Chapter 1
Composition and Particle Sizes of Soils

1.1 INTRODUCTION

The purpose of this chapter is to introduce you to the composition and particle sizes of soils. Soils are complex, natural materials, and soils vary widely. The composition and particle sizes of soils influence the load-bearing and settlement characteristics of soils.

Learning outcomes

When you complete this chapter, you should be able to do the following:

- Understand and describe the formation of soils.
- Understand and describe the composition of soils.
- Determine particle size distribution of a soil mass.
- Interpret grading curves.

1.2 DEFINITIONS OF KEY TERMS

Minerals are chemical elements that constitute rocks.
Rocks are the aggregation of minerals into a hard mass.
Soils are materials that are derived from the weathering of rocks.
Effective particle size (D_{10}) is the average particle diameter of the soil at the 10th percentile; that is, 10% of the particles are smaller than this size (diameter).
Average particle diameter (D_{50}) is the average particle diameter of the soil.
Uniformity coefficient (Cu) is a numerical measure of uniformity (majority of grains are approximately the same size).
Coefficient of curvature (CC) is a measure of the shape of the particle distribution curve (other terms used are the coefficient of gradation and the coefficient of concavity).

Soil Mechanics Fundamentals, First Edition. Muni Budhu.

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1.3 COMPOSITION OF SOILS

1.3.1 Soil formation

Engineering soils are formed from the physical and chemical weathering of rocks. Soils may also contain organic matter from the decomposition of plants and animals. In this textbook, we will focus on soils that have insignificant amounts of organic content. Physical weathering involves reduction of size without any change in the original composition of the parent rock. The main agents responsible for this process are exfoliation, unloading, erosion, freezing, and thawing. Chemical weathering causes both reductions in size and chemical alteration of the original parent rock. The main agents responsible for chemical weathering are hydration, carbonation, and oxidation. Often chemical and physical weathering takes place in concert.

Soils that remain at the site of weathering are called residual soils. These soils retain many of the elements that comprise the parent rock. Alluvial soils, also called fluvial soils, are soils that were transported by rivers and streams. The composition of these soils depends on the environment under which they were transported and is often different from the parent rock. The profile of alluvial soils usually consists of layers of different soils. Much of our construction activity has been and is occurring in and on alluvial soils.

1.3.2 Soil types

Gravels, sands, silts, and clays are used to identify specific textures in soils. We will refer to these soil textures as soil types; that is, sand is one soil type, clay is another. Texture refers to the appearance or feel of a soil. Sands and gravels are grouped together as coarse-grained soils. Clays and silts are fine-grained soils. Coarse-grained soils feel gritty and hard. Fine-grained soils feel smooth. The coarseness of soils is determined from knowing the distribution of particle sizes, which is the primary means of classifying coarse-grained soils. To characterize fine-grained soils, we need further information on the types of minerals present and their contents. The response of fine-grained soils to loads, known as the mechanical behavior, depends on the type of predominant minerals present.

Currently, many soil descriptions and soil types are in usage. A few of these are listed below.

- *Alluvial soils* are fine sediments that have been eroded from rock and transported by water, and have settled on river- and streambeds.
- *Calcareous soil* contains calcium carbonate and effervesces when treated with hydrochloric acid.
- *Caliche* consists of gravel, sand, and clay cemented together by calcium carbonate.
- *Collovial soils* (collovium) are soils found at the base of mountains that have been eroded by the combination of water and gravity.
- *Eolian* soils are sand-sized particles deposited by wind.
- *Expansive soils* are clays that undergo large volume changes from cycles of wetting and drying.
- *Glacial soils* are mixed soils consisting of rock debris, sand, silt, clays, and boulders.
- *Glacial till* is a soil that consists mainly of coarse particles.

- *Glacial clays* are soils that were deposited in ancient lakes and subsequently frozen. The thawing of these lakes has revealed soil profiles of neatly stratified silt and clay, sometimes called varved clay. The silt layer is light in color and was deposited during summer periods, while the thinner, dark clay layer was deposited during winter periods.
- *Gypsum* is calcium sulfate formed under heat and pressure from sediments in ocean brine.
- *Lacustrine* soils are mostly silts and clays deposited in glacial lake waters.
- *Lateritic* soils are residual soils that are cemented with iron oxides and are found in tropical regions.
- *Loam* is a mixture of sand, silt, and clay that may contain organic material.
- *Loess* is a wind-blown, uniform, fine-grained soil.
- *Marine soils* are sand, silts, and clays deposited in salt or brackish water.
- *Marl* (marlstone) is a mud (see definition of mud below) cemented by calcium carbonate or lime.
- *Mud* is clay and silt mixed with water into a viscous fluid.

1.3.3 Soil minerals

Minerals are crystalline materials and make up the solids constituent of a soil. Minerals are classified according to chemical composition and structure. Most minerals of interest to geotechnical engineers are composed of oxygen and silicon, two of the most abundant elements on earth.

Quartz (a common mineral in rocks) is the principal mineral of coarse-grained soils. Quartz is hard and composed of silicon dioxide (SiO_2) in colored, colorless, and transparent hexagonal crystals. The particles of coarse-grained soil are thus naturally angular. Weathering, especially by water, can alter the angular shape to a rounded one.

Clay minerals are made up of phyllosilicates, which are parallel sheets of silicates. Silicates are a group of minerals with a structural unit called the silica tetrahedron. A central silica cation (positively charged ion) is surrounded by four oxygen anions (negatively charged ions), one at each corner of the tetrahedron (Figure 1.1a). The charge on a single tetrahedron is -4, and to achieve a neutral charge, cations must be added or single tetrahedrons must be linked to each other sharing oxygen ions. Silicate minerals are formed by the addition of cations and interactions of tetrahedrons. Silica tetrahedrons combine to form sheets, called silicate sheets or laminae, which are thin layers of silica tetrahedrons in which three oxygen ions are shared between adjacent tetrahedrons (Figure 1.1b). Silicate sheets may contain other structural units such as alumina sheets. Alumina sheets are formed by combination of alumina minerals, which consists of an aluminum ion surrounded by six oxygen or hydroxyl atoms in an octahedron (Figure 1.1c, d).

The mineral particles of fine-grained soils are platy. The main groups of crystalline materials that make up fine-grained soils, principally clays, are the minerals kaolinite, illite, and montmorillonite. These minerals are the products from weathering of feldspar and muscovite mica, families of rock-forming silicate minerals that are abundant on the Earth's surface. Kaolinite has a structure that consists of one silica sheet and one alumina sheet bonded together into a layer about 0.72 nm thick and stacked repeatedly (Figure 1.2a). The layers are held together by hydrogen bonds. Tightly stacked layers result from numerous hydrogen bonds. Kaolinite is common in clays in humid tropical regions. Illite consists of repeated layers of one alumina sheet sandwiched by two silicate sheets (Figure 1.2b). The layers, each of thickness 0.96 nm, are held together by potassium ions.

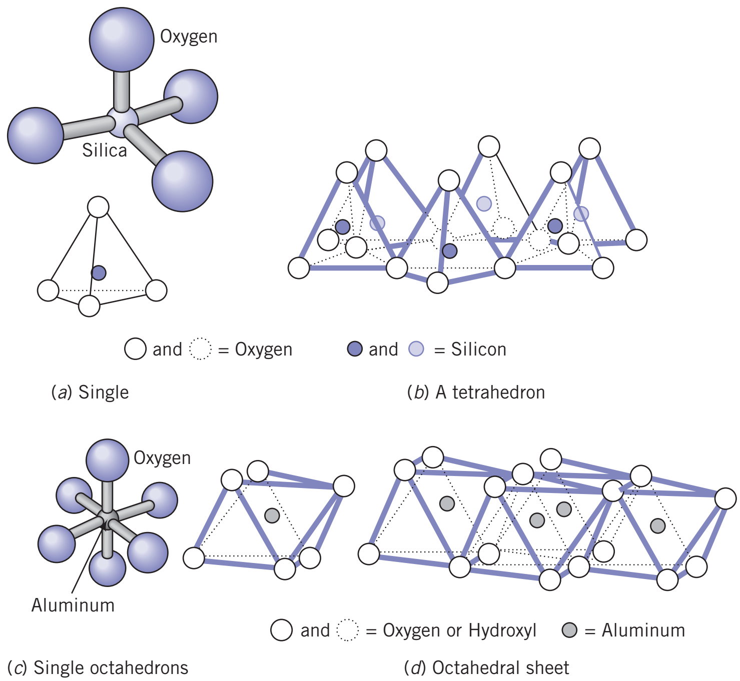


Figure 1.1 (a) Silica tetrahedrons, (b) silica sheets, (c) single aluminum octahedrons, and (d) aluminum sheets.

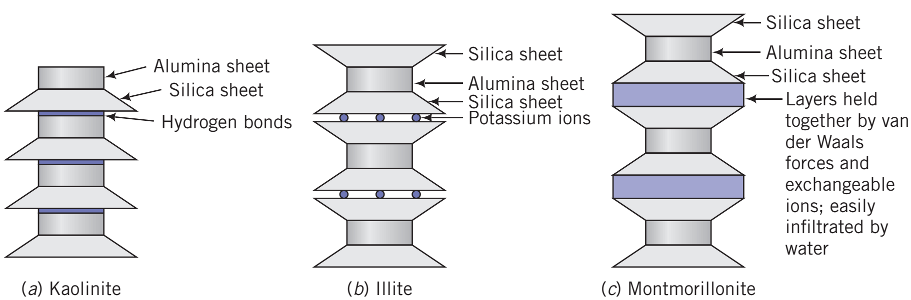


Figure 1.2 Structure of (a) kaolinite, (b) illite, and (c) montmorillonite.

Montmorillonite has a structure similar to illite, but the layers are held together by weak van der Waals forces. Montmorillonite belongs to the smectite clay family. It is an aluminum smectite with a small amount of Al^{+3} replaced by Mg^{2+}. This causes a charge inequity that is balanced by exchangeable cations Na^{+} or Ca^{2+} and oriented water (Figure 1.2c). Additional water can easily enter the bond and separate the layers in montmorillonite, causing swelling. If the predominant exchangeable cation is Ca^{2+} (calcium smectite), there are two water layers, whereas if it is Na^{+} (sodium smectite), there is usually only one water layer. Sodium smectite can absorb enough water to cause the particles to fully separate. Calcium smectites do not usually absorb enough water to cause particle separation because of their divalent cations. Montmorillonite is often called a swelling or expansive clay. Worldwide, it is responsible for billions of dollars in damages to structures (on ground and below ground).

1.3.4 Surface forces and adsorbed water

If we subdivide a body, the ratio of its surface area to its volume increases. For example, a cube with sides of 1 cm has a surface area of 6 cm^2. If we subdivide this cube into smaller cubes with sides of 1 mm, the original volume is unchanged, but the surface area increases to 60 cm^2. The surface area per unit mass (specific surface) of sands is typically 0.01 m^2 per gram, whereas for clays it is as high as 1000 m^2 per gram (montmorillonite). The specific surface of kaolinite ranges from 10 to 20 m^2 per gram, while that of illite ranges from 65 to 100 m^2 per gram. The surface area of 45 grams of illite is equivalent to the area of a football field. Because of the large surface areas of fine-grained soils, surface forces significantly influence their behavior compared to coarse-grained soils. The clay–water interaction coupled with the large surface areas results in clays having larger water-holding capacity in a large number of smaller pore spaces compared with coarse-grained soils.

The surface charges on the particles of fine-grained soils are negative (anions). These negative surface charges attract cations and the positively charged side of water molecules from surrounding water. Consequently, a thin film or layer of water, called adsorbed water, is bonded to the mineral surfaces. The thin film or layer of water is known as the diffuse double layer (Figure 1.3). The largest concentration of cations occurs at the mineral surface and decreases exponentially with distance away from the surface (Figure 1.3).

Surface forces on clay particles are of two types. One type, called attracting forces, is due to London–van der Waals forces. These forces are far-reaching and decrease in inverse proportion to l^2 (l is the distance between two particles). The other type, called repelling forces, is due to the diffuse double layer. Around each particle is an ionic cloud. When two particles are far apart, the electric charge on each is neutralized by equal and opposite charge of the ionic cloud around it. When the particles move closer together such that the clouds mutually penetrate each other, the negative charges on the particles cause repulsion.

Drying of most soils, with few exceptions (e.g., gypsum), using an oven for which the standard temperature is $105 \pm 5°C$ cannot remove the adsorbed water. The adsorbed water influences the way a soil behaves. For example, plasticity in soils, which we will deal with in Chapter 4, is attributed to the adsorbed water. Toxic chemicals that seep into the ground contaminate soil and groundwater. Knowledge of the surface chemistry of fine-grained soils is important in understanding the migration, sequestration, rerelease, and ultimate removal of toxic compounds from soils.

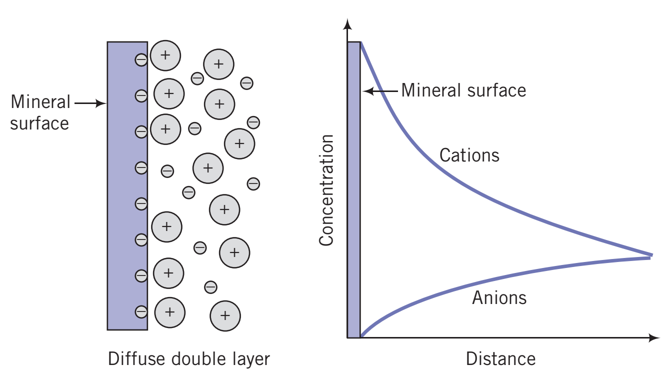


Figure 1.3 Diffuse double layer.

1.3.5 Soil fabric

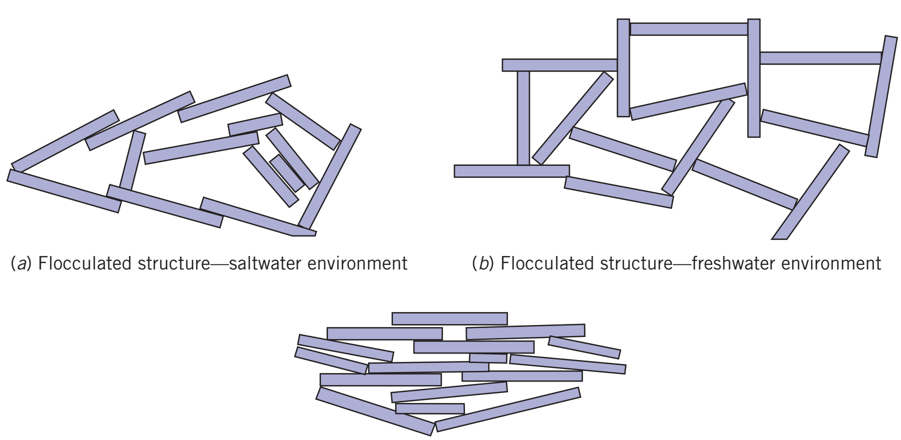
Soil (minerals) particles are assumed to be rigid. During deposition, the mineral particles are arranged into structural frameworks that we call soil fabric (Figure 1.4). Each particle is in random contact with neighboring particles. The environment under which deposition occurs influences the structural framework that is formed. In particular, the electrochemical environment has the greatest influence on the kind of soil fabric that is formed during deposition of fine-grained soils.

Two common types of soil fabric—flocculated and dispersed—are formed during soil deposition of fine-grained soils, as shown schematically in Figure 1.4. A flocculated structure, formed in a saltwater environment, results when many particles tend to orient parallel to one another. A flocculated structure, formed in a freshwater environment, results when many particles tend to orient perpendicular to one another. A dispersed structure occurs when a majority of the particles orient parallel to one another.

Any loading (tectonic or otherwise) during or after deposition permanently alters the soil fabric or structural arrangement in a way that is unique to that particular loading condition. Consequently, the history of loading and changes in the environment is imprinted in the soil fabric. The soil fabric is the brain; it retains the memory of the birth of the soil and subsequent changes that occur.

The spaces between the mineral particles are called voids, which may be filled with liquids (essentially water), gases (essentially air), and cementitious materials (e.g., calcium carbonate). Voids occupy a large proportion of the soil volume. Interconnected voids form the passageway through which water flows in and out of soils. If we change the volume of voids, we will cause the soil to either compress (settle) or expand (dilate). Loads applied by a building, for example, will cause the mineral particles to be forced closer together, reducing the volume of voids and changing the orientation of the structural framework.

Consequently, the building settles. The amount of settlement depends on how much we compress the volume of voids. The rate at which the settlement occurs depends on the interconnectivity of the voids. Free water, not the adsorbed water, and/or air trapped in the voids must be forced out for settlement to occur. The decrease in volume, which results in settlement of buildings and other structures, is usually very slow (almost ceaseless) in fine-grained



(*a*) Flocculated structure—saltwater environment

(*b*) Flocculated structure—freshwater environment

(*c*) Dispersed structure

Figure 1.4 Soil fabric.

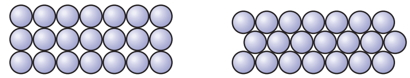


Figure 1.5 Loose and dense packing of spheres.

soils because these soils have large surface areas compared with coarse-grained soils. The larger surface areas provide greater resistance to the flow of water through the voids.

If the rigid (mostly quartz) particles of coarse-grained soils can be approximated by spheres, then the loosest packing (maximum void spaces) would occur when the spheres are stacked one on top of another (Figure 1.5a). The densest packing would occur when the spheres are packed in a staggered pattern, as shown in Figure 1.5b. Real coarse-grained soils consist of an assortment of particle sizes and shapes, and consequently, the packing is random. From your physics course, mass is volume multiplied by density. The density of soil particles is approximately 2.7 grams/cm^3. For spherical soil particles of diameter D (cm), the mass is $2.7 \times (\pi D^3/6)$. So the number of particles per gram of soil is $0.7/D^3$. Thus, a single gram of a fine sand of diameter 0.015 cm would consist of about 207,400 particles.

Key points

1. Soils are derived from the weathering of rocks and are broadly described by terms such as gravels, sands, silts, and clays.
2. Physical weathering causes reduction in size of the parent rock without change in its composition.
3. Chemical weathering causes reduction in size and chemical composition that differs from the parent rock.
4. Gravels and sands are coarse-grained soils; silts and clays are fine-grained soils.
5. Coarse-grained soils are composed mainly of quartz.
6. Clays are composed of three main types of minerals: kaolinite, illite, and montmorillonite.
7. The clay minerals consist of silica and alumina sheets that are combined to form layers. The bonds between layers play a very important role in the mechanical behavior of clays. The bond between the layers in montmorillonite is very weak compared with kaolinite and illite. Water can easily enter between the layers in montmorillonite, causing swelling.
8. A thin layer of water, called adsorbed water, is bonded to the mineral surfaces of soils. This layer significantly influences the physical and mechanical characteristics of fine-grained soils.

1.4 DETERMINATION OF PARTICLE SIZE

1.4.1 Particle size of coarse-grained soils

The distribution of particle sizes or average grain diameter of coarse-grained soils—gravels and sands—is obtained by screening a known weight of the soil through a stack of sieves of progressively finer mesh size. A typical stack of sieves is shown in Figure 1.6.

Sieve no.	Opening (mm)
3/8″	9.53
4	4.75
10	2
20	0.85
40	0.425
100	0.15
200	0.075

Figure 1.6 Stack of US sieves.

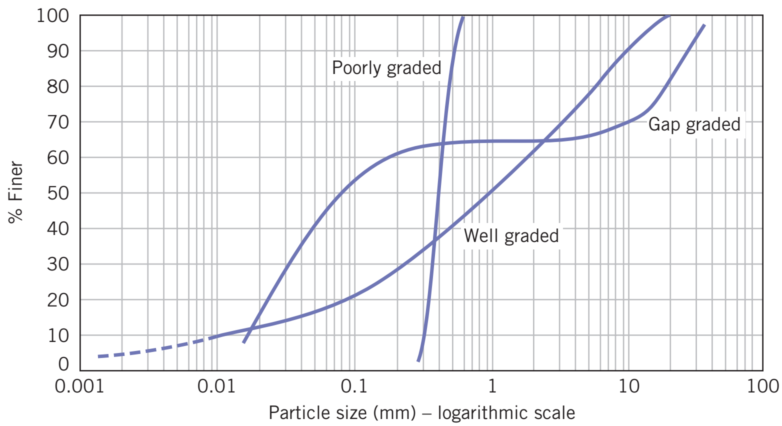


Figure 1.7 Particle size distribution curves.

In the United States, each sieve is identified by either a number that corresponds to the number of square holes per linear inch of mesh or the size of the opening. Large sieve (mesh) openings (75 mm to 9.5 mm) are designated by the sieve opening size, while smaller sieve sizes are designated by numbers. Other countries define sieves based on their actual opening in either millimeters or microns. The particle diameter in the screening process, often called sieve analysis, is the maximum dimension of a particle that will pass through the square hole of a particular mesh. A known weight of dry soil is placed on the largest sieve (the top sieve), and the nest of sieves is then placed on a vibrator, called a sieve shaker, and shaken. The nest of sieves is dismantled, one sieve at a time. The soil retained on each sieve is weighed, and the percentage of soil retained on each sieve is calculated. The results are plotted on a graph of percentage of particles finer than a given sieve size (not the percentage retained) as the ordinate versus the logarithm of the particle sizes, shown in Figure 1.7. The resulting plot is called a particle size distribution curve, or simply, the gradation curve. Engineers have found it convenient to use a logarithmic scale for particle size because the ratio of particle sizes from the largest to the smallest in a soil can be greater than 10^4.

Let W_i be the weight of soil retained on the ith sieve from the top of the nest of sieves and W be the total soil weight. The percentage weight retained is

$$\% \text{ retained on } i\text{th sieve} = \frac{W_i}{W} \times 100 \tag{1.1}$$

The percentage finer is

$$\% \text{ finer than } i\text{th sieve} = 100 - \sum_{i=1}^{i} (\% \text{ retained on } i\text{th sieve}) \tag{1.2}$$

The particles less than 0.075 mm (passing the No. 200 sieve) are collectively called fines. The fines content (usually greater than 35%) can significantly influence the engineering properties and behavior of a soil.

1.4.2 Particle size of fine-grained soils

The screening process cannot be used for fine-grained soils—silts and clays—because of their extremely small size. The common laboratory method used to determine the size distribution of fine-grained soils is a hydrometer test (Figure 1.8). The hydrometer test involves mixing a small amount of soil into a suspension and observing how the suspension settles in time. Larger particles will settle quickly, followed by smaller particles. When the hydrometer is lowered into the suspension, it will sink until the buoyancy force is sufficient to balance the weight of the hydrometer.

The length of the hydrometer projecting above the suspension is a function of the density, so it is possible to calibrate the hydrometer to read the density of the suspension at different times. The calibration of the hydrometer is affected by temperature and the specific gravity of the suspended solids. A correction factor must be applied to the hydrometer reading based on the test temperatures used.

Typically, a hydrometer test is conducted by taking a small quantity of a dry, fine-grained soil (approximately 50 grams) and thoroughly mixing it with distilled water to form a paste. The paste is placed in a 1000 mL (=1 liter = 1000 cm^3) glass cylinder, and distilled water is added to bring the level to the 1000 mL mark. The glass cylinder is then repeatedly shaken and inverted before being placed in a constant-temperature bath. A hydrometer is placed in the glass cylinder and a clock is simultaneously started. At different times, the hydrometer

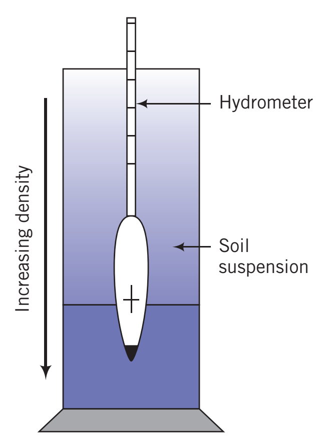


Figure 1.8 Hydrometer in soil-water suspension.

is read. The diameter D (mm) of the particle at time t_D (minute) is calculated from Stokes's law as

$$D = \sqrt{\frac{30\mu z}{980(G_s - 1)t_D}} = K\sqrt{\frac{z}{t_D}} = K\sqrt{v_{set}} \tag{1.3}$$

where μ is the viscosity of water [0.01 Poise at 20°C; 10 Poise = 1 Pascal second (Pa.s) = 1000 centiPoise], z is the effective depth (cm) of the hydrometer, G_s is the specific gravity of the soil particles, and $K = \sqrt{30\mu/980(G_s - 1)}$ is a parameter that depends on temperature and the specific gravity of the soil particles, and v_{set} is the settling velocity. For most soils, $G_s \approx 2.7$. At a temperature of 20°C and for $G_s = 2.7$, $K = 0.01341$.

In the application of Stokes's law, the particles are assumed to be free-falling spheres with no collision. But the mineral particles of fine-grained soils are platelike, and collision of particles during sedimentation is unavoidable. Also, Stokes's law is valid only for laminar flow with Reynolds number ($\text{Re} = vD\gamma_w/\mu g$, where v is velocity, D is the diameter of the particle, γ_w is the unit weight of water, μ is the viscosity of water at 20°C, and g is the acceleration due to gravity) smaller than 1. Laminar flow prevails for particle sizes in the range $0.001\text{ mm} < D < 0.1\text{ mm}$. By using the material of average particle size < 0.075 mm, laminar flow is automatically satisfied for particles greater than 0.001 mm. Particles smaller than 0.001 mm are colloids. Electrostatic forces influence the motion of colloids, and Stokes's law is not valid. Brownian motion describes the random movement of colloids.

It is important to distinguish silts from clays because, apart from particle size differences, they have different strength and deformation properties. Silts have lower strength than clays and absorb smaller amounts of water to become "liquid like." Silts tend to dry and become powdery, whereas clays become brittle on drying.

The results of the hydrometer test suffice for most geotechnical engineering needs. For more accurate size distribution measurements in fine-grained soils, other, more sophisticated methods are available (e.g., light-scattering methods). The dashed line in Figure 1.7 shows a typical particle size distribution for fine-grained soils.

1.5 CHARACTERIZATION OF SOILS BASED ON PARTICLE SIZE

The grading curve is used for textural classification of soils. Various classification systems have evolved over the years to describe soils based on their particle size distribution. Each system was developed for a specific engineering purpose. In the United States, the popular systems are the Unified Soil Classification System (USCS), the American Society for Testing and Materials (ASTM) system (a modification of the USCS system), and the American Association of State Highway and Transportation Officials (AASHTO) system (Figure 1.9). Other countries such as those in Europe use the Euro-Standards. We will discuss soil classification in more detail in Chapter 2.

In this textbook, we will use the USCS system because this is sufficiently general for educational purposes. We will modify it slightly by delimiting clays as having particles less than 0.002 mm. Soils are separated into two categories. One category is coarse-grained soils, which are thus delineated if more than 50% of the soil is greater than 0.075 mm. The other category is fine-grained soils, which are thus delineated if more than 50% of the soil is finer than 0.075 mm. Coarse-grained soils are subdivided into gravels and sands, while fine-grained soils are divided into silts and clays. Each soil type—gravel, sand, silt, and clay—is identified by grain size, as shown in Table 1.1. Clays have particle sizes less than 0.002 mm.

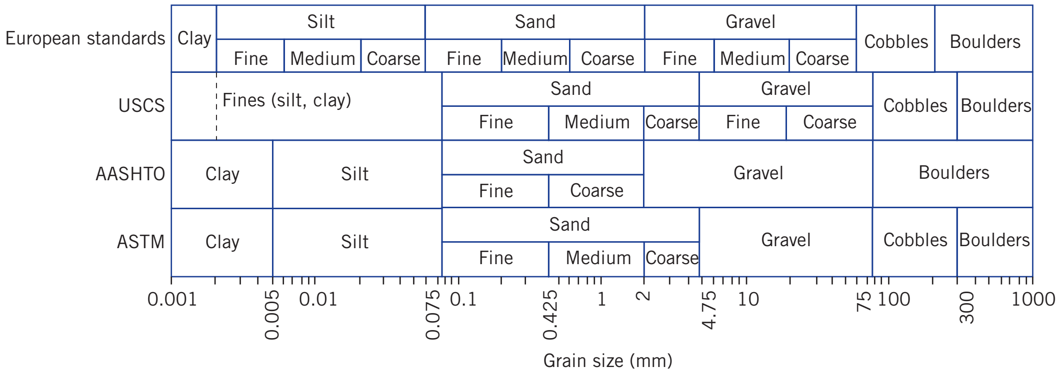


Figure 1.9 Comparison of four systems describing soil types based on particle size.

Table 1.1 Soil types, descriptions, and average grain sizes.

Category	Soil type	Symbol	Description	Grain size, D
Coarse-grained	Gravel	G	Rounded and/or angular bulky hard rock, coarsely divided	Coarse: >75 mm Fine: 4.75 mm–19 mm
	Sand	S	Rounded and/or angular hard rock, finely divided	Coarse: 2.0 mm–4.75 mm Medium: 0.425 mm–2.0 mm Fine: 0.075 mm–0.425 mm
Fine-grained (also called fines)	Silt	M	Particle size between clay and sand; nonplastic or very slightly plastic; exhibits little or no strength when dried; easily brushed off when dried	0.002 mm–0.075 mm
	Clay	C	Particles are smooth and mostly clay minerals; greasy and sticky when wet; exhibits plasticity and significant strength when dried; water reduces strength	<0.002 mm

These sizes are established for convenience. Sand, which consists mainly of quartz minerals, can be grounded to a powder with particle sizes less than 0.002 mm, but the powder will not behave like a clay. Clays have high specific surface area, which is the surface area of the particles divided by the mass. Real soils consist of a mixture of particle sizes.

The amount of fines (materials with particle sizes < 0.075 mm) can considerably influence the response of a soil to loads. For example, a soil containing more than 35% of fines is likely to behave like a fine-grained soil. Fines content less than 5% has little or no influence on the soil behavior. Thus knowledge of the fines content in a soil is critical to understanding how that soil can be used as a construction material or as a foundation for a structure. The selection of a soil for a particular use may depend on the assortment of particles it contains. Two coefficients have been defined to provide guidance on distinguishing soils based on the distribution of the particles.

One of these is a numerical measure of uniformity, called the *uniformity coefficient*, Cu, defined as

$$Cu = \frac{D_{60}}{D_{10}} \tag{1.4}$$

where D_{60} is the diameter of the soil particles for which 60% of the particles are finer, and D_{10} is the diameter of the soil particles for which 10% of the particles are finer. Both of these diameters are obtained from the grading curve.

The other coefficient is the *coefficient of curvature*, CC (other terms used are the coefficient of gradation and the coefficient of concavity), defined as

$$CC = \frac{(D_{30})^2}{D_{10}D_{60}} \tag{1.5}$$

where D_{30} is the diameter of the soil particles for which 30% of the particles are finer. The average particle diameter is D_{50}.

The minimum value of Cu is 1 and corresponds to an assemblage of particles of the same size. The shape of the gradation curve indicates the range of particles in a soil. The gradation curve for a poorly graded soil is almost vertical (Figure 1.7). Humps in the gradation curve indicate two or more poorly graded soils. A well-graded soil is indicated by a flat curve (Figure 1.7). The absence of certain grain sizes, termed gap graded, is diagnosed by a sudden change of slope in the particle size distribution curve, as shown in Figure 1.7.

Poorly graded soils are sorted by water (e.g., beach sands) or by wind. Gap-graded soils are also sorted by water, but certain sizes were not transported. Well graded soils are produced by bulk transport processes (e.g., glacial till). The uniformity coefficient and the coefficient of concavity are strictly applicable to coarse-grained soils. The limits of uniformity coefficient and the coefficient of concavity to characterize well graded and poorly graded are as follows:

Well graded	gravel content > sand content	$Cu \geq 4$; $1 \leq CC \leq 3$
	sand content > gravel content	$Cu \geq 6$; $1 \leq CC \leq 3$
Poorly graded	gravel content > sand content	$Cu < 4$; $CC < 1$ or $CC > 3$
	sand content > gravel content	$Cu < 6$; $CC < 1$ or $CC > 3$

Gap graded soils are outside the limits of Cu and CC for well-graded and poorly graded soils.

The diameter D_{10} is called the effective size of the soil and was described by Allen Hazen (1892) in connection with his work on soil filters. The effective size is the diameter of an artificial sphere that will produce approximately the same effect as an irregularly shaped particle. The effective size is particularly important in regulating the flow of water through soils, and can dictate the mechanical behavior of soils since the coarser fractions may not be in effective contact with each other; that is, they float in a matrix of finer particles. The higher the D_{10} value, the coarser is the soil and the better are the drainage characteristics.

Particle size analyses have many uses in engineering. They are used to select aggregates for concrete, soils for the construction of dams and highways, soils as filters for drainage, and soils as material for grouting and chemical injection. In Chapter 2, you will learn about how the particle size distribution is used with other physical properties of soils in a classification system designed to help you select soils for particular applications.

Key points

1. A sieve analysis is used to determine the grain size distribution of coarse-grained soils.
2. For fine-grained soils, a hydrometer analysis is used to find the particle size distribution.
3. Particle size distribution is represented on a semi-logarithmic plot of percentage finer (ordinate, arithmetic scale) versus particle size (abscissa, logarithmic scale).
4. The particle size distribution plot is used to delineate the different soil textures (percentages of gravel, sand, silt, and clay) in a soil.
5. The effective size, D_{10}, is the diameter of the particles of which 10% of the soil is finer. D_{10} is an important value in regulating flow through soils and can significantly influence the mechanical behavior of soils.
6. D_{50} is the average grain size diameter of the soil.
7. Two coefficients—the uniformity coefficient and the coefficient of curvature—are used to characterize the particle size distribution. Poorly graded soils have steep gradation curves. Well graded soils are indicated by relatively flat particle distribution curves and have uniformity coefficients >4, coefficients of curvature between 1 and 3. Gap-graded soils are indicated by one or more humps on the gradation curves.

EXAMPLE 1.1 *Calculation of Percentage Finer than a Given Sieve in a Sieve Analysis Test*

A particle analysis test was conducted on a dry soil. The total mass used in test was 500 grams. All 500 grams are greater than 9.5 mm. The total mass of particles greater than 0.075 mm was 220 grams. Determine the percentage of coarse-grained and fine-grained soil particles.

Strategy Calculate the cumulative percentage greater than 0.075 mm, and then subtract it from 100 to get percentage finer than. Use Table 1.1 to guide you to get the amount of each soil category.

Solution 1.1

Step 1: Determine percentage greater than 0.075 mm.

Mass of soil particles greater than 0.075 mm, $M_r = 220$ grams.

Total mass, $M_t = 500$ grams.

% of soil particles greater than 0.075 mm =

$$\frac{M_r}{M_t} \times 100 = \frac{220}{500} \times 100 = 44\%$$

Step 2: Determine percentage finer than 0.075 mm.

% finer than 0.075 mm = 100 − 44 = 56%.

Step 3: Determine % coarse-grained and fine-grained particles.

% coarse-grained soil particles = % of particles greater than 0.075 mm = 44%.

% fine-grained soil particles = % of particles finer than 0.075 mm = 56%.

EXAMPLE 1.2 *Calculating Particle Size Distribution and Interpretation of Soil Type from a Sieve Analysis Test*

A sieve analysis test was conducted using 650 grams of soil. The results are as follows.

Sieve opening (mm)	9.53	4.75	2	0.85	0.425	0.15	0.075	Pan
Mass retained (grams)	0	53	76	73	142	85.4	120.5	99.8

Determine (**a**) the amount of coarse-grained and fine-grained soils, and (**b**) the amount of each soil type based on the USCS system.

Strategy Calculate the percentage finer and plot the gradation curve. Extract the amount of coarse-grained soil (particle sizes ≥ 0.075 mm) and the amount of fine-grained soil (particle sizes < 0.075 mm). Use Table 1.1 to guide you to get the amount of each soil type.

Solution 1.2

Step 1: Set up a table or a spreadsheet to do the calculations.

A	B	C		D	E
Sieve opening (mm)	**Mass retained (grams), M_r**	**% Retained ($100 \times M_r/M_t$)**		**Σ (% Retained) (Σ column D)**	**% Finer (100 − column E)**
9.53	0	0.0		0.0	100.0
4.75	53.0	8.2	add	8.2	91.8
2.00	76.0	11.7		19.9	80.1
0.85	73.0	11.2		31.1	68.9
0.425	142.0	21.9		52.9	47.1
0.15	85.4	13.1		66.1	33.9
0.075	120.5	18.5	check	84.6	15.4
	99.8	15.4			
Total mass = M_t =	649.7	100.0			

Note: In the sieve analysis test, some mass is lost because particles are stuck in the sieves. Use the sum of the mass after the test. You should always check that the sum of the soil retained on all sieves plus the pan is equal to 100% (column C in the table).

Step 2: Plot grading curve.

See Figure E1.2.

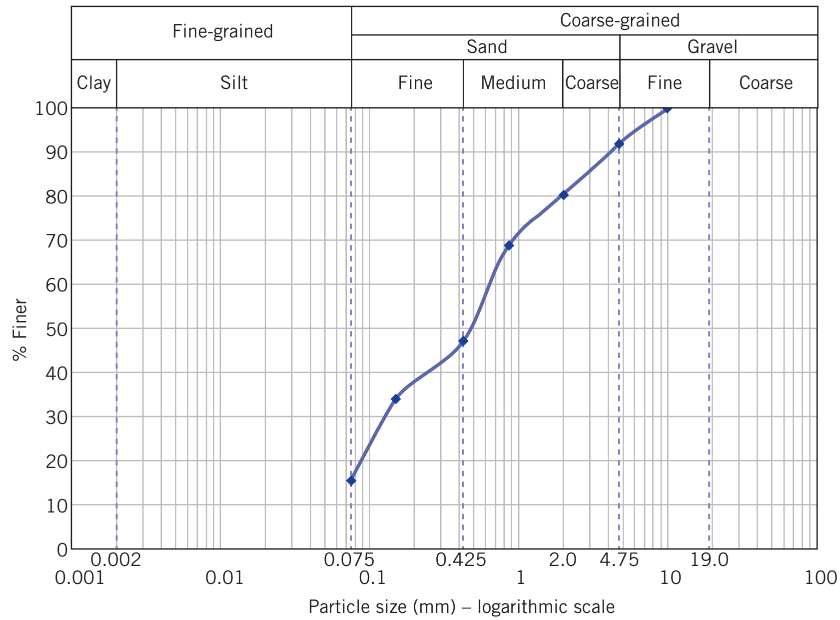


Figure E1.2

Step 3: Extract soil type.

(a) The amount of fine-grained soil is the percentage finer than 0.075 mm. The amount of coarse-grained soil is the percentage coarser than 0.075 mm.

$$\% \text{ fine-grained soil} = 15.4\%.$$

$$\% \text{ coarse-grained soil} = 100 - 15.4 = 84.6\%.$$

Check answer: % fine-grained soil + % coarse-grained soil must be 100%.

That is: 15.4 + 84.6 = 100%.

(b)

$$\text{Fine gravel } (\%) = 8.2$$

$$\text{Total gravel } (\%) = 8.2$$

$$\text{Coarse sand } (\%) = 11.7$$

$$\text{Medium sand } (\%) = 33.0$$

$$\text{Fine sand } (\%) = 31.7$$

$$\text{Total sand } (\%) = 76.4$$

$$\text{Silt} + \text{clay } (\%) = 15.4$$

Check answer: total gravel (%) + total sand (%) + silt (%) + clay (%) must equal 100%

That is: 8.2 + 76.4 + 15.4 = 100%

EXAMPLE 1.3 *Interpreting Sieve Analysis Data*

A sample of a dry, coarse-grained material of mass 500 grams was shaken through a nest of sieves, and the following results were as given in the table below.

(a) Plot the particle size distribution (gradation) curve.

(b) Determine (1) the effective size, (2) the average particle size, (3) the uniformity coefficient, and (4) the coefficient of curvature.

(c) Determine the textural composition of the soil (the amount of gravel, sand, etc.).

Sieve opening (mm)	Mass retained (grams)
4.75	0
2.00	14.8
0.85	98.0
0.425	90.1
0.15	181.9
0.075	108.8
	6.1

Strategy The best way to solve this type of problem is to make a table to carry out the calculations and then plot a gradation curve. Total mass (M) of dry sample used is 500 grams, but on summing the masses of the retained soil in column 2 we obtain 499.7 grams. The reduction in mass is due to losses mainly from a small quantity of soil that is stuck in the meshes of the sieves. You should use the "after sieving" total mass of 499.7 grams in the calculations.

Solution 1.3

Step 1: Tabulate data to obtain percentage finer.

See the table below.

Mass retained (grams), M_r	% Retained (M_r/M) × 100	Σ% retained	% Finer
0	0	0	100 − 0 = 100
14.8	3.0	add 3.0	100 − 3.0 = 97.0
98.0	19.6	22.6	100 − 22.6 = 77.4
90.1	18.0	40.6	100 − 40.6 = 59.4
181.9	36.4	77.0	100 − 77 = 23.0
108.8	21.8	98.8	100 − 98.8 = 1.2
6.1	1.2	check	
Total mass M_t = 499.7	100.0		

Step 2: Plot the gradation curve.

See Figure E1.3 for a plot of the gradation curve.

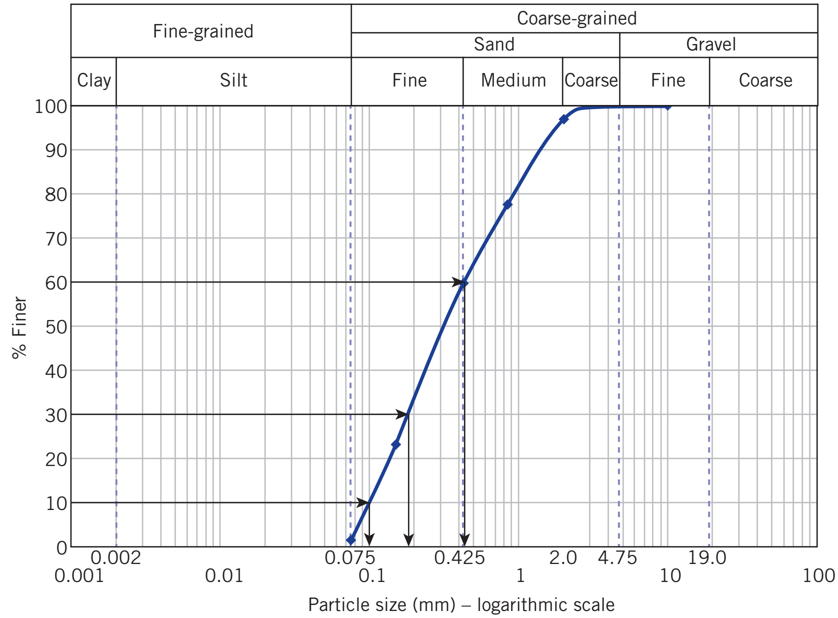


Figure E1.3

Step 3: Extract the effective size.

$$\text{Effective size} = D_{10} = 0.1 \text{ mm}$$

Step 4: Extract percentages of gravel, sand, silt, and clay.

$$\text{Gravel} = 0\%$$

$$\text{Sand} = 98.8\%$$

$$\text{Silt and clay} = 1.2\%$$

Check answer: gravel (%) + sand (%) + silt (%) + clay (%) must equal 100%.

That is: 0 + 98.8 + 1.2 = 100%

Step 5: Calculate *Cu* and *CC*.

$$Cu = \frac{D_{60}}{D_{10}} = \frac{0.45}{0.1} = 4.5$$

$$CC = \frac{(D_{30})^2}{D_{10}D_{60}} = \frac{0.18^2}{0.1 \times 0.45} = 7.2$$

EXAMPLE 1.4 *Calculation of Particle Diameter from Hydrometer Test Data*

After a time of 1 minute in a hydrometer test, the effective depth was 0.8 cm. The average temperature measured was 20°C and the specific gravity of the soil particles was 2.7, calculate the diameter of the particles using Stokes's law. Are these silt or clay particles?

Strategy This is a straightforward application of Equation (1.3).

Solution 1.4

Step 1: Calculate the particle diameter using Stokes's law.

$z = 0.8$ cm and $t_D = 1$ minute. For the temperature and specific gravity of the soil particles, $K = 0.01341$

$$D = K\sqrt{\frac{z}{t_D}} = 0.01341\sqrt{\frac{0.8}{1}} = 0.012 \text{ mm}$$

Step 2: Identify the soil type.

Silt particles have sizes between 0.075 mm and 0.002 mm.

Therefore, the soil particles belong to the silt fraction of the soil.

EXAMPLE 1.5 *Interpreting Hydrometer Analysis*

Sixty-five grams of the soil finer than 0.075 mm (passing the No. 200 sieve) in Example 1.2 was used to conduct a hydrometer test. The results are shown in the table below. What are the amounts of clays and silts in the soil?

Time (min)	Hydrometer reading (gram/liter)	Temperature (°C)	Corrected distance of fall (cm)	Grain size (mm)	% Finer by weight
1	40.0	22.5	8.90	0.0396	82.2
2	34.0	22.5	9.21	0.0285	68.8
3	32.0	22.0	9.96	0.0243	64.2
4	30.0	22.0	10.29	0.0214	59.7
8	27.0	22.0	10.96	0.0156	53.1
15	25.0	21.5	11.17	0.0116	48.4
30	23.0	21.5	11.45	0.0083	43.9
60	21.0	21.5	11.96	0.0060	39.5
240	17.0	20.0	12.45	0.0031	30.0
900	14.0	19.0	13.10	0.0017	22.9

Solution 1.5

Step 1: Plot percentage finer versus particle size (log scale).

See Figure E1.5.

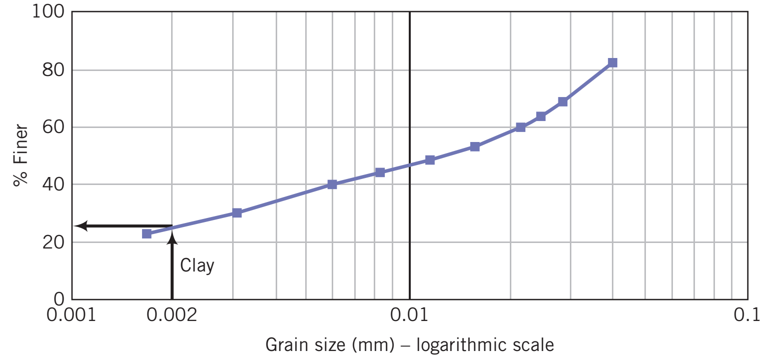


Figure E1.5

Step 2: Extract percentage finer than 0.002 mm.

$$\% \text{ finer than } 0.002 \text{ mm} = 25\%.$$

$$\% \text{ of clay and silt from Example 1.2} = 15.4\%.$$

$$\% \text{ clay in the soil in Example 1.2 is } (25/100) \times 15.4 = 3.9\%.$$

$$\% \text{ silt} = 15.4 - 3.9 = 11.5\%.$$

Check answer: silt (%) + clay (%) must equal 15.4%:

$$11.5 + 3.9 = 15.4\%$$

1.6 COMPARISON OF COARSE-GRAINED AND FINE-GRAINED SOILS FOR ENGINEERING USE

Coarse-grained soils have good load-bearing capacities and good drainage qualities, and their strength. They are practically incompressible when dense, but significant volume changes can occur when they are loose. Vibrations accentuate volume changes in loose, coarse-grained soils by rearranging the soil fabric into a dense configuration. Coarse-grained soils with angular particles have higher strengths, higher compressibilities, and lower densities than coarse-grained soils with rounded particles. The engineering properties of coarse-grained soils are controlled mainly by the grain size of the particles and their structural arrangement. Changes in moisture conditions do not significantly affect the volume change under static loading.

Coarse-grained soils are generally described as free draining. However, the term free draining means that the soil allows free passage of water in a relatively short time (a few minutes). Fines content (silts and clays) can significantly alter the flow conditions in these soils. Gravel, boulders, and coarse sands with fines content less than 5% are free draining. Fine sand, especially if it exists as a thick layer, is not free draining.

Fine-grained soils have poor load-bearing capacities compared with coarse-grained soils. Fine-grained soils are practically impermeable (not free draining), change volume and strength with variations in moisture conditions, and are susceptible to frost. Mineralogical factors rather than grain size control the engineering properties of fine-grained soils. Thin layers of fine-grained soils, even within thick deposits of coarse-grained soils, have been responsible for many geotechnical failures, and therefore, you need to pay special attention to fine-grained soils.

Key points

1. Fine-grained soils have much larger surface areas than coarse-grained soils and are responsible for the major physical and mechanical differences between coarse-grained and fine-grained soils.
2. The engineering properties of fine-grained soils depend mainly on mineralogical factors.
3. Coarse-grained soils have good load-bearing capacities and good drainage qualities. Changes in moisture conditions do not significantly affect the volume-change characteristics under static loading.
4. Fine-grained soils have low load-bearing capacities and poor drainage qualities. Changes in moisture conditions strongly influence the volume-change characteristics and strength of fine-grained soils.

1.7 SUMMARY

Soils are derived from the weathering of rocks by physical and chemical processes. The main groups of soils for engineering purposes from these processes are coarse-grained soils—sand and gravels—and fine-grained soils—silts and clays. Particle size is sufficient to identify coarse-grained soils. Fine-grained soils require mineralogical characterization in addition to particle size for identification. Coarse-grained and fine-grained soils have different engineering properties. Moisture content changes strongly influence the behavior of fine-grained soils. Moisture content changes do not significantly influence the behavior of coarse-grained soils under static loading.

EXERCISES

Concept understanding

1.1 Describe the processes responsible for the formation of soils from rock.

1.2 (a) What is a mineral?

(b) Describe the differences among the three main soil minerals.

(c) Which mineral group is most important for soils and why?

1.3 Which of the three main clay minerals undergo large volume change in contact with water and why?

1.4 (a) What is soil fabric?
(b) What is the name for the spaces between mineral particles?
(c) Why are the spaces between mineral particles important to geoengineers?
(d) Explain the differences between a flocculated and a dispersed structure?

1.5 Describe the differences among alluvial, collovial, glacial, and lateritic soils.

1.6 (a) What are the two types of surface forces in clayey soils?
(b) What is adsorbed water?
(c) Can you remove the adsorbed water by oven drying at 105°C? Explain.

1.7 What is the shape of the hole in a standard sieve?

1.8 What tests would you specify to determine the grain size of a sand that contains fine-grained soils?

Problem solving

1.9 In a sieve analysis test, the amount of soil retained on all sieves with 0.425 mm opening and above is 100 grams. The total mass used in the test is 500 grams.
(a) Determine the percentage of the soil greater than 0.425 mm (No. 40 sieve).
(b) Determine the percentage finer than 0.425 mm.

1.10 The data from a particle size analysis on a sample of a dry soil at a depth of 0.5 m near a mountain range (colluvium) are given in the table below.

Sieve opening (mm)	9.53	4.75	2.0	0.84	0.425	0.15	0.075	Pan
Mass retained (grams)	0	31	38	58	126	120	68	58

(a) What is the total mass of the soil retained on all sieves including the pan?
(b) If the total mass used at the start of the test is 500 grams, what is the percentage loss? Explain why this loss occurred in the test.
(c) Plot the particle size distribution curve.
(d) What are the percentages of coarse-grained and fine-grained soils in the sample.

1.11 The effective depth measured in a hydrometer test after 8 minutes is 1 cm. (a) Determine the average particle size if K is 0.01341, and (b) identify the soil type (e.g., silt or clay) corresponding to the average particle size.

1.12 The following results were obtained from sieve analyses of two soils.

Sieve opening (mm)	Mass (grams)	
	Soil A	**Soil B**
4.75	0	0
2.00	20.2	48.1
0.85	25.7	219.5
0.425	60.4	67.3
0.15	98.1	137.2
0.075	127.2	22.1
	168.2	5.6

Hydrometer tests on these soils gave the following results.

Particle size (mm)	% finer	
	Soil A	Soil B
0.05	22.6	1.0
0.01	13.8	0.9
0.005	12.2	0.8
0.002	5	0.5

(a) Plot the gradation curve for each soil on the same graph.

(b) How much coarse-grained and fine-grained soils are in each soil?

(c) What are the percentages of clay and silt in each soil according to USCS?

(d) Determine D_{10} for each soil.

(e) Determine the uniformity coefficient and the coefficient of concavity for each soil.

(f) Describe the gradation curve (e.g., well graded) for each soil?

Critical thinking and decision making

1.13 Why do geoengineers plot particle distribution curves on a semi-log scale with particle size on the abscissa (logarithmic scale) versus percentage finer on the ordinate (arithmetic scale)? Is there any theoretical justification for this? Would the shape of the grain size graph be different if arithmetic rather than semi-log scale is used?

1.14 If a soil consists of sand and fines, would drying the soil and then sieving it through a standard stack of sieves give accurate results on the fines content? Justify your answer.

1.15 If you have to select a soil for a roadway that requires good drainage qualities, what soil type would you select and why?

1.16 A house foundation consists of a concrete slab casted on a clay soil. The homeowner planted vegetation near one side of the foundation and watered it regularly, sometimes excessively. She noticed that this side of the foundation curled upward, the concrete slab cracked and several cracks appeared on the wall. What do you think is likely the predominant mineral in the clay soil? Justify your answer.