◢ Chapter 20

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COLLUVIUM AND TALUS

1. INTRODUCTION

Physical and chemical weathering of bedrock produce disaggregated particles that accumulate on the land surface in the absence of erosional processes adequate to remove them. In locations with sufficient topographic relief, gravitational forces acting on these disaggregated particles cause them to move down the slopes and accumulate as distinctive deposits along the lower portions of slopes, in topographic depressions, and especially at the bases of cliffs. The terms *colluvium* or *colluvial materials* are used to refer to deposits that have been transported by gravitational forces.

The characteristics of colluvial materials vary according to the characteristics of the bedrock sources and the climate under which weathering and transport occur. Generally, colluvium is weakly stratified and consists of a heterogeneous mixture of soil and rock fragments ranging in size from clay particles to rocks a meter or more in diameter. These deposits are often only marginally stable. Because they are found along the lower portions of valley sides, such deposits frequently need to be partially excavated to allow passage of transportation facilities (Figure 20-1). The resulting cut slopes are commonly unstable and require constant monitoring and maintenance.

In humid tropical climates rapid chemical weathering promotes the formation of deep residual soils, or residuum. Creep of such soils on slopes may cause them to gradually take on the characteristics of colluvial materials. In cold climates colluvium is affected by the presence of permanently frozen ground, or *permafrost*. As discussed in Chapter 25, frozen ground conditions impede internal drainage and often lead to saturation of the surficial layers. *Solifluction*, the slow flowage of saturated surficial materials, produces characteristic lobate topographic patterns reflecting slope instability.

Instability of colluvial slopes in tropical conditions is discussed in Chapter 19, and Chapter 25 contains a discussion of such slopes in very cold climates. Information provided in this chapter

FIGURE 20-1
Colluvial slope along Denver and Rio Grande Western Railroad, Glenwood Canyon, Colorado.
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should be combined with that in Chapters 19 and 25 for a complete evaluation of these materials.

1.1 Definition of Colluvium

Bates and Jackson defined colluvium as follows:

> A general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rain wash, sheet wash, or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides. (Bates and Jackson 1980, 125)

Typically, colluvium is a poorly sorted mixture of angular rock fragments and fine-grained materials. These deposits rarely are more than 8 to 10 m thick, and they usually are thinnest near the crest and thickest near the toe of each slope (Figure 20-2).

Colluvium may be the most ubiquitous surficial deposit. Costa and Baker (1981) reported estimates that colluvium covers more than 95 percent of the ground surface in humid temperate regions and from 85 to 90 percent of the ground surface in semiarid mountainous areas. At the base of slopes, colluvium interfingers with alluvial deposits and may actually constitute the major portion of these deposits.

1.2 Definition of Talus and Scree

Relatively rapid physical fragmentation of bedrock exposed on cliffs frequently produces large numbers of rock fragments ranging in size from small to very large. After falling from the cliff, these frag-
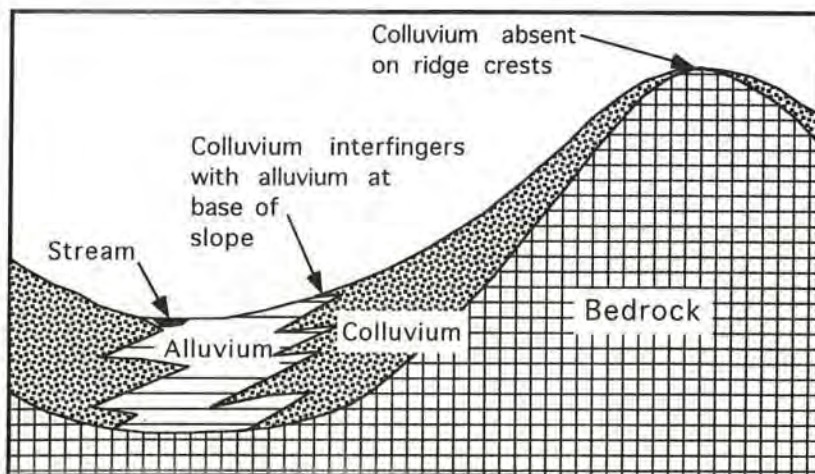

FIGURE 20-3
Talus slope in western Colorado.
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ments accumulate at the base to form a wedge-shaped deposit (Figure 20-3). A number of terms are used to describe these deposits, *talus* and *scree* being the most common. The term *talus* is derived from the French word for a slope on the outside of a fortification; originally it referred to the landform rather than the material. More recently, *talus* has been used to describe the material itself and *talus slope* has been used to define the landform. Often the cliff is not perfectly straight but contains recesses or ravines that tend to funnel the rock fragments into a chute (Figure 20-4); these fragments form a conical pile called a *talus cone* (Figure 20-5). In many cases multiple chutes form overlapping cones, creating a complex intermixing of talus materials (Figure 20-6).

Some geologists use *talus* and *scree* interchangeably, but there is considerable confusion concerning the definition and use of both terms. Bates and Jackson defined talus as

> rock fragments of any size or shape (usually coarse and angular) derived from and lying at the base of a cliff or very steep rocky slope. Also, the outward sloping and accumulated heap or mass of such loose broken rock, considered as a unit, and formed chiefly by gravitational falling, rolling, or sliding. (Bates and Jackson 1980, 638)

According to Bates and Jackson, scree is defined as follows:

> A term commonly used in Great Britain as a loose equivalent of *talus* in each of its senses: broken rock fragments; a heap of such frag-

FIGURE 20-2
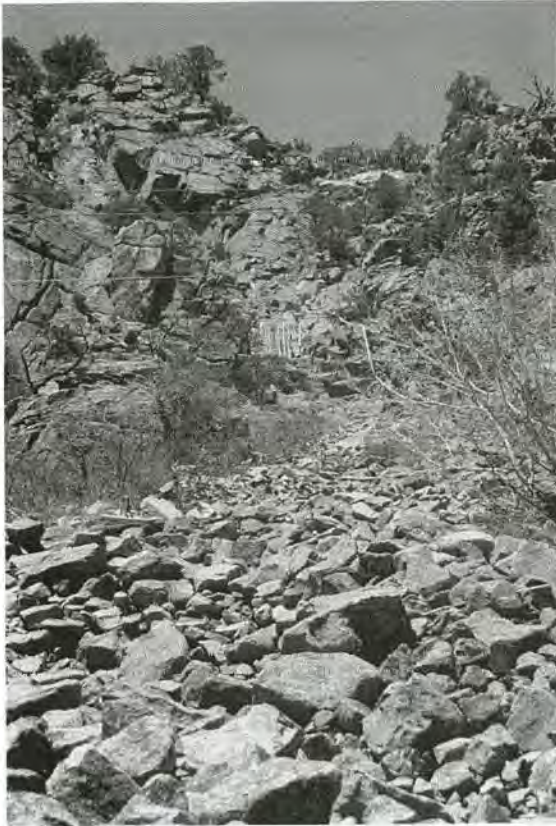Idealized cross
section of colluvial
deposit.

FIGURE 20-4
Rock chute as source of talus, Glenwood Canyon, Colorado.
J.D. HIGGINS, COLORADO SCHOOL OF MINES, GOLDEN, COLORADO

FIGURE 20-5
Talus cone, Glenwood Canyon, Colorado.
J.D. HIGGINS, COLORADO SCHOOL OF MINES, GOLDEN, COLORADO

FIGURE 20-6
Multiple overlapping talus cones forming complex talus deposit, Glenwood Canyon, Colorado. Construction of Interstate-70 is under way at base of this deposit.
R. D. ANDREW, COLORADO DEPARTMENT OF TRANSPORTATION

ments; and the steep slope consisting of such fragments. Some authorities regard scree as the material that makes up a sloping land feature known as talus; others consider scree as a sheet of any loose, fragmented material lying on or mantling a slope and talus as that material accumulating specifically at the base of, and obviously derived from, a cliff or other projecting mass. (Bates and Jackson 1980, 562)

Talus fragments can range in size to include huge boulders tens of meters across; however, a lower size limit has not been well defined. Typically, large fragments are found near the toe of the deposit and smaller particles are found near the top because the greater momentum and larger radius of the bigger particles permit them to travel further (Figures 20-3 and 20-4). The maximum angle of slope that can be held by a loose pile of rock fragments, regardless of their size, is termed the *angle of repose*. Talus slopes composed of frag-

ments of varying sizes typically exhibit angles of repose that are rarely less than 34 degrees or greater than 37 degrees (Strahler 1971, 583). The angles of most talus slopes appear relatively uniform from top to bottom (Figure 20-3). However, several authors suggest that these slopes may be slightly concave, with steeper angles on the highest portions.

1.3 Terms Used in This Chapter

In this chapter the terms *colluvium* or *colluvial deposits* will be considered the most generic for all deposits created by the accumulation of disaggregated particles largely by gravitational forces. For such deposits composed of predominantly coarse rocky fragments, the term *talus* will generally be used to refer to both the landform and the material, and the term *talus slope* will be used only when it is necessary to distinguish between the landform and the material. The term *scree* will not be used.

2. SLOPE INSTABILITY IN COLLUVIUM

Given the ubiquitous nature of colluvium and its distribution within many hilly or mountainous areas, it should not be surprising that the instability of colluvial slopes has resulted in major economic losses and on some occasions the loss of human life (Costa and Baker 1981).

The most common class of landslides in colluvium involves two distinct components of movement: an initial shallow rotational or translational slide followed by flowage of the disturbed mass (Ellen and Fleming 1987; Ellen 1988). This failure mode results in a relatively small circular scar

at the location of the initial slide, a long narrow track leading directly down the hillside formed by the flowage of the liquefied soil and debris, and a zone of deposition in the minor drainage channel at the base of the slope (Figure 20-7). Numerous individual such slides provide large volumes of debris that clog stream channels. Liquefaction of this material causes it to remobilize and produce large and rapidly moving debris flows that destroy lives and property downstream.

Various terms have been used for such landslides in the past, including *debris avalanche* (Sharpe 1938), *soil slip/debris flow* (Campbell 1975), *flow slide* (Hutchinson 1968), *soil avalanche* (Wentworth 1943; Keefer 1984), and *disintegrating soil slip* (Kesseli 1943). In this chapter these landslides will be referred to as *debris flows* to conform with the terminology developed in Chapter 3. However, it should be noted that in these landslides both sliding and flowing are critical to the process. Sliding determines the timing and location of the initiation of the movement, whereas flowing determines movement path and rate. A more complete term for these landslides would be *soil slide–debris flow*; however, the simpler term *debris flow* will be used except in cases where a distinction between slide and flow is useful.

Debris flows involving colluvium may move with velocities exceeding 3 m/sec, and their composition will reflect not only the colluvium materials, which may range from fine-grained soils to coarse-grained debris, but also abundant coarse organic materials (such as trees) and materials from within and adjacent to stream channels (including buildings and automobiles). Accordingly, debris flows may include movements that others have termed *mudflows, debris avalanches,* or *debris torrents* (Sharpe 1938; Swanston and Swanson 1976; Varnes 1978). This simplification appears justified because all these processes are similar (Costa 1984; Ellen and Wieczorek 1988, 4).

Much colluvium in midlatitude regions originated during Pleistocene glacial periods when a mantle of rubble was formed by vigorous frost action on bedrock exposed beyond the ice-sheet margins. In areas subjected to glaciation, colluvial deposits overlie, and thus are younger than, glacial deposits. In investigations of slope stability in midlatitude regions, it must be recognized that many of these colluvial deposits formed under different climate regimes. Since their physical properties reflect

FIGURE 20-7
Principal features of a soil slide–debris flow (modified from Smith 1988).
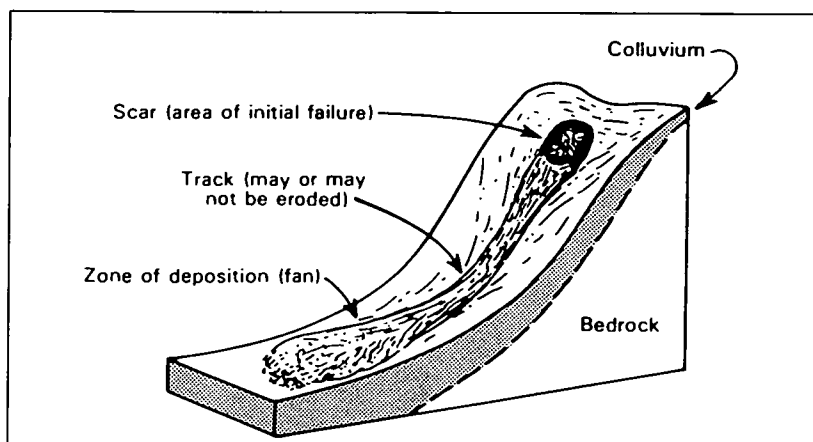
both their age and their origin, their stability may be marginal under current climate conditions.

Sidle et al. (1985) identified five natural factors that have the greatest influence on the stability of colluvial slopes:

1. Soil properties, especially the hydrologic and mineralogic conditions that affect engineering soil behavior and strength properties of the colluvium;
2. Geomorphology, including the geologic and tectonic setting, slope gradient, and shape;
3. Hydrology, especially soil water recharge and effective evapotranspiration rates that reflect local climate and vegetation conditions;
4. Vegetative cover, including the reinforcing effect of root systems and the loss of such strength when roots deteriorate following timber harvesting or fire; and
5. Seismicity, especially the potential for liquefaction of marginally stable soils on steep slopes.

These natural factors are important on all slopes, but they must be evaluated in special ways when slopes are formed with colluvial materials. Section 2.3 contains a discussion of commonly found characteristics of colluvial deposits that must be considered when field investigations are conducted or strength properties are assigned for stability calculations. Geomorphic factors, especially the importance of topographic hollows in many situations, are evaluated in Section 2.4. Hydrology and the importance of vegetative cover to the stability of colluvial slopes are discussed in Sections 2.5 and 2.6, and the frequently overlooked effects of fire on the strength and erosion resistance of colluvium are discussed in Section 2.7. Seismic shaking frequently results in widespread failures of colluvial slopes, but since this topic is addressed in Chapter 4, only a brief discussion is included in Section 2.8 of this chapter.

2.1 Studies of Landslides in Colluvium

Before the 1960s, the importance of landslides in colluvium was largely ignored except by researchers in southern California (Eaton 1935; Sharpe 1938; Kesseli 1943). Several collections of technical reports now exist that address colluvial landslides from several aspects and at various levels of detail. The Geological Society of America

has published three major collections of studies of colluvial landslides (Coates 1977; Costa and Wieczorek 1987; Schultz and Jibson 1989). Books by Sidle et al. (1985) and Anderson and Richards (1987) also contain considerable information about such landslides as well as examples of landslides that do not involve colluvium. Numerous references will be made to these publications in the subsequent discussion.

Japanese researchers have also conducted detailed evaluations of the landslide danger on colluvial slopes (Sassa 1984; Sassa et al. 1981; Takahashi 1978). Reviews and assessments of these Japanese studies were provided by Chen (1987) and Okunishi and Okimura (1987).

Unusually large rainstorms have triggered catastrophic landslide events in colluvium at several locations around the world. These events led to considerable economic damage and loss of life. They were thus studied in some detail to determine their underlying causes in the hope that this information would prove useful in preventing future disasters. These studies form the basis for much of the current knowledge and theories concerning landslide processes involving colluvium.

Jones (1973) was the first to emphasize the potential severity of colluvial landslides in areas beyond southern California. He reported on the tens of thousands of landslides that occurred along the Serra das Araras escarpment in Brazil following a severe storm on January 22–23, 1967. Debris flows developed on valley sideslopes in colluvial and residual soils several meters thick overlying the crystalline bedrock. The steep vegetation-covered slopes were nearly denuded as soil and rock debris flowed into local valleys. Once deposited in the valleys, the materials became remobilized and formed huge debris flows that caused severe damage to roads and a major power plant and killed more than 1,700 people (Jones 1973; Costa and Baker 1981). Very similar thin landslides and debris flows were observed in saturated residual soils in southwestern Colombia (Figure 20-8). In this case, however, the landslides were triggered by earthquake shaking rather than intense rainfall.

In August 1969, Hurricane Camille caused severe damage in the Blue Ridge Mountains region of Virginia (Williams and Guy 1973). Thick colluvium and weathered bedrock were destabilized by a 24-hr precipitation that exceeded 600 mm, and debris flows surged rapidly down heavily

FIGURE 20-8
Thin landslides and debris flows on steep slopes of saturated residual soils at headwaters of San Vicente River, southwestern Colombia, triggered by 1994 Paez earthquake.
R. L. SCHUSTER, U.S. GEOLOGICAL SURVEY

FIGURE 20-9
Debris flows along East Branch of Hat Creek, Virginia, caused by Hurricane Camille in 1969 (Williams and Guy 1973, Figure 14a).

forested natural slopes (Figure 20-9). Most of the 150 people killed by this storm were overwhelmed by these rapidly moving debris flows (Costa and Baker 1981).

An unusually powerful storm affected the San Francisco Bay region of California in January 1982. It caused numerous colluvial landslides that resulted in considerable property damage and several deaths. These landslides were subjected to exten-

sive investigations (Smith and Hart 1982; Ellen and Wieczorek 1988). Other studies in the eastern United States (Schultz and Jibson 1989) and in Puerto Rico (Jibson 1989) have been reported. More recently, there has been a series of studies on colluvial landslides in the Cincinnati area of Ohio (Baum 1994; Fleming and Johnson 1994; Haneberg and Gökce 1994; Riestenberg 1994).

Southern California has had long experience with colluvial landslides that occurred after fires had removed slope vegetation. Much research has been conducted to evaluate the effects of fire on the rate of landsliding on colluvial slopes in southern and central California (DeBano et al. 1967; Campbell 1975; DeBano 1980; Wells 1987) as well as in Scotland, New South Wales, and Oregon (Fairbairn 1967; Brown 1972; Mersereau and Dyrness 1972; Bennett 1982).

2.2 Description and Mechanics of Colluvial Landslide Processes

Several workers have noted that the initiation and style of movement of landslides on colluvial slopes reflect the thickness of the colluvium (Ellen and Fleming 1987; Fleming and Johnson 1994). Landslides involving thick colluvium are usually relatively slow-moving rotational slides that rarely exhibit subsequent disaggregation and flowage. In contrast, landslides on slopes mantled with thin colluvium exhibit an initial translational sliding failure and a subsequent disaggregation of this sliding mass to form a debris flow. This *soil slide debris flow* movement is the most commonly observed failure mode involving colluvial slopes. The mechanism causing the mobilization and flowage of the sliding mass has been the subject of considerable investigation and debate (Johnson and Rahn 1970; Morton and Campbell 1974; Campbell 1975; Sassa 1984; Ellen and Fleming 1987; Ellen 1988; Howard et al. 1988).

Howard et al. (1988) defined the transformation of an initially rigid sliding soil mass into a debris flow as consisting of five stages (Figure 20-10). The first stage [Figure 20-10(a)] occurs as the colluvium slides along, or just above, the soil-bedrock contact. The sliding process is controlled by tension cracks in the colluvium and by high pore-water pressures caused by a permeability contrast between soil and bedrock. With continued movement, the second stage [Figure 20-10(b)] evolves as internal shearing causes a reduction in strength
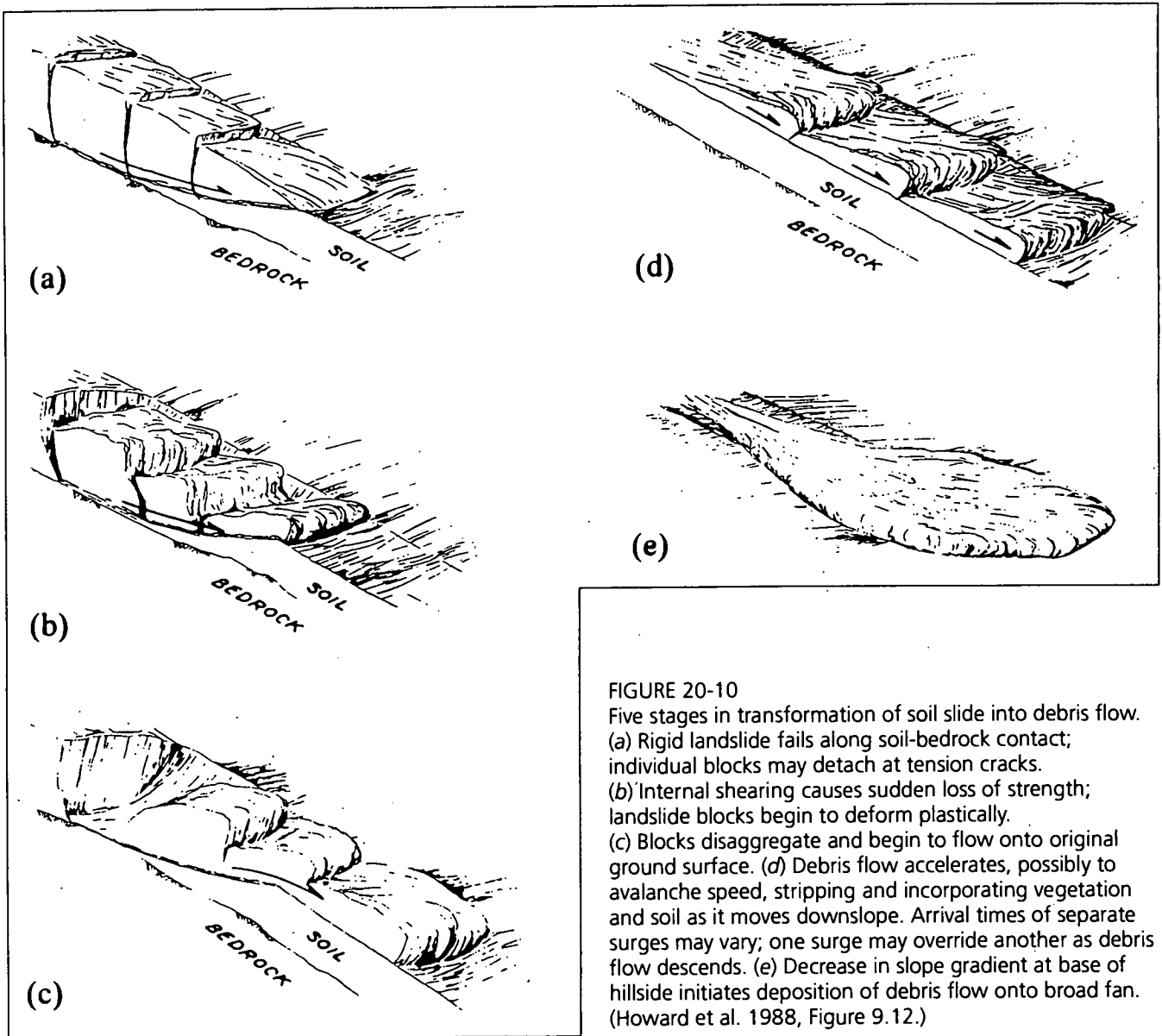
FIGURE 20-10
Five stages in transformation of soil slide into debris flow.
(a) Rigid landslide fails along soil-bedrock contact;
individual blocks may detach at tension cracks.
(b) Internal shearing causes sudden loss of strength;
landslide blocks begin to deform plastically.
(c) Blocks disaggregate and begin to flow onto original
ground surface. (d) Debris flow accelerates, possibly to
avalanche speed, stripping and incorporating vegetation
and soil as it moves downslope. Arrival times of separate
surges may vary; one surge may override another as debris
flow descends. (e) Decrease in slope gradient at base of
hillside initiates deposition of debris flow onto broad fan.
(Howard et al. 1988, Figure 9.12.)

of the colluvium. Increasing levels of plastic de-formation result (Johnson and Rahn 1970; Campbell 1975). Shearing causes dilation of the soil mass. Water from tension cracks is drawn into the dilating mass, further weakening and disag-gregating the soil material. In stage three, the soil material begins to flow over the ground surface [Figure 20-10(c)]. As the initial mass continues to flow down the slope, it commonly accelerates and incorporates soils and debris, forming, in stage four, a debris flow [Figure 20-10(d)]. At the base of the slope, the decreased gradient causes deposi-tion of the debris in stage five [Figure 20-10(e)].

Ellen and Fleming (1987) and Ellen (1988) re-ported on investigations of the numerous colluvial landslides that occurred in the San Francisco Bay Area following a severe storm in January 1982. These investigations combined field observations with laboratory testing of soil samples to produce a better understanding of the mechanisms con-trolling landslides in colluvium.

Field observations confirmed that the most com-mon form of landsliding was a combination soil slide-debris flow. The initial failure produced a shal-low, relatively small landslide scar caused by trans-lational sliding of the colluvium over the bedrock.

Most of these initial soil slides mobilized completely to form debris flows that drained the scars, leaving them empty of failed material. The debris flows ran rapidly downhill in relatively narrow tracks. However, in some cases the mobilization of the sliding material was less complete. Such partially mobilized flows left dislocated masses of materials in the initial landslide scar and carried intact blocks of material down the slope within the debris flow. Reliable eyewitness reports suggested that rates of mobilization varied from just a few seconds to more than 24 hr (Ellen and Fleming 1987).

Ellen and Fleming wished to identify reasons for such differences in degree and speed of mobilization and flow of the initial soil slide materials. Previous studies (Rodine 1974; Pierson 1981) suggested that some clay in the colluvium is necessary to sustain flow. However, Ellen and Fleming suspected that there must be an upper limit to the amount of clay. They suggested that increased clay content adds cohesive strength to soils, which impedes remolding and also reduces permeability. Ellen and Fleming considered reduced permeability as critical because most soils having normal densities dilate when subjected to shearing and must then take up additional water to continue flowing. Reduced permeability would interfere with the rapid intake of water.

In the Ellen and Fleming study, the clay contents of 50 soil samples ranged from about 3 to 35 percent; however, 98 percent of the samples had clay contents greater than 8 percent. When samples obtained from very slow-moving debris flows in cut slopes or old landslides were removed from consideration, the largest clay content was 25 percent. Ellen and Fleming concluded that the range in clay contents, from 8 to 25 percent, was still so broad that clay content by itself was inadequate to define colluvial slopes that might be susceptible to landsliding. They looked for some additional quantitative measures that might help define this susceptibility.

Rodine (1974) and Johnson (1984) proposed a mobility index (MI) defined as

$$MI = \frac{\text{Saturated water content of in-place soil}}{\text{Water content required for that soil to flow}}$$

$$(20.1)$$

Although it is obvious that flow is most apt to occur when MI ≥ 1.0, they demonstrated that it can take place when MI is as low as 0.85. However,

the determination of MI required soils testing to obtain a value for the denominator, the water content required for the soil to flow. This appeared inconvenient to Ellen and Fleming, and they proposed an approximate mobility index (AMI) defined as

$$AMI = \frac{\text{Saturated water content of in-place soil}}{\text{Liquid limit}}$$

$$(20.2)$$

Ellen and Fleming (1987) justified this change on practical grounds. Qualitatively, the liquid limit represents a water content at which soils exhibit marginally fluid behavior at near-surface conditions. Quantitatively, the liquid limit corresponds to a shear strength of about 2 kPa, and if this shear-strength value is used in the equation describing shear flow proposed by Johnson (1970), flow is predicted for colluvium slabs thicker than about 20 cm on slopes of 30 degrees for typical soil materials having saturated unit weights of 20 kN/m³ (Ellen and Fleming 1987, 34). Since this critical thickness value of 20 cm was considerably less than the 1-m thicknesses typically observed in the San Francisco Bay Area, Ellen and Fleming believed that this validated the AMI concept.

Ellen and Fleming suggested that the observed differences in degree and rates of mobilization could be explained by differences in soil structure or fabric. Soils that have a relatively flocculated or loose fabric will collapse when subjected to even small shear movements. Under wet conditions, the collapse leads to a rapid liquefaction due to increased pore pressure. Collapsible soils having low permeability are especially susceptible, since rapid drainage of the excess water is unlikely. In contrast, relatively dense colluvial soils dilate when subjected to shear. The increased volume requires water to be drawn into the soil mass in order for flowage to continue. This water inflow requires time, especially if the soil has a relatively low permeability.

From the foregoing considerations, Ellen and Fleming (1987) concluded that loose, contractive colluvium with relatively low permeability is the most likely source of rapidly mobilized debris flows. These soils have void ratios greater than those at the liquid limit and hence when saturated have AMI values greater than 1.0. Liquefaction is almost instantaneous, occurring after strains as small as 1 percent, and the debris flows empty the initial landslide scars and flow rapidly downslope
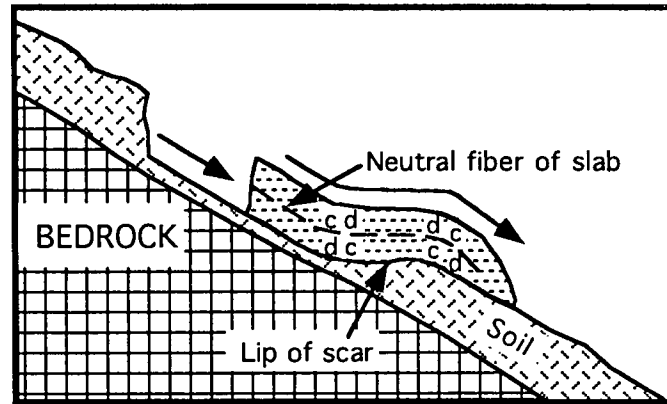
forming debris deposits with smooth surfaces. In contrast, dilative, denser colluvium is less likely to mobilize rapidly. Shear deformation along the base of the sliding mass is usually inadequate to remobilize the entire soil mass. Selective mobilization along the flanks and margins is possible, creating blocks within the mass. Cracks may channel water to selected areas, further encouraging selective remobilization. At the toe of the sliding slab, liquefaction may result from the greater volume of available water coupled with greater strains and remolding caused by oversteepening and bending as the slab moves out of the scar (Figure 20-11). Consequently, dilative, denser colluvial deposits produce slower-moving debris flows containing lumps or blocks of undeformed material. In some cases these denser colluvial soils produce more slablike, broader landslide areas (Figure 20-12).

2.3 Characteristics of Colluvium Affecting Slope Stability

Colluvium is formed by the movement and deposition of particles by gravity, although water and wind are sometimes secondary transportation agents. Colluvium may accumulate one small grain at a time or as a result of large catastrophic movement of materials, especially debris flows. In rugged terrain, colluvium can be merged and interlayered with alluvium in debris fans and cones associated with minor drainages. The aprons or wedges of colluvium may be modified over time by deposition, flooding, and dissection of stream channels and by internal composition changes resulting from weathering. Within any given colluvial deposit, particle gradation and density vary with depth and in irregular patterns across the extent of the deposit.

Colluvium frequently contains stratigraphic horizons that represent changes in deposition rates. For example, long periods of inactivity may allow the development of organic soil horizons that are then covered during periods of intense deposition. These horizons can be observed in excavations but are difficult to discern by conventional drilling methods.

Colluvium formed in arid regions often results from a combination of gravity-driven grain-by-grain downslope movements with debris-flow materials rapidly deposited from rare flash floods. These floods are of short duration and lose their moisture

FIGURE 20-11 Schematic downslope cross section of soil slide–debris flow as it leaves scar, showing zones of dilation d and contraction c in slab as it passes over lip. Position of neutral fiber depends on soil behavior (modified from Ellen 1988, Figure 6.30).

rapidly by evaporation and infiltration. The resulting deposits often exhibit a very flocculated or loose soil structure that is stable only as long as it remains dry. Wetting of these soils, such as may be caused by diversion of water from a paved highway surface, will cause the flocculated structure to collapse to a much smaller volume. This collapse may further lead to temporary liquefaction of the soils and their rapid erosion by flowage. These arid colluvial soils are said to be subject to *hydrocompaction*. Hydrocompaction may lower the ground surface by as much as 1 m (Figure 20-13).

Hydrocompaction is obviously damaging to transportation facilities. Its potential can be readily determined by evaluating in situ soil densities. Stabilization can be achieved by saturating the materials before construction, but a considerable period of time may be required for complete saturation and compaction. Also, stabilization requires large volumes of water, which may not be available in arid regions where hydrocompaction risk is most frequent. Even after compaction is achieved, these soils remain highly erodible, so careful design of culverts and water collection and dispersal systems is necessary.

Shales and other soft rocks generally produce fine-grained colluvium, often containing significant proportions of clay. The slow downslope creep of colluvium results in a progressive alignment of mineral grains and the creation of numerous microscopic shear surfaces. These surfaces greatly reduce the normally expected shear strength of colluvial materials, and yet the surfaces are hard to identify or retain in samples. Fleming and Johnson reported on their examination of colluvial landslide materials from the Cincinnati, Ohio, area:
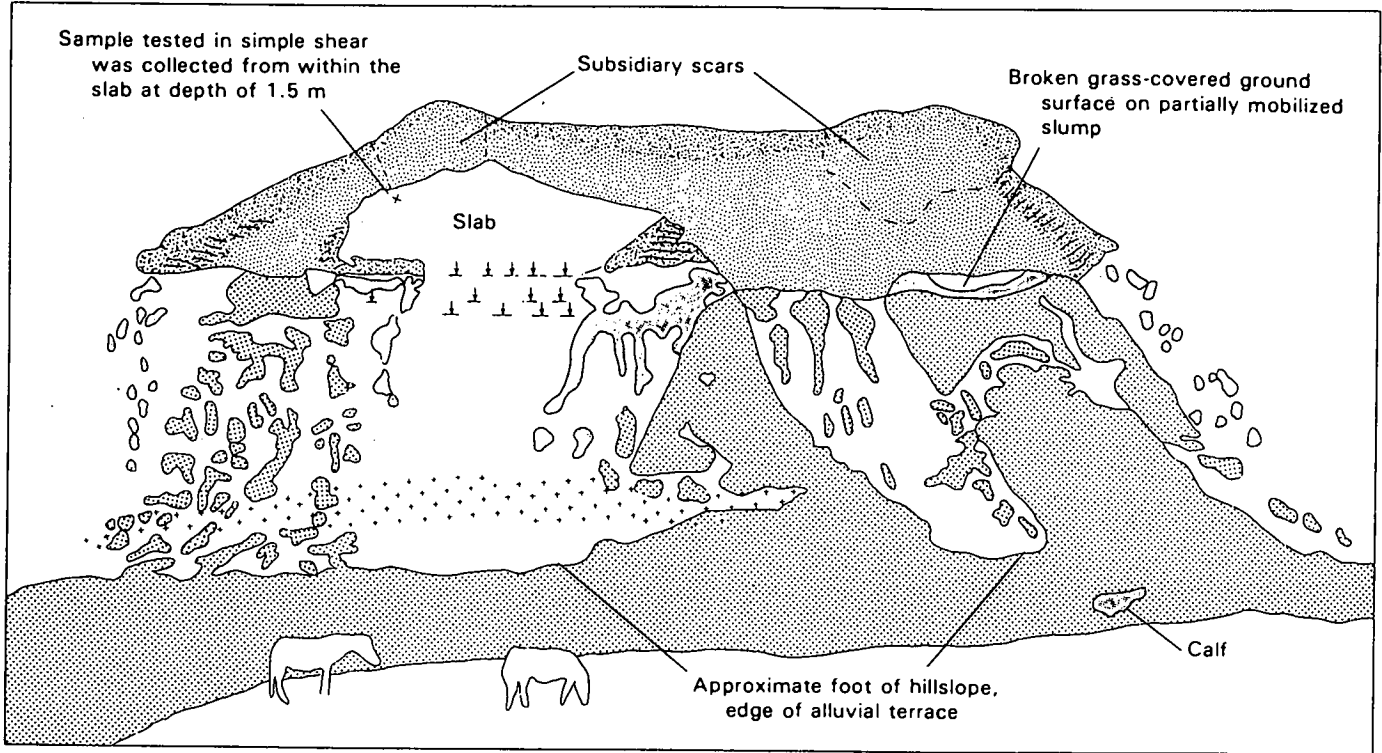
FIGURE 20-12 Sketch based on photograph of landslide in shallow colluvium along Salmon Creek, Marin County, California. Hillside slopes toward observer at about 22 degrees. Both margins of landslide have mobilized as debris flows; slab remaining within arcuate scar above horses has slid downward about 1 m (Ellen 1988, Figure 6.35B).

0   5 METERS

APPROXIMATE SCALE AT SCAR

EXPLANATION

☐ Ground surface covered by grass or brush

▨ Dark soil exposed in scar

▨ Light-colored soil and bedrock exposed in scar, and lesser light-colored deposits on floor of scar

☐ Deposits from dark soil

▨ Deposits largely from light-colored soil

⬛ Remnants of slip surface at base of dark soil

· · · Area of seepage

⊥ ⊥ Slip surface at toe of slab

— — — Boundary of subsidiary scars

The failure surfaces are paper thin, highly polished, and striated. At all scales of observation, roughness is evident on the surfaces. At a scale of a few micrometers, the surfaces have small steps between shiny surfaces that appear to be analogous to chatter marks on rocks in fault zones. At a larger scale, the surfaces are scratched by fossil fragments and sand-size grains in the colluvium. At a still larger scale, the surfaces bifurcate around rock fragments, and multiple surfaces occur where the shape of the failure surface is changing. (Fleming and Johnson 1994, B-1)

Fleming and Johnson (1994) differentiated between landslides that occurred in thin colluvium (less than about 2 m thick) and those that occurred in thicker colluvium. They noted that the thick-colluvium landslides moved relatively slowly, perhaps only a few centimeters a year, and exhibited multiple overlapping scarps at their heads, multiple toe bulges downslope, and indis-

tinct flanks. In contrast, the landslides in the thin colluvium moved more rapidly, typically exhibited a "stick-slip" behavior in which they accelerated after initial movement, and often moved completely out of their initial failure scars. These landslides had well-defined flanks, multiple head scarps, and a single toe.

Fleming and Johnson conducted laboratory tests on soil samples collected near the failure zones. Strength values varied according to the way the samples were collected and tested. Minimum strength values were obtained from a ring-shear device using samples that had had their coarse fractions removed. These estimates of residual shear strength values matched values obtained by back calculation of stability for the thick-colluvium landslides. The measured, laboratory-derived shear-strength values appeared insufficient to support the colluvium on the thin-colluvium slopes. Fleming and Johnson suggested that additional strength provided by tree roots, roughness of the failure surface, or a small residual cohesion might explain the discrepancy between the apparent strength and the slope stability.

2.4 Geomorphic Factors

A uniform thickness of colluvium is rarely present on any slope, and thicker deposits may effectively mask minor hollows in the underlying bedrock surface (Figure 20-14). The presence of such hollows may materially affect the stability of a colluvium-covered slope (Dietrich et al. 1986). Hack and Goodlett (1960) proposed that slopes be divided geomorphically into hollows, noses, and side slopes. Hollows are "any area on the slope in which the contours are concave outward away from the ridge" and they "generally occur in the valley axis at the stream head as a sort of extension of the channel" (Hack 1965, 20). Noses are areas "on the interfluve in which the slopes are convex outward toward the valley" (Hack 1965, 21), and side slopes are areas with straight contours located between noses and either hollows or channels.

The importance of hollows as locations susceptible to the initiation of colluvial landsliding varies, both locally and between regions, because of complex interactions and small variations in geologic, topographic, and climate factors. Hollows frequently appear to be important sources of debris flows. However, their importance as initiators of shallow colluvial landslides is more variable.

Hack and Goodlett (1960) first noted that hollows appeared to be an important factor in initiating debris flows in the Appalachian Mountains of Virginia. Their observations were subsequently confirmed by others (Woodruff 1971; Williams and Guy 1973; Lessing et al. 1976; Bogucki 1977; Pomeroy 1981, 1984). The importance of hollows was also revealed by studies in other regions: in coastal Alaska (Swanston 1967, 1969), British Columbia (O'Loughlin 1972), and the Oregon Coast Range (Pierson 1977; Deitrich and Dunne 1978; Swanson et al. 1981; Swanson and Roach 1985). Studies conducted in the San Francisco Bay Area following the damaging storm of January 1982 focused on hollows as a source of debris (Smith and Hart 1982; Reneau and Dietrich 1987; Ellen and Wieczorek 1988; Smith 1988).

In general, it appears that hollows are most important in areas where hill slopes are underlain by fairly massive bedrock and there is a regular dissection of the topography into minor drainages, and hollows are less important where the bedrock is variable and the topography is less regular. Along the Oregon coast, where the bedrock is composed of volcanic rocks including lava flows, tuffs, and breccias, Marion (1981) reported that side slopes were more important sites of landslide initiation than hollows. Jacobson (1985) reported that shallow landslides tended to initiate on benches on side

FIGURE 20-13 Results of saturation test on hydrocompactible colluvial soils in western Colorado; land surface has collapsed about 1 m.

A.K. TURNER, COLORADO SCHOOL OF MINES, GOLDEN, COLORADO

EXPLANATION

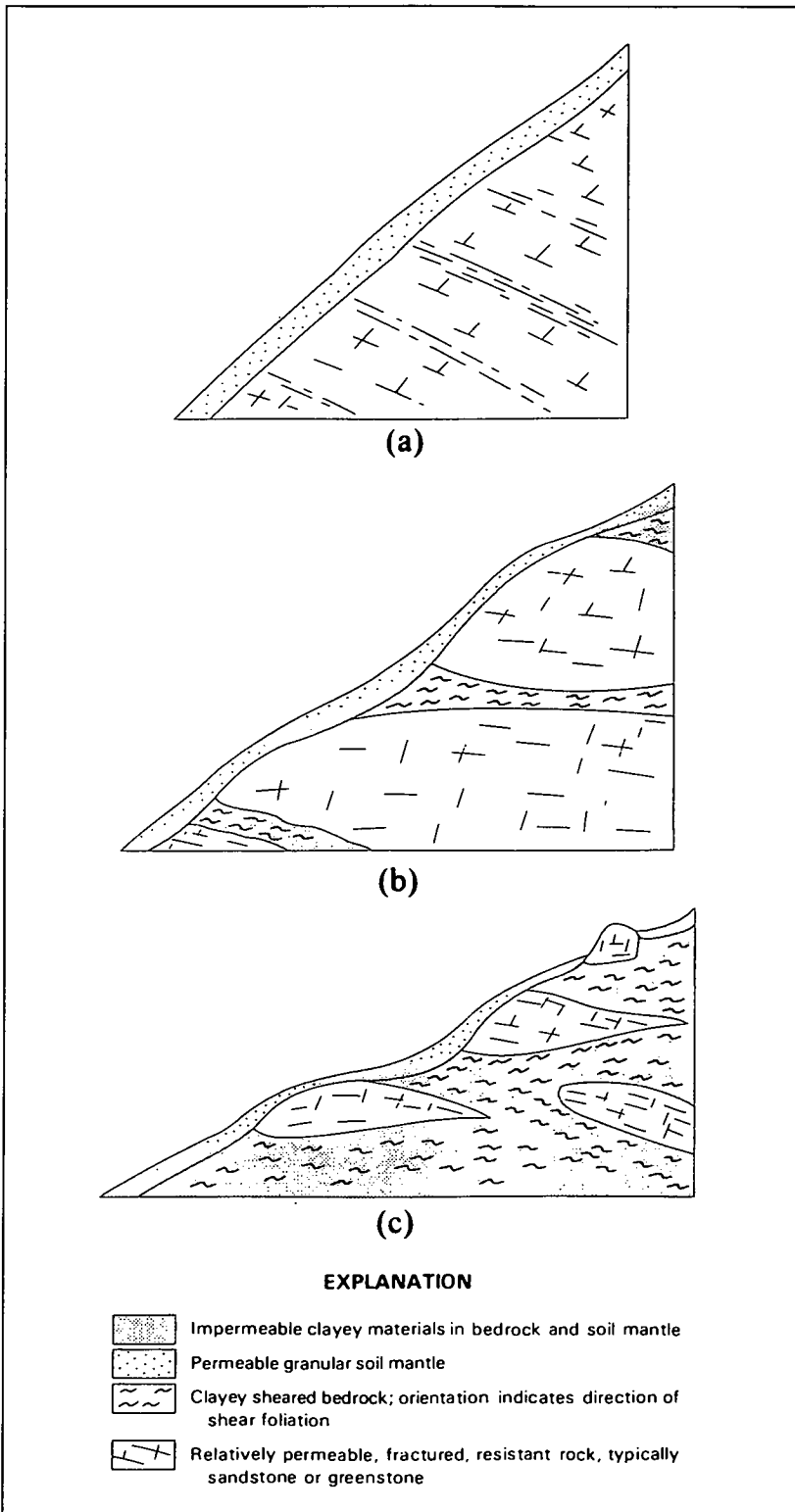|	
░░░	Impermeable clayey materials in bedrock and soil mantle
∴∴∴	Permeable granular soil mantle
∼∼∼	Clayey sheared bedrock; orientation indicates direction of shear foliation
⌐⊥⊢	Relatively permeable, fractured, resistant rock, typically sandstone or greenstone

FIGURE 20-14
Schematic downslope cross sections of hillsides in (a) hard,
(b) intermediate, and (c) soft bedrock terrain, showing how hollows may
mask bedrock irregularities (Ellen et al. 1988, Figure 7.5).

slopes formed of stratified sandstone and shale and not along hollow axes. Pomeroy (1981, 1984) reported that in areas of Pennsylvania where sandstone and shale are interbedded, the topography lacks a regular division into noses and hollows, and in these regions hollows are not important factors in initiating landslides. However, in nearby regions where steeper slopes are underlain by more sandstone and less shale, hollows appear to be the most important source of landslides.

In the San Francisco region, about two-thirds of the shallow colluvial landslides are initiated in hollows (Smith and Hart 1982; Reneau and Dietrich 1987; Smith 1988). This finding suggests that the mapping and identification of hollows be given priority in producing landslide hazard maps for this region. Hollows act not only as sources of landslides but also as conduits for debris flows that frequently result from the initial landsliding. Landslide hazard and susceptibility mapping procedures based on analysis of drainage patterns have been implemented (Hollingsworth and Kovacs 1981; Baldwin et al. 1987; Smith 1988).

2.5 Hydrology

Intense rainfall is cited as the most common triggering mechanism for landslides involving colluvium (Jones 1973; Campbell 1975; Fukuoka 1980; Brand et al. 1984; Cannon and Ellen 1985; Church and Miles 1987; Neary and Smith 1987; Wieczorek 1987). Much work has been done to relate debris-flow occurrences to rainfall intensity and duration (Campbell 1975; Mark and Newman 1988; Cannon 1988; Cannon and Ellen 1988; Wieczorek and Sarmiento 1988). Campbell (1975) suggested that at least 267 mm of rainfall is necessary in southern California after a dry season to bring the soils to field capacity, the water content at which water drains from the soil at the same rate as it is added. Campbell further demonstrated that a rainfall intensity of 5 to 6 mm/hr is necessary to trigger debris flows once field capacity has been achieved.

Kesseli (1943) postulated that slope failure of colluvium occurs when rainfall intensity is great enough to cause water to percolate into the colluvium at a rate that exceeds the rate at which the water can percolate into bedrock (Figure 20-15). This condition forms a temporary perched water table in the colluvium, and a downslope seepage force develops within the soil mass. Excess pore

FIGURE 20-15
Buildup of perched
water table in
colluvium during
heavy rainfall
(Campbell 1975,
Figure 16).
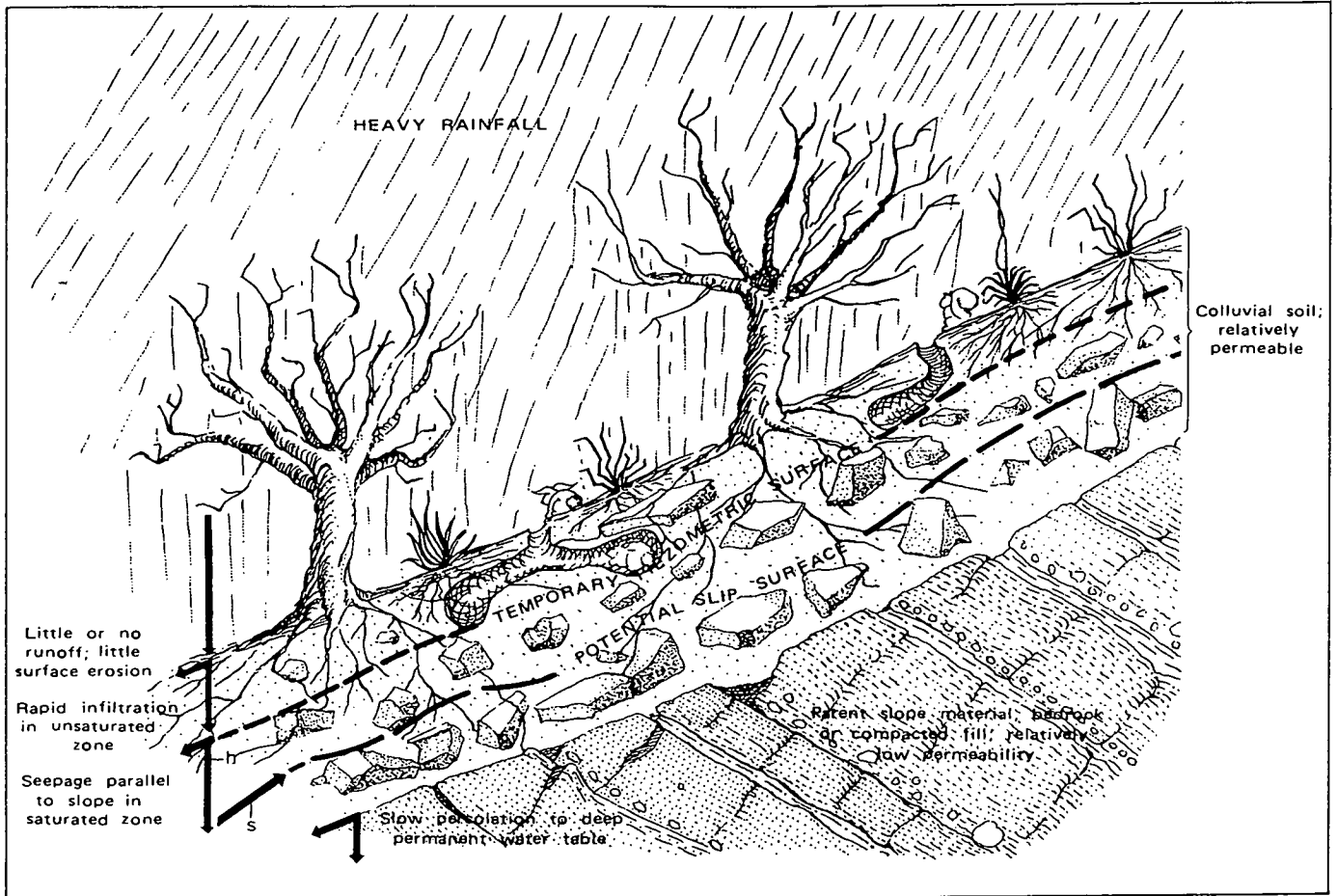
pressures develop, the soil becomes buoyant, and the resisting forces are decreased. This Kesseli model has been adopted by Campbell (1975) and many other workers to explain the initiation of soil sliding in colluvium, the most commonly observed initial failure mechanism.

Water can be concentrated at certain locations within a colluvial slope by various means. Topographic effects, especially the presence of hollows, are discussed in Section 2.4. Ellen (1988) noted that the flow of water within the colluvium may be concentrated by several other factors: the shape of the bedrock surface, breaks in the slope, differences in permeability within both the colluvium and the bedrock, and human-induced modifications to the slope. This last factor includes many of the modifications resulting from the construction of transportation facilities, such as cut-slope geometries and installation of ditches and culverts that modify the patterns of surface flow and concentrate flows at specific locations. Designers of transportation facilities that cross colluvium must carefully consider the possible effects of the proposed drainage collection and discharge systems on the future stability of these slopes.

The relationship between groundwater conditions within the bedrock and initiation of colluvial landslides has also been noted (Ellen 1988; Ellen et al. 1988). Permeability contrasts within the bedrock may result in artesian conditions. Seepage of water from bedrock into the colluvium is more likely where the bedrock has layers with strong permeability contrasts that dip out of the slope. Seepage rates within bedrock aquifers are usually quite low, but Ellen (1988) stated that at least some of the bedrock seepage that affected initial soil slides in the San Francisco Bay Area appeared to have been fed by storm rainfall.

2.6 Vegetation

Plant root systems may increase slope stability for colluvial materials on steep slopes, and the nearly

total removal of forest cover by clearcutting may cause increased slope instability. Nevertheless, vegetation growing on a slope was traditionally considered to have a negligible effect on slope stability and was ignored in slope stability computations (Greenway 1987). However, studies in the mountainous forested regions of the United States, Canada, Japan, and New Zealand have shown that neglecting the effects of vegetation on steep slopes mantled with relatively thin colluvial soils can yield stability estimates that are considerably in error. Still, vegetation-slope interactions are complex, and this complexity has hampered attempts to quantify such interactions in slope-stability analyses (Greenway 1987).

The importance of roots for the stability of shallow colluvial soils on steep slopes and the effects of forest removal have been documented for western North America (Swanston 1970; O'Loughlin 1974b; Ziemer and Swanston 1977; Burroughs and Thomas 1977; Wu et al. 1979; Gray and Megahan 1981; Sidle and Swanston 1982). Similar studies have been conducted in Japan (Endo and Tsuruta 1969; Kitamura and Namba 1976; Nakano 1971) and in New Zealand (O'Loughlin 1974a; O'Loughlin and Pearce 1976; O'Loughlin et al. 1982; Selby 1982). Recent studies have reported on the role of roots in slope stability of colluvial soils in the Cincinnati, Ohio, area (Riestenberg 1994).

Generally, it is claimed that root systems contribute to soil strength by providing an additional cohesion component, referred to as ΔC. Available data, including the data presented in Table 20-1 from studies in New Zealand, suggest that roots increase the cohesion but do not influence the angle of internal friction (Sidle et al. 1985). Bishop and Stevens (1964) identified a fourfold to fivefold increase in the number of shallow landslides on steep hillsides in southeastern Alaska within 10 years of clearcutting. They suggested that the increase was at least partially attributable to root deterioration.

Some studies have attempted to quantify the strength of soil-root systems. Large metal shear boxes of various sizes and designs have been used in field tests to shear undisturbed blocks of soil containing roots (Endo and Tsuruta 1969; O'Loughlin 1974a, 1974b; Waldron and Dakessian 1981; O'Loughlin et al. 1982; Waldron et al. 1983). These tests demonstrated that the majority of the roots that broke failed in tension rather than by shear. This finding confirms many observations of actual landslides in which failed roots were reported around colluvial landslide scars. Estimates of the magnitude of ΔC provided by roots have been made by several investigators using different methods. These estimates are summarized in Table 20-2.

Sidle et al. (1985) concluded that roots influence soil strength and increase colluvial slope stability in three ways:

1. They bind unstable soil mantles to stable subsoils or substrata. This effect is most pronounced when a potential failure zone exists within the rooting zone.
2. They form a dense interwoven network in the upper 30 to 50 cm of soil, and this network provides lateral membrane strength that tends to reinforce the shallow soil mass and hold it in place.
3. Roots of individual trees may provide deeper anchors, stabilizing soil arches that extend across the slope (Figure 20-16). The trees act as buttresses or pile anchors. It may be possible to apply soil-arching restraint theory to determine a critical spacing of trees that maximizes the stabilization of a colluvial slope.

Vegetation may also lead to slope instability. Keller (1979, 117–118) reported that shallow soil slips are especially common in southern California on steep cut slopes covered with ice plant (*Carpobrotus edulis*). The stems of this

Table 20-1
Shear-Strength Parameters for New Zealand Beech Forest Soils with and Without Competent Roots (Sidle et al. 1985)

Shear-Strength Parameter	Intact Forest with Competent Roots	Clearcut Area Without Competent Roots
Apparent cohesion (kPa)	6.6	3.3
Internal friction angle (degrees)	36	36

Table 20-2
Results of Studies of Root Strength Factor ΔC (Sidle et al. 1985)

INFORMATION SOURCE	SOIL-VEGETATION SITUATION	ΔC (kPa)	METHOD USED
Swanston (1970)	Mountain till soils under conifers in Alaska	3.4-4.4	Back calculations
O'Loughlin (1974a)	Mountain till soils under conifers in British Columbia	1.0-3.0	Back calculations
Endo and Tsuruta (1969)	Cultivated loam soils (nursery) under Alder	2.0-12.0	Direct shear tests
Wu et al. (1979)	Mountain hill soils under conifers in Alaska	5.9	Tensile root-strength equations
Waldron and Dakessian (1981)	Clay loams in small containers growing pine seedlings	5.0	Direct shear tests
O'Loughlin et al. (1982)	Shallow stony loam hill soils under mixed evergreen forests, New Zealand	3.3	Direct shear tests
Gray and Megahan (1981)	Sandy loam soils under conifers in Idaho	10.3	Tensile root-strength equations
Burroughs and Thomas (1977)	Mountain and hill soils under conifers in west Oregon and Idaho	3.10-17.5	Root density information
Sidle and Swanston (1982)	Stony mountain soil under conifers and brush	2.2	Back calculations
Waldron et al. (1983)	Clay loam over gravel in large columns growing 5-year pine seedlings	8.9-10.8	Direct shear tests
Waldron et al. (1983)	Clay loam in large columns growing 5-year pine seedlings	9.9-11.8	Direct shear tests

creeping, low succulent plant contain sacs or beads that are swollen with watèr (Spellenberg 1979, 318). During wet winter months, the shallow-rooted ice plant absorbs great quantities of water into their vascular systems, adding considerable weight and increasing downslope driving forces. Failures commonly résult in a shallow translational slide of several centimeters of soil and roots that extends a considerable distance across the face of the slope.

Other investigations also suggest that the type of vegetation covering a slope may affect slope stability. Studies in southern California by Campbell (1975) reported that soil slips were three to five times more frequent on grass-covered slopes than on chaparral-covered slopes. On grass-covered slopes, the landslides were shorter and wider and the failures began where there were lower slope angles than on chaparral-covered slopes composed of similar soils. However, the complete removal of vegetation, especially the effects of removal of vegetation by fire (discussed in the following section), suggests that vegetation generally has a positive effect on the stability of colluvial slopes.
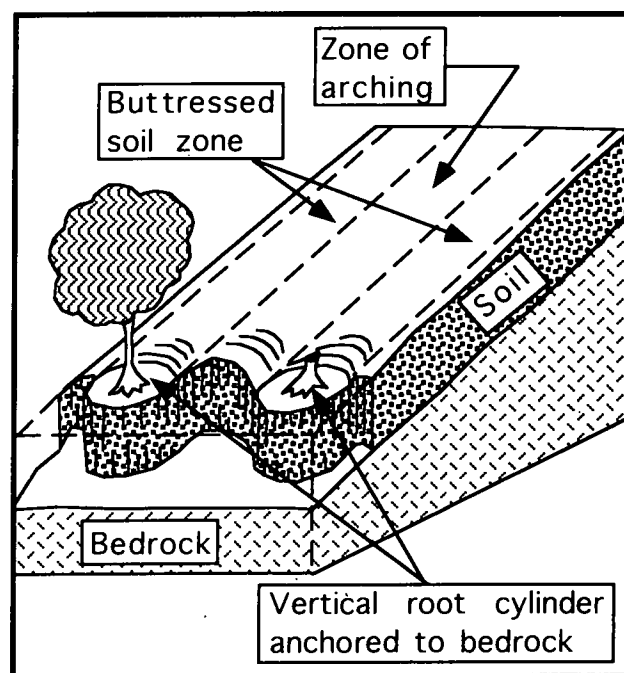

FIGURE 20-16
Schematic diagram showing soil anchoring, buttressing, and arching by trees on colluvial slope (modified from Greenway 1987, Figure 6.23).
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2.7 Fire

Increased instability of colluvial slopes has been observed following naturally occurring or human-induced fires. Wildfires are a common occurrence in many ecosystems; for example, Hanes (1977) estimated that the chaparral vegetation of southern California burns every 10 to 40 years. Human-induced fires are a widely used component of land management practices in many parts of the world. Fire is used to clear vegetation before development, to burn residues after cropping or timber harvesting, to aid in the establishment or maintenance of preferred vegetation species, and to reduce wildfire hazard by controlled, prescribed burning. As a consequence, fire is a fairly common occurrence at many landslide sites.

Many soils exhibit water-repellent properties after burning. On a typical burned slope, the surficial soil is loosely compacted and easily wettable. However, a few millimeters below the surface, a layer of soil forms that is water repellent, or *hydrophobic* (Figure 20-17). This water repellency is created when waxy organic molecules formed by the burning of vegetative litter in and on the soil surface are driven down into the soil, where they coat individual soil particles. The waxy organic coating resists penetration by water and forms a barrier to infiltration of the water into the regolith below (DeBano 1980). DeBano et al. (1967) indicated that water repellency in soil develops at a temperature of about 200°C and increases to a maximum at about 370°C. At higher temperatures

FIGURE 20-17
Schematic diagram of postfire colluvial soil slope, showing effects of hydrophobic soil layer.
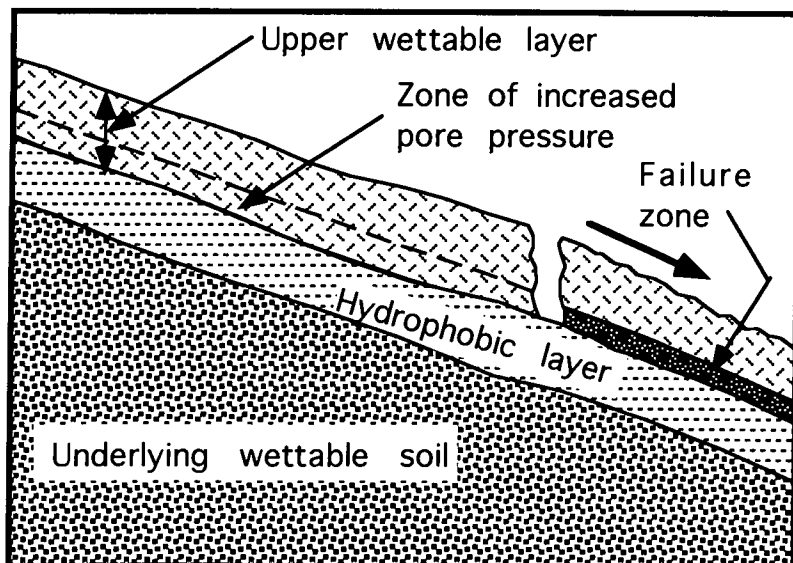
the water repellency is destroyed, so the existence, thickness, and continuity of a water-repellent layer within the colluvium depend on the intensity and duration of the fire.

The most widely documented cases of increased landsliding following fires are based on studies conducted in the Los Angeles region of southern California (Wells 1987). The mediterranean climate there with its warm, dry summers and winter rainy season causes the peak fire season to immediately precede a period of increased precipitation. Early rains fall on barren, freshly burned slopes. These effects were first reported by Eaton (1935), who correctly identified the flooding responses as debris flows. From Eaton's descriptions, it is clear that the phenomenon was recognized and understood by those working in the Los Angeles area but not by those in other regions (Wells 1987).

The problem of slope instability after fires and subsequent flooding by debris flows is not confined to southern California. Brown (1972) reported debris flows and increased sedimentation rates from freshly burned watersheds in Australia. Increased landsliding was observed in Scotland where hill heathland was burned to prevent tree regeneration (Fairbairn 1967). Mersereau and Dyrness (1972) and Bennett (1982) reported the effects on slope instability of slash burning following clearcut timber harvesting in the Cascade Mountains and Coast Range of western Oregon. Cannon et al. (1995) provided a detailed evaluation of postfire debris flows that inundated a 3-mi stretch of Interstate-70 west of Glenwood Springs, Colorado. Following a period of extremely intense rainfall, debris flows originated in areas near the highway that had been subjected to an intense fire in July 1994 that burned more than 800 ha. These debris flows engulfed more than 30 vehicles and their drivers, pushing several into the adjacent Colorado River, and at one location formed an alluvial fan deposit within the river channel (Figure 20-18). Fortunately, no deaths and only a few minor injuries resulted. However, this major highway, which carries about 15,000 vehicles a day, was completely closed for more than 16 hr before emergency cleanup crews succeeded in opening one lane in each direction to traffic.

In colluvium the relationship between fire and landsliding is complex. Decreased infiltration capacity due to the development of a water-repellent zone generally occurs at moderately to severely burned sites. The decreased infiltration capacity has

two opposing effects on slope instability: a possible decrease in landsliding due to reduced moisture within the colluvium and a possible increase in sheet erosion and shallow landsliding due to saturation and erosion of the surface layers. In southern California, Rice (1977) observed an initial decrease in landsliding immediately following a fire and peak landslide activity about 2 to 3 years later. This increased slope instability was explained as a result of decomposition of former root systems and development of root systems by new vegetation that opened passages through the water-repellent layers, allowing increased infiltration into the colluvium.

Greatly accelerated rates of surface erosion by both wet and dry processes have been observed during the days and weeks following a fire (Wells 1987). During and immediately following a fire, significant amounts of hillslope debris are delivered to minor stream channels by a process called *dry ravel*. This process involves downslope movement by gravitational forces of individual soil grains, aggregates of grains, and coarser fragments. It is particularly active on steeper slopes (those more than 30 degrees) and in dry, noncohesive soils such as those derived from granites, pumice, and certain sandy sedimentary rocks (Sidle 1980).

The cause of dry ravel has been related to lower bulk densities of nonwettable materials, leading to decreased angles of internal friction. Thus, materials that were at or near their natural angle of repose before the fire would experience dry ravel during and after the burning (Sidle et al. 1985).

The effects of dry ravel are increased by the rapid development of extensive rill networks on many slopes during the season immediately after a fire. These rill networks form in the surficial soil layers in response to the underlying shallow, water-repellent soil. They form extremely rapidly, sometimes in minutes, and provide an efficient means of moving surficial materials into the minor stream channels (Wells 1987). Once the stream channels become clogged with sediment derived from both dry ravel and rill erosion processes, saturation of these materials and initiation of debris flows down the channels are the obvious consequences.

More material may be added to the stream channels by soil slide—debris flows along the valley sides. Such slope failures are also a consequence of the presence of shallow, water-repellent layers in the colluvium. The material merely adds to the volume of material already clogging the stream channels and further increases the potential for

disastrous debris flows downstream. This combination of events helps explain why comparatively large postfire debris flows result from very small storms or after relatively short periods of rainfall. Frequently these debris flows disrupt or even destroy transportation facilities (Figure 20-18).

2.8 Seismicity

Earthquake shaking, a major triggering factor for many types of landslides, is discussed in Chapter 4. Many of the examples used in Chapter 4 are landslides involving materials other than colluvium and so are beyond the scope of this chapter. However, numerous landslides on colluvial slopes are common when moderate to large earthquakes occur in hilly regions. For example, more than 2,000 land-

slides and avalanches were reported in a 5000-km² zone around the epicenter of the 1964 Good Friday earthquake in Alaska (Hackman 1965) and more than 1,000 landslides occurred in a 250-km² region during the 1971 San Fernando Valley earthquake in southern California (Morton 1971).

Sidle et al. (1985) suggested that inadequate attention had been paid to documenting the intensity of landslides caused by earthquake shaking or to the geomorphic, ecologic, and socioeconomic significance of such landslides. This lack of attention seems to be no longer the case. Chapter 4 contains several references to recent (post-1980) studies of the socioeconomic effects and geotechnical issues of earthquake-induced landslides. Relevant studies concerning landslides involving colluvium and residual soils include case histories in Guatemala and Ecuador (Harp et al. 1981; Crespo et al. 1991; Schuster 1991) and reports of studies following two recent earthquakes in California—the Loma Prieta earthquake near San Francisco in October 1989 and the Northridge earthquake north of Los Angeles in January 1994 (Plafker and Galloway 1989; Harp and Jibson 1995; Keefer and Manson in press). The Loma Prieta earthquake triggered an estimated 2,000 to 4,000 landslides on colluvial slopes that blocked a major highway and many secondary roads in the region (Plafker and Galloway 1989; Keefer and Manson in press). Interpretation of aerial photographs has identified more than 12,000 landslides with a width of at least 3 m that were triggered by the 1994 Northridge earthquake (Harp and Jibson 1995).

3. SLOPE INSTABILITY IN TALUS

Classic examples of massive talus deposits are common in high mountainous regions, where steep slopes, durable bedrock, lack of vegetation, and harsh climate combine to produce abundant rock fragments (Figure 20-19). In these regions movements of talus fragments are frequent and rock-fall hazards are considerable. Fortunately, transportation facilities rarely cross such regions and thus these unstable and hazardous conditions affect them infrequently. However, in regions of relatively high relief, transportation facilities commonly must pass through valleys and canyons in order to find acceptable routes at lower elevations. Talus deposits are commonly encountered along such valley and canyon routes (Figures 20-20 and 20-21).

FIGURE 20-19
Extensive and active talus deposits in mountainous region.
K.E. KOLM, COLORADO
SCHOOL OF MINES, GOLDEN,
COLORADO

The recent construction of Interstate-70 (I-70) through Glenwood Canyon in the state of Colorado encountered extensive talus deposits, and the experiences gained there have considerably enhanced the knowledge of geotechnical characteristics of talus and appropriate construction procedures where talus is encountered. Glenwood Canyon was eroded through a series of sedimentary and igneous rocks by the Colorado River. It reaches a depth of more than 1000 m and is characterized by steep slopes and cliffs, with extensive colluvium and talus deposits at their bases. The canyon provides an important low-gradient east-west route through an otherwise rugged plateau region. A railroad and an existing highway shared the narrow canyon bottom with the Colorado River. The scenic nature of the canyon raised environmental concerns that required the new four-lane Interstate highway to be constructed in such a way as to minimize impacts on canyon features. As a consequence, major roadway structures traverse and are founded on extensive talus slopes (Figure 20-22).

Existing knowledge was insufficient to design the required structures. Only a few studies are available that relate talus properties to the design and construction of transportation facilities (Ritchie 1963). Consequently, exploration techniques and foundation treatment methods were developed during the Glenwood Canyon project, several of which are discussed later in this chapter.

Talus is colluvium composed of predominantly large fragments. Talus thus shares many of the characteristics of colluvium discussed in Section 2.3. Hard, massive bedrock formations frequently produce very coarse, open-graded talus deposits. With time, the coarse fragments of these deposits may degrade or finer materials may be added by wind or water transport so that these deposits slowly become infilled with a matrix of fine-grained materials. The degree of infilling of these talus deposits may vary horizontally and vertically. In other cases, the talus may initially be formed from a mixture of coarse and fine particles.

Thus, talus deposits may range from extremely coarse-grained deposits with large voids to much more dense deposits consisting of coarse fragments embedded in a matrix of finer particles. Following the concepts proposed by Clift (1994) for describing rockfills, these talus deposits may be classified as rock-supported, transitional, or matrix-supported (Figure 20-23).

FIGURE 20-20
Typical talus deposit along road in valley.
R.D. ANDREW, COLORADO DEPARTMENT OF TRANSPORTATION

Rock-supported talus is often inherently unstable and may be hazardous even to walk across. The weight of the deposit is transmitted as point loads among the fragments. These concentrated loadings may result in crushing or breakage of fragments or even in sudden realignments to a more stable configuration. In contrast, matrix-supported talus transmits most of the load by compaction of the relatively fine-grained matrix materials, and the larger fragments are supported, or "float," within the

FIGURE 20-21
Talus deposit in canyon setting, western Colorado.
R.D. ANDREW, COLORADO DEPARTMENT OF TRANSPORTATION

FIGURE 20-22
Completed Interstate-70 crossing extensive talus, Glenwood Canyon, Colorado.
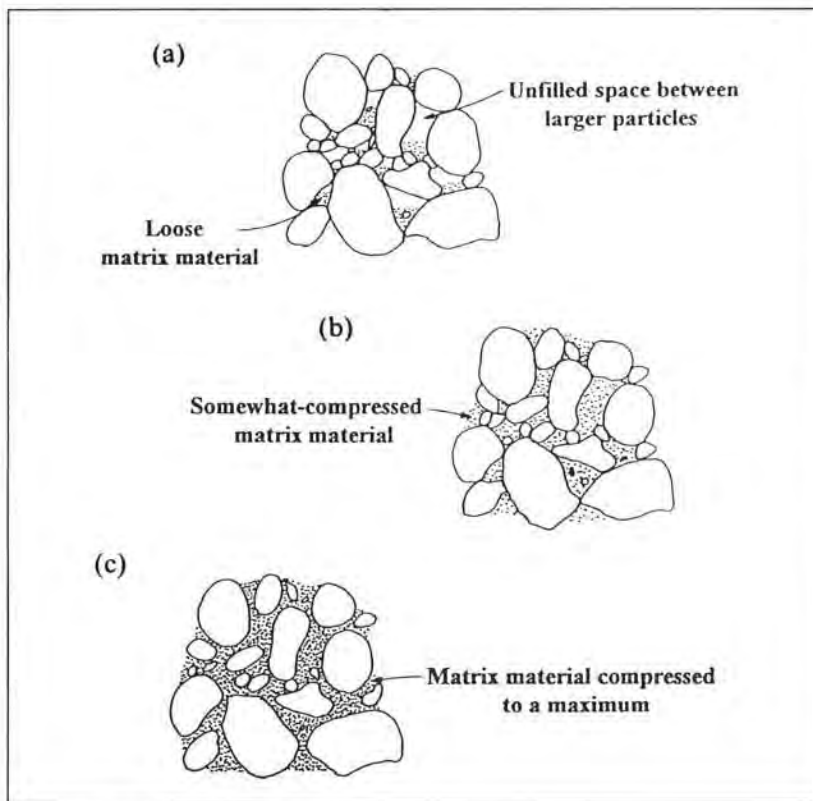A.K. TURNER, COLORADO SCHOOL OF MINES, GOLDEN, COLORADO

FIGURE 20-23
Schematic diagrams of three classes of talus: (a) rock-supported, (b) transitional, and (c) matrix-supported (modified from Clift 1994, Figure 15).

matrix. Transitional talus has intermediate properties; the matrix materials may be loosely compacted since they only partially fill many of the voids, and the weight of the deposit is transmitted mostly by the contact between the large fragments. Each of these three talus categories behaves differently in a kinematic sense. Often a single talus deposit will contain sections from all three categories. Because the surface of most talus deposits is armored with larger-sized particles, the degree of infilling with depth is difficult to predict.

Estimating strength and stability properties of talus is extremely difficult. Stabilizing or densifying open-graded talus may be accomplished by grouting. However, experience with I-70 in Glenwood Canyon demonstrated that determining the best method of injecting grout, estimating the volume of grout required, or defining improved bearing capacity involved much trial and error, in situ field testing, and experience with the characteristics of talus in the area. Gaining suitable access for the necessary exploration equipment is often difficult on talus and may be hazardous in some cases (Figure 20-24).

Ritchie (1963) noted that talus becomes stratified because of the gradual accumulation of rock fragments. Once a rock fragment comes to rest on the sloping surface of a talus deposit, Ritchie (1963, 23) stated, "it never, of itself, begins to roll again (although much of the material may move about by debris sliding). On mature natural slopes, rock roll is seldom a problem for highways located near their base." Ritchie emphasized that excavations into talus slopes are especially troublesome. Talus slopes reflect the natural angle of repose of the talus material, and generally cut slopes are constructed at a steeper angle. Even so, these cut slopes extend large distances away from the transportation facility, and once a rock begins to roll on such a slope, it cannot stop until it reaches the base of the cut. Many cut slopes are constructed slightly steeper than the inclination of the crude stratification of the talus. This constructed slope angle causes individual rock fragments to ravel, or pop out, from the face of the cut, resulting in continuous and progressive failure of the cut. Ritchie recommended that some form of slope protection for the traveling public is most desirable, if not mandatory, where such cut slopes are necessary in talus.

Talus slopes present other hazards. Although most talus is unlikely to initiate debris flows such

as those in finer-grained colluvium, debris flows often issue from rock chutes above talus deposits. In severe cases these debris flows may extend completely across the talus slope and cause damage to transportation facilities located on the lower portions of the talus deposit.
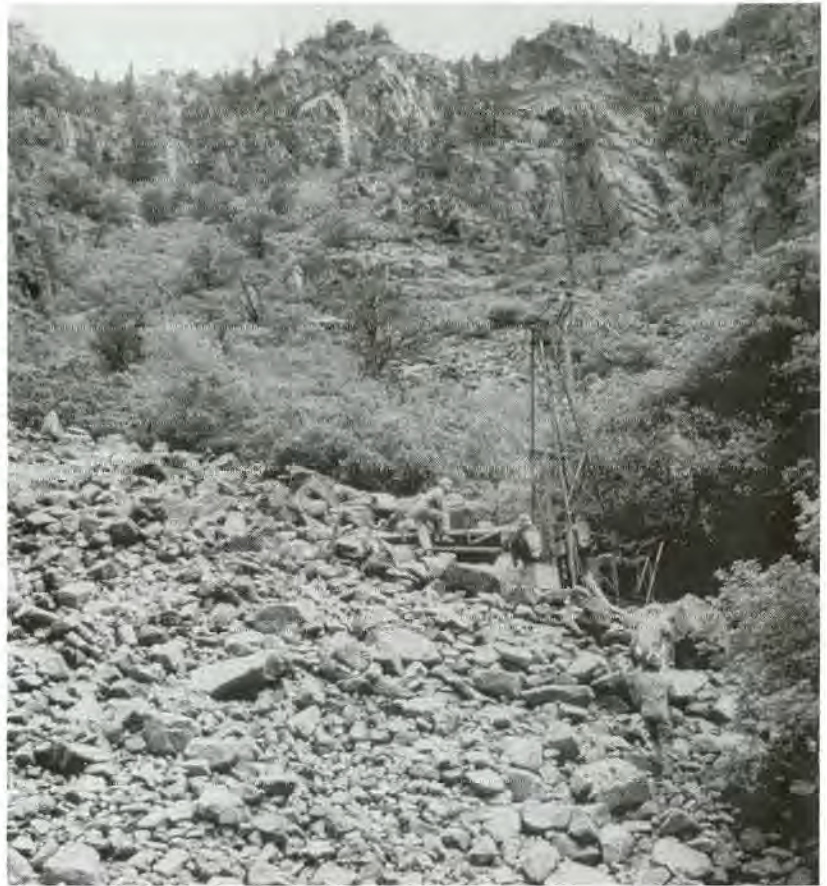
4. SUBSURFACE INVESTIGATIONS

Traditional technologies, such as drilling, test pits, trenches, and geophysical methods, are all employed to obtain information on the physical characteristics of colluvium. However, each method has limitations in evaluating colluvial deposits. Internal heterogeneity of colluvial deposits coupled with the tendency for the strength of colluvium to degrade over time increase uncertainty and risk concerning characterizations of engineering properties. Colluvium deposited in water-deficient environments may exhibit a flocculated or honeycomb soil-particle structure that can lead to hydrocompaction.

4.1 Planning Subsurface Investigations

Engineering geologists and geotechnical engineers should plan very carefully any subsurface investigations for site-specific determination of the engineering properties of colluvium in order to take into account and reflect the following characteristics of this material:

- Colluvium at depth may be deeply weathered and is often more dense (infilled);
- The moisture profile can increase to saturation with depth;
- Internal friction and cohesion may vary horizontally and vertically within the deposit;
- Climate and parent materials are major contributors to the engineering parameters of colluvium;
- Typical slope angles, particle size and distribution, strength properties, and moisture content are all related to the origin and location of the colluvium;
- Colluvial deposits are often only marginally stable, and their relatively steep slopes may make equipment access difficult or even impossible; and
- Colluvial slopes frequently are located in areas subject to rock-fall and debris-flow hazards, so precautions to protect field investigation personnel may be necessary.

FIGURE 20-24 Exploratory drilling on talus, Glenwood Canyon, Colorado. COLORADO DEPARTMENT OF TRANSPORTATION

By recognizing these characteristics and planning investigative procedures to account for them, the engineering geologist or geotechnical engineer is more likely to develop a successful investigation. For example, exploratory drill holes should be extended to greater than typical depths to check for unusual conditions, and areas subjected to subsurface investigations should be extended to add confidence to global stability calculations. Many years of water-level measurements may be required to provide confidence in the estimated maximum water levels assumed in design calculations.

4.2 Drilling Methods

Drilling in colluvium, and especially in talus, is difficult, relatively expensive, and often does not provide the geologist with a complete profile of the deposit. Drilling in fine-grained colluvium can be accomplished with conventional tools, such as solid and hollow flight augers and split-tube samplers. However, the supervising engineering geologist must be prepared for sudden changes in the

properties of the deposit and to expect zones with no drilling recovery.

In Glenwood Canyon, Colorado, numerous talus deposits were encountered during construction of I-70. At one point near the center of the canyon, a large ventilation structure for two tunnels was to be located in the bottom of a narrow tributary canyon that had extensive talus deposits. Construction planning required a detailed subsurface evaluation of these talus deposits. These explorations provided much new experience concerning the best methods for investigating the nature of talus deposits.

The Colorado Department of Transportation (CDOT) cooperated with manufacturers to develop wire-line core drilling bits and procedures to successfully drill the test holes in these talus deposits. Severe problems resulted from the use of traditional exploratory drilling methods. In the initial exploration, soil-sampling drill rigs equipped with tri-cone bits and drive casings, or casings with diamond shoes, were used. These methods resulted in very slow production rates and poor-quality samples. When traditional diamond coring bits were used, they were damaged by heat buildup during periodic losses of drilling fluid. At this location, loss of drilling fluid was a common occurrence because of void spaces within the talus. Although void spaces are rarely found deep within a talus deposit, some voids exceeding 3 m were found at depth during this investigation. Uneven or eccentric loadings are detrimental to most rock-coring bits; thus, in spite of the best efforts of the drilling personnel, the diamond bit was frequently damaged because it became placed between a boulder and a void.

4.3 Test Pits and Trenches

Test pits and trenches often provide better observations of the profile of a colluvial deposit than can be obtained by examining samples removed from exploratory holes. Visual inspection of the walls of a trench can lead to more accurate design of sampling and testing programs and ultimately to a more accurate determination of engineering properties. The geologist and the designer are cautioned to consider that any excavations in colluvium may collapse rapidly. These deposits are among the most dangerous in which to perform steep-sided excavations.

4.4 Geophysical Exploration Methods

Geophysical methods often are not satisfactory or especially reliable for determining subsurface interfaces such as water horizons and bedrock contacts. The third dimension of a hillside deposit adds considerable uncertainty to the interpretation. These methods are better used to supplement drilling and test pit data.

5. DESIGN CONSIDERATIONS FOR COLLUVIUM

Although colluvium is unconsolidated and therefore a soil according to engineering classifications, construction in colluvium is typically much more difficult than in other major deposits, including alluvial, glacial, lacustrine, or eolian soils. Colluvium is more likely to exhibit unfavorable properties such as particle size and strength variations, large void spaces, and unexpected excavation failures.

5.1 Creep

Creep is a phenomenon of concern when structures are placed on colluvial deposits. It is known that some long-term translation or movement of materials can occur, especially within the near-surface regime. However, little definitive information exists on this phenomenon. A series of inclinometers were installed by CDOT through a major talus deposit in Glenwood Canyon, Colorado. These inclinometers were monitored for 4 years to support design calculations for foundations of a planned extensive viaduct along the base of the deposit. No movement was observed during the monitoring period. However, this single short-term program certainly cannot be used to conclude that this talus deposit will not exhibit creep in the future. The viaduct foundations were designed to accommodate lateral loadings that would result from some creep movements of the talus.

5.2 Installation of Ground Anchors

Installation of ground anchors in talus can cost an order of magnitude more than a similar installation in a clay soil. Drilling of horizontal or subhorizontal holes into colluvium, especially talus, requires special equipment and experienced crews (Figures 20-25 and 20-26). During construction of

Interstate-70 through Glenwood Canyon, many of the slope stabilization systems required either temporary or permanent retaining walls that relied on tiebacks into talus or colluvial slopes for their stability (Figures 20-26 and 20-27). Where talus deposits were encountered, conventional ground anchor installations employing stage grouting were not feasible because of the numerous void spaces and zones of very loose matrix material. Most of the grout was being lost, resulting in inadequate bond strength and a lack of corrosion protection.

A system that used geotextile "socks" to contain grout, known as grout containment devices (GCDs), was ultimately employed to install these anchors. Experiments were conducted with many different types of geotextiles, including both woven and nonwoven products, to determine which performed best as GCDs. Most of the nonwoven GCDs ruptured against the sharp fragments in the talus deposits under the high pumping pressures required to inject the grout. The most effective method of installation was to grout a woven geotextile material in short sections (approximately 1.5 m long) as the drill casing was removed. In coarse talus, the only other technique that was successful involved a proprietary expander-body anchor that utilized a steel GCD.

5.3 Pile Foundations

Foundations for structures that must be placed on colluvium must account for potential nonuniform bearing capacities beneath them. Nonuniform bearing capacities lead to unexpected eccentricities that may result in distress or failure of the structure. The depth and configuration of most colluvial deposits favor a pile-foundation design. Installation of deep pile foundations can be very difficult and expensive if large boulders, which may be randomly dispersed within many of these deposits, are encountered.

In Glenwood Canyon, the foundations for an extensive viaduct had to be placed on a talus deposit (Figure 20-28). Preblasting techniques were developed by CDOT and successfully used to allow the driving of large-diameter piles through this talus. The method involved predrilling a small-diameter hole at the location of each steel pile using wire-line drilling. The hole was cased with polyvinylchloride (PVC) pipe and backfilled with drill cuttings. Gelatin dynamite was attached

FIGURE 20-25
Large specialized rig drilling horizontal ground anchor holes in talus, Glenwood Canyon, Colorado.
COLORADO DEPARTMENT OF TRANSPORTATION

FIGURE 20-26
Smaller rig drilling ground anchor holes in talus for temporary slope-retention devices (*square concrete pads, upper part of photograph*), Glenwood Canyon, Colorado.
COLORADO DEPARTMENT OF TRANSPORTATION

FIGURE 20-27
Installation of permanent retaining walls that utilize tiebacks into talus,
Glenwood Canyon, Colorado.
COLORADO DEPARTMENT OF TRANSPORTATION

FIGURE 20-28
Interstate-70 viaduct founded on talus, Glenwood Canyon, Colorado.
J.D. HIGGINS, COLORADO SCHOOL OF MINES, GOLDEN, COLORADO

to reinforced detonator cords and lowered into the
hole, which was then stemmed. Detonation of the
charges fractured any large talus fragments so the
piling could be driven through the small broken
fragments. The process was repeated as necessary
until the pile had been driven to the desired tip el-
evation. This procedure obviously added to the
cost for installation of these steel piles. However,
when compared with other alternatives, it was a
feasible and cost-effective solution.

5.4 Control of Groundwater and Surface Water

Control of groundwater and surface water is a crit-
ical design consideration. Every effort must be
made to avoid increasing water sources in the col-
luvial soils. Design intentions must be enforced by
construction personnel. One common mistake is
to allow the concentration of roadway runoff into
pipes that discharge into minor drainages.
Improperly designed drainage structures may cause
erosion or even landslides, and collection of water
around foundations can lead to damaged struc-
tures. A properly designed drainage system should
take into consideration its relationship to the ge-
ologic history of the deposit.

5.5 Dangers of Rock Fall and Debris Flow

When evaluating the stability of colluvial and
talus deposits, the engineering geologist must be
concerned with rock-fall and debris-flow hazards.
A historical perspective that emphasizes the origin
of these deposits through downslope movement of
materials must be emphasized to designers of trans-
portation facilities. In spite of careful evaluation
and design in Glenwood Canyon, rock-fall inci-
dents have caused minor damage to roadway struc-
tures (Figure 20-29) and killed three occupants of
one vehicle when it was hit by a large rock.

ACKNOWLEDGMENTS

FIGURE 20-29
Minor rock-fall damage at base of talus slope, Interstate-70, Glenwood Canyon, Colorado.
J.D. HIGGINS, COLORADO SCHOOL OF MINES, GOLDEN, COLORADO

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