3 Soils and Environment

Soil erosion on the Piedmont of the southeastern United States. (*Edward A. Keller*)

Soil erosion is a serious environmental problem on a global scale. Shown here are the red soils of the Piedmont of the southeastern United States at Charlotte, North Carolina, where a series of gullies has developed. The erosion has multiple effects including loss of soil resources as well as degradation of the quality of the water that the sediment enters. Such soil erosion is particularly a problem in urban environments, where vegetation may be removed prior to development. Although we have many safeguards in effect to minimize soil erosion resulting from urbanization, the problem persists in many parts of the United States and is severe in many parts of the world, where protection of soil resources may not be a high priority.

3.1 Introduction to Soils

Soil may be defined in several ways. To soil scientists, soil is solid earth material that has been altered by physical, chemical, and organic processes such that it can support rooted plant life. To engineers, on the other hand, soil is any solid earth material that can be removed without blasting. Both of these definitions are important in environmental geology. Geologists must be aware not only of the different definitions, but also of the different points of view of researchers in various fields concerning soil-producing processes and the role of soils in environmental problems.

Consideration of soils, particularly with reference to land-use limitations, is becoming an important aspect of environmental work:

- In the field of *land-use planning*, land capability (suitability of land for a particular use) is often determined in part by the soils present, especially for such uses as urbanization, timber management, and agriculture.
- Soils are critical when we consider *waste management* because interactions between waste, water, soil, and rock often determine the suitability of a particular site to receive waste.

LEARNING OBJECTIVES

Soils comprise an important part of our environment. Virtually all aspects of the terrestrial environment interact at one level or another with soils. With this in mind, primary learning objectives for this chapter are:

- *To become familiar with soils terminology and the processes responsible for the development of soils.*
- *To understand what soil fertility is, as well as the interactions of water in soil processes.*
- *To gain a modest acquaintance with how we classify soils, particularly for engineering purposes.*
- *To understand the more important engineering properties of soil.*
- *To understand relationships between land use and soils.*
- *To be aware of what sediment pollution is and how it may be minimized.*
- *To have a modest acquaintance with the process of desertification and what drives it.*
- *To be aware of how soils surveys are useful in land-use planning.*

Web Resources

Visit the "Environmental Geology" Web site at www.prenhall.com/keller to find additional resources for this chapter, including:

- Web Destinations
- On-line Quizzes
- On-line "Web Essay" Questions
- Search Engines
- Regional Updates

- Study of soils helps land-use planners evaluate *natural hazards*, including floods, landslides, and earthquakes. In the case of floods, because floodplain soils differ from upland soils, consideration of soil properties helps delineate natural floodplains. Evaluation of the relative ages of soils on landslide deposits may provide an estimate of the frequency of slides and thus assist in planning to minimize their impact. The study of soils has also been a powerful tool in establishing the chronology of earth materials deformed by faulting, which has led to better calculations of the recurrence intervals of earthquakes at particular sites.

3.2 Soil Profiles

The development of a soil from inorganic and organic materials is a complex process. Intimate interactions of the rock and hydrologic cycles produce the weathered rock materials that are basic ingredients of soils. **Weathering** is the physical and chemical breakdown of rocks and the first step in soil development. Weathered rock is further modified by the activity of soil organisms into soil, which is called either *residual* or *transported*, depending on where and when it has been modified. The more insoluble weathered material may remain essentially in place and be modified to form a residual soil, such as the red soils of the Piedmont in the southeastern United States. If weathered material is transported by water, wind, or glaciers and then modified in its new location, it forms a transported soil, such as the fertile soils formed from glacial deposits in the American Midwest.

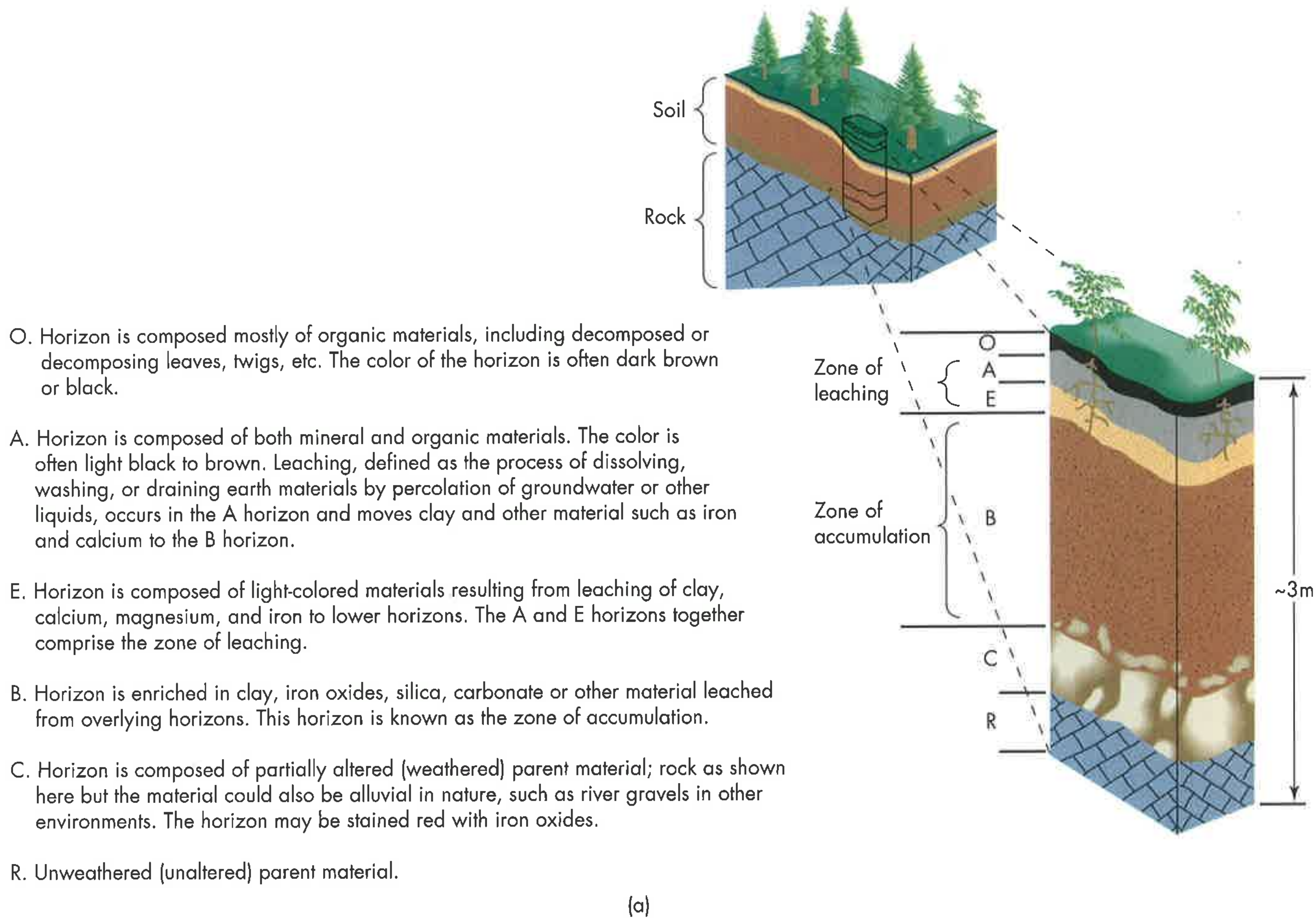
A soil can be considered an open system that interacts with other components of the geologic cycle. The characteristics of a particular soil are a function of *climate*, *topography*, *parent material* (the rock or alluvium from which the soil is formed), *time* (age of the soil), and *organic processes* (activity of soil organisms). Many of the differences we see in soils are effects of climate and topography, but the type of parent rock, the organic processes, and the length of time the soil-forming processes have operated are also important.

Soil Horizons

Vertical and horizontal movements of the materials in a soil system create a distinct layering, parallel to the surface, collectively called a *soil profile*. The layers are called zones or **soil horizons.** Our discussion of soil profiles will mention only the horizons most commonly present in soils. Additional information is available from detailed soils texts (1,2).

Figure 3.1a shows the common master (prominent) soil horizons. The ***O* horizon** and ***A* horizon** contain highly concentrated organic material; the differences between these two layers reflect the amount of organic material present in each. Generally, the *O* horizon consists entirely of plant litter and other organic material, while the underlying A horizon contains a good deal of both organic and mineral material. Below the *O* or *A* horizon, some soils have an ***E* horizon**, or *zone of leaching*, a light-colored layer that is leached of iron-bearing components. This horizon is light in color because it contains less organic material than the *O* and *A* horizons and little inorganic coloring material such as iron oxides.

The ***B* horizon**, or *zone of accumulation*, underlies the *O*, *A*, or *E* horizon and consists of a variety of materials translocated downward from overlying horizons. Several types of *B* horizon have been recognized. Probably the most



◀ **FIGURE 3.1** Soil profiles. (a) Idealized diagram showing a soil profile with soil horizons. (b) Soil profile showing a black *A* horizon, a light-red *B* horizon, a white *K* horizon rich in calcium carbonate, and a lighter *C* horizon. (*Edward A. Keller*)

important type is the *argillic B*, or B_t horizon. A B_t horizon is enriched in clay minerals that have been translocated downward by soil-forming processes. Another type of *B* horizon of interest to environmental geologists is the B_k horizon, characterized by accumulation of calcium carbonate. The carbonate coats individual soil particles in the soils and may fill some pore spaces (the spaces between soil particles), but it does not dominate the morphology (structure) of the horizon. A soil horizon that is so impregnated with calcium carbonate that its morphology is dominated by the carbonate is designated a ***K* horizon** (Figure 3.1b). Carbonate completely fills the pore spaces in *K* horizons, and the carbonate often forms in layers parallel to the surface. The term *caliche* is often used for irregular accumulation or layers of calcium carbonate in soils.

The ***C* horizon** lies directly over the unaltered parent material and consists of parent material partially altered by weathering processes. The ***R* horizon,** or unaltered parent material, is the consolidated bedrock that underlies the soil. However, some of the fractures and other pore spaces in the bedrock may contain clay that has been translocated downward (1).

The term *hardpan* is often used in the literature on soils. A hardpan soil horizon is defined as a hard (compacted) soil horizon. Hardpan is often composed of compacted and/or cemented clay with calcium carbonate, iron oxide, or silica. Hardpan horizons are nearly impermeable and thus restrict the downward movement of soil water.

Soil Color

One of the first things we notice about a soil is its color, or the colors of its horizons. The *O* and *A* horizons tend to be dark because of their abundant organic material. The *E* horizon, if present, may be almost white, owing to the leaching of iron and aluminum oxides. The *B* horizon shows the most dramatic differences in color, varying from yellow-brown to light red-brown to dark red, depending upon the presence of clay minerals and iron oxides. The B_k horizons may be light-colored due to their carbonates, but they are sometimes reddish as a result of iron oxide accumulation. If a true *K* horizon has developed, it may be almost white because of its great abundance of calcium carbonate. Although soil color can be an important diagnostic tool for analyzing a soil profile, one must be cautious about calling a red layer a *B* horizon. The original parent material, if rich in iron, may produce a very red soil even when there has been relatively little **soil profile development.**

Soil color may be an important indicator of how well drained a soil is. Well-drained soils are well aerated (oxidizing conditions), and iron oxidizes to a red color. Poorly drained soils are wet, and iron is reduced rather than oxidized. The color of such a soil is often yellow. This distinction is important because poorly drained soils are associated with environmental problems such as lower slope stability and inability to be utilized as a disposal medium for household sewage systems (septic tank and leach field).

Soil Texture

The texture of a soil depends upon the relative proportions of sand-, silt-, and clay-sized particles (Figure 3.2). *Clay particles* have a diameter of less than 0.004 mm, *silt particles* have diameters ranging from 0.004 to 0.074 mm, and *sand particles* are 0.074 to 2.0 mm in diameter. Earth materials with particles larger than 2.0 mm in diameter are called *gravel*, *cobbles*, or *boulders* depending on the particle size. Note that the sizes of particles given here are for engineering classification and are slightly different from those used by the U.S. Department of Agriculture for soil classification.

Soil texture is commonly identified in the field by estimation, then refined in the laboratory by separating the sand, silt, and clay and determining their proportions. A useful field technique for estimating the size of sand-sized or smaller soil particles is as follows: It is sand if you can see individual grains; silt if you can see the grains with a 10× hand lens; and clay if you cannot see grains with such a hand lens. Another method is to feel the soil: Sand is gritty (crunches between the teeth), silt feels like baking flour, and clay is cohesive. When mixed with water, smeared on the back of the hand, and allowed to dry, clay cannot be dusted off easily, whereas silt or sand can.

Soil Structure

Soil particles often cling together in aggregates, called *peds*, that are classified according to shape into several types. Figure 3.3 shows some of the common structures of peds found

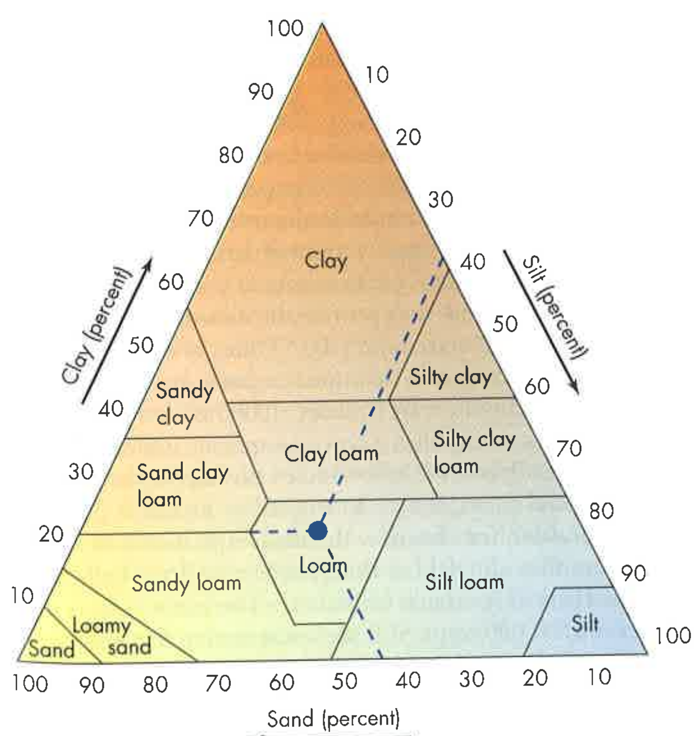


FIGURE 3.2 Soil textural classes. The classes are defined according to the percentage of clay-, silt-, and sand-sized particles in the soil sample. The point connected by dashed lines represents a soil composed of 40% sand, 40% silt, and 20% clay, which is classified as loam. (*U.S. Department of Agriculture standard textural triangle*)

▶ **FIGURE 3.3** Chart of different soil structures (peds).

Type	Typical size range	Horizon usually found in	Comments
Granular 	1–10 mm	A	Can also be found in B and C horizons
Blocky 	5–50 mm	B_t	Are usually designated as angular or subangular
Prismatic 	10–100 mm	B_t	If columns have rounded tops, structure is called *columnar*
Platy 	1–10 mm	E	May also occur in some B horizons

in soils. The type of structure present is related to soil-forming processes, but some of these processes are poorly understood (1). For example, *granular structure* is fairly common in *A* horizons, whereas *blocky* and *prismatic structures* are most likely to be found in *B* horizons. Soil structure is an important diagnostic tool in helping to evaluate the development and approximate age of soil profiles. In general, as the profile develops with time, structure becomes more complex and may go from granular to blocky to prismatic as the clay content in the *B* horizons increases.

Relative Profile Development

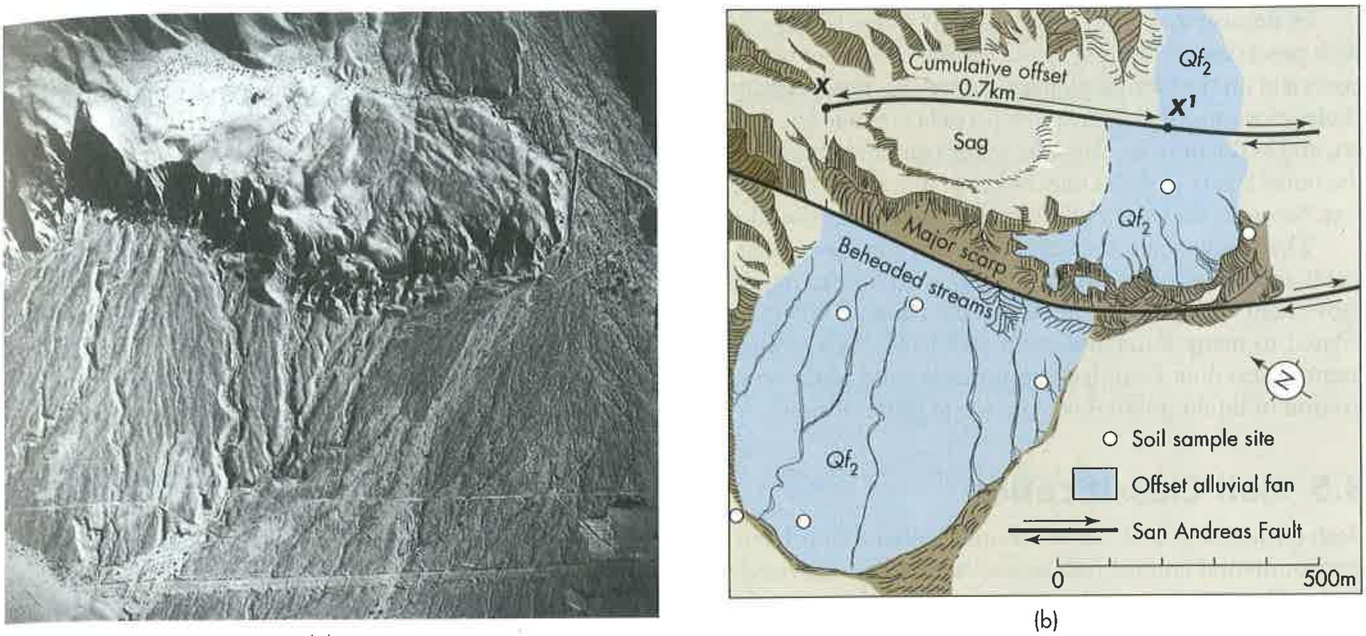
Most environmental geologists will not have occasion to make detailed soil descriptions and analyses of soil data. However, it is important for geologists to recognize differences among weakly developed, moderately developed, and well-developed soils, that is, to recognize their **relative profile development.** These distinctions are useful in preliminary evaluation of soil properties and help determine whether the opinion of a soil scientist is necessary in a particular project:

- *A weakly developed soil profile* is generally characterized by an *A* horizon directly over a *C* horizon (there is no *B* horizon or it is very weakly developed). The *C* horizon may be oxidized. Such soils tend to be only a few hundred years old in most areas, but may be several thousand years old.
- *A moderately developed soil profile* may consist of an *A* horizon overlying an argillic B_t horizon that overlies the *C* horizon. A carbonate B_k horizon may also be present but is not necessary for a soil to be considered moderately developed. These soils have a *B* horizon with translocated changes, a better-developed texture, and redder colors than those that are weakly developed. Moderately developed soils often date from at least the Pleistocene (more than 10,000 years old).
- *A well-developed soil profile* is characterized by redder colors in the B_t horizon, more translocation of clay to the B_t horizon, and stronger structure. A *K* horizon may also be present but is not necessary for a soil to be considered strongly developed. Well-developed soils vary widely in age, with typical ranges between 40,000 and several hundred thousand years and older.

Soil Chronosequences

A **soil chronosequence** is a series of soils arranged from youngest to oldest on the basis of their relative profile development. Such a sequence is valuable in hazards work, because it provides information about the recent history of a landscape, allowing us to evaluate site stability when locating such critical facilities as a waste disposal operation or a large power plant. A chronosequence combined with numerical dating (applying a variety of dating techniques, such as radiocarbon, ^{14}C, to obtain a date in years before the present time of the soil) may provide the data necessary to make such inferential statements as, "There is no evidence of ground rupture due to earthquakes in the last 1000 years," or "The last mudflow was at least 30,000 years ago." It takes a lot of work to establish a chronosequence in soils in a particular area. However, once such a chronosequence is developed and dated, it may be applied to a specific problem.

Consider, for example, the landscape shown in Figure 3.4, an offset alluvial fan along the San Andreas fault in the Indio Hills of southern California. The fan is offset about 0.7 km (700,000 mm). Soil pits excavated in the alluvial fan suggest that it is about 20,000 years old. The age was estimated on the basis of correlation with a soil chronosequence in the nearby Mojave Desert, where numerical dates for



(a) (b)

▲ **FIGURE 3.4** Offset alluvial fan along the San Andreas fault near Indio, California. (a) Aerial photograph. (*Woodward-Clyde Consultants*) (b) Sketch map.

similar soils are available. Soil development on the offset alluvial fan allowed the age of the fan to be estimated. This allowed the slip rate (the amount of offset of the fan divided by the age of the fan—that is, 700,000 mm ÷ 20,000 years, which is about 35 mm/yr) for this part of the San Andreas fault to be estimated at 35 mm annually (3). The slip rate for this segment of the fault was not previously known. The rate is significant because it is a necessary ingredient in the eventual estimation of the probability and recurrence interval of large, damaging earthquakes.

3.3 Soil Fertility

A soil may be considered a complex ecosystem. A single cubic meter of soil may contain millions of living things, including small rodents, insects, worms, algae, fungi, and bacteria. These organisms are important in the mixing and aeration of soil particles and in releasing or converting nutrients in soils into forms that are useful for plants (4). **Soil fertility** refers to the capacity of the soils to supply the nutrients (such as nitrogen, phosphorus, and potassium) needed for plant growth when other factors are favorable (5).

Soils developed on some floodplains and glacial deposits contain sufficient nutrients and organic material to be naturally fertile. Other soils, developed on highly leached bedrock or on loose deposits with little organic material, may be nutrient-poor with low fertility. Soils are often manipulated to increase plant yield by applying fertilizers to supply nutrients or materials that improve the soil's texture and moisture retention. Soil fertility can be reduced by soil erosion or leaching that removes nutrients, by interruption of natural processes (such as flooding) that supply nutrients, or by continued use of pesticides that alter or damage soil organisms.

3.4 Water in Soil

If you analyze a block of soil, you will find it is composed of bits of solid mineral and organic matter with pore spaces between them. The pore spaces are filled with gases (mostly air) or liquids (mostly water). If all the pore spaces in a block of soil are completely filled with water, the soil is said to be in a *saturated condition;* otherwise it is said to be *unsaturated.* Soils in swampy areas may be saturated year-round, whereas soils in arid regions may be saturated only occasionally.

The amount of water in a soil, called its *water content* or its *moisture content,* can be very important in determining such engineering properties as the strength of a soil and its potential to shrink and swell. If you have ever built a sand castle at the beach, you know that dry sand is impossible to work with, but that moist sand will stand vertically, producing walls for your castle. Differences between wet and dry soils are also very apparent to anyone who lives in or has visited areas with dirt roads that cross clay-rich soils. When the soil is dry, driving conditions are excellent, but following rainstorms, the same roads become mud pits and nearly impassable (6).

Water in soils may flow laterally or vertically through soil pores, which are the void spaces between grains, or in fractures produced as a result of soil structure. The flow is termed *saturated flow* if all the pores are filled with water and *unsaturated flow* when, as is more common, only part of the pores is filled with water.

In unsaturated flow, movement of water is related to such processes as thinning or thickening of films of water in pores and on the surrounding soil grains (6). The water molecules closest to the surface of a particle are held the tightest, and as the films thicken, the water content increases and the outer layers of water may begin to move. Flow is therefore fastest in the center of pores and slower near the edges.

The study of soil moisture relations and movement of water and other liquids in soils, along with how to monitor movement of liquids, is an important research topic. It is related to many water pollution problems, such as movement of gasoline from leaking underground tanks or migration of liquid pollutants from waste disposal sites.

3.5 Soil Classification

Both terminology and classification of soils are a problem in environmental studies because we are often interested in both soil processes and the human use of soil. A taxonomy (classification system) that includes engineering as well as physical and chemical properties would be most appropriate—but none exists. We must therefore be familiar with two separate systems of soil classification: *soil taxonomy*, used by soil scientists, and the *engineering classification*, which groups soils by material types and engineering properties.

Soil Taxonomy

Soil scientists have developed a comprehensive and systematic classification of soils known as **soil taxonomy,** which emphasizes the physical and chemical properties of the soil profile. This classification is a sixfold hierarchy, with soils grouped into Orders, Suborders, Great Groups, Subgroups, Families, and Series. The eleven Orders (Table 3.1) are mostly based on gross soil morphology (number and types of horizons present), nutrient status, organic content (plant debris, etc.), color (red, yellow, brown, white, etc.), and general climatic considerations (amount of precipitation, average temperature, etc.). With each step down the hierarchy, more information about a specific soil becomes known.

Soil taxonomy is especially useful for agricultural and related land-use purposes. It has been criticized for being too complex and for lacking sufficient textural and engineering information to be of optimal use in site evaluation for engineering purposes. Nevertheless, the serious earth

Table 3.1 General properties of soil order used with soil taxonomy by soil scientists

Order	General Properties
Entisols	No horizon development; many are recent alluvium; synthetic soils are included; are often young soils.
Vertisols	Include swelling clays (greater than 35 percent) that expand and contract with changing moisture content. Generally form in regions with a pronounced wet and dry season.
Inceptisols	One or more of horizons have developed quickly; horizons are often difficult to differentiate; most often found in young but not recent land surfaces, have appreciable accumulation of organic material; most common in humid climates but range from the Arctic to the tropics; native vegetation is most often forest.
Aridisols	Desert soils; soils of dry places; low organic accumulation; have subsoil horizon where gypsum, caliche (calcium carbonate), salt, or other materials may accumulate.
Mollisols	Soils characterized by black, organic-rich *A* horizon (prairie soils); surface horizons are also rich in bases. Commonly found in semiarid or subhumid regions.
Andisols	Soils derived primarily from volcanic materials; relatively rich in chemically active minerals that rapidly take-up important biologic elements such as carbon and phosphorus.
Spodosols	Soils characterized by ash-colored sands over subsoil, accumulations of amorphous iron-aluminum sesquioxides and humus. They are acid soils that commonly form in sandy parent materials. Are found principally under forests in humid regions.
Alfisols	Soils characterized by a brown or gray-brown surface horizon and an argillic (clay-rich) subsoil accumulation with an intermediate to high base saturation (greater than 35 percent as measured by the sum of cations, such as calcium, sodium, magnesium, etc.). Commonly form under forests in humid regions of the midlatitudes.
Ulfisols	Soils characterized by an argillic horizon with low base saturation (less than 35 percent as measured by the sum of cations); often have a red-yellow or reddish-brown color; restricted to humid climates and generally form on older landforms or younger, highly weathered parent materials.
Oxisols	Relatively featureless, often deep soils, leached of bases, hydrated, containing oxides of iron and aluminum (laterite) as well as kaolinite clay. Primarily restricted to tropical and subtropical regions.
Histosols	Organic soils (peat, muck, bog).

Source: After Soil Survey Staff. 1994. *Keys to Soil Taxonomy*, 6th ed. Soil Conservation Service, U.S. Department of Agriculture.

Table 3.2 Unified soil classification system used by engineers

Major Divisions				Group Symbols	Soil Group Names
COARSE-GRAINED SOILS (Over half of material larger than 0.074 mm)	Gravels	Clean Gravels	Less than 5% fines	GW	Well-graded gravel
				GP	Poorly graded gravel
		Dirty Gravels	More than 12% fines	GM	Silty gravel
				GC	Clayey gravel
	Sands	Clean Sands	Less than 5% fines	SW	Well-graded sand
				SP	Poorly graded sand
		Dirty Sands	More than 12% fines	SM	Silty sand
				SC	Clayey sand
FINE-GRAINED SOILS (Over half of material smaller than 0.074 mm)	Silts	Non-plastic		ML	Silt
				MH	Micaceous silt
				OL	Organic silt
	Clays	Plastic		CL	Silty clay
				CH	High plastic clay
				OH	Organic clay
Predominantly Organics				PT	Peat and Muck

scientist must have knowledge of this classification because it is commonly used by soil scientists and Quaternary geologists, those who study earth materials and processes of recent (last 1.65 million years) earth history.

Engineering Classification of Soils

The **unified soil classification system,** widely used in engineering practice, is shown in Table 3.2. Because all natural soils are mixtures of coarse particles (gravel and sand), fine particles (silt and clay), and organic material, the major divisions of this system are *coarse-grained soils, fine-grained soils,* and *organic soils.* Each group is based on the predominant particle size or the abundance of organic material. Coarse soils are those in which more than 50 percent of the particles (by weight) are larger than 0.074 mm in diameter. Fine soils are those with less than 50 percent of the particles greater than 0.074 mm (7). Organic soils have a high organic content and are identified by their black or gray color and sometimes by an odor of hydrogen sulfide, which smells like rotten egg.

3.6 Engineering Properties of Soils

All soils above the **water table** (the surface below which all the pore space in rocks is saturated) have three distinct parts, or phases: *solid material, liquid,* and *gas* (as, for example, air or carbon dioxide). The usefulness of a soil is greatly affected by the variations in the proportions and structure of the three phases. The types of solid materials, the particle sizes, and the water content are some of probably the most significant variables that determine engineering properties (see *Putting Some Numbers On Properties of Soils*). For planners, the most important engineering properties of soils are plasticity, strength, sensitivity, compressibility, erodibility, permeability, corrosion potential, ease of excavation, and shrink-swell potential.

Plasticity, which is related to the water content of a soil, is used to help classify fine-grained soils for engineering purposes. The *liquid limit* (LL) of a soil is the water content (w) above which the soil behaves as a liquid; the *plastic limit* (PL) is the water content below which the soil no longer behaves as a plastic material. The numerical difference between the liquid and plastic limits is the *plasticity index* (PI), the range in moisture content within which a soil behaves as a plastic material. Soils with a very low plasticity index (5%) may cause problems because only a small change in water content can change the soil from a solid to a liquid state. On the other hand, a large PI, one greater than 35 percent, is suggestive of a soil likely to have excessive potential to expand and contract on wetting and drying.

Soil strength is the ability of a soil to resist deformation. It is difficult to generalize about the strength of soils. Numerical averages of the strength of a soil are often misleading, because soils are often composed of mixtures, zones, or layers of materials with different physical and chemical properties.

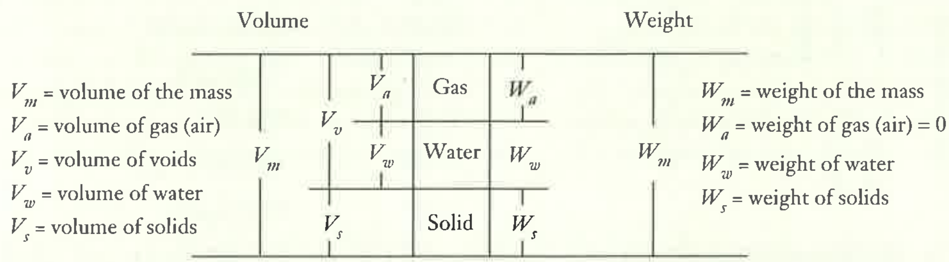
The strength of a particular soil type is a function of cohesive and frictional forces. **Cohesion** is a measure of the

(continued on page 66)

PUTTING SOME NUMBERS ON Properties of Soil

The subject of **soil mechanics** is the study of soils with the objective of understanding and predicting the behavior of soil for a variety of purposes, including foundations of buildings, use as construction materials, and construction of slopes and embankments for a variety of engineering projects (8). In 1948 Carl Terzagi published a book on soil mechanics that for the first time utilized concepts of physics and mathematics integrated with geology and engineering to put the "art" of soil mechanics on a "firm foundation" (pun intended). Our purpose here is to provide basic information concerning selected properties of soils and the roll of fluid pressure in the strengths of soils.

A phase diagram for soil that consists of solids, water, and gas (mostly air) is shown in Figure 3.A. Notice that the left side of the diagram is in terms of volume and the right side in terms of weight. The symbols are defined as follows: V_m is the volume of the mass (volume of total sample), V_v is the volume of the voids (spaces between grains that may contain soil gases or liquids, such as water), V_a is the volume of air, V_w is the volume of water, V_s is the volume of the solids, W_m is the weight of the mass (weight of



weight, W, is a force, units, N (Newton, kg m/sec^2); **mass,** m, units, kg;
volume, V, units are m^3

unit weight (γ) = weight/volume; unit weight of mass = γ_m = weight of mass/volume mass = W_m/V_m;
unit weight of solids = γ_s = weight of solids/volume of solids = W_s/V_s;
unit weight of water = γ_w = weight of water/volume of water = W_w/V_w = constant = 1×10^4N/m^3 (or 10^4N/m^3) = 62.4 lb/ft^3

density, ρ = mass/volume (unit mass), units are kg/m^3 or gm/cm^3

Remember γ_w = mass water × acceleration of gravity ÷ volume of water
acceleration of gravity, g; $g = 9.8$ m/sec^2 ≅ 10 m/sec^2 or 32 ft/sec^2;
$\rho_w = 1$ gm/cm^3 = 10^3 kg/m^3; then $\gamma_w \cong 10^3$ kg/m^3 × 10 m/sec^2 ≅ 10^4 N/m^3 (62.4 lb/ft^3)

specific gravity, G = unit weight of sample/unit weight of water, G_s is specific gravity of solids, G_m is specific gravity of the mass

$$G_s = \frac{\gamma_s}{\gamma_w} = \frac{W_s}{V_s\gamma_w}; \; G_m = \frac{\gamma_m}{\gamma_w} = \frac{W_m}{V_m\gamma_w}, \text{ no units}$$

porosity, $n = \dfrac{V_v}{V_m}$, no units reported as a decimal, reported as a percentage, in calculations as a decimal

void ratio, $e = \dfrac{V_v}{V_s}$, no units reported as a decimal

moisture content (also called water content), $w = \dfrac{W_w}{W_s}$, reported as a percentage, in calculations as a decimal

volumetric water content, $\Theta = \dfrac{V_w}{V_m}$, reported as a percentage, in calculations as a decimal

degree of saturation with respect to water, $S_w = \dfrac{V_w}{V_v}$, reported as a percentage, calculations as a decimal

degree of saturation with respect to air, $S_a = \dfrac{V_a}{V_v}$, reported as a percentage, in calculations as a decimal

$S_w + S_a = 1$

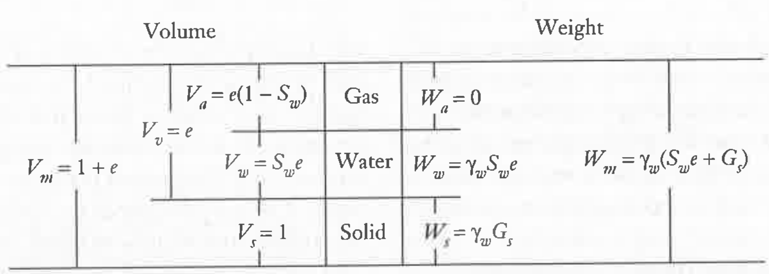
▲ **FIGURE 3.A** Phase diagram for soil consisting of solids, water, and gas (mostly air). Also shown are selected symbols and definitions used for soil mechanics in geotechnical engineering.

total sample), W_a is the weight of air (taken as zero), W_w is the weight of the water, and W_s is the weight of the solids. Given this, we may define a number of soil properties including unit weight (γ), density (ρ), specific gravity *(G)*, porosity *(n)*, void ratio *(e)*, moisture content *(w)* and the degree of saturation (S_w) as shown on Figure 3.A.

Probably the best way to understand the properties shown is to solve a problem or two. For example, Figure 3.B is a problem where void ratio *(e)*, specific gravity of the solids (G_s), and degree of saturation with respect to water (S_w) are known, and we are asked to compute the water content *(w)*. Water content is a particularly important property of soils because as it varies, so does the strength of the soil as well as other properties, including the unit weight and degree of saturation. Of particular importance to understanding the hydrology of the vadose zone, which is the unsaturated soil above the water table, is the volumetric water content (Θ). As the volumetric water content increases in the vadose zone, the rate of movement of water in the vadose zone increases.

As a second example, assume you have a moist soil with a volume (V_m) of $4.2\times10^{-3}m^3$ and that the weight of the mass (W_m) is 60 N. After drying, the mass has a weight of 48 N. If the specific gravity of the solids (G_s) is 2.65, compute the degree of saturation with respect to water (S_w), the volumetric water content (Θ), and void ratio *(e)*. It's probably worth mentioning here that there are three volumetric ratios we have introduced: the void ratio *(e)*, porosity *(n)*, and degree of saturation (S_w). The void ratio *(e)* is expressed as a decimal, while the other two are expressed as a percentage. In theory the void ratio can vary from a minimum of zero to infinity but values of soils composed of sand and gravel vary from about 0.3 to 1.0, whereas for fine-grained soils composed of clay-sized particles, the void ratio may vary from approximately 0.4 to 1.5 (8). Returning now to our problem: The first step is to produce a phase diagram as shown on Figure 3.C. The weight of the mass (W_m) is 60 N; after drying this is reduced to 48 N. Thus the weight of the water (W_w) is 12 N and that value can be placed on the diagram. The weight of the solids (W_s) is the difference between W_m and W_w, which is 48 N. The volume of the mass (V_m) is given, and this is also placed on the diagram. Using the fact that the specific gravity of the solids (G_s) is 2.65, we can calculate the volume of the solids (V_s) as $1.8\times10^{-3}m^3$. Similarly, because we know the weight of the water, we can use the unit weight of the water, which is a constant (see Figure 3.A, to calculate the volume of the water and place this also on the diagram). Knowing the volume of the water and the volume of the solids, we can calculate the volume of the voids and the volume of air. Given this information, we may then apply our definitions for degree of saturation with respect to water, water content, and void ratio to calculate that S_w = 50 percent, Θ = 29 percent, and e = 1.33.

(continued on next page)



To solve for *w*:

assume $V_s = 1$. then because $e = \frac{V_v}{V_s}$, $e = V_v$

$S_w = \frac{V_w}{V_v}$, (given), then since $V_v = e$, $V_w = S_w e$

$V_w = S_w e$, and $\gamma_w = \frac{W_w}{V_w}$, then $W_w = \gamma_w S_w e$

$G_s = \frac{\gamma_s}{\gamma_w} = \frac{W_s}{V_s \gamma_w}$ (given), and since $V_s = 1$, then $W_s = \gamma_w G_s$

$w = \frac{W_w}{W_s}$ (and substituting for W_w and W_s), $w = \frac{\gamma_w S_w e}{\gamma_w G_s} = \frac{S_w e}{G_s}$

$w = \frac{(0.5)(0.4)}{1.5} = \frac{0.2}{1.5} = 0.13 = 13\%$

Hint: when given *e*, assume $V_s = 1$; when given *n*, assume $V_m = 1$

Given: $S_w = 0.5$
$e = 0.4$, $G_s = 1.5$

▲ **FIGURE 3.B** Example problem: A soil has a value of $e = 0.40$; $G_s = 1.5$; and $S_w = 0.50$. What is the water content *w*?

Volume			Weight	
	$V_a = 1.2\times10^{-3}\text{m}^3$	Gas	$W_a = 0$	
$V_m = 4.2\times10^{-3}\text{m}^3$	$V_w = 1.2\times10^{-3}\text{m}^3$	Water	$W_w = 12$ N	$W_m = 60$ N
	$V_s = 1.8\times10^{-3}\text{m}^3$	Solid	$W_s = 48$ N	

To solve for S_w, Θ, e:

$$G_s = \frac{W_s}{V_s\gamma_w}\text{, then } V_s = \frac{W_s}{G_s\gamma_w} = \frac{48\text{ N}}{2.65(1\times10^4\text{ N/m}^3)} = \frac{48\text{ N}}{2.65\times10^4\text{ N/m}^3}$$

$$V_s = 1.8\times10^{-3}\text{m}^3$$

$$\gamma_w = \frac{W_w}{V_w}\text{, then } V_w = \frac{W_w}{\gamma_w} = \frac{12\text{ N}}{1\times10^4\text{ N/m}^3}$$

$$V_w = 1.2\times10^{-3}\text{m}^3$$

Then since $V_m = V_a + V_w + V_s$, then $V_a = V_m - V_w - V_s$

$$V_a = 1.2\times10^{-3}\text{m}^3$$

$$\text{Now } S_w = \frac{V_w}{V_v} = \frac{1.2\times10^{-3}\text{m}^3}{2.4\times10^{-3}\text{m}^3} = 0.50 = 50\%$$

$$\Theta = \frac{V_w}{V_m} = \frac{1.2\times10^{-3}\text{m}^3}{4.2\times10^{-3}\text{m}^3} = 0.29 = 29\%$$

$$e = \frac{V_v}{V_s} = \frac{2.4\times10^{-3}\text{m}^3}{1.8\times10^{-3}\text{m}^3} = 1.33$$

▲ **FIGURE 3.C** Example problem: Given $V_m = 4.2\times10^{-3}\text{m}^3$, $W_m = 60$ N, $W_s = 48$ N, and $G_s = 2.65$, calculate S_w, Θ, e.

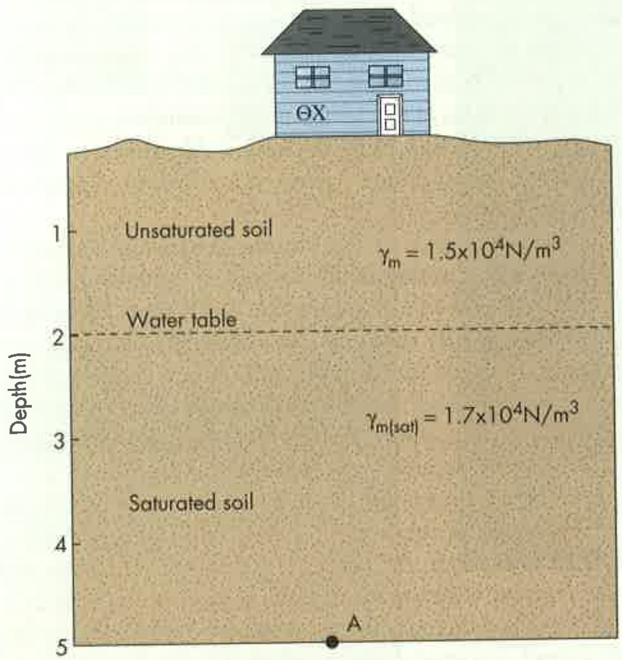
A large number of soil mechanics problems may be solved using the relationships outlined. Students of soil mechanics or geotechnical engineering become proficient at manipulating the equations for the properties of soils to calculate water content, degree of saturation, porosity, and other properties that define the engineering properties of the soil.

Our next task is to evaluate the role of fluid pressure (water pressure) on the shear strength of a soil. A good way to introduce the concept of fluid pressure and its effect on shear strength of the soil is to introduce the effective and neutral pressures in a soil. The effective pressure ($\bar{p}$) is the pressure acting on the grain-to-grain contact; and the neutral pressure or water pressure (μ_w) is defined as the product of the height of a column of water (h) and the unit weight of water (γ_w), which is $1\times10^4\text{N/m}^3$. The (fluid pressure) water pressure at the bottom of a 2 meter deep swimming pool is μ_w = (2 m)($1\times10^4\text{N/m}^3$),

ability of soil particles to stick together. The cohesion of particles in fine-grained soils is primarily the result of electrostatic forces between particles and is a significant factor in the strength of a soil. In partly saturated coarse-grained soils, moisture films between the grains may cause an apparent cohesion due to surface tension (Figure 3.5). This explains the ability of wet sand (which is cohesionless when dry) to stand in vertical walls in children's sand castles on the beach (9).

Friction between grains also contributes to the strength of a soil. The total frictional force is a function of the density, size, and shape of the soil particles, as well as the weight of overlying particles forcing the grains together. Frictional forces are most significant in coarse-grained soils rich in sand and gravel. Frictional forces explain why you don't sink far into the sand when walking on dry sand on beaches. Because most soils are a mixture of coarse and fine particles, the strength is usually the result of both cohesion and internal friction. Although it is dangerous to generalize, clay and organic-rich soils tend to have lower strengths than do coarser soils.

Vegetation may play an important role in soil strength. For example, tree roots may provide considerable apparent cohesion through the binding characteristics of a continuous root mat or by anchoring individual roots to bedrock beneath thin soils on steep slopes.



▲ **FIGURE 3.D** Idealized diagram showing a building, water table, and depth to point A where we calculate the effective pressure. See text for calculation.

and $\mu_w = 2\times10^4 N/m^2$. If the pool were filled with water-saturated sand and gravel, the fluid pressure at the bottom would still be $2\times10^4 N/m^2$, as the pore spaces between grains are connected and the height of the continuous water column (although a torturous path around grains) remains 2 m. The total pressure (p) is then equal to the sum of the effective and the neutral pressure ($p = \bar{p} + \mu_w$). This relationship can be rearranged to give the equation $\bar{p} = p - \mu_w$. The quantity $\bar{p}$ (the effective pressure) is a term in the equation that defines the shear strength of a soil:

$$S = C + \bar{p} \tan ø$$

where S is the shear strength; C is cohesion; $\bar{p}$ is the effective pressure; and ø is the angle of internal friction. If we substitute for $\bar{p}$, the equation becomes:

$$S = C + (p - \mu_w) \tan ø$$

Thus we see that the shear strength equation of a soil includes the effective pressure, which can be written as the difference between the total pressure and the water pressure.

An example here will help clear up some of the mystery concerning these relationships. Figure 3.D shows a simple diagram in which the water table is found at a depth of 2.0 m. We are interested in the effective pressure at point A at a depth of 5.0 m. The unit weight of the soil above the water table is given at $1.5\times10^4 N/m^3$, unit weight of the saturated soil below the water table is given at $1.7\times10^4 N/m^3$, and the unit weight of water is a constant $1\times10^4 N/m^3$.

$$\bar{p} \text{ (at point } A) = p - \mu_w$$

$$\bar{p} = (2.0 \text{ m})(1.5\times10^4 N/m^3) + (3.0 \text{ m})(1.7\times10^4 N/m^3) - (3.0 \text{ m})(1\times10^4 N/m^3)$$

$$\bar{p} = (3.0\times10^4 N/m^2) + (5.1\times10^4 N/m^2) - (3.0\times10^4 N/m^2)$$

$$\bar{p} = 5.1\times10^4 N/m^2$$

What would $\bar{p}$ be if the water table were to rise to the surface?

$$\bar{p} = (5.0 \text{ m})(1.7\times10^4 N/m^3) - (5.0 \text{ m})(1\times10^4 N/m^3)$$

$$\bar{p} = (8.5\times10^4 N/m^2) - (5\times10^4 N/m^2)$$

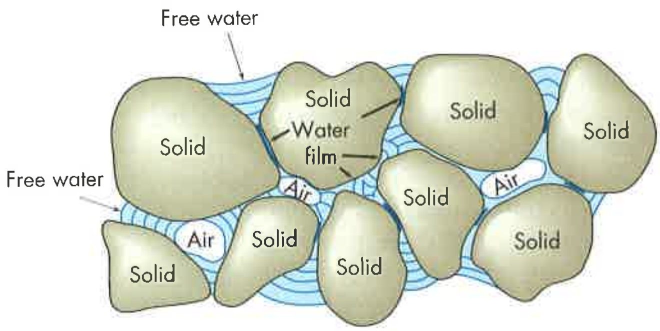
$$\bar{p} = 3.5\times10^4 N/m^2$$

Thus we see by raising the water table the effective pressure at point A has been significantly reduced. Since the effective pressure is part of the equation for the shear strength of the soil, we learn an important principle: If the water table rises, water pressure increases and shear strength is reduced. Conversely if the water table drops, the shear strength increases. The inverse relationship between water pressure and shear strength has important consequences in environmental geology. For example, if we wish to stabilize a landslide we may attempt to drain the potential slide mass, lowering the water table and increasing the shear strength, thus decreasing the likelihood of failure.

Sensitivity measures changes in soil strength resulting from disturbances such as vibrations or excavations. Sand and gravel soils with no clay are the least sensitive. As fine material becomes abundant, soils become more and more sensitive. Some clay soils may lose 75 percent or more of their strength following disturbance (7). Sand with a high water content may liquefy when shaken or vibrated. This process is called **liquefaction.** To observe this, stand on the wet sand of a beach and vibrate your feet. The sand will often liquefy and you will sink in a bit. Liquefaction is discussed further in Chapter 7.

Compressibility is a measure of a soil's tendency to *consolidate*, or decrease in volume. Compressibility is partly a function of the elastic nature of the soil particles and is directly related to settlement of structures. Excessive settlement will crack foundations and walls. Coarse materials, such as gravels and sands, have a low compressibility, and settlement will be considerably less in these materials than in highly compressible fine-grained or organic soils.

Erodibility refers to the ease with which soil materials can be removed by wind or water. Easily eroded materials (soils with a high erosion factor) include unprotected silts, sands, and other loosely consolidated materials. Cohesive soils (more than 20 percent clay) and naturally cemented soils are not easily moved by wind or water erosion and therefore have a low erosion factor.



▲ **FIGURE 3.5** Partly saturated soil showing particle-water-air relationships. Particle size is greatly magnified. Attraction between the water and soil particles (surface tension) develops a stress that holds the grains together. This apparent cohesion is destroyed if the soil dries out or becomes completely saturated. (*After* R. *Pestrong*. 1974. Slope Stability. *American Geological Institute.*)

Permeability is a measure of the ease with which water moves through a material. Clean gravels or sands have the highest permeabilities. As fine particles in a mixture of clean gravel and sand increase, permeability decreases. Clays generally have a very low permeability.

Corrosion is a slow weathering or chemical decomposition that proceeds from the surface into the ground. All objects buried in the ground—pipes, cables, anchors, fenceposts—are subject to corrosion. The corrosiveness of a particular soil depends upon the chemistry of both the soil and the buried material and on the amount of water available. It has been observed that the more easily a soil carries an electrical current (low resistivity due to more water in the soil), the higher its **corrosion potential.** Therefore, measurement of soil resistivity is one way to estimate the corrosion hazard (10).

Ease of excavation pertains to the procedures, and hence equipment, required to remove soils during construction. There are three general categories of excavation techniques. *Common excavation* is accomplished with an earth mover, backhoe, or dragline. This equipment essentially removes the soil without having to scrape it first (most soils can be removed by this process). *Rippable excavation* requires breaking the soil up with a special ripping tooth before it can be removed (examples include a tightly compacted or cemented soil). *Blasting* or *rock cutting* is the third, and often most expensive, category (for example, a hard silica-cemented soil, as with concrete, might need to be cut with a jackhammer to be removed).

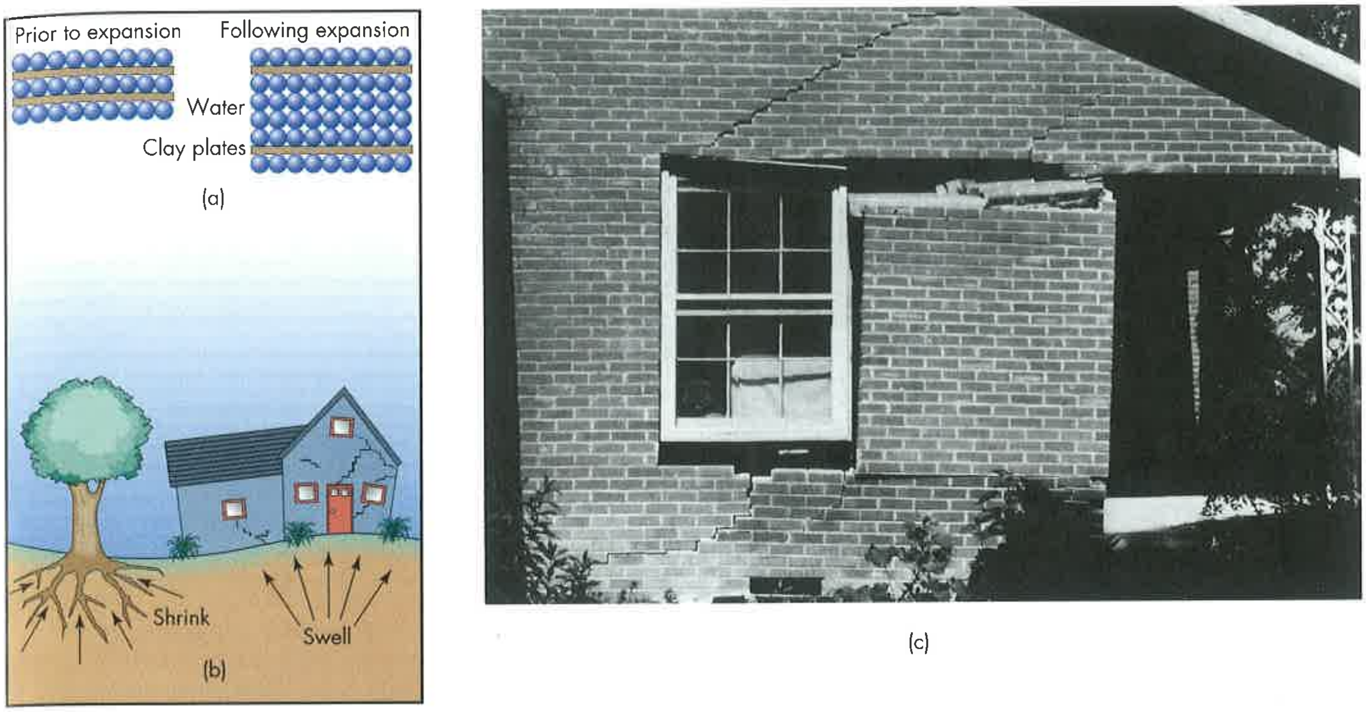
Shrink-swell potential refers to the tendency of a soil to gain or lose water. Soils that tend to increase or decrease in volume with water content are called **expansive soils.** The swelling is caused by the chemical attraction of water molecules to the submicroscopic flat particles, or plates, of certain clay minerals. The plates are composed primarily of silica, aluminum, and oxygen atoms, and layers of water are added between the plates as the clay expands or swells (Figure 3.6a) (11). Expansive soils often have a high *plasticity index*, reflecting their tendency to take up a lot of water while in the plastic state. *Montmorillonite* is the common clay mineral associated with most expansive soils. With sufficient water, pure montmorillonite may expand up to 15 times its original volume, but fortunately most soils contain limited amounts of this clay, so it is unusual for an expansive soil to swell beyond 25 to 50 percent. However, an increase in volume of more than 3 percent is considered potentially hazardous (11).

Expansive soils in the United States cause significant environmental problems and, as one of our most costly natural hazards, are responsible for more than $3 billion in damages annually to highways, buildings, and other structures. Every year more than 250,000 new houses are constructed on expansive soils. Of these, about 60 percent will experience some minor damage such as cracks in the foundation, walls, or walkways (Figure 3.6b,c), but 10 percent will be seriously damaged—some beyond repair (12,13).

Damages to structures on expansive soils are caused by volume changes in the soil in response to changes in moisture content. Factors affecting the moisture content of an expansive soil include *climate, vegetation, topography, drainage, site control,* and *quality of construction* (12). Regions such as the southwestern United States, which have a pronounced wet season followed by a dry season, thus allowing for a regular shrink-swell sequence, are more likely to experience an expansive soil problem than regions where precipitation is more evenly distributed throughout the year. Vegetation can cause changes in the moisture content of soils. Especially during a dry season, large trees draw and use a lot of local soil moisture, facilitating soil shrinkage (Figure 3.6b). Therefore, in areas with expansive soil, trees should not be planted close to foundations of light structures (such as homes).

Topography and drainage are significant because adverse topographic and drainage conditions cause ponding of water around or near structures, increasing the swelling of expansive clays. However, homeowners and contractors can do a great deal to avoid this problem. Laboratory testing prior to construction can identify soils with a shrink-swell potential. Proper design of subsurface drains, rain gutters, and foundations can minimize damages associated with expansive soils by improving drainage and allowing the foundation to accommodate some shrinking and swelling of the soil (12).

It should be apparent that some soils are more desirable than others for specific uses. Planners concerned with land use will not make soil tests to evaluate engineering properties of soils, but they will be better prepared to design with nature and take advantage of geologic conditions if they understand the basic terminology and principles of earth materials. Our discussion of engineering properties established two general principles. First, because of their low strength, high sensitivity, high compressibility, low permeability, and variable shrink-swell potential, clay soils should be avoided in projects involving heavy structures, structures with minimal allowable settling, or projects needing well-drained soils. Second, soils that have high corrosive potentials or that require other than common excavation



▲ **FIGURE 3.6** Expansive soils. (a) Expansion of a clay (montmorillonite) as layers of water molecules are incorporated between clay plates. (b) Effects of soil shrinking and swelling at a home site. (*After Mathewson and Castleberry,* Expansive Soils: Their Engineering Geology, *Texas A & M University*) (c) Cracked wall resulting from expansion of clay soil under the foundation. (*Courtesy of U.S. Department of Agriculture*)

should be avoided if possible. If such soils cannot be avoided, extra care, special materials and/or techniques, and higher-than-average initial costs (planning, design, and construction) must be expected. Secondary costs (operation and maintenance) may also be greater. Table 3.3 summarizes engineering properties of soils in terms of the unified soil classification.

3.7 Rates of Soil Erosion

Rates of soil erosion as a volume, mass, or weight of soil eroded from a location in a specified time and area (example, kilograms per year per hectare, kg/yr/ha) vary with engineering properties of the soil, land use, topography, and climate.

There are several approaches to measuring rates of soil erosion. The most direct method is to make actual measurements on slopes over a period of years (at least several) and use these values as representative of what is happening over a wider area and longer time span. This approach is not often taken, however, because data from individual slopes and drainage basins are very difficult to obtain.

A second approach is to use data obtained from resurveying reservoirs to calculate the change in the reservoirs' storage capacity of water (Table 3.4); the depletion of storage capacity (of water) tells us the volume of stored sediment. If we use the data from many reservoirs, we can obtain a sediment yield rate curve for an entire region. Figure 3.7 is an example of such a curve for drainages in the southwestern United States. This approach has merit but is unlikely to be reliable for small drainage basins, where sediment yield can vary dramatically. Note that on Figure 3.7 there is an inverse relationship between sediment yield per unit area and drainage area (upstream area contributing water and sediment, in this case to a reservoir). Smaller drainage areas have a larger sediment yield per unit area because smaller drainage areas tend to be steeper with great erosion potential.

A final approach is to use an equation to calculate rates of sediment eroded from a particular site. Probably the most commonly used equation is the Universal Soil Loss Equation (14). This equation uses data about rainfall runoff, the size and shape of the slope, the soil cover, and erosion-control practices to predict the amount of soil eroded from its original position (15) (see *A Closer Look: Universal Soil Loss Equation*).

3.8 Sediment Pollution

Sediment is probably our greatest pollutant. In many areas, sediment pollution chokes the streams, fills in lakes, reservoirs, ponds, canals, drainage ditches, and harbors, buries vegetation, and generally creates a nuisance that is difficult to remove. Natural pollutional sediment—eroded soil—is truly a resource out of place. It depletes soil at its site of origin (Figure 3.8), reduces the quality of the water it enters, and may deposit sterile materials on productive croplands or other useful land (Figure 3.9) (16). Rates of storage depletion

Table 3.3 Generalized sizes, descriptions, and properties of soils

Soil	Soil Component	Symbol	Grain Size Range and Description	Significant Properties
Coarse-grained components	Boulder	None	Rounded to angular, bulky, hard, rock particle; average diameter more than 25.6 cm.	Boulders and cobbles are very stable components used for fills, ballast, and riprap. Because of size and weight, their occurrence in natural deposits tends to improve the stability of foundations. Angularity of particles increases stability.
	Cobble	None	Rounded to angular, bulky, hard, rock particle; average diameter 6.5–25.6 cm.	
	Gravel	G	Rounded to angular, bulky, hard, rock particles greater than 2 mm in diameter.	Gravel and sand have essentially the same engineering properties, differing mainly in degree. They are easy to compact, little affected by moisture, and not subject to frost action. Gravels are generally more pervious and more stable and resistant to erosion and piping than are sands. The well-graded* sands and gravels are generally less pervious and more stable than those that are poorly graded and of uniform gradation.
	Sand	S	Rounded to angular, bulky, hard, rock particles 0.074–2 mm in diameter.	
Fine-grained components	Silt	M	Particles 0.004–0.074 mm in diameter; slightly plastic or nonplastic regardless of moisture; exhibits little or no strength when air dried.	Silt is inherently unstable, particularly with increased moisture, and has a tendency to become quick when saturated. It is relatively impervious, difficult to compact, highly susceptible to frost heave, easily erodible, and subject to piping and boiling. Bulky grains reduce compressibility, whereas flaky grains (such as mica) increase compressibility, producing an elastic silt.
	Clay	C	Particles smaller than 0.004 mm in diameter; exhibits plastic properties within a certain range of moisture; exhibits considerable strength when air dried.	The distinguishing characteristic of clay is cohesion or cohesive strength, which increases with decreasing moisture. The permeability of clay is very low; it is difficult to compact when wet and impossible to drain by ordinary means; when compacted, is resistant to erosion and piping; not susceptible to frost heave; and subject to expansion and shrinkage with changes in moisture. The properties are influenced not only by the size and shape (flat or platelike), but also by their mineral composition. In general, the montmorillonite clay mineral has the greatest and kaolinite the least adverse effect on the properties.
	Organic matter	O	Organic matter in various sizes and stages of decomposition.	Organic matter present even in moderate amounts increases the compressibility and reduces the stability of the fine-grained components. It may decay, causing voids, or change the properties of a soil by chemical alteration; hence, organic soils are not desirable for engineering purposes.

*The term *well-graded* indicates an even distribution of sizes and is equivalent to *poorly sorted*.

Note: The Unified Soil Classification does not recognize cobbles and boulders with symbols. The size range for these as well as the upper limit for clay are classified according to Wentworth (1922).

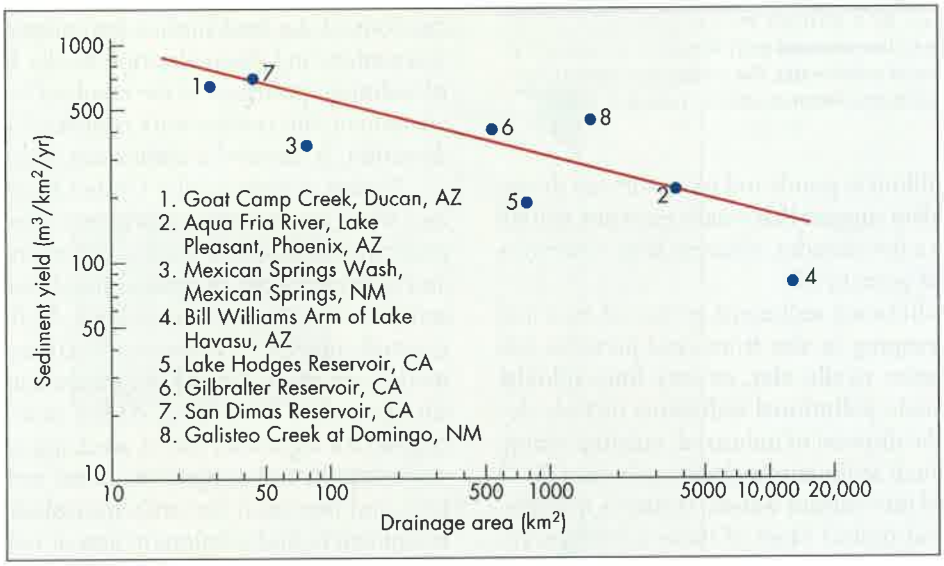
Source: After Wagner, "The Use of the Unified Soil Classification System by the Bureau of Reclamation." International Conference on Soil Mechanics and Foundation Engineering, Proceedings [London], 1957.

Table 3.4 Summary of reservoir capacity and storage depletion of the nation's reservoirs

Reservoir Capacity (acre-ft)[a]	Number of Reservoirs	Total Initial Storage Capacity (acre-ft)[a]	Total Storage Depletion		Individual Reservoir Storage Depletion		Average Period of Record
			(acre-ft)[a]	%	Average %/yr	Median %/yr	yr
0–10	161	685	180	26.3	3.41	2.20	11.0
10–100	228	8,199	1,711	20.9	3.17	1.32	14.7
100–1,000	251	97,044	16,224	16.7	1.02	.61	23.6
1,000–10,000	155	488,374	51,096	10.5	.78	.50	20.5
10,000–100,000	99	4,213,330	368,786	8.8	.45	.26	21.4
100,000–1,000,000	56	18,269,832	634,247	3.5	.26	.13	16.9
Over 1,000,000	18	38,161,556	1,338,222	3.5	.16	.10	17.1
Total or average	968	61,239,020	2,410,466	3.9	1.77	.72	18.2[b]

[a] 1 acre-ft = approximately 1234 m^3.
[b] The capacity-weighted period of record for all reservoirs was 16.1 years.

Source: F. E. Dendy, "Sedimentation in the Nation's Reservoirs." *Journal of Soil and Water Conservation* 23, 1968.



▲ **FIGURE 3.7** Sediment yield for the southwestern United States, based on rates of sediment accumulation in reservoirs. (Data *from* R. I. Strand. 1972. "*Present and Prospective Technology for Predicting Sediment Yield and Sources.*" Proceedings of the Sediment-Yield Workshop. U.S. *Department of Agriculture Publication* ARS-5-40, 1975, *p.* 13)

A CLOSER LOOK Universal Soil Loss Equation

The Universal Soil Loss Equation is:

$$A = RKLSCP$$

where A = the long-term average annual soil loss for the site being considered

R = the long-term rainfall runoff erosion factor

K = the soil erodibility index

L = the hillsope/length factor

S = the hillslope/gradient factor

C = the soil cover factor

P = the erosion-control practice factor.

The advantage of using this equation is that once the various factors have been determined and multiplied together to produce predicted soil loss, conservation practices may be applied through factors C and P to reduce the soil loss to the desired level. In the case of slopes that are amenable to shaping, factors of K, L, and S may also be manipulated to achieve desired results in terms of sediment loss. This is particularly valuable when evaluating construction sites, such as those for the development of shopping centers, and along corridors such as pipelines and highways. For construction sites, the Universal Soil Loss Equation can be used to predict the impact of sediment loss on local streams and other resources and to develop management strategies for minimizing this impact (14,15).

▲ **FIGURE 3.8** Serious soil erosion and gully formation in central California related to diversion of runoff water. The surface was essentially ungullied several months prior to the photograph. (*Edward A. Keller*)

▲ **FIGURE 3.9** Soil erosion has caused unwanted red sediment at this site in Charlotte, North Carolina. (*Edward A. Keller*)

caused by sediment filling in ponds and reservoirs are shown in Table 3.4. These data suggest that small reservoirs will fill up with sediment in a few decades, whereas large reservoirs will take hundreds of years to fill.

Most natural pollutional sediments consist of rock and mineral fragments ranging in size from sand particles less than 2 mm in diameter, to silt, clay, or very fine colloidal particles. Human-made pollutional sediments include debris resulting from the disposal of industrial, manufacturing, and public wastes. Such sediments include trash directly or indirectly discharged into surface waters. (Litter is not confined to roadsides and parks.) Most of these sediments are very fine-grained and difficult to distinguish from the naturally occurring sediments unless they contain unusual minerals or other particular characteristics. The principal sources of artificially induced pollutional sediments are disruptions of the land surface for construction, farming, deforestation, and channelization works. In short, a great deal of sediment pollution is the result of human use of the environment and civilization's continued change of plans and direction. It cannot be eliminated, only ameliorated.

In this century in the United States, emphasis on soil and water conservation has grown considerably. The first programs emphasized stabilization of areas of excessive wind and water erosion, as well as flood control and irrigation water for arid and semiarid land. As these programs progressed, adverse environmental effects from some of the work, such as accelerated stream erosion and rapid reservoir siltation, were discovered. At the same time, demands increased for expanded use of areas improved for recreation, water supply, and navigation. These new environmental effects and increased demands necessitated research and development to find solutions to new or rediscovered problems. Design changes developed and applied to correct the ero-

CASE HISTORY Reduction of Sediment Pollution, Maryland

A study in Maryland demonstrates that sediment-control measures can reduce sediment pollution in an urbanizing area (17). The suspended sediment transported by the northwest branch of the Anacostia River near Colesville, Maryland, with a drainage area of 54.6 km^2, was measured over a 10-year period. During that time, construction within the basin involved about 3 percent of the area annually. The total urban land area in the basin was about 20 percent at the end of the 10-year study.

Sediment pollution was a problem because the soils are highly susceptible to erosion, and there is sufficient precipitation to ensure their erosion when not protected by a vegetative cover. Most of the sediment is transported during spring and summer rainstorms (17). A sediment-control program was initiated, and the sediment yield was reduced by about 35 percent. The basic sediment-control principles were to tailor development to the natural topography, expose a minimum amount of land, provide protection for exposed soil, minimize surface runoff from critical areas, and trap eroded sediment on the construction site. Specific measures included scheduled grading to minimize the time of soil exposure, mulch protection and temporary vegetation to protect exposed soils, sediment diversion berms, stabilized waterways (channels), and sediment basins. This Maryland study concluded that even further sediment control can be achieved if major grading is scheduled during periods of low erosion potential and if better sediment traps are designed to control runoff during storms (17).

sion and sedimentation problems included contour plowing, changes in farming practices, and construction of small dams and ponds to hold runoff or trap sediments.

Currently, the same basic problems—erosion control and sediment pollution—occupy a significant portion of the public's attention. Sources of the sediment have expanded, however, to include those from land development, highways, mining, and production of new and unusual chemical compounds and products, all in the interest of a better life. Sediment pollution affects rivers, streams, the Great Lakes, and even the oceans, and the problem promises to be with us indefinitely. Solutions will involve sound conservation practices, particularly in urbanizing areas where tremendous quantities of sediment are produced during construction (see *Case History: Reduction of Sediment Pollution, Maryland*). Figure 3.10 shows a typical sediment- and erosion-control plan for a commercial development. The plan calls for diversions to collect runoff and a sediment basin to collect sediment and keep it on the site, thus preventing stream pollution. A generalized cross section of a sediment-control basin is shown in Figure 3.11.

3.9 Land Use and Environmental Problems of Soils

Human activities affect soils by influencing the pattern, amount, and intensity of surface-water runoff, erosion, and sedimentation. The most important of these human influences are the conversion of natural areas to various land uses and manipulations of our surface water.

Figure 3.12 shows the changes in water and sediment processes that might occur as a landscape is modified from natural forest (Figure 3.12a) to various uses. Trees modify the effects of precipitation by intercepting rain as it falls and by returning water to the atmosphere through evapotranspiration (the combined effect of evaporation and transpiration).

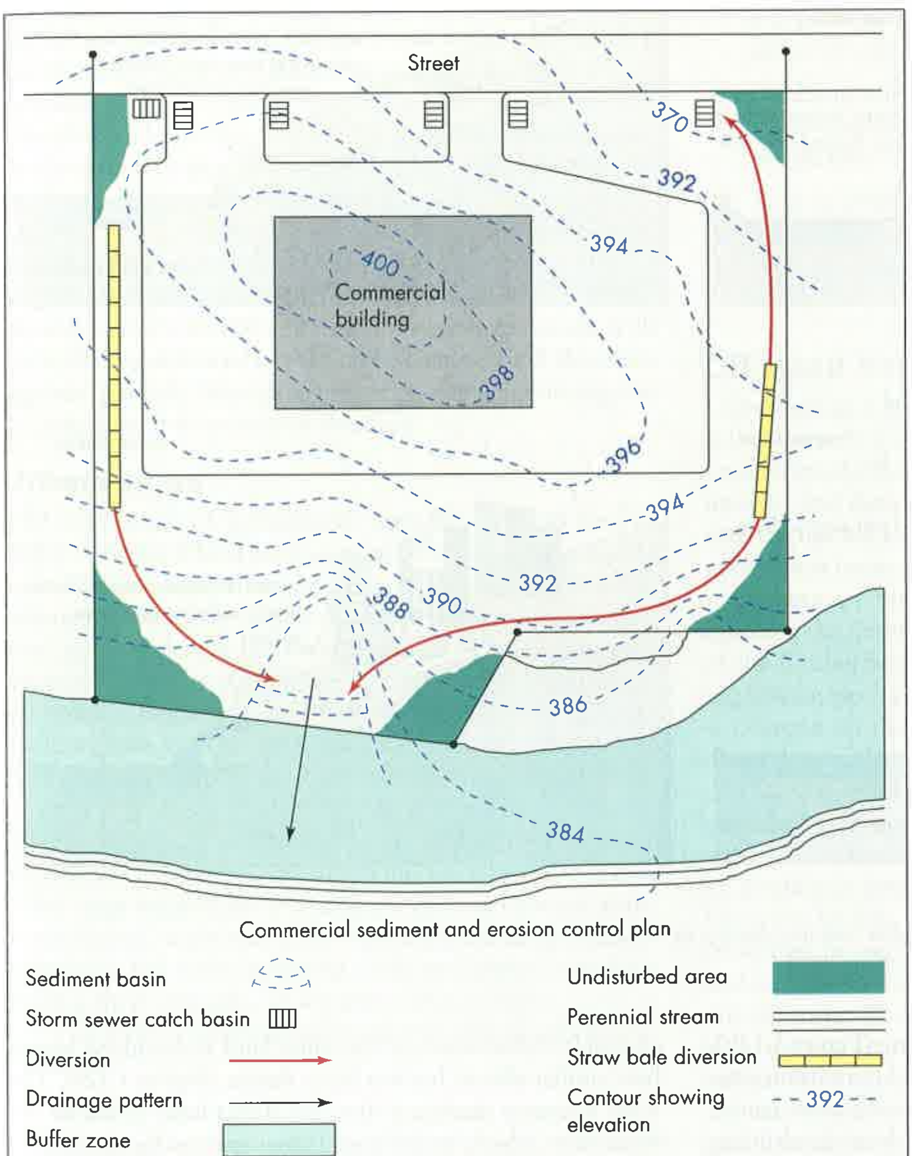
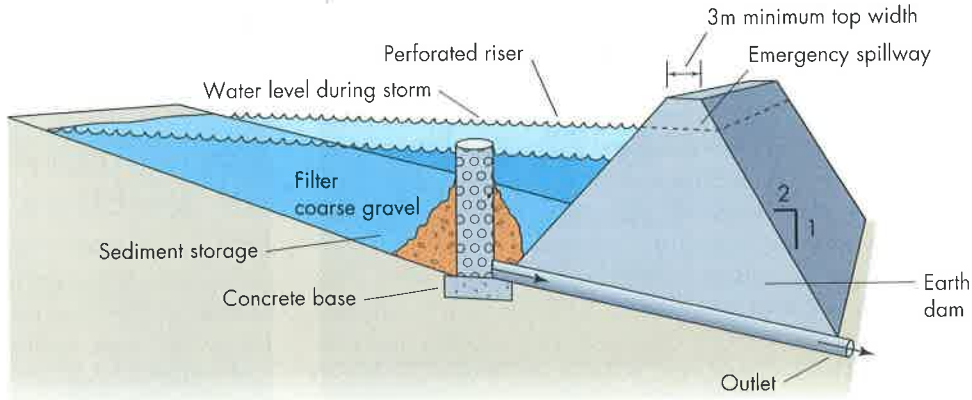
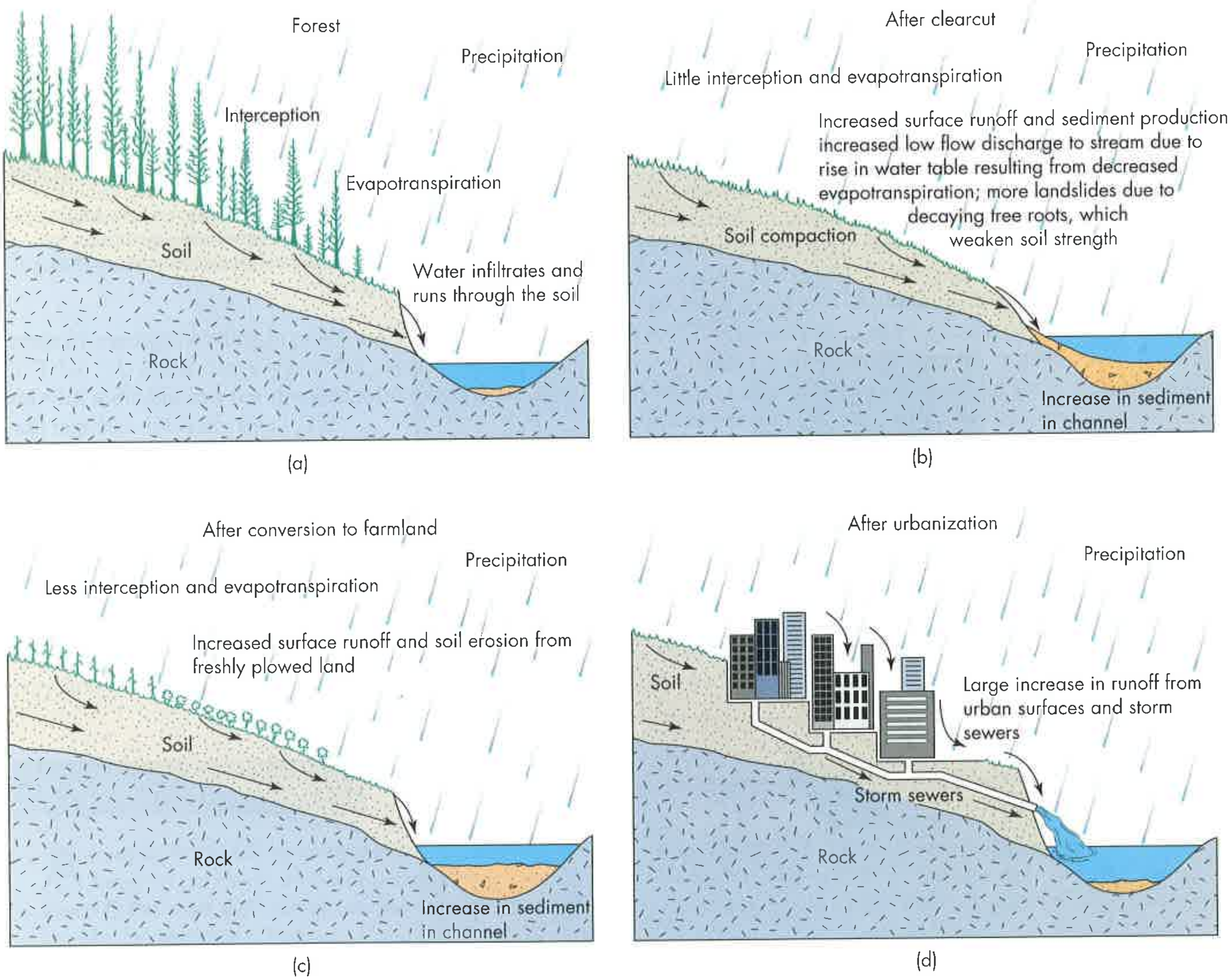


FIGURE 3.10 Example of a sediment- and erosion-control plan for a commercial development. (*Courtesy of Braxton Williams, Soil Conservation Service*) (384 to 400 ft = 117 to 122 m)



▶ **FIGURE 3.11** Cross section of a sediment basin. Storm water runs into the sediment basin, where the sediment settles out and the water filters through loose gravel into a pipe outlet. Accumulated sediment is periodically removed mechanically. (*After* Erosion and Sediment Control. 1974. *Soil Conservation Service*)



▲ **FIGURE 3.12** Water relationships before and after land-use changes. (a) A natural forested slope. (b) After clearcut. (c) After conversion to farmland. (d) After urbanization.

Following timber harvesting by clear-cutting (Figure 3.12b), one can expect decline in interception and evapotranspiration, resulting in rise in water table, increased surface runoff and production of sediment. As tree roots decay, landsliding may also increase, further delivering sediment to local stream channels. Conversion of the same land to farmland would have similar effects, but to a lesser degree (Figure 3.12c). The most intensive change in the use of this land would be urbanization, which would bring large increases in runoff from urban surfaces and stormwater sewers (Figure 3.12d).

- Declining groundwater table.
- Salinization of soil and near-surface-soil water.
- Reduction in areal extent of surface water in streams, ponds, and lakes.
- Unnaturally high rates of soil erosion.
- Damage to native vegetation.

An arid area undergoing desertification may have any or all of these symptoms to a lesser or greater extent (see *Case History: Desertification of the San Joaquin Valley*). Furthermore, the symptoms are interrelated: salinization of topsoil, for example, may lead to loss of vegetation, which then leads to accelerated soil erosion.

Prevention, minimization, and reversal of desertification involves the following (21,22):

- Protection and improvement of high-quality land rather than expending great amounts of time and money on poor land
- Application of simple, sound range management techniques to protect the land from overgrazing by livestock
- Application of sound conservation measures to agricultural lands to protect soil resources
- Use of appropriate technology to increase crop production that allows poorer lands to be returned to less-intensive land uses other than intensive agriculture (for example, forestry, wildlife, or grazing)
- Increased land restoration efforts through vegetation management, stabilization of sand dunes, and control of soil erosion

3.12 Soil Surveys and Land-Use Planning

Soils greatly affect the determination of the best use of land, and a soil survey is an important part of planning for nearly all engineering projects. A **soil survey** should include a soil description; soil maps showing the horizontal and vertical extent of soils; and tests to determine grain size, moisture content, shrink-swell potential, and strength. The purpose of the survey is to provide necessary information for identifying potential problem areas before construction.

The information from detailed soil maps can be extremely helpful in land-use planning if used in combination with guidelines to the proper use of soils. Soils can be rated according to their limitations for a specific land use, such as housing, light industry, septic-tank systems, roads, recreation, agriculture, and forestry. Soil characteristics that help determine these limitations include slope, water content, permeability, depth to rock, susceptibility to erosion, shrink-swell potential, bearing strength (ability to support a load, such as a building), and corrosion potential. Table 3.5 shows how some of these characteristics limit the use of land for recreation.

Table 3.5 Soil limitations for buildings in recreational areas

Soil Items Affecting Use	Degree of Soil Limitation[a]		
	None to Slight	**Moderate**	**Severe[b]**
Wetness	Well to moderately well drained soils not subject to ponding or seepage. Over 1.2 meters to seasonal water table.	Well and moderately well drained soils subject to occasional ponding or seepage. Somewhat poorly drained, not subject to ponding. Seasonal water table 0.6–1.2 meters.[c]	Somewhat poorly drained soils subject to ponding. Poorly and very poorly drained soils.
Flooding	Not subject to flooding	Not subject to flooding	Subject to flooding
Slope	0%–8%	8%–15%	15% +
Rockiness[d]	None	Few	Moderate to many
Stoniness[d]	None to few	Moderate	Moderate to many
Depth to hard bedrock	More than 1.5 meters	0.9–1.5 meters[c]	Less than 1 meter

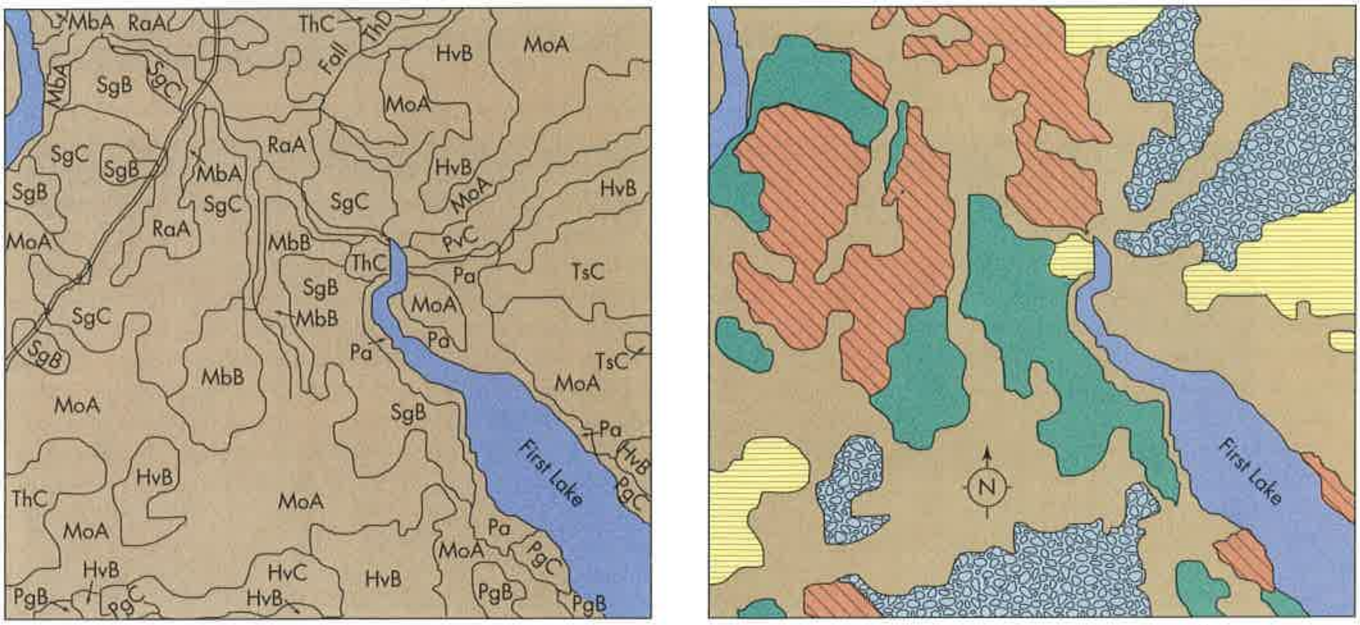
[a]Soil limitations for septic-tank filter fields; hillside slippage, frost heave, piping, loose sand, and low bearing capacity when wet are not included in this rating, but must be considered. Soil ratings for these items have been developed.

[b]Soils rated as having severe soil limitations for individual cottage sites may be best from an aesthetic or use standpoint, but they do require more preparation or maintenance for such use.

[c]These items are limitations only where basements and underground utilities are planned.

[d]Rockiness refers to the abundance of stones or rock outcrops greater than 25 cm in diameter. Stoniness refers to the abundance of stone 8 to 25 cm in diameter.

Source: Reproduced from *Soil Surveys and Land Use Planning* (1966) by permission of the Soil Science Society of America.



(a)

HvB	Howland very stony loam, 0 to 8 percent slopes
HvC	Howland very stony loam, 8 to 15 percent slopes
MbA	Madawaska fine sandy loam, 0 to 2 percent slopes
MbB	Madawaska fine sandy loam, 2 to 8 percent slopes
MoA	Monarda and Burnham silt loams, 0 to 2 percent slopes
Pa	Peat and Muck
PgB	Plaisted gravelly loam, 2 to 8 percent slopes
PgC	Plaisted gravelly loam, 8 to 15 percent slopes
PvC	Plaisted and Howland very stony loam, 8 to 15 percent slopes
RaA	Red Hook and Atherton silt loams
SgB	Stetson gravelly loam, 2 to 8 percent slopes
SgC	Stetson gravelly loam, 8 to 15 percent slopes
ThC	Thorndike shaly silt loam, 8 to 15 percent slopes
ThD	Thorndike shaly silt loam, 15 to 25 percent slopes
TsC	Thorndike and Howland soils, 8 to 15 percent slopes

(b) 0 1 2km

Soil limitations for building in recreational areas

None to slight
Deep, well-drained, gently sloping (2%–8%) soils

Moderate
Sloping (8%–15%) soils

Severe
Very stony soils

Wet soils

Shallow sloping (8%–25%) soils

▲ **FIGURE 3.20** Use of soil maps for land-use planning. (a) Detailed soil map of a 4-km^2 tract of land, Aroostook County, Maine. (b) Soil limitations for buildings in recreational areas for the same tract. (*Reproduced from* Soil Surveys and Land Use Planning, 1966, *by permission of the Soil Science Society of America*)

SUMMARY

Engineers define soil as earth material that may be removed without blasting, whereas to a soil scientist, a soil is solid earth material that can support rooted plant life. A basic understanding of soils and their properties is becoming crucial in several areas of environmental geology, including land-use planning, waste disposal, and evaluation of natural hazards such as flooding, landslides, and earthquakes.

Soils result from interactions of the rock and hydrologic cycles. As open systems, they are affected by such variables as climate, topography, parent material, time, and organic activity. Soil-forming processes tend to produce distinctive soil layers, or horizons, defined by the processes that formed them and the type of materials present. Of particular importance are the processes of leaching, oxidation, and accumulation of materials in various soil horizons. Development of the argillic *B* horizon, for example, depends on the translocation of clay minerals from upper to lower horizons. Three important properties of soils are color, texture (particle size), and structure (aggregation of particles).

An important concept in studying soils is relative profile development. Very young soils are weakly developed. Soils older than 10,000 years tend to show moderate development, characterized by stronger development of soil structure, redder soil color, and more translocated clay in the *B* horizon. Strongly developed soils are similar to those of moderate development, but the properties of the *B* soil horizon tend to be better developed. Such soils can range in age from several tens of thousands of years to several hundred thousand years or older. A soil chronosequence is a series of soils arranged from youngest to oldest in terms of relative soil profile development. Establishment of a soil chronosequence in a region is useful in evaluating rates of processes and recurrence of hazardous events such as earthquakes and landslides.

A soil may be considered as a complex ecosystem in which many types of living things convert soil nutrients into forms that plants can use. *Soil fertility* refers to the capacity of the soil to supply nutrients needed for plant growth.

Soil has a solid phase consisting of mineral and organic matter; a gas phase, mostly air; and a liquid phase, mostly water. Water may flow vertically or laterally through the pores (spaces between grains) of a soil. The flow is either saturated (all pore space filled with water) or, more commonly, unsaturated (pore space partially filled with water). The study of soil moisture and how water moves through soils is becoming a very important topic in environmental geology.

Several types of soil classification exist, but none of these integrate both engineering properties and soil processes. Environmental geologists must be aware of both the soil-science classification (soil taxonomy) and the engineering classification (unified soil classification).

Basic understanding of engineering properties of soils is crucial in many environmental problems. These properties include plasticity, soil strength, sensitivity, compressibility, erodibility, permeability, corrosion potential, ease of excavation, and shrink-swell potential. Shrink-swell potential is particularly important because expansive soils in the United States today cause significant environmental problems and is one of our most costly natural hazards.

Rates of soil erosion can be determined by direct observation of soil loss from slopes, by measurement of accumulated sediment in reservoirs, or by calculation (the most common method). The Universal Soil Loss Equation uses variables that affect erosion to predict the amount of soil moved from its original position. These variables can often be manipulated as part of a management strategy for minimizing erosion and sediment pollution from a particular site. Sediment, both natural and human-made, may be one of our greatest pollutants. It reduces water quality and chokes streams, lakes, reservoirs, and harbors. With good conservation practice, sediment pollution can be significantly reduced.

Land use and manipulation of surface water affect the pattern, amount, and intensity of surface water runoff, soil erosion, and sediment pollution. Urbanization often involves loss of soil, change of soil properties, accelerated soil erosion during construction, and pollution of soils. Use of motorized and nonmotorized off-road vehicles causes soil erosion, changes in hydrology, and damage to plants and animals. Soil pollution occurs when hazardous materials are inadvertently or deliberately added to soils. Pollution limits the usefulness of soils or even renders them hazardous to life. Use of new pollution abatement technology such as bioremediation is assisting in solving some soil pollution problems. Desertification, now a major problem, is the conversion of land from a productive state to one more resembling a desert. It is associated with malnutrition and starvation, particularly in parts of Africa and India. Driving forces of desertification include overgrazing, deforestation, adverse soil erosion, poor drainage of irrigated land, overdraft of water supplies, and damage from off-road vehicles.

Soil maps are extremely useful in land-use planning. Soils can be rated according to their limitations for various land uses, and this information can be combined with information from detailed soil maps to produce a simplified map that shows limitations for a specific use.

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