# 6 Landslides and Related Phenomena

Reactivated prehistoric landslide destroyed this home in Southern California. (*Edward A. Keller*)

This landslide in the foothills above the community of Santa Barbara, California, is threatening several homes and has the potential to block a nearby stream channel, perhaps causing a flood hazard. The homes built on these slopes were constructed on top of a prehistoric landslide, and the present problem results from reactivation of that slide. In order to minimize the landslide hazard of this area and many others in the United States, we need to carefully recognize and map prehistoric as well as historic landslides to avoid building homes and other structures on unstable lands.

## 6.1 Introduction to Landslides

Landslides and related phenomena cause substantial damage and loss of life. Each year about 25 people are killed by landslides in the United States, and this number increases to between 100 and 150 if we include collapses of trenches and other excavations. The total annual cost of damages exceeds $1 billion (1).

Landslides and other types of ground failure are natural phenomena that would occur with or without human activity. However, human land use has led to an increase in these events in some situations and a decrease in others. For example, landslides may occur on previously stable hillsides that have been modified for housing development; on the other hand, landslides on naturally sensitive slopes are sometimes averted by means of stabilizing structures or techniques.

In its more restricted sense, the term **landslide** refers to a rapid downslope movement of rock or soil as a more or less coherent mass. It is also used as a comprehensive term for any type of downslope movement of earth materials. Other general terms for downslope movement of earth materials are **slope failure** and *mass wasting*. In this chapter we consider landslides in the restricted sense, as well as the related phenomena of earthflows and mudflows, rockfalls, and snow or debris avalanches. For the sake of convenience, we sometimes refer to all of these as landslides. We will also

## LEARNING OBJECTIVES

Landslides constitute a serious natural hazard in many parts of the world, particularly in urban areas. Learning objectives of this chapter are:

- *To gain a basic understanding of the processes operating on slopes and the mechanisms by which slope failures may occur.*
- *To understand the role of driving and resisting forces on slopes and how these are related to determination of slope stability.*
- *To learn how topography, climate, vegetation, water, and time affect slope processes and the incidence of landslides.*
- *To understand how human use of the land has resulted in landslides.*
- *To become familiar with methods of identification, prevention, warning, and correction of landslides.*
- *To gain an appreciation for processes related to land subsidence.*

### Web Resources

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

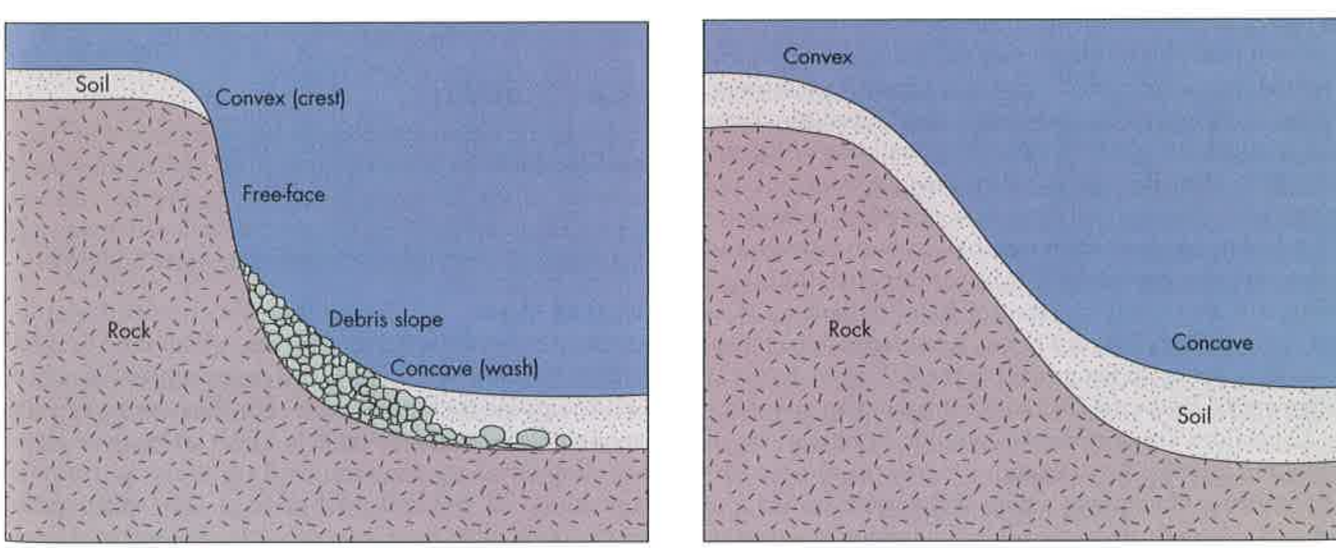
- ▶ Web Destinations
- ▶ On-line Quizzes
- ▶ On-line "Web Essay" Questions
- ▶ Search Engines
- ▶ Regional Updates

discuss *subsidence*, a type of ground failure characterized by near vertical deformation (downward sinking) of earth material that often produces circular surface pits but may produce linear or irregular patterns of failure.

## 6.2 Slope Processes and Slope Stability

Slopes are the most common landforms, and although most slopes appear stable and static, they are dynamic, evolving systems. Material on most slopes is constantly moving down the slope at rates that vary from imperceptible creep of soil and rock to thundering avalanches and rockfalls moving at tremendous velocities. These slope processes are one significant reason that stream valleys are much wider than the stream channel and adjacent floodplain. As with floods, it may not be the largest and least frequent event nor the smallest and most common one that moves the most material down slopes as valleys develop. Rather, events of moderate magnitude and frequency may play the most important role.

To examine slope processes, it is useful to identify slope elements. The slope in Figure 6.1a shows four distinct elements: a **convex slope,** or **crest;** a nearly vertical **free-face** (cliff); a **debris slope** at approximately 30 to 35°; and a lower




(a) (b)

▲ **FIGURE 6.1** Common slope elements. (a) Slope elements common in semiarid regions or on rocks resistant to weathering and erosion. (b) A convex-concave slope more common to semihumid regions or in areas with relatively soft rocks.

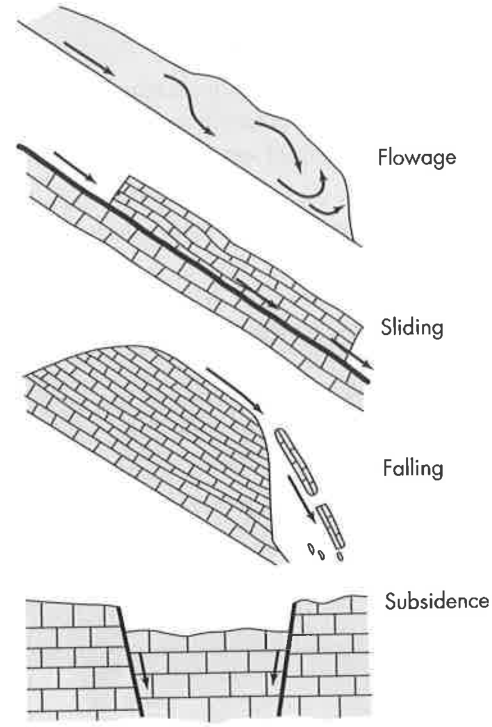
**concave slope,** or **wash slope.** Note that *wash*, as used by geologists, means an area of loose earth material that has been transported and deposited by water. (In Chapter 5 the word was used to mean a dry stream channel, a usage common in the western United States). All slopes are composed of one or more of these elements, and different slope processes are associated with each element. The convex slope is associated with a slow downslope movement of rock and soil known as *creep*. The free-face is usually associated with processes such as *rockfall*, and the debris slope is where the material from the free-face accumulates. The angle of the debris slope is the **angle of repose,** which is the steepest angle that a given loose material can maintain. The concave slope is produced by processes associated with running water. Steep slopes with a free-face like the one shown in Figure 6.1a commonly occur in semiarid regions and in places where resistant rocks are found.

In subhumid regions and in areas with relatively soft rocks, we find a simpler form of slope, as is also illustrated in Figure 6.1. The elements of this slope are an upper convex slope and a lower concave slope. These gentler (more gradual) slope profiles are often associated with a thick soil cover and often are underlain by rocks of low resistance. Thus, we see that the form of a slope is controlled in part by climate and rock resistance. However, other processes such as stream erosion or wave erosion may produce a prominent free-face, as may tectonic processes such as uplift.

The two types of slope shown in Figure 6.1 are distinguished by the distribution of their soil cover as well as by their shape. On the steeper slope, soil is found at the crest and on the wash slope, but not on the free-face, where weathering is accompanied by rapid erosional removal of the weathered material. On the gentler slope, the soil is thick at the top and bottom portions of the slope and thin in the steeper central portion, where downslope processes are more rapid. Removal of weathered material in the central part of the slope nearly matches its accumulation there.

Earth materials on slopes may fail and move or deform in several ways, which are illustrated in Figure 6.2. **Flowage,** or **flow,** is the downslope movement of unconsolidated material in which the particles move about and mix within the mass. Very slow flowage is called *creep;* extremely rapid flowage is an *avalanche*. Sliding is the downslope movement of a coherent block of earth material. In both flowage and sliding, the moving material is in contact with the slope; **falling,** in contrast, refers to the free fall of earth material, as from the free-face (cliff) of a slope. **Subsidence,** which may occur on slopes or on flat ground, is the sinking of a mass of earth material below the level of the surrounding material.

Landslides are commonly complex combinations of sliding and flowage. As an example, Figure 6.3 shows a failure consisting of an upper slump that is transformed to a flow in the lower part of the slide. (Slumping is a type of sliding, as we will discuss shortly.) Such complex landslides may form when water-saturated earth materials flow from the lower part of the slope, undermining the upper part and causing slumping of blocks of earth materials.



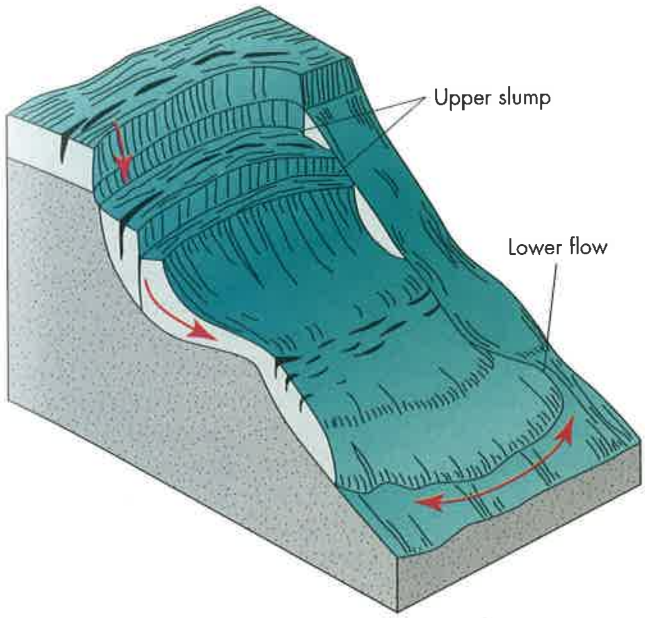

▲ **FIGURE 6.2** Common ways that earth materials fail and move in landslides and related phenomena.

Table 6.1 classifies the common types of downslope movements and reflects the terminology used in this discussion and in other chapters. Important variables in classifying downslope movements are type of movement (slide, fall, flow, or complex movement), slope material type, amount of water present, and rate of movement. In general, the movement is considered rapid if it can be discerned with the naked eye; otherwise it is classified as slow. Actual rates vary from a slow creep of a few millimeters or centimeters per year to very rapid, at 1.5 m/day, to extremely rapid, at several tens of meters per second (2).

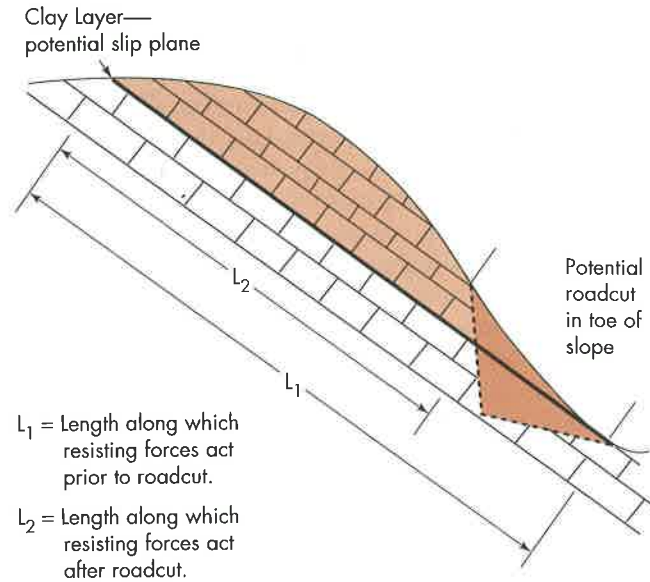
## Slope Stability

To determine the causes of landslides we must examine slope stability, which can be expressed in terms of the forces acting on slopes. These forces are determined by the interrelationships of the following variables: type of earth materials, slope angle (topography), climate, vegetation, water, and time.

**Forces on Slopes** The stability of a slope expresses the relationship between **driving forces,** which tend to move earth materials down a slope, and **resisting forces,** which tend to oppose such movement. *The most common driving force is the downslope component of the weight of the slope material,* including anything superimposed on the slope, such as vegetation, fill material, or buildings. *The most common resisting force is the shear strength of the slope material acting along potential slip planes.* Recall from our discussion of soils in Chapter 3 that shear strength is a function of an earth material's cohesion and internal friction. Potential slip planes are geologic planes of weakness in the slope material.




▲ **FIGURE 6.3** Block diagram of a common type of landslide consisting of an upper slump motion and a lower flow. (*After* R. *Pestrong*, 1974, Slope Stability, *American Geological Institute*)




▲ **FIGURE 6.4** Effects on slope stability of a roadcut in the toe of a slope.

**Table 6.1** Classification of landslides and other downslope movements

| Type of Movement | | Materials: Rock | Materials: Soil |
|---|---|---|---|
| Slides (variable water content and rate of movement) | | Slump blocks<br>Translation slide | Slump blocks (Rotational slide)<br>Soil slip (planar) |
| Falls | | Rock fall | Soil fall |
| | Slow | Rock creep | Soil creep |
| | ↓ | Unconsolidated materials (saturated) | |
| Flows | | Earthflow<br>Mudflow<br>Debris flow | |
| | Rapid | Debris avalanche | |
| Complex | | Combinations of slides and flows | |

Slope stability is evaluated by computing a **factor of safety** (FS), defined as the *ratio of the resisting forces to the driving forces.* If the factor of safety is greater than 1, the resisting forces exceed the driving forces and the slope is considered stable. If the factor of safety is less than 1, the driving forces exceed the resisting forces and a slope failure can be expected. Driving and resisting forces are not static: As local conditions change, these forces may change, increasing or decreasing the factor of safety. For example, consider construction of a roadcut in the toe of a slope with a potential slip plane (Figure 6.4). The roadcut reduces the driving forces on the slope because some of the slope material has been removed. However, the cut also reduces the resisting forces because the length of the slip plane is reduced, and the resisting force (shear strength) acts along this plane. If you examine Figure 6.4, you can see that only a small portion of the potential slide mass has been removed, while a relatively large portion of the length of the slip plane has been removed. Therefore, the overall effect of the roadcut is to *lower the factor of safety*, because the reduction of the driving force is small compared to the reduction of the resisting force. Factor of safety is commonly computed for natural slopes and slopes constructed as part of site development or highway construction (see *Putting Some Numbers On Landslides*).

***The Role of Earth Material Type*** The material composing a slope affects both the type and the frequency of downslope movement. Slides have two basic patterns of movement, rotational and translational. In **rotational slides,** or **slumps,** the sliding occurs along a curved slip surface (Figure 6.5a). Because the movement follows a curve, slump blocks tend to produce topographic benches (sometimes rotated and tilted in the upslope direction) like those in Figure 6.5a. Slumps are most common on soil slopes, but they also occur on some rock slopes, especially weak rock such as shale. **Translational slides** are planar; that is, they occur along inclined slip planes within a slope. (The slide shown in Figure 6.2 is translational.) Common translation slip planes in rock slopes include fractures in all rock types, bedding planes (Figure 6.5b), clay partings in sedimentary rocks, and foliation planes in metamorphic rocks. In some areas, very shallow slides in soil over rock parallel to the slope, known as **soil slips,** a kind of translation slide, also occur (Figure 6.5c). For soil slips, the slip plane is usually above the bedrock but below the soil,

## PUTTING SOME NUMBERS ON Landslides

Analysis of a slope for landslide potential involves determination of resisting and driving forces and the ratio of the two, which is the factor of safety (FS). This may be done for both translational slides or rotational slides. For example, consider the cross section shown on Figure 6.A, which shows a limestone bluff with a potential slip plane composed of clay that is found between bedding planes of the limestone and is inclined at an angle of 30° to horizontal. The potential slip plane is said to "daylight" in the bluff, presenting a potential landslide hazard. Assume that the area above the slip plane in the cross section is 500 $m^2$, the unit weight of the limestone is $1.6\times10^4\ N/m^3$, shear strength of the clay has been determined from laboratory studies to be $9\times10^4\ N/m^2$, and the length of the slip plane is 50 m. The FS is calculated as the ratio of resisting to driving forces by the equation:

$$FS = \frac{SLT}{W \text{ sine } \Theta}$$

We use what is known as the "unit thickness method," which we use to analyze the resisting and driving forces for a slice (cross section in Figure 6.A) of the bluff, orientated perpendicular to the bluff, which is 1 m thick. The resisting forces are the product of *SLT*, where *S* is the shear strength of the clay, *L* is the length of the slip plane, and *T* is the unit thickness. The driving force is the downslope component of the weight of the slope material above the potential slip plane. This is *W* sine Θ, where *W* is equal to the product of the area above the slip plane *(A)*, the unit weight of the slope material; and the unit thickness *(T)*. Then $W = (500\ m^2)(1\ m)(1.6\times10^4\ N/m^3) = 8\times10^6\ N$. *W* is then multiplied by the sine of the angle of the slip plane, and the product (*W* sine Θ) is the downslope component of the weight of the slope materials above the potential slip plane (Figure 6.A).

The factor of safety is calculated as

$$FS = \frac{SLT}{W \text{ sine } \Theta}$$

$$FS = \frac{(9\times10^4\ N/m^2)(50\ m)(1\ m)}{(500\ m^2)(1\ m)(1.6\times10^4\ N/m^3)(0.5)}$$

$$FS = 1.125$$

The conclusion from our analysis, which resulted in a factor of safety of 1.125, is not all that encouraging; generally, a safety factor less than 1.25 is considered as conditionally stable. What could be done to increase the factor of safety to at least 1.25? One possibility would be to remove some of the weight of the limestone above the potential slip plane by reducing the steep slope of the limestone bluff. We can calculate the volume of limestone that would be needed to be removed per unit thickness of the slope using the following equation, setting the factor of safety to 1.25 and solving for *W*.

$$FS = 1.25 = \frac{SLT}{W \text{ sine } \Theta}$$

Then, rearranging:

$$W = \frac{SLT}{1.25 \text{ sine } \Theta}$$

$$W = \frac{(9\times10^4\ N/m^2)(50\ m)(1\ m)}{(1.25)(0.5)}$$

$$W = 7.2\times10^6\ N$$

The weight of the slope material above the slip plane for a unit thickness of our original slope is $8\times10^6$ N, and therefore $8\times10^6\ N - 7.2\times10^6\ N$ or $8\times10^5$ N of limestone must be removed per unit thickness. To convert this to a volume of slope (per unit thickness), use the relationship weight of limestone removed = volume *(V)* limestone removed per unit thickness × unit weight of limestone. That is $8\times10^5\ N = (V)(1.6\times10^4\ N/m^3)$. Solving for *V* yields 50 $m^3$. That is, the original volume of limestone per unit thickness must be reduced by 50 $m^3$ to a value of 450 $m^3$ to increase the factor of safety to 1.25. This could be done by removing a uniform thickness of about 1 m of limestone from the top of the slope or a tapered wedge

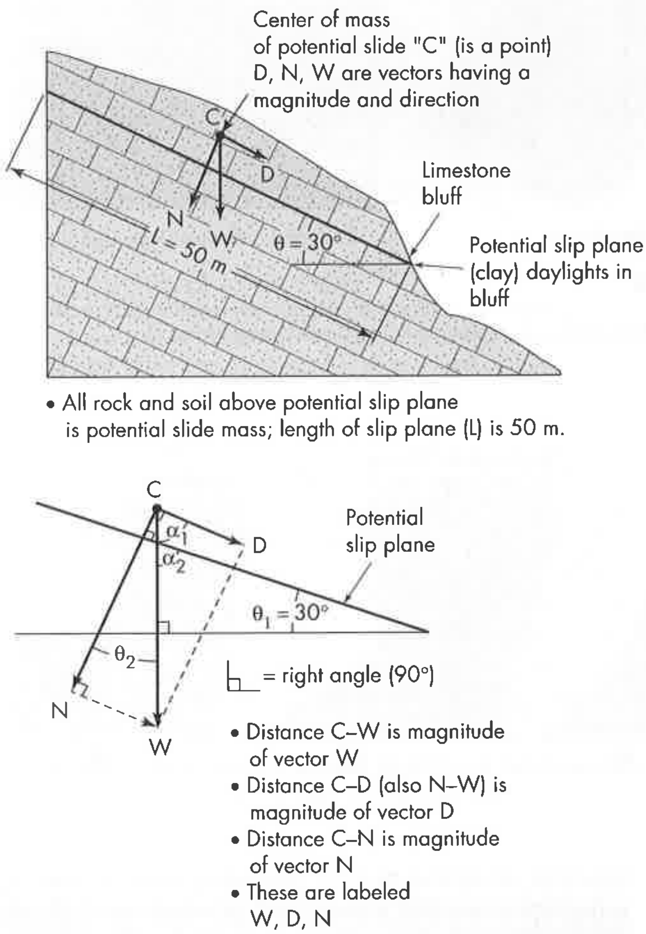
within a slope material known as **colluvium,** a mixture of weathered rock and other material.

Soil type is a factor in both falls and slides. If a very resistant rock overlies a rock of very low resistance, then rapid undercutting of the resistant rock may cause a slab failure (rock fall) (Figure 6.6).

The strength of the slope materials may greatly influence the magnitude and frequency of landslides and related events. For example, **creep** (the very slow downslope movement of soil and/or rock), **earthflows** (downslope flow of saturated earth materials, may be slow or rapid), slumps, and soil slips are much more common on shale slopes or slopes on weak pyroclastic (volcanic) materials than on slopes on more resistant rock such as well-cemented sandstone, limestone, or granite. In fact, shales are so notorious for landslide activity that what is called **"shale terrain"** is characterized by irregular, hummocky topography produced by a variety of downslope movement processes. For all types of land use, from agricultural to urban, on shale or other weak rock slopes, one must carefully consider the possible landslide hazard prior to development.

***The Role of Slope and Topography*** The *slope angle* (usually called the *slope*) greatly affects the relative magnitude of driving forces on slopes. As the angle of a potential slip plane increases, the driving force also increases; so, thickening upslope equivalent to 50 $m^2$ area (of the cross section) per unit thickness of slope (50 $m^3$).

The above evaluation of the factor of safety is overly simplified, as it assumes that the shear strength is constant along the slip plane, which often is not the case. Our example also doesn't consider fluid pressure in the slide mass (see Chapter 3), which is usually important in landslide analysis. As a result, more detailed evaluation would be necessary, but the principle is the same. That is, resisting and driving forces are calculated and their ratio (FS) is computed. A similar type analysis may be done for rotational or other types of failures, but the mathematics is more complex. Environmental and engineering geologists working on slope stability problems often use computer programs and analyze a number of potential slip planes for both translational and rotational failures as part of slope stability analysis.




Some trigonometry

$\alpha_1 = \alpha_2$: parallel lines crossed by a line

Show $\theta_1 = \theta_2$, after which $\theta_1 = \theta_2 = \theta$ (slope angle)

$\theta_1 + \alpha_2 = 90°$ right triangle

$\theta_1 + \alpha_1 = 90°$, because $\alpha_1 = \alpha_2$

$\theta_2 + \alpha_1 = 90°$ right triangle

Then $\theta_1 = \theta_2$, follows from $\theta_1 + \alpha_2 = 90°$ & $\theta_2 + \alpha_1 = 90°$

Triangle C W N is a right triangle with hypotenuse W

$$\sin\theta_2 = \frac{\text{side opposite}}{\text{hypotenuse}} = \frac{D}{W}, \text{ or } D = W\sin\theta_2 = W\sin\theta$$

$$\cos\theta_2 = \frac{\text{side adjacent}}{\text{hypotenuse}} = \frac{N}{W}, \text{ or } N = W\cos\theta_2 = W\cos\theta$$

W is the weight of slope materials (potential slide mass) above the slip plane acting down under gravity.

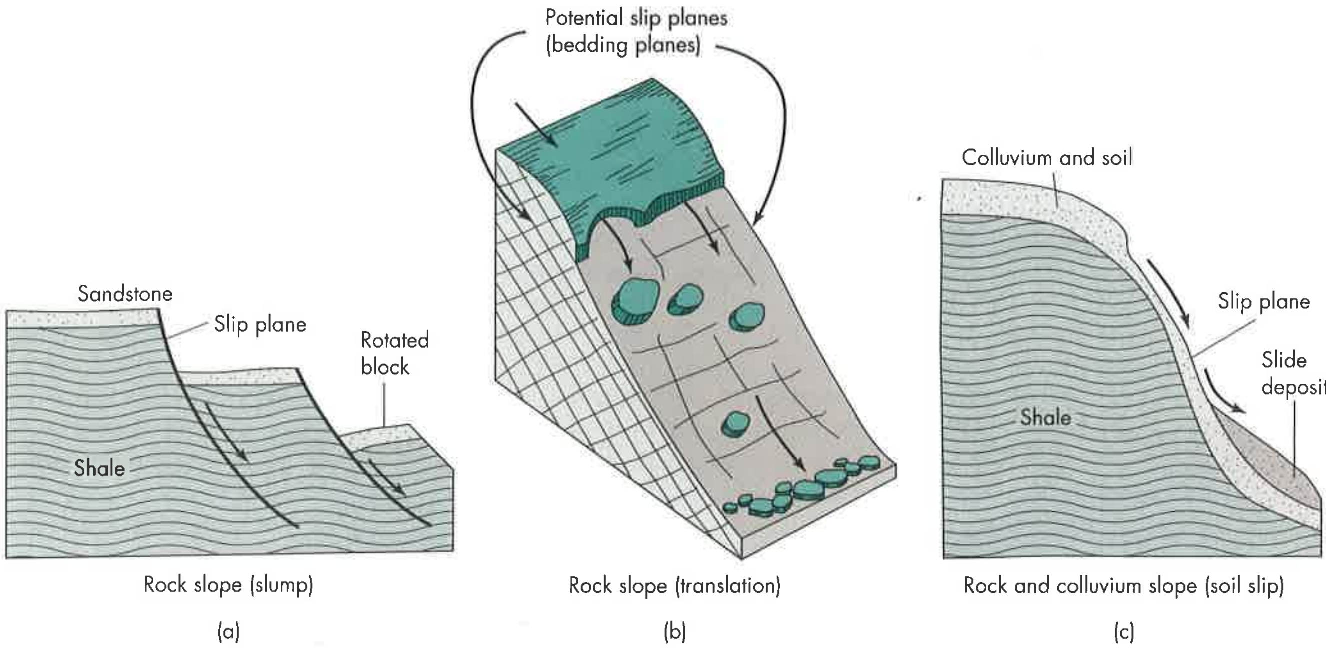
$D = W\sin\theta$ is the downslope component of the weight of the potential slide mass (W); the driving force.

$N = W\cos\theta$ is the normal component (at right angles to the slip plane) of the weight (W) of the potential slide mass. N is part of the shear strength along the slip plane and is thus part of the resisting force.

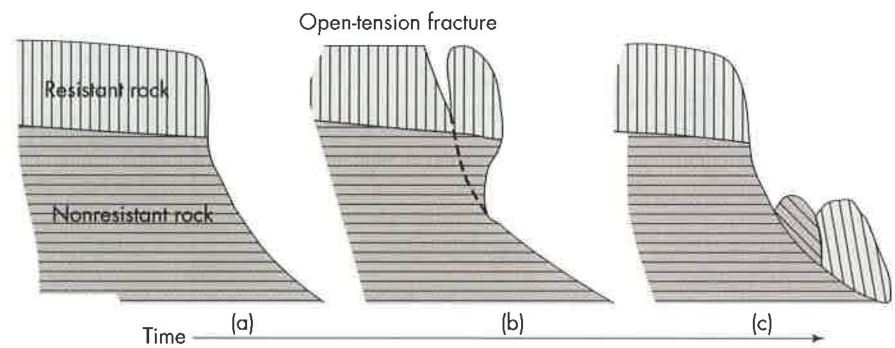
▲ **FIGURE 6.A** Cross section of a limestone slope (bluff) with a clay layer (potential slip plane) that **daylights**. See text for calculation of factor of safety (FS).

everything else being equal, landslides should be most frequent on steep slopes. A study of landslides that occurred during two rainy seasons in California's San Francisco Bay area established that 75 to 85 percent of landslide activity is closely associated with urban areas on slopes greater than 15 percent, or 8.5° (3). Nationally, the coastal mountains of California and Oregon, the Rocky Mountains, and the Appalachian Mountains have the greatest frequency of landslides. All the types of downslope movement listed in Table 6.1 occur in those locations.

To some extent, the type of landslide activity is also a function of slope and topography. For example, rockfalls and **debris avalanches** (very rapid downslope movement of soil, rock, and organic debris, such as trees) are associated with very steep slopes, and in southern California shallow soil slips are common on steep saturated slopes. These soil slips are often transformed downslope into earthflows or **mudflows** that may be extremely hazardous (Figure 6.7). At the other extreme, earthflows may occur on moderate slopes, and the effect of creep can be observed on slopes of only a few degrees. Another term (you must be tired of new terms by now!) is **debris flow,** which is the downslope flow of relatively coarse material. More than 50 percent of particles in a debris flow are coarser than sand. Debris flows may move very slowly or rapidly depending on conditions. Mudflows and debris flows associated with volcanic processes are discussed in Chapter 8.




▲ **FIGURE 6.5** Patterns of downslope movement: (a) rotational, (b) translational, and (c) shallow soil slip, also translational.



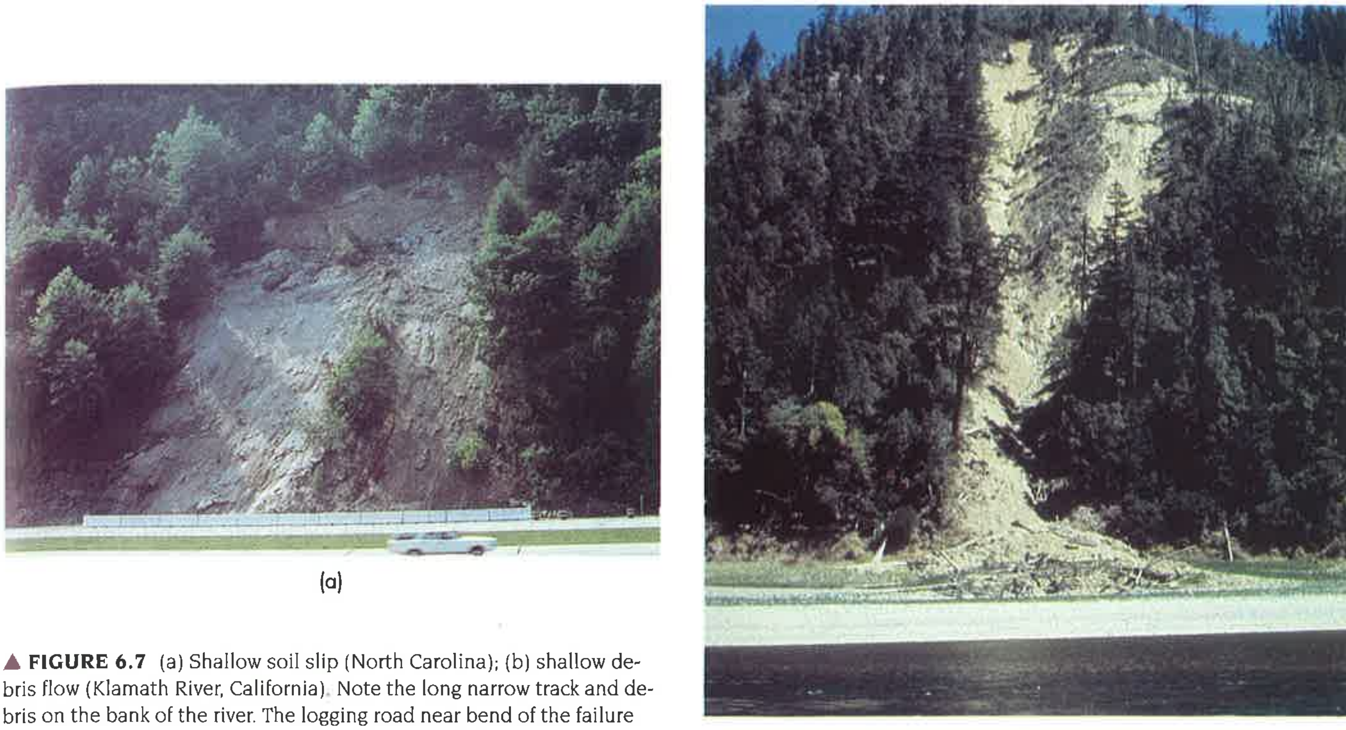

▶ **FIGURE 6.6** Development of a slab slide (type of rock fall). Undercutting of resistant "cap" rock at time (b) causes the development of tension fractures and eventual failure by rock fall at time (c).

***The Role of Climate and Vegetation*** Climate and vegetation can influence the type of landslide or other downslope movement that occurs on a particular slope. Climate controls the nature and extent of precipitation and thus the moisture content of slope materials. For example, both earthflows (which usually occur on slopes) and mudflows or debris flows (which initially may be confined to channels) involve downslope movement of water-saturated earth materials. However, earthflows are common and mudflows relatively rare in humid regions, where a good deal of water infiltrates into slopes, facilitating earthflows. Furthermore, humid regions have many perennial streams (streams that flow throughout the year), which continuously transport the materials delivered from slopes out of the drainage basin. Nevertheless, hazardous debris flows do occur in humid regions in response to high-magnitude storms.

The role of vegetation in landslides and related phenomena is complex because the vegetation in an area is a function of several factors, including climate, soil type, topography, and fire history, each of which also influences what happens on slopes. Vegetation is a significant factor in slope stability for three reasons.

1. Vegetation provides a cover that cushions the impact of rain falling on slopes, facilitating infiltration of water into the slope while retarding grain-by-grain erosion on the surface.
2. Vegetation has root systems that tend to provide an apparent cohesion to the slope materials.
3. Vegetation adds weight to the slope.

Most problems concerning slope stability and vegetation are complicated but related to disturbing, changing, or removing vegetation on or above slopes. Figure 6.8 shows a complex landslide that failed in 1995. The steep slope where the slide occurred is a 40,000-year-old seacliff. At the top of the slope, the topography becomes relatively flat, and an av-



(a)

(b)

▲ **FIGURE 6.7** (a) Shallow soil slip (North Carolina); (b) shallow debris flow (Klamath River, California). Note the long narrow track and debris on the bank of the river. The logging road near bend of the failure may have helped destabilize the slope. (*Edward A. Keller*)

ocado orchard was developed there. It is speculated that irrigation of the orchard increased soil moisture, reducing the stability of the slope by decreasing the resisting forces. (The influence of water on slope stability is discussed below.) There was also a road constructed across the slope that may have contributed to the failure (see Section 6.3). Other complicating factors are that the slide followed heavy precipitation and was a reactivation of an older, smaller slide on a steep slope in an area with many previous natural slides. Thus, the cause and the slide are both complex, involving linkages between weak slope material, topography, water, and human use.

Disturbance or removal of vegetation by logging has also been associated with an increase in landslides. Clear-cutting, or removal of all trees, has caused several problems:

- The rate of transpiration (loss of soil water through leaves) is greatly reduced; thus, soil moisture increases and slope stability is reduced.
- In specific instances, infiltration of water into a slope may be increased. This is especially likely if a permeable soil on relatively low-gradient slopes is covered in winter with thick snow pack that slowly melts in the spring.

(a)

(b)

▲ **FIGURE 6.8** Complex landslide consisting of an upper slump block and lower flow at La Conchita, California, in 1995 (a). Close-up of destruction of home in La Conchita. The house was originally three stories (b). (*Edward A. Keller*)

- With the exception of redwood trees, which regenerate after logging, the roots of cut trees decay with time, reducing their strength and thus the apparent cohesion of the soil. This tends to reduce resisting forces within the slope, helping to explain the increased frequency in shallow landslides several years following timber harvesting (4).

In some cases the *presence* of vegetation increases the probability of a landslide, especially for shallow soil slips on steep slopes. One type of soil slip in southern California coastal areas occurs on steep-cut slopes covered with ice plants (Figure 6.9). During especially wet winter months, the shallow-rooted ice plants take up water, adding considerable weight to steep slopes (each leaf stores water and looks like a small canteen!) and increasing the driving forces. By intercepting rainfall, the plants also cause an increase in the infiltration of water into the slope, which decreases the resisting forces. When failure occurs, the plants and several centimeters of roots and soil slide to the base of the slope.

Soil slips on natural steep slopes are a more serious problem in southern California (Figure 6.10). In this case chaparral (dense shrubs or brush) facilitates an increase in water infiltrating into the slope, lowering the safety factor. One study concluded that, in some instances, susceptibility to soil slip may be greater on vegetated slopes than on slopes where vegetation had been recently removed by fire. This should not be interpreted to mean that burning reduces the landslide hazard. Even though soil slips may sometimes be reduced by removal of vegetation, they are not eliminated; in addition, the grain-by-grain erosion caused by rain splash and sheet wash on the surface greatly increases. The eroded sediment tends to fill up the ravines (steep stream valleys) with a meter or more of debris that may be mobilized into debris flows and mudflows during wet winters (5).

**The Role of Water** Water is almost always directly or indirectly involved with landslides, so its role is particularly important. Much of the chemical weathering of rocks, which slowly reduces their shear strength, is caused by the chemical action of water in contact with soil and rock near the surface of the earth. Natural water ($H_2O$) is often acidic because it reacts with carbon dioxide ($CO_2$) in the atmosphere and soil to produce a weak acid—carbonic acid ($H_2CO_3$). This reaction is $H_2O + CO_2 \rightarrow H_2CO_3$. This chemical weathering is especially significant in areas with limestone, which is very susceptible to weathering and decomposition by carbonic acid.

The ability of water to erode affects the stability of slopes as well. Stream or wave erosion (Figure 6.11) may remove material and steepen a slope, thus reducing the safety factor. This problem is particularly critical if the toe of the slope is an old, inactive landslide that is likely to move again if stability is reduced (Figure 6.12). Therefore, it is important to recognize old landslides along potential roadcuts and other excavations prior to construction and to isolate and correct potential problems.

It has been argued that water has a lubricating effect on individual soil grains and potential slide planes, but this is incorrect: Water is not a lubricant (6). On the contrary, the surface tension of the water surrounding soil grains provides an apparent cohesion. For example, dry sand will form a cone when dumped, whereas moist sand will stand nearly vertical because surface tension (apparent cohesion) in the water holds the grains together. With all its pore spaces filled, saturated sand may flow like mud.

The effects of water on slopes and landslides are quite variable. First, saturation of earth materials causes a rise in pore-water pressure. In general, as the pore-water pressure (the water pressure that develops in the pore spaces between grains, as a result of water filling the pores; see Chapter 3) in slopes increases, the shear strength (resisting force) of the slope decreases and the weight (driving force) increases; thus, the net effect is to lower the factor of safety. This is thought to be a significant factor in the development of soil slips and debris avalanches, as well as other types of landslides. A rise in pore-water pressure is present prior to many landslides, and most landslides are caused by an abnormal increase of the water pressure in the slope-forming materials (6).


(a) (b)

▲ **FIGURE 6.9** Shallow soil slips on steep slopes covered with shallow-rooted ice plants near Santa Barbara, California. (a) An embankment on a road; (b) beneath a home. (*Edward A. Keller*)

(a)

(b)

▲ **FIGURE 6.10** (a) Shallow soil slips on steep southern California, vegetated slopes. (*Edward A. Keller*) (b) Home in southern California destroyed by debris flow that originated as a soil slip. This 1969 event claimed two lives. (*John Shadle/Los Angeles Department of Building and Safety*)

(a)

(b)

◀ **FIGURE 6.11** (a) Stream bank erosion caused this failure, which damaged a road, San Gabriel Mountains, California. (*Edward A. Keller*) (b) Beachfront home being threatened by a landslide, Cove Beach, Oregon. (*Gary Braasch/Tony Stone Images*)

Soil slips generally occur during heavy rainfall when near-surface temporary or **perched water table** conditions may be present (Figure 6.13). During a rainstorm, the rate of surface infiltration in the unsaturated (vadose) zone of the soil or colluvium exceeds the rate of deep percolation in the rock below the colluvium, and even though some water moves as seepage parallel to the slope, a temporary (perched) water table develops. Failure of the slope occurs when resisting forces are reduced sufficiently—that is, when the factory of safety becomes less than 1. The factor of safety is at a minimum when the perched water table rises to the surface, indicating that the potential slide mass is entirely saturated.

A second way that water may reduce the stability of slopes is by **rapid draw-down,** the rapid lowering of the

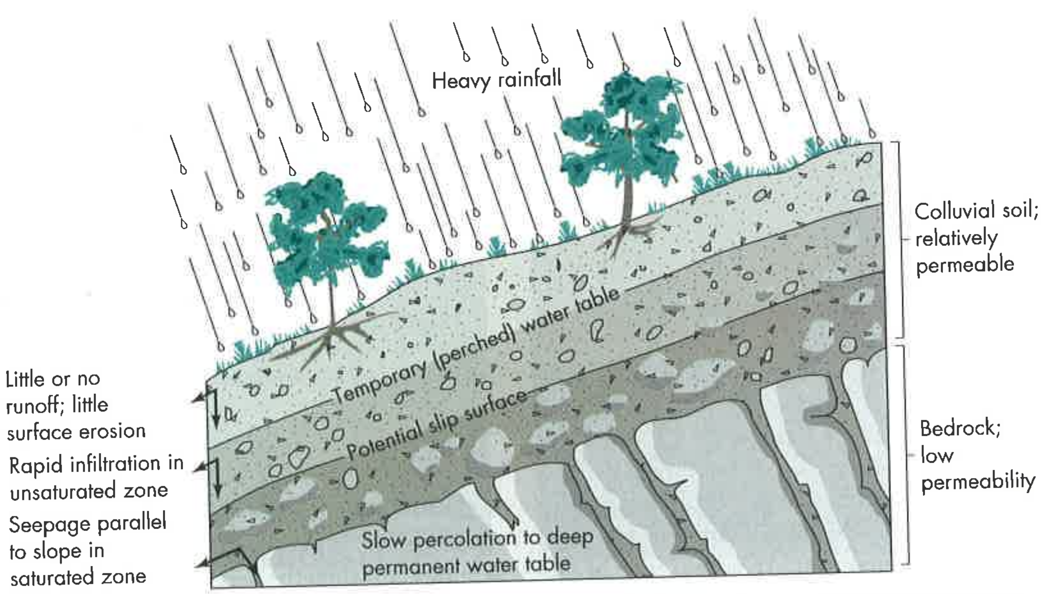
(a)

(b)

▲ **FIGURE 6.12** (a) Aerial view of landslide along the Santa Barbara coastal area. Note bulge in coastline; (b) close-up of the slide that destroyed two homes. The slide is a reactivation of an older failure. (*Don Weaver*)

water level in a reservoir or river (at a rate of at least a meter per day). When the water is at a relatively high level, a large amount may enter the banks, a phenomenon called *bank storage*. Then, when the water level suddenly drops, the water stored in the banks is left unsupported. This produces an abnormal distribution of pore-water pressures that reduces the resisting forces; simultaneously, the weight of the stored water increases the driving forces. For this reason, bank failures (slumps) tend to occur along streams after floodwaters have receded.

A third way that water can cause landslides is by contributing to spontaneous **liquefaction** of clay-rich sediment, or **quick clay.** When disturbed, some clays lose their shear strength, behave as a liquid, and flow. The shaking of clay below Anchorage, Alaska, during the 1964 earthquake produced this effect and was extremely destructive. Other examples of slides associated with sensitive clays are found in Quebec, Canada, where several large slides have destroyed numerous homes and killed about 70 people in recent years. The slides occur on river valley slopes in initially solid material that is converted into a liquid mud as the sliding movement begins (7). They are especially interesting because the liquefaction of clays occurs without earthquake shaking. The slides are often initiated by river erosion at the toe of the slope and, although they start in a small area, may develop into large events. Because they often involve the reactivation of an older slide, future problems may be avoided by restricting development. Fortunately, older slides, even though masked from ground view by vegetation, are often visible on aerial photographs.




▲ **FIGURE 6.13** Idealized diagram showing development of a perched water table in colluvial material during heavy rainfall and relationship to increased instability of the slope. (*After* R. H. *Campbell*. 1975. U.S. *Geological Survey Professional Paper* 851.)

Seepage of water from artificial sources, such as reservoirs, septic systems, and unlined canals, into adjacent slopes may also affect slope stability by adding weight (the addition of water) to a slope or by removing cementing materials, as was the case in the St. Francis Dam failure (see Chapter 2). Seepage may also cause an increase of the pore-water pressure in adjacent slopes, causing a reduction in the resisting force.

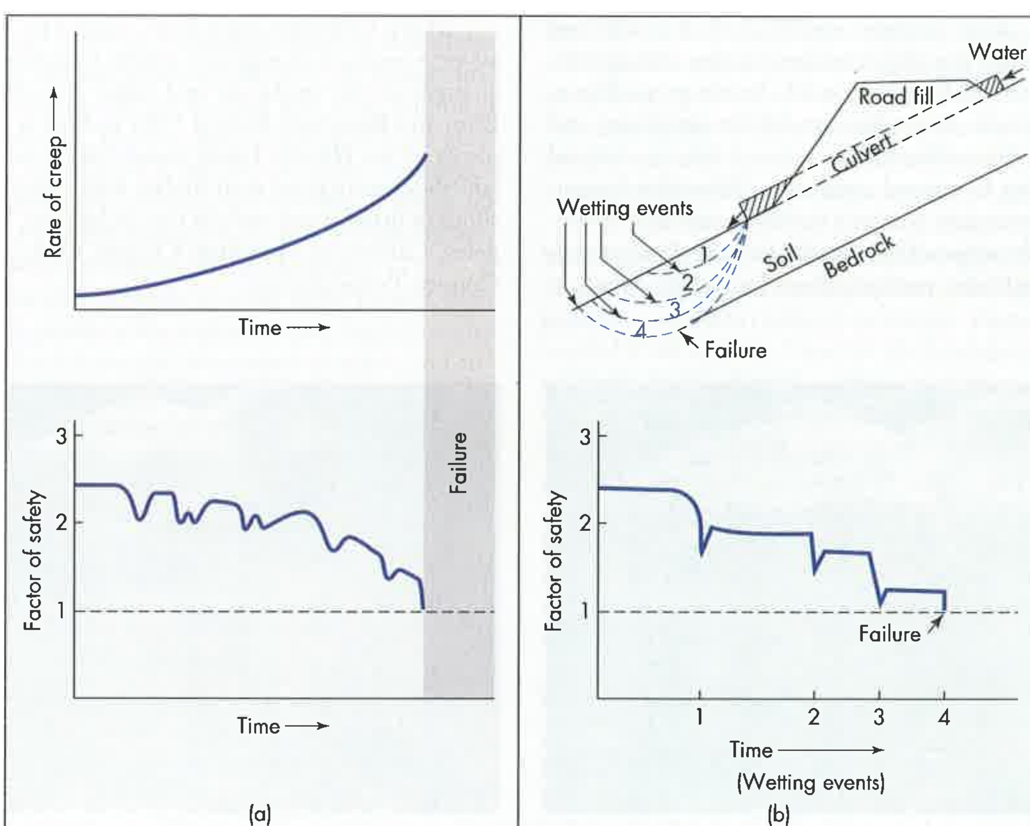
***The Role of Time*** The forces on slopes often change with time. For example, both driving and resisting forces may change seasonally as the moisture content or water-table position alters. These changes are greater in especially wet years, as reflected by the increased frequency of landslides in or following wet years. In other slopes, a continuous reduction in resisting forces may occur with time, perhaps due to weathering, which reduces the cohesion in slope materials, or to a regular increase in water pressure from natural or artificial conditions. A slope that is becoming less stable with time may have an increasing rate of creep until failure occurs (Figure 6.14a).

A slope's factor of safety may also decrease with time because of progressive wetting, which causes disarrangement of the soil particles in the slope, lowering internal friction and thus the strength of the slope materials. Figure 6.14b illustrates this phenomenon as a result of road building and culvert installation that periodically dumps water downslope. This situation emphasizes an important point: We may design slopes that are stable when constructed, but stability has a way of changing with time. Therefore, slope design should include provisions to minimize processes that might progressively weaken slope materials.

## Causes of Landslides

The **real causes** of landslides—an increase in driving force or a decrease in resisting force—are often masked by **immediate causes** such as earthquake shocks, vibrations, or a sudden increase in the amount of water entering a slope. The distinction between real and immediate causes is very important when a landslide case is heard in court and an earth scientist is expected to provide a definitive statement concerning the cause of a landslide (8). For example, a translation slide may have as an *immediate cause* heavy rains that saturated the earth material, whereas the *real* cause is the potential to slide upon weak, clay layers. Another example might be the failure of an artificial slope in a housing development, where the immediate cause is an earthquake shock, but the real cause is a poorly designed slope.

Causes of landslides may also be grouped according to whether they are external or internal. **External causes** produce an increase in the shear stress (driving force per unit




▲ **FIGURE 6.14** Idealized diagrams showing the influence of time on the development of a landslide: progressive creep (a) and progressive wetting (b). Progressive creep is symptomatic of a decreasing safety factor, whereas progressive wetting may cause a reduction in the resisting forces and thus produce a lower safety factor. (*Diagram (b) after* C. S. *Yee and* D. R. *Harr.* 1977. Environmental Geology, *vol.* 1, *p.* 374) area) at relatively constant shear strength (resisting force per unit area). Examples of external causes include loading of a slope, steepening of a slope by erosion or excavation, and earthquake shocks. **Internal causes** produce landslides without any recognized external changes and include processes that *reduce the shear strength*. Examples include such changes as increase in pore-water pressure or decrease in cohesion of the slope materials. In addition, some causes of landslides are *intermediate*, having some attributes of both external and internal causes. For example, rapid drawdown involves an increase in the shear stress (caused by weight of water remaining in the slope) accompanied by decrease in shear strength (caused by high pore pressure). Other intermediate causes include spontaneous liquefaction, and subsurface weathering and erosion (6).

## 6.3 Human Use and Landslides

Effects of human use and interest on the magnitude and frequency of landslides vary from nearly insignificant to very significant. In cases where our activities have little to do with the magnitude and frequency of landslides, we need to learn all we can about where, when, and why they occur, to avoid hazardous areas and to minimize damage. In cases where human use has increased the number and severity of landslides, we need to learn how to recognize, control, and minimize their occurrence wherever possible.

Mixtures of adverse geologic conditions such as weak soil or rock and potential slip planes on steep slopes with torrential rains, heavy snowfall, or seasonably frozen ground (permafrost) will continue to produce landslides, mudflows, and avalanches regardless of human activities. These are natural processes reacting to natural conditions. However, human land-use and settlement patterns (urbanization and deforestation) affect the scope of the disaster (see the discussion in Chapter 4 of landslides resulting from Hurricane Mitch in 1998). Let us compare, for example, the effects of debris avalanches in a sparsely populated and a heavy populated area.

A widespread episode of debris avalanches occurred in August 1969. Remnants of Hurricane Camille, moving eastward from Kentucky and the Appalachian Mountain ridges, mixed with a mass of saturated air to produce thunderstorms of catastrophic proportions. These storms locally produced 71 cm of rain in 8 hours and triggered a great many debris avalanches in central Virginia. The storms claimed 150 lives. The greatest loss of life was the result of flooding, although most people died from broken bones and blunt-force injuries rather than drowning. It is impossible to estimate how many perished as a result of the avalanches, but the amount of debris delivered to channels in floods certainly was significant. The avalanches generally followed preexisting depressions, moved a layer of soil and vegetation 0.3 to 1 m thick, and left a pronounced linear scar of exposed bedrock. The average amount of rock and soil debris moved was 2500 $m^3$, or about 36,000 metric tons (9).

Although loss of life in Virginia was terrible, it was relatively low because of the sparse population. In 1970 inhabitants of Yungay and Ranrahirca, Peru, were not so fortunate when a debris avalanche triggered by an earthquake roared 3660 m down Mt. Huascaran at a speed in excess of 300 km/hr, killing about 20,000 persons, depositing many meters of mud and boulders, and leaving only scars where the villages had been (Figure 6.15) (10).

Many landslides have been caused by interactions of adverse geologic conditions, excess moisture, and artificial changes in the landscape and slope material. The Vaiont Dam and Reservoir slide of 1963 in Italy is a classic example (see *Case History: Vaiont Dam*). Other examples include landslides associated with timber harvesting and numerous slides in urban areas such as Rio de Janeiro, Brazil; Los Angeles, California; Hamilton County, Ohio; and Allegheny County, Pennsylvania.

(a) (b)

▲ **FIGURE 6.15** Yungay, Peru, prior to the earthquake and debris avalanche (a); and after the earthquake and debris avalanche (b). The debris avalanche had its origin near the north peak of Nevado Huascaran (the right peak in the photograph). Generated by the earthquake, the debris avalanche moved a distance of approximately 14 km downslope and 4000 m lower in only 3 to 4 minutes (average speed of approximately 320 km/hr). (*Lloyd S. Cluff*)

◀ **FIGURE 6.16** Panoramic view of Rio de Janeiro, Brazil, showing the steep (sugarloaf) hills. Combination of steep slopes, fractured rock, shallow soils, and intense precipitation contribute to the landslide problem, as do human activities such as urbanization, logging, and agriculture. Virtually all of the bare rock slopes were at one time vegetated, and that vegetation has been removed by landsliding and other erosional processes. (*Tony Stone Images*)

## Timber Harvesting and Landslides

The possible cause-and-effect relationship between timber harvesting and erosion in northern California, Oregon, and Washington is a controversial topic. Landslides become important in the discussion because there is good reason to believe that landslides, especially shallow soil slips, debris avalanches, and more deeply seated earthflows, are responsible for much of the erosion. In fact, one study in the western Cascade Range of Oregon concluded that shallow slides are the dominant erosion process in the area. Whereas timber-harvesting activities (clear-cutting and road building) over approximately a 20-year observation period on geologically stable land did not greatly increase landslide-related erosion over the same period of time, logging on weak, unstable slopes did increase landslide erosion by several times that which occurred on forested land (11).

The construction of roads in areas to be logged is an especially serious problem because roads may interrupt surface drainage, alter subsurface movement of water, and adversely change the distribution of mass on a slope by cut-and-fill (grading) operations (11). As we learn more about erosional processes in forested areas, we are developing improved management procedures to minimize the adverse effects of timber harvesting. Nevertheless, we are not yet out of the woods with respect to landslide erosion problems associated with timber harvesting.

## Urbanization and Landslides

Human use and interest in the landscape are most likely to cause landslides in urban areas where there are high densities of people and supporting structures such as roads, homes, and industries. Examples from Rio de Janeiro, Brazil, and Los Angeles, California, illustrate the situation.

With a population of more than 6 million people, Rio de Janeiro may have more slope-stability problems than any other city its size. The city is noted for the beautiful granite peaks that spectacularly frame the urban area (Figure 6.16). Combinations of steep slopes and fractured rock mantled with surficial deposits contribute to the problem. In earlier times, many such slopes were logged for lumber and fuel and to clear space for agriculture. This early activity was followed by landslides associated with heavy rainfall. More recently, lack of room on flat ground has led to increased urban development on slopes. Vegetation cover has been removed, and roads leading to development sites at progressively higher areas are being built. Excavations have cut the toe of many slopes and severed the soil mantle at critical points. In addition, placing slope fill material below excavation areas has increased the load (driving force) on slopes already unstable before the fill. Because this area periodically experiences tremendous rainstorms, it is easy to see that Rio de Janeiro has a serious problem (13).

In February 1988 an intense rainstorm dumped more than 12 cm of rain on Rio de Janeiro in 4 hours. The storm caused flooding and mudslides that killed about 90 people, leaving some 3000 residents homeless. Restoration costs exceeded $100 million. Many of the landslides were initiated on steep slopes where housing is precarious and control of stormwater runoff nonexistent. It was in these hill-hugging shantytown areas that most of the deaths from mudslides occurred. However, one wing of a three-story nursing home in a more affluent mountainside area was also knocked down by a landslide, killing about 25 patients and members of the staff. If future disasters are to be avoided, Rio de Janeiro is in dire need of measures to control storm runoff and increase slope stability.

Los Angeles, and more generally southern California, has experienced a remarkable frequency of landslides associated with hillside development. Landslides in southern California result from complex physical conditions, in part because of the great local variation in topography, rock and soil types, climate, and vegetation. Interactions between the natural environment and human activity are complex and notoriously unpredictable. For this reason, the area has the sometimes dubious honor of showing the ever-increasing value of urban geology (14). Los Angeles has led the nation

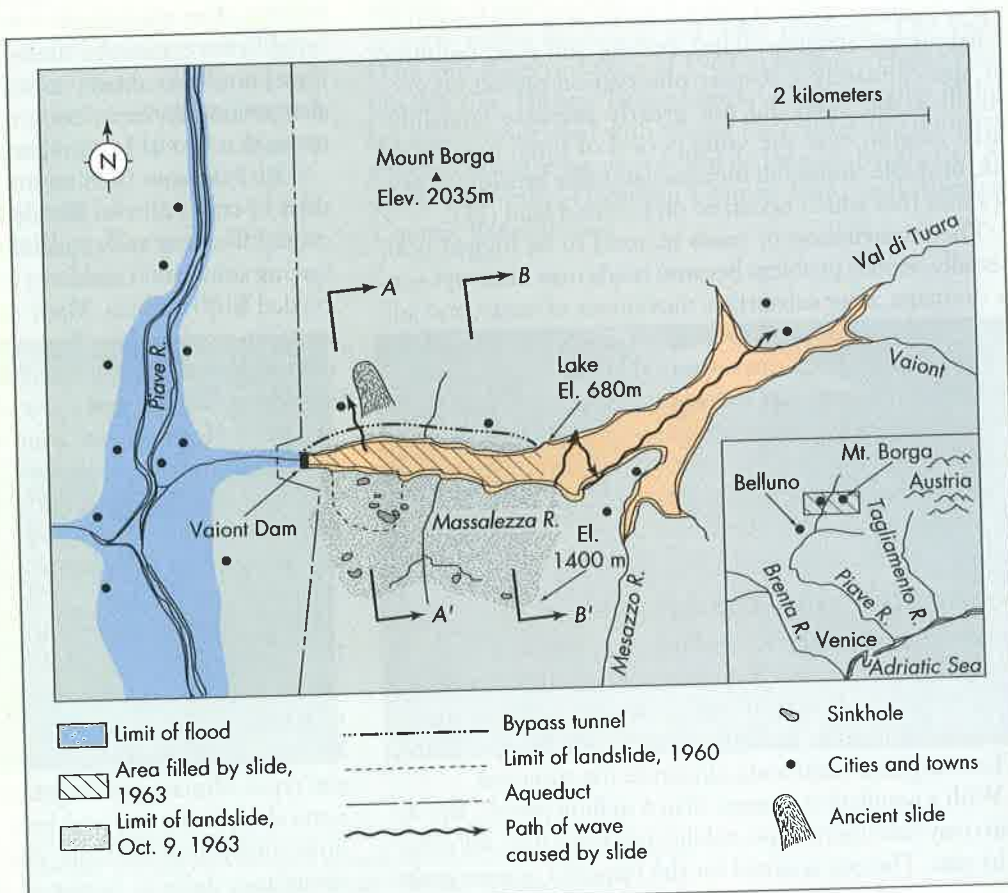
## CASE HISTORY Vaiont Dam

The world's worst dam disaster occurred on October 9, 1963, when approximately 2600 lives were lost at the Vaiont Dam in Italy. As reported by George Kiersch (12), the disaster involved the world's highest thin-arch dam (267 m at the crest), yet, strangely, no damage was sustained by the main shell of the dam or the abutments (12). The tragedy was caused by a huge landslide, in which more than 238,000,000 $m^3$ of rock and other debris moved at speeds of about 95 km/hr down the north face of the mountain above the reservoir, completely filling it with slide material for 1.8 km along the axis of the valley to heights of nearly 152 m above the reservoir level (Figure 6.B). The rapid movement created a tremendous updraft of air and propelled rocks and water up the north side of the valley, higher than 250 m above the reservoir level. The slide and accompanying blasts of air and water and rock produced strong earthquakes recorded many kilometers away. It blew the roof off one man's house well over 250 m above the reservoir and pelted the man with rocks and debris. The filling of the reservoir produced waves of water more than 90 m high that swept over the abutments of the dam. More than 1.5 km downstream, the waves were still more than 70 m high, and everything for kilometers downstream was completely destroyed. The entire event (slide and flood) was over in less than 7 minutes.

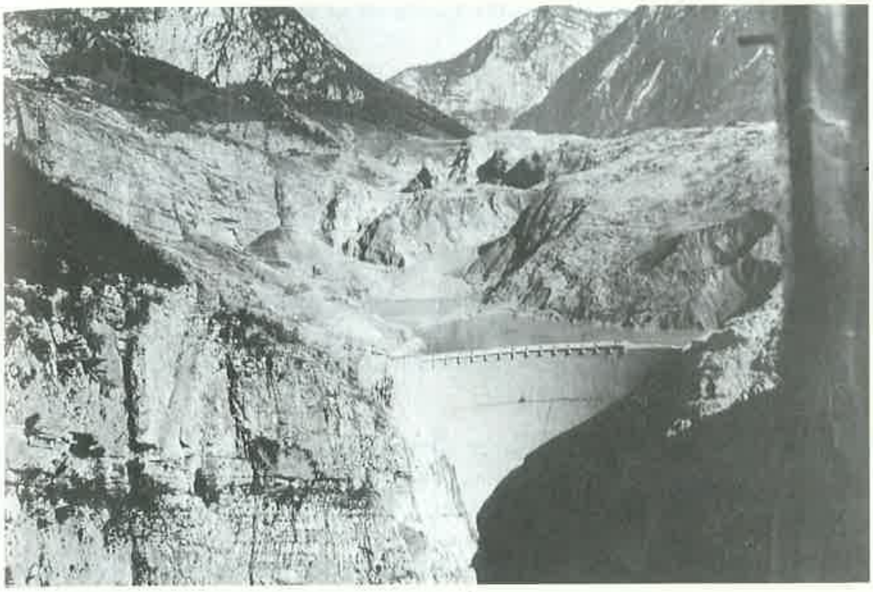
The landslide followed a 3-year period of monitoring the rate of creep on the slope, which varied from less than 1 to as many as 30 cm per week, until September 1963, when it increased to 25 cm daily. Finally, on the day before the slide, it was about 100 cm per day. Engineers expected a landslide, but one of much smaller magnitude, and they did not realize until October 8, one day before the slide, that a large area was moving as a uniform, unstable mass. Animals grazing on the slope had sensed danger and moved away on October 1.

The slide was caused by a combination of factors. First, adverse geologic conditions, including weak rocks and limestone with open fractures, sinkholes, and clay partings, which were inclined toward the reservoir, produced unstable blocks (Figure 6.C), and very steep topography created a strong driving (gravitational) force. Second, pore-water pressure was increased in the valley rocks because of the impounded water in the reservoir. Groundwater migration into bank storage raised the pore-water pressure and reduced the resisting forces in the slope. The rate of creep before the slide increased as the water table rose in response to higher reservoir levels. Third, heavy rains from late September until the day of the disaster further increased the weight of the slope materials, raised the pore-water pressure in the rocks, and produced runoff that continued to fill the reservoir even after engineers tried to lower the reservoir level.

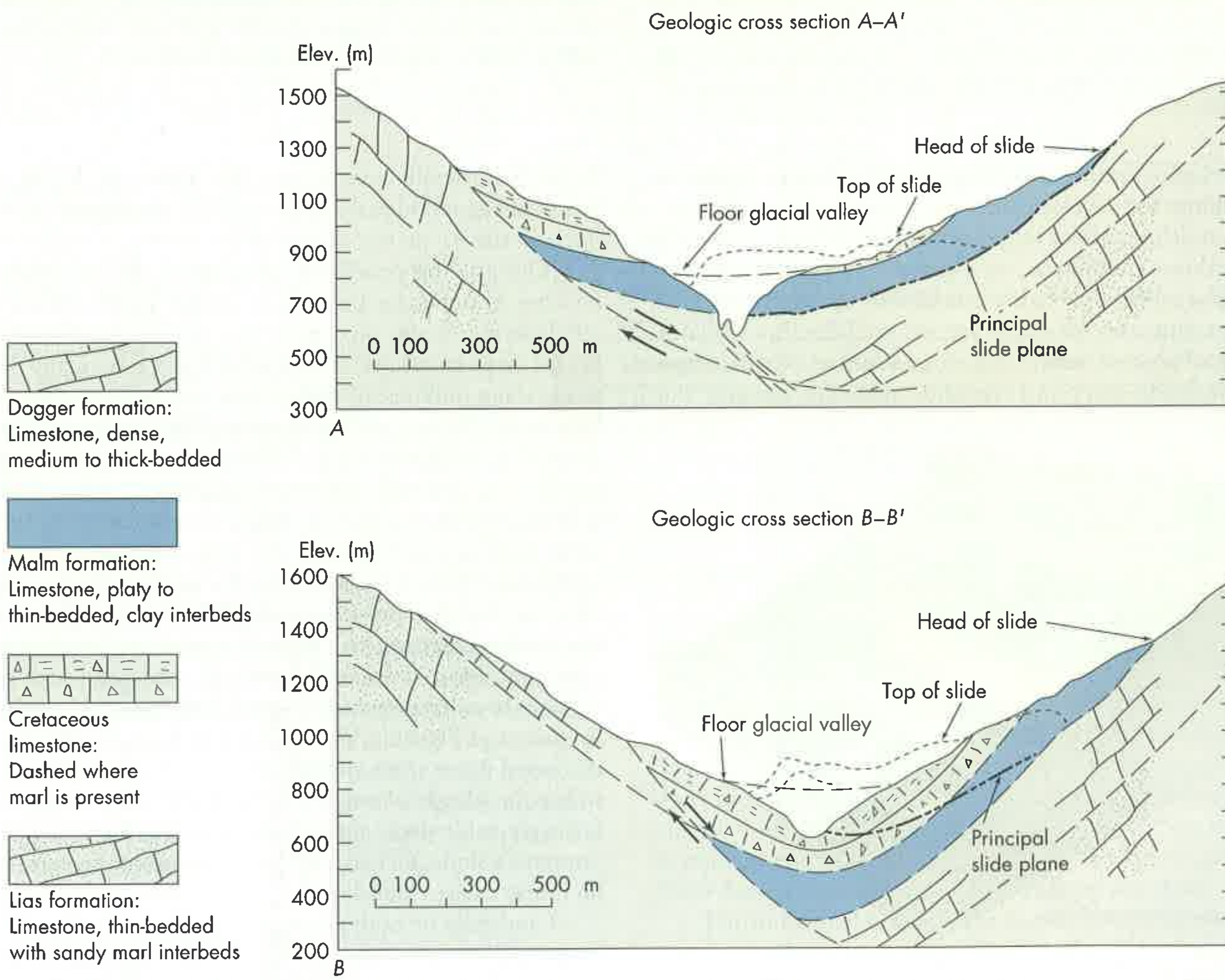
It was concluded that the cause of the disaster was an increase in the driving forces accompanied by great decrease in the resisting forces, as rising groundwater in the slope increased the pore-water pressure along planes of weakness in the rock (12).




▶ **FIGURE 6.B** Sketch map of the Vaiont Reservoir showing the 1963 landslide that displaced water that overtopped the dam and caused severe flooding and destruction over large areas downstream. A–A′ and B–B′ are section lines shown on Figure 6.C. (*After Kiersch.* 1964. Civil Engineering 34)



◀ **FIGURE 6.B (*continued*)** Photograph of the Vaiont Dam following the landslide. Notice that the concrete dam is still intact but the reservoir above the dam is completely filled (or nearly so) with landslide deposits. (ANSA)




▲ **FIGURE 6.C** Generalized geologic cross sections through the slide area of the Vaiont River Valley. Location of sections are shown on Figure 6.B. (*After Kiersch*, 1964, Civil Engineering 34)

## A CLOSER LOOK Determining Landslide Hazard and Risk

The procedure for evaluating the landslide hazard is to first make a landslide inventory, which may be a reconnaissance map showing areas that apparently have experienced slope failure. This may be done by aerial photographic interpretation with field check. At a more detailed level, the landslide inventory may be a map that shows definite landslide deposits in terms of their relative activity as being active, inactive (geologically young), or inactive (geologically old). An example of such a map for part of Santa Clara County, California, is shown on the left in Figure 6.D. Information concerning past landslide activity may then be combined with land-use considerations to develop a slope stability or landslide-hazard map with recommended land uses, as shown on the right in Figure 6.D. The latter map is of most use to planners, whereas the former supplies useful information for the engineering geologist. These maps do not take the place of detailed fieldwork to evaluate a specific site but serve only as a general guideline for land-use planning and more detailed geologic evaluation.

Determining the landslide risk and making landslide-risk maps is more complicated, for this involves probability of occurrence and assessment of potential losses. The **specific risk** *(Rs)* associated with a landslide of a particular magnitude is

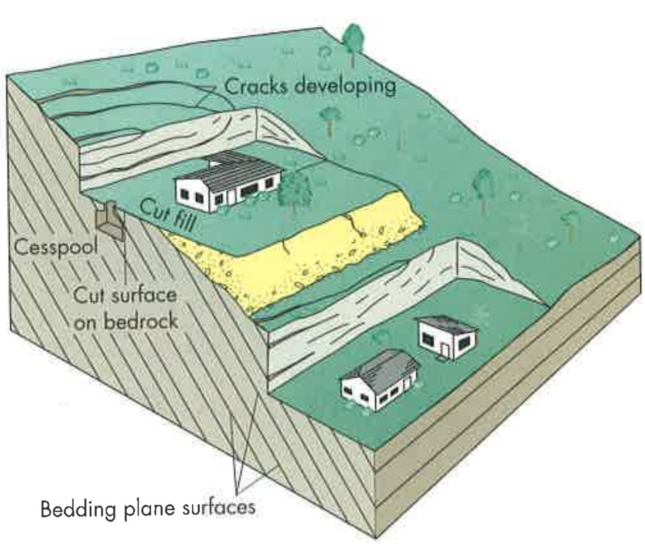
$$Rs = E \times H \times V, \text{ where}$$

- *E* is the elements at risk (i.e., value of property and social and economic activity) in the area being considered.
- *H* is the probability that a landslide of specified magnitude will occur (in a given time period).
- *V* is the vulnerability, defined as the proportion of the elements at risk *(E)* affected by the specified landslide. The value of *V* ranges from 0 (no damage) to 1 (complete destruction) (16).

For example, if an urban area has a value of \$100 billion and the probability of a large landslide happening in a 10-year period is 1 in a 1000, or 0.001, and the vulnerability is 1 percent (.01), then $Rs = 100 \times 10^9 \times 10^{-3} \times 10^{-2} = 100 \times 10^4 =$ \$1 million. Once the risks for various areas are determined, the information may be combined to produce a landslide-risk map. The method outlined here to produce risk maps is a variation of that generalized in Chapter 4 and is applicable to other hazards such as earthquakes, wildfires, and hurricanes.

in developing codes concerning grading (artificial excavation and filling) for development.

Landslides affect 60 percent of the length of seacliffs in southern California (see Figure 6.12), and the retreat of the seacliff is probably controlled by landslides (14). Similar estimates for slopes are not available, but the complex geology and terrain features, as well as evidence from old landslide scars and landslide deposits, suggest that slopes historically have been active. However, human activity has tremendously increased the magnitude and especially the frequency of landslides.

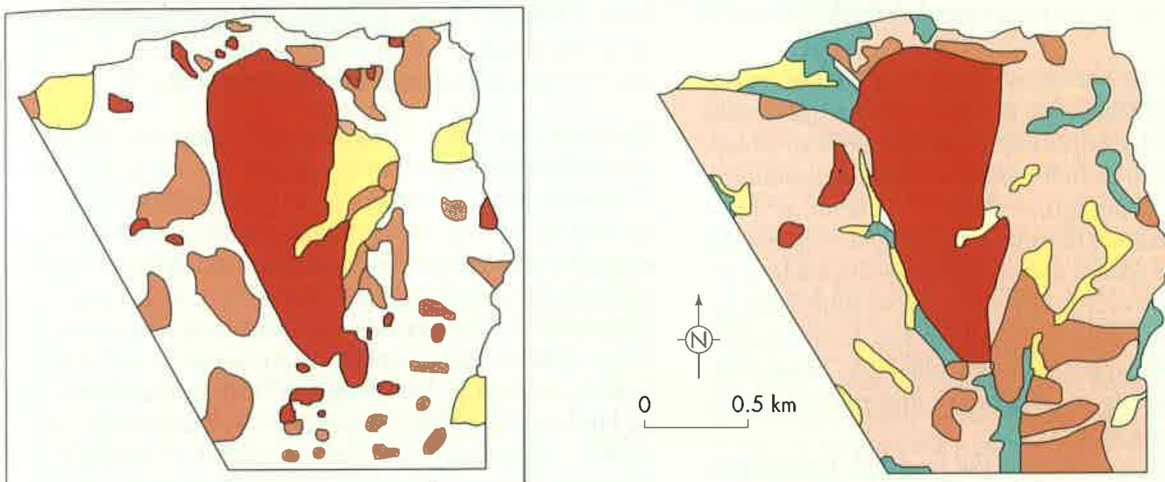



▲ **FIGURE 6.17** Development of artificial translation landslides. Stable slopes may be made unstable by removing support from the bedding plane surfaces. The cracks shown in the upper part of the diagram are an early sign that a landslide is likely to occur soon. *(Reprinted by permission from F. B. Leighton. 1966. "Landslides and Urban Development,"* Engineering Geology in Southern California *[Whittier, California: Association of Engineering Geologists])*

The grading process in southern California (cutting benches in slopes for home sites, called "pads"—hence the 1960s saying, "come on over to my pad") has been responsible for many landslides. It took natural processes many thousands, if not millions, of years to produce valleys, ridges, and hills. In this century, we have developed the machines to grade them. F. B. Leighton writes: "With modern engineering and grading practices and appropriate financial incentive, no hillside appears too rugged for future development" (14). No earth material can withstand the serious assault of modern technology. Thus, human activity is a geological agent capable of carving the landscape as do glaciers and rivers, but at a tremendously faster pace. We can convert steep hills almost overnight into a series of flat lots and roads, and such conversions have led to numerous artificially induced landslides. As shown in Figure 6.17, oversteepened slopes mixed with increased water from sprinkled lawns or septic systems, as well as the additional weight of fill material and a house, make formerly stable slopes unstable. Any project that steepens or saturates a slope, increases its height, or places an extra load on it may cause a landslide (14).

Landslides on both private and public land in Hamilton County, Ohio, have been a serious problem. The slides occur in glacial deposits (mostly clay, lakebeds, and till) and colluvium and soil developed on shale; the average cost of damage exceeds \$5 million per year. Major landslides in Cincinnati have damaged highways and several private structures (1).

Modification of sensitive slopes associated with urbanization in Allegheny County, Pennsylvania, is estimated to




Explanation

- Active landslide
- Inactive landslide, geologically young
- Inactive landslide, geologically old

| *Relative stability* | *Map area* | *Geologic conditions* | *Recommended land use* Houses | Roads Public | Roads Private |
|---|---|---|---|---|---|
| Most stable | | Flat or gentle slopes; subject to local shallow sliding, soil creep and settlement | Yes | Yes | Yes |
| | | Gentle to moderately steep slopes in older stabilized landslide debris; subject to settlement, soil creep, and shallow and deep landsliding | Yes* | Yes* | Yes* |
| | | Steep to very steep slopes; subject to mass-wasting by soil creep, slumping and rock fall | Yes* | Yes* | Yes* |
| | | Gentle to very steep slopes in unstable material subject to sliding, slumping and soil creep | No* | No* | No* |
| | | Moving, shallow (<3 m) landslide | No* | No* | No* |
| Least stable | | Moving, deep landslide, subject to rapid failure | No | No | No |

Yes*
The land use would normally be expected to be permitted, provided the geologic data and (or) engineering solutions are favorable. However, there will be instances where the use will not be appropriate.

No*
The land use would normally be expected to not be permitted. However, there will be circumstances where geologic data and (or) engineering solutions will permit the use.

▲ **FIGURE 6.D** Landslide inventory map (left) and landslide risk and land-use map (right) for part of Santa Clara County, California. (After U.S. Geological Survey Circular 880. 1982. *Goals and tasks of the landslide part of a ground-failure hazards reduction program.*)

be responsible for 90 percent of the landslides, which produce an average of about $2 million in damages annually. Most of the landslides are slow-moving, but one rockfall in an adjacent county crushed a bus and killed 22 passengers. Most of the landslides in Allegheny County result from construction activity that loads the top of a slope, cuts into a sensitive location such as the toe of a slope, or alters water conditions on or in a slope (15).

## 6.4 Minimizing the Landslide Hazard

To minimize the landslide hazard, it is necessary to identify areas in which landslides are likely to occur, design slopes or engineering structures to prevent landslides, to warn people in danger areas of impending slides, and to control slides after they have started moving.

### Identification of Potential Landslides

Identifying areas with a high potential for landslides is a first step in developing a plan to avoid landslide hazards. Slide tendency can be recognized by examining geologic conditions in the field and by examining aerial photographs to identify previous slides. This information can then be used to evaluate the risk and produce slope stability maps (see *A Closer Look: Determining Landslide Hazard and Risk*).

The individual homeowner, buyer, or builder can evaluate the landslide hazard on hillside property by looking for specific physical evidence that may indicate a potential or real landslide problem. Signs include cracks in buildings or walls around yards; doors and windows that stick or jam; retaining walls, fences, or posts that are not aligned in a normal way; breakage of underground pipes or other utilities; leaks in swimming pools; tilted trees and utility poles with taut or sagging wires; cracks in the ground; hummocky or steplike ground features; and seeping water from the base or toe of a slope (15).

The presence of one or more of these features is not absolute proof that a landslide is likely. For example, cracks in walls may also be caused by expansive soils or creep. Other features, such as hummocky or steplike ground on moderately steep slopes (greater than 15 percent, or 15-m fall in 100-m horizontal distance), probably do represent a potential landslide hazard that should be evaluated by a geologist. Furthermore, it is advisable not to limit your inspection only to the property in which you are interested; landslides are often larger than individual lots. Inspect adjacent areas, especially those that are upslope and downslope from your property (15).

Grading codes to minimize the landslide hazard have been in effect in the Los Angeles area since 1963. Motivation to institute these codes came in the aftermath of very high loss of lives and property to landsliding in the 1950s and 1960s (see *Case History: Portuguese Bend Landslide*). Since detailed engineering geology studies have been required, the number of hillside homes damaged by landslides and floods has been greatly reduced. Although initial building costs are greater because of the strict codes, they are more than balanced by the reduction of losses in subsequent wet years. And even though landslide disasters during extremely wet years will continue to plague us, the application of geologic and engineering information prior to hillside development can help minimize the hazard.

## Prevention of Landslides

Prevention of large, natural landslides is difficult, but common sense and good engineering practice can do much to minimize the hazard. For example, loading the top of slopes, cutting into sensitive slopes, placing fills on slopes, or changing water conditions on slopes should be avoided or done very cautiously (15). Common engineering techniques for landslide prevention include provisions for surface and subsurface drainage, removal of unstable slope materials (grading), construction of retaining walls or other supporting structures, or some combination of these (2,10).

***Drainage Control*** Surface and subsurface **drainage control** measures are usually effective in stabilizing a slope. The basic idea is to keep water from running across or infiltrating into the slope. Surface water may be diverted around the slope by a series of drains. This practice is common for roadcuts (Figure 6.18a). The amount of water infiltrating a slope may also be controlled by covering the slope with an impermeable layer, such as soil-cement, asphalt, or even plastic (Figure 6.18b). Groundwater may be inhibited from entering a slope by excavating a cutoff trench. The trench is filled with gravel or crushed rock and positioned so as to intercept and divert groundwater away from a potentially unstable slope (2).

***Grading*** Although **grading of slopes** for development has increased the landslide hazard in many areas, carefully planned grading can be used to increase slope stability. Two common techniques are reducing the gradient of a slope by a single cut-and-fill operation, and benching. In the first case, material from the upper part of a slope is removed and placed near the base. The overall gradient is thus reduced, and material is removed from an area where it contributes to the driving force and placed at the toe of the slope, where it increases the resisting forces. This method is not practical on very steep, high slopes. As an alternative, the slope may be cut into a series of benches or steps. The benches, designed with surface drains to divert runoff, do reduce the slope and, in addition, are good collection sites for falling rock and small slides (2).

***Slope Supports*** Retaining walls constructed from concrete cribbing (Figure 6.19), gabions (stone-filled wire baskets), or piles (long concrete, steel, or wooden beams driven into the

(a)

(b)

▲ **FIGURE 6.18** (a) Drains on a roadcut to remove surface water from the cut before it infiltrates the slope. (b) Covering a slope with a soil-cement in Greece to reduce infiltration of water and provide strength. (*Edward A. Keller*)

## CASE HISTORY Portuguese Bend Landslide

The Portuguese Bend landslide along the southern California (Los Angeles) coast (Figure 6.E) has damaged or destroyed more than 150 homes. The slide is part of an older, larger slide that was reactivated partly by road-building activities and partly by alteration of a delicate subsurface water situation by urban development. The recent movement started in 1956 during construction of a county road that placed approximately 23 m of fill over the upper area of the landslide, increasing the driving forces. During subsequent litigation, the county of Los Angeles was found responsible for the landslide.

Movement of the Portuguese Bend slide was continuous from 1956 to 1978, averaging approximately 0.3 to 1.3 cm per day. The rate accelerated to more than 2.5 cm daily in the late 1970s and early 1980s following several years of above-normal precipitation. Total displacement near the coast has been more than 200 m. The Abalone Cove slide, part of the Portuguese Bend slide complex, began to move during the above-mentioned wet period. The new slide prompted additional geologic investigation, and a landslide-control program was initiated. The program consisted of several dewatering wells installed in 1980 to remove groundwater from the slide mass. By 1985 the slide had apparently been stabilized (17). However, depending on future conditions related to precipitation and groundwater conditions, it may again cause problems.

During a two-decade period of activity, one home on the Portuguese Bend landslide moved about 25 m and constantly shifted in position. Other homes have moved up to 50 m in the same time, and some people living in homes about 1 km from the ocean apparently adjusted to the slow movement and the ever-changing view! Structures remaining in the active slide area had to be adjusted every year or so with hydraulic jacks, and utilities are on the surface. With one exception, no new homes have been constructed since the landslide began to move. The remaining occupants have elected to adjust to the landslide rather than bear total loss of their property. Nevertheless, few geologists would probably choose to live there now.


(a) (b)

▲ **FIGURE 6.E** (a) Entrance to the Portuguese Bend development (*Edward A. Keller*) and (b) aerial view of the Portuguese Bend landslide. Note kink in the pier near the toe of the landslide. Eventually most of the homes as well as the swim club and pier shown here were destroyed by the slow-moving landslide. (*John S. Shelton*)

▲ **FIGURE 6.19** Retaining wall (concrete cribbing) used to help stabilize a roadcut. (*Edward A. Keller*)

ground) are designed to provide support at the base of a slope. They should be keyed in well below the slope base, backfilled with permeable gravel or crushed rock, and provided with drain holes to reduce the chances of water pressure building up in the slope. A less common method of increasing slope stability involves insertion of heavy bolts (rock bolts) into holes drilled through potentially unstable rocks into stable rocks. This technique was used to secure the slopes at the Glen Canyon Dam on the Colorado River and the Hanson Dam on the Green River in Washington (18).

*Preventing landslides* can be expensive, but the rewards can be even greater. It has been estimated that the benefit-to-cost ratio for landslide prevention ranges from approximately 10 to 2000. That is, for every dollar spent on landslide prevention, the savings will vary from \$10 to \$2000 (19).

The cost of not preventing a slide is illustrated by a massive landslide in Utah known as the Thistle slide. This slide moved across a canyon in April 1983, creating a natural dam about 60 m high and flooding the community of Thistle, the Denver-Rio Grande railroad and its switchyard, and a major U.S. highway (Figure 6.20) (19). The landslide and resulting flooding caused approximately $200 million in damages.

The Thistle slide involved a reactivation of an older slide, which had been known for many years to be occasionally active in response to high precipitation. Therefore, it could have been recognized that the extremely high amounts of precipitation in 1983 would cause a problem. In fact, a review of the landslide history suggests that the Thistle landslide was recognizable, predictable, and preventable! Analysis of the pertinent data suggests that emplacement of subsurface drains and control of surface runoff would have lowered the water table in the slide mass enough to have prevented failure. Cost of preventing the landslide was estimated to be between $300,000 and $500,000, a small amount compared to the damages (19). Because the benefit-to-cost ratio in landslide prevention is so favorable, it seems prudent to evaluate active and potentially active landslides in areas where considerable damage may be expected and possibly prevented.

▲ **FIGURE 6.20** Thistle landslide, Utah. This landslide, which occurred in 1983, involved the reactivation of an older slide. The landslide blocked the canyon, creating a natural dam, flooding the community of Thistle as well as the Denver-Rio Grande Railroad and a major U.S. highway. *(Michael Collier)*

## Landslide Warning Systems

Landslide warning systems do not prevent landslides, but they can provide time to evacuate people and their possessions, and to stop trains or reroute traffic. Surveillance provides the simplest type of warning. Hazardous areas can be visually inspected for apparent changes, and small rockfalls on roads and other areas can be noted for quick removal. Having people monitor the hazard has advantages of reliability and flexibility but becomes disadvantageous during adverse weather and in hazardous locations (20). Other warning methods include electrical systems, tilt meters, and geophones that pick up vibrations from moving rocks. Shallow wells can be monitored to signal when slopes contain a dangerous amount of water. In some regions, monitoring rainfall is useful for detecting when a threshold precipitation has been exceeded and shallow soil slips become much more probable.

## Landslide Correction

After movement of a slide has begun, the best way to stop it is to attack the process that started the slide. In most cases, the cause of the slide is an increase in water pressure, and in such cases, an effective drainage program must be initiated. This may include surface drains at the head of the slide to keep additional surface water from infiltrating and subsurface drainpipes or wells to remove water and lower the water pressure. Draining tends to increase the resisting force of the slope material and therefore stabilizes the slope.

The tremendous success of drainage is demonstrated by this description from Karl Terzaghi (6). After a high-magnitude rainstorm, movement on a 30° slope of deeply weathered metamorphic rock was noted. The slide plane was approximately 40 m below the surface, and the slide area was about 150 m wide by 300 m long. The slide was close to a hydroelectric power station, so immediate action was deemed necessary. Fieldwork established that if the water level could be lowered approximately 5 m, then the increase in resisting force would be sufficient to stabilize the slide. Drainage was accomplished by trenches and horizontal drill holes extending into the water-bearing zones of the rock. After drainage, the movement stopped, and even though the next rainy season brought record rainfall, no new movement was observed (6).

# 6.5 Snow Avalanche

An avalanche is a rapid downslope movement of snow. If abundant rock, soil, and trees are incorporated, it may be much like a debris avalanche. As with landslides, **snow avalanches** are subject to driving and resisting forces on the slope.

Approximately 10,000 snow avalanches occur each year in the mountains of the western United States, and about 1 percent of these cause loss of human life or property damage, killing an average of seven people and inflicting \$300,000 in damage (21). Loss of life is increasing, however, as more people venture into mountain areas for recreation during the winter.

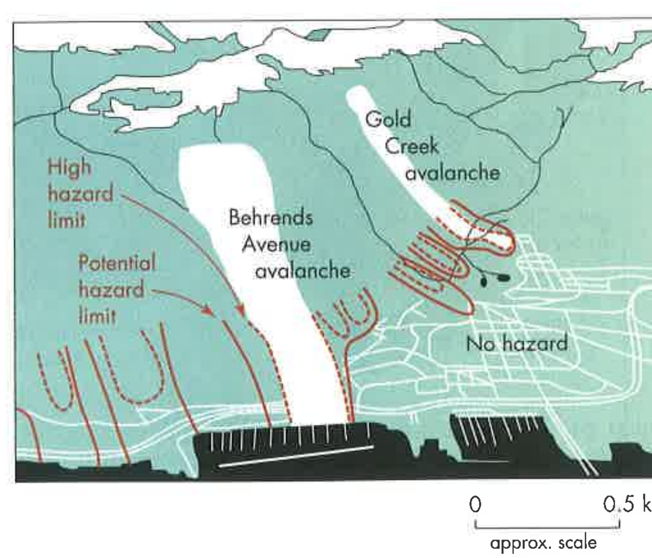
Avalanches can occur in dry or wet snow and are of two general types: **loose-snow avalanches,** which occur in cohesionless snow and tend to be relatively small and shallow failures; and **slab avalanches,** which may initially vary from about 100 to 10,000 $m^2$ in area and 0.1 to 10 m in thickness (21). Large slab avalanches are the most dangerous, releasing tremendous energy by mobilizing up to a million tons of snow and ice and moving downslope at velocities of 5 to 30 m/sec (18 to 100 km per hr) or more. Horizontal thrust (or impact) from such events tends to vary from 5 to 50 tons/$m^2$, but may in extreme cases exceed 100 tons/$m^2$. To appreciate the magnitude of this thrust, consider that a thrust of only about 3 tons/$m^2$ is necessary to collapse a frame house, and 100 tons/$m^2$ can move reinforced concrete structures (21).

Avalanches are initiated when a mass of snow and ice on a slope fails because of the overload of a large volume of new snow, or when internal changes in a snowpack produce zones of weakness (low shear strength) along which failure occurs. When conditions are very unstable, even the weight of a single skier can start an avalanche. Once started, avalanches tend to follow certain paths, chutes, or tracks (see Figure 6.21a). These are often well channeled; however, unconfined tracks on open slopes also occur. Avalanche tracks often have several branches near the top that coalesce downslope; thus, it is possible for several avalanches to move through the main track in a short period of time as snowpacks in upper branches fail. Failure to recognize this possibility has caused the loss of several lives when workers clearing debris from a first avalanche have been struck by a second (21).

The avalanche hazard can be reduced by avoiding dangerous areas; stabilizing slopes by clearing them with carefully placed explosions; building structures to divert or retard avalanches; and reforesting avalanche paths, since large avalanches are seldom initiated on densely forested slopes (21).

Avalanches are primarily a threat to skiers on high, steep mountain slopes, but they also threaten mountain resorts, villages, railways, highways, and even sections of some cities. For example, Juneau, Alaska, has a significant avalanche hazard. In the last 100 years, a major avalanche chute above Juneau has released snow and ice six times, events that reached the sea. No damaging avalanches have occurred over the last quarter century, however, so an entire subdivision has been constructed across the chute (Figure 6.21b). If another large event occurs, it will destroy about 30 homes, part of a school, and a motel, and eventually roar into the harbor where several hundred boats are docked. It has been estimated that a home in the chute area, with a 40-year life span, has a 96 percent probability of being struck by an avalanche, yet the people who live there have been almost nonchalant about the hazard (22).

(a)




(b)

◀ **FIGURE 6.21** (a) Avalanche chute or track in the Swiss Alps. (*Edward A. Keller*) (b) Map of part of Juneau, Alaska, avalanche hazard. (*After* D. *Cupp*. 1982. National Geographic 162:290–305)

## 6.6 Subsidence

Interactions between geologic conditions and human activity have been factors in numerous incidents of **subsidence,** the very slow to rapid sinking or settling of earth materials. Most subsidence is caused by withdrawal of fluids from subsurface reservoirs or by the collapse of surface and near-surface soil and rocks over subterranean voids.

Withdrawals of oil with associated gas and water, of groundwater, and of mixtures of steam and water for geothermal power have caused subsidence (23). In all cases, the general principles are the same. Fluids in earth materials below the earth's surface have a high fluid pressure that tends to support the material above. This is why a large rock at the bottom of a swimming pool seems lighter: Buoyancy produced by the liquid tends to lift the rock. If support or buoyancy is removed from earth materials by pumping out the fluid, the support is reduced, and surface subsidence may result.

The actual subsidence mechanism involves compaction of individual grains of the earth material as the grain-to-grain load increases because of a lowering of fluid pressure. Subsidence of oil fields generally involves considerable reduction of fluid pressure, up to $2.8 \times 10^7$ Pa (N/m$^2$), at great depth (thousands of meters) over a relatively small area, less than 150 km$^2$. On the other hand, subsidence resulting from withdrawal of groundwater generally involves a relatively low reduction of fluid pressure, often less than $1.4 \times 10^6$ Pa, at relatively shallow depths (less than 600 m), over a large area, sometimes many hundreds of square kilometers (23). See Chapter 2 for a discussion of stress (pressure).

Thousands of square kilometers of the central valley of California have subsided as a result of overpumping groundwater (Figure 6.22). More than 5000 km$^2$ in the Los Banos–Kettleman City area alone have subsided more than 0.3 m, and within this area, one 113-km stretch has subsided an average of more than 3 m, with a maximum of about 9 m (Figure 6.22). As the water was mined, the fluid pressure was reduced and the grains were compacted (Figure 6.23) (24,25); the effect at the surface was subsidence. Similar examples of subsidence caused by overpumping are documented near Phoenix, Arizona; Las Vegas, Nevada; Houston–Galveston, Texas; and Mexico City, Mexico. The subsidence can cause surface fissures (open cracks) to form in sediments, and these fissures can be hundreds of meters long and several meters deep (25).

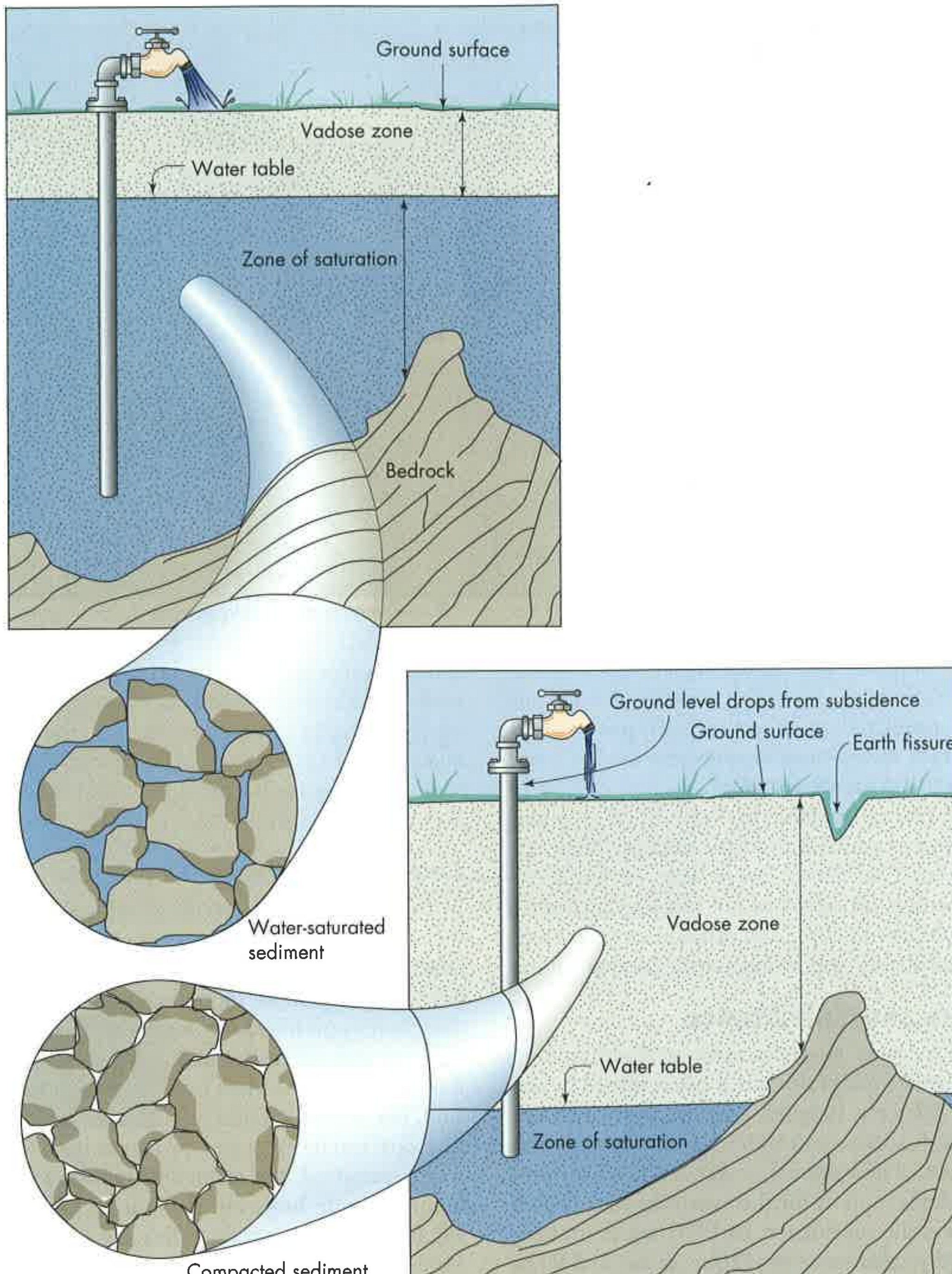
### Sinkholes

Subsidence is also caused by removal of subterranean earth materials (rock) by natural processes. Voids often form within soluble rocks such as limestone and dolomite, and the resulting lack of support for overlying rock may cause it to collapse. The result is the formation of a **sinkhole,** a circular area of subsidence caused by collapse into a subterranean void. Some sinkholes are more than 30 m across and 15 m deep. One near Tampa, Florida, collapsed suddenly in 1973, swallowing part of an orange orchard. What may be the largest sinkhole in the United States formed in 1972 near Montevallo, Alabama (26). A massive hole 120 m wide and 45 m deep, named the "December Giant" by the press, de-


(a)


(b)

▲ **FIGURE 6.22** (a) Principal areas of land subsidence in California resulting from groundwater withdrawal. (*After* W. B. Bull. 1973. Geological Society of America Bulletin 84. *Reprinted by permission*.) (b) Photograph illustrating the amount of subsidence in the San Joaquin Valley, California. Marks on telephone pole are positions of the ground surface in recent decades. The photo shows approximately 8 m of subsidence. (*Courtesy of Ray Kenny*)




▲ **FIGURE 6.23** Idealized diagram showing how surface subsidence results from pumping groundwater. Pore (empty) spaces between grains collapse following pumping. (*From* R. *Kenny*. 1992. *Fissures*. Earth 2(3):34–41)

veloped suddenly when topsoil and subsurface clay collapsed into an underlying limestone cavern. The collapse was caused by loss of support to the clay and soil over the cavern. A nearby resident reported hearing a roaring noise accompanied by breaking timber and earth tremors that shook his house.

Sinkholes have caused considerable damage to highways, homes, sewage facilities, and other structures. Natural or artificial fluctuations in the water table are probably the trigger mechanism. High water-table conditions favor solutional enlarging of the cavern, and the buoyancy of the water helps support the overburden. Lowering of the water table eliminates some of the buoyant support and facilitates collapse. This was dramatically illustrated on May 8, 1981, in Winter Park, Florida, when a large sinkhole began developing. The sink grew rapidly for 3 days, swallowing part of a community swimming pool, parts of two businesses, several automobiles, and a house (Figure 6.24). Damage caused by the sinkhole exceeded $2 million. Sinkholes form nearly every year in central Florida when the groundwater level is lowest.

▶ **FIGURE 6.24** The Winter Park, Florida, sinkhole that grew rapidly for three days, swallowing part of a community swimming pool as well as several businesses, houses, and automobiles. (*Leif Skoogfors/Woodfin Camp and Associates*)

The Winter Park sinkhole formed during a drought, when groundwater levels were at a record low. Although exact positions cannot be predicted, their occurrence is greater during droughts; in fact, several smaller sinks appeared at about the same time as the Winter Park event.

Sometimes a natural sinkhole has been filled and built upon, with disastrous results. A dramatic example is the Allentown sinkhole (see *Case History: Lehigh Valley, Pennsylvania*). In this case the cumulative effects of not recognizing a sinkhole, filling it with urban debris, and subsequently developing the site were probably responsible for the sudden failure.

## Salt Deposits and Subsidence

Serious subsidence events have been associated with mining of salt, coal, and other minerals. Salt is often mined by solution methods: Water is injected through wells into salt deposits, the salt dissolves, and water supersaturated with salt is pumped out. The removal of salt leaves a cavity in the rock and weakens support for the overlying rock, which may lead to large-scale subsidence. In 1970 one event near Detroit produced a subsidence pit 120 m across and 90 m deep. Another near Saltville, Virginia, produced 75 m of subsidence relatively quickly. Two homes went down with the Saltville subsidence. According to local residents, one family moved out the day before the event because a family member had dreamed the mountain was falling. Mining of salt by other methods can also produce subsidence (see *Case History: Lake Peigneur, Louisiana*).

Large sinks associated with bedded salt may also occur without mining. For example, in June 1980 a large depression southwest of Kermit, Texas, known as the "Wink Sink," developed over a period of about 48 hours. At the end of that time, the sinkhole was approximately 110 m across and 34 m deep. The Wink Sink and similar features evidently form by natural processes when groundwater slowly dissolves caverns in bedded salt underlying less soluble rock, such as sandstone. When a cavern reaches a critical size, the overlying rocks can no longer be supported, and collapse occurs. Because this is a natural process and other caverns undoubtedly exist, future sinks probably will develop in the area without warning (28).

## Coal Mining and Subsidence

In coal mining, the practice of full recovery (removing all the coal) in subsurface mines has produced subsidence problems. A good example is the Pittsburgh area, where mining has been going on for more than a century. In the early years, companies purchased mining rights permitting removal of the coal with no responsibility for surface damage. Results were not so serious when mining was conducted under farmland, but as recent rapid urbanization has progressed faster than coal can be extracted, problems have resulted. If all the coal is removed, the chance of subsidence and damage to homes is high; however, if about 50 percent of the coal is left, it will usually provide sufficient support. The Bituminous Mine Subsidence and Land Conservation Act of 1966 provided for protection of public health, welfare, and safety by regulating coal mining, but this act will cause hundreds of millions of tons of coal to remain in the ground, attesting to the nature of trade-offs when there is conflict in surface and subsurface human use of the land (29).

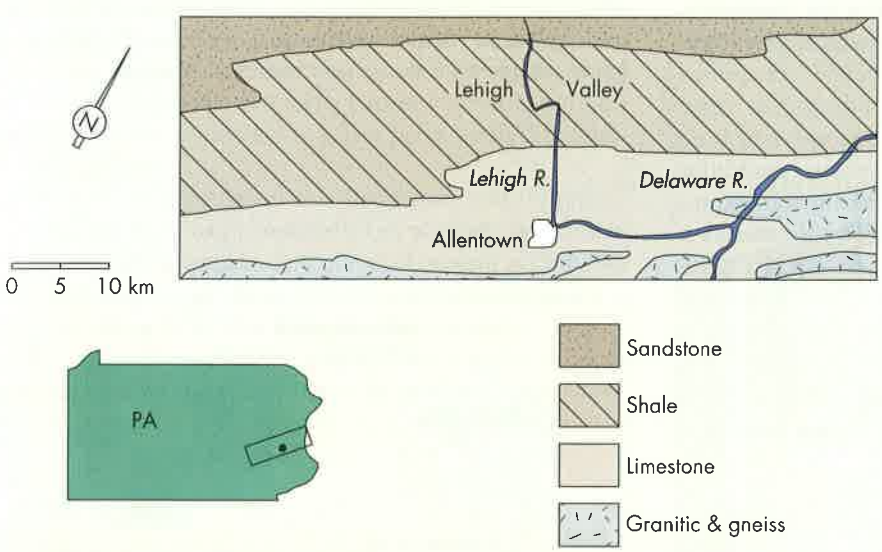
Subsidence incidents have also been reported over coal mines that have not been worked for more than 50 years (29). On a January morning in 1973, a few residents of Wales (Britain) were driving over a section of the road that suddenly collapsed into a pit 10 m deep. Their car tottered on the brink while they scrambled to safety. The collapse, which occurred over an air shaft of a lost mine, disrupted some utility service. Other similar subsidence events have happened in the past and are likely to occur in the future.

## CASE HISTORY Lehigh Valley, Pennsylvania

On June 23, 1986, a large subsidence pit developed at the site of an unrecognized, filled sinkhole in Lehigh Valley near Allentown, in eastern Pennsylvania. Within a period of only a few minutes, the collapse left a pit approximately 30 m in diameter and 14 m deep. Fortunately, the damage was confined to a street, parking lots, sidewalks, sewer lines, water lines, and utilities. Seventeen residences adjacent to the sinkhole narrowly escaped damage or loss; subsequent stabilization and repair costs were nearly one-half million dollars. Figure 6.F shows the generalized geology of Lehigh Valley. The northern part of the valley is underlain by shale, whereas limestone comprises the southern portion. The valley is bounded by resistant sandstone rocks to the north and resistant Precambrian granitic and gneissic rocks to the south (27).

Photographs from the 1940s to 1969 provide evidence of the sinkhole's history. In the 1940s the sinkhole was delineated by a pond of approximately 65 m in diameter. By 1958 the pond had dried up, the sinkhole was covered by vegetation, and the surrounding area was planted in crops. Ground photographs in 1960 suggest that people were using the sinkhole as a site to dump tree stumps, blocks of asphalt, and other trash. By 1969 there was no surface expression of the sinkhole; it evidently was completely filled and corn was planted over it.

Even though the sinkhole was completely filled with trash and other debris, it still received runoff water that was later increased in volume by urbanization. Sources of water included storm runoff from adjacent apartments and townhouses, as well as streets and parking lots. It is also suspected that an old, leaking water line contributed to runoff into the sinkhole area. In addition, urbanization placed increased demand on local groundwater resources, resulting in the lowering of the water table. Geologists believe that hydrologic conditions contributed to the sudden failure. The increased urban runoff facilitated the loosening or removal of the plug (soil, clay, and trash) that filled the sinkhole, while the lowering of the groundwater table reduced the overlying support, as was the case with the Winter Park sinkhole (27).




◀ **FIGURE 6.F** Generalized geologic map of the Lehigh Valley in eastern Pennsylvania. [*Modified from* P. H. *Dougherty and* M. Perlow, Jr. 1987. Environmental Geology and Water Science 12(2):89–98.]

## 6.7 Perception of the Landslide Hazard

The common reaction of southern California homeowners to talk of landslides is, "It could happen on other hillsides, but never this one" (14). As with flooding, landslide-hazard maps will probably not prevent people from moving into hazardous areas, and prospective hillside occupants who are initially unaware of the hazards may not be swayed by technical information. The infrequency of large slides tends to reduce awareness of the hazard where evidence of past events is not readily visible. Unfortunately, it often takes catastrophic events such as the recent massive landslide in the Laguna Hills area of California, which claimed numerous expensive homes, to bring the problem to the attention of many people. In the meantime, residents in many parts of the Rocky Mountains, Appalachian Mountains, and other areas continue to build homes in areas subject to future (and even present) landslides.

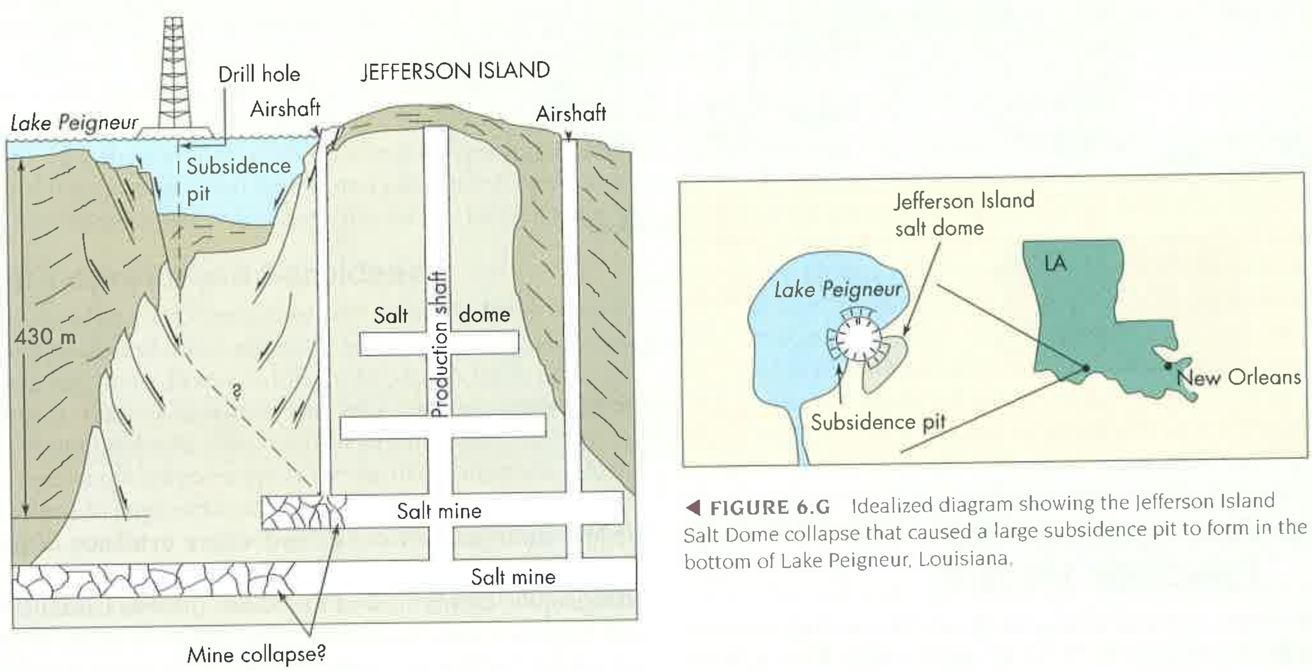
## CASE HISTORY Lake Peigneur, Louisiana

A bizarre example of subsidence associated with a salt mine occurred on November 21, 1980, in southern Louisiana, when shallow Lake Peigneur (with an average depth of 1 m) drained following collapse of the salt mine below. The collapse occurred after an oil-drilling operation apparently punched a hole into an abandoned mine shaft of a still active multimillion-dollar salt mine located about 430 m below the surface of the Jefferson Island salt dome. As the hole enlarged because of water entering the mine—scouring and dissolving pillars of salt—the roof of the mine collapsed, producing a large subsidence pit (Figure 6.G).

The lake drained so fast that 10 barges, a tugboat, and an oil-drilling barge disappeared in a whirlpool of water into the mine, which in places has tunnels as wide as four-lane freeways and 25 m high. (Mining is done with the aid of trucks and bulldozers.) Fortunately, the 50 miners and 7 people on the oil rig escaped. The subsidence also claimed more than 25 ha of Jefferson Island, including historic botanical gardens, greenhouses, and a $500,000 private home. What is left of the gardens is disrupted by large fractures that roughly step the land down to the new edge of the lake. These fractures are tensional in origin and are commonly found on the margins of large subsidence pits.

Lake Peigneur immediately began refilling with water from a canal connecting it to the Gulf of Mexico, and 9 of the barges popped to the surface 2 days later. There was fear at first that even larger subsidence would take place as pillars of salt holding up the roof of the salt dome dissolved. However, the hole was apparently sealed by debris in the form of soil and lake sediment that was pulled into the mine. Approximately 15 million $m^3$ of water entered the salt dome, and the mine became a total loss. The previously shallow lake now has a large, deep hole in the bottom, which undoubtedly will change the aquatic ecology. In a 1983 out-of-court settlement, the salt mining company reportedly was compensated $30 million by the oil company involved. The owners of the botanical garden and private home apparently were compensated $13 million by the oil company, drilling company, and mining company.

The flooding of the mine raises important questions concerning the structural integrity of salt mines. The federal strategic petroleum reserve program is planning to store 75 million barrels of crude oil in an old salt mine of the Weeks Island salt dome about 19 km from Jefferson Island. On the other hand, while the role of the draining lake in the collapse is very significant, few salt domes have lakes above them. The Jefferson Island subsidence is thus a very rare type of event.




◀ **FIGURE 6.G** Idealized diagram showing the Jefferson Island Salt Dome collapse that caused a large subsidence pit to form in the bottom of Lake Peigneur, Louisiana.

## SUMMARY

Landslides and related phenomena cause substantial damage and loss of life. Although they are natural events, their occurrence can be increased or decreased by human activity.

The most common landforms are slopes—dynamic, evolving systems in which surficial material is constantly moving downslope at rates varying from imperceptible creep to thundering avalanches. All slopes are composed of one or more slope elements, including the crest, free-face, debris slope, and wash slope. The presence of particular slope elements on a specific slope is related to climate and rock type, which affect slope processes. Slope failure may involve *flowage, sliding,* or *falling* of earth materials; landslides are often complex combinations of sliding and flowage.

Forces producing landslides are determined by the interactions of several variables: the type of earth material on the slope, topography, climate, vegetation, water, and time. The cause of most landslides can be determined by examining the relations between forces that tend to make earth materials slide *(driving forces)* and forces that tend to oppose movement *(resisting forces).* The most common driving force is the weight of the slope materials, and the most common resisting force is the shear strength of the slope materials. The *factor of safety* of a slope is the ratio of resisting forces to driving forces; a ratio greater than 1 suggests that the slope is stable. The type of rock or soil on a slope influences both the type and the frequency of landslides.

Water has an especially significant role in producing landslides. Water in streams, lakes, or oceans erodes the toe area of slopes, increasing the driving forces. Excess water increases the weight of the slope materials while raising the water pressure, which in turn decreases the resisting forces in the slope materials. A rise in pore-water pressure occurs before many landslides, and, in fact, most landslides are a result of an abnormal increase in water pressure in the slope-forming materials.

Effects of human use on the magnitude and frequency of landslides vary from insignificant to very significant. Where landslides occur independent of human activity, we need to learn enough about them to avoid development in hazardous areas or to provide protective measures. Where human use has increased the number and severity of landslides, we have to learn how to minimize these occurrences. In some cases dams and reservoirs have increased migration of groundwater into slopes, resulting in slope failure. Logging operations on weak, unstable slopes have increased landslide erosion. Grading of slopes for development has created or increased erosion problems in many urbanized areas of the world.

To minimize landslide hazard, it is necessary to establish identification, prevention, and correction procedures. Monitoring and mapping techniques facilitate identification of hazardous sites. Where identification of potential landslides has been used to establish grading codes, landslide damage has been decreased. Prevention of large natural slides is very difficult, but good engineering practices can do much to minimize the hazard when it cannot be avoided. Engineering techniques for landslide prevention include drainage control, proper grading, and construction of supports, such as retaining walls. Correction of landslides must attack the processes that started the slide; this usually means initiating a drainage program that lowers water pressure in the slope.

Snow avalanches present a serious hazard on snow-covered, steep slopes. Loss of human life because of avalanches is increasing as more people venture into mountain areas for winter recreation.

Withdrawal of fluids such as oil and water and subsurface mining of salt, coal, and other minerals have both caused widespread *subsidence.* In the case of fluid withdrawal, the cause of subsidence is a reduction of fluid pressures that tend to support overlying earth materials. In the case of solid material removal, subsidence may result from loss of support for the overlying material. The latter situation occurs naturally when voids are formed in soluble rock such as limestone and the collapse of overlying earth material produces sinkholes.

Perception of the landslide hazard by most people, unless they have prior experience, is low. Furthermore, hillside residents, like floodplain occupants, are not easily swayed by technical information.

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## KEY TERMS

**landslide** (p. 132)
**driving forces** (p. 134)
**resisting forces** (p. 134)
**factor of safety** (p. 135)
**rotational slide** (p. 135)
**translational slide** (p. 135)
**perched water table** (p. 141)
**rapid draw-down** (p. 141)
**quick clay** (p. 142)
**specific risk** (p. 148)
**drainage control** (p. 150)
**grading of slopes** (p. 150)
**snow avalanche** (p. 152)
**subsidence** (p. 154)
**sinkhole** (p. 154)

## SOME QUESTIONS TO THINK ABOUT

1. In this chapter we established that variables such as climate, topography, vegetation, water, and time are important in affecting the nature and occurrence of landslides. Write down as many links as you can between these various processes to discover how they might be interrelated. For example, climate is obviously related to water and vegetation on slopes.
2. Your consulting company is hired by the national park or parks in your region to estimate the future risk from landsliding. Outline a plan of attack of what must be done to achieve this objective.
3. Why do you think that many people are not easily swayed by technical information concerning hazards such as landslides? Assume you have been hired by a community to make the citizens more aware of the landslide hazard in their area, which has a lot of steep topography. Outline a plan of action and defend it.