400,000 tons of water-saturated soil and rock tore through **the upper part of the community**

7



APPLYING the 5 fundamental concepts La Conchita, Southern California: Landslide Disaster

1

Science helps us predict hazards.

Geologic studies illustrate that regular landsliding has occurred over a protracted period in this region. La Conchita and other communities along this part of the California coast, therefore, have a high probability of experiencing mass wasting events.

2

Knowing hazard risks can help people make decisions.

Many of the residents of La Conchita consider the high mass wasting risk acceptable, being outweighed by the opportunity to live in this idyllic beach community. In contrast, other residents stay because they are unable to sell their homes due the high risk of mass wasting.

Mass Wasting

La Conchita, Southern California: Landslide Disaster

Monday, January 10, 2005, was a disaster for the small beachside community of La Conchita, California, 80 km (~50 mi.) northwest of Los Angeles. Ten people lost their lives, and about 30 homes were destroyed or damaged when 400,000 tons of water-saturated soil and rock tore through the upper part of the community (see chapter-opener photograph).

Although it had been raining for days prior to the 2005 slide and a similar but larger landslide had occurred in the same location in 1995 (Figure 7.1),[1] neither residents nor local officials recognized that another slide was imminent. As a result, some people were trapped in their homes and others ran for their lives.

Following the 1995 landslide, a geologic investigation was conducted to evaluate the risk of future events as well as to estimate the cost of stabilizing the hillslope behind the community. Although the report showed that landslides were common along the steep sea cliff behind La Conchita, the findings indicated that the slope could be completely stabilized for a cost of about $150 million,[2] or

< Reactivated Landslide Turns Deadly

Search and rescue personnel attempt to stabilize collapsed home before attempting to enter and search for survivors buried in the debris and mud generated by the 2005 La Conchita landslide. *(John Shea/Fema.)*

LEARNING Objectives

Landslides, the movement of materials down a slope, constitute a serious natural hazard in many parts of North America and the world. Landslides are often linked to other hazards such as earthquakes and volcanoes. Most landslides are small and slow, but a few are large and fast. Both may cause significant loss of life and damage to property, particularly in urban areas.

After reading this chapter, you should be able to:

LO:1 Describe slope processes and the different types of landslides.

LO:2 Analyze the forces that act on slopes and how they affect the stability of a slope.

LO:3 Evaluate what geographic regions are at risk from landslides.

LO:4 Compare different mass wasting processes and their linkages with other natural hazards.

LO:5 Describe the ways in which people can affect the landslide hazard.

LO:6 Explain the adjustments people can make to avoid death and damage caused by landslides.

LO:7 Summarize the ways in which you can protect yourself and property from the processes of mass wasting.

3

Linkages exist between natural hazards.

The 2005 slide was clearly linked to the heavy rain that preceded the event. When we return to La Conchita at the end of this chapter, you will learn about several other natural hazards that contribute to mass wasting along this section of California's scenic coastline.

4

Humans can turn disastrous events into catastrophes.

According to the 2010 U.S. census data, Southern California is in the top 10 states for population growth. Homes in coastal communities with similar geologic settings and natural hazards as La Conchita are highly desirable, leading to more structures being built in hazard zones.

5

Consequences of hazards can be minimized.

The 1995 and 2005 landslides in La Conchita exemplify the challenges facing scientists, government agencies, and individuals seeking to minimize the effects of mass wasting.



(a) (b)

▲ FIGURE 7.1 La Conchita 1995 and 2005
(a) Aerial view of the 1995 La Conchita landslide with part of the community of La Conchita in the foreground. The cliff face contains mostly older slide deposits and sediments near the top of the slope, a large slump block partially covered with vegetation on the side of the slope, and earthflow deposits at the base of the slope. This slide buried, collapsed, or damaged houses at the base of the slope. *(USGS)* (b) Aerial view of the 2005 reactivation of the same landslide. For reference, the white arrow on the left side of each photograph points to the same building. To the right of this building the partially buried and destroyed retaining wall built following the 1995 slide can be seen. At the base of the slope, the landslide has formed two lobe-shaped earthflows, a large one on the right and a much smaller one in the center of the photograph. Mud and debris have covered parts of four streets and damaged or buried about 30 houses. *(AP Photo/Kevork Djansezian)*

about $1 million for every home in the community. Due to the prohibitive cost of complete slope stabilization, several less costly strategies, such as building a retaining wall and installing a limited drainage system, were employed to minimize the potential hazard and to mitigate the effects of a future slide. However, the 2005 event clearly showed that this approach was ineffectual.

Although property values in La Conchita plummeted following each slide, within just a few years some housing prices rebounded and the community remains a highly desirable place to live along the rapidly urbanizing coast of California.

7.1 An Introduction to Landslides

Mass wasting is a comprehensive term for any type of downslope movement of earth materials. In its more restricted sense, mass wasting refers to a rapid downslope movement of rock or soil as a more or less coherent mass. In this chapter, we consider landslides in this restricted sense. We will also discuss the related phenomena of earthflows and debris flows, rockfalls, and avalanches. For the sake of convenience, we sometimes refer to all of these as **landslides**.

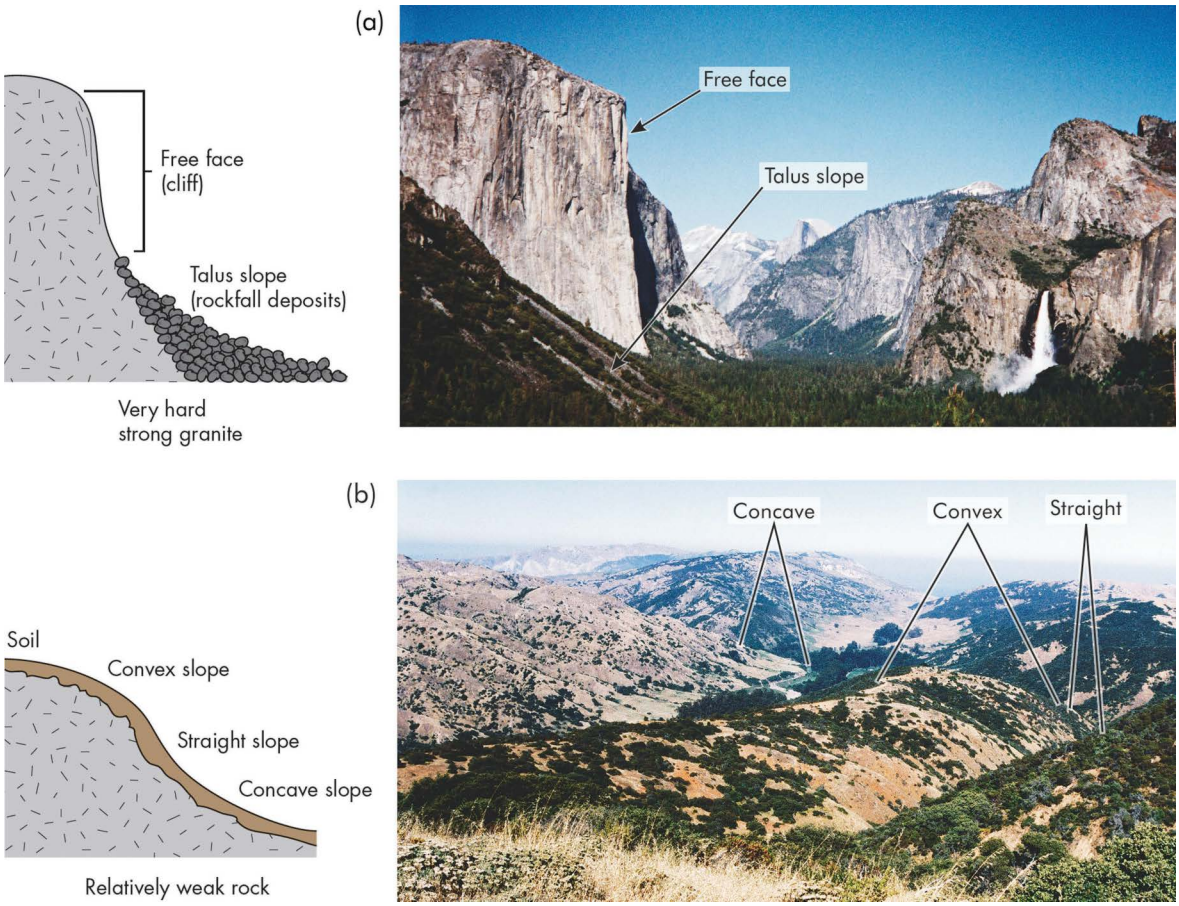
SLOPE PROCESSES

Slopes are the most common landforms on Earth. Although most slopes appear stable and static, they are actually dynamic, evolving systems. The processes that are active in these systems generally do not produce uniform slopes. Rather, most slopes are composed of several segments that are either straight or curved (Figure 7.2).

A spectacular example of these segments can be seen on the north side of Yosemite Valley in Yosemite National Park, California (Figure 7.2a). The prominent landform there, El Capitan, has a high cliff face or *free face* of hard granite that forms a straight, nearly vertical slope segment. The free face and adjacent valley wall regularly shed pieces of rock that accumulate at the base of the cliff to form a **talus** slope (Figure 7.2a and Figure 7.3). Both the free face and the talus slope are segments of the overall slope. Frequent rockfalls keep soil from developing on the free face and much of the talus slope.

In contrast to the strong granite of Yosemite Valley, gentler hillslopes develop on other types of rocks. For example, on Santa Cruz Island, California, slopes are developed on weaker metamorphic rocks and lack a free face. Instead, the slopes have three segments: an upper convex slope, a straight slope on the hillside, and a lower concave slope (Figure 7.2b).

As illustrated in Yosemite Valley and Santa Cruz Island, slopes are usually composed of different slope segments. The five segment types in the foregoing examples—free face, talus, upper convex, straight, and lower concave slopes—are sufficient to describe most slopes encountered in nature. Which slope segments are present on a particular slope depends on the rock type and the climate of the area. Free face development is more common on strong, hard rocks or in arid environments where there is little vegetation. Convex and concave slopes are more common on softer rocks or in



▲ FIGURE 7.2 Slope Segments
(a) Slope on hard granite in Yosemite National Park, California. The cliff on the left side of the image is the several-thousand-foot-high free face of El Capitan. Below the cliff is a talus slope. *(Edward A. Keller)* (b) These slopes on Santa Cruz Island, California, formed on relatively weak metamorphic rock with convex, straight, and concave slope segments. (*Edward A. Keller)*



FIGURE 7.3 Rockfall and Talus Pile
View of a huge rockfall in 2009 near Half Dome in Yosemite National Park, California. The rockfall originated from 540 m (~1800 ft.) above the valley floor (out of this photo), knocking down hundreds of trees and burying a part of the popular Mirror Lake trail. The impact of the rock on the valley floor registered on seismographs around California as a magnitude 2.5 earthquake. Broken rock from the large rockfall forms the light-colored talus pile covering the ground where the trees have been bowled over. *(Duane E. DeVecchio)*

humid environments where thick soil and vegetation are present. However, there are many exceptions to these general rules, depending on local conditions. For example, the gentle, convex, red-colored slopes in the foreground of Figure 7.2b have formed on weak, easily eroded metamorphic rock (schist) in a semiarid climate on Santa Cruz Island, California.

Material on most slopes is constantly moving down the slope at rates that vary from an imperceptible creep of soil and rock to thundering avalanches and rockfalls that move at velocities of 160 km/hr (~100 mph) or more. Through time, this downslope movement is important in eroding valley walls. Slope processes are one reason that valleys are usually much wider than the streams they contain.

TYPES OF LANDSLIDES

Earth materials on slopes may fail and move or deform in several ways (Table 7.1). **Falling** refers to the free fall of earth material, as from the free face of a cliff (Figure 7.4a). **Sliding** is the downslope movement of a

TABLE 7.1 Common Types of Landslides and Other Downslope Movements

Mechanism	Type of Mass Movement	Characteristics
Falling	Rockfall	Individual rocks fall through the air and may accumulate as talus.
Sliding	Slump	Cohesive blocks of soft earth material slide on a curved surface; also called a rotational landslide.
	Soil slip	Soil and other weathered earth material slide on a tilted surface of bedrock or cohesive sediment; also called a debris slide or earth slide.
	Rock slide	Large blocks of bedrock slide on a planar surface, such as layering in sedimentary or metamorphic rocks.
Flowing	Avalanche	Granular flow of various combinations of snow, ice, organic debris, loose rocks, or soil that moves rapidly downslope.
	Creep	Very slow, downslope movement of rocks and soil.
	Earthflow	Wet, partially cohesive, and internally deformed mass of soil and weathered rock.
	Debris flow	Fluid mixture of rocks, sand, mud, and water that is intermediate between a landslide and a water flood; includes mudflows and lahars.
More than one	Complex	A combination of two or more types of sliding, flowage, and occasionally falls; forms where one type of landslide changes into another as it moves downslope.

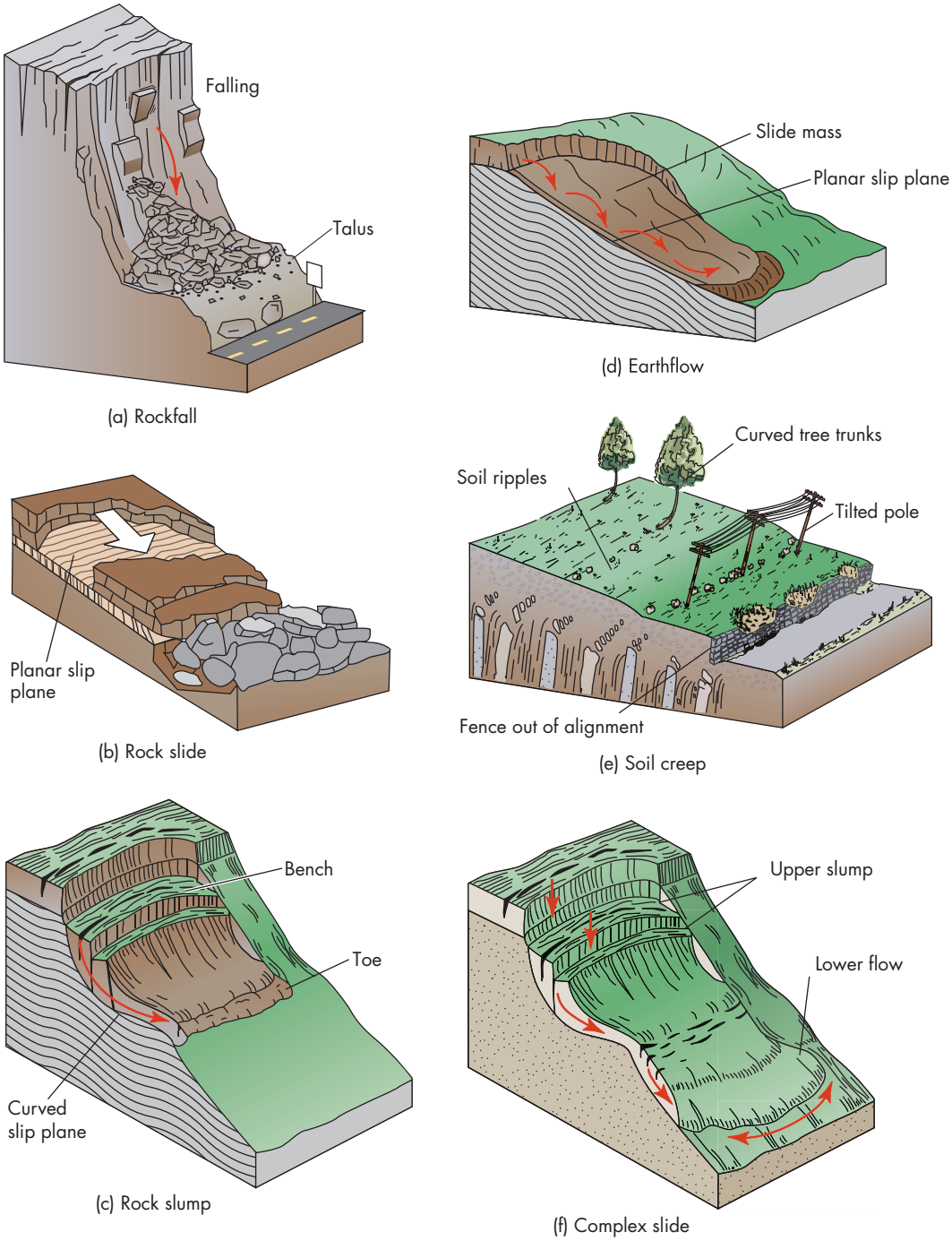


FIGURE 7.4 Types of Landslides

(a) Rockfall, in which blocks of bedrock fall through air and accumulate at the base of the cliff as a talus slope. (b) Rock slide, in which blocks of bedrock slide down a bedding plane in sedimentary rock. Soil slips are similar movements except soil, rather than rock, slides down a bedrock surface. (c) Slump, in which cohesive blocks of soft earth material slide down a curved slip surface. (d) Earthflow, in which mud, sand, rock, and other material are mixed with water and become partially liquified. (e) Soil creep, causing telephone poles to tilt and trees trunks to become curved. (f) Complex landslide, consisting of upper slump and lower flow.

coherent block of earth material along a planar *slip plane* (Figure 7.4b). **Slumping** of rock or soil is sliding along a curved slip plane producing *slump blocks* (Figure 7.4c). *Flowage*, or **flow**, is the downslope movement of unconsolidated material in which particles move about and mix within the mass, such as earthflows, debris flows, or avalanches (Figure 7.4d). Very slow flowage, called **creep**, progressively tilts telephone poles, fences, and tree trunks (Figure 7.4e). Creep occurs at such a low rate that the progressive upward growth of trees outpaces the tilting, resulting in trees trunks that are curved skyward (Figure 7.5).

Many landslides are complex combinations of sliding and flowage (Figure 7.4f). For example, a landslide may start out as a *slump*, then pick up water as it moves downslope, and transform into an earthflow in the lower part of the slide. Some complex landslides may form when water-saturated earth materials flow from the lower part of a slope, undermining the upper part and causing slump blocks to form (Figure 7.4f and Figure 7.6).

Downslope movements are classified according to four important variables: (1) the mechanism of movement (slide, fall, flow, or complex movement), (2) type of earth material (e.g., solid rock, soft consolidated sediment, or loose unconsolidated material), (3) amount of water present, and (4) rate of movement. In general, 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 a rapid 1.5 m (~5 ft.) per day, to an extremely rapid 30 m (~100 ft.) or more per second.[3]



FIGURE 7.5 Trees Affected by Soil Creep
Curved tree trunks in Lassen Volcanic National Park are due to soil creep. Soil creep is likely the result of construction of the road (lower left corner of the photo), which steepened the hillside after the older trees were firmly anchored into the bedrock, which is why only the younger trees exhibit highly curved trunks. *(Duane E. DeVecchio)*



FIGURE 7.6 Houses Buried by Complex Landslide
In the distance is the amphitheater-like scar in the hillslope that was the source of the 1995 La Conchita landslide. The slide started out as a slump and then liquefied into an earthflow as it moved downhill. Several homes, including the three-storied home behind the orange plastic fence, were destroyed. *(Edward A. Keller)*

FORCES ON SLOPES

To determine the causes of landslides, we must examine the forces that influence slope stability. The stability of a slope can be assessed by determining the relationship between **driving forces** that move earth materials down a slope and **resisting forces** that oppose such movement. The most common driving force is the downslope component of the weight of the slope material. That weight can be from anything superimposed or otherwise placed on the slope, such as vegetation, fill material, or buildings. The most common resisting force is the **shear strength** of the slope material, that is, its resistance to failure by sliding or flowing along potential slip planes (see Case Study 7.1: A Closer Look). Potential *slip planes* are geologic surfaces of weakness in the slope material, such as bedding planes in sedimentary rocks and fractures in all types of rock.

Slope stability is evaluated by computing a **safety factor** (SF), defined as the ratio of the resisting forces to the driving forces. If the safety factor is greater than 1, the resisting forces exceed the driving forces and the slope is considered stable. If the safety factor 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 safety factor.

Driving and resisting forces on slopes are determined by the interrelationships of the following variables:

- type of earth materials
- slope angle and topography
- climate
- vegetation
- water
- time.

The Role of Earth Material Type The material composing a slope can affect both the type and the frequency of downslope movement. Important material characteristics include mineral composition, degree of cementation or consolidation, the presence of zones of weakness, and the ability of the earth material to transmit water. These weaknesses may be natural breaks in consistency of the earth materials, such as sedimentary and metamorphic layering, or they may be zones along which the earth has moved before, such as an old landslide slip surface or geologic fault. Weak zones can be especially hazardous if the zone or plane of weakness intersects or parallels the slope of a hill or mountain. Where the planes of weakness are rock bedding planes, they are referred to as *daylighting beds* (Figure 7.7).

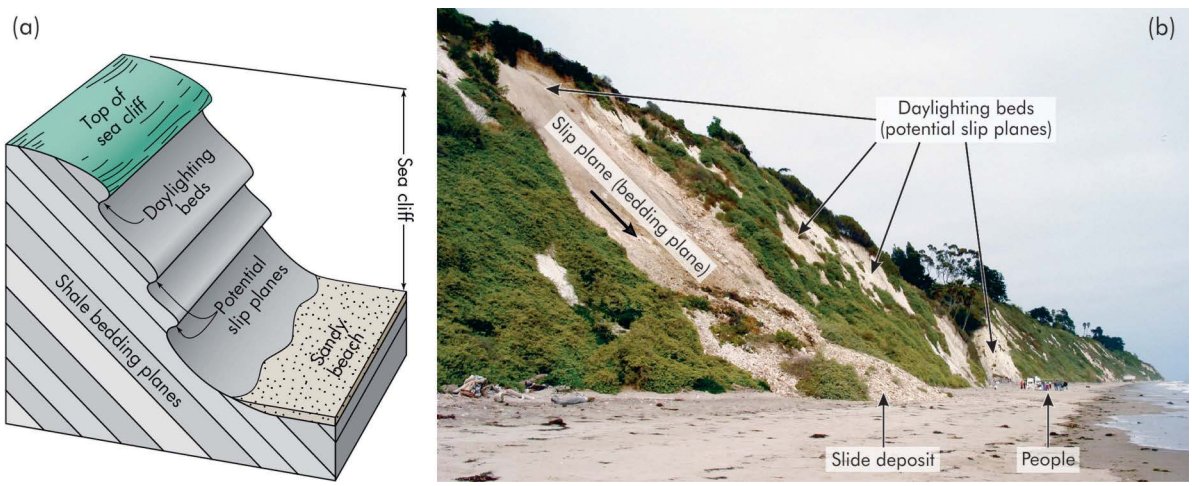


FIGURE 7.7 Daylighting Beds
(a) Bedding planes that intersect the surface of the land on a slope are said to "daylight." Such beds are potential slip planes. (b) This slide occurred in late 2003. Failure was along a daylighting bedding plane. Slide deposits cover part of the beach. *(Edward A. Keller)*

CASE study

7.1 A Closer Look

Forces on Slopes

The fundamental driving force of mass wasting processes is gravity. Over time, the ever-constant downward pull of gravity exceeds resisting forces and causes slopes to fail, rocks to fall, soils to creep, and water-saturated earth materials to flow. Over geologic time scales, gravity-driven erosional processes have sculpted Earth's surface and worn away countless ancient mountain ranges and washed them out to the sea.

The downward pull of gravity exerts a quantifiable force toward the center of Earth, giving weight to potential slide masses (Figure 7.1.A). Yet, because earth materials cannot be pulled straight down through the underlying rocks, the gravitational pull is divided between a downslope force and the normal force, which are at right angles to each other. The downslope force or driving force (D) is parallel to the slope of the potential slip plane, whereas the normal force (N) is perpendicular (Figure 7.1.A). The shear strength of the potential slip plane (resisting force) is proportional to the magnitude of the normal force, which adds frictional resistance onto the surface of the plane. The relative magnitudes of the normal and driving forces are directly related to the angle of the slope. Specifically, as the slope angle (θ) increases, the normal force decreases and the driving force increases proportionally; the opposite is true as θ decreases. It follows then that the safety factor decreases with increasing slope angle, because the safety factor is the magnitudinal ratio of resisting forces over the driving forces.

As local conditions change naturally or as a result of human interaction with the landscape, driving and resisting forces will

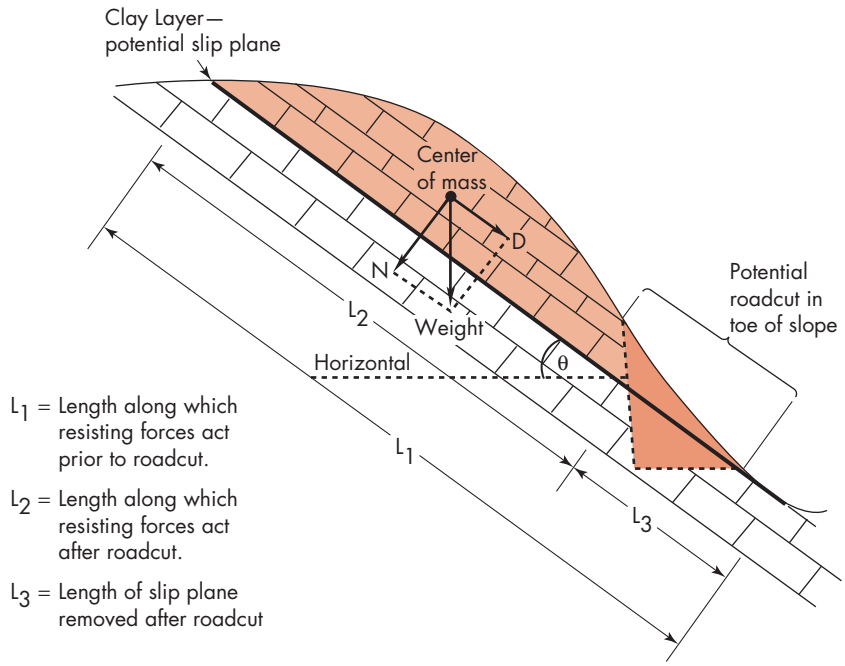


FIGURE 7.1.A Effects on Slope Stability
Cross-section of a slope showing the principal forces acting on a potential slide mass and the effects of undermining a slope due to road construction.

change. These changes may lead to an increase or decrease in the safety factor. For example, consider the construction of a road in which part of a hillside must be excavated to provide a suitable surface for automobile traffic. Removal of the material at the toe (base) of the slope exposes a potential slip plane, a daylighting bed in this case (see Figure 7.1.A and Figure 7.8). Although the roadcut reduces the driving forces on the slope by removing some of the weight of the potential slide mass, the cut also decreases the length of the slip plane, thereby reducing the resisting force (shear strength). If you examine Figure 7.1.A, you can see that only a small portion of the potential slide mass has been removed, whereas a relatively large portion of the length of the slip plane has been removed (L1 versus L2). Therefore, the overall effect of the roadcut is to *lower the safety factor* because the reduction of the driving force is small compared to the reduction of the resisting force.

For slides, the shape of the slip surface is strongly controlled by the type of earth material. Slides have two basic patterns of movement, *rotational* and *translational.* Rotational slides, or slumps, have curved slip surfaces (Figure 7.4c), whereas translational slides generally have planar slip surfaces (Figure 7.4b).

In slumps, the rotational sliding of slump blocks tends to produce small topographic benches, which may rotate and tilt in an upslope direction (Figure 7.4c). Slumps are most common in unconsolidated earth material and in mudstone, shale, and other weak rock types. In translational slides, material moves along inclined slip planes within and parallel to a slope (Figure 7.7). The zones of weakness for these slip planes include fractures in all rock types, surfaces between layers in sedimentary rocks referred to as *bedding planes*, weak clay layers, and surfaces between layers in metamorphic rocks referred to as *foliation planes.* Generally, once a slip surface is established for a landslide, that plane of weakness will continue to exist within the earth material. The material that moves along these planes can be large blocks of bedrock or unconsolidated and weathered earth material.

A common type of translational side is a *soil slip*, a shallow slide of unconsolidated material over bedrock (Figure 7.8). The plane of weakness for soil slips is usually in **colluvium**, a mixture of weathered rock and other debris that is above the bedrock and below the soil.

Material type is also a factor in rockfalls. Where resistant rock overlies weaker rock, rapid erosion of the underlying weaker rock may cause a slab failure and a subsequent rockfall (Figure 7.9).

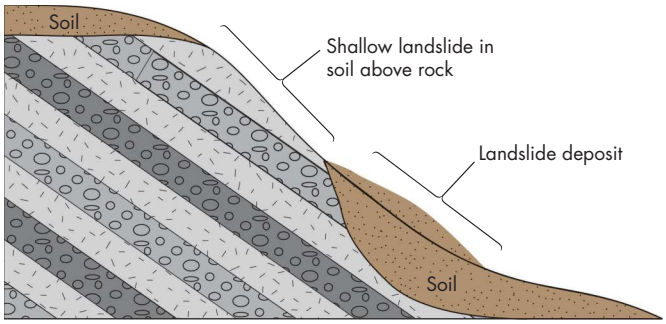
The nature of the earth material composing a slope can greatly influence the type of slope failure. For example, on slopes of shale or weak volcanic pyroclastic material, failure commonly occurs as creep, earthflows, debris flows, or slumps. Slopes formed in resistant rock such as well-cemented sandstone, limestone, or granite are much less likely to experience the same problems. Thus, builders should assess the landslide hazard before starting construction on shale or other types of weak rock.

The ability of the earth material to transmit water, referred to as *permeability*, determines how easily soil, sediment, or rock absorbs water (see Appendix 2). As discussed later, water is involved in nearly all landslides, and permeability barriers can allow the buildup of water. For example, soil slips commonly develop because of contrasts between more permeable soil and less permeable, unweathered bedrock below the soil. Downward percolating rainwater builds up in the soil because it cannot easily infiltrate the underlying bedrock. The accumulation of water can break down cohesion between soil particles and facilitate slippage of the soil, especially on steep hillsides.

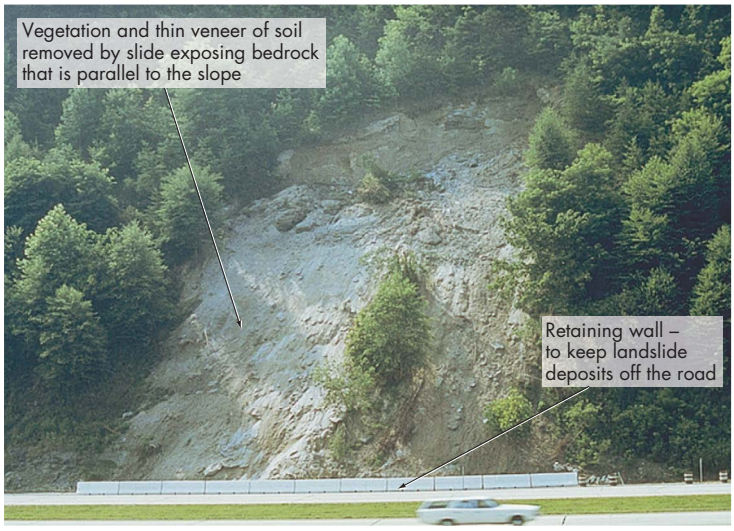
The Role of Slope and Topography Two factors are important with slope and topography: steepness of the slope and amount of topographic relief. By *slope*, we mean the slant or incline of the land surface. In general, the steeper the slope, the greater the driving force. For example, a study of landslides that occurred during two rainy seasons in California's San Francisco Bay area established that 75 percent to 85 percent of landslide activity is closely associated with urban areas on steep slopes.[4]

Topographic *relief* refers to the height of the hill or mountain above the land below. Areas of high relief are hilly or mountainous, have tens or hundreds of meters of relief, and are generally more prone to mass wasting. Within the contiguous United States and Canada, the coastal mountains of California, Oregon, Washington, and British Columbia; the Rocky Mountains; the Appalachian Mountains; and coastal cliffs and bluffs have the greatest frequency of landslides. All types of downslope movement occur on steep slopes within these areas.

Steep slopes are also associated with rockfalls, avalanches, and soil slips. In Southern California, shallow soil slips are common on steep slopes when a hillside



(a)



(b)

< FIGURE 7.8 Soil Slips
(a) Cross-sectional diagram of a shallow soil slip in which the gray bands are sedimentary layers parallel to the slope. Soil slides off the slope and piles up at its base. (b) This shallow soil slip in North Carolina has removed slope vegetation. Highway engineers installed the white barrier at the base of the slide to keep debris off of the road. *(Edward A. Keller)*



< FIGURE 7.9 Rockfall Damages House
The large boulder embedded in the right end of this house fell 120 m (400 ft.) from a ledge of resistant sandstone in the early morning of October 18, 2001, in Rockville, Utah. Weighing an estimated 200 to 300 tons and measuring approximately 5 m (~16 ft.) by 5 m (~16 ft.) by 3.6 m (~12 ft.), the boulder destroyed the living room, bathroom, and service area. It then entered a bedroom, narrowly missing the sleeping homeowner. The specific cause of the rockfall is unknown, but there are numerous large boulders in the area from earlier rockfalls. *(Utah Geological Survey)*

becomes saturated with water. Once soil slips move downslope, they often become earthflows or debris flows, which can be extremely hazardous (Figure 7.10). In Southern California, earthflows are common on moderate slopes, and creep can be observed on gentle slopes.

Debris flows are thick mixtures of mud, debris, and water. They range in consistency from thick mud

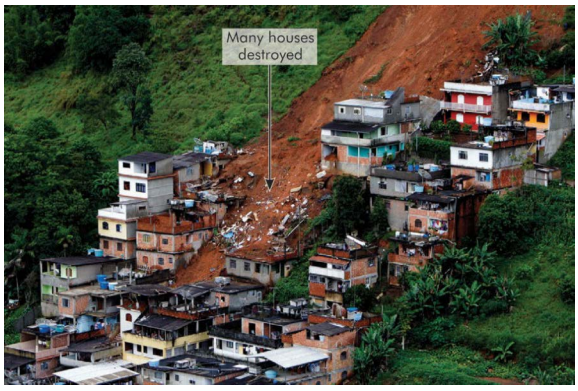


FIGURE 7.10 Shallow Soil Slips Can Kill
Following several days of rain in 2011, mass wasting events, like this soil slip, killed at least 600 people in the Rio De Janeiro area. *(AP Photo/Felipe Dana)*

soups to wet concrete and are capable of carrying house-size boulders. Debris flows can move either slowly or rapidly depending on conditions. They can move down established stream valleys, flow from channels filled with colluvium, or take long narrow tracks or chutes on steep hillsides. These flows can be relatively small to moderate events, transporting a few hundred to hundreds of thousands of cubic meters of debris down a single valley, or they can be huge events transporting cubic kilometers of material from the failure of an entire flank of a mountain (see volcanic mudflows and debris flows discussed in Chapter 5).

The Role of Climate *Climate* can be defined as the weather that is typical in a place or region over a period of years or decades. A description of climate is more than just the average air temperature and amount of precipitation. It also includes the type of precipitation and its seasonal patterns. In North America, examples of type and pattern are winter rains along the West Coast of the United States, summer thunderstorms in the southwestern United States, winter blizzards in the Arctic and Great Plains, heavy snows on the eastern shores of the Great Lakes, and late summer and fall hurricane activity on the Mexican and southeastern U.S. coasts. For landslides, the type of climate influences the amount and timing of water that infiltrates or erodes a hillslope and the type and abundance of hillslope vegetation.

In arid and semiarid climates, vegetation tends to be sparse, soils are thin, and bare rock is exposed. Free faces and talus slopes are common where erosion-resistant bedrock is present (Figure 7.11a). Resistant rock forms steep slopes (cliffs), and less resistant rock forms more gentle slopes. Rockfalls, debris flows, and shallow soil slips are common types of landslides in these climatic regions.

In subhumid to humid regions of the world, abundant vegetation and thick soils cover most slopes (Figure 7.11b). These two characteristics cause the widespread development of convex and concave slope segments (see Figure 7.2b). Landslide activity in these areas includes deep complex landslides, earthflows, and soil creep.

The Role of Vegetation Vegetation has a complex role in the development of landslides and related phenomena. The nature of the vegetation in an area is a function of the climate, soil type, topography, and fire history, each of which also independently influences



(a) (b)

FIGURE 7.11 Climate and Mass Wasting
Different climate zones around the world play an important role in not only the appearance of the landscape but also in the processes that sculpt it. (a) Semiarid landscape in Boysen State Park, Wyoming. *(Jack Jeffers/SuperStock)* (b) Humid landscape in Taiwan in Southeast Asia. *(Sean Sprague/The Image Works)*

what happens on slopes. Vegetation is a significant factor in slope stability for three reasons:

1. Vegetation provides a protective cover that cushions the impact of falling rain. This cushion allows the water more time to infiltrate the slope rather than running downhill, retarding surface erosion.
2. Plant roots add strength and cohesion to slope materials. They act like steel rebar reinforcements in concrete, anchoring soil and unconsolidated material, and increasing the resistance of a slope to landsliding.[5]
3. Vegetation also adds weight to a slope.

In some cases, this additional weight increases the probability of a landslide, especially with shallow soils on steep slopes. Such soil slips are common along the California coast where ice plant, an invasive plant imported from South Africa in the early 1900s, covers steep-cut slopes (Figure 7.12). During especially wet winter months, these shallow-rooted plants take up water and store it in their leaves. This stored water adds considerable weight to steep slopes, thereby increasing the driving forces. These plants also cause increased water infiltration 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.

In Southern California, soil slips are also a serious problem on steep slopes covered with chaparral, a dense growth of native shrubs and small trees (Figure 7.13). Chaparral facilitates water infiltration into a slope and lowers its safety factor.[6]



FIGURE 7.13 Multiple Shallow Slides
Shallow soil slips on steep slopes in Southern California are common due to low, brushy vegetation that does not root deeply, known as chaparral. *(Edward A. Keller)*

The Role of Water Water is almost always directly or indirectly involved with landslides, so its role is particularly important.[7] When studying a landslide, scientists first examine what water is doing both on and within the slope. Water affects slope stability in three basic ways:

1. Many landslides, such as shallow soil slips and debris flows, develop during rainstorms when slopes become saturated.
2. Other landslides, such as slumps, develop months or even years following the deep infiltration of water into a slope.



(a)



(b)

FIGURE 7.12 Ice Plants on Slopes Are Often Unstable
Ice plant was first introduced in California to protect slopes along railroads and was later widely used along highways. Instead of stabilizing slopes, ice plant often contributes to landslides because of its shallow roots and the added weight of water stored in its leaves. The plant caused these soil slips near Santa Barbara, California, (a) on a steep roadside embankment *(Edward A. Keller)* and (b) at a home site. A black plastic sheet was placed over the upper part of the slide to reduce the infiltration of rain water. *(Edward A. Keller)*

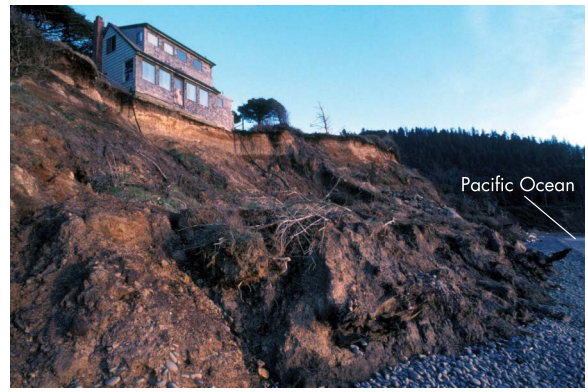
3. Water erosion of the base or toe of a slope decreases its stability.

Erosion by flowing water along a stream bank or by wave action on the coast can remove earth material from the base of a hill or cliff. This loss of material steepens the slope, reduces the safety factor, and increases the likelihood of a landslide (Figure 7.14). Erosion is especially problematic if it removes the toe of an old landslide, thereby increasing the potential for the landslide to move again (Figure 7.15). Therefore, it is important for planners and engineers to identify old landslides before cutting into hillslopes for the construction of roads and buildings. Excavations of hillslopes must be carefully planned so that potential problems can be isolated and corrected prior to construction.

Another way that water can cause landslides is by contributing to the spontaneous liquefaction of quick or expansive clay. These clays are fine-grained earth



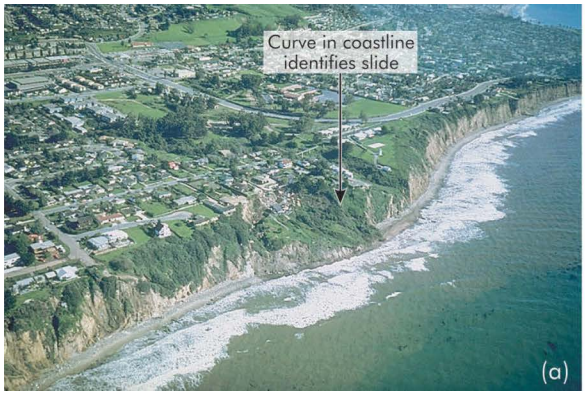
(a)



(b)

< FIGURE 7.14 Water Eroding the Toe of a Slope Causes Instability

(a) Stream-bank erosion seen in the lower left corner of this image has caused slope failure and damage to a road in the San Gabriel Mountains, California. *(Edward A. Keller)* (b) Wave erosion was a major cause of this landslide in Cove Beach, Oregon. Further movement of the slide threatens the homes above. *(Gary Braasch/ZUMAPRESS/Newscom)*





^ FIGURE 7.15 Reactivation of a Slide

(a) Part of the beach (end of thin arrow) in Santa Barbara, California, has been buried by reactivation of an older landslide. Reactivation of the slide may have resulted due to erosion of the old slide toe by ocean waves. *(Donald W. Weaver)* (b) Close-up of the head of this slide where it destroyed two homes. The thick, black arrow in (a) points to the location of this picture. *(Donald W. Weaver)*

material that lose their shear strength and flow as a liquid when disturbed (see Case Study 7.2: Portuguese Bend, California). The shaking of quick clay beneath Anchorage, Alaska, during the 1964 earthquake produced this effect and caused three extremely destructive landslides. In Quebec, Canada, several large slides associated with quick clays destroyed numerous homes and killed more than 70 people. These slides occurred on river valley slopes when initially solid material was converted into a liquid mud as the sliding movement began.[8] The slides in Quebec are especially interesting because the liquefaction of clays occurred without earthquake shaking. In many cases, the slides were triggered by river erosion at the toe of a slope. Liquefaction first started in a small area and spread to a much larger area. Since these movements have often involved the reactivation of older slides, future problems may be avoided by mapping existing slides and restricting development on them.

The Role of Time The forces acting on slopes often change with time. For example, both driving and resisting forces may change seasonally with fluctuations in the moisture content of the slope or with changes in the position of the water table. Much of the chemical weathering of rocks, which slowly reduces their strength, is caused by the chemical action of water in contact with soil and rock near Earth's surface. Soil water is often acidic because it reacts with carbon dioxide in the atmosphere and soil to produce weak carbonic acid that can dissolve rock. This type of chemical weathering is significant in areas underlain by limestone, a rock type that is easily dissolved by carbonic acid. Changes are greater in especially wet years, as reflected by the increased frequency of landslides during or following these years. In other slopes, resisting forces may continuously diminish through time from weathering, which reduces the cohesion in slope materials, or from an increase in underground water pressure within the slope. A slope that is becoming less stable with time may have an increasing rate of creep until failure occurs.

7.2 CASE study — Portuguese Bend, California

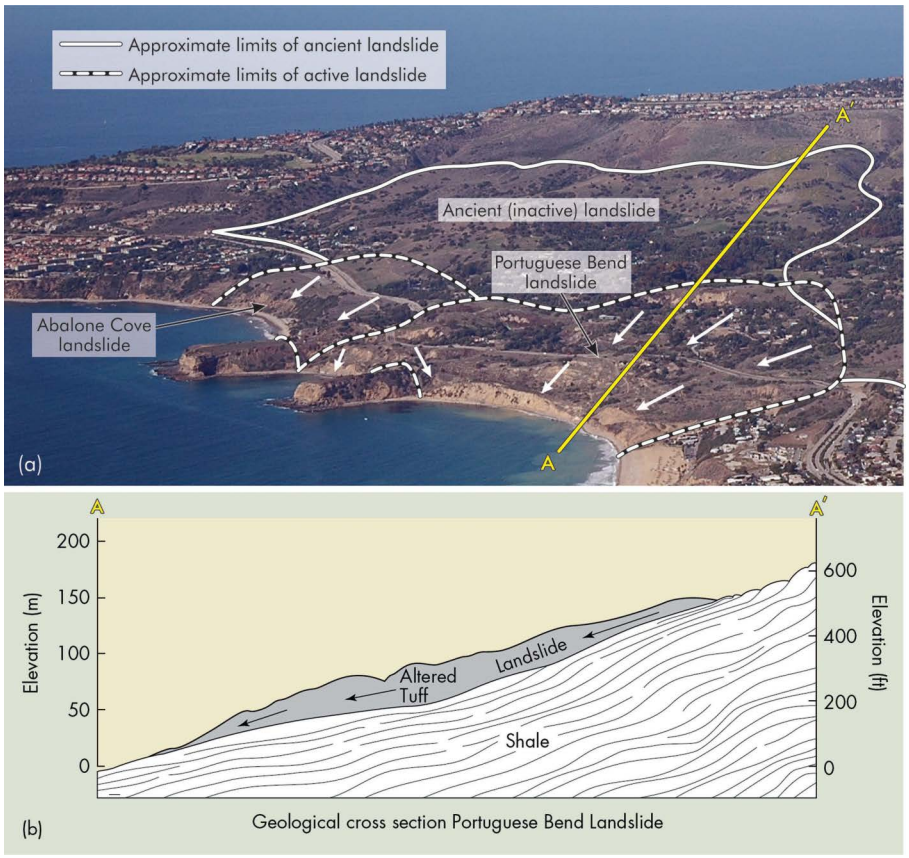
The Portuguese Bend landslide along the Southern California coast near Los Angeles is a famous example of how people can increase the landslide hazard. This landslide, which destroyed more than 150 homes, is part of a larger ancient slide (Figure 7.16). Road building and changes in subsurface drainage associated with urban development reactivated the ancient slide.

Aerial photography of the lower part of the reactivated landslide shows evidence of its movement (Figure 7.17). This evidence includes bare ground west of the highway, where recent movement destroyed homes and roads, and a kink in the pier caused by landsliding into the ocean. Eventually the slow-moving landslide destroyed the pier and the adjacent swim club. Recent movement of the slide started in 1956 during construction of a county road. Fill dirt placed over the upper part of the ancient slide increased its instability. During subsequent litigation, Los Angeles County was found responsible for the landslide.

From 1956 to 1978, the slide moved continually at an average rate of 0.3 to 1.3 cm (~0.1 to 0.5 in.) per day. Several years of above-normal precipitation accelerated the movement to more than 2.5 cm (~1 in.) per day in the late 1970s and early 1980s. Since 1956, the total displacement of the slide near the coast has been more than 200 m (~660 ft.). The above-normal rainfall reactivated a second part of the ancient slide to form the Abalone Cove landslide to the north (Figure 7.16). The second slide prompted additional geologic investigation, and a successful landslide-control program was initiated. Wells were drilled into the wet rocks of the Portuguese Bend landslide in 1980 to remove groundwater from the slide mass. The pumping was an attempt to dry out and stabilize the rocks in the slide. By 1985, the slide had apparently been stabilized. However, precipitation and groundwater conditions in the future will determine the fate of the "stabilized" slides.[9]

During the two-decade period of activity, homes on the Portuguese Bend landslide continued to move. One home constantly shifted position as it moved more than 25 m (~80 ft.). Other homes were not in constant motion but still moved up to 50 m (~160 ft.) in the same time period. Homes remaining on Portuguese Bend during the slide's active period were adjusted every year or so with hydraulic jacks. Utility lines were placed on the surface to avoid breakage as the ground shifted. 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 the total loss of their property (Figure 7.18). Nevertheless, few geologists would choose to live there now.

The story of the Portuguese Bend landslides emphasizes that science can be used to understand landslides, sometimes allowing us to at least temporarily stop their movement. However, recognizing landslides and using land-use planning to avoid building on active



< FIGURE 7.16 Ancient Landslides Can Be Reactivated

(a) Extent of ancient inactive landslide, part of which was reactivated to form the Portuguese Bend slide in the 1950s and Abalone Cove slide in the 1970s. Arrows show the direction of landslide movement toward the Pacific Ocean in the foreground. *(California State University)* (b) Cross-section through the right side of the Portuguese Bend slide. The landslide is underlain by a consolidated pyroclasitc volcanic tuff that has been altered to bentonite, a type of expansive clay that deforms readily when a force is applied to it. *(Photograph and cross-section courtesy of Los Angeles County, Department of County Engineer)*



< FIGURE 7.17 Homes Destroyed

The kink in the pier in the upper-left portion of this image shows initial damage from the Portuguese Bend landslide. Eventually most of the homes seen here, as well as the swim club and pier, were destroyed by the slow-moving landslide. *(University of Washington Library Special Collections KC5892)*

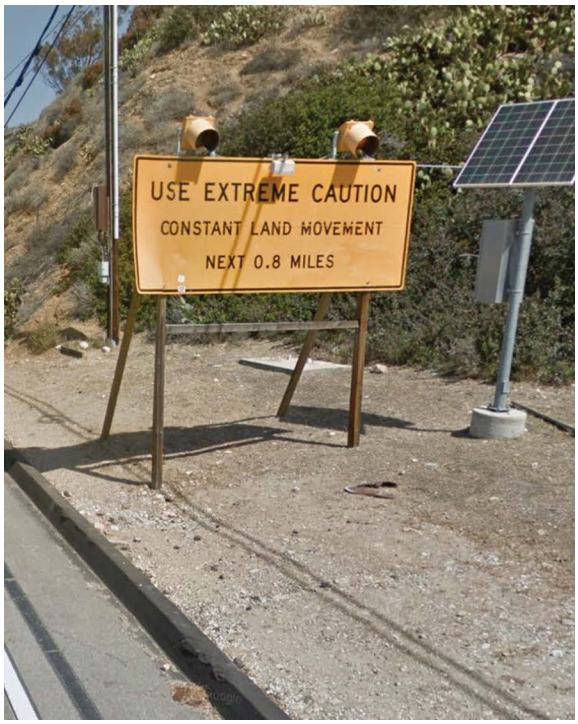


FIGURE 7.18 Living with Landslides
Homes, roads, and streets were built on Portuguese Bend southwest of Los Angeles in spite of geologic maps published in the 1940s that revealed most of the area as a landslide. Palos Verdes Drive South, shown here, crosses the landslide and requires constant roadwork as it moves several feet each year toward the ocean. *(Chris Cantelmo)*

slides is preferable to reacting to landslide movement after homes have been constructed.

SNOW AVALANCHES

A **snow avalanche** is the rapid downslope movement of snow and ice, sometimes with the addition of rock, soil, and vegetation. Thousands of avalanches occur every year in the western United States and Canada. As more people venture into avalanche-prone areas and more development takes place, the loss of life and property from avalanches increases. Avalanche accidents in the winter of 2005–06 killed 32 people in North America.[10] Most avalanches that kill people are triggered by the victims themselves or by members of their party.[11]

Three variables interact to create unstable conditions for snow avalanches: steepness of the slope, stability of the snowpack, and the weather. Snow avalanches generally occur on slopes steeper than about 25°.[11] The steepest angle at which snow, or any loose material, is stable is its *angle of repose*. For snow, this angle is affected by temperature, wetness, and shape of the snow grains.[12] Most snow avalanches occur on slopes between 35° and 40°.[12] On slopes steeper than 50° to 60°, the snow tends to continually fall off the slope. Snow-covered slopes may become unstable when the wind piles up snow on the leeward or downwind side of a ridge or hillcrest, when rapid precipitation adds weight to the slope, or when temperatures rapidly warm to make the snow very wet.

There are two common types of snow avalanches: loose-snow and slab. *Loose-snow avalanches* typically start at a point and widen as they move downslope. *Slab avalanches* start as cohesive blocks of snow and ice that move downslope. The latter type of avalanche is far more dangerous and damaging. Slab avalanches typically are triggered by the overloading of a slope or the development of zones of weakness in the snowpack. Millions of tons of snow and ice then move rapidly downslope at velocities of up to 100 km (~60 mi.) per hour.

Avalanches tend to move down tracks, called *chutes*, which have previously produced avalanches (Figure 7.19). As a result, it is easier to prepare maps showing potentially hazardous areas. Avoiding these areas is obviously the preferable and least expensive adjustment to avalanches. Other adjustments include clearing excess snow with carefully placed explosives, constructing buildings and structures to divert or retard avalanches, or planting trees on slopes in avalanche-prone areas to better anchor the snow.

7.1 CHECK your understanding

1. What are slope segments, and how do the common types of slope segments differ?
2. What are the three main ways that materials on a slope may fail?
3. What is the safety factor, and how is it defined?
4. How do slumps (rotational slides) differ from soil slips and rock slides (translational slides)?
5. How and where do debris flows occur?
6. Name the five factors that affect driving and resisting forces on slopes, and explain how these are interrelated.
7. What are the three ways that vegetation affects slope stability?
8. What is the relationship between the downslope force and normal force?
9. What are the two types of snow avalanches, and how do they differ?

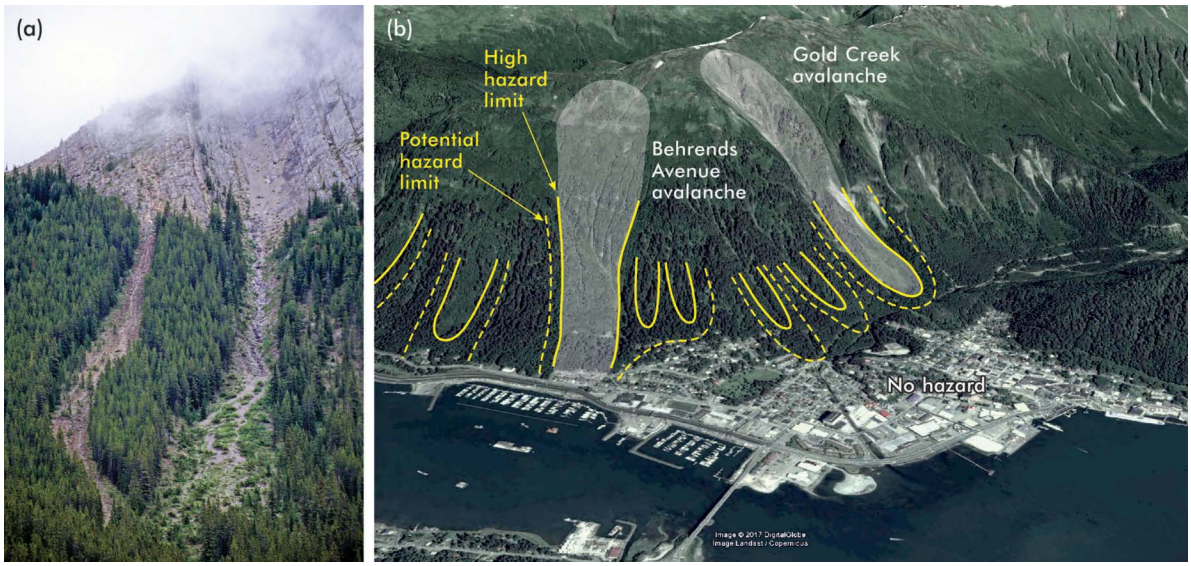


FIGURE 7.19 Snow Avalanche Hazard
(a) Avalanche chutes can be clearly identified in forested areas by an absence of large trees. Only young saplings with flexible trunks survive in areas that experience regular avalanches. *(Robert McGouey/Alamy)* (b) Map of part of Juneau, Alaska, showing areas at highest risk for snow avalanches. Most of the downtown business district is in the "no hazard" area in the lower right. *(Robert McGouey/Alamy)*

7.2 Geographic Regions at Risk from Landslides

As you may imagine, landslides occur everywhere that significant slopes exist, and mountainous areas have a higher risk for landslides than most areas of low relief. The latter generalization is supported by a map of major landslide areas in the contiguous United States (Figure 7.20). On this map, the areas shown in red, which experience frequent landslide activity, are concentrated in the mountainous areas of the West Coast, the Rocky Mountains, and the Appalachian Mountains. The Plains states are flatter and, therefore, relatively safe from landslides. The Rocky Mountains and coastal mountains of the East Coast and West Coast are at particularly high risk. Parts of central Canada, such as Saskatchewan, Manitoba, and eastern Ontario, have a relatively lower risk.

Three factors are expected to increase worldwide landslide activity in the decades to come:

1. Urbanization and development will expand in landslide-prone areas.
2. Tree cutting will continue in landslide-prone areas.
3. Changing global climate patterns will result in regional increases in precipitation.[13]

The consequences of these human activities alter the variables that affect driving and resisting forces on slopes as explained in Section 7.5.

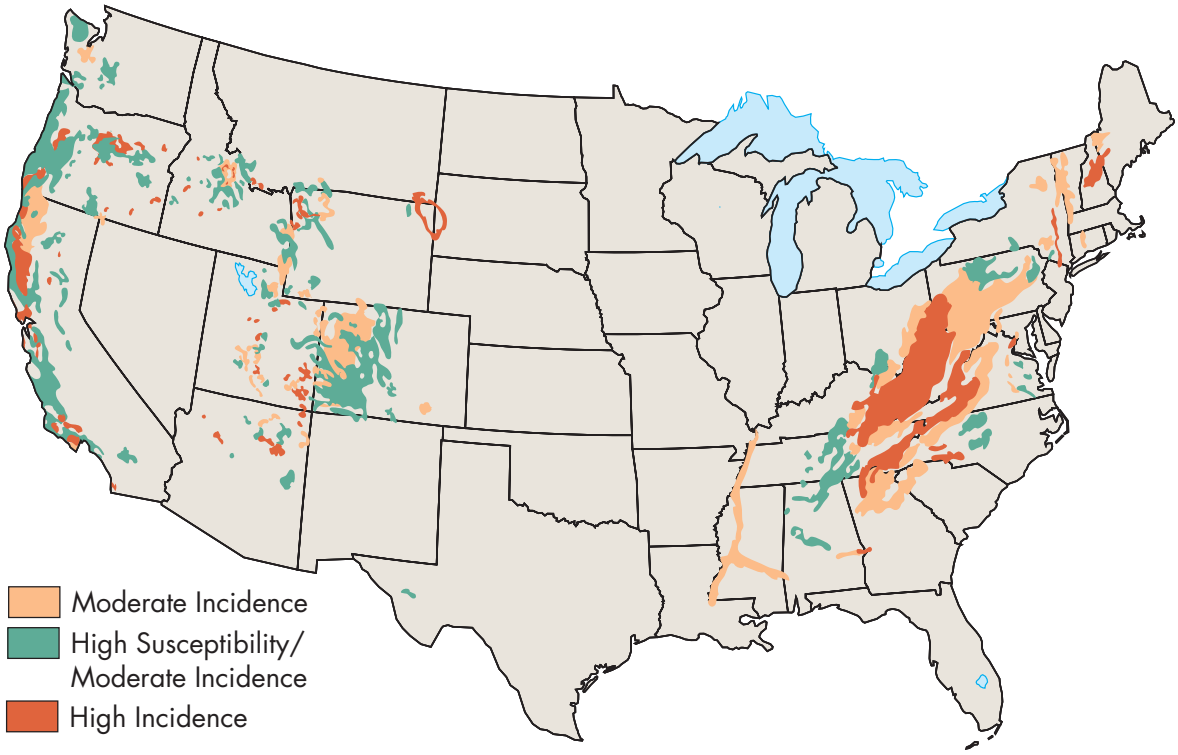
7.2 CHECK your understanding

1. Using Figure 7.20, explain the general distribution of regions at risk from mass wasting.
2. Why is there little risk of mass wasting in the Midwest and Great Plains region of the United States?
3. How might processes involved in urbanization increase or decrease the stability of slopes?

7.3 Effects of Landslides and Linkages with Other Natural Hazards

EFFECTS OF LANDSLIDES

Landslides and related phenomena have the capacity to cause substantial damage and loss of life. In the United States alone, on average 25 people are killed each year



▲ FIGURE 7.20 Areas of High-to-Moderate Landslide Incidence
On this map of landslide areas in the contiguous United States, the colored areas either have a high-to-moderate number of landslides or they have a moderate number of landslides and are highly susceptible to additional landslides. *(U.S. Geological Survey)*

by landslides, and this number increases to between 100 and 150 if collapses of trenches and other excavations are included. The total annual cost of damages exceeds $2.8 billion and may be as high as $8.5 billion.[14]

Direct effects of landslides on people and property include being hit with or buried in falling debris (see Case Study 7.4: Survivor Story). Landslides may also damage homes, roads, and utilities that have been constructed on the top or side of a hill. They regularly block roads and railroads, delaying travel for days or weeks. One massive landslide, the 1983 Thistle slide discussed later, blocked commerce on major highways and a transcontinental rail line for months. Rerouting of traffic significantly increased transportation costs in south-central Utah and resulted in the temporary or permanent closure of coal mines, oil companies, motels, and other businesses. Landslides may even block shipping lanes. In 1980, a debris flow from the volcano Mount St. Helens (see Chapter 5) filled the Columbia River with more than 34 million m^3 (~44 million $yd.^3$) of sediment. This sediment stopped cargo ships from reaching Portland, Oregon, until dredging was completed.

Indirect effects include flooding upstream from a landslide that blocks a river and the transmission of disease from fungal spores disturbed by landslides, as happened following the 1994 Northridge earthquake (see Chapter 3).

LINKAGES BETWEEN LANDSLIDES AND OTHER NATURAL HAZARDS

Landslides and other types of mass movement are intimately linked to just about every other natural hazard. Earthquakes, volcanoes, storms, and fires all have the potential to cause landslides (see Case Study 7.5: Professional Profile). These relationships are discussed in their respective chapters. As described earlier, landslides themselves may be responsible for flooding if they form an earthen dam across a river. A large landslide may also cause a tsunami or widespread flooding if it displaces water out of a lake or bay. In 1963, more than 2.5 km^2 (~1 $mi.^2$) of a hillside slid into the Vaiont reservoir in northeastern Italy. The landslide and resulting flood killed more than 2,600 people during this tragedy.

7.3 CHECK your understanding

1. Explain how large landslides are related to flooding and tsunamis.
2. How does the annual cost of damage due to landslides compare to other natural hazards?

7.3 CASE study

2014 Oso Landslide, Washington

The deadliest landslide in U.S. history occurred on March 22, 2014, along the North Fork of the Stillaguamish River valley east of Oso, Washington. Killing 43 and destroying 49 homes and other structures in the Steelhead Haven neighborhood, the Oso landslide buried a 2.5 km^2 (~1 mi^2) area several meters deep (Figure 7.21). Although the Director of the County's Department of Emergency Management stated that the slide was "completely unforeseen," engineers, geologists, and local residence for decades had referred to the hillside above the community as "Slide Hill."[15] Moreover, a 2010 study warned that the hillslope was one of the most dangerous in the county.[15]

Historic landslides and evidence of mass wasting all along the Stillaguamish River valley are visible in the landscape (Figure 7.22).[16] In fact, much of the 2014 landslide mass was composed of material that had slumped off of the Whitman Bench in the 2006 Hazel Landslide (Figure 7.22). Including the Hazel slide, the runouts—distance from landslide headscarp to toe—of the three previous landslides, were only 100–200 m (325–650 ft.).[17] Therefore, some experts did not predict that landslide debris from Whitman bench could flow more than 1000 m (~3,300 ft.).[17] However, that is just what happened in 2014.

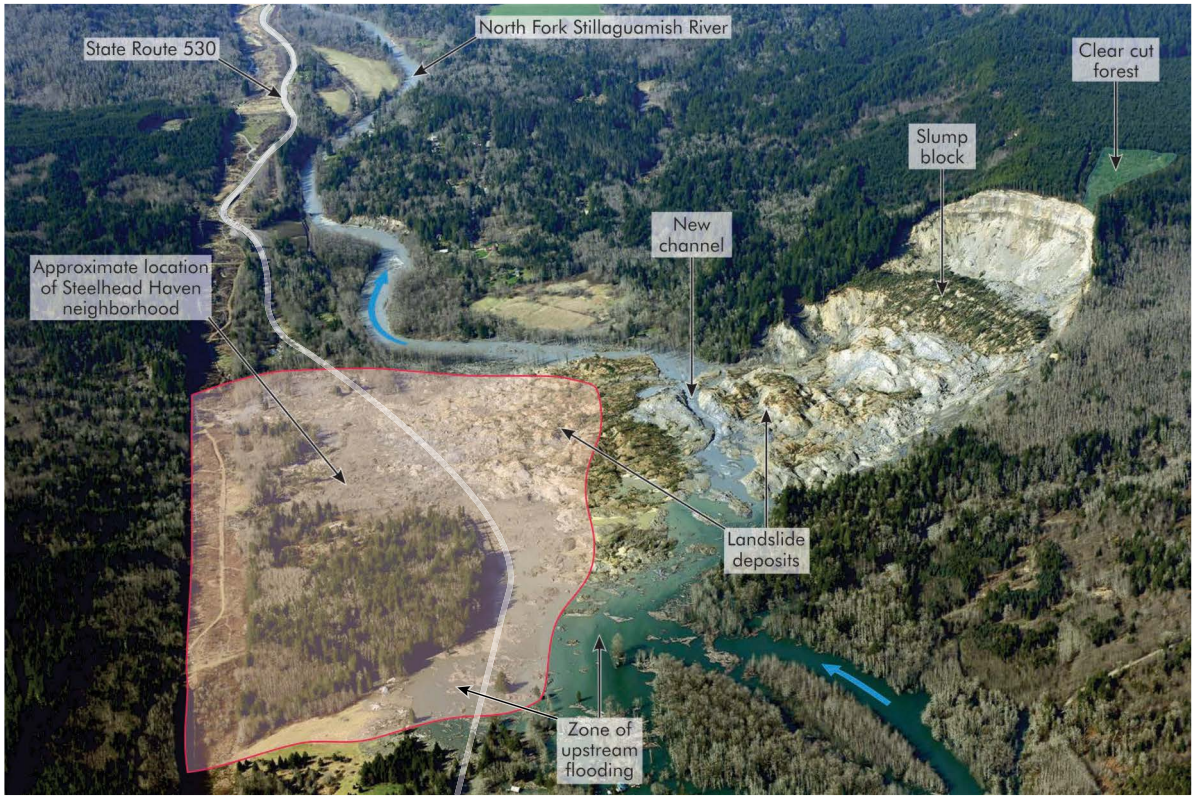


FIGURE 7.21 Deadliest Landslide in U.S. History
Near complete destruction of the Steelhead Haven neighborhood (shaded area) occurred when millions of tons of earth and rock of the 2014 Oso landslide raced down the steep slope and crossed the North Fork of the Stillaguamish River—killing 43 people.

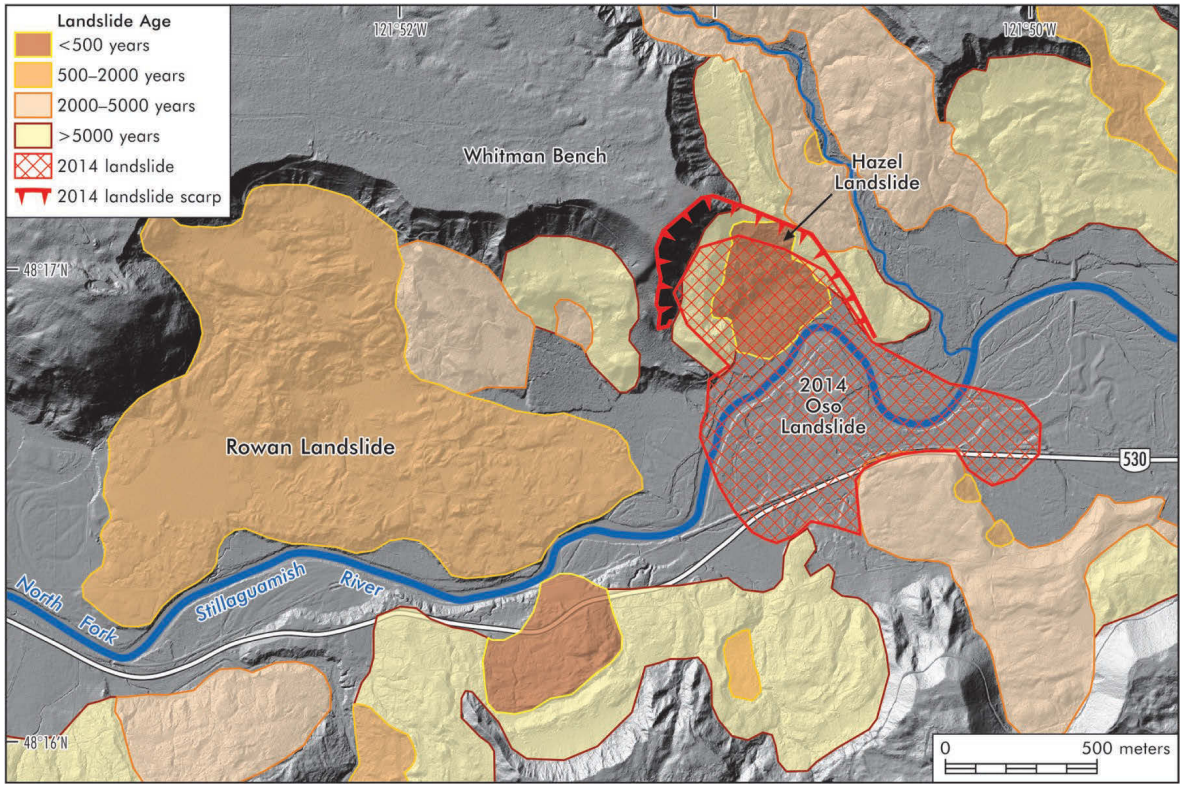


FIGURE 7.22 5,000-Year History of Landsliding Near Oso
Shadded-relief map of the North Fork of the Stillaguamish River highlighting the location of numerous historic landslides (colored by age) in the area surrounding the location of the 2014 Oso landslide.

For the 20 days preceding the Oso landslide, the region experienced more than 200 percent the normal precipitation for that time of year. It is likely that this high rainfall played a fundamental role in not only triggering the landslide, but also the great mobility of the slide material. The Oso landslide can best be described as a complex slide (see Figure 7.4f). Figure 7.21 clearly shows a single large slump block which detached from the Whitman bench and moved downslope. However the majority of the slide mass, saturated with water, became completely fluidized and flowed across the Stillaguamish River, the Steelhead Haven neighborhood, and State Route 530 beyond (Figure 7.21)

The Oso landslide mass blocked the Stillaguamish River for 10 days following the event causing upstream inundation of the flood plain, and further blocking State Route 530 (Figure 7.21). Concerns about the mud and debris damn failing and unleashing a torrent of water lead the National Weather Service (NWS) to issue a flash flood watch for communities downstream. Although, on April 2 the river began flowing in a new channel across the slide mass, the NWS continued to issue flood warnings for the Stillaguamish Valley for another month until the water-level lowered beyond concern (Figure 7.21).

Some experts have speculated that forestry practices on Whitman Bench over the past 50 years has contributed to the instability of the high banks of the Stillaguamish River.[17] A triangular region that was cleared of all trees in 2004 immediately upslope of the Oso Landslide head scarp can be seen clearly in Figure 7.21. Such forestry practices lead to a loss of sediment cohesion, as well as increased surface and subsurface water runoff all, of which are known to cause instability of steep slopes (see Section 7.1). Consequently, the State of Washington and the forestry company responsible for logging the Whitman Bench paid a $60 million settlement in 2016 to the Oso Landslide survivors and victim's families.[18]

Landslide in Colorado

7.4 Survivor Story

CASE study

Danny Ogg Thought He Was "a Goner" When the First Boulder Hit His Truck

Danny Ogg was goin' round the mountain, as they say, on Interstate 70 west of Denver, when a giant granite boulder crashed across his windshield, leaving him with only one thought: "I'm going to be buried alive."

The boulder was one of about 20 or 30 that rocketed down the steep slopes onto the interstate highway, which winds through the Rocky Mountains, early on the morning of April 8, 2004 (Figure 7.4.A). The largest of the rocks weighed 30 tons. Surprisingly, though, Ogg, a 50-year-old driver from Tennessee, said he had no indication that a landslide was occurring until his semitrailer hit the first rock. After that, it was "bang bang bang, crunch crunch," as he put it, as his truck collided with the falling debris and eventually hit the median. The vehicle's fuel tank was torn open in the process, spilling hundreds of gallons of diesel fuel.

Ogg's sense of time was skewed in the terrifying moments of the landslide. "After I hit the first boulder, it took two, three minutes, I guess. It was fast but it wasn't," he said.

Luckily, Ogg suffered only an injured back and some torn cartilage and ligaments, compared to the much more serious injuries he could have incurred. "I thought I was a goner," he said. "I don't know how long I was in there. It idled me. I was silly as a goose, as we say in Tennessee."

His sense of location was also askew: "You know you ain't dead yet, but you don't know where you are," he said. "I didn't know if I was hanging off the mountain or what."

Ogg said some of the boulders left potholes in the road a foot or two deep, and a *Rocky Mountain News* article reported that some of them bounced as high as 20 feet after impact.

Although landslides are difficult to predict and avoid, Ogg said he would be more vigilant now when driving in the mountains. "When you go around the mountain now, you look up," he said.

— CHRIS WILSON



< FIGURE 7.4.A Boulders on I-70
These granite boulders, some as large as 4 m^3 (~140 $ft.^3$), fell onto I-70 near Glenwood Springs, Colorado, on the morning of May 9, 2003. Heavy rain, combined with ice wedging in cracks within the granite, dislodged one or more of these large rocks from a free face more than 100 m (~330 ft.) above the interstate. One car-sized boulder bounced across the highway and landed in the nearby Colorado River. A highway crew had to drill or blast apart the largest boulders and push them over to the shoulder so traffic could resume. The low retaining wall behind the boulders in this image was shattered in several places. *(USGS)*

CASE study

7.5 Professional Profile

Bob Rasely, Mass Wasting Specialist

Bob Rasely's line of work may be the very definition of "down and dirty" (Figure 7.5.A). A Utah-based geologist with the Natural Resources Conservation Service, Rasely specializes in predicting the likelihood of mass wasting in the wake of a wildfire. "You don't see the dirt you got on you until you take your shirt off," Rasely said.

While most of the situations Rasely encounters are not emergencies, there are certainly times when the possibility of mass wasting, especially debris flows, poses an immediate threat to populated areas. "If there's a town down below, we have to rush to get ahead of the next storm," Rasely said. "In the worst-case scenario, we plant someone halfway up the mountain with a radio." In such cases, Rasely said, they often set up evacuation plans that can remain in effect for long periods of time.

The probability and scale of a potential disaster depend on many factors. Rasely classifies most wildfires or "burns" as either light or heavy. Light burns destroy only the surface growth and have a recovery span of about one year, whereas heavy burns destroy the roots and require three to five years for recovery. "First, we want to know the condition of the burn, if the roots are intact," he said. Light burns increase the erosion rate on a given surface by 3 to 5 times, whereas heavy burns increase the rate 6 to 10 times.

Other factors include the steepness and length of the slope, as well as whether established paths for water to flow already exist on the surface—a bad sign, since this means the water will run off the mountain at a much faster rate. Pine needles and oaks also leave a waxy residue when they burn, which can further expedite the flow, Rasely said.



< FIGURE 7.5.A Geologist Examines Recent Landslide

Bob Rasely, retired Utah State geologist for the Natural Resources Conservation Service, stands on the uneven, hummocky surface of the Thistle landslide shown in Figure 7.32. Irregular land surfaces such as this are common on landslides. *(Bob Rasely)*

Once the general risk of mass wasting has been assessed, Rasely and his team have a variety of tricks they can use to minimize the potential damage, including erecting fencing made out of mesh material called "geofabric," as well as digging what they call a "debris basin" to catch falling material. "If there's any kind of little terrace, you can stop a lot of stuff," he said.

Rasely's job has taken him to all but two of Utah's mountain ranges, and he frequently works in the many state and national parks in Utah. And although the severity of the situation may vary widely, time is always important in this line of work. "It's by the seat of the pants, live time," Rasely said.

— CHRIS WILSON

7.4 Natural Service Functions of Landslides

Although most hazardous natural processes provide important natural service functions, it is difficult to imagine any good coming from landslides except the creation of new habitats in forests and aquatic ecosystems.

Landslides, like fire, are a major source of ecological disturbance in forests. For some old-growth forests, this disturbance can be beneficial by increasing both plant and animal diversity.[19] In aquatic environments, landslide-dammed lakes create new habitat for fish and other organisms.[20]

Mass wasting can produce deposits that become mineral resources. Weathering frees mineral grains from rocks, and mass wasting transports these minerals downslope. Heavier minerals, particularly gold and diamonds, can be concentrated at the base of the slope and in adjacent streams. Although not as abundant as in stream deposits, gold and diamonds have been mined from colluvium and debris flow deposits.

7.4 CHECK your understanding

1. List the different natural service functions of landslides.
2. What role do mass wasting and erosion play in the mining of precious earth materials, such as gold and diamonds?

7.5 Human Interaction with Landslides

Landslides and other types of ground failure are natural phenomena that would occur with or without human activity. However, in many instances, the expansion of urban areas, transportation networks, and natural resource use has increased the number and frequency of landslides. In other settings where the potential for landslides has been recognized, the number of events has decreased because of preventive measures. For example, grading of land surfaces for housing developments may initiate landslides on previously stable hillsides; on the other hand, building stabilizing structures and improving drainage may reduce the number of landslides on naturally sensitive slopes.

The effect of human endeavors on the magnitude and frequency of landslides varies from nearly insignificant to very significant. In cases where human activities rarely cause landslides, we may still need to learn all we can about this natural phenomenon to avoid development in hazardous areas and to minimize damage. When human activities such as road construction (see Case Study 7.1: A Closer Look) increase the number and severity of landslides, we need to learn how our practices cause slides and how we can control or minimize their occurrence. Following is a description of several human activities that interact with landslides.

TIMBER HARVESTING AND LANDSLIDES

The possible cause-and-effect relationship between timber harvesting and erosion is a major environmental and economic issue in northern California, Oregon, and Washington. Two controversial practices are *clear-cutting*, the harvesting of all trees from large tracts of land, and road building, the construction of an extensive network of logging roads used to remove cut timber from the forest. Landslides, especially shallow soil slips, debris avalanches, and more deeply seated earthflows are responsible for much of the erosion in these areas.

One 20-year study in the Western Cascade Range of Oregon found that shallow slides are the dominant form of erosion. This study also found that timber-harvesting activities, such as clear-cutting and road building, did not significantly increase landslide-related erosion on geologically stable land; however, logging on weak, unstable slopes did increase landslide erosion by several times compared to slopes that had not been logged.[21]

Road construction in areas to be logged can be an especially serious problem because roads can interrupt surface drainage, alter subsurface movement of water, and adversely change the distribution of earth materials on a slope by cut-and-fill or grading operations.[21] As we learn more about erosional processes in forested areas, soil scientists, geologists, and foresters are developing improved management practices to minimize the adverse effects of logging. Nevertheless, landslide erosion problems continue to be associated with timber harvesting (see Case Study 7.3).

URBANIZATION AND LANDSLIDES

Human activities are most likely to cause landslides in urban areas where there are high densities of people, roads, and buildings. Examples from Los Angeles, California, Oso, Washington, and Rio de Janeiro, Brazil illustrate this situation (see Case Studies 7.2, 7.3, and 7.6). Los Angeles in particular (and Southern California in general) has also experienced a high frequency of landslides associated with hillside development. Large variations in topography, rock and soil types, climate, and vegetation make interactions with the natural environment complex and notoriously unpredictable. For this reason, the area has the sometimes dubious honor of showing the ever-increasing value of studying urban geology.[22]

It took natural processes many thousands, and perhaps millions, of years to produce valleys, ridges, and hills. In a little over a century, humans have developed the machines to grade them. Nearly 40 years ago, F. B. Leighton, a geological consultant in Southern California, wrote: "With modern engineering and grading practices and appropriate financial incentive, no hillside appears too rugged for future development."[22] Thus, human activity has become a geological agent that is capable of carving out the landscape at a much faster pace than glaciers and rivers. Almost overnight, we can convert steep hills into a series of flat lots and roads. The grading process, in which benches, referred to as pads, are cut into slopes for home sites, has been responsible for many landslides. Because of the extent of grading, Los Angeles has led the nation in developing codes concerning grading for development.

Grading codes that minimize the landslide hazard have been in effect in the Los Angeles area since 1963. These codes were adopted in the aftermath of destructive and deadly landslides in the 1950s and 1960s (see Case Study 7.2: Portuguese Bend, California). Since these codes have been in effect and detailed engineering geology studies have been required, the percentage 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.

Oversteepened slopes, increased water from lawn irrigation and septic systems, and the additional weight of fill material and buildings make formerly stable slopes unstable (Figure 7.23). As a rule, any project that steepens or saturates a slope, increases its height, or places an extra load on it may cause a landslide.[23]

Landslides related to urbanization have also been a problem in the eastern United States. In Cincinnati and surrounding Hamilton County, Ohio, most slides have taken place in colluvium, although clay-rich glacial deposits and soil developed on shale have also slipped.[23] At an average cost of more than $14 million per year (estimates adjusted for 2013), these slides are a serious problem.[14]

In Pittsburgh and surrounding Allegheny County, Pennsylvania, urban construction is estimated to be responsible for 90 percent of the landslides.[24] Most of these slides are slow moving and take place on hillslopes of weathered mudstone or shale. In one deadly exception in an adjacent county, a rockfall crushed a bus and killed 22 passengers. Most of the landslides in Allegheny County are caused by placing fill dirt or buildings on the top of a slope, by cuts in the toe of a slope, or by the alteration of water conditions on or beneath a slope.[20] Damages from these slides average $4 million per year.

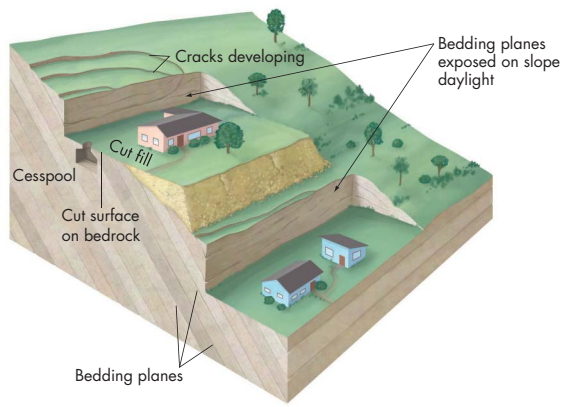


FIGURE 7.23 Urbanization and Landslide Potential
This diagram shows how building on hillslopes can contribute to slope instability. The diagonal lines in the gray side of the diagram are bedding planes in sedimentary rock. Cuts into the hillside behind the houses have removed support from these bedding surfaces. The yellow fill material used to extend the flat pad for building adds weight to the slope. Cracks shown in the upper part of the diagram are an early sign that a landslide is likely to occur soon. Leaking wastewater from "cesspools" and landscape irrigation can add lubricating water to the hillslope. *(Based on F. Beach Leighton, Landslides and Urban Development, 1966)*

CASE study 7.6

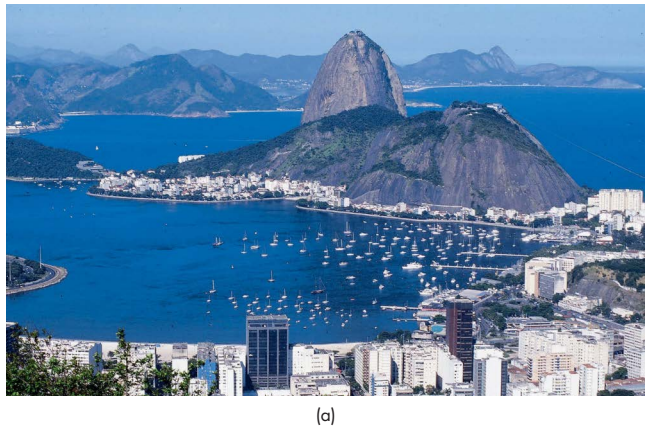
Rio de Janeiro, Brazil

Rio de Janeiro, with a population of more than 6.3 million, may have more slope-stability problems than any other city of its size.[25] Several factors contribute to a serious landslide problem in the city and surrounding area: (1) The beautiful granite peaks that spectacularly frame the city (Figure 7.24) have steep slopes of fractured rock that are covered with thin soil, (2) the area is periodically inundated by torrential rains, (3) cut-and-fill construction has seriously destabilized many slopes, and (4) vegetation has been progressively removed from the slopes.

The landslide problem started early in the city's history when many of the slopes were logged for lumber and fuel and to clear land for agriculture. Landslides associated with heavy rainfall followed the early logging activity. More recently, a lack of building sites on flat ground has led to increased urban development on slopes. The removal of additional vegetative cover and the construction of roads have led to building sites at progressively higher elevations. Excavations have cut the base of many slopes and severed the soil cover at critical points. In addition, placing fill material on slopes to expand the size of building sites has increased the load on already unstable land. Since this area periodically experiences tremendous rainstorms, it becomes apparent that Rio de Janeiro has a serious problem.

In February 1988, an intense rainstorm dumped more than 12 cm (~5 in.) of rain on Rio de Janeiro in 4 hours. The storm caused flooding and debris flows that killed at least 90 people and left 3,000 people homeless. Most of the deaths occurred from debris flows in hill-hugging shantytowns where housing is precarious and control of storm water runoff nonexistent. However, more affluent mountainside areas were not spared from destruction. In one area, a landslide destroyed a more affluent nursing home and killed 25 patients and staff. Restoration costs for the entire city have exceeded $100 million. A similar story played out in April 2010, when heavy rains caused numerous landslides that destroyed 60 homes and killed more than 200 people. Much of the damage and loss of life occurred in low-income slums, where, in addition to poor construction practices, the homes were built on the steep slopes that surround the city (Figure 7.24b). If future disasters are to be avoided, Rio de Janeiro must take extensive and decisive measures to control storm runoff and increase slope stability.

FIGURE 7.24 Landslides are Common in the Rio De Janeiro Area
(a) Panoramic view of Rio de Janeiro, Brazil, showing the steep "sugarloaf" mountains and hills (right center of the image). A combination of steep slopes, fractured rock, shallow soils, and intense rainfall contributes to the landslide problem, as do human activities such as urbanization, logging, and agriculture. Virtually all the bare rock slopes were at one time vegetated, and that vegetation has been removed by landslides and other erosional processes. *(B. Martinez/Roger Viollet/Getty Images)* (b) Aerial view of the Morro dos Prazeres slum, where several homes were destroyed by landsliding in Rio de Janeiro on April 8, 2010. *(Antonio Scorza/AFP/Getty Images/Newscom)*



(a)



(b)

7.5 CHECK your understanding

1. Explain how timber harvesting, specifically clear-cutting, affects the occurrence of landslides.
2. How does road construction increase the occurrence of landslides?
3. Explain how human activity in Rio de Janeiro has resulted in devastating landslides.

7.6 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 them, warn people of impending slides, and control slides after they have started moving. The most preferable and least expensive option to minimize the landslide hazard is to avoid development on sites where landslides are occurring or are likely to occur.

IDENTIFYING POTENTIAL LANDSLIDES

Recognizing areas with a high potential for landslides is the first step in minimizing this hazard. These areas can be identified where slopes are underlain by sensitive earth materials, such as clay or shale, and by a variety of surface features:

- Crescent-shaped cracks or terraces on a hillside (see Figure 7.23)
- A tongue-shaped area of bare soil or rock on a hillside (Figure 7.25)
- Large boulders or talus piles at the base of a cliff (see Figure 7.2a)
- A linear path of cleared or disturbed vegetation extending down a hillslope (Figure 7.19)
- Exposed bedrock with layering that is parallel to the slope (see Figure 7.8b)
- Tongue-shaped masses of sediment, especially gravel, at the base of a slope (Figure 7.25) or at the mouth of a valley
- An irregular, often referred to as *hummocky*, land surface at the base of a slope (Figure 7.23).

Geologists look for these features in the field and on aerial photographs. This information is used to assess the hazard and to produce several types of maps.

The first type of map is the direct result of the landslide inventory just described. It may be a reconnaissance map showing areas that have experienced slope failure or a more detailed map showing landslide deposits in terms of their relative activity (Figure 7.26a). Information concerning past landslides may be combined with land-use considerations to develop a *slope stability map* for engineering geologists or a *landslide hazard map* with recommended land uses (Figure 7.26b) for planners. These maps do not take the place of detailed evaluation of a specific site. Preparing a *landslide risk map* is more complicated because it involves evaluating the probability of a landside occurring and an assessment of potential losses.[26]

PREVENTING LANDSLIDES

Prevention of large, natural landslides is difficult, but common sense and good engineering practices can help minimize the hazard. For example, loading the top of slopes, cutting into sensitive slopes, placing fill material on slopes, or changing water conditions on slopes should be avoided or done with caution.[19] Common engineering techniques for landslide prevention include surface and subsurface drainage, removal of

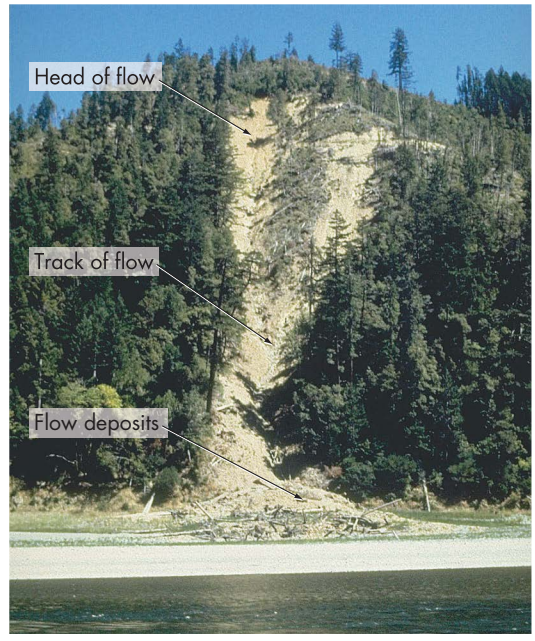
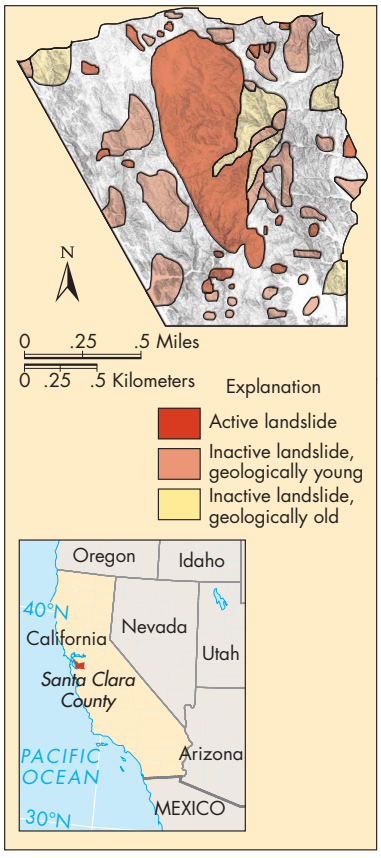
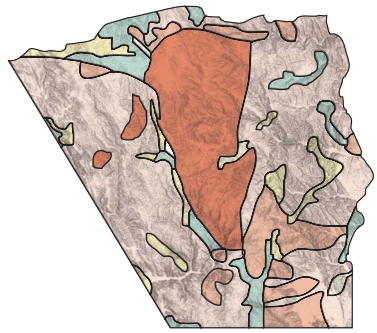


FIGURE 7.25 Evidence of a Mass Wasting
The long, narrow area of bare soil on this Northern California hillslope was created by a debris flow. Trees and sediment carried by the flow are in a tongue-shaped pile at the bottom of the hill along the bank of the Klamath River. A logging road at the head of the flow (end of the arrow) may have helped destabilize the slope. (*Edward A. Keller*)



(a)



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.

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 rockfall	Yes*	Yes*	Yes*
		Gentle to very steep slopes in unstable material subject to sliding, slumping, and soil creep	No*	No*	No*
		Moving, shallow (<3m, <3.3yds) landslide	No*	No*	No*
Least stable		Moving, deep landslide, subject to rapid failure	No	No	No

(b)

▲ FIGURE 7.26 Landslide Hazard Maps

(a) Landslide inventory map and (b) a landslide risk and land-use map for part of Santa Clara County, California. Goals and tasks of the landslide part of a ground-failure hazards reduction program. *(Based on U.S. Geological Survey, "Goals and Tasks of the Landslide Part of a Ground-failure Hazards Reduction Program," U.S. Geological Survey Circular 880, 1982)*

unstable slope materials, construction of retaining walls or other supporting structures, or some combination of these techniques.[3]

Drainage Control Surface and subsurface drainage control is usually effective in stabilizing a slope. The objective is to divert water to keep it from running across or infiltrating the slope. Surface runoff can be diverted around the slope by a series of surface drains (Figure 7.27a). The amount of water infiltrating a slope can also be controlled by covering the slope with an impermeable layer, such as soil-cement, asphalt, or even plastic (Figure 7.27b). Underground water can be inhibited from entering a slope by subsurface drains. To construct a drain, a drainpipe with holes along its length is surrounded with permeable gravel or crushed rock and is positioned underground to intercept and divert water away from a potentially unstable slope.[3]

Grading Although grading of slopes for development has increased the landslide hazard in many areas, carefully planned grading can increase slope stability. In a single cut-and-fill operation, 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 the upper slope, where it contributes to the driving force, and placed at the toe of the slope, where it increases the resisting force. However, this method is not practical on a high, steep slope. Instead, the slope may be cut into a series of benches or steps, each of which contains surface drains to divert runoff. The benches reduce the overall slope and are good collection sites for falling rock and small slides (Figure 7.28).[3]

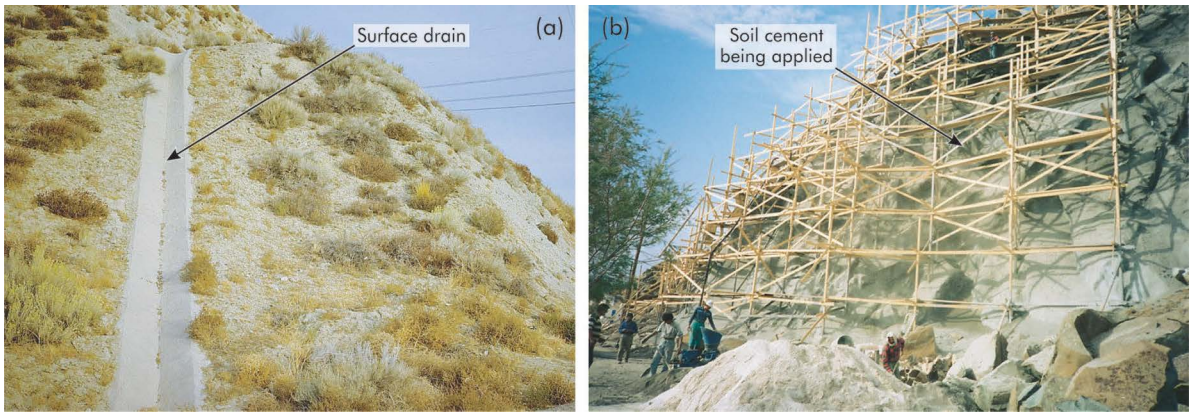


FIGURE 7.27 Two Ways to Increase Slope Stability
(a) Concrete drain on a roadcut that removes surface water runoff before it can infiltrate the slope. *(Edward A. Keller)* (b) Workers are covering this slope in Greece with soil-cement to reduce the infiltration of water and provide strength. Soil-cement is a blend of pulverized soil, Portland cement, and water. *(Edward A. Keller)*



FIGURE 7.28 Benches on a Highway Roadcut
The stepped surfaces, or benches, seen in the upper-right part of this image reduce the overall steepness of the slope and provide better drainage. Benches along roadcuts into bedrock can catch rockfalls before they reach a highway. *(Edward A. Keller)*

Slope Supports One of the most common methods of slope stabilization is a retaining wall that supports the slope. These walls can be constructed of concrete or brick; stone-filled wire baskets called *gabions* or series of piles of long concrete, steel, or wooden beams are driven into the ground (Figure 7.29). To function effectively, the walls must be anchored well below the base of the slope, back-filled with permeable gravel or crushed rock (Figure 7.30), and provided with drain holes to reduce water pressure in the slope (Figure 7.29). With the addition of plants, these walls can be aesthetically pleasing or blend in with the natural hillside (Figure 7.31).

Preventing landslides can be expensive, but the rewards can be well worth the effort. Estimates of the benefit-to-cost ratio for landslide prevention range from 10 to 2,000. That is, for every dollar spent on

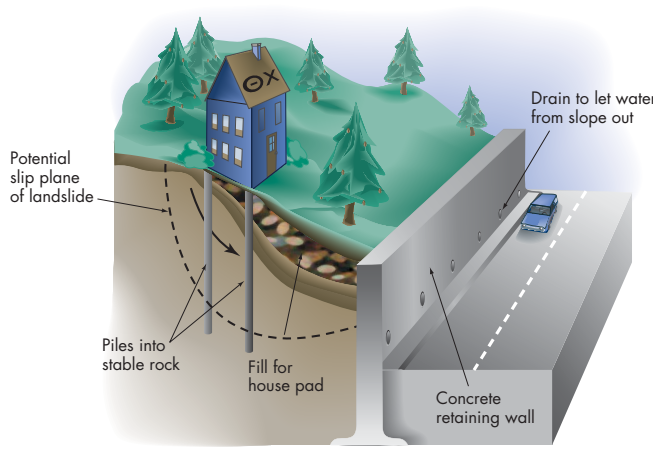


FIGURE 7.29 How to Support a Slope
The types of slope support shown in this illustration include a roadside concrete retaining wall that is deeply anchored into the slope, concrete or steel piles sunk into stable rock, and subsurface drains that reduce water pressure within the slope.



FIGURE 7.30 Retaining Wall
This retaining wall of concrete cribbing was installed and then backfilled to help stabilize the roadcut. *(Edward A. Keller)*

landslide prevention, the savings will range from $10 to $2,000.[27] The cost of *not* preventing a slide is illustrated by the massive Thistle landslide southeast of Salt Lake City in April 1983. This slide moved down a mountain slope and across a canyon to form a natural dam about 60 m (~200 ft.) high. This dam created a lake that flooded the community of Thistle, the Denver–Rio Grande Railroad switchyard and tracks, and two major U.S. highways (Figure 7.32).[26] The total costs (direct and indirect) from the landslide and associated flooding exceeded $400 million.[28]

The Thistle slide was a reactivated older slide, which had been known for many years to be occasionally active in response to high precipitation. It came as no surprise that those extremely high rainfall totals were produced by a climatic event called El Niño (see Chapter 12). In fact, a review of the landslide history suggests that this slide was recognizable, predictable, and preventable! A network of subsurface and surface drains would have prevented failure. The cost of preventing the landslide was between $300,000 and $500,000, a small amount compared to the damages caused by the slide.[27] 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.

LANDSLIDE WARNING SYSTEMS

Landslide warning systems do not prevent landslides, but they can provide time to evacuate people and their possessions and stop trains or reroute traffic. Surveillance provides the simplest type of warning. Hazardous areas



(a)



(b)



(c)

FIGURE 7.31 Steps in Making a Retaining Wall
(a) This shallow slide occurred in the early 1990s. *(Edward A. Keller)* (b) A retaining wall of cemented stone was constructed in 1999 to correct the problem. (*Edward A. Keller)* (c) Benches behind the retaining walls were landscaped as shown by this 2001 photograph. *(Edward A. Keller)*



▲ FIGURE 7.32 Landslide Blocks a Canyon
The costliest landslide in U.S. history, this 1983 slide at Thistle, Utah, was a reactivation of an older slide. Debris from the slide blocked the Spanish Fork River and created a natural dam. This dam produced a lake that flooded the community of Thistle, the Denver–Rio Grande Railroad, and two major U.S. highways. Nearly the entire extent of the landslide moved again in 1999. *(Michael Collier)*

can be visually inspected for apparent changes, and small rockfalls on roads and other areas can be noted for quick removal of debris. Human monitoring has the advantages of reliability and flexibility but becomes difficult during adverse weather and in hazardous locations.[29] For example, snow avalanche conditions in the United States have been monitored for decades by park rangers and volunteers of the National Ski Patrol.

Other warning methods include electrical systems, tiltmeters, and geophones that pick up vibrations from moving rocks. Many U.S. and Canadian railroads have slide fences on slopes above their tracks that are tied to signal systems. When a large rock hits the fence, a signal is sent to stop trains before they are in danger. This and other mitigation measures have significantly reduced the number of railroad accidents, injuries, and fatalities.[29]

In western Washington State, the U.S. Geological Survey and Pierce County joined forces in 1995 to develop and deploy acoustic flow monitors to detect debris flows (lahars) from Mt. Rainier.[30] By detecting the vibrations caused by a large debris flow, the automated detection and warning system is capable of giving communities in danger between 40 minutes and three hours to evacuate. With no warning a large debris flow from the mountain, similar to one that occurred about 500 years ago, would devastate more than a dozen communities and kill thousands or possibly tens of thousands of people.

For existing slides, shallow wells can be drilled into a slope and monitored to signal when the slide contains a dangerous amount of water. In some regions, a rain-gauge network is useful for warning when a precipitation threshold has been exceeded and shallow soil slips are probable.

7.6 CHECK your understanding

1. What types of surface features are associated with landslides?
2. What are the main steps that can be taken to prevent landslides?
3. Explain how a cut-and-fill operation can increase the safety factor of a particular slope.

7.7 Perception of and Adjustment to the Landslide Hazard

PERCEPTION OF THE LANDSLIDE HAZARD

Homeowners talking about landslides typically say, "It could happen on other hillsides, but never this one."[25] Just as flood hazard mapping does not prevent development in flood-prone areas, landslide hazard maps will not prevent many people from moving into hazardous areas. Prospective hillside occupants who are initially unaware of the hazard may not be swayed by technical information. The infrequency of large slides reduces awareness of the hazard, especially where evidence of past events is not readily visible. Unfortunately, it often takes catastrophic events to bring the problem to people's attention. In the meantime, people in many parts of the Rocky Mountains, Appalachian Mountains, California, and elsewhere continue to build homes in areas subject to future landslides.

ADJUSTMENT TO THE LANDSLIDE HAZARD

Although the most reasonable adjustment to the landslide hazard is simply not to build in landslide-prone

areas, many people still go ahead. As long as people continue to build and buy expensive homes "with a view," we will need to find other adjustments to avoid death and damage from landslides. Such adjustments can include locating critical facilities away from landslide-prone areas and landslide correction.

Siting of Critical Facilities As with earthquakes (Chapter 3), safely siting critical facilities such as hospitals, schools, and police stations is crucial. Ensuring that these buildings are not located on or directly below hillsides is a simple way to guarantee that they will remain functional in the event of a landslide. In urban areas that have been built up against mountains, such as Juneau, Alaska, such selective siting can be difficult.

Landslide Correction After a slide has begun, the best way to stop it is to attack the process that started the slide. In most cases, the cause is an increase in underground water pressure within and below the slide. The pressure may be reduced by an effective drainage program. This program often includes surface drains at the head of the slide to reduce surface water infiltration and subsurface drainpipes or wells to remove groundwater and lower the water pressure. Draining tends to increase the resisting force of the slope material, thereby stabilizing the slope.[7]

PERSONAL ADJUSTMENTS: WHAT YOU CAN DO TO MINIMIZE YOUR LANDSLIDE HAZARD

Consider the following advice if purchasing property on a slope:

- Landslides often develop in areas of complex geology, and a geologic evaluation by a professional geologist is recommended for any property on a slope.
- Avoid homes at the mouth of a valley or canyon, even a small one, where debris flows may originate from upstream slopes and travel down the channel.
- Consult local agencies such as city or county engineering departments that may be aware of landslides in your area.
- Watch out for "little landslides" in the corner of the property—they usually get larger with time.
- If purchasing a home, look for cracks in house walls and look for retaining walls that lean or are cracked. Be wary of doors or windows that stick or floors that are uneven. Foundations should be checked for cracks or tilting. If cracks in walls of the house or foundation can be followed to the land outside the house, be especially concerned that a landslide may be present.
- Be wary of leaks in a swimming pool or septic tank, trees or fences tilted downslope, or utility wires that are taut or sagging.
- Be wary if small springs are present because landslides tend to leak water. Look for especially "green" areas, other than a septic system leach field, where more subsurface water is present.
- Walk the property and surrounding property, if possible, looking for linear or curved cracks (even small ones) that might indicate instability of the land surface.
- Look for the surface features listed earlier that geologists use to identify potential landslides.
- Although correcting a potential landslide problem is often cost-effective, it can still be expensive; much of the fix is below ground where you will never see the improvement. Overall it is better not to purchase land with a potential landslide hazard.
- The presence of one or more of these features does not prove that a landslide is present or will occur. For example, cracks in walls and foundations, doors or windows that stick, or floors that are uneven can be caused by soils that shrink and swell. However, further investigation is warranted if these features are present.

If you enjoy snow sports, hike, climb, live, or travel in areas that have snow avalanches, you should be aware of the following:

- Most avalanches that involve people are triggered by the victims themselves or by others in their party.[11]
- Obtain forecasts from the nearest avalanche center. Remember that changing weather conditions can affect the avalanche hazard.
- Most people who survive avalanches are rescued by the other members in their party.[12]
- Learn avalanche safety procedures and how to evaluate snow conditions before traveling in an area that has avalanches.

7.7 CHECK your understanding

1. List five signs you would look for as evidence of potential landslides if you were inspecting a piece of property and house for purchase.
2. With the exception of buying property on a low-relief surface, what is the best thing you could do to minimize the probability of a landslide occurring on your land? Explain.

APPLYING the 5 Fundamental Concepts

La Conchita, Southern California: Landslide Disaster

1. **Science helps us predict hazards.**
2. **Knowing hazard risks can help people make decisions.**
3. **Linkages exist between natural hazards.**
4. **Humans can turn disastrous events into catastrophes.**
5. **Consequences of hazards can be minimized.**

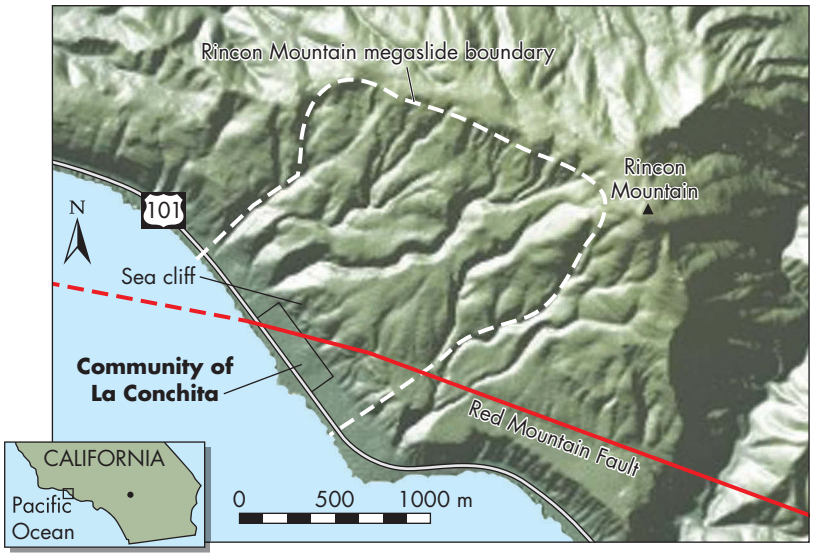
La Conchita is one of only three small communities occupying a 25 km (~16 mi.) long stretch of land along California's scenic coastline between Ventura and Carpinteria. Development along this section of the coast is fairly limited because there are only a few patches between the mountains and the Pacific Ocean wide enough for development. In most places, the coastal strip is barely wide enough for U.S. Highway 101 to navigate the rugged coastline (Figure 7.33). To most people driving up the coast, with little or no education in the geological sciences or natural hazards, La Conchita would appear to be an idyllic location to own a home.

The high topography along this stretch of the coastline is indicative of active tectonic uplift of the region. One of the highest peaks in this part of Southern California is Rincon Mountain, which is uplift on the Red Mountain reverse fault east of La Conchita (Figure 7.33). The Red Mountain fault has extremely high rates of deformation and is also responsible for the steep 180 m (~800 ft.) high sea cliff that looms above the community (Figure 7.33 and Figure 7.34a). Exposed in the sea cliff about 250 m (~820 ft.) above La Conchita are unconsolidated beach sand and shell material that were deposited at sea level 40,000 years ago and have since been uplifted by the Red Mountain and other parallel faults in the area. This rapid rate of uplift is similar to that of the Himalayan Mountains! In addition to the obvious earthquake hazard presented by the presence of such an active faulting so close to La Conchita, movement along the fault during seismic events has caused pervasive fracturing of the older rocks that underlie the marine deposits in the sea cliff.

Even if no knowledge of the fault-related damage of the bedrock was known before the 1995 event, the potential for a major landslide of the sea cliff behind La Conchita was clear. While driving U.S. 101, landslide after landslide in the slopes above can be seen all along this section of the coastline. Some of these slides are recent, while others are probably thousands of years old, including the prehistoric slide within which the 1995 and 2005 events were located (Figure 7.34a). Furthermore, every few years, including in 1995 and 2005, Highway 101 is closed for a day or so due to mudflows covering the roadway (Figure 7.34b).

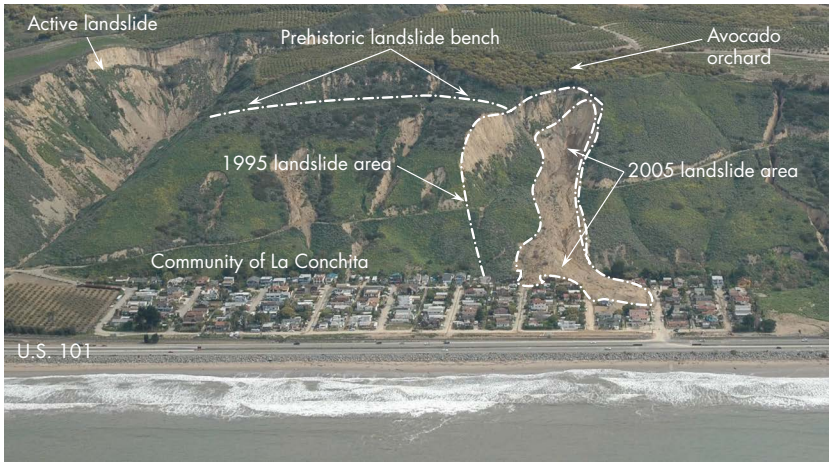
During the summer of 1994, about six months before the 1995 landslide, cracking in the upper part of the slope was observed above La Conchita.[31] Cracking was a clear sign of movement, and these cracks continued to grow into the rainy season. By December 1994 open cracks had started to channel water into the subsurface beneath the slope. January 1995 was a particularly wet month for the region with about 62.5 cm (~24.6 in.) of rain, which is more than the total annual average rainfall and six times as much as usually falls in January. Although February was a relatively dry month, heavy rains fell again on March 2–3. On March 4, 1.3 million m^3 (~1.7 million $yd.^3$) of rock and soil started to move downslope toward La Conchita.

It took the landslide several minutes to move about 100 m (~330 ft.) down the slope and into the community. The moving mass formed a complex landslide with most of the material



< FIGURE 7.33 Geology and Topography of La Conchita

False color hillshade image of part of the California coast showing the location of La Conchita with respect to important geologic and topographic features. The dashed white line shows the approximate boundaries of the proposed Rincon Mountain megaslide.



(a)



(b)

< FIGURE 7.34 Mass Wasting Activity Near La Conchita

(a) Annotated photograph of La Conchita illustrating the locations of the ancient and active landslides near the 1995 and 2005 La Conchita slides. *(Modified after Gurrola, L. D., DeVecchio, D. E., Keller, E. A., 2010, Rincon Mountain Megaslide, La Conchita, Ventura County, California,* Journal of Geomorphology *114: 311–18)* (b) Debris flows are common along the La Conchita coast, such as this one that occurred on the same day as the deadly 2005 La Conchita mudflow. The debris flow covered about 0.5 km (~0.3 mi.) of U.S. 101 just north of La Conchita. The flow broke through concrete barriers and continued onto the beach on the left. (*©Getty Images/Mathew Imaging/Contributor)*

moving as a slump block, while small regions lost cohesion and moved as an earthflow down the slope (see Figure 7.7). It is thought that the two days of heavy rain preceding the slide caused the slope failure by adding to the already elevated groundwater level that had built up due to January's extraordinarily high rainfall.[1] When the mass finally came to rest, it was 120 m (~400 ft.) long, covered about 10 acres, and had destroyed or severely damaged nine houses (see Figure 7.1a). Fortunately, the slide moved slowly enough that residents of the community were able to leave their homes and get out of the way. La Conchita was immediately declared a geologic hazard area by Ventura County, and restrictions on new construction were imposed.

Following the 1995 landslide, the county commissioned a study to evaluate the risk of future events and to estimate the cost of stabilizing the sea cliff behind La Conchita. One of the key findings of the study showed that landslides are a common feature along this part of the coast and that the land beneath the homes is composed of about 25 m (~80 ft.) of landslide deposits. Age dating of these deposits showed that these sediments had all accumulated in the last 6,000 years.[32] A more recent study suggests that a large part of Rincon Mountain is part of a mega-landslide, similar to Portuguese Bend (see Case Study 7.2: Portuguese Bend, California), that occurred about 20,000 years ago.[33] Ironically, it appears as though La Conchita owes its existence to landslides, which have provided the sediment over the past several thousand years to build the broad strip of land on which the community is constructed.

The study also proposed constructing benches to reduce the slope of the sea cliff and installing an elaborate dewatering system, measures estimated to total about $150 million. However, due to the prohibitive cost of engineering such a structure for this small community, a less aggressive approach was undertaken, which included a limited drainage system and a modest wall designed to prevent mud from small slides and hillslope erosion from covering the road (Figure 7.35). This wall was not designed to stop another slide, and to make things worse, part of the landslide toe had to be removed to construct the wall, which likely weakened the slope.

Between 1995 and 2005, residents were repeatedly warned of the landslide hazard. Some people moved away following the 1995 slide; others, however, decided to stay or had no choice but to stay due to decreased property values following the slide. Others felt that the area was safer following the slide, and some people bought new property in the community. These were personal decisions based on individual perceptions of the hazard. However, the question was never whether another slide would occur, but when!



(a) (b)

▲ FIGURE 7.35 Retaining Wall Built Following the 1995 Landslide

(a) This retaining wall was constructed following the 1995 landslide and was installed to stop loose material from covering the road but was not designed to prevent another landslide. *(R. L. Schuster/USGS)* (b) The retaining wall was partially destroyed and locally overtopped during the 2005 mudflow (see also Figure 7.1b). *(USGS)*



< FIGURE 7.36 Earthflow Buries People, Houses, and Cars
The toe of the 2005 La Conchita landslide shown here buried at least 10 people and damaged or destroyed about 30 houses. When this mass of mud and debris flowed into and over these homes, it had the consistency of thick concrete pouring out of a cement truck. *(Edward A. Keller)*

The 2005 La Conchita landslide occurred on January 10 following 15 days of near-record rainfall levels in many parts of Southern California. U.S. Highway 101 had been shut down earlier that day due to a debris flow from one of the canyons northwest of La Conchita that had buried the roadway (Figure 7.34b). News crews were on site filming the aftermath of the debris flow and highway closure when at 12:30 P.M. the sea cliff above La Conchita started to move again. Unlike the 1995 landslide, the 2005 slide moved rapidly down the slope as an incohesive mass of flowing debris, which was actually caught on film by news crews. The earthflow was composed almost entirely of remobilized material from the southeastern portion of the 1995 landslide (Figure 7.34a). Although only about one-fifth the volume of the 1995 slide, the fluid flow of the 2005 landslide knocked down and locally overtopped the retaining wall built after the 1995 slide and moved into La Conchita, causing widespread damage, destroying 13 homes and severely damaging 23 others (Figure 7.36 and see Figure 7.1b). It is estimated that the flow moved at about 5 m (~15 ft.) per second through La Conchita.[1] Those who were outside and saw the flow coming ran for their lives, while those indoors had no time to escape; unfortunately, 10 people were killed when their homes were buried in the muddy debris.

The residents of La Conchita organized after the 2005 mudflow to coordinate with government officials on the best way to protect the community from yet another future landslide. Govenor Arnold Schwarzenegger allocated $667,000 toward scientific research into what could be done to stop mass wasting of the sea cliff behind La Conchita in March 2006. A lawsuit filed by residents of the community against the La Conchita Ranch Co., which operated an avocado ranch above the community (Figure 7.34a), found that the ranch was 50 percent negligent due to a lack of adequate drainage during the heavy rains that preceded the 2005 slide. Although the courts found human negligence to be partly to blame for the La Conchita disaster, it is clear now that the nature of the location, the original site selection for the community, and the residents' decision to stay were to blame for the damage and loss of life.

A 2010 report suggests that most of the homes could be protected from future events for a cost of only $50 million.[34] However, to date very little has been done to stabilize the slope. Moreover, the fear of triggering yet another slide by removing debris from the 2005 slide means the residents of La Conchita live with a daily reminder of the mass wasting hazard they face, and those who choose to live there do so at their own risk.

APPLYING THE 5 FUNDAMENTAL CONCEPTS

1. Discuss the evidence of the landslide hazard that was known before the landslide disasters in La Conchita. What precursor events occurred before the 1995 and 2005 landslides?
2. What steps could have been taken to reduce the landslide risk in La Conchita following the 1995 landslide, and what factors prevented these steps from being implemented?
3. Describe the linkages between the landslide hazard in La Conchita and other natural hazards.
4. Explain how and why human error made the disaster at La Conchita even worse.
5. How were the residents of La Conchita and Ventura County and state government agencies involved in attempting to minimize the consequences of landslides in the community?

CONCEPTS in review

7.1 An Introduction to Landslides

LO:1 Describe slope processes and the different types of landslides.
LO:2 Analyze the forces that act on slopes and how they affect the stability of a slope.

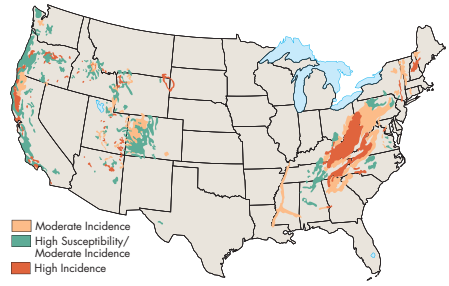
- The most common landforms are slopes—dynamic, evolving systems in which surface material is constantly moving downslope in the process of mass wasting at rates ranging from imperceptible creep to thundering avalanches.
- Slope failure may involve flowage, sliding, or falling of earth materials; landslides are often complex combinations of sliding and flowage.
- The forces that produce landslides are determined by the interactions of several variables: the type of earth material on the slope, topography and slope angle, climate, vegetation, water, and time.
- Determining the cause of most landslides can be accomplished by examining the relations between forces that tend to make earth materials slide, the driving forces, and forces that tend to oppose movement, the resisting forces.
- The most common driving force is the weight of the slope materials, while the most common resisting force is the shear strength of the slope materials. Geologists and engineers determine the safety factor of a slope by calculating the ratio of resisting forces to driving forces; a ratio greater than 1 means that the slope is stable; a ratio less than 1 indicates potential slope failure. 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. Moving water in streams, lakes, or oceans erodes the base of slopes, increasing the driving forces. Excess water within a slope increases both the weight and the underground water pressure of the earth material, which in turn decreases the resisting forces on the slope.
- Snow avalanches present a serious hazard on snow-covered, steep slopes. Loss of human life from avalanches is increasing as more people venture into mountain areas for winter recreation.



KEY WORDS

colluvium (p. 265), **creep** (p. 262), **debris flows** (p. 266), **driving forces** (p. 263), **falling** (p. 260), **flow** (p. 262), **landslides** (p. 258), **mass wasting** (p. 258), **resisting forces** (p. 263), **safety factor** (p. 263), **shear strength** (p. 263), **sliding** (p. 260), **slumping** (p. 262), **snow avalanche** (p. 272), **talus** (p. 259)

7.2, 7.3, and 7.4 Geographic Regions at Risk from Landslides Effects of Landslides and Linkages with Other Natural Hazards Natural Service Functions of Landslides



LO:3 Evaluate what geographic regions are at risk from landslides.

LO:4 Compare different mass wasting processes and their linkages with other natural hazards.

- Landslides may occur just about anywhere that slopes exist. The areas of greatest hazard in the United States include the mountainous areas of the West Coast and Alaska, the Rocky Mountains, and the Appalachian Mountains.
- Landslides are also linked to other hazards, especially floods, earthquakes, and wildfires.
- Landslides are locally responsible for creation of new habitats in forest and aquatic ecosystems and the generation of new land along the continental coasts.
- Landslides also expose deeply buried rocks and may expose and move precious minerals and elements so they may be concentrated at the base of the slope or in river deposits to be mined.

7.5 Human Interaction with Landslides

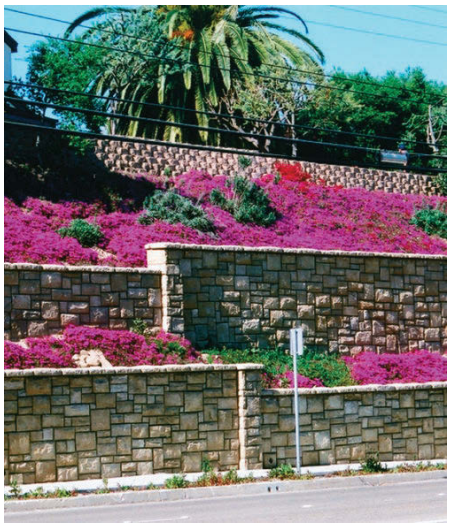


LO:5 Describe the ways in which people can affect the landslide hazard.

- The effects of land use on the magnitude and frequency of landslides range from insignificant to very significant. Where landslides occur independent of human activity, we need to avoid development or provide protective measures. In other cases, when land use has increased the number and severity of landslides, we need to learn how to minimize their recurrence.
- In some cases, filling large water reservoirs has altered groundwater conditions along their shores and caused slope failure. Logging operations on weak, unstable slopes have increased landslide erosion. Grading of slopes for development has created or increased landslide problems in many urbanized areas of the world.

7.6 Minimizing the Landslide Hazard

LO:6 Explain the adjustments people can make to avoid death and damage caused by landslides.



- To minimize the landslide hazard, it is necessary to establish identification, prevention, and correction procedures. Monitoring and mapping techniques help identify hazardous sites.
- Identification of potential landslides has been used to establish grading codes that have reduced landslide damage.
- Preventing large natural slides is difficult, but careful engineering practices can minimize the hazard where they cannot be avoided. Engineering techniques for landslide prevention include drainage control, proper grading, and construction of supports such as retaining walls.
- Efforts to stop or slow existing landslides must attack the processes that started the slide—usually by initiating a drainage program that lowers water pressure in the slope. Even with these improvements in recognizing, predicting, and mitigating landslides, the incidence of landslides is expected to increase throughout this century.

7.7 Perception of and Adjustment to the Landslide Hazard

LO:7 Summarize the ways in which you can protect yourself and property from the processes of mass wasting.

- Most people perceive the landslide hazard as minimal unless they have had prior experience. Furthermore, hillside residents, like floodplain occupants, are not easily swayed by technical information. Nevertheless, the wise person will have a geologist inspect property on a slope before purchasing.

CRITICAL thinking questions

1. Your consulting company is hired by the national park department in your region to estimate the future risk from landsliding. Develop a plan of attack that outlines what must be done to achieve this objective.
2. Why do you think that few people are easily swayed by technical information concerning hazards such as landslides? Assume you have been hired by a municipality to make its citizens more aware of the landslide hazard on the steep slopes in the community. Outline a plan of action and defend it.
3. The Wasatch Front in central Utah frequently experiences wildfires followed by debris flows that exit mountain canyons and flood parts of communities built next to the mountain front. You have been hired by the state emergency management office to establish a warning system for subdivisions, businesses, and highways in this area. How would you design a warning system that will alert citizens to evacuate hazardous areas?

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