

Eighth Edition

Soils and Foundations



Cheng Liu
Jack B. Evett

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EIGHTH EDITION

Cheng Liu

Jack B. Evett

The University of North Carolina at Charlotte

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To Kimmie, Jonathan, Michele, Ryan, Alexander, Chloe, and Colin

and

Linda, Susan, Scott, Sarah, Sallie, Kayla, Ashlee, Carley, Camryn, Abbey, Trevor,

Jordan, Tyler, and Emilie.

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PREFACE

We have attempted to prepare an introductory, practical textbook for soil mechanics and foundations, which emphasizes design and practical applications that are supported by basic theory. Written in a simple and direct style that should make it very easy to read and understand the subject matter, this book contains an abundance of both example problems within each chapter and work problems at the end of each chapter. In addition, there are ample diagrams, charts, and illustrations throughout to help better explain the subject matter. In summary, we have tried to extract the salient and essential aspects of soils and foundations and to present them in a simple and straightforward manner.

NEW TO THIS EDITION

- Sections on “Pressuremeter Test” and “Dilatometer Test” (Chapter 3)
- A section on “Bernoulli’s Theorem” (Chapter 5)
- A section on “Uplift Pressure on Dams” (Chapter 5)
- A section on “Dewatering” (Chapter 5)
- Updated chapter title to “Subsurface Stresses in Soil” and added section on “Subsurface Stresses Caused by Overlying Soil Masses” (Chapter 6)
- Combined previous Chapters 10 and 11 into one new chapter titled “Deep Foundations” (Chapter 10)

We urge students using this book to review each illustration as it is cited and to study each example problem carefully. Believing that example problems are an extremely effective means of learning a subject such as soils and foundations, we have included an abundance of these problems, and we believe that they will be very useful in mastering the material in the book.

Incidentally, several users and reviewers of our book have suggested that we move Chapter 3 on soil exploration to follow Chapter 8 on shear strength of soil. The reason for the shift was to delay covering soil exploration until after more theory was covered. In other words, we need to

know what we are looking for before we go looking for it. We thought that was a good suggestion and planned on making the change. However, we soon realized that there are some cases in the intervening chapters where material covered in Chapter 3 is prerequisite. Hence, we decided not to make this change. The user may elect to delay fully covering Chapter 3 until after covering Chapter 8 while covering small parts of Chapter 3 as needed.

We want to express our sincere appreciation to Carlos G. Bell, formerly of The University of North Carolina at Charlotte, and to W. Kenneth Humphries, former Dean of Engineering at the University of South Carolina, who read our original manuscript and offered many helpful suggestions. Also, we would like to acknowledge the late Donald Steila of the Department of Geography and Earth Science at The University of North Carolina at Charlotte, who reviewed Chapter 1. We also thank Alan Stadler, formerly of the Department of Civil Engineering at The University of North Carolina at Charlotte, for reviewing the material on soil stabilization in Chapter 4. Finally, we thank the other reviewers of this edition for their helpful comments and suggestions: Salman Azhar, Auburn University; Carmine J. Desio, Nassau Community College; Tanya Kunberger, Florida Gulf Coast University; Kunchi Madhavan, Christian Brothers University; Paul Nasados, Pennsylvania College of Technology; Tim Ray, Midlands Technical College; Dianne Slattery, Southern Illinois University, Edwardsville; Jonathon Smalley, Ohio Northern University; and Timothy Zeigler, Southern Polytechnic State University.

We hope that you will enjoy using the book. We would be pleased to receive your comments, suggestions, and/or criticisms.

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Soils and Foundations

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FORMATION OF NATURAL SOIL DEPOSITS

1-1 INTRODUCTION

Soil is more or less taken for granted by the average person. It makes up the ground on which we live, it is for growing crops, and it makes us dirty. Beyond these observations, most people are not overly concerned with soil. There are, however, some people who *are* deeply concerned. These include certain engineers as well as geologists, contractors, hydrologists, farmers, agronomists, soil chemists, and others.

Most structures of all types rest either directly or indirectly upon soil, and proper analysis of the soil and design of the structure's foundation are necessary to ensure a safe structure free of undue settling and/or collapse. A comprehensive knowledge of the soil in a specific location is also important in many other contexts. Thus, study of soils should be an important component in the education of civil engineers.

Chapter 1 relates the formation of natural soil deposits; it describes the sources of soil. Chapter 2 introduces and defines various engineering properties of soil. Subsequent chapters deal with evaluation of these properties and with essential interrelationships of soil with structures of various types.

1-2 ROCKS—THE SOURCES OF SOILS

Soil is composed of particles, large and small, and it may be necessary to include as “soil” not only solid matter but also air and water. Normally, the particles are the result of weathering (disintegration and decomposition) of rocks and decay of vegetation. Some soil particles may, over a period of time, become consolidated under the weight of overlying material and become rock. In fact, cycles of rock disintegrating to form soil, soil becoming consolidated under great pressure and heat to form rock, rock disintegrating to form soil, and so on have occurred repeatedly throughout

geologic time. The differentiation between soil and rock is not sharp; but from an engineering perspective, if material can be removed without blasting, it is usually considered to be “soil,” whereas if blasting is required, it might be regarded as “rock.”

Rocks can be classified into three basic groups that reflect their origin and/or method of formation: *igneous*, *sedimentary*, and *metamorphic*.

Igneous Rocks

Igneous rocks form when magma (molten matter) such as that produced by erupting volcanoes cools sufficiently to solidify. Volcanic action, normally referred to as *volcanism*, can occur beneath or upon the earth's surface. Volcanoes probably produced the minority of earth's igneous rocks, however. During the earth's formative stages, its surface may well have been largely molten, thus not requiring magma to move to the surface from great depths. It is likely that great amounts of Precambrian rock formed in this fashion.

Igneous rocks can be coarse-grained or fine-grained, depending on whether cooling occurred slowly or rapidly. Relatively slow cooling occurs when magma is trapped in the crust below the earth's surface (such as at the core of a mountain range), whereas more rapid cooling occurs if the magma reaches the surface while molten (e.g., lava flow).

Of coarse-grained igneous rocks, the most common is *granite*, a hard rock rich in quartz, widely used as a construction material and for monuments. Others are *syenites*, *diorites*, and *gabbros*. Most common of the fine-grained igneous rocks is *basalt*, a hard, dark-colored rock rich in ferromagnesian minerals and often used in road construction. Others are *rhyolites* and *andesites*.

Being generally hard, dense, and durable, igneous rocks often make good construction materials. Also, they typically have high bearing capacities and therefore make good foundation material.

Sedimentary Rocks

Sedimentary rocks compose the great majority of rocks found on the earth's surface. They are formed when mineral particles, fragmented rock particles, and remains of certain organisms are transported by wind, water, and ice (with water being the predominant transporting agent) and deposited, typically in layers, to form sediments. Over a period of time as layers accumulate at a site, pressure on lower layers resulting from the weight of overlying strata hardens the deposits, forming sedimentary rocks. In addition, deposits may be solidified and cemented by certain minerals (e.g., silica, iron oxides, calcium carbonate). Sedimentary rocks can be identified easily when their layered appearance is observable. The most common sedimentary rocks are *shale*, *sandstone*, *limestone*, and *dolomite*.

Shale, the most abundant of the sedimentary rocks, is formed by consolidation of clays or silts. Organic matter or lime may also be present. Shales have a laminated structure and often exhibit a tendency to split along laminations. They can become soft and revert to clayey or silty material if soaked in water for a period of time. Shales vary in strength from soft (may be scratched with a fingernail and easily excavated) to hard (requiring explosives to excavate). Shales are sometimes referred to as *claystone* or *siltstone*, depending on whether they were formed from clays or silts, respectively.

Sandstone, consisting primarily of quartz, is formed by pressure and the cementing action of silica (SiO_2), calcite (calcium carbonate, CaCO_3), iron oxide, or clay. Strength and durability of sandstones vary widely depending on the kind of cementing material and degree of cementation as well as the amount of pressure involved.

Limestone is sedimentary rock composed primarily of calcium carbonate hardened underwater by cementing action (rather than pressure); it may contain some clays or organic materials within fissures or cavities. Like the strength of shales and sandstones, that of limestones varies considerably from soft to hard (and therefore durable), with actual strength depending largely on the rock's texture and degree of cementation. (A porous texture means lower strength.) Limestones occasionally have thin layers of sandstone and often contain fissures, cavities, and caverns, which may be empty or partly or fully filled with clay.

Dolomites are similar in grain structure and color to limestones and are, in fact, limestones in which the calcite (CaCO_3) interbonded with magnesium. Hence, the principal ingredient of dolomites is calcium magnesium carbonate [$\text{CaMg}(\text{CO}_3)_2$]. Dolomites and limestones can be differentiated by placing a drop of diluted hydrochloric acid on the rock. A quick reaction forming small white bubbles is indicative of limestone; no reaction, or a very slow one, means that the rock is dolomite.

As indicated, the degrees of strength and hardness of sedimentary rocks are variable, and engineering use of such rocks varies accordingly. Relatively hard shale makes a good foundation material. Sandstones are generally good construction

materials. Limestone and dolomite, if strong, can be both good foundation and construction materials.

Metamorphic Rocks

Metamorphic rocks are much less common at the earth's surface than are sedimentary rocks. They are produced when sedimentary or igneous rocks literally change their texture and structure as well as mineral and chemical composition, as a result of heat, pressure, and shear. Granite metamorphoses to *gneiss*, a coarse-grained, banded rock. *Schist*, a medium- to coarse-grained rock, results from high-grade metamorphism of both basalt and shale. Low-grade metamorphism of shale produces *slate*, a fine-textured rock that splits into sheets. Sandstone is transformed to *quartzite*, a highly weather-resistant rock; limestone and dolomite change to *marble*, a hard rock capable of being highly polished. Gneiss, schist, and slate are *foliated* (layered); quartzite and marble are *nonfoliated*.

Metamorphic rocks can be hard and strong if unweathered. They can be good construction materials—for example, marble is often used for buildings and monuments—but foliated metamorphic rocks often contain planes of weakness that can diminish strength. Metamorphic rocks sometimes contain weak layers between very hard layers.

1-3 ROCK WEATHERING AND SOIL FORMATION

As related in the preceding section, soil particles are the result of weathering of rocks and organic decomposition. Weathering is achieved by *mechanical* (*physical*) and *chemical* means.

Mechanical weathering disintegrates rocks into small particles by temperature changes, frost action, rainfall, running water, wind, ice, abrasion, and other physical phenomena. These cause rock disintegration by breaking, grinding, crushing, and so on. The effect of temperature change is especially important. Rocks subjected to large temperature variations expand and contract like other materials, possibly causing structural deterioration and eventual breakdown of rock material. When temperatures drop below the freezing point, water trapped in rock crevices freezes, expands, and can thereby break rock apart. Smaller particles produced by mechanical weathering maintain the same chemical composition as the original rock.

Chemical weathering causes chemical decomposition of rock, which can drastically change its physical and chemical characteristics. This type of weathering results from reactions of rock minerals with oxygen, water, acids, salts, and so on. It may include such processes as oxidation, solution (strictly speaking, solution is a physical process), carbonation, leaching, and hydrolysis. These cause chemical weathering actions that can (1) increase the volume of material, thereby causing subsequent material breakdown; (2) dissolve parts of rock matter, yielding voids that make remaining matter more susceptible to breaking; and (3) react with the cementing material, thereby loosening particles.

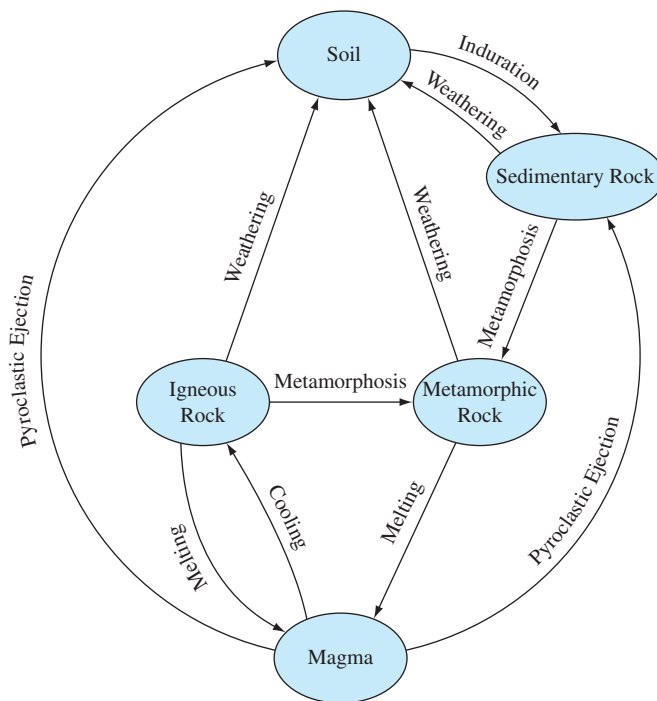


FIGURE 1-1 Primary processes in the geologic cycle.

Source: Donald P. Coduto, *Geotechnical Engineering Principles and Practices*, 1999. Reprinted by permission of Pearson Education, Upper Saddle River, NJ.

The type of soil produced by rock weathering is largely dependent on rock type. Of igneous rocks, granites tend to decompose to silty sands and sandy silts with some clays. Basalts and other rocks containing ferromagnesian minerals (but little or no silica) decompose primarily to clayey soils. With regard to sedimentary rocks, decomposed shales produce clays and silts, whereas sandstones again become sandy soils. Weathered limestones can produce a variety of soil types, with fine-grained ones being common. Of metamorphic rocks, gneiss and schist generally decompose to form silt-sand soils, whereas slate tends more to clayey soils. Weathered marble often produces fine-grained soils; quartzite decomposes to more coarse-grained soils, including both sands and gravels.

Figure 1-1 shows the cycle of weathering of rock into soil, consolidation of soil under great pressure and heat to form rock, weathering of rock into soil, and so on; this cycle is known as the geologic cycle. The figure also shows processes in the cycle that form igneous, sedimentary, and metamorphic rocks.

1-4 SOIL DEPOSITS

Soils produced by rock weathering can be categorized according to where they are ultimately deposited relative to the location of the parent rock. Some soils remain where they were formed, simply overlying the rock from which they came. These are known as *residual soils*. Others are

transported from their place of origin and deposited elsewhere. They are called *transported soils*.

Residual Soils

Residual soils have general characteristics that depend in part on the type of rock from which they came. Particle sizes, shapes, and composition can vary widely, as do depths of residual soil deposits—all depending on the amount and type of weathering. The actual depth of a residual soil deposit depends on the rate at which rock weathering has occurred at the location and the presence or absence of any erosive agents that would have carried soil away.

Transported Soils

Transported soils are formed when rock weathers at one site and the particles are moved to another location. Some common transporting agents for particles are (1) gravity, (2) running water, (3) glaciers, and (4) wind. Transported soils can therefore be categorized with regard to these agents as *gravity deposits*, *alluvial deposits*, *glacial deposits*, and *wind deposits*.

Gravity Deposits. Gravity deposits are soil deposits transported by the effect of gravity. A common example is the landslide. Gravity deposits, which are not generally carried very far, tend to be loosely compacted and otherwise exhibit little change in the general character of soil material as a result of being transported.

Alluvial Deposits. Alluvial deposits, having been transported by moving water, are found in the vicinity of rivers. Rainwater falling on land areas runs overland, eroding and transporting soil and rock particles as it goes, and eventually enters a creek or river. Continuously moving water can carry particles and deposit them a considerable distance from their former location. All soils carried and deposited by flowing water are called *alluvial deposits*. Lack of vegetation may allow enormous amounts of erosion leading to vast alluvial deposits (e.g., the Mississippi Delta).

Rivers are capable of transporting particles of all sizes, ranging from very fine silts in suspension to, in some cases, large boulders. The greater the velocity of river flow, the larger will be the size of particles that can be carried. Hence, a sluggish creek may carry only fine-grained sediment, whereas a flooding river transports all particle sizes, including large rocks. The relationship between river velocity and size of particle carried also affects the manner in which particles are deposited. As river velocity decreases, relatively larger particles settle and are deposited first. If the velocity decreases further, the next-larger-size particles settle out.

Alluvial deposits are often composed of various soil types because different types of soil tend to mix as they are carried downstream. They do, however, tend to be layered because settling rates are proportional to particle size.

The nature of soil can be greatly influenced by past alluvial transport and deposits. For example, at a location where

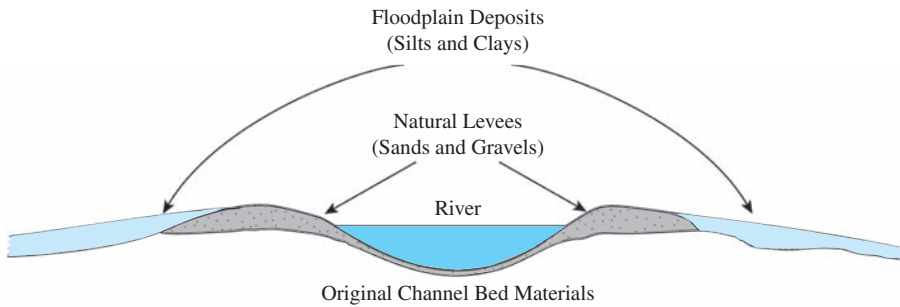


FIGURE 1-2 Natural levees and floodplain deposits.

a river's velocity decreases, such as when the channel widens significantly or its slope decreases substantially, coarser soil particles settle, forming submerged, flat, triangular deposits known as *alluvial fans*. When flooding rivers, which normally carry a heavy sediment load, overflow their banks, the overflowing water experiences a decrease in velocity. Larger particles, such as sands and gravels, tend to settle more quickly; their deposits can form *natural levees* along riverbanks (see Figure 1-2). (These natural levees may someday be washed away by a more severe flood.) Smaller particles, such as silts and clays, settle less quickly, forming *floodplain deposits* in areas beyond the levees (Figure 1-2). (However, smaller rivers can have floodplain deposits without forming levees.)

Another type of alluvial deposit occurs when rivers meander (i.e., follow a winding and turning course). As water moves through a channel bend, velocity along the inside edge decreases, whereas that along the outer one increases. Consequently, particle erosion may occur along the outer edge with deposition along the inner edge. This action can, over a period of time, increase the amount of bend and significantly alter the river channel and adjacent land area. Eventually, the river may cut across a large bend, as shown in Figure 1-3, leaving the old channel bend isolated. Water remaining in the isolated bend forms an *oxbow lake*, which can eventually fill in with floodplain deposits (usually silty and organic materials). Ultimately, the entire filled-in oxbow lake may be covered by additional floodplain deposits, leaving a hidden deposit of undesirable, high plastic, and/or organic silt, silty clay, and peat.

Sediments deposited at the mouths of creeks and rivers flowing into lakes, bays, or seas are known as *deltas*. Those deposited in lakes and seas are called *lacustrine* and *marine deposits*, respectively. These deposits tend to be loose and compressible and may contain organic material. They are therefore generally undesirable from an engineering point of view.

Glacial Deposits. Glacial deposits result, of course, from the action of glaciers. Many years ago (over 10,000), glaciers, enormous sheets of ice, moved southward across much of the northern United States (as well as Europe and other areas). As they progressed, virtually everything in their paths, including soils and rocks ranging in size from the finest clays to huge boulders, was picked up and transported.

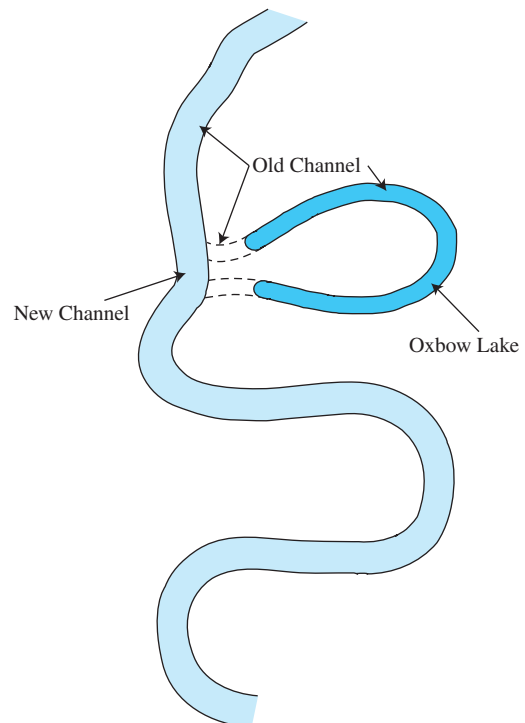


FIGURE 1-3 Oxbow lake.

As they were being carried by glaciers, soils and rocks were mixed together, thrashed about, broken, crushed, and so on by enormous internal glacial pressures. Consequently, glacial deposits can contain all types of soils.

Some soil particles were directly deposited by moving glaciers; others were taken from glaciers by water flowing from the ice to be deposited in lakes or transported in rivers flowing away from the ice; still others were deposited *en masse* when glaciers ultimately melted and disappeared. Direct glacial deposits, known as *moraines*, are heterogeneous mixtures composed of all sizes of particles (from boulders to clay) that the ice accumulated as it traveled. *Eskers* are ridges or mounds of boulders, gravel, and sand formed when such materials flowing in streams on, within, or beneath glaciers were deposited as the stream's bed load.

The quality of soils in glacial deposits as foundations and construction materials is somewhat variable because of the different types of soils found in such deposits. Often

these soils make good materials for construction purposes because of the intense compaction they have undergone, although those containing mostly clays are not as strong, are often compressible, and may therefore cause problems if used for foundations or construction materials.

Wind Deposits. Wind deposits (also known as *aeolian deposits*) obviously have wind as the transporting agent. Wind is a very important agent in certain areas and has the potential to move soil particles over large distances.

Winds can move sandy soil particles by rolling them along the ground as well as sending them short distances through the air. Wind-deposited sands are known as *dunes*, and they tend to occur in sandy desert areas and along sandy beaches on the downwind side. Sands from dunes can be used for certain construction purposes.

Fine-grained soils can be airborne over long distances by winds. Silty soils are more amenable than clayey soils to wind transport, however, because a clayey soil's bonding or cohesion reduces its wind erosion. A wind-deposited silt is known as *loess*, significant deposits of which are found in the general vicinity of the Mississippi and Missouri Rivers in the United States, and in Europe and Asia (especially northern China). Loess is generally a hard and stable soil when unsaturated because of cementation from calcium carbonate and iron oxide. It tends to lose its cementation when wetted, however, and become soft and mushy. Loessial deposits

typically have a yellow-brown (buff) color, low density, and relatively uniform grain size. These deposits are generally able to stand on vertical cuts and exhibit high vertical permeability. Because of their low strength when wet, however, special care must be taken during the design and construction of foundations over such deposits.

Ashes from erupting volcanoes can also produce wind deposits. Consisting of fine-sized igneous rock fragments, volcanic ash is light and porous, and deposits tend to decompose quickly, often changing into plastic clays. The great Mt. St. Helens eruption produced not lava but ash.

It should be noted in concluding this section that soil deposits seldom occur in nature in neat "packages"—that is, a soil of exactly the same type at all depths throughout a construction site. An area with "original" glacial deposits may subsequently have been overlain by alluvial deposits possessing different characteristics. Even if all the soil at a given job site is of the same deposit, its properties may vary from place to place throughout the site.

For these reasons, subsurface investigation of an area is extremely important. One cannot just look at the surface and know what is beneath. Using quantitative results obtained from subsurface investigation together with qualitative knowledge of the origins of the soil(s) at the site, geotechnical engineers can produce an adequate foundation design to ensure against failure or undue settling of a structure. (Subsurface investigation is covered in Chapter 3.)

ENGINEERING PROPERTIES OF SOILS

2-1 SOIL TYPES

Soils may be classified into three very broad categories: *cohesionless*, *cohesive*, and *organic* soils. In the case of cohesionless soils, the soil particles do not tend to stick together. Cohesive soils are characterized by very small particle size where surface chemical effects predominate. The particles do tend to stick together—the result of water-particle interaction and attractive forces between particles. Cohesive soils are therefore both sticky and plastic. Organic soils are typically spongy, crumbly, and compressible. They are undesirable for use in supporting structures.

Three common types of cohesionless soils are *gravel*, *sand*, and *silt*. Gravel has particle sizes greater than 2 millimeters (mm), whereas particle sizes for sand range from about 0.1 to 2 mm. Both gravel and sand may be further divided into “fine” (as fine sand) and “coarse” (as coarse sand). Gravel and sand can be classified according to particle size by sieve analysis. Silt has particle sizes that range from about 0.005 to 0.1 mm.

The common type of cohesive soil is clay, which has particle sizes less than about 0.005 mm. Clayey soils cannot be separated by sieve analysis into size categories because no practical sieve can be made with openings so small; instead, particle sizes may be determined by observing settling velocities of the particles in a water mixture.

More precise classifications of these soil types by particle size according to two systems—the American Association of State Highway and Transportation Officials (AASHTO) system and the Unified Soil Classification System (USCS)—are given in Table 2-1. It is clear from variations between these classification systems that boundaries between soil types are more or less arbitrary.

Soils can also be categorized strictly in terms of grain size. Two such categories are *coarse-grained* and *fine-grained*. Gravel and sand, with soil grains coarser than 0.075 mm, or a No. 200 sieve size, are coarse-grained (also referred to as *granular* soils); silt and clay, with soil grains finer than 0.075 mm, are fine-grained.

Engineering properties of granular soils are affected by their grain sizes and shapes as well as by their grain-size distributions and their compactness (see Section 2-11). Granular soils, except for loose sand, generally possess excellent engineering properties. Exhibiting large bearing capacities and experiencing relatively small settlements, they make outstanding foundation materials for supporting roads and structures. Granular soils also make excellent backfill materials for retaining walls because they are easily compacted and easily drained, and because they exert small lateral pressures. In addition, as a result of high shear strengths and ease of compaction, granular soils make superior embankment material. One drawback, however, is that the high permeabilities of granular soils make them poor, or even unacceptable, for use alone as earthen dikes or dams.

Cohesive soils (mostly clays but also silty clays and clay-sand mixtures with clay being predominant) exhibit generally undesirable engineering properties compared with those of granular soils. They tend to have lower shear strengths and to lose shear strength further upon wetting or other physical disturbances. They can be plastic and compressible, and they expand when wetted and shrink when dried. Some types expand and shrink greatly upon wetting and drying—a very undesirable feature. Cohesive soils can *creep* (deform plastically) over time under constant load, especially when the shear stress is approaching its shear strength, making them prone to landslides. They develop large lateral pressures and have low permeabilities. For these reasons, cohesive soils—unlike granular soils—are generally poor materials for retaining-wall backfills. Being impervious, however, they make better core materials for earthen dams and dikes.

Silty soils are on the border between clayey and sandy soils. They are fine-grained like clays but cohesionless like sands. Silty soils possess undesirable engineering properties. They exhibit high capillarity and susceptibility to frost action, yet they have low permeabilities and low densities.

Table 2-1 Soil Classification Based on Grain Size¹

Agency	Coarse-Grained				Fine-Grained	
	Gravel	Coarse Sand	Medium Sand	Fine Sand	Silt	Clay
AASHTO	75–2.00 (3-in.–No. 10 sieves)	2.00–0.425 (No. 10–No. 40 sieves)		0.425–0.075 (No. 40–No. 200 sieves)	0.075–0.002	<0.002
USCS	Coarse: 75–19.0 (3-in.–3/4-in. sieves) Fine: 19.0–4.75 (3/4-in.–No. 4 sieves)	4.75–2.00 (No. 4–No. 10 sieves)	2.00–0.425 (No. 10–No. 40 sieves)	0.425–0.075 (No. 40–No. 200 sieves)	Fines <0.075 (silt or clay)	

¹All grain sizes are in millimeters.

Any soil containing a sufficient amount of organic matter to affect its engineering properties is called *organic soil*. As mentioned previously, organic soils are typically spongy, crumbly, and compressible. In addition, they possess low shear strengths and may contain harmful materials. Organic soils are essentially unacceptable for supporting foundations.

In most applications in this book, soils are categorized as cohesionless or cohesive, with cohesionless generally implying a sandy soil and cohesive, a clayey soil. Some soils encountered in practice are mixtures of both types and therefore exhibit characteristics of both.

2-2 GRAIN-SIZE ANALYSIS

Never will a natural soil be encountered in which all particles are exactly the same size and shape. Both cohesionless and cohesive soils, as well as mixtures of the two, will always contain particles of varying sizes. Properties of a soil are greatly influenced by the sizes of its particles and distribution of grain sizes throughout the soil mass. Hence, in many engineering applications, it is not sufficient to know only that a given soil is clay, sand, rock, gravel, or silt. It is also necessary to know something about the distribution of grain sizes of the soil.

In the case of most cohesionless soils, distribution of grain size can be determined by sieve analysis. A sieve is similar to a cook's flour sifter. It is an apparatus containing a wire mesh with openings the same size and shape. When soil is passed through a sieve, soil particles smaller than the opening size of the sieve will pass through, whereas those larger than the opening size will be retained. Certain sieve-size openings between 4.75 and 0.075 mm are designated by U.S. Standard Sieve Numbers, as given in Table 2-2. Thus, grain sizes within this range can be classified according to U.S. Standard Sieve Numbers.

In practice, sieves of different opening sizes are stacked, with the largest opening size at the top and a pan at the bottom. Soil is poured in at the top, and soil particles pass downward through the sieves until they are retained on a particular sieve (see Figure 2-1). The stack of sieves is mechanically agitated during this procedure. At the end of the procedure, the soil particles retained on each sieve can be weighed and the results presented graphically in the form

Table 2-2 U.S. Standard Sieve Numbers and Their Sieve Openings

U.S. Standard Sieve Number	Sieve Opening (mm)
4	4.75
10	2.00
20	0.850
40	0.425
60	0.250
100	0.150
200	0.075

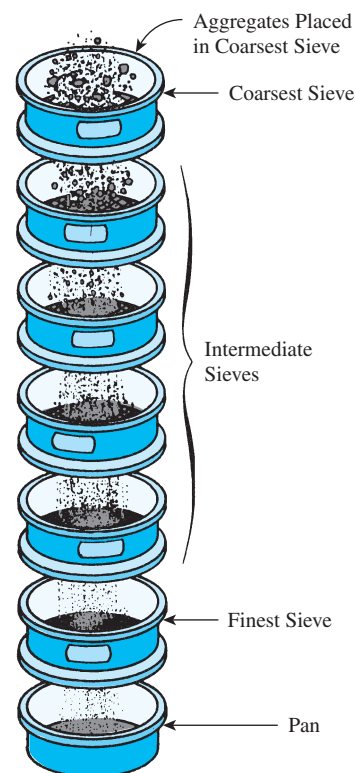


FIGURE 2-1 Sieve analysis.

Source: *The Asphalt Handbook*, Manual Series No. 4 (MS-4), Asphalt Institute, Lexington, KY, 2007.

of a grain-size distribution curve. This is normally a semilog plot with grain size (diameter) along the abscissa on a logarithmic scale and percentage passing that grain size along the ordinate on an arithmetic scale. Example 2-1 illustrates the analysis of the results of a sieve test, including the preparation of a grain-size distribution curve.

Example 2-1

Given

An air-dry soil sample weighing 2000 grams (g) is brought to the soils laboratory for mechanical grain-size analysis. The laboratory data are as follows:

U.S. Sieve Size	Size Opening (mm)	Mass Retained (g)
3/4 in.	19.0	0
3/8 in.	9.50	158
No. 4	4.75	308
No. 10	2.00	608
No. 40	0.425	652
No. 100	0.150	224
No. 200	0.075	42
Pan	—	8

Required

A grain-size distribution curve for this soil sample.

Solution: To plot the grain-size distribution curve, one must first calculate the percentage retained on each sieve, the cumulative percentage retained, and the percentage passing through each sieve, then tabulate the results, as shown in Table 2-3.

$$\text{Total sample weight} = 2000 \text{ g}$$

1. The percentage retained on each sieve is obtained by dividing the mass retained on each sieve by the total sample mass. Thus,

$$\text{Percentage retained on } 3/4\text{-in. sieve} = \frac{0 \text{ g}}{2000 \text{ g}} \times 100\% = 0\%$$

$$\text{Percentage retained on } 3/8\text{-in. sieve} = \frac{158 \text{ g}}{2000 \text{ g}} \times 100\% = 7.9\%$$

$$\text{Percentage retained on No. 4 sieve} = \frac{308 \text{ g}}{2000 \text{ g}} \times 100\% = 15.4\% \text{ etc.}$$

Therefore,

$$\text{Column(4)} = \frac{\text{Column(3)}}{\text{Total sample mass}} \times 100\%$$

2. The cumulative percentage retained on each sieve is obtained by summing the percentage retained on all coarser sieves. Thus,

$$\text{Cumulative percentage retained on } 3/4\text{-in. sieve} = 0\%$$

$$\text{Cumulative percentage retained on } 3/8\text{-in. sieve} = 0\% + 7.9\% = 7.9\%$$

$$\text{Cumulative percentage retained on No. 4 sieve} = 7.9\% + 15.4\% = 23.3\%$$

$$\text{Cumulative percentage retained on No. 10 sieve} = 23.3\% + 30.4\% = 53.7\% \text{ etc.}$$

3. The percentage passing through each sieve is obtained by subtracting from 100% the cumulative percentage retained on the sieves. Thus,

$$\text{Percentage passing through } 3/4\text{-in. sieve} = 100\% - 0\% = 100\%$$

$$\text{Percentage passing through } 3/8\text{-in. sieve} = 100\% - 7.9\% = 92.1\%$$

$$\text{Percentage passing through No. 4 sieve} = 100\% - 23.3\% = 76.7\% \text{ etc.}$$

Therefore, column (6) = 100 - column (5).

Table 2-3 Sieve Analysis Data for Example 2-1

(1) Sieve Number	(2) Sieve Opening (mm)	(3) Mass Retained (g)	(4) Percentage Retained	(5) Cumulative Percentage Retained	(6) Percentage Passing
3/4 in.	19.0	0	0	0	100.0
3/8 in.	9.50	158	7.9	7.9	92.1
No. 4	4.75	308	15.4	23.3	76.7
No. 10	2.00	608	30.4	53.7	46.3
No. 40	0.425	652	32.6	86.3	13.7
No. 100	0.150	224	11.2	97.5	2.5
No. 200	0.075	42	2.1	99.6	0.4
Pan	—	8	0.4	100.0	—

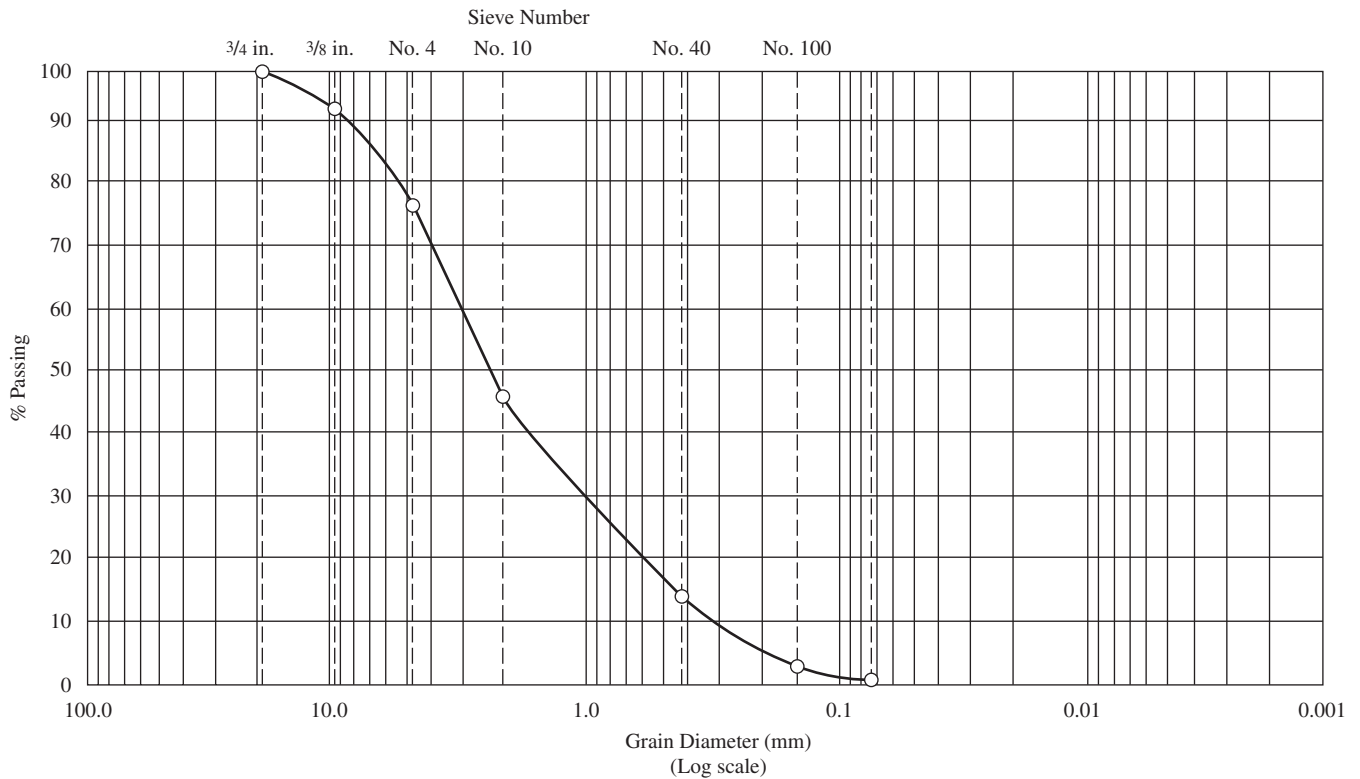


FIGURE 2-2 Grain-size distribution curve for Example 2-1.

4. Upon completion of these calculations, the grain-size distribution curve is obtained by plotting column (2), sieve opening (mm), versus column (6), percentage passing through, on semilog paper. The percentage passing is always plotted as the ordinate on the arithmetic scale and the sieve opening as the abscissa on the log scale (see Figure 2-2).

Several useful parameters can be determined from grain-size distribution curves. The diameter of soil particles at which 50% passes (i.e., 50% of the soil by weight is finer than this size) is known as the *median size* and is denoted by D_{50} . The diameter at which 10% passes is called the *effective size* and is denoted by D_{10} . Two coefficients used only in the Unified Soil Classification System for classifying coarse-grained soils (see Section 2-4) are the *coefficient of uniformity* (C_u) and the *coefficient of curvature* (C_c), which are defined as follows:

$$C_u = \frac{D_{60}}{D_{10}} \tag{2-1}$$

$$C_c = \frac{(D_{30})^2}{D_{60}D_{10}} \tag{2-2}$$

where D_{60} and D_{30} are the soil particle diameters corresponding to 60 and 30%, respectively, passing on the cumulative grain-size distribution curve.

Median size gives an “average” particle size for a given soil sample; other parameters offer some indication of the particle size range. Effective size gives the maximum particle diameter of the smallest 10% of soil particles. It is this size to which permeability and capillarity are related. C_u and C_c have little or no meaning when more than 5% of the soil is finer than a No. 200 sieve opening (0.075 mm).

Figure 2-3 shows some typical grain-size distribution curves. Well-graded soils have particle sizes varying over a wide range and have higher C_u values (15 or higher). Poorly graded soils have either (1) a deficiency or an excess of some particle sizes or (2) most soil particles approximately the same size. Uniformly graded soils, as shown in Figure 2-3, are poorly graded soils because most particles are about the same size. Uniformly graded soils have low C_u values. Gap-graded (or skip-graded) soils are also poorly graded soils because of a deficiency of some particle sizes. For example, the proportion of particle sizes between 0.425 mm (No. 40 sieve) and 4.75 mm (No. 4 sieve) is low (deficient) in the gap-graded soil shown in Figure 2-3.

In the case of cohesive soils, distribution of grain size is not determined by sieve analysis because the particles are too small. Particle sizes may be determined by the hydrometer method, which is a process for indirectly observing the settling velocities of the particles in a soil-water mixture. Another valuable technique for analyzing cohesive soils is by use of *Atterberg limits*, which is described in the next section.