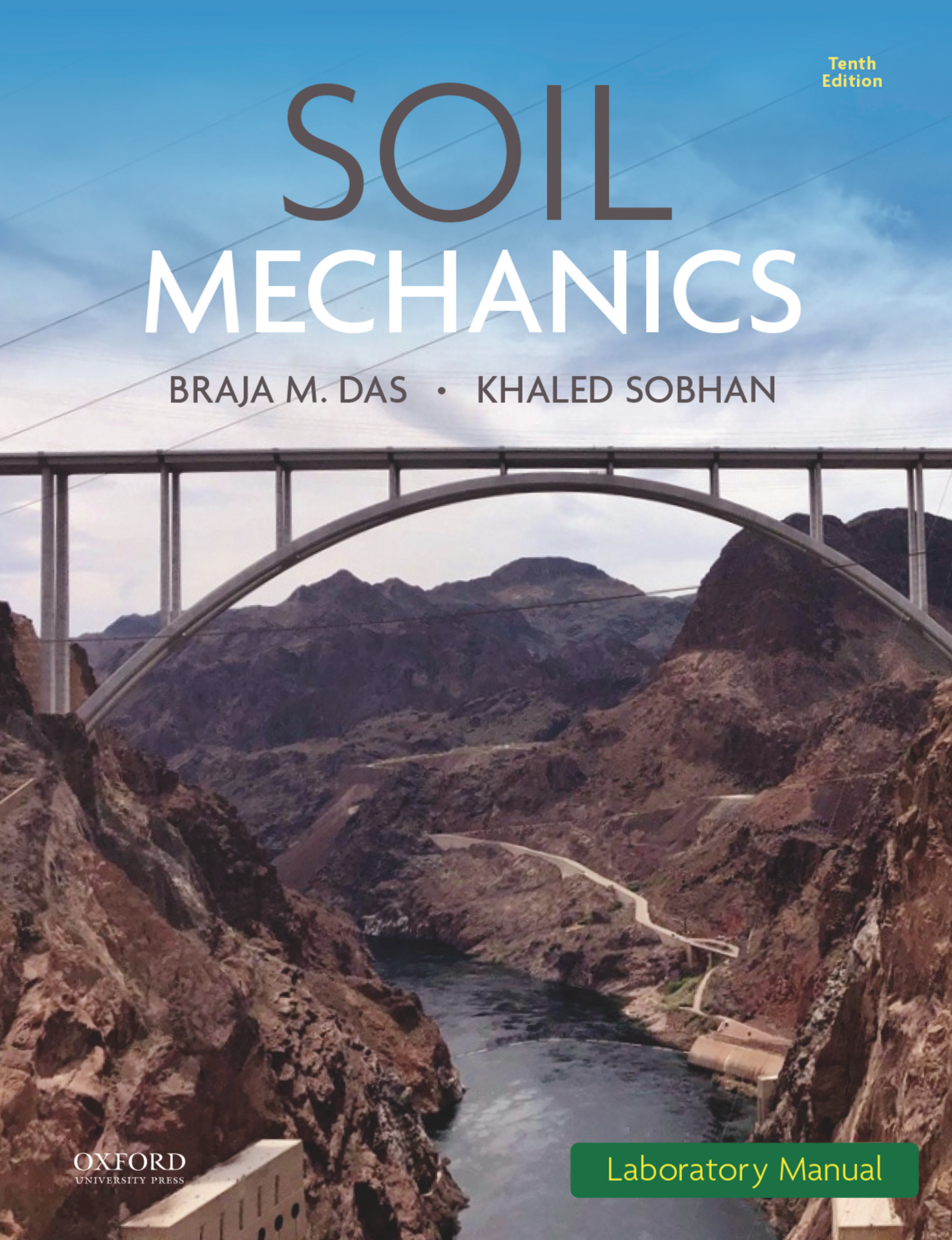

Tenth Edition

SOIL MECHANICS

BRAJA M. DAS • KHALED SOBHAN

OXFORD
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Laboratory Manual

SOIL MECHANICS
LABORATORY MANUAL

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TENTH EDITION

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To Elizabeth Madison, Armaan and Shaiza

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PREFACE

Since the early 1940s, the study of soil mechanics has made great progress all over the world. A course in soil mechanics is generally required for undergraduate students in four-year civil engineering and civil engineering technology programs. The course constitutes classroom lectures along with a laboratory component. The purpose of the laboratory component is to familiarize students with the properties of soils and their behavior under stress by means of hands-on experiments. Strong hands-on laboratory experience in soil mechanics, along with an instructor's enthusiastic personal laboratory supervision, is necessary for students to appreciate the importance of this area of civil engineering. This manual was developed through the personal experiences of the authors gained both by giving classroom lectures and presenting course laboratory components over many years. The manual, a supplement to the soil mechanics text used for the lecture sessions, incorporates input from students enrolled in the authors' courses.

In the United States, as well as in many other countries around the world, the standards set for laboratory testing by the American Society of Testing and Materials (ASTM) are used as a guide. The test procedures used in this manual are close to those given by ASTM with some minor deviations, since the book is intended for classroom use as an initial experience for the students. The liquid limit test—fall cone method (Chapter 7) and the falling-head permeability test in sand (Chapter 15) do not have ASTM standards. "Resilient Modulus Test in Cohesive and Granular Soils" described in Chapter 22 is based on AASHTO guidelines. The procedures and equipment described here are fairly common. For a few tests, such as permeability, direct shear, and unconfined compression, the existing equipment in a given laboratory may differ slightly. In those cases, the instructor will have to familiarize students with the operation of the equipment. Triaxial test assemblies are costly, and the equipment varies widely. For that reason, only general guidelines for triaxial tests are presented. Students in an introductory soil mechanics course get approximately 10 to 14 laboratory sessions, depending upon whether they are on a quarter or semester system. The duration of each session is 3 hours. Keeping this in mind, and also the original premises on which this manual was developed, several other laboratory tests that may be useful for graduate work and/or research are not included.

Each laboratory test procedure included in this manual contains sample calculation(s) and graph(s). Additional tables for each test are provided for student use in the laboratory.

The original manual was published during the summer of 1981 with a 1982 copyright by Engineering Press. For this 10th edition Khaled Sobhan of Florida Atlantic University has joined as the coauthor.

Revisions For This Edition

Following is a list of major changes/modifications for this edition.

- In Chapter 1, the Table 1.1 with a list of important ASTM designations has been updated. Added to this table is the AASTHO standard for resilient modulus test on granular and cohesive soil.
- Chapter 3 has a table with a list of specific gravity for various types of building materials for comparison with that of soil.
- Chapter 4 on sieve analysis now includes a list of Australian standard sieve sizes.
- A discussion on the readings obtained in hydrometer tests ASTM 151H and 152H hydrometers has been included in Chapter 5. Also added to this chapter is the method to determine boulder, cobble, gravel, sand and silty and clay fractions present in a soil sample using the AASHTO classification method.
- Chapter 6 has a list of some natural soils with their liquid limits.
- In chapter 7—liquid limit determination using fall cone—the following items have been added:
  - Definition of flow index
  - Empirical relationship between liquid limit determined by percussion cup method and fall cone method
  - Proposed relationships for one-point test using fall cone.
- Activity values of some natural clays have been added to Chapter 8 on plastic limit test. Also included in this chapter is an empirical relationship between activity, liquid limit, and clay-size fraction. Empirical correlations between plasticity index and flow index are also included.
- A discussion on the test designations by ASTM for shrinkage limit determination has been presented in Chapter 9. An empirical procedure to estimate shrinkage limit based on the plasticity chart is included.
- One recent correlation for maximum dry unit weight and optimum moisture content for granular soils has been added to Chapter 11.
- Chapter 12 has a summary of soil type and the rollers that provide the best results in field compaction.
- In Chapter 13, a table with the range of friction angle for sand has been added.
- The trend of the reduction of coefficient of permeability of various types of soil under applied pressure is given in Chapter 14 (Table 14.6).
- Chapter 16 on direct shear test in sand has a correlation between the friction angle obtained from the direct shear test and the triaxial compression test.
- The magnitude of sensitivity of some natural clays has been added to Chapter 17 on unconfined compression test. Also added to this chapter are some correlations for undrained cohesion of remolded clayey soils.
- Chapter 18 on consolidation test discusses alternative methods to Casagrande's suggested procedure to graphically determine the preconsolidation pressure.

- Chapter 19 on triaxial test in clay as it appeared in the ninth edition of this manual is now being presented in two chapter—Chapter 19 as unconsolidated-undrained triaxial test and Chapter 20 as consolidated-undrained triaxial test on cohesive soil.
- Chapters 21, 22, and 23 are new to this edition. Chapter 21 is on the consolidated-drained triaxial test on sandy soil, Chapter 22 covers the resilient modulus test on granular and cohesive soils, and Chapter 23 deals with the California bearing ratio for laboratory compacted soils.

The authors hope that this manual will be useful to the users in conducting the laboratory soil test.

We would like to thank Valerie Stephan for providing the photograph for the cover of the manual.

Braja M. Das, Henderson, Nevada
Khaled Sobhan, Boca Raton, Florida

SOIL MECHANICS
LABORATORY MANUAL

1

Laboratory Test and Preparation of Report

1.1 Introduction

Proper laboratory testing of soils to determine their physical properties is an integral part in the design and construction of structural foundations, the placement and improvement of soil properties, and the specifications and quality control of soil compaction works. It must be kept in mind that natural soil deposits often exhibit a high degree of nonhomogeneity. The physical properties of a soil deposit can change to a great extent even within a few hundred feet. The fundamental theoretical and empirical equations that are developed in soil mechanics can be properly used in practice if, and only if, the physical parameters used in those equations are properly evaluated in the laboratory. So, learning to perform laboratory tests of soils plays an important role in the geotechnical engineering profession. This text has been prepared exclusively for hands-on classroom use by undergraduate civil engineering and civil engineering technology students taking the introductory soil mechanics (geotechnical engineering) course.

In the United States, most laboratories conducting tests on soils for engineering purposes generally follow the procedures outlined by the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportion Officials (AASHTO). The procedures and equipment for soil tests may vary slightly from laboratory to laboratory, but the basic concepts remain the same. The test procedures described in this manual may not be exactly the same as specified by ASTM. However, for students it is beneficial to know the standard test designations and to compare them with the laboratory work they have performed. For this reason, some selected ASTM and AASHTO standard test designations are given in Table 1-1.

Table 1-1. Some Important ASTM and AASHTO Standard Test Designations*

Standard	ASTM Title	Chapter No. Citation
D-2216	Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass	2
D-854	Specific Gravity of Soil Solids by Water Pycnometer	3
D-422†	Particle-Size Analysis of Soils	4, 5
D-4318	Liquid Limit, Plastic Limit, and Plasticity Index of Soils	6, 8
D-3282	Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes	10
D-2487	Standard Practice for Classification of Soils and Soil-Aggregate Mixtures for Engineering Purposes (Unified Soil Classification System)	10
D-698	Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort [12,400 ft·lb/ft^3 (600 kN·m/m^3)]	11
D-1557	Standard Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort [56,000 ft·lb/ft^3 (2700 kN·m/m^3)]	11
D-1556	Standard Test Method for Density and Unit Weight of Soil in Place by the Sand Cone Method	12
D-2167	Standard Test Method for Density and Unit Weight of Soil in Place by the Rubber Balloon Method	12
D-4253	Standard Test Method for Maximum Index Density and Unit Weight of Soils Using a Vibrating Table	13
D-4354	Standard Test Method for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density	13
D-2434‡	Standard Test Method for Permeability of Granular Soils (Constant Head)	14
D-5084	Standard Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible-Wall Permeameter	15

Table 1-1. (Continued)

Standard	ASTM Title	Chapter No. Citation
D-3080	Standard Test Method for Direct Shear Test of Soil under Consolidated Drained Condition	16
D-2166	Standard Test Method for Unconfined Compression Strength for Cohesive Soil	17
D-4648	Standard Test Method for Laboratory Miniature Vane Shear Test for Saturated Fine-Grained Clayey Soil	17
D-2573	Standard Test Method for Field Vane Shear Test in Cohesive Soil	17
D-2435	Standard Test Method for One-dimensional Consolidation Properties of Soils Using Incremental Loading	18
D-2850	Standard Test Method for Unconsolidated Undrained Triaxial Compression Test on Cohesive Soils	19
D-4767	Standard Method for Triaxial Compression Test on Cohesive Soils	20
D-7181	Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils	21
T-294	Standard Method of Test for Resilient Modulus of Unbound Granular Base/Subbase Materials and Subgrade Soil - SHRP Protocol P46	22
D-1883	Standard Test Method for California Bearing Ratio (CBR) of Laboratory Compacted Soils	23

Based on ASTM (2017, 2019) and AASHTO (2020b).

[*] Standards starting with a D are ASTM standards; those starting with a T are AASHTO standards.

[†] Withdrawn in January 2016 in accordance with Section 10.6.3 of the *Regulations Governing ASTM Technical Committees*, which requires that the Standard shall be updated by the end of the eighth year after the last approval date. Also see ASTM (2017, p. 960) as to the fact that ASTM Subcommittee D-18.03 is preparing a new method.

[‡] Withdrawn in 2015. See ASTM (2017), p. X.

There are several other standards for testing of soil in various other countries, of which the most quoted is the British Standards BS 1377 (1990).

1.2 Use of Equipment

Laboratory equipment is never cheap, but the cost may vary widely. For accuracy of the experimental results, the equipment should be properly maintained. The calibration of certain equipment, such as balances and proving rings, should be checked periodically. It is also essential that all equipment be cleaned—both before and after use. More accurate results will be obtained when the equipment being used is clean, so always maintain the equipment as if it were your own.

Some of the equipment for the direct shear test (Chapter 16), unconfined compression test (Chapter 17), consolidation test (Chapter 18), and triaxial test (Chapters 19, 20, and 21) may vary from laboratory to laboratory. It is possible that, in a given institution, more modern and sophisticated equipment is placed in a research laboratory compared to a teaching laboratory. The photographs for equipment shown in this manual are fairly consistent with those found in a teaching laboratory.

1.3 Safety

There is always a possibility that an accident may occur while one is performing a test in the laboratory and/or in the field. Proper care must be taken to prevent such accidents from occurring.

1.4 Data Recording

In any experiment, it is always good practice to record all data in the proper table immediately after they have been taken. Scribbles on scratch paper may later be illegible or even misplaced, which may result in having to conduct the experiment again or in obtaining inaccurate results.

1.5 Report Preparation

In the classroom laboratory, most experiments described herein will probably be conducted in small groups. However, the laboratory report should be written by each student individually. This is one way that students can improve their technical writing skills. Each report should contain:

1. Cover page—The cover page should include the title of the experiment, name, group number, and date on which the experiment was performed.
2. After the cover page, the following items should be included in the body of the report:
   a. Purpose of experiment
   b. Equipment used
   c. Schematic diagram of main equipment used
   d. Brief description of test procedure

3. Results—These should include the data sheet(s), sample calculation(s), and required graph(s). Graphs and tables should be prepared as neatly as possible. *Always* give the units. Graphs should be as large as possible, and they should be labeled properly. When a computer is used to draw a graph, its authenticity should be properly verified.
4. Discussion—Depending on the laboratory test, this section of the report may involve comparison of the test results with existing empirical relationship(s), sources of error, and other details not included in the report.

1.6 Units

Two systems of units are commonly used around the world now. They are (a) the English units and (b) the SI units (Le Système International d'Unités). Since 1950, the SI units (a modern form of the metric system) are increasingly used in all countries. In 1972, the United Kingdom converted to the SI system. Both systems of units are commonly used in the United States.

In the SI system, the base units for length, mass, and time are in m (meters), kg (kilograms), and s (seconds). The units for all other physical quantities are derived units such as

- Newton (N) for force
- Pascal (P) for pressure
- Joule (J) for work done

Table 1-2 gives some of the prefixes used in the SI system.

Table 1-2. Some Prefixes Used in SI Units

Prefix	Factor	Symbol
giga	10^9	G
mega	10^6	M
kilo	10^3	kilo
hecto	10^2	h
deca	10^1	da
deci	10^{-1}	d
centi	10^{-2}	c
milli	10^{-3}	m

As an example,

$$1 \text{ kilometer } (1 \text{ km}) = (1 \text{ m})(10^3) = 1000 \text{ m}$$

$$1 \text{ millimeter } (1 \text{ mm}) = (1 \text{ m})(10^{-3}) = 0.001 \text{ m}$$

For conducting laboratory tests and preparing reports, the conversion of units may be necessary. Tables 1-3 and 1-4 provide, respectively, the conversion of English to SI units and SI to English units.

Table 1-3. Conversion from English to SI Units

Quantity	English	SI
Length	1 in.	25.4 mm
	1 ft	0.3048 m
		304.8 mm
Area	1 in.^{2}	6.4516×10^{-4} m^2
		6.4516 cm^2
		645.16 mm^2
	1 ft^2	929×10^{-4} m^2
		929.03 cm^2
		92,903 mm^2
Volume	1 in.^{3}	16.387 cm^3
	1 ft^3	0.028317 m^3
		28,317 mm^3
Velocity	1 ft/s	304.8 mm/s
		0.3048 m/s
	1 ft/min	5.08 mm/s
		0.00508 m/s
Force	1 lb	4.448 N
Stress	1 lb/in.^{2}	6.9 kN/m^2
	1 lb/ft^2	47.88 N/m^2
Unit weight	1 lb/ft^3	157.06 N/m^3
Coefficient of consolidation	1 in.^{2}/s	6.452 cm^2/s
	1 ft^2/s	929.03 cm^2/s

Table 1-4. Conversion from SI to English Units

Quantity	English	SI
Length	1 mm	3.937×10^{-2} in.
		3.218×10^{-3} ft
	1 m	39.37 in.
		3.281 ft
Area	1 cm^2	0.155 $in.^2$
		1.076×10^{-3} ft^2
	1 m^2	1550 $in.^2$
		10.76 ft^2
Volume	1 cm^3	0.061 $in.^3$
		3.531×10^{-5} ft^3
	1 m^3	61,023.74 $in.^3$
		35.315 ft^3
Velocity	1 cm/s	1.969 ft/min
		1,034,643.6 ft/year
Force	1 N	0.22482 lb
	1 kN	0.22482 kip
Stress	1 kN/m^2	0.145 $lb/in.^2$
		20.89 lb/ft^2
Unit weight	1 kN/m^3	6.361 lb/ft^3
Coefficient of consolidation	1 cm^2/s	0.155 $in.^2/s$
		2.883×10^3 ft^2/month
Mass	1 kg	2.2046 lb
		2.2046×10^{-3} kip

2

Determination of Water Content

2.1 Introduction

ASTM Standard: D-2216

British Standard: 1377-2

Most laboratory tests in soil mechanics require determination of the water content (which is sometimes also referred to as moisture content). Water content is defined as

$$w = \frac{\text{weight (or mass) of water present in a given soil mass}}{\text{weight (or mass) of dry soil}} \tag{2.1}$$

Water content is usually expressed in percent.

For better results, the *minimum* size of most soil specimens should be approximately as given in Table 2-1. These values are consistent with ASTM test designation D-2216.

2.2 Equipment

1. Moisture can(s)—Moisture cans are available in various sizes [e.g., 2 in. (50.8 mm) in diameter and 7/8 in. (22.2 mm) high; 3.5 in. (88.9 mm) in diameter and 2 in. (50.8 mm) high].
2. Oven with temperature control—For drying, the oven temperature is generally kept at 110 ± 5°C. A higher temperature should be avoided to prevent the burning of organic matter in the soil.

Table 2-1. Minimum Size of Moist Soil Samples to Determine Water Content

Maximum Particle Size in Soil (mm)	U.S. Sieve No.	Minimum Mass of Soil Sample (g)
0.425	40	20
2.0	10	50
4.75	4	100
9.5	3/8 in.	500
19.0	3/4 in.	2500
37.5	1.5 in.	10,000
75.0	3.0 in.	50,000

Table 2-2. Required Readability of Balance

Maximum Particle Size in Soil (mm)	Readability of Balance (g)
0.425	0.01
2.0	0.01
4.75	0.1
9.5	0.1
19.0	1
37.5	10
75.0	10

3. Balance—The readability of the balance to be used is given in Table 2-2 (ASTM, 2010). Figure 2-1 shows some moisture cans and a balance having a readability of 0.01 g.

Figure 2-1. Moisture cans and balance.

2.3 Procedure

1. Determine the mass (g) of three empty moisture cans plus their caps, M_1, and also record the numbers (lines 1 and 2 of Table 2-3).
2. Place samples of representative moist soil in the cans. Close the cans with their caps to avoid loss of moisture.
3. Determine the combined mass (g) of the closed cans and moist soil, M_2 (line 3 of Table 2-3).
4. Remove the caps from the top of the cans and place them at the bottom (of the cans).
5. Put the cans (Step 4) in the oven to dry the soil to a constant weight. In most cases, 24 hours of drying is enough.
6. Determine the combined mass (g) of the dry soil samples plus the cans and their caps, M_3 (line 4 of Table 2-1).

2.4 Calculations

1. Calculate the mass of moisture, $M_2 - M_3$ (line 5 of Table 2-2)
2. Calculate the mass of dry soil, $M_3 - M_1$ (line 6 of Table 2-3)
3. Calculate the water content (line 7 of Table 2-3),

$$w\,(\%) = \frac{M_2 - M_3}{M_3 - M_1} \times 100 \tag{2.2}$$

4. Calculate the average of the three water contents determined in Step 3 (see bottom of Table 2-3).

Report the average water content to the nearest 1% or 0.1%, as appropriate, based on the size of the specimen.

Table 2-3. Determination of Water Content

Description of soil Brown silty clay Sample no. 4

Location

Tested by Date

Item	Test No.		
	1	2	3
1. Can no.	42	31	54
2. Mass of can, M_1 (g)	17.31	18.92	16.07
3. Mass of can + wet soil, M_2 (g)	43.52	52.19	39.43
4. Mass of can + dry soil, M_3 (g)	39.86	47.61	36.13
5. Mass of moisture, $M_2 - M_3$ (g)	3.66	4.58	3.30
6. Mass of dry soil, $M_3 - M_1$ (g)	22.55	28.69	20.06
7. Water content, $w\ (\%) = \dfrac{M_2 - M_3}{M_3 - M_1} \times 100$	16.2	16.0	16.5

Average water content w 16.2 %

A complete sample calculation of water content is given in Table 2-3.

2.5 General Comments

1. Most natural soils that are sandy and gravelly in nature may have water contents of up to about 15–20%. In natural fine-grained (silty or clayey) soils, water contents of up to about 50–80% can be found. However, peat and highly organic soils with water contents of up to about 500% are not uncommon. Typical values of water content for various types of natural soils in a saturated state are shown in Table 2-4. The term "*saturated state*" means that all the void spaces between the solid particles are filled with water.
2. Some organic soils may decompose during oven drying at 110 ± 5°C. This oven drying temperature may be too high for soils containing gypsum, as this material dehydrates slowly. For such soils, a drying temperature of 60°C is more appropriate.

Table 2-4. Typical Values of Water Content in a Saturated State

Soil	Natural Water Content in a Saturated State (%)
Loose uniform sand	25–30
Dense uniform sand	12–16
Loose angular-grained silty sand	25
Dense angular-grained silty sand	15
Stiff clay	20
Soft clay	30–50
Soft organic clay	80–130
Glacial till	10

Figure 2-2. A desiccator. (Courtesy of N. Sivakugan, James Cook University, Australia.)

3. Cooling the dry soil after oven drying (Step 5 of Section 2.3) in a desiccator is recommended. A desiccator, as shown in Figure 2-2, is a glass container that contains a desiccant, such as anhydrous silica gel, that keeps the air within the glass container dry.

2.6 Laboratory Report

The laboratory report should contain the following:

- Cover page
- Equipment used
- Description of test procedure
- Results—data sheet and sample calculations
- Sources of error, if any

3

Specific Gravity of Soil Solids

3.1 Introduction

ASTM Standard: D-854
British Standard: 1377-2

The specific gravity of a given material is defined as the ratio of the density of a given volume of the material to the density of an equal volume of distilled water. In soil mechanics, the specific gravity of soil solids (which is often referred to as the specific gravity of soil) is an important parameter for calculating the weight–volume relationship. Thus, specific gravity G_s is defined as

$$G_s = \frac{\text{density of soil solids only}}{\text{density of water}}$$

or

$$G_s = \frac{M_s/V_s}{\rho_w} = \frac{M_s}{V_s \rho_w} \tag{3.1}$$

where M_s = mass of soil solids (g)
V_s = volume of soil solids (cm^3)
ρ_w = density of water (g/cm^3)

Most soils found in nature are combinations of various types of minerals. The ranges of the values of G_s for common minerals found in soil are given in Table 3-1. The general ranges of the values of G_s for various soils are given in Table 3-2. It is also interesting to

Table 3-1. General Ranges of G_s for Common Minerals

Mineral	Range of G_s
Quartz	2.65
Kaolinite	2.6
Illite	2.8
Montmorillonite	2.65–2.80
Halloysite	2.0–2.55
Potassium feldspar	2.57
Sodium and calcium feldspar	2.62–2.76
Chlorite	2.6–2.9
Biotite	2.8–3.2
Muscovite	2.76–3.1
Hornblende	3.0–3.47
Limonite	3.6–4.0
Olivine	3.27–3.7

Table 3-2. General Ranges of G_s for Various Soils

Soil Type	Range of G_s
Sand	2.63–2.67
Silts	2.65–2.7
Clay and silty clay	2.67–2.9
Organic soil	Less than 2

compare the values of G_s for various types of soil with those for various types of building materials, as given in Table 3-3.

The procedure for determining the specific gravity G_s described here is applicable for soils composed of particles *smaller than* 4.75 mm in size (No. 4 U.S. sieve). Note that Table 4-1 provides the opening sites for all U.S. sieves.

Table 3-3. Approximate G_s Values for Building Materials

Building Material	Approximate G_s
Crushed asphalt	0.73
Fire clay brick	2.5
Portland cement	3.15
Glass	2.58
Cast iron	7.21
Cement mortar	2.15

3.2 Equipment

1. Volumetric flask (500 ml)
2. Thermometer graduated in 0.5°C division scale
3. Balance sensitive up to 0.01 g
4. Distilled water
5. Bunsen burner and stand (and/or vacuum pump or aspirator)
6. Evaporating dishes
7. Spatula
8. Plastic squeeze bottle
9. Drying oven

The equipment for this experiment except for the drying oven is shown in Figure 3-1.

3.3 Procedure

1. Clean the volumetric flask well and dry it.
2. Carefully fill the flask with de-aired, distilled water up to the 500-ml mark (bottom of the meniscus should be at the 500-ml mark).
3. Determine the mass of the flask and the water filled to the 500-ml mark, M_1 [Fig. 3-2(a) and line 2 of Table 3-6].
4. Insert the thermometer into the flask with the water and determine the temperature of the water, $T = T_1$°C (see top of Table 3-6).
5. Put the air-dried soil into an evaporating dish. Table 3-4 gives the approximate mass of dry soil to be used for the test (ASTM test designation D-854).
6. If the soil is cohesive, add water (de-aired and distilled) to the soil and mix it to the form of a smooth paste. Keep it soaked in the evaporating dish for about 1/2 to 1 hour. (*Note:* This step is not necessary for granular, i.e., noncohesive soils.)

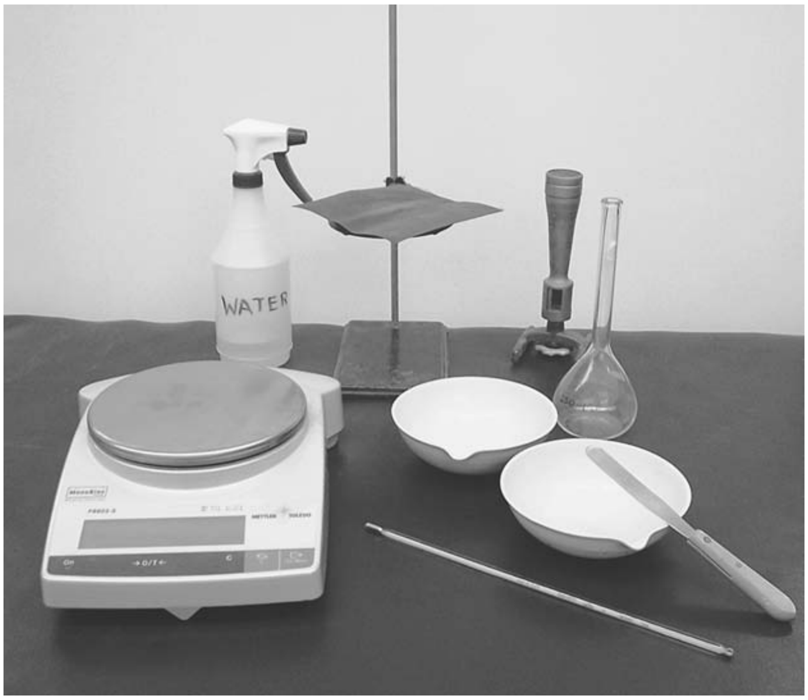

Figure 3-1. Equipment for conducting specific gravity test.

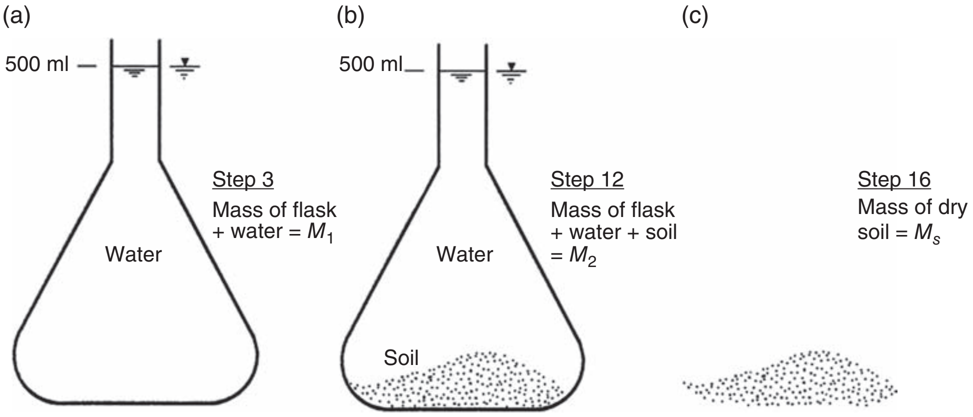

Figure 3-2. Stages of specific gravity test.

Table 3-4. Approximate Mass of Dry Soil to Be Used for Test

Soil Type*	General Description	Dry Mass of Specimen (g)
SP, SP–SM	Poorly graded sand; poorly graded sand with silt	100 ± 10
SP–SC, SM, SC	Poorly graded sand with clay; silty sand; clayey sand	75 ± 10
Silt and clay	—	50 ± 10

*Unified soil classification; see Chapter 10.

7. Transfer the soil (if granular) or the soil paste (if cohesive) into the volumetric flask.
8. Add distilled water to the volumetric flask containing the soil (or the soil paste) to make it about two-thirds full.
9. Remove the air from the soil–water mixture. This can be done by either:
    a. Gently boiling the flask containing the soil–water mixture for about 15–20 minutes. Accompany the boiling with continuous agitation of the flask. (If too much heat is applied, the soil may boil over.)
    b. Applying vacuum by a vacuum pump or aspirator until all of the entrapped air is out.

    This is an *extremely important* step. Most errors in the results of this test are due to *entrapped air that was not removed.*
10. Bring the temperature of the soil–water mixture in the volumetric flask down to room temperature, T_1°C; see Step 4. (This temperature of the water is room temperature.)
11. Add de-aired, distilled water to the volumetric flask until the bottom of the meniscus touches the 500-ml mark. Also dry the outside of the flask and the inside of the neck above the meniscus.
12. Determine the combined mass of the flask plus soil plus water, M_2 [Fig. 3-2(b) and line 3 of Table 3-6].
13. Just as a precaution, check the temperature of soil and water in the flask to see whether or not it is $T_1 \pm 1$°C.
14. Pour the soil and water into an evaporating dish. Use a plastic squeeze bottle and wash the inside of the flask. Make sure that no soil is left inside.
15. Put the evaporating dish in an oven to dry to a constant weight.
16. Determine the mass of the dry soil in the evaporating dish, M_s [Fig. 3-2(c) and line 4 of Table 3-6].

3.4 Calculations

A complete sample calculation is shown in Table 3-6. Calculate the specific gravity,

$$G_s = \frac{\text{mass of soil } M_s}{\text{mass of equal volume of water } M_w} \tag{3.2}$$

where the mass of equal volume of water is

$$M_w = (M_1 + M_s) - M_2 \quad \text{(line 5 of Table 3-6)}$$

So,

$$G_{s\,(\text{at } T_1{}^\circ\text{C})} = \frac{M_s}{M_w} \quad \text{(line 6 of Table 3-6)} \tag{3.3}$$

Specific gravity is generally reported at a temperature corresponding to 20°C. So,

$$\begin{aligned} G_{s\,(\text{at } 20^\circ\text{C})} &= G_{s\,(\text{at } T_1{}^\circ\text{C})} \left[\frac{\rho_{w\,(\text{at } T_1{}^\circ\text{C})}}{\rho_{w\,(\text{at } 20^\circ\text{C})}} \right] \\ &= G_{s\,(\text{at } T_1{}^\circ\text{C})}\, A \quad \text{(line 7 of Table 3-6)} \end{aligned} \tag{3.4}$$

where

$$A = \frac{\rho_{w\,(\text{at } T_1{}^\circ\text{C})}}{\rho_{w\,(\text{at } 20^\circ\text{C})}} \tag{3.5}$$

and ρ_w is the density of water. The density of water ρ_w at 20°C is 0.99821 g/cm^3. The density of water at a temperature T_1 can be given as (ASTM, 2019),

$$\rho_w \ (\text{at } T_1{}^\circ\text{C}) = 1.00034038 - (7.77 \times 10^{-6})T_1 - (4.95 \times 10^{-6})T_1^2 \tag{3.6}$$

where ρ_w is in g/cm^3 and T_1 is in °C

Using Eqs. (3.5) and (3.6) and ρ_w (at 20°C), the variation of A with T_1 has been calculated and given in Table 3-5.

At least two specific gravity tests should be conducted. From the sample calculations shown in Table 3-6, check R_g [see Eq. (3.7) and discussion in Section 3.5]

$$R_g = \frac{2.678}{2.658} \approx 1.008 < 1.2 \quad \text{OK}$$

3.5 General Comments

Once the values of G_s from the two tests have been determined, obtain the ratio

$$R_g = \frac{\text{larger value of } G_s}{\text{smaller value of } G_s} \tag{3.7}$$

- If $R_g \leq 1.2$, calculate the average value of G_s.

Table 3-5. Values of *A* [Eq. (3.5)]

Temperature (T_1°C)	A	Temperature (T_1°C)	A
15.0	1.00090	23.0	0.99933
15.5	1.00082	23.5	0.99921
16.0	1.00074	24.0	0.99909
16.5	1.00066	24.5	0.99897
17.0	1.00057	25.0	0.99884
17.5	1.00048	25.5	0.99871
18.0	1.00039	26.0	0.99858
18.5	1.00030	26.5	0.99844
19.0	1.00020	27.0	0.99831
19.5	1.00010	27.5	0.99817
20.0	1.00000	28.0	0.99803
20.5	0.99990	28.5	0.99788
21.0	0.99979	29.0	0.99774
21.5	0.99968	29.5	0.99759
22.0	0.99957	30.0	0.99744
22.5	0.99945		

- If $R_g > 1.2$, perform an additional test and determine R_g. When the two values of G_s agree sufficiently, take the average of the two values and round it to the nearest 0.01.

3.6 Laboratory Report

The laboratory report should contain the following:

- Cover page
- Equipment used
- Description of test procedure
- Results—data sheet and sample calculations

Table 3-6. Specific Gravity of Soil Solids

Description of soil Light brown sandy silt Sample no. 23

Volume of flask at 20°C 500 ml Temperature of test, T_1 23 °C A 0.9993 (Table 3-5)

Location

Tested by Date

Item	Test No.	
	1	2
1. Volumetric flask no.	6	8
2. Mass of flask + water filled to mark, M_1 (g)	660.0	674.0
3. Mass of flask + soil + water filled to mark, M_2 (g)	722.0	738.3
4. Mass of dry soil, M_s (g)	99.0	103.0
5. Mass of equal volume of water and soil solids, M_w (g) = $(M_1 + M_s) - M_2$	37.0	38.7
6. $G_{s\,(\text{at } T_1{}^\circ\text{C})} = M_s/M_w$	2.68	2.66
7. $G_{s\,(\text{at } 20^\circ\text{C})} = G_{s\,(\text{at } T_1{}^\circ\text{C})} \times A$	2.678	2.658

Average $G_s = \frac{2.678 + 2.658}{2} = 2.668 \approx 2.67$

- Sources of error—If $R_g > 1.2$ [Eq. (3.7)] from the two initial tests, discuss the possible error (e.g., not using the same balance for weighing, poor adjustment of the balance, and also de-airing).

4

Sieve Analysis

4.1 Introduction

ASTM Standard: D-422 (withdrawn by the ASTM; see footnote in Table 1-1)
To classify a soil for engineering purposes, one needs to know the distribution of the grain sizes in a given soil mass. Sieve analysis is a method used to determine the grain size distribution of soils. Sieves are made of woven wires with square openings. The current size designation for U.S. sieves uses 100 mm to 6.3 mm, and they are as follows:

100.0 mm
75.0 mm
63.0 mm
50.0 mm
45.0 mm
37.5 mm
31.5 mm
25.0 mm
19.0 mm
16.0 mm
12.5 mm
9.5 mm
8.0 mm
6.3 mm

After the 6.3 mm size designation, a number designation is used, that is, No. 4 to No. 400. These are shown in Table 4-1.

Table 4-1. U.S. Sieve Sizes

Sieve No.	Opening (mm)	Sieve No.	Opening (mm)
4	4.75	45	0.355
5	4.00	50	0.300
6	3.35	60	0.250
7	2.80	70	0.212
8	2.36	80	0.180
10	2.00	100	0.150
12	1.70	120	0.125
14	1.40	140	0.106
16	1.18	170	0.090
18	1.00	200	0.075
20	0.85	230	0.063
25	0.71	270	0.053
30	0.60	325	0.045
35	0.500	400	0.038
40	0.425		

The opening for the *i*th sieve given in Table 4-1 can be approximately given as

$$\text{Opening for the } i\text{th sieve} = \frac{\text{Opening for the } (i-1)\text{th sieve}}{(2)^{0.25}} \tag{4.1}$$

For example,

$$\begin{aligned}\text{Opening for the No. 5 sieve} &= \frac{\text{Opening for the No. 4 sieve}}{(2)^{0.25}}\\ &= \frac{4.75 \text{ mm}}{1.1892} = 3.994 \text{ mm} \approx 4.00 \text{ mm}\end{aligned}$$

Similarly,

$$\text{Opening for the No. 50 sieve} = \frac{\text{Opening for the No. 45 sieve}}{(2)^{0.25}}$$

$$= \frac{0.335\ \text{mm}}{1.1892} = 0.2985\ \text{mm} \approx 0.300\ \text{mm}$$

Several other countries have their own sieve sizes which are commonly referred to by their aperture sizes. For example, the British Standard (BS) sieve sizes commonly used are shown in Table 4-2.

Table 4-2. British Standard Sieve Sizes

75 mm	3.35 mm
63 mm	2 mm
50 mm	1.18 mm
37.5 mm	0.600 mm
28 mm	0.425 mm
20 mm	0.300 mm
14 mm	0.212 mm
10 mm	0.15 mm
6.3 mm	0.063 mm
5.0 mm	

Table 4-3 shows the Australian standard sieve sizes.

In this manual, the U.S. Standard sieves will be used for all tests as needed. For sandy and fine-grained soils, generally sieve Nos. 4, 10, 20, 40, 60, 140, and 200 are used.

For all practical purposes, the No. 200 sieve is the sieve with the smallest opening that should be used for the test. The sieves that are most commonly used for soil tests have a diameter of 8 in. (203 mm). A stack of sieves is shown in Figure 4-1.

The method of sieve analysis described here is applicable for soils that are *mostly granular, with some or no fines.* Sieve analysis does not provide information about the shape of the particles.

Table 4-3. Australian Standard Sieve Sizes

75.0 mm	2.36 mm
63.0 mm	2 mm
37.5 mm	1.18 mm
26.5 mm	0.60 mm
19.0 mm	0.425 mm
13.2 mm	0.30 mm
9.5 mm	0.212 mm
6.7 mm	0.15 mm
4.75 mm	0.063 mm

Figure 4-1. Stack of sieves with a pan at the bottom and a cover at the top.

4.2 Equipment

1. Sieves, a bottom pan, and a cover. (*Note:* Sieve Nos. 4, 10, 20, 40, 60, 140, and 200 are generally used for most standard sieve analysis work.)
2. A balance sensitive to 0.1 g
3. Mortar and rubber-tipped pestle
4. Oven
5. Mechanical sieve shaker

4.3 Procedure

1. Collect a *representative* oven-dry soil sample. Samples with the largest particles being of the size of No. 4 sieve openings (4.75 mm) should weigh about 500 g. For soils with the largest particles of a size greater than 4.75 mm, larger weights are needed.
2. Break the soil sample into individual particles using a mortar and a rubber-tipped pestle. (*Note:* The idea is to break up the soil into individual particles, not to break the particles themselves.)
3. Determine the mass M of the sample accurately to 0.1 g (see top of Table 4-4).
4. Prepare a stack of sieves. A sieve with larger openings is placed above a sieve with smaller openings. The sieve at the bottom should be No. 200. A bottom pan should be placed under the No. 200 sieve. As mentioned before, the sieves that are generally used in a stack are Nos. 4, 10, 20, 40, 60, 140, and 200; however, more sieves can be placed in between.
5. Pour the soil prepared in Step 2 into the stack of sieves from the top.
6. Place the cover on the top of the stack of sieves.
7. Run the stack of sieves through a sieve shaker for about 10–15 minutes (Fig. 4-2).
8. Stop the sieve shaker and remove the stack of sieves.
9. Weigh the amount of soil retained on each sieve and in the bottom pan (col. 3 of Table 4-4).
10. If a *considerable* amount of soil with silty and clayey fractions is retained on the No. 200 sieve, it has to be washed. Washing is done by taking the No. 200 sieve with the soil retained on it and pouring water through the sieve from a tap in the laboratory (Fig. 4-3).
11. When the water passing through the sieve is clean, stop the flow of water. Transfer the soil retained on the sieve at the end of washing to a porcelain evaporating dish by back washing (Fig. 4-4). Put it in the oven to dry to a constant weight. (*Note:* This step is not necessary if the amount of soil retained on the No. 200 sieve is small.)

Determine the mass of the dry soil retained on the No. 200 sieve. The difference between this mass and that retained on the No. 200 sieve determined in Step 9 is the mass of soil that has washed through.

Figure 4-2. Stack of sieves in a sieve shaker.

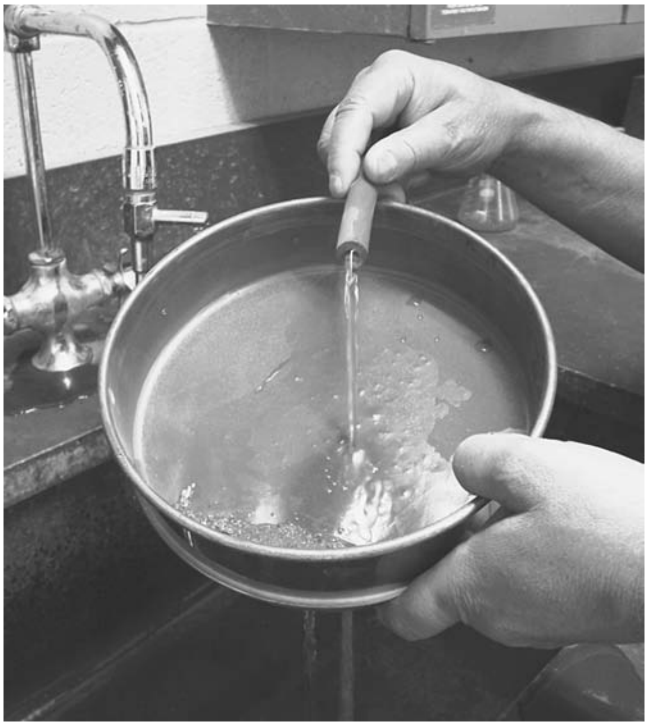

Figure 4-3. Washing of soil retained on No. 200 sieve.

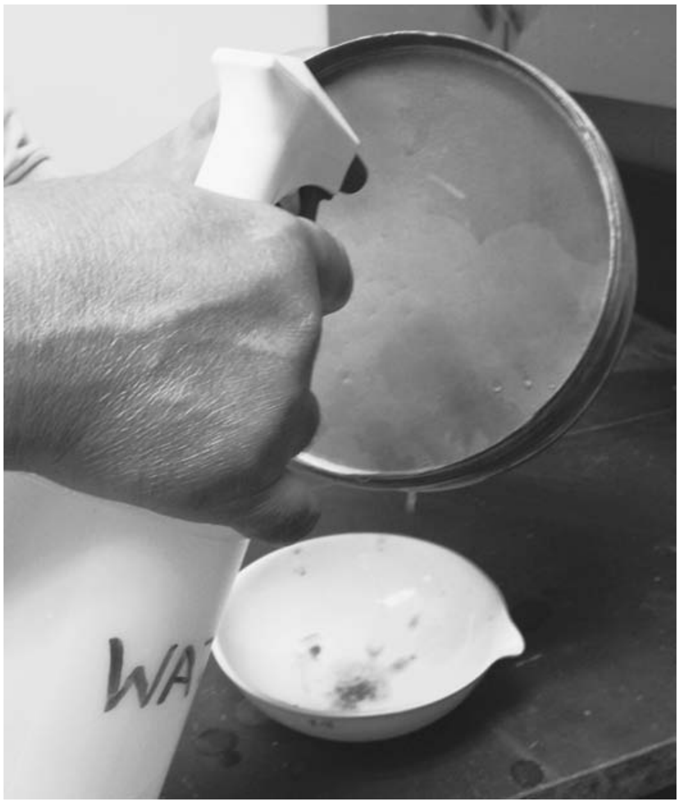

Figure 4-4. Back washing to transfer soil retained on No. 200 sieve to an evaporating dish.

4.4 Calculations

A complete sample calculation is shown in Table 4-4.

1. Calculate the percent of soil retained on the *n*th sieve (counting from the top),

$$\frac{\text{mass retained } M_n}{\text{total mass } M \text{ (Step 3)}} \times 100 = R_n \quad \text{(col. 4 of Table 4-4)} \tag{4.2}$$

2. Calculate the cumulative percent of soil retained on the *n*th sieve,

$$\sum_{i=1}^{i=n} R_n \quad \text{(col. 5 of Table 4-4)} \tag{4.3}$$

Table 4-4. Sieve Analysis

Description of soil Sand with some fines Sample no. 2

Mass of oven-dry specimen M 500 g

Location ________

Tested by ________ Date ________

Sieve No. (1)	Sieve Opening (mm) (2)	Mass of Soil Retained on Each Sieve M_n (g) (3)	Percent of Mass Retained on Each Sieve R_n (4)	Cumulative Percent Retained $\sum R_n$ (5)	Percent Finer $100 - \sum R_n$ (6)
4	4.750	0	0	0	100.0
10	2.000	40.2	8.0	8.0	92.0
20	0.850	84.6	16.9	24.9	75.1
30	0.600	50.2	10.0	34.9	65.1
40	0.425	40.0	8.0	42.9	57.1
60	0.250	106.4	21.3	64.2	35.8
140	0.106	108.8	21.8	86.0	14.0
200	0.075	59.4	11.9	97.9	2.1
Pan	—	8.7			

$\sum$ 498.3 $= M_1$

Mass loss during sieve analysis: $\frac{M - M_1}{M} \times 100 =$ 0.34 % (OK if less than 2%)

3. Calculate the cumulative percent passing through the nth sieve,

$$\text{percent finer} = 100 - \sum_{i=1}^{i=n} R_n \quad \text{(col. 6 of Table 4-4)} \tag{4.4}$$

Note: If soil retained on the No. 200 sieve is washed, the dry weight determined after washing (Step 11) should be used to calculate the percent finer (than No. 200 sieve). The weight lost due to washing should be added to the weight of the soil retained on the pan.

4.5 Graphs

The grain-size distribution obtained from the sieve analysis is plotted on semilogarithmic graph paper with the grain size on a log scale and percent finer on a natural scale. Figure 4-5 is a grain-size distribution plot for the calculations shown in Table 4-4. The grain-size distribution plot helps to estimate the percent finer than a given sieve size that might not have been used during the test.

4.6 Other Calculations

If 12% or less is passing a No. 200 sieve:

1. Determine D_{10}, D_{30}, and D_{60} (from Fig. 4-5), which are the diameters corresponding to percents finer of 10%, 30%, and 60%, respectively.
2. Calculate the uniformity coefficient C_u and the coefficient of gradation C_c using the following equations:

$$C_u = \frac{D_{60}}{D_{10}} \tag{4.5}$$

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} \tag{4.6}$$

The determination of C_u and C_c is required for classification of sandy and gravelly soils that have 12% or less passing a No. 200 sieve (Unified Soil Classification System; see Chapter 10).

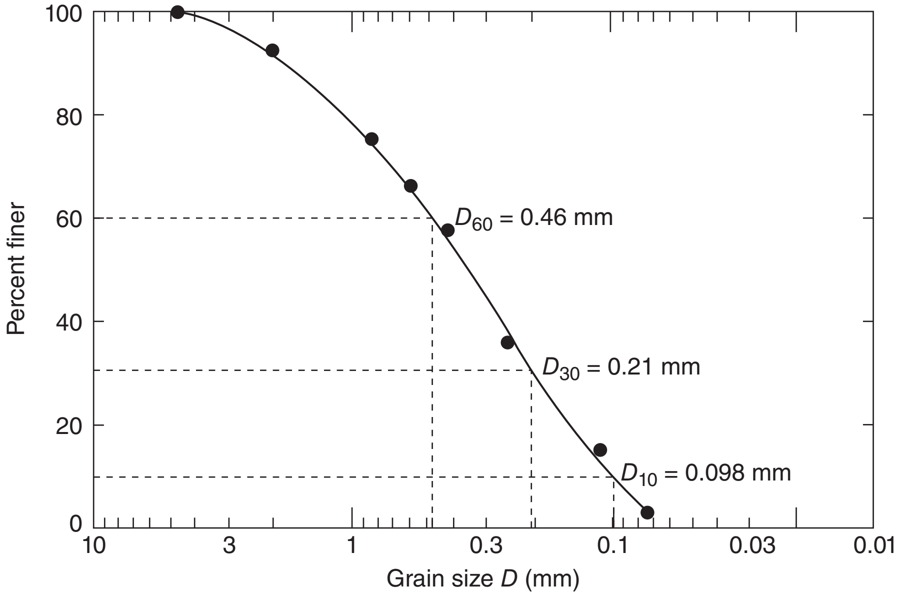

Figure 4-5. Plot of percent finer vs. grain-size from calculations shown in Table 4-4.

As an example, from Figure 4-5, $D_{60} = 0.46$ mm, $D_{30} = 0.21$ mm, and $D_{10} = 0.098$ mm. So,

$$C_u = \frac{0.46}{0.098} = 4.69$$

and

$$C_c = \frac{(0.21)^2}{0.46 \times 0.098} = 0.98$$

A parameter called the *sorting coefficient* (S_0) is another measure of uniformity, which can be defined as

$$S_0 = \sqrt{\frac{D_{75}}{D_{25}}} \tag{4.7}$$

This parameter is not frequently used by geotechnical engineers.

4.7 General Comments

The diameter D_{10} is generally referred to as *effective size*. The effective size is used for several empirical correlations, such as the *coefficient of permeability*. The *uniformity coefficient* C_u is a parameter that indicates the range of distribution of the grain sizes in a given soil specimen. If C_u is relatively large, it indicates a well-graded soil. If C_u is nearly equal to 1, it means that the soil grains are of approximately equal size, and the soil may be referred to as a poorly graded soil.

Figure 4-6 shows the general nature of the grain-size distribution curves for a well-graded and a poorly graded soil. In some instances, a soil may have a combination of two or more uniformly graded fractions, and this soil is referred to as *gap graded*. The grain-size distribution curve for a gap-graded soil is also shown in Figure 4-6.

The parameter C_c is also referred to as the *coefficient of curvature*. For sand, if C_u is greater than 6 and C_c is between 1 and 3, it is considered well graded. However, for a gravel to be well graded, C_u should be greater than 4 and C_c must be between 1 and 3.

The D_{15} and D_{85} sizes are used for the design of filters. The D_{50} size is used for correlation of the liquefaction potential of saturated granular soil during earthquakes and other parameters needed for design of foundations and other structures.

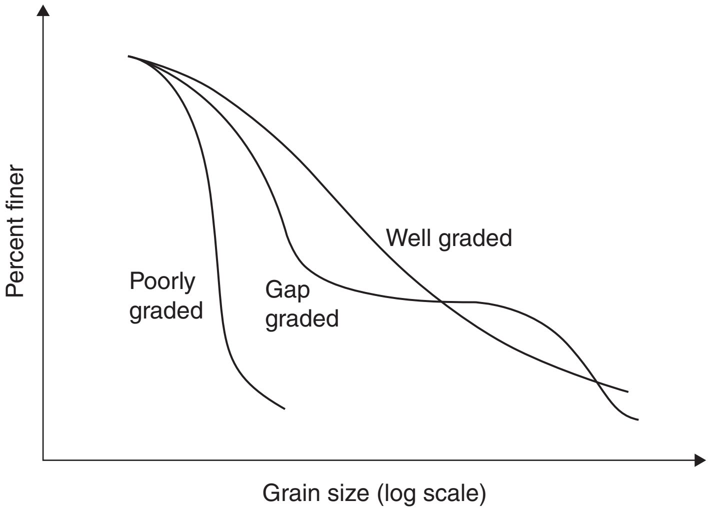

Figure 4-6. **General nature of grain-size distribution of well-graded, poorly graded, and gap-graded soil.**

4.8 Laboratory Report

The laboratory report should contain the following:

- Cover page
- Equipment used
- Description of test procedure
- Results—data sheet, sample calculations, and the semilogarithmic graph showing the grain-size distribution
- Discussion, including determination of C_u and C_c
- Sources of error, if any

5

Hydrometer Analysis

5.1 Introduction

ASTM: Standard: D-422 (withdrawn by the ASTM; see footnote in Table 1-1)
Hydrometer analysis is the procedure generally adopted for determining the particle-size distribution in a soil for the fraction that is finer than U.S. No. 200 sieve size (0.075 mm). The lower limit of the particle size determined by this procedure is about 0.001 mm.

In hydrometer analysis, a soil specimen is dispersed in water. In a dispersed state in the water, the soil particles will settle individually. It is assumed that the soil particles are spheres, and the velocity of the particles can be given by Stokes' law,

$$v = \frac{\gamma_s - \gamma_w}{18\eta} D^2 \tag{5.1}$$

where v = velocity (cm/s)
γ_s = specific weight of soil solids (g/cm^3)
γ_w = unit weight of water (g/cm^3)
η = dynamic viscosity of water (g · s/cm^2)
D = diameter of soil particle

There are two major types of ASTM hydrometers. They are ASTM 151-H and ASTM 152-H. The ASTM 151-H hydrometer measures the specific gravity of the soil–water suspension near the center of the hydrometer bulb. It is graduated from 0.995 to 1.038. The ASTM 152-H hydrometer is graduated to read the amount of soil solids per liter of the soil–water suspension near the center of the hydrometer bulb. It is graduated from −5 to 60.

To illustrate the relationship between 151-H and 152-H hydrometer readings, consider a soil–water suspension at time t. Let the *mass* of soil solids in suspension be m (g) and the volume of the suspension be $V(\text{cm}^3)$. So,

$$\rho_{\text{suspension}} = \frac{m + \left(V - \frac{m}{G_s \rho_w}\right)\rho_w}{V} \tag{5.2}$$

or

$$\rho_{\text{suspension}} = \frac{m}{V} + \rho_w - \frac{m}{G_s V} \tag{5.3}$$

where $\rho_{\text{suspension}}$ = density of soil–water suspension (g/cm^3)

ρ_w = density of water (1 g/cm^3)

Thus,

$$\rho_{\text{suspension}} = \frac{m}{V} + 1 - \frac{m}{G_s V}$$

or

$$\underset{\substack{\uparrow\\ \boxed{\begin{array}{c}\text{152-H}\\ \text{Reading}\end{array}}}}{m} = \left(\frac{G_s}{G_s - 1}\right) V(\underset{\substack{\uparrow\\ \boxed{\begin{array}{c}\text{151-H}\\ \text{Reading}\end{array}}}}{\rho_{\text{suspension}}} - 1) \tag{5.4}$$

If $G_s = 2.65$, $V = 1000$ cm^3, and $m = 0$, then from Eq. (5.4),

- 152-H will give a reading of 0
- 151-H will give a reading of 1 (= $\rho_{\text{suspension}}$)

If $G_s = 2.65$, $V = 1000$ cm^3, and $m = 60$ g, then from Eq. (5.4),

- 152-H will give a reading of 60
- 151-H will give a reading of 1.0374 g/cm^3

In the test procedure described here, the ASTM 152-H type hydrometer will be used (see Fig. 5-1). If a hydrometer is suspended in water in which soil is dispersed (Fig. 5-2), it will measure the specific gravity of the soil–water suspension at a depth L. The depth L is called the *effective depth.* So at a time t minutes from the beginning of the test, the soil particles that settle beyond the zone of measurement (i.e., beyond the effective depth L) will have a diameter given by

$$\frac{L\,(\text{cm})}{t\,(\text{min}) \times 60} = \frac{\gamma_s - \gamma_w(\text{g/cm}^3)}{18\eta\,(\text{g}\cdot\text{s/cm}^2)}\left[\frac{D\,(\text{mm})}{10}\right]^2$$

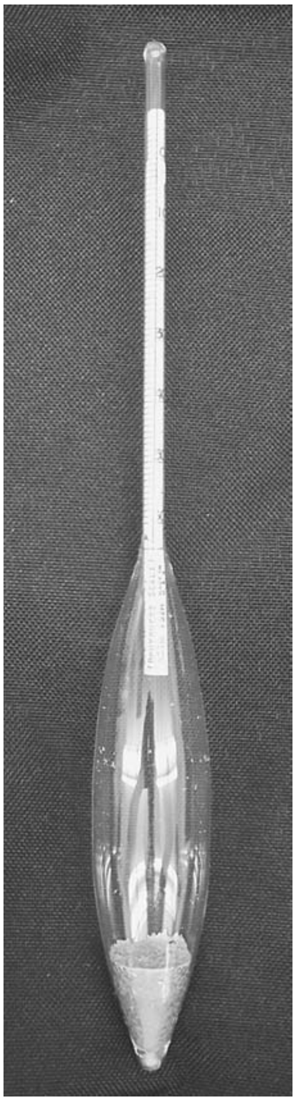

Figure 5-1. ASTM 152-H hydrometer.

Then,

$$D\,(\mathrm{mm}) = \frac{10}{\sqrt{60}}\sqrt{\frac{18\eta}{\gamma_s - \gamma_w}}\sqrt{\frac{L}{t}} = A\sqrt{\frac{L\,(\mathrm{cm})}{t\,(\mathrm{min})}} \tag{5.5}$$

where

$$A = \sqrt{\frac{1800\eta}{60\,(\gamma_s - \gamma_w)}} = \sqrt{\frac{30\eta}{\gamma_s - \gamma_w}} \tag{5.6}$$

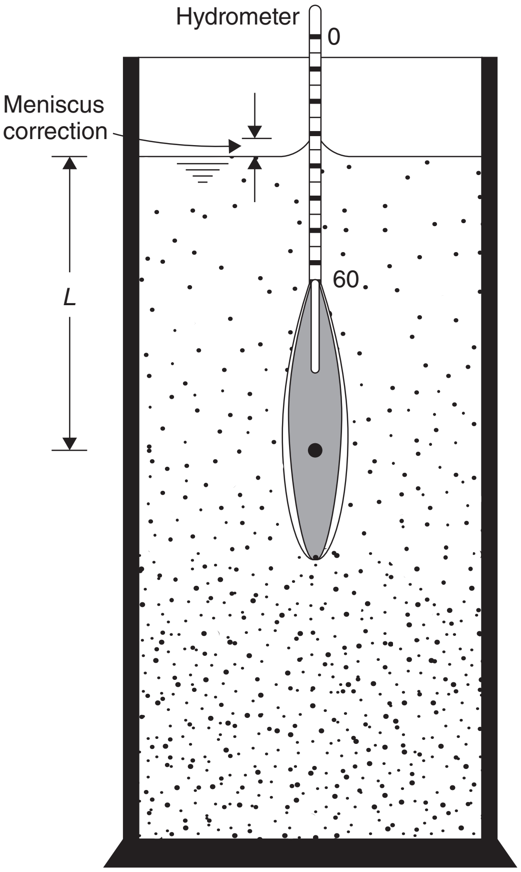

Figure 5-2. Hydrometer suspended in water in which soil is dispersed.

From Figure 5-2, it can be seen that, based on the hydrometer reading (which increases from zero to 60 in the ASTM 152-H type hydrometer), the value of L will change. The magnitude of L can be given as

$$L = L_1 + \frac{1}{2}\left(L_2 - \frac{V_B}{A_C}\right) \tag{5.7}$$

where $L_1 =$ distance between top of hydrometer bulb and mark for a hydrometer reading. For a hydrometer reading of zero, $L_1 = 10.5$ cm. Also, for a hydrometer reading of 50, $L_1 = 2.3$ cm. Thus, in general, for a given hydrometer reading,

$$L_1 \text{ (cm)} = 10.5 - \left(\frac{10.5 - 2.3}{50}\right) \times \text{hydrometer reading}$$

L_2 = 14 cm
V_B = volume of hydrometer bulb = 67.0 cm^3
A_C = cross-sectional area of hydrometer cylinder = 27.8 cm^2

Based on Eq. (5.7), the variations of L with the hydrometer readings are shown in Table 5-1.

For actual calculation purposes, we also need to know the values of A given by Eq. (5.6). An example of this calculation is

$$\gamma_s = G_s \gamma_w$$

where G_s is the specific gravity of soil solids. Thus,

$$A = \sqrt{\frac{30\eta}{(G_s - 1)\gamma_w}} \tag{5.8}$$

For example, if the temperature of the water is 25°C, $\eta = 0.0911 \times 10^{-4}$ ($\text{g} \cdot \text{s/cm}^2$), and $G_s = 2.7$,

$$A = \sqrt{\frac{30\left(0.0911 \times 10^{-4}\right)}{(2.7 - 1)(1)}} = 0.0127$$

The variations of A with G_s and the water temperature are shown in Table 5-2.

The ASTM 152-H type hydrometer is calibrated up to a reading of 60 at a temperature of 20°C for soil particles having $G_s = 2.65$. A hydrometer reading of, say, 30 at a given time of a test means that there are 30 g of soil solids ($G_s = 2.65$) in suspension per 1000 cm^3 of soil–water mixture at a temperature of 20°C at a depth where the specific gravity of the soil–water suspension is measured (i.e., L). From this measurement, we can determine the percentage of soil still in suspension at time t from the beginning of the test, and all the soil particles will have diameters smaller than D calculated by Eq. (5.5). However, in the actual experimental work, some corrections to the observed hydrometer readings need to be applied. They are as follows:

Table 5-1. Variations of *L* with Hydrometer* Readings

Hydrometer Reading	*L* (cm)	Hydrometer Reading	*L* (cm)
0	16.3	26	12.0
1	16.1	27	11.9
2	16.0	28	11.7
3	15.8	29	11.5
4	15.6	30	11.4
5	15.5	31	11.2
6	15.3	32	11.1
7	15.2	33	10.9
8	15.0	34	10.7
9	14.8	35	10.6
10	14.7	36	10.4
11	14.5	37	10.2
12	14.3	38	10.1
13	14.2	39	9.9
14	14.0	40	9.7
15	13.8	41	9.6
16	13.7	42	9.4
17	13.5	43	9.2
18	13.3	44	9.1
19	13.2	45	8.9
20	13.0	46	8.8
21	12.9	47	8.6
22	12.7	48	8.4
23	12.5	49	8.3
24	12.4	50	8.1
25	12.2	51	7.9

*ASTM 152-H hydrometer.