters, thoughtfully designed and developed for a one-semester course in undergraduate civil engineering programmes. The content of the chapters is presented clearly in plain English, with an optimal balance of text, illustrations, examples and practice questions. Each chapter includes valuable references cited within the text and listed at the end of the chapter, providing resources for further study and deeper understanding.

Chapter 1 presents the basic description of soil, including the fundamentals of soil phases, phase relationships, weathering and soil formation, and clay mineralogy. Chapter 2 describes soil particle size and shape, index properties of soil, and soil classification and description. Chapter 3 covers stresses within soil, including effective stress and stress induced by loading. Chapter 4 contains a description of flow through soil by explaining the basics of fluid flow, permeability, seepage forces, flow equation and flow nets. Chapter 5 deals with the consolidation and compressibility aspects of soil. Chapter 6 presents the details of shear strength of soil and explains the principles of different shear tests. The details of laboratory and field compaction of soil are given in Chapter 7. The basic concepts of lateral earth pressure, slope stability and bearing capacity of soil are described in Chapter 8. Chapter 9 covers the principles of specialised topics, including expansive soils, reinforced soils, thermal and electrical properties of soils and soil liquefaction.

This introductory textbook has been developed as a student-centred learning resource, drawing on my over 30 years of teaching, research and consultancy experience in geotechnical engineering. Civil engineering students will find it particularly useful for studying soil mechanics and understanding the fundamentals of the subject with minimal external assistance. For teachers, this textbook eliminates the need to prepare handwritten lecture materials, as the content has been refined and used effectively in my own classroom teaching for many years. Beyond students and teachers, this textbook also serves as a valuable reference for practising engineers and professionals in related fields, helping them refresh their understanding of the core principles and concepts of soil mechanics when addressing soil-related challenges in their projects.

Revised and updated, this second edition offers the following key features.

- A new chapter (Chapter 9) focused on principles of special topics, including expansive soil, reinforced soil, thermal and electrical properties of soil and soil liquefaction.
- Enhancements to existing chapters, with the addition of new sections in Chapters 2, 3, 4, 5 and 7, providing expanded coverage and greater depth.
- Comprehensive updates throughout the book, featuring additional illustrative examples, new and updated illustrations, a fresh set of multiple choice questions, numerical practice problems and conceptual questions. This edition also includes updated test standards, codes of practice and references to ensure relevance and to support enhanced learning and practical application.

I would like to express my heartfelt gratitude to the team at Emerald/ICE Publishing, London, especially Michael Fenton, Ryan Molyneux, Benn Linfield, S. Rajachitra, Alison Gilmour and Cathy Sellars, for their strong support and cooperation throughout the various stages of preparing and producing this textbook. Their dedication and professionalism have been invaluable.

I extend my sincere appreciation to my wife, Sharmila, for her constant encouragement and support during the preparation of the manuscript. I am equally grateful to my daughter, Sakshi, and my son, Sarthak, for their patience and understanding as I worked on this textbook at home.

Finally, I warmly welcome suggestions from readers and users of this textbook to further enhance its content in future editions. Your feedback is invaluable in making this resource even more useful and comprehensive.

Sanjay Kumar Shukla
Perth, Australia, 2025

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About the author

Dr Sanjay Kumar Shukla is a globally renowned expert in Civil (Geotechnical) Engineering. He is the Founding Editor-in-Chief of the *International Journal of Geosynthetics and Ground Engineering*, published by Springer, Switzerland, and the Founding Leader of the Geotechnical and Geoenvironmental Engineering Research Group at Edith Cowan University, Joondalup, Perth, Australia. He holds distinguished professorships at several universities, including the prestigious Delhi Technological University, Delhi, India, and Southern Illinois University, Carbondale, USA.

Dr Shukla is a Chartered Professional Engineer in Civil and Geotechnical Engineering, registered with Engineers Australia. He also holds the designation of Asia Pacific Economic Cooperation (APEC) Engineer in Civil Engineering and is recognised as an International Professional Engineer in Civil Engineering by the International Engineering Association.

He is a distinguished Fellow of the American Society of Civil Engineers and Engineers Australia, as well as a Life Fellow of the Institution of Engineers (India) and the Indian Geotechnical Society. His prolific academic contributions include 28 books and over 320 research articles, earning him recognition among the world's top 2% of scientists by Elsevier, and among the top 0.5% globally by ScholarGPS.

Dr Shukla has received numerous accolades, including the 2021 ECU Aspire Award and the prestigious IGS Award 2018 from the International Geosynthetics Society, USA. In 2024, the Consulate General of India in Perth honoured him with the Distinguished Honour for his outstanding academic contributions to Geotechnical Engineering.

His pioneering works, such as his generalised expressions for seismic active thrust (2015) and passive resistance (2013), along with the innovative Shukla's wraparound reinforcement technique, are widely used in engineering practice and form integral components of engineering education worldwide. His Seven Research Mantras, introduced in 2022, have inspired sustainable research practices and influenced researchers globally.

A highly regarded speaker, Dr Shukla frequently delivers keynote talks and short courses internationally. He is also widely consulted by researchers and practising engineers for his expertise in advancing practical engineering solutions.

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Chapter 1
Basic description of soil

Learning aims

This chapter explores the core concepts of the following topics

- soil, soil mechanics and geotechnical structures
- soil phases, phase relationships and inter-relationships
- weathering and soil formation
- clay mineralogy
- types of soil and soil structures.

1.1. Introduction

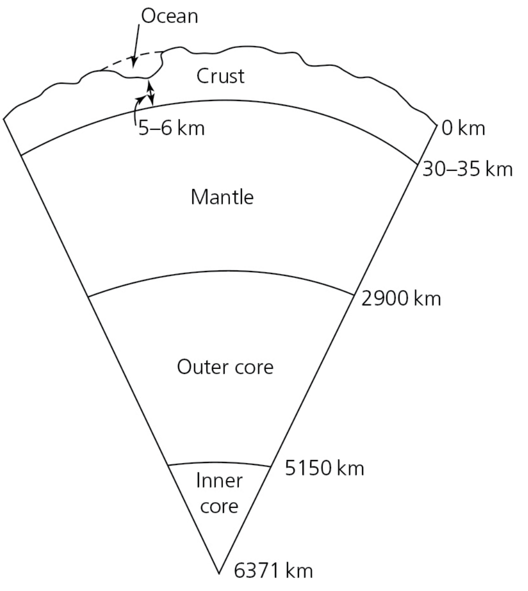
The Earth is composed of three well-defined layers: the crust, the mantle and the core, which is divided into the outer core and the inner core (Figure 1.1). The crust is the topmost layer, which has a thickness of about 30–35 km in continents and 5–6 km in oceans. The materials that constitute the Earth's crust are arbitrarily divided by civil engineers into the following two categories for practical purposes

- soil (Figure 1.2(a))
- rock (Figure 1.2(b)).

Soil comprises all the materials in the surface layer of the Earth's crust that are loose enough to be moved by a spade or shovel. These materials include natural systems such as sediments or other unconsolidated accumulations of solid particles, and they may also contain organic matter. According to Karl Terzaghi, widely regarded as the father of soil mechanics, soil is a natural aggregate of mineral grains or particles that can be separated by gentle means, such as agitation in water (Terzaghi et al., 1996). Rock, on the other hand, is a natural aggregate of mineral grains, connected by strong and permanent internal cohesive forces, occurring in large masses and fragments. The distinction between soil and rock is not very clear; the dividing line between them is a matter of convenience and varies depending on the purpose under consideration.

Soil mechanics is the branch of science that deals with the application of the laws of mechanics and hydraulics to problems related to soil. It includes the study of the physical properties of soil and the behaviour of soil masses in connection with their practical applications. The core principles of soil mechanics are also applied to other soil-like granular materials, such as coal ashes (fly ash, bottom ash), furnace slags and mine tailings.

Figure 1.1 Structure of the Earth



Note: not to scale

Soil supports structural foundations and serves as a construction material in civil engineering and other infrastructure projects. Soil mechanics provides scientific information for the analysis, design, construction, maintenance and renovation of geotechnical and ground structures, forming the basis of geotechnical engineering, as presented by Shukla (2025). Figure 1.3 illustrates seven basic types of geotechnical structures: foundation, slope, embankment, earth dam, retaining wall, tunnel and pavement, which are the most commonly recognised terms. Other geotechnical structures can be considered variations or combinations of these basic types.

The design and stability of geotechnical structures are largely governed by the properties of soil, primarily permeability (ability of a soil to conduct liquid or gas), compressibility (property of a soil pertaining to its susceptibility to change in volume when subjected to loading or unloading) and shear strength (maximum resistance of a soil to shearing stresses). These properties are described in detail in Chapters 4, 5 and 6, respectively.

This chapter introduces the basic description of soil, focusing on its phases, origin and types as considered in civil engineering practice.

1.2. Phases in a soil mass

An element of soil (Figure 1.4(a)) consists of

- solid, usually mineral particles
- liquid, usually water
- gas, usually air and/or water vapour.

A phase in a soil mass is its one part (solid, liquid or gas) which is physically and chemically different from its other parts. Soil is thus a multiphase system consisting of, in general, three phases: solid, liquid and gas.

Figure 1.2 Field project sites with (a) soil formation and (b) rock formation

(a)

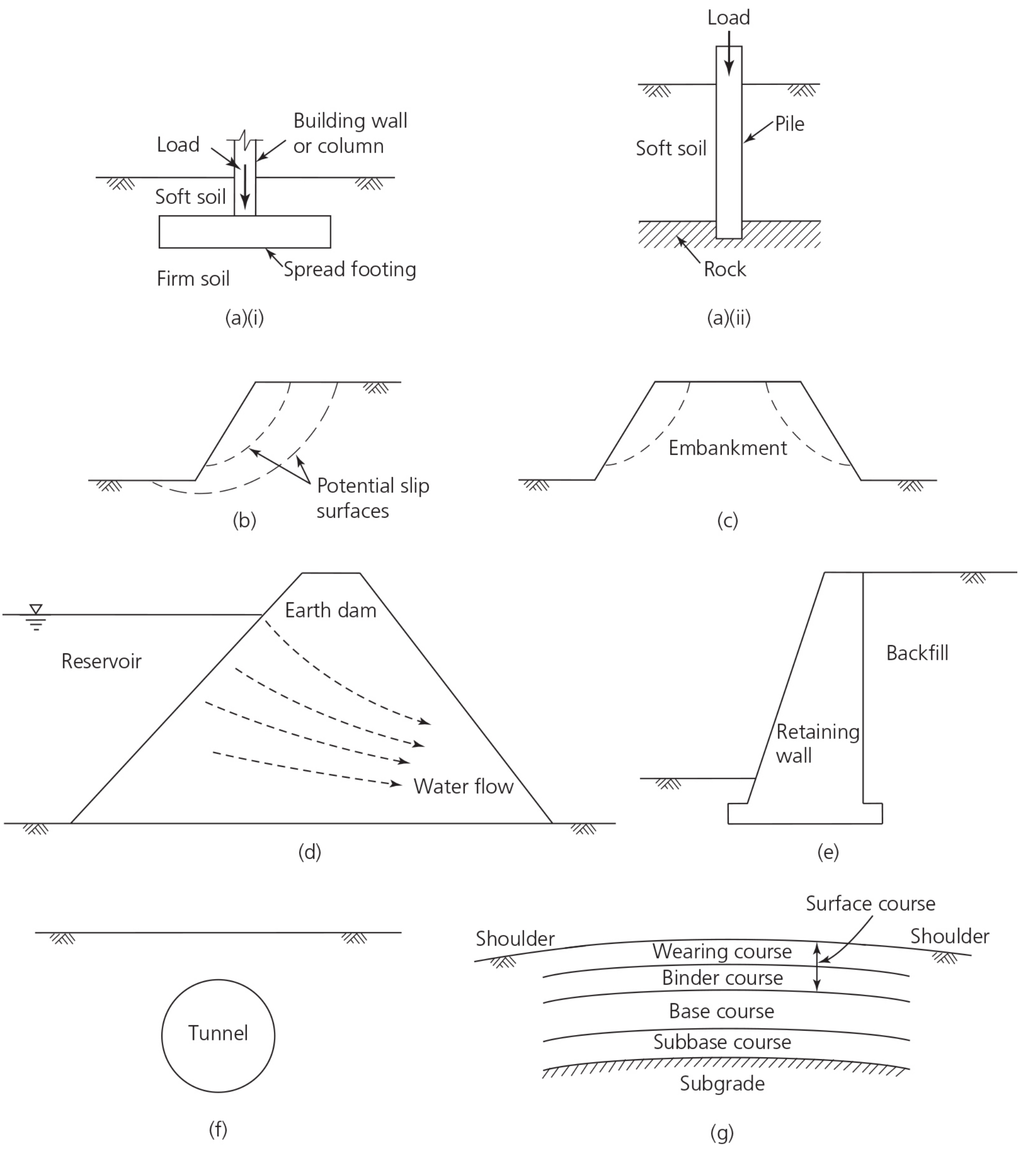
(b)

The space in a soil mass occupied by liquid and/or gas is known as the void. The soil is described as

- dry if the void volume is full of gas
- fully saturated or simply saturated if the void volume is full of liquid
- partially saturated or unsaturated if the void volume contains both gas and liquid.

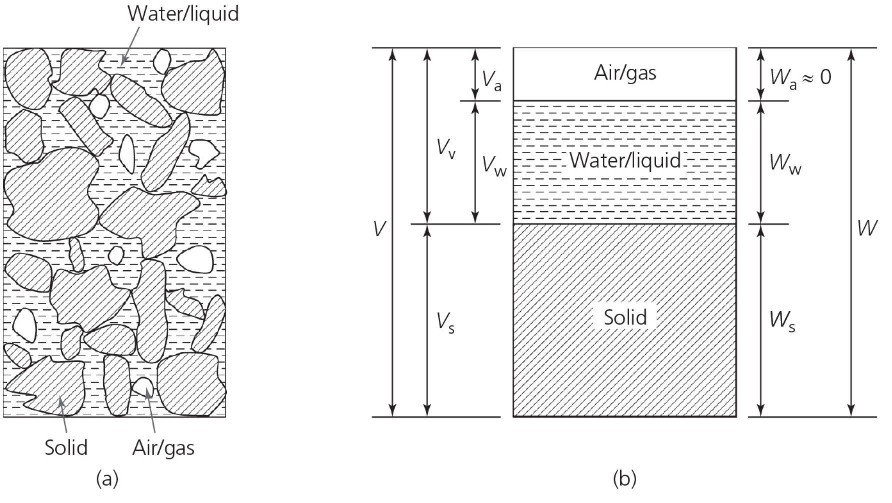
For the solution of geotechnical engineering problems, it is often necessary to know the proportions by weight (or mass) and volume of the various soil phases within a soil element. Therefore, it is convenient to use a soil phase diagram (Figure 1.4(b)) which separately shows the phases within a soil element.

Figure 1.3 Basic types of geotechnical structures: (a) foundation: (i) shallow foundation, (ii) deep foundation; (b) slope; (c) embankment; (d) earth dam; (e) retaining wall; (f) tunnel and (g) pavement



In Figure 1.4(b), the volumes of three phases are indicated on the left side and the corresponding weights on the right side. For geotechnical engineering applications, it is generally assumed that the weight of gas phase (air and water vapour) present in the voids of soil is zero. In some books and other literature, mass (M) is used in place of weight (W) in the phase diagram. In dealing with geotechnical engineering applications at various locations of the Earth, weight is preferred. The SI

Figure 1.4 (a) Element of soil with its phases in the natural state; (b) element of soil separated into its phases



Note: V and W denote volume and weight, respectively; subscripts a, w, s and v refer to air, water, solid and void, respectively.

units of mass and weight are kilogram (kg) and newton (N), respectively. Newton's second law of motion establishes the following relationship between mass and weight

$$W = Mg \tag{1.1}$$

where g denotes the acceleration due to gravity, which is usually taken as approximately 9.81 m/s^2 or sometimes 10 m/s^2, although it varies somewhat over the surface of the Earth depending on location and altitude relative to mean sea level. A 10 kg soil sample collected from a construction site will have a weight of 98.1 N. However, by rounding 9.81 m/s^2 to 10 m/s^2, the weight of the 10 kg soil sample becomes 100 N, introducing an error of approximately 2%. In professional practice, some engineers use a value of g equal to 10 m/s^2 to simplify calculations, assuming the resulting error is negligible and does not compromise the safety of engineering designs.

1.3. Phase relationships

1.3.1 Volume relationships

There are three important volume relationships: porosity, void ratio and degree of saturation.

The porosity of a soil element is the ratio of void volume, V_v, to total volume, V. Therefore, if n denotes the porosity, then

$$n = \frac{V_v}{V} \tag{1.2}$$

Porosity is normally expressed as a percentage.

The void ratio of a soil element is the ratio of void volume, V_v, to solid volume, V_s. Therefore, if e denotes the void ratio, then

$$e = \frac{V_v}{V_s} \tag{1.3}$$

Void ratio is normally expressed as a decimal.

The degree of saturation of a soil element is the ratio of water volume, V_w, to void volume, V_v. Therefore, if S denotes the degree of saturation, then

$$S = \frac{V_w}{V_v} \tag{1.4}$$

Degree of saturation is normally expressed as a percentage.

1.3.2 Weight relationships

There is only one weight relationship, namely water content (also known as moisture content), which is a crucial phase relationship in soil mechanics.

Water content of a soil element, w, is defined as the ratio of weight (or mass) of water, W_w, present in the voids to weight (or mass) of soil solids or particles (mineral matter), W_s. Thus,

$$w = \frac{W_w}{W_s} \tag{1.5}$$

The water content of soil is typically expressed as a percentage and is commonly determined in the laboratory using the oven-drying method. In this method, the soil specimen is dried generally at a temperature of about 110°C in a thermostatically controlled oven to a constant weight. The water loss due to drying is considered to represent the water in the voids of the soil specimen, while the dry weight of the soil specimen is regarded as the weight of the soil solids. This test requires the following three measurements

W_1 = weight of container
W_2 = weight of container and moist soil specimen
W_3 = weight of container and oven-dry soil specimen.

To calculate w, Equation 1.5 is used with $W_w = W_2 - W_3$, and $W_s = W_3 - W_1$, resulting in

$$w = \frac{W_2 - W_3}{W_3 - W_1} \tag{1.6}$$

Note that if the test soil contains organic materials or materials having a significant amount of hydrated water (e.g. gypsum, $CaSO_4 \cdot 2H_2O$), it may be desirable to dry such soils at a temperature much lower than 110°C, such as 65°C, or in a desiccator at room temperature. The procedure for determining the water content of soil is detailed in the standards of several countries, such as AS 1289.2.1.1 (Standards Australia, 2005), ASTM D2216-19 (ASTM, 2019), BS 1377-2:2022 (BSI, 2022) and IS 2720(Part 2):1973 (Bureau of Indian Standards, 2020).

1.3.3 Volume–weight relationships

The most commonly used volume–weight relationships, defined to serve the purpose of geotechnical projects, are as follows: total unit weight (also known as bulk, wet or moist unit weight), dry unit weight, unit weight of solids, saturated unit weight and submerged unit weight (also known as buoyant unit weight or effective unit weight). All these unit weights are expressed in SI units of N/m^3 but are typically represented in practice as kilonewtons per cubic metre (kN/m^3).

The total unit weight of a soil element, γ, is the weight of the entire soil element, W, divided by its total volume, V. Thus,

$$\gamma = \frac{W}{V} \tag{1.7}$$

Example 1.1

A cubical soil sample with an edge length of 20 cm was collected from the base level of a proposed shallow foundation. The mass of the sample was found to be 16.1 kg. Determine the total unit weight of the soil.

Solution

From Equation 1.1, the weight of soil

$W = (16.1)(9.81) = 157.9\,\text{N}$

Since the soil sample is cubical, its volume

$V = (0.2)^3 = 0.008\,\text{m}^3$

From Equation 1.7, the total unit weight

$$\gamma = \frac{157.9}{0.008} = 19737.5\,\text{N/m}^3 \approx 19.74\,\text{kN/m}^3$$

Using Equation 1.1 with M as the total mass of the entire soil element, Equation 1.7 can be expressed as

$$\gamma = \frac{Mg}{V} = \left(\frac{M}{V}\right)g = \rho g \tag{1.8}$$

where

$$\rho = \frac{M}{V} \tag{1.9}$$

is the total density (also known as bulk, wet or moist density) of soil, expressed in kg/m^3.

It should be noted that some engineers report the total density of soil rather than its total unit weight. Therefore, you should be familiar with how to obtain the total unit weight using Equation 1.8, which is often required in most geotechnical design and stability calculations, including calculations for stresses and settlements.

Example 1.2

In a geotechnical site investigation report, the total density of the foundation soil is reported to be 1728 kg/m^3. What will be the total unit weight of soil?

Solution

From Equation 1.8, the total unit weight of soil

$\gamma = (1728)(9.81) = 16951.7\,\text{N/m}^3 \approx 16.95\,\text{kN/m}^3$

The dry unit weight of a soil element, γ_d, is the weight of the soil solids in the entire soil element, W_s, divided by its total volume, V. Thus,

$$\gamma_d = \frac{W_s}{V} \tag{1.10}$$

The unit weight of solids of a soil element, γ_s, is the weight of the solids in the entire soil element, W_s, divided by the volume of the mineral matter, V_s. Thus,

$$\gamma_s = \frac{W_s}{V_s} \tag{1.11}$$

The saturated unit weight of a soil element, γ_{sat}, is the weight of the entire soil element in saturated condition, W_{sat}, divided by its total volume, V. Thus,

$$\gamma_{sat} = \frac{W_{sat}}{V} \tag{1.12}$$

When a soil element exists in nature in a submerged condition – that is, it exists below the groundwater table – it experiences an upward force. Consequently, the weight of the soil element in submerged condition is diminished by an amount equal to the weight of water equal in volume to the soil element. In view of this fact, the submerged (or buoyant) unit weight of a soil element is the weight of the entire soil element in submerged condition, W', divided by its total volume, V. Therefore, if γ' denotes the submerged unit weight of the soil element, then

$$\gamma' = \frac{W'}{V} = \frac{W_{sat} - V\gamma_w}{V} = \gamma_{sat} - \gamma_w \tag{1.13}$$

where $\gamma_w (= \rho_w g)$ is the unit weight of water with ρ_w as its density, which is 1000 kg/m^3 or 1 Mg/m^3 or 1 t/m^3 at standard conditions. The unit weight of water at standard conditions is approximately 9810 N/m^3 or 9.81 kN/m^3. For most civil engineering purposes, the unit weight of water may be taken as 10 kN/m^3.

For each unit weight, a corresponding density can be defined, as shown in Table 1.1.