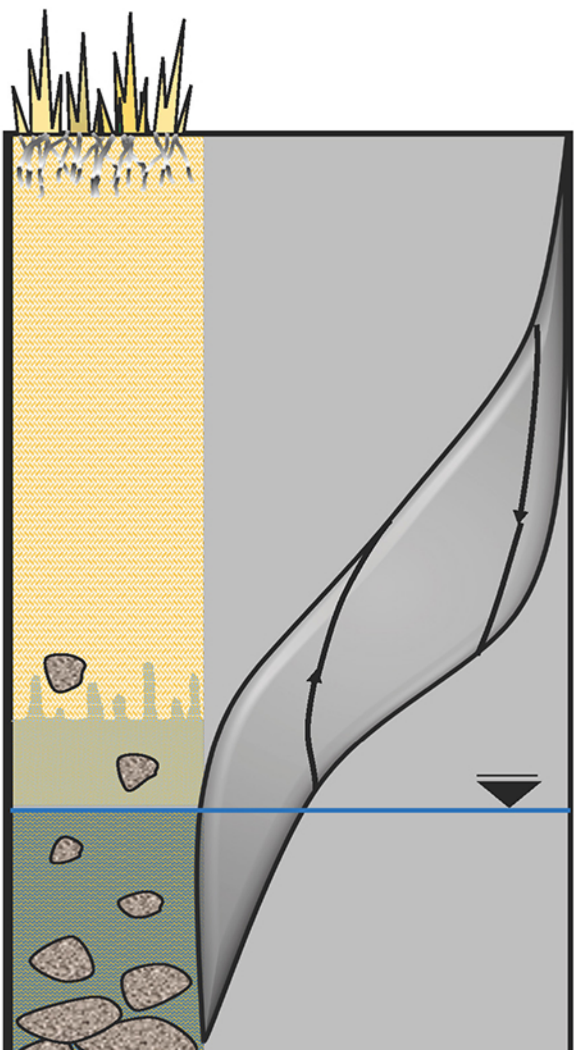
Laboratory Tests for Unsaturated Soils



Eng-Choon Leong
Martin Wijaya

CRC Press
Taylor & Francis Group

Laboratory Tests for Unsaturated Soils

The testing of unsaturated soils requires greater care and effort than that of saturated soils. Although unsaturated soil mechanics has been embraced by geotechnical engineering, engineering practice has not yet caught up as the characterisation of unsaturated soils is difficult and time-consuming, and made harder still by a lack of standards.

Laboratory Tests for Unsaturated Soils collates test procedures to cover all laboratory tests for characterising unsaturated soils. It covers the background, theory, test procedures and interpretation of test results. Each test procedure is broken down into simple stages and described in detail. The pitfalls of each test and the interpretation of the test results are explained. Test data and calculation methods are given, along with numerical examples to illustrate the methods of interpretation and to offer the presentation of typical results.

The book is especially useful for students and researchers who are new to the field and provides a practical handbook for engineering applications.

Laboratory Tests for Unsaturated Soils

Eng-Choon Leong
and
Martin Wijaya

CRC Press
Taylor & Francis Group
Boca Raton New York London

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

First edition published 2023
by CRC Press
6000 Broken Sound Parkway NW, Suite 300, Boca Raton, FL
33487-2742

and by CRC Press
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

Library of Congress Cataloging-in-Publication Data
Names: Leong, E. C., author. | Wijaya, Martin, author.
Title: Laboratory tests for unsaturated soils / Eng-Choon Leong and Martin Wijaya.
Description: First edition. | Boca Raton : CRC Press, [2023] | Includes bibliographical references and index.
Identifiers: LCCN 2022034960 | ISBN 9781138093829 (hbk) | ISBN 9780367860585 (pbk) | ISBN 9781315105147 (ebk)
Subjects: LCSH: Soil mechanics--Laboratory manuals. | Arid soils--Testing--Laboratory manuals.
Classification: LCC TA710 .L444 2023 | DDC 624.1/5136--dc23/eng/20221011
LC record available at https://lccn.loc.gov/2022034960

ISBN: 978-1-138-09382-9 (hbk)
ISBN: 978-0-367-86058-5 (pbk)
ISBN: 978-1-315-10514-7 (ebk)

DOI: 10.1201/b22304

Typeset in Sabon
by SPi Technologies India Pvt Ltd (Straive)

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Contents

Preface

The development of unsaturated soil mechanics lagged the development of saturated/classical soil mechanics. Our understanding of unsaturated soil mechanics has vastly improved in the last four to five decades. However, the application of unsaturated soil mechanics has still not become commonplace in practice. This is hardly surprising as noted by the late Professor Geoffrey Blight in his book *Unsaturated Soil Mechanics in Geotechnical Practice* that

> unsaturated soils do not usually give rise to geotechnical problems, as long as they remain in their unsaturated state at an approximately constant water content. … Problems arise when unsaturated soils become subject to wetting … that settlement, collapse or heave of soil surfaces occurs, when loss of strength results in slope failures or landslides, when piping failure is initiated, and compacted earth liners leak. Without the absorption of excess water, none of these widespread problems occur.

When these "special" problems do occur, practicing engineers who may not be familiar with unsaturated soil mechanics also faced the major problem of determining the properties of unsaturated soils. Testing of unsaturated soils entails greater care, patience and effort than saturated soils. The testing of unsaturated soils has remained mostly in the research laboratories of universities. The testing of unsaturated soils is made more difficult due to a lack of standards. Often cited problems of testing unsaturated soils are cost of the testing apparatus is expensive, the tests are complicated and the test duration is very long. While there is a workaround solution to obtaining properties of unsaturated soils by using estimation, the gold standard in obtaining unsaturated soil properties as is for saturated soils is still through tests. Hence, we have endeavoured to collate our experiences on the testing of unsaturated soils together with those of others from the literature into this book to provide a convenient source of reference for students and practitioners, as well as early researchers in unsaturated soils. Where applicable, it complements existing standards for testing of unsaturated soils and augments with current developments and knowledge.

This book assumes that the user has knowledge of classical soil mechanics and the testing of saturated soils to appreciate the significance and limitations of soil tests. Nevertheless, description of each unsaturated soil test is organised into three main parts: background and theory, test method and interpretation and analysis. The first and third parts distinguished it from the usual testing manual and are meant to help the reader to quickly grasp the basic principles of the unsaturated soil test. The test procedures are broken down into stages so that readers can associate the stages with the stages in the corresponding saturated soil test. The pitfalls in each test and the interpretation of the test results are carefully explained where applicable. The distillation of only the essential information of each test will enable the newcomer to embark on unsaturated soil testing quickly. The book contains references and further reading list to encourage readers to further develop their understanding and advanced their knowledge on unsaturated soil mechanics and unsaturated soil tests.

We hope that this book will become a useful resource and testing of unsaturated soils will become more common in practice.

Acknowledgments

This book contains the experiences in the authors' journey into unsaturated soil mechanics and unsaturated soil testing. The experiences are the collective efforts of colleagues, collaborators, students, research staff and friends who have shared the journey with the authors.

We acknowledge the influence of Professor Harianto Rahardjo who brought unsaturated soil mechanics to Nanyang Technological University. We have benefited greatly from the interactions with distinguished researchers in the field of unsaturated soils (not in any order of merit): Professors Geoffrey Blight (late), Delwyn G Fredlund, Pierre Delage, David Toll, James Graham and Sandra Houston who were at Nanyang Technological University at various points in time. We are grateful for the collaboration with various individuals: Professors Rifat Bulut, Hosaam Albuel-Naga, Ria Soemitro, Snehasis Tripathy, Arun Prasad, Alexandro Tarantino Devendra N. Singh and Lyesse Laloui.

We learnt through the experiences of many postgraduate and undergraduate students, and research staff who worked on unsaturated soils: Yeo Sir Hoon, Tran Sy Kien, Chin Kheng Boon, Than Than Nyunt, Cheng Zhuoyuan, Richard Kizza, Huang Wengui, Zou Lei, Sam Bulolo, He Liangcai, Zhang Xihu, Agus S. Samingan, Tou Jen Hau, Sri Widiastuti, Julianto Cahyadi, Lee Chin Chye, Tsen-Tieng Daryl, Trinh Min Thu, Henry Krisdani, Yang Hong, Goh Shin Guan, Alfrendo Satyanaga, Deny Tami, Harnas F.R., Indrawan I.G.B., Inge Meilani, Fifi Melinda, Lee Siew Beng, Ang Sok Ser, Senthikumar s/o Alagan, Koh Xin Yun, Jasmine Soh Xiang Qin, Rayner Wee Jian De, Ong Lay Sah @ Lisa, Peh Qingli, Tan Ee Jin, Tan Wenli Kyna, Tan Wei Jian, Liu Fang Ming, Phoong Bo Jun, Wong Kah Chou, Hardy Kek, Timothy Toh Hong Ern, Feng Yuyun, Ho Lun Fa, Muhammad Ashraf Assawaf B S, Chia Wei Ning Samuel, Ng Rui Kang Keith, Ng Teik Ting, K Loshana, Jesslyn Chua Jie Si, Jerome Tiah Sze Kiat, Eng Zheng, Leong Yoke Mun, Toh Jia Ming, Cui Xiao, Liu Chenying, Tang Weilun, Chen Xingyu, Lee Wen Yan, Jasmine Bte Sadimin, Li Lingyan, Poorooye Harivansh, Khairul Anwar Bin Ramli, Jeffrey Ho Jun Hua, V Madhavan Narayanan, Jenell A Sy Hui Zhen, Tong Wan Yi, Chong Han Siang, Chan Win Kit, Muhammad Amirul Haziq Bin Yahya, Chia You Xun, and Sarah Peter.

The second author would like to specially thank all his peers who accompanied him through his Ph.D. journey at Nanyang Technological University: Dr. Abdul Halim Hamdany, Dr. Alfrendo Satyanaga, Dr. Huang Wengui, Dr. Sam Bulolo, Dr. Richard and Felicia; friends who supported his research: Bjorn Tan and Lai Shan from Wykeham Farrance; former colleagues at Kiso-Jiban for all the great time in learning in situ and laboratory testing: Triwi Hayuningrum and Vivian Sim.

We apologise if we inadvertently omitted the names of individuals who should have been in the previous list. All contributions are gratefully acknowledged.

Last but not least, we thank the staff at Taylor & Francis: Tony Moore, who got us started on writing this book, as well Frazer Merritt and Aimee Wragg, for their patience and professionalism in handling editorial matters.

Chapter 1

Introduction

1.1 HISTORICAL DEVELOPMENT

The early study of soil mechanics was not separated into saturated and unsaturated soils as evidenced by the papers presented since the First International Society for Soil Mechanics and Foundation Engineering Conference in 1936. However, the principles and theories for saturated soils started emerging from that conference, and the concept of effective stress was first presented by Terzaghi at the same conference. The establishment of the principles of effective stress led to rapid developments in saturated soil mechanics and its application to numerous geotechnical engineering problems. In hindsight, the development of saturated soil mechanics first is natural, as saturated soils involved only two phases, soil and air (dry soil) or soil and water (saturated soil). The understanding of unsaturated soils faced many challenges in the early years. First, three phases are involved; second, soil testing was still in its infancy stage of development, and finally, most serious geotechnical engineering problems at that time involved saturated clay soils. The development of saturated soil mechanics led to the design of better soil tests, equipment and instruments. Although research on unsaturated soils did not stop completely, it was only in 1959 that a concept of effective stress for unsaturated soils appeared (Bishop 1959). In 1977, Fredlund and Morgenstern proposed two stress-state variables to describe the behaviour of unsaturated soils. With the advent of data acquisition and personal computers in the 1970s, longer duration tests and feedback control systems were made possible, and this in part helped with development of testing of unsaturated soils at constant suction where a very low shearing rate has to be applied, much lower than the shearing rate of drained tests for saturated soils.

At the same time when saturated soil mechanics was developing since the First International Society for Soil Mechanics and Foundation Engineering Conference in 1936, a separate group of people was studying a peculiar soil

DOI: 10.1201/b22304-1

known as expansive soils that cause problems to many building structures around the world. The expansive soils problem occurs with soils in which the initial condition was dry/unsaturated, but they swell extensively when wetted. Such an expansive soil problem was first recognised by the U.S. Bureau of Reclamation in 1938 for a foundation of a steel siphon at their Owyhee Project in Oregon (Holtz and Gibbs 1956). Interest in expansive soils grew, and the first national conference on expansive clay was held at the Colorado School of Mines in Golden, Colorado, in 1959. The first and second International Conferences on Expansive Soils were held at Texas A & M University in 1965 and 1969, respectively. This was followed by five more conferences on expansive soils with the seventh or last International Conference on Expansive Soils being held in Dallas, Texas, in 1992. It was realised that expansive soils fall naturally into the domain of unsaturated soils and since then it was subsumed under the International Conference of Unsaturated Soils where the first conference was held in 1995 in Paris, France. Since then many international and regional conferences have been regularly held to disseminate the latest research and developments in unsaturated soils.

Despite the numerous advances made in the testing of unsaturated soils, unsaturated soil testing remains largely in the research laboratories of the universities, although a few unsaturated soil tests have been standardised. Currently, there is no book solely on the laboratory testing of unsaturated soils. This book collates our experiences and those of others from the literature on testing of unsaturated soils to bring the advances made in unsaturated soil tests in research to commercial soil testing laboratories.

1.2 UNSATURATED SOILS

Unsaturated soils usually exist near the ground surface and arise mainly due to a deep groundwater table and climatic conditions. Hence, unsaturated soils are encountered widely in the world. Commonly, unsaturated soils are associated with residual soils, expansive soils and loess. Brief descriptions of residual soils, expansive soils and loess are given in the following sections.

1.2.1 Residual soils

The wet and humid climatic conditions in the tropics led to extensive physical and chemical weathering of rocks and rock formations, leading to the formation of residual soils (Figure 1.1). The degree of weathering is most extensive near the ground surface and decreases with depth. The depth of weathering can be quite variable. The weathering profile is commonly described using Little's (1969) six grades weathering profile as shown in Figure 1.2 where weathering grade I refers to fresh intact rock and weathering grade VI refers

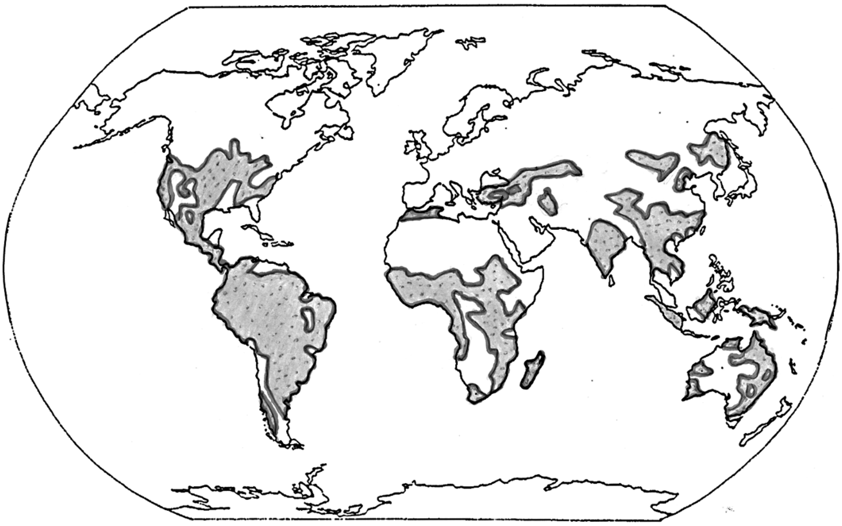

Figure 1.1 World distribution of residual soils.

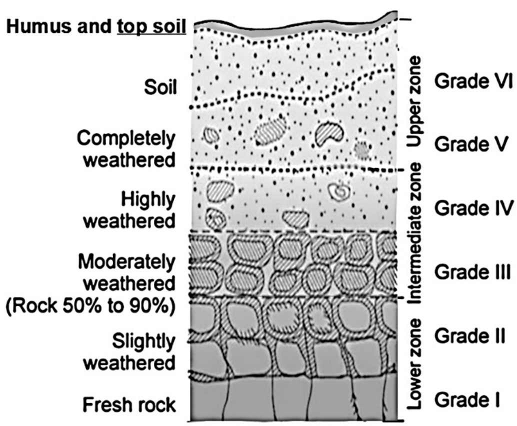

Figure 1.2 Weathering profile based on Little (1969).

to residual soil. The zones of highly weathered (grade IV) and completely weathered (grade V) which still bears the original rock structure are termed saprolite, while the zone that bears no resemblance to the original parent rock (grade VI) is termed a lateritic or residual soil. The boundary between each weathering grade is not clearly defined, and tests on residual soils can involve weathering grades IV to VI.

1.2.2 Expansive soils

Expansive soils refer to soils which swell significantly on wetting and are responsible for extensive damage to residential structures and infrastructures such as roads (Figure 1.3). Volume changes in expansive soils usually exceed 10% (Chen 1988; Nelson and Miller 1992). Damages due to expansive soils have been estimated to cost billions of dollars annually (Steinberg 1985; Dasog and Mermut 2013). The properties of expansive soils are due to the presence of swelling clay minerals, smectite or vermiculite (Rogers et al. 1993). Expansive soils are developed by geological processes which allow accumulation of predominantly silt and clay-sized particles that contained large quantities of expansive minerals (Rollings and Rollings 1996). The swelling and shrinkage of expansive soils depend on soil suction. Soil suction gives a measure of the tendency of the soil to undergo volume change when its moisture content changes with time (Cameron and Walsh 1984; Chen 1988; Nelson and Miller 1992; Bulut et al. 2001). All engineering structures on expansive soils are subjected to variations of suction at the soil surface due to climate, vegetation, drainage, site cover and watering patterns (Lytton 1977).

Hence, measuring soil suction is crucial for investigating expansive soil behaviour, and knowledge of moisture flow in expansive soils enables the estimation of the swelling and shrinkage behaviour (e.g., Arampatzis et al. 2001; Baumgartl and Kock 2004; Wray et al. 2005).

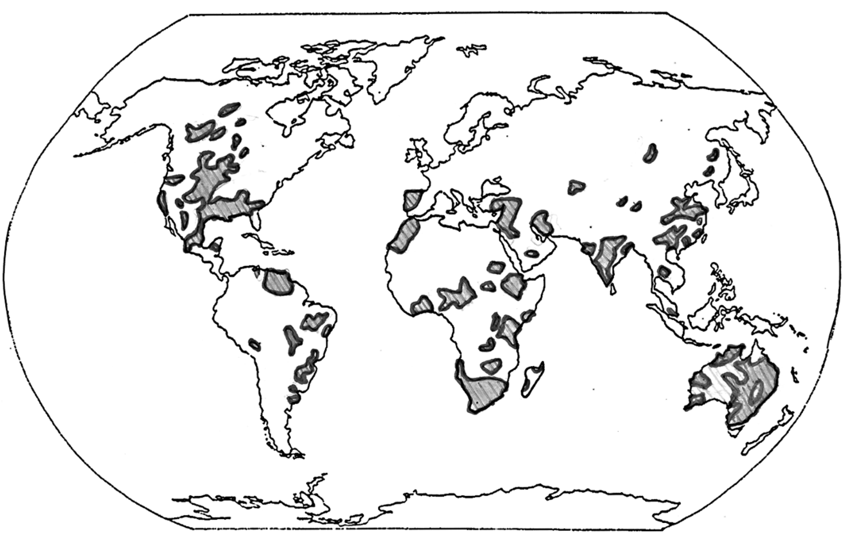

Figure 1.3 World distribution of expansive soils.

1.2.3 Loess

Loess is mainly an aeolian deposit but can also be formed by glacier grinding rocks to a fine powder and transporting them to the end of the glacier where the sediment becomes loess. The composition of loess is primarily silt-sized particles with small quantities of clay and sand particles. Loess can be found in many parts of the world (Figure 1.4), including Africa, Antarctica, Asia, central and southern Europe, northern Russia, north-western and central USA and South America (Porter 2007; Roberts et al. 2007; Rousseau et al. 2007; Zárate 2007). The most extensive occurrence of loess can be found in China. The Loess Plateau in northern and north-western China occupies a total area of about 65 × 104 km^2, which accounts for more than 6% of China's land area (Tan 1988; Derbyshire 2001; Xu et al. 2014; Li et al. 2019).

Dry loess deposits can stand vertically. However, loess is susceptible to collapse upon wetting and is associated with many geotechnical engineering problems such as wetting-induced landslides, hydroconsolidation and seismic settlement (Feda 1988; Feda et al. 1993; Dijkstra et al. 1994, 1995; Rogers et al. 1994; Derbyshire 2001; Delage et al. 2005; Yuan and Wang 2009; Xu et al. 2014). The engineering properties of loess are primarily controlled by its mineralogical composition and structure, including macroscopic texture and microstructure. Soil structure refers to both fabric and the non-frictional interparticle forces between soil particles (Lambe and Whitman 1969, Mitchell and Soga 2005). Soil fabric usually refers to the arrangement and association of particles, particle groups and pore spaces.

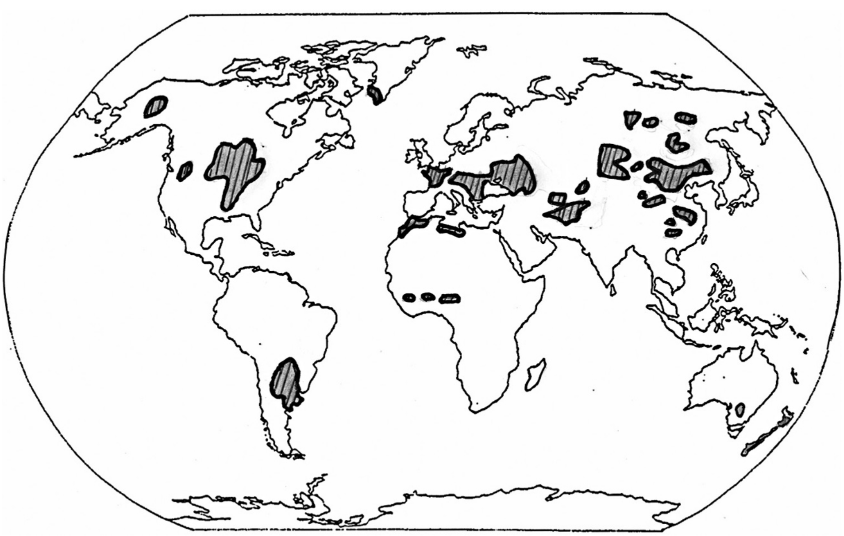

Figure 1.4 World distribution of loess.

1.3 STRESSES AND STRESS-STATE VARIABLES

In testing, the stress condition of a soil specimen in an element test such as oedometer, direct shear or triaxial test is important for interpretation. The establishment of the effective stress concept by Terzaghi (1936) has enabled the successful application of saturated soil mechanics to many geotechnical problems involving saturated soils. Hence, it is easy to understand why soil tests typically involve soil specimens in the fully saturated condition.

When a soil is fully saturated, it has two phases: soil solids and water. Both phases are incompressible, but the soil skeleton consisting of soil particles in contact (for inert particles such as sand) or in close proximity due to attractive and repulsive forces (for clay particles) reacts to the externally applied stresses. The soil particles can be re-arranged into a more compact structure with smaller voids resulting in deformation and a stronger and stiffer soil. The stresses leading to such a change are attributed to the stresses acting on the solid phase (normal stresses, σ) and the stress acting on the water phase (pore-water pressure, u_w). According to Terzaghi (1936), it is the difference between σ and u_w given by the effective stress σ' that is causing the change in state. Hence, in an element test for saturated soils, σ and u_w are applied or monitored and test results are more often interpreted based on the principles of effective stress.

Bishop (1959) proposed an effective stress for unsaturated soils:

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \tag{1.1}$$

where
u_a = pore-air pressure
χ = a parameter related to degree of saturation of the soil.

The value of χ is unity for a fully saturated soil and zero for a dry soil. However, the expression for χ is non-unique and depends on soil type. In 1961, Bishop and Donald published triaxial test results where σ, u_a and u_w were controlled independently. The test results show that the response of the soil under different σ, u_a and u_w were the same as long as $(\sigma - u_a)$ and $(u_a - u_w)$ were constant. These test results did not demonstrate the validity of Equation 1.1 but that $(\sigma - u_a)$ and $(u_a - u_w)$ are the variables that control the response of the soil.

Using multi-phase continuum principles, Fredlund and Morgenstern (1977) presented a theoretical analysis of unsaturated soils and concluded that any two of three possible normal stress variables can be used to describe the stress state of unsaturated soils. There are three possible combinations of the normal stress variables: (1) $(\sigma - u_a)$ and $(u_a - u_w)$, (2) $(\sigma - u_w)$ and $(u_a - u_w)$ and (3) $(\sigma - u_a)$ and $(\sigma - u_w)$. Among the three combinations, $(\sigma - u_a)$ and $(u_a - u_w)$

is the most convenient combination to apply in laboratory tests and shall be the stress-state variables used in this book.

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Chapter 2

Basic definitions, test environment and general apparatuses

2.1 INTRODUCTION

In all soil mechanics textbooks, phase relationships appear at the beginning of the book, as it is the most elementary way to describe a soil where the relationship of one phase of the soil is related to other phases of the soil in terms of mass and volume. It is also the phase relationships that recognise that soil in its most general state is unsaturated. Some phase relationships used in unsaturated soils were borrowed from other disciplines, and these have been included in this chapter for the benefit of those not familiar with unsaturated soil mechanics. In addition, a glossary of terms uncommon to saturated soil mechanics is given in Appendix A.

Unsaturated soils present challenges to the current norm of sampling, storage and sample preparation. Unlike saturated soils where it is sufficient to maintain the soil in a fully saturated condition during sampling, storage and sample preparation, the meaning of degree of saturation of unsaturated soils needs to be considered, as the degree of saturation of an unsaturated soil represents a transient condition which changes with the climatic condition. The purpose of obtaining the soil sample must be made known, which dictates the procedures needed for sampling, storage and sample preparation. If the purpose is to determine the in situ moisture content and suction, it is important to obtain the soil sample at its natural moisture condition and to ensure that there is no change in its moisture condition during sampling, storage and sample preparation. Being unsaturated, a soil exhibits higher strength and lower ductility. Hence, an unsaturated soil sample is harder to sample and more susceptible to cracks and breakage during sampling. Sampling at depth becomes more challenging.

2.2 PHASE RELATIONSHIPS

It is common to represent a soil as three phases where each phase has a mass and volume as shown in Figure 2.1. Generally, the mass of air is assumed to be negligible in relation to the other phases.

DOI: 10.1201/b22304-2

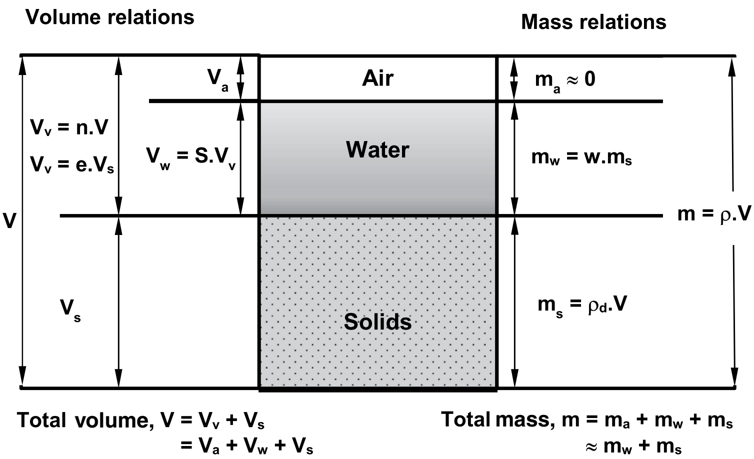


Figure 2.1 Volume-mass relations.

2.2.1 Porosity

Porosity n is defined as the ratio of volume of voids V_v to the total volume V, and is commonly expressed in percent:

$$n = \frac{V_v}{V}(100\%) \tag{2.1}$$

According to Equation 2.1, n can range from 0% to 100%, but in the loosest soils, the minimum value of n is about 10%.

2.2.2 Void ratio

Void ratio e is defined as the ratio of the volume of voids V_v to the volume of soil solids V_s:

$$e = \frac{V_v}{V_s} \tag{2.2}$$

According to Equation 2.2, e can range from 0 to greater than 1. In the densest soil, e typically ranges between 0.1 and 0.2.

2.2.3 Degree of saturation

Degree of saturation S is defined as the ratio of the volume of water in the void space to the volume of the voids and is usually expressed in percent:

$$S = \frac{V_w}{V_v}(100\%) \tag{2.3}$$

According to Equation 2.3, S can range from 0% for dry soil to 100% for a saturated soil and is between 0% and 100% for an unsaturated soil.

2.2.4 Gravimetric water content

Gravimetric water content w is defined as the ratio of mass of water M_w to the mass of soil soils M_s and is usually expressed in percent:

$$w = \frac{M_w}{M_s}(100\%) \tag{2.4}$$

Gravimetric water content w is more commonly referred to as water content in geotechnical engineering.

2.2.5 Volumetric water content

Volumetric water content θ_w is defined as the ratio of the volume of water V_w to the total volume of a soil V:

$$\theta_w = \frac{V_w}{V} \tag{2.5}$$

When the soil is saturated, i.e., $S = 100\%$, V_w will be equal to V_v, and the saturated volumetric water content θ_s will be numerically equal to the porosity n.

2.2.6 Soil density

There are two commonly used soil densities, i.e., total density and dry density. Total density of a soil is defined as the ratio of the total mass of the soil M and the total volume of the soil V:

$$\rho = \frac{M}{V} \tag{2.6}$$

Total density ρ is also referred to as bulk density, and when the soil is fully saturated ($S = 100\%$), it is usually referred to as the saturated density ρ_{sat}.

As total density ρ does not take into account the degree of saturation of the soil, it is more useful to use dry density ρ_d to express the quantity of soil solids that are packed into a unit volume of soil as a measure of its compactness. The dry density ρ_d is defined as the ratio of the mass of soil solids M_s and the total volume of the soil V:

$$\rho_d = \frac{M_s}{V} \tag{2.7}$$

2.2.7 Volume-mass relationships

Using Equations 2.1–2.7, other useful volume-mass relationships can be derived as summarised next:

$$S \cdot e = w \cdot G_s \tag{2.8}$$

$$\rho = \frac{1+w}{1+e}\rho_s = \frac{G_s(1+w)}{1+e}\rho_w = \frac{G_s + S \cdot e}{1+e}\rho_w \tag{2.9}$$

$$\rho_d = \frac{1}{1+e}\rho_s = \frac{G_s}{1+e}\rho_w \tag{2.10}$$

$$\theta_w = \frac{S \cdot e}{1+e} = S \cdot n = \frac{w \cdot G_s}{1+e} = \frac{S \cdot w \cdot G_s}{S + w \cdot G_s} \tag{2.11}$$

2.3 ROLE OF AIR

In the previous phase relationships, the air phase is "invisible". However, in the testing of unsaturated soils, the air phase is always present and in some tests leads to "inconveniences" and in other tests leads to poor test results. There are three different situations where the role of air has to be considered in the testing of unsaturated soils:

Situation 1:

Whenever there is water and air, water is present in the air as water vapour. In a closed environment where air is above water, water molecules leave the water surface as water vapour and re-enter the water surface eventually reaching equilibrium when the number of water molecules leaving and entering becomes equal at the saturated vapour condition. According to Dalton's law, the water vapour in the air has a partial pressure, and at the saturated vapour condition, the partial pressure of the water vapour is equal to the saturation vapour pressure. Equations to estimate the saturated vapour pressure of water are given in Appendix B. The saturated vapour pressure depends on the temperature (Figure 2.2). Evaporation takes place when there are more water molecules leaving than entering the water surface, and the partial pressure of water vapour in the air is below the saturation vapour. Condensation takes place when there are more water molecules entering than leaving the water surface, and the partial pressure of water vapour in the air exceeds the saturation vapour pressure. Hence, the partial pressure of the water vapour in the air represents the degree to which the air is saturated with water vapour, and the ratio of the partial pressure of the water vapour in the air to the saturated vapour pressure is called relative humidity.

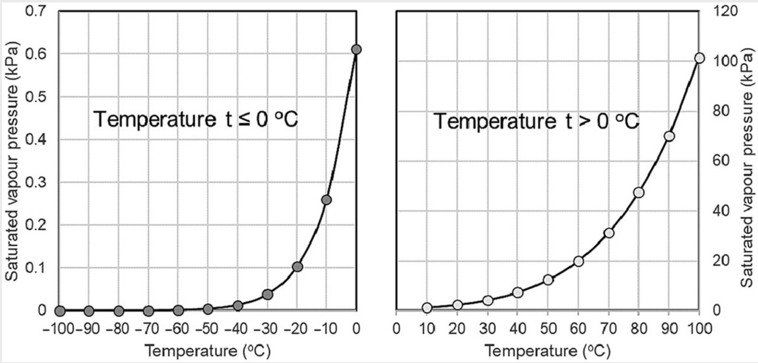


Figure 2.2 Saturated vapour pressure of water based on Huang (2018).

Condensation is observed in low suction tests (high relative humidity) when there is a drop in temperature. If the condensate falls onto the soil specimen, suction of the soil specimen may be affected. Usually, evaporation occurs during unsaturated soil tests due to two reasons: (1) air pressure above atmospheric pressure supplied to the test apparatus (closed chamber) is usually dried before entering the test apparatus, and (2) the soil specimen is exposed to ambient conditions where relative humidity is low. The suction of a soil increases as it dries. The effect of (1) on the soil specimen is dependent on the air space around the soil specimen and the air voids in the soil specimen. It is negligible when the ratio of the volume of air space to the volume of the soil specimen is small. The effect of (2) may be minimised by increasing the relative humidity of the air space around the specimen.

Situation 2:

In a test system where both air and water are present, the air can dissolve in water. The volume of air that can dissolve in a unit volume of water is called volumetric coefficient of solubility, and the rate at which air dissolves in water is called diffusivity. The amount of dissolved air in water is governed by Henry's law, which states that the amount of dissolved gas in a liquid is proportional to its partial pressure above the liquid. The higher the amount of dissolved air in water, the higher the compressibility of the water becomes, thus affecting the response behaviour of the pore-water pressure measurement in the test system. This is well known in saturated soil tests where the use of de-aired water is highly recommended. In unsaturated soil tests where air pressure remains elevated above atmospheric pressure for a long duration, the water in the system and the soil will become more and more saturated with dissolved air. However, to date, no effect of dissolved air in the pore-water of unsaturated soil on its engineering properties has been reported.

Situation 3:

Air can diffuse through water and through the water phase of soils and other porous materials. The diffusion process is governed by Fick's first law and the mass rate of transfer across a unit area of water J_m depends on the coefficient of diffusion D and the concentration gradient ∇u_a (Equation 2.12).

$$J_m = -D\nabla u_a \tag{2.12}$$

Coefficients of diffusion for air through the water phase of soils and porous elements measured by Sides and Barden (1970) are summarised in Table 2.1. The implication of Table 2.1 is that air will diffuse through the rubber membrane, soil specimen and porous elements during an unsaturated soil test in the laboratory. Hence, caution needs to be exercised when the diffused air presents a measurement error.

It is common in laboratory unsaturated soil tests, where a high air-entry ceramic disk is used to separate the air and water phases, to track the volume of water flowing out from the unsaturated soil specimen. In such tests, the diffused air will accumulate below the high air-entry ceramic disk and interfere with water flowing out of the soil specimen and, hence, its volume measurement. Padilla et al. (2006) measured the average diffusion rate of air through a 15-bar ceramic disk as shown in Figure 2.3. The average diffusion rate increases as the applied air pressure increases. Padilla et al. (2006) recommended that the tests involved be flushed according to the frequency shown in Table 2.2.

Table 2.1 Coefficients of diffusion for air through different materials

Material	*Coefficient of Diffusion, D (m^2/s) × 10^{-10}*
Free water	22.0
Latex rubber (0.5 mm thick)	1.1
Coarse porous stone (6 mm thick)	25.0
High air-entry ceramic disk (6 mm thick)	1.6
Kaolin (saturated, w = 75%)	6.2
Dement clay (saturated, w = 53%)	4.7
Jackson's-bentonite clay mix (saturated, w = 39%)	0.1
Compacted west water clay (w = 16.5%)	0.38

(data from Sides and Barden (1970)).

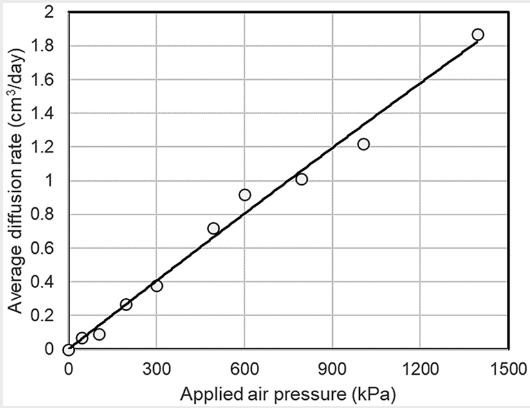


Figure 2.3 Average diffusion rate of air through saturated 15-bar high air-entry ceramic disk with applied air pressure (data from Padilla et al. (2006)).

Table 2.2 Frequency of flushing of high air-entry ceramic disks recommended by Padilla et al. (2006)

Ceramic disk	*Frequency of flushing*
1-bar	Once in three days
3-bar	Once in three days
5-bar	Once in two days
15-bar	Once a day for applied air pressures < 750 kPa Twice or more times a day for applied air pressure > 750 kPa

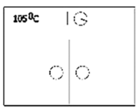
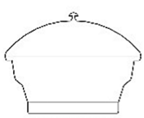
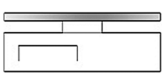
2.4 TEST ENVIRONMENT

Control of temperature and relative humidity of the test environment is needed when required, especially in the testing of unsaturated soils. When required, tests shall be conducted in an environment where the temperature and relative humidity can be controlled to within acceptable limits. For temperature, British Standards (BS1377, 1990) typically specify that the temperature should be kept to within ±4°C, whereas American Society for Testing and Materials (ASTM) typically specifies ±5°C. Commonly adopted standard temperature is taken as 20°C, but this may be difficult to achieve in tropical countries laboratories, and usually more attention is placed on recording the daily maximum and minimum temperatures and observing that the temperature fluctuation range is kept within ±4°C or ±5°C during the test. For relative humidity, there is no specific mention except for the storage of samples. Relative humidity may play a bigger role in testing unsaturated soils, as temperature and relative humidity affect the rate of drying of soil specimens during the test where such specimens are exposed to the ambient condition.

2.5 GENERAL APPARATUSES

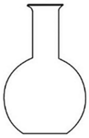
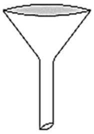
The general apparatuses that are used for soil tests can be found in many books and standards and will not be elaborated on here. For this book, we shall only look at the general apparatuses that are needed for unsaturated soil tests. Table 2.3 shows the general apparatuses which are referred to in this book.

Table 2.3 General apparatuses

Apparatus	*Description*
	Beaker 500 ml conical beaker in BS 1377-3:2018 250 ml beaker in BS 1377-3:2018
	Oven Temperature of 105°C to 110°C to be maintained for drying soil samples in BS. Temperature of 45°C to 50°C are to be used for soil samples that experience physical changes at the higher drying temperature of 105°C to 110°C Temperature of 110 ± 5°C to be maintained for drying soil samples in BS
	Burette 50 ml Burette in BS 1377-3:2018
	Desiccator Used to cool specimen after oven dry. Can be either using vacuum pump or using silica gel
	Electronic weight scales Accuracy depends on the test 0.1 g for particle density test using gas jar 0.01 g for typical water content measurement 0.001 g for particle density test using small pycnometer
	Evaporating dish 150 mm diameter – BS 1377-2 (1990)
	Round bottom flask

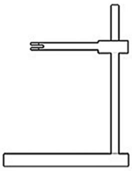
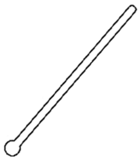
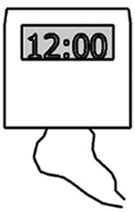
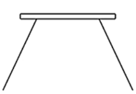
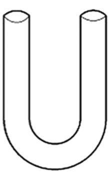
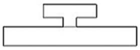
(*Continued*)

Table 2.3 (Continued)

Apparatus	*Description*
	Flat bottom flask
	BS1377-2 Small pycnometer – 50 mL Large pycnometer – 1L
	Funnel BS1377-2 (1990) Glass filter funnel – 100 mm diameter Buchner funnel – 150 mm diameter
	Gas jar 1L in capacity – BS1377-2 (1990)
	Hand vacuum pump
	Burette/pipette pump
	Hydrometer Apparatus used to conduct sedimentation test by hydrometer method according to BS 1377-2 (1990)
	Measuring cylinder 25 mL, 50 mL, 100 mL, 500 mL, 1L measuring cylinder BS1377-2 (1990)

(*Continued*)

Table 2.3 (Continued)

Apparatus	*Description*
	Pestle and mortar Used to pulverise material in Atterberg Limit (D4318-2017)
	Tube/tubing Used to provide water or air pressure
	Retort stand with clamp Typically used to support burette
	Stirrer Usually made of glass
	Stopwatch Used to record time
	Tripod Used to place non-flat bottom apparatus such as Tempe cell or round bottom flask
	U tube Used as manometer
	Weight Used to apply small seating pressure to a specimen

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