Chapter 2

Slope Movement Types and Processes

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This chapter reviews a fairly complete range of slope-movement processes and identifies and classifies them according to features that are also to some degree relevant to their recognition, avoidance, control, or correction. Although the classification of landslides presented in Special Report 29 (*2.182*) has been well received by the profession, some deficiencies have become apparent since that report was published in 1958; in particular, more than two dozen partial or complete classifications have appeared in various languages, and many new data on slope processes have been published.

One obvious change is the use of the term slope movements, rather than landslides, in the title of this chapter and in the classification chart. The term landslide is widely used and, no doubt, will continue to be used as an all-inclusive term for almost all varieties of slope movements, including some that involve little or no true sliding. Nevertheless, improvements in technical communication require a deliberate and sustained effort to increase the precision associated with the meaning of words, and therefore the term slide will not be used to refer to movements that do not include sliding. However, there seems to be no single simple term that embraces the range of processes discussed here. Geomorphologists will see that this discussion comprises what they refer to as mass wasting or mass movements, except for subsidence or other forms of ground sinking.

The classification described in Special Report 29 is here extended to include extremely slow distributed movements of both rock and soil; those movements are designated in many classifications as creep. The classification also includes the increasingly recognized overturning or toppling failures and spreading movements. More attention is paid to features associated with movements due to freezing and thawing, although avalanches composed mostly of snow and ice are, as before, excluded.

Slope movements may be classified in many ways, each having some usefulness in emphasizing features pertinent to recognition, avoidance, control, correction, or other purpose for the classification. Among the attributes that have been used as criteria for identification and classification are type of movement, kind of material, rate of movement, geometry of the area of failure and the resulting deposit, age, causes, degree of disruption of the displaced mass, relation or lack of relation of slide geometry to geologic structure, degree of development, geographic location of type examples, and state of activity.

The chief criteria used in the classification presented here are, as in 1958, type of movement primarily and type of material secondarily. Types of movement (defined below) are divided into five main groups: falls, topples, slides, spreads, and flows. A sixth group, complex slope movements, includes combinations of two or more of the other five types. Materials are divided into two classes: rock and engineering soil; soil is further divided into debris and earth. Some of the various combinations of movements and materials are shown by diagrams in Figure 2.1 (in pocket in back of book); an abbreviated version is shown in Figure 2.2. Of course, the type of both movement and

Figure 2.2. Abbreviated classification of slope movements. (Figure 2.1 in pocket in back of book gives complete classification with drawings and explanatory text.)

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			BEDROCK	ENGINEERING SOILS	
				Predominantly coarse	Predominantly fine
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	FEW UNITS	Rock slump	Debris slump	Earth slump
	TRANSLATIONAL	FEW UNITS	Rock block slide	Debris block slide	Earth block slide
		MANY UNITS	Rock slide	Debris slide	Earth slide
LATERAL SPREADS			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow (deep creep)	Debris flow (soil creep)	Earth flow
COMPLEX			Combination of two or more principal types of movement		

materials may vary from place to place or from time to time, and nearly continuous gradation may exist in both; therefore, a rigid classification is neither practical nor desirable. Our debts to the earlier work of Sharpe (*2.146*) remain and are augmented by borrowings from many other sources, including, particularly, Skempton and Hutchinson (*2,154*), Nemčok, Pašek, and Rybář (*2.116*), de Freitas and Watters (*2.37*), Záruba and Mencl (*2.193*), and Zischinsky (*2.194*). Discussions with D. H. Radbruch-Hall of the U.S. Geological Survey have led to significant beneficial changes in both content and format of the presentation.

The classification presented here is concerned less with affixing short one- or two-word names to somewhat complicated slope processes and their deposits than with developing and attempting to make more precise a useful vocabulary of terms by which these processes and deposits may be described. For example, the word creep is particularly troublesome because it has been used long and widely, but with differing meanings, in both the material sciences, such as metallurgy, and in the earth sciences, such as geomorphology. As the terminology of physics and materials science becomes more and more applied to the behavior of soil and rock, it becomes necessary to ensure that the word creep conveys in each instance the concept intended by the author. Similarly, the word flow has been used in somewhat different senses by various authors to describe the behavior of earth materials. To clarify the meaning of the terms used here, verbal definitions and discussions are employed in conjunction with illustrations of both idealized and actual examples to build up descriptors of movement, material, morphology, and other attributes that may be required to characterize types of slope movements satisfactorily.

TERMS RELATING TO MOVEMENT

Kinds of Movement

Since all movement between bodies is only relative, a description of slope movements must necessarily give some attention to identifying the bodies that are in relative motion. For example, the word slide specifies relative motion between stable ground and moving ground in which the vectors of relative motion are parallel to the surface of separation or rupture; furthermore, the bodies remain in contact. The word flow, however, refers not to the motions of the moving mass relative to stable ground, but rather to the distribution and continuity of relative movements of particles within the moving mass itself.

Falls

In falls, a mass of any size is detached from a steep slope or cliff, along a surface on which little or no shear displacement takes place, and descends mostly through the air by free fall, leaping, bounding, or rolling. Movements are very rapid to extremely rapid (see rate of movement scale, Figure 2.1u) and may or may not be preceded by minor movements leading to progressive separation of the mass from its source.

Rock fall is a fall of newly detached mass from an area of bedrock. An example is shown in Figure 2.3. Debris fall is a fall of debris, which is composed of detrital fragments prior to failure. Rapp (*2.131*, p. 104) suggested that falls of newly detached material be called primary and those involving earlier transported loose debris, such as that from shelves, be called secondary. Among those termed debris falls here, Rapp (*2.131*, p. 97) also distinguished pebble falls (size less than 20 mm), cobble falls (more than 20 mm, but less than 200 mm), and boulder falls (more than 200 mm). Included within falls would be the raveling of a thin colluvial layer, as illustrated by Deere and Patton (*2.36*), and of fractured, steeply dipping weathered rock, as illustrated by Sowers (*2.162*).

The falls of loess along bluffs of the lower Mississippi River valley, described in a section on debris falls by Sharpe (*2.146*, p. 75), would be called earth falls (or loess falls) in the present classification.

Topples

Topples have been recognized relatively recently as a distinct type of movement. This kind of movement consists of the forward rotation of a unit or units about some pivot point, below or low in the unit, under the action of gravity and forces exerted by adjacent units or by fluids in cracks. It is tilting without collapse. The most detailed descriptions have been given by de Freitas and Watters (*2.37*), and some of their drawings are reproduced in Figure 2.1d1 and d2. From their studies in the British Isles, they concluded that toppling failures are not unusual, can develop in a variety of rock types, and can range in volume from 100 m^3 to more than 1 Gm^3 (130 to 1.3 billion yd^3). Toppling may or may not culminate in either falling or sliding, depending on the geometry of the failing mass and the orientation and extent of the discontinuities. Toppling failure has been pictured by Hoek (*2.61*), Aisenstein (*2.1*, p. 375), and Bukovansky, Rodríquez, and Cedrún (*2.16*) and studied in detail in laboratory experiments with blocks by Hofmann (*2.63*). Forward rotation was noted in the Kimbley copper pit by Hamel (*2.56*), analyzed in a high rock cut by Piteau and others (*2.125*), and described among the prefailure movements at Vaiont by Hofmann (*2.62*).

Slides

In true slides, the movement consists of shear strain and displacement along one or several surfaces that are visible or may reasonably be inferred, or within a relatively narrow zone. The movement may be progressive; that is, shear failure may not initially occur simultaneously over what eventually becomes a defined surface of rupture, but rather it may propagate from an area of local failure. The displaced mass may slide beyond the original surface of rupture onto what had been the original ground surface, which then becomes a surface of separation.

Slides were subdivided in the classification published in 1958 (*2.182*) into (a) those in which the material in motion is not greatly deformed and consists of one or a few units and (b) those in which the material is greatly deformed or consists of many semi-independent units. These subtypes were further classed into rotational slides and planar slides. In the present classification, emphasis is put on the distinction between rotational and translational slides, for that

Figure 2.3. Rock fall due to undercutting along shore of Las Vegas Bay, Lake Mead, Nevada (photograph taken February 24, 1949) (*2.182*). Rock is Muddy Creek formation (Pliocene) consisting here of siltstone overlain by indurated breccia.

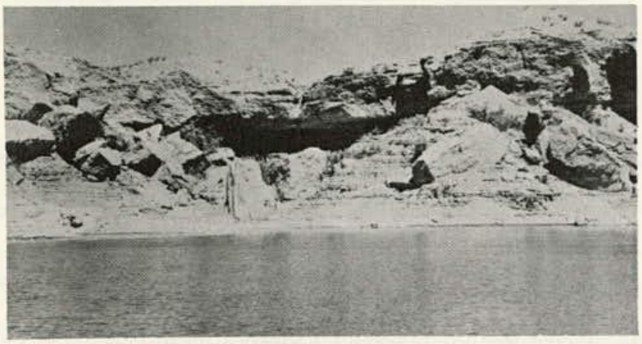
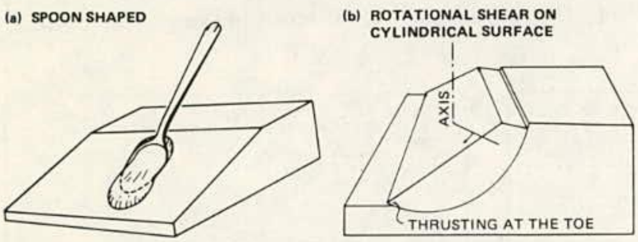


Figure 2.4. Slope failure in uniform material (*2.182*).



difference is of at least equal significance in the analysis of stability and the design of control methods. An indication of degree of disruption is still available by use of the terms block or intact for slides consisting of one or a few moving units and the terms broken or disrupted for those consisting of many units; these terms avoid a possible source of confusion, pointed out by D. H. Radbruch-Hall, in the use of the term debris slide, which is now meant to indicate only a slide originating in debris material, which may either proceed as a relatively unbroken block or lead to disruption into many units, each consisting of debris.

Rotational Slides

The commonest examples of rotational slides are little-deformed slumps, which are slides along a surface of rupture that is curved concavely upward. Slumps, and slumps combined with other types of movement, make up a high proportion of landslide problems facing the engineer. The movement in slumps takes place only along internal slip surfaces. The exposed cracks are concentric in plan and concave toward the direction of movement. In many slumps the underlying surface of rupture, together with the exposed scarps, is spoon-shaped (Figure 2.4). If the slide extends for a considerable distance along the slope perpendicular to the direction of movement, much of the rupture surface may approach the shape of a sector of a cylinder whose axis is parallel to the slope (Figure 2.4). In slumps, the movement is more or less rotational about an axis that is parallel to the slope. In the head area, the movement may be almost wholly downward and have little apparent rotation; however, the top surface of each unit commonly tilts backward toward the slope (Figures 2.1g, 2.1i, 2.4, 2.5, 2.6, and 2.7), but some blocks may tilt forward.

Figure 2.6 shows some of the commoner varieties of slump failure in various kinds of materials. Figure 2.7 shows the backward tilting of strata exposed in a longitudinal section through a small slump in lake beds. Although the rupture surface of slumps is generally concave upward, it is seldom a spherical segment of uniform curvature. Often the shape of the surface is greatly influenced by faults, joints, bedding, or other preexisting discontinuities of the material. The influence of such discontinuities must be considered carefully when the engineer makes a slope-stability analysis that assumes a certain configuration for the surface of rupture. Figures 2.7 and 2.8 show how the surface of rupture may follow bedding planes for a considerable part of its length. Upward thrusting and slickensides along the lateral margin of the toe of a slump are shown in Figure 2.9.

The classic purely rotational slump on a surface of smooth curvature is relatively uncommon among the many types of gravitational movement to which geologic materials are subject. Since rotational slides occur most frequently in fairly homogeneous materials, their incidence among constructed embankments and fills, and hence their interest to engineers, has perhaps been high relative to other types of failure, and their methods of analysis have in the past been more actively studied. Geologic materials are seldom uniform, however, and natural slides tend to be complex or at least significantly controlled in their mode of movement by internal inhomogeneities and discontinuities. Moreover, deeper and deeper artificial cuts for damsites, highways, and other engineering works have increasingly produced failures not amenable to analysis by the methods appropriate to circular arc slides and have made necessary the development of new methods of analytical design for prevention or cure of failures in both bedrock and engineering soils.

The scarp at the head of a slump may be almost vertical. If the main mass of the slide moves down very far, the steep scarp is left unsupported and the stage is set for a new failure (similar to the original slump) at the crown of the slide. Occasionally, the scarps along the lateral margins of the upper part of the slide may also be so high and steep that slump blocks break off along the sides and move downward and inward toward the middle of the main slide. Figure 2.10 (*2.183*) shows a plan view of slump units along the upper margins of a slide; the longest dimensions of these units are parallel with, rather than perpendicular to, the direction of movement of the main slide. Any water that finds its way into the head of a slump may be ponded by the backward tilt of the unit blocks or by other irregularities in topography so that the slide is kept wet constantly. By the successive creation of steep scarps and trapping of water, slumps often become self-perpetuating areas of instability and may continue to move and enlarge intermittently until a stable slope of very low gradient is attained.

Translational Slides

In translational sliding the mass progresses out or down and out along a more or less planar or gently undulatory surface and has little of the rotary movement or backward tilting characteristic of slump. The moving mass commonly slides out on the original ground surface. The distinction between rotational and translational slides is useful in planning control measures. The rotary movement of a slump, if the surface of rupture dips into the hill at the foot of the slide, tends to restore equilibrium in the unstable mass; the driving moment during movement decreases and the slide may stop moving. A translational slide, however, may progress indefinitely if the surface on which it rests is sufficiently inclined and as long as the shear resistance along this surface remains lower than the more or less constant driving force. A translational slide in which the moving mass consists of a single unit that is not greatly deformed or a few closely related units may be called a block slide. If the moving mass consists of many semi-independent units, it is termed a broken or disrupted slide.

The movement of translational slides is commonly controlled structurally by surfaces of weakness, such as faults, joints, bedding planes, and variations in shear strength between layers of bedded deposits, or by the contact between firm bedrock and overlying detritus (Figure 2.11). Several examples of block slides are shown in Figures 2.1j2, 2.11, 2.12, 2.13 (*2.136*), 2.14 (*2.107*), and 2.15. In many translational slides, the slide mass is greatly deformed or breaks up into many more or less independent units. As deformation and disintegration continue, and especially as water content or velocity or both increase, the broken or disrupted slide mass may change into a flow; however, all gradations exist. Broken translational slides of rock are shown in Figure 2.1j3 and of debris in Figures 2.1k and 2.16 (*2.83*).

Lateral Spreads

In spreads, the dominant mode of movement is lateral extension accommodated by shear or tensile fractures. Two types may be distinguished.

1. Distributed movements result in overall extension

Figure 2.5. Varieties of slump (*2.182*).

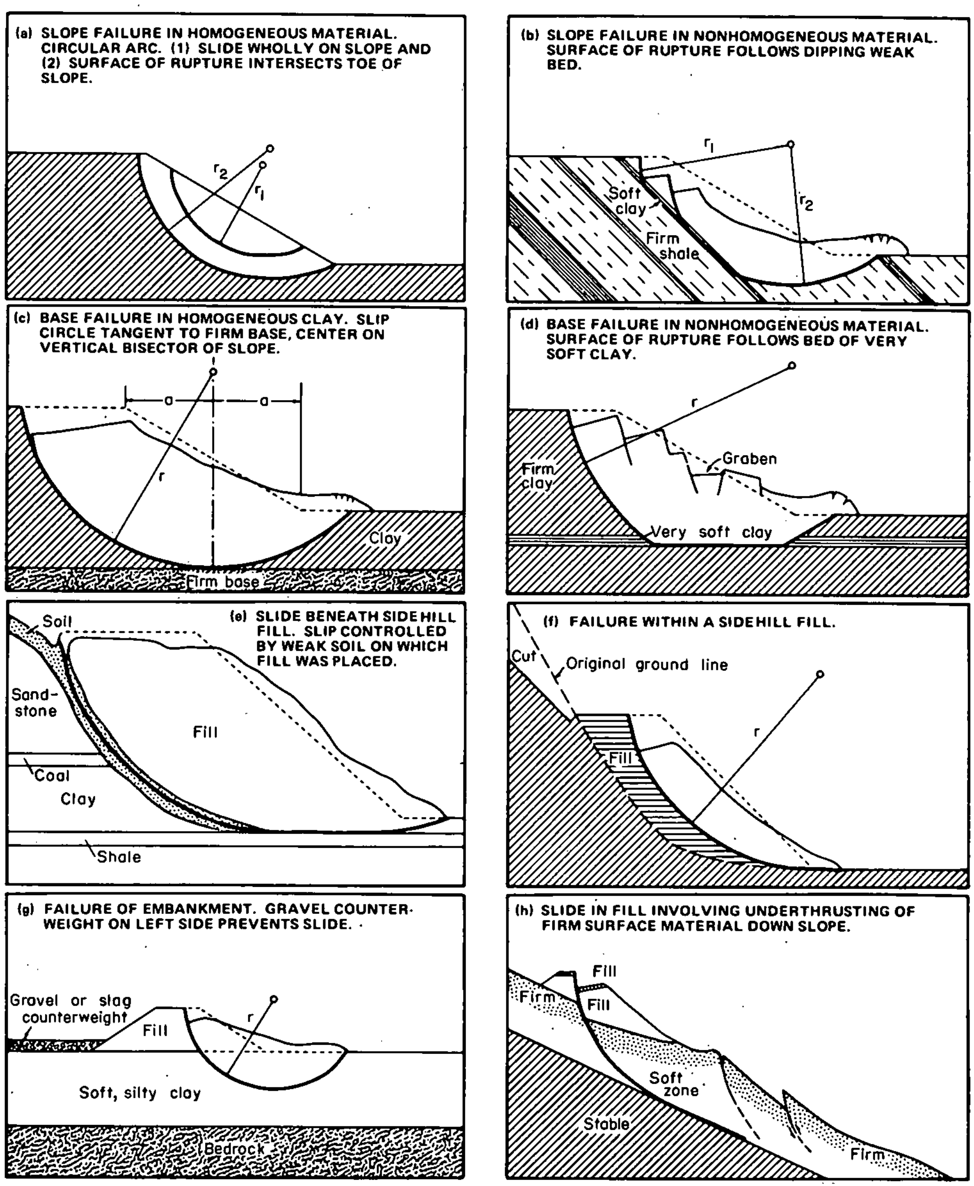


Figure 2.6. Slump of fill, controlled in this instance by failure in underlying soil (*2.182*).

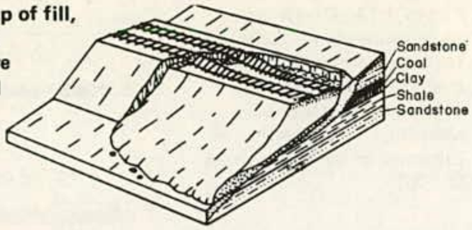


Figure 2.7. Slump in thinly bedded lake deposits of silt and clay in Columbia River valley (note backward tilting of beds above surface of rupture) (*2.182*).

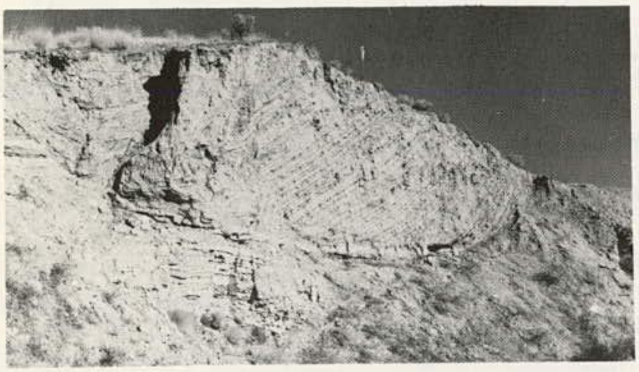


Figure 2.8. Slump in bedded deposits similar to those shown in Figure 2.7 (note that surface of rupture follows horizontal bedding plane for part of its length) (*2.182*).

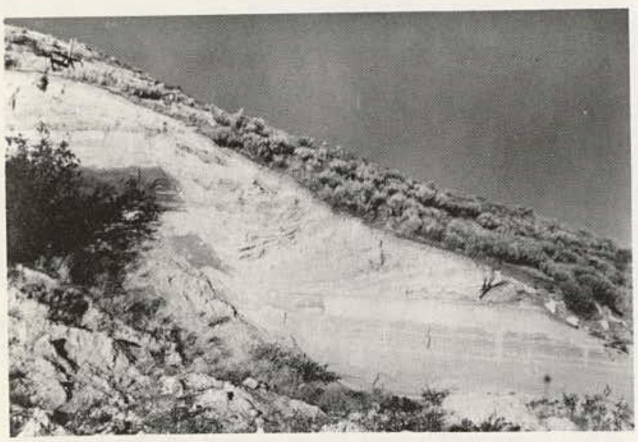
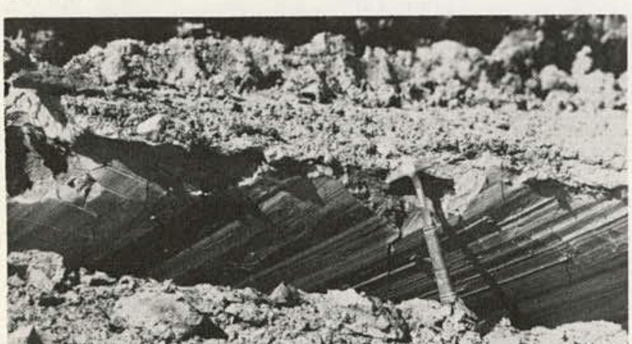


Figure 2.9. Slickensides in foot area of shallow slide in Pennington shale residuum (highly weathered clay shale) along I-40 in Roane County, Tennessee.



but without a recognized or well-defined controlling basal shear surface or zone of plastic flow. These appear to occur predominantly in bedrock, especially on the crests of ridges (Figure 2.1m1). The mechanics of movement are not well known.

2. Movements may involve fracturing and extension of coherent material, either bedrock or soil, owing to liquefaction or plastic flow of subjacent material. The coherent upper units may subside, translate, rotate, or disintegrate, or they may liquefy and flow. The mechanism of failure can involve elements not only of rotation and translation but also of flow; hence, lateral spreading failures of this type may be properly regarded as complex. They form, however, such a distinctive and dominant species in certain geologic situations that specific recognition seems worthwhile.

Examples of the second type of spread in bedrock are shown in Figure 2.1m2 and 2.1m3. In both examples, taken from actual landslides in the USSR and Libya respectively, a thick layer of coherent rock overlies soft shale and

Figure 2.10. Ames slide near Telluride, Colorado (*2.182, 2.183*). This slump-earth flow landslide occurred in glacial till overlying Mancos shale. Repeated slumping took place along upper margins after main body of material had moved down. Long axes of slump blocks *B* and *B'* are parallel with rather than perpendicular to direction of movement of main part of slide. Blocks *B* and *B'* moved toward left, rather than toward observer.

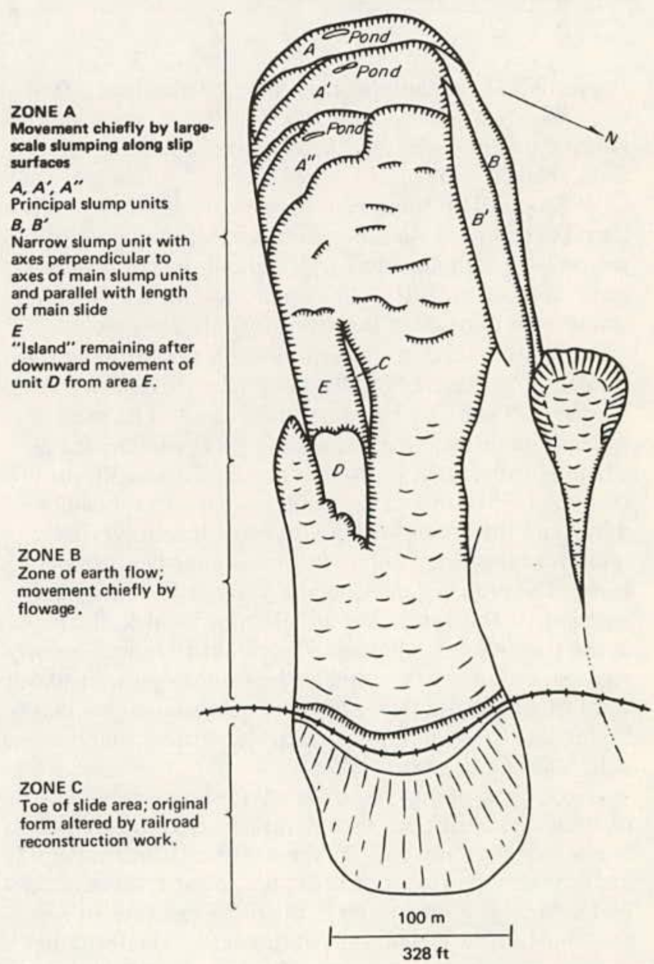


Figure 2.11. Thin layer of residual debris that slid on inclined strata of metasiltstone along I-40 in Cocke County, Tennessee.

Figure 2.12. Block slide at quarry (*2.182*).

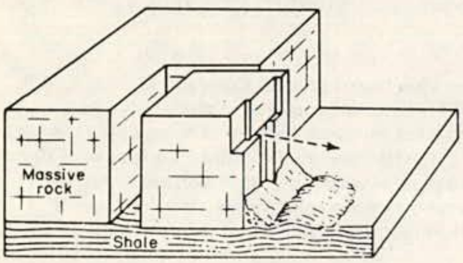


Figure 2.13. Development of landslides in horizontal sequence of claystone and coal caused by relaxation of horizontal stresses resulting from reduction in thickness of overlying strata (*2.136*).

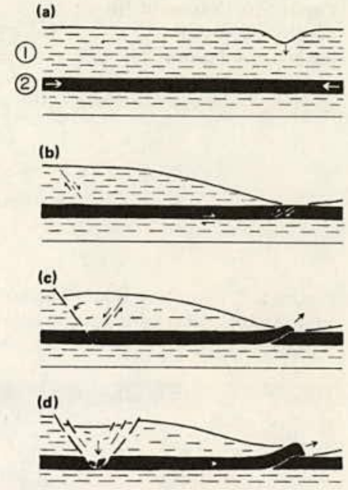
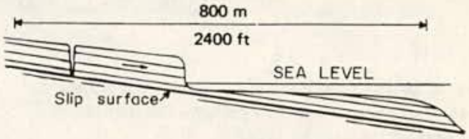


Figure 2.14. Section view of translational slide at Point Fermin, near Los Angeles, California (see also Figure 2.15) (*2.107, 2.182*). Maximum average rate of movement was 3 cm/week (1.2 in).



claystone. The underlying layer became plastic and flowed to some extent, allowing the overlying firmer rock to break into strips and blocks that then became separated. The cracks between the blocks were filled with either soft material squeezed up from below or detritus from above. The lateral extent of these slides is remarkable, involving bands several to many kilometers wide around the edges of plateaus and escarpments. The rate of movement of most lateral spreads in bedrock is apparently extremely slow.

Laterally spreading slope movements also form in fine-grained earth material on shallow slopes, particularly in sensitive silt and clay that loses most or all of its shear strength on disturbance or remolding. The failure is usually progressive; that is, it starts in a local area and spreads. Often the initial failure is a slump along a stream bank or shore, and the progressive failure extends retrogressively back from the initial failure farther and farther into the bank. The principal movement is translation rather than rotation. If the underlying mobile zone is thick, the blocks at the head may sink downward as grabens, not necessarily with backward rotation, and there may be upward and outward extrusion and flow at the toe. Movement generally begins suddenly, without appreciable warning, and proceeds with rapid to very rapid velocity.

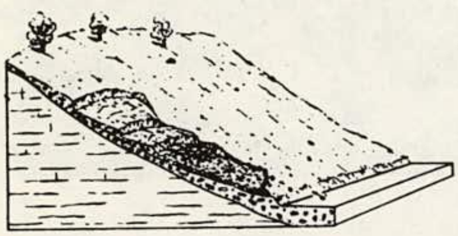
These types appear to be members of a gradational series of landslides in surficial materials ranging from block slides at one extreme, in which the zone of flow beneath the sliding mass may be absent or very thin, to earth flows or completely liquefied mud flows at the other extreme, in which the zone of flow includes the entire mass. The form that is taken depends on local factors. Most of the larger landslides in glacial sediments of northern North America and Scandinavia lie somewhere within this series.

Lateral spreads in surficial deposits have been destructive of both life and property and have, therefore, been the subject of intensive study. Examples may be cited from Sweden (Caldenius and Lundstrom, *2.18*), Canada (Mitchell and Markell, *2.108*), Alaska (Seed and Wilson, *2.144*), and California (Youd, *2.191*). Most of the spreading failures in the western United States generally involve less than total liquefaction and seem to have been mobilized only by seismic shock. For example, there were damaging failures in San Fernando Valley, California, during the 1969 earthquake because of liquefaction of underlying sand and silt and spreading of the surficial, firmer material. The spreading failure of Bootlegger Cove clay beneath the Turnagain Heights residential district at Anchorage, Alaska, during the 1964 great earthquake resulted in some loss of life and extensive damage. In some areas within the city of San Francisco, the principal damage due to the 1906 earthquake resulted from spreading failures that not only did direct damage to structures but also severed principal water-supply lines and thereby hindered firefighting.

All investigators would agree that spreading failures in glacial and marine sediments of Pleistocene age present some common and characteristic features: Movement often occurs for no apparent external reason, failure is generally sudden, gentle slopes are often unstable, dominant movement is translatory, materials are sensitive, and pore-water pressure is important in causing instability. All de-

Figure 2.15. Translational slide at Point Fermin, California. Photograph, which was taken January 17, 1965, indicates minor slumping into gap at rear of main mass and imminent rock falls at sea cliff. Principal motion, however, was by sliding along gently seaward dipping strata.

Figure 2.16. Debris slide of disintegrating soil slip variety (*2.83, 2.182*).



grees of disturbance of the masses have been observed; some failures consist almost entirely of one large slab or "flake," but others liquefy almost entirely to small chunks or mud.

Flows

Many examples of slope movement cannot be classed as falls, topples, slides, or spreads. In unconsolidated materials, these generally take the form of fairly obvious flows, either fast or slow, wet or dry. In bedrock, the movements most difficult to categorize include those that are extremely slow and distributed among many closely spaced, noninterconnected fractures or those movements within the rock mass that result in folding, bending, or bulging. In many instances, the distribution of velocities resembles that of viscous fluids; hence, the movements may be described as a form of flow of intact rock.

Much of what is here described under flowlike distributed movements has been classified as creep, both of rock and soil. But creep has come to mean different things to different persons, and it seems best to avoid the term or to use it in a well-defined manner. As used here, creep is considered to have a meaning similar to that used in mechanics of materials; that is, creep is simply deformation that continues under constant stress. Some of the creep deformation may be recoverable over a period of time upon release of the stress, but generally most of it is not. The movement commonly is imperceptible (which is usually one of the essential attributes of creep as defined in geomorphology), but increasingly sophisticated methods of measurement make this requirement difficult to apply. Furthermore, the usual partition of creep into three stages—primary (decelerating), secondary (steady or nearly so), and tertiary (accelerating to failure)—certainly includes perceptible deformation in the final stages. Laboratory studies show that both soil and rock, as well as metals, can exhibit all three stages of creep. Observations in the field, such as those reported by Müller (*2.112*) at Vaiont, embrace within the term creep perceptible movements that immediately preceded catastrophic failure.

There is disagreement also as to whether creep in rock and soil should be restricted to those movements that are distributed through a mass rather than along a defined fracture. Authorities are about equally divided on this point but, in keeping with the use of the term in engineering mechanics, the acceptance of this restriction is not favored. Creep movements can occur in many kinds of topples, slides, spreads, and flows, and the term creep need not be restricted to slow, spatially continuous deformation. Therefore, spatially continuous deformations are classified as various types of flow in rock, debris, and earth.

Flows in Bedrock

Flow movements in bedrock include deformations that are distributed among many large or small fractures, or even microfractures, without concentration of displacement along a through-going fracture. The movements are generally extremely slow and are apparently more or less steady in time, although few data are available. Flow movements may result in folding, bending, bulging, or other manifestations of plastic behavior, as shown in Figure 2.1p1, 2.1p2, 2.1p3, and 2.1p4. The distribution of velocities may roughly simulate that of viscous fluids, as shown in Figure 2.1p5.

These kinds of movements have come under close study only within the last decade or so and are being recognized more and more frequently in areas of high relief in many parts of the world. They are quite varied in character, and several kinds have been described as creep by Nemčok, Pašek, and Rybář (*2.116*) in a general classification of landslides and other mass movements, as gravitational slope deformation by Nemčok (*2.114, 2.115*), by the term Sackung (approximate translation: sagging) by Zischinsky (*2.194, 2.195*), as depth creep of slopes by Ter-Stepanian (*2.172*), and as gravitational faulting by Beck (*2.5*). In the United States, ridge-top depressions due to large-scale creep have been described by Tabor (*2.166*). A review of gravitational creep (mass rock creep) together with descriptions of examples from the United States and other countries has been prepared by Radbruch-Hall (*2.130*). The significance of these relatively slow but pervasive movements to human works on and within rock slopes is only beginning to be appreciated.

Flows in Debris and Earth

Distributed movements within debris and earth are often more accurately recognized as flows than those in rocks because the relative displacements within the mass are commonly larger and more closely distributed and the general appearance is more obviously that of a body that has behaved like a fluid. Moreover, the fluidizing effect of water itself is, as a rule, a part of the process. Slip surfaces within the moving mass are usually not visible or are short lived, and the boundary between moving mass and material in place may be a sharp surface of differential movement or a zone of distributed shear.

There is complete gradation from debris slides to debris flows, depending on water content, mobility, and character of the movement, and from debris slide to debris avalanche as movement becomes much more rapid because of lower cohesion or higher water content and generally steeper slopes. Debris slides and, less commonly, debris avalanches may have slump blocks at their heads. In debris slides, the moving mass breaks up into smaller and smaller parts as it advances toward the foot, and the movement is usually slow. In debris avalanches, progressive failure is more rapid, and the whole mass, either because it is quite wet or because it is on a steep slope, liquefies, at least in part, flows, and tumbles downward, commonly along a stream channel, and may advance well beyond the foot of the slope. Debris avalanches are generally long and narrow and often leave a serrate or V-shaped scar tapering uphill at the head, as shown in Figures 2.1q3 and 2.17, in contrast to the horseshoe-shaped scarp of a slump.

Debris flows, called mud flows in some other classifications, are here distinguished from the latter on the basis of particle size. That is, the term debris denotes material that contains a relatively high percentage of coarse fragments, whereas the term mud flow is reserved for an earth flow consisting of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles. Debris flows commonly result from unusually heavy precipitation or from thaw of snow or frozen soil. The kind of flow shown in Figure 2.1q1 often occurs during torrential runoff following cloudbursts. It is favored by the presence of soil on steep mountain slopes from which the vegetative cover has been removed by fire or other means, but the absence of vegetation is not a prerequisite. Once in motion, a small stream of water heavily laden with soil has transporting power that is disproportionate to its size, and, as more material is added to the stream by caving of its banks, its size and power increase. These flows commonly follow preexisting drainageways, and they are often of high density, perhaps 60 to 70 percent solids by weight, so that boulders as big as automobiles may be rolled along. If such a flow starts on an unbroken hillside it will quickly cut a V-shaped channel. Some of the coarser material will be heaped at the site to form a natural levee, while the more fluid part moves down the channel (Figure 2.17). Flows may extend many kilometers, until they drop their loads in a valley of lower gradient or at the base of a mountain front. Some debris flows and mud flows have been reported to proceed by a series of pulses in their lower parts; these pulses presumably are caused by periodic mobilization of material in the source area or by periodic damming and release of debris in the lower channel.

The term avalanche, if unmodified, should refer only to

Figure 2.17. Debris avalanche or very rapid debris flow at Franconia Notch, New Hampshire, June 24, 1948, after several days of heavy rainfall (*2.182*). Only soil mantle 2 to 5 m (7 to 6 ft) thick, which lay over bedrock on a slope of about 1:1, was involved. Scar is about 450 m (1500 ft) long; natural levees can be seen along sides of flow. US-3 is in foreground.

slope movements of snow or ice. Rapp (*2.132*) and Temple and Rapp (*2.169*), with considerable logic, recommend that, because the term debris avalanche is poorly defined, it should be abandoned, and that the term avalanche should be used only in connection with mass movements of snow, either pure or mixed with other debris. The term debris avalanche, however, is fairly well entrenched and in common usage (Knapp, *2.86*); hence, its appearance in the classification as a variety of very rapid to extremely rapid debris flow seems justified.

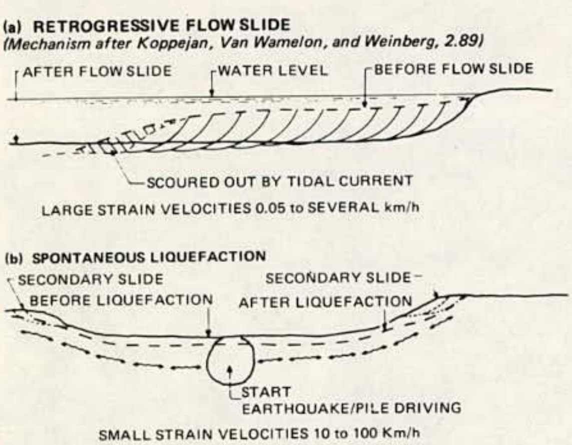
Recent studies have contributed much to a better understanding of the rates and duration of rainfall that lead to the triggering of debris flows, the physical properties of the material in place, the effect of slope angle, the effect of pore-water pressure, the mobilization of material and mechanism of movement, and the properties of the resulting deposit. The reader is referred especially to the works of Campbell (*2.20*), Daido (*2.34*), Fisher (*2.46*), Hutchinson (*2.70*), Hutchinson and Bhandari (*2.72*), Johnson and Rahn (*2.76*), Jones (*2.78*), Prior, Stephens, and Douglas (*2.129*), Rapp (*2.131*), K. M. Scott (*2.141*), R. C. Scott (*2.142*), and Williams and Guy (*2.188*). Flowing movements of surficial debris, including creep of the mantle of weathered rock and soil, are shown in Figure 2.1q2, 2.1q4, and 2.1q5. Soil flow, or solifluction, which in areas of perennially or permanently frozen ground is better termed gelifluction, takes many forms and involves a variety of mechanisms that can be treated adequately only in works devoted to this special field, which is of great significance to engineering works at high latitudes and altitudes. The reader is referred to summaries by Dylik (*2.40*), Washburn (*2.187*), and Corte (*2.27*); the proceedings of the International Conference on Permafrost (*2.111*); and recent work by McRoberts and Morgenstern (*2.104, 2.105*) and Embleton and King (*2.42*).

Subaerial flows in fine-grained materials such as sand, silt, or clay are classified here as earth flows. They take a variety of forms and range in water content from above saturation to essentially dry and in velocity from extremely rapid to extremely slow. Some examples are shown in Figure 2.1r1 through 2.1r5. At the wet end of the scale are mud flows, which are soupy end members of the family of predominantly fine-grained earth flows, and subaqueous flows or flows originating in saturated sand or silt along shores.

In a recent paper reviewing Soviet work on mud flows, Kurdin (*2.91*) recommended a classification of mud flows based on (a) the nature of the water and solid-material supply; (b) the structural-rheological model, that is, whether the transporting medium is largely water in the free state or is a single viscoplastic mass of water and fine particles; (c) the composition of the mud flow mass, that is, whether it consists of mud made up of water and particles less than 1 mm (0.04 in) in size or of mud plus gravel, rubble, boulders, and rock fragments; and (d) the force of the mud flow as defined by volume, rate of discharge, and observed erosive and destructive power. In the Soviet literature mud flows include not only what are here classified as debris flows but also heavily laden flows of water-transported sediment.

According to Andresen and Bjerrum (*2.3*), subaqueous flows are generally of two types: (a) retrogressive flow slide or (b) spontaneous liquefaction, as shown in Figure 2.18. The retrogressive flows, as shown in Figure 2.1r1, occur mostly along banks of noncohesive clean sand or silt. They are especially common along tidal estuaries in the coastal provinces of Holland, where banks of sand are subject to scour and to repeated fluctuations in pore-water pressure because of the rise and fall of the tide (Koppejan,

Figure 2.18. Retrogressive flow slide and spontaneous liquefaction (*2.3*).



Note: 1 km/h = 0.6 mph.

Figure 2.19. Earth flow near Greensboro, Florida (*2.80, 2.182*). Material is flat-lying, partly indurated clayey sand of the Hawthorn formation (Miocene). Length of slide is 275 m (900 ft) from scarp to edge of trees in foreground. Vertical distance is about 15 m (45 ft) from top to base of scarp and about 20 m (60 ft) from top of scarp to toe. Slide occurred in April 1948 after year of unusually heavy rainfall, including 40 cm (16 in) during 30 d preceding slide.

Van Wamelon, and Weinberg, *2.89*). When the structure of the loose sand breaks down along a section of the bank, the sand flows rapidly along the bottom, and, by repeated small failures, the slide eats into the bank and enlarges the cavity. Sometimes the scarp produced is an arc, concave toward the water, and sometimes it enlarges greatly, retaining a narrow neck or nozzle through which the sand flows. An extensive discussion and classification of subaqueous mass-transport processes and the resulting deposits have been presented by Carter (*2.21*).

Rapid earth flows also occur in fine-grained silt, clay, and clayey sand, as shown in Figures 2.1r2 and 2.19 (*2.80*). These flows form a complete gradation with slides involving failure by lateral spreading, but they involve not only liquefaction of the subjacent material but also retrogressive failure and liquefaction of the entire slide mass. They usually take place in sensitive materials, that is, in those materials whose shear strength on remolding at constant water content is decreased to a small fraction of its original value. Rapid earth flows have caused loss of life and immense destruction of property in Scandinavia, the St. Lawrence River valley in Canada, and Alaska during the 1964 earthquake. The properties of the material involved, which is usually a marine or estuarine clay of late Pleistocene age, have been thoroughly studied by many investigators during the last 15 years. Summary papers have been written by Bjerrum and others (*2.12*) on flows in Norway and by Mitchell and Markell (*2.108*), and Eden and Mitchell (*2.41*) on flows in Canada. Shoreline flows produced by the Alaskan earthquake at Valdez and Seward have been described by Coulter and Migliaccio (*2.28*) and Lemke (*2.98*). The large failure on the Reed Terrace near Kettle Falls, Washington, shown in Figures 2.20 and 2.21 (*2.79*), resembles in some respects the earth flow at Riviere Blanche, Quebec, shown in Figure 2.1r2 (*2.146*).

The somewhat drier and slower earth flows in plastic earth are common in many parts of the world wherever there is a combination of clay or weathered clay-bearing rocks, moderate slopes, and adequate moisture; Figure 2.22 shows a typical example. A common elongation of the flow, channelization in depression in the slope, and spreading of the toe are illustrated in Figure 2.1r3 and also shown in an actual debris flow in Figure 2.23.

The word flow naturally brings water to mind, and some content of water is necessary for most types of flow movement. But small dry flows of granular material are common, and a surprising number of large and catastrophic flow movements have occurred in quite dry materials. Therefore, the classification of flows indicates the complete range of water content—from liquid at the top to dry at the bottom. Tongues of rocky debris on steep slopes moving extremely slowly and often fed by talus cones at the head are called block streams (Figure 2.1q5). Because of rainwash, a higher proportion of coarse rocks may be in the surface layers than in the interior. Dry flows of sand are common along shores or embankments underlain by dry granular material. In form, they may be channelized, as shown in Figures 2.1r4 and 2.24, or sheetlike, as shown in Figure 2.25 (*2.79*). Small flows of dry silt, powered by impact on falling from a cliff, have been recognized, but so far as is known none has been studied in detail (Figure 2.26).

Flows of loess mobilized by earthquake shock have been more destructive of life than any other type of slope failure. Those that followed the 1920 earthquake in Kansu Province, China (Close and McCormick, *2.23*), shown in Figure 2.1r5, took about 100 000 lives. Apparently the normal, fairly coherent internal structure of the porous silt was destroyed by earthquake shock, so that, for all practical purposes, the loess became a fluid suspension of silt in air and flowed down into the valleys, filling them and overwhelming villages. The flows were essentially dry, according to the report. Extensive flows of loess accompanied the Chait earthquake of July 10, 1949, in Tadzhikistan, south-central Asia, and buried or destroyed 33 villages as the flows covered the bottoms of valleys to depths of several tens of meters for many kilometers (Gubin, *2.54*).

Complex

More often than not, slope movements involve a combina-

Figure 2.20. Reed Terrace area, right bank of Lake Roosevelt reservoir on Columbia River, near Kettle Falls, Washington, May 15, 1951 (*2.182*). Landslide of April 10, 1952, involving about 11 Mm^3 (15 million yd^3) took place by progressive slumping, liquefaction, and flowing out of glaciofluvial sediments through narrow orifice into bottom of reservoir.

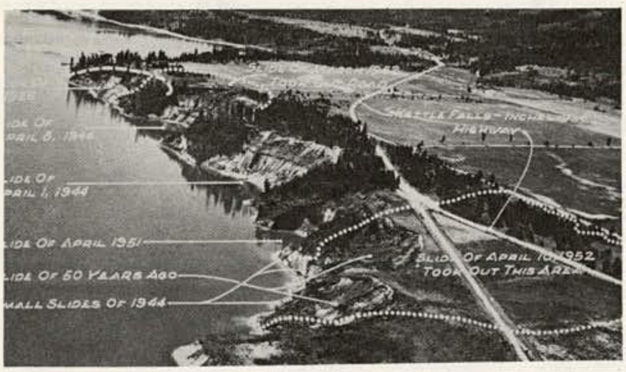


Figure 2.21. Reed Terrace area, Lake Roosevelt, Washington, August 1, 1952, after landslide of April 10, 1952 (*2.79, 2.182*).

Figure 2.22. Earth flow developing from slump near Berkeley, California (*2.182*).

Figure 2.23. Old debris flow in altered volcanic rocks west of Pahsimeroi River in south central Idaho.

Figure 2.24. Dry sand flow in Columbia River valley (*2.182*). Material is sand over lake-bed silt; dry sand from upper terrace flowed like liquid through notch in more compact sand and silt below.

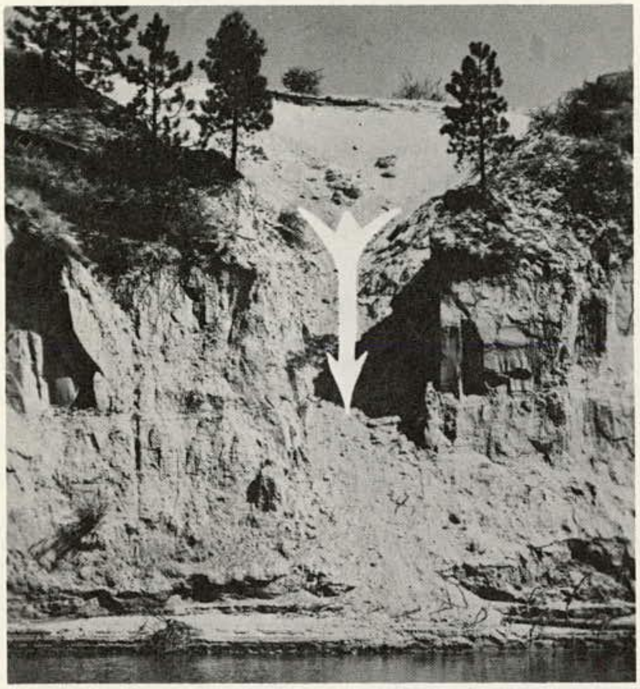


Figure 2.25. Shallow, dry, sand flow along shore of Lake Roosevelt, Washington (*2.79*). Wave erosion or saturation of sediment by lake water caused thin skin of material to lose support and ravel off terrace scarp.

Figure 2.26. Dry flow of silt (*2.182*). Material is lake-bed silt of Pleistocene age from high bluff on right bank of Columbia River, 4 km (2.5 miles) downstream from Belvedere, Washington. Flow was not observed while in motion, but is believed to result from blocks of silt falling down slope, disintegrating, forming a single high-density solid-in-air suspension, and flowing out from base of cliff.

tion of one or more of the principal types of movement described above, either within various parts of the moving mass or at different stages in development of the movements. These are termed complex slope movements, and a few examples of the many possible types are illustrated in Figure 2.1s1 through 2.1s5.

Of particular interest regarding hazards of landslides to life and property are large, extremely rapid rock fall-debris flows, referred to as rock-fragment flow (variety rock-fall avalanche) in the 1958 classification (*2.182*). Rock slide- and rock fall-debris flows are most common in rugged mountainous regions. The disaster at Elm, Switzerland (Heim, *2.58*, pp. 84, 109-112), which took 115 lives, started with small rock slides at each side of a quarry on the mountainside. A few minutes later the entire mass of rock above the quarry crashed down and shot across the valley. The movement of the rock fragments, which had to that moment been that of a rock slide and rock fall, appears to have taken on the character of a flow. The mass rushed up the other side of the small valley, turned and streamed into the main valley, and flowed for nearly 1.5 km (1 mile) at high velocity before stopping (Figure 2.1s1). About 10 Mm^3 (13 million yd^3) of rock descended an average of 470 m (1540 ft) vertically in a total elapsed time of about 55 s. The kinetic energy involved was enormous. A similar and even larger rock-fall avalanche occurred at Frank, Alberta, in 1903 and also caused great loss of life and property (McConnell and Brock, *2.103*; Cruden and Krahn, *2.33*).

These rock fall-debris flows are minor, however, compared with the cataclysmic flow that occurred at the time of the May 31, 1970, earthquake in Peru, which buried the city of Yungay and part of Ranrahirca, causing a loss of more than 18 000 lives. According to Plafker, Ericksen, and Fernandez Concha (*2.126*), the movement started high on Huascarán Mountain at an altitude of 5500 to 6400 m and involved 50 Mm^3 to 100 Mm^3 (65 million to 130 million yd^3) of rock, ice, snow, and soil that traveled 14.5 km (9 miles) from the source to Yungay at a velocity between 280 and 335 km/h (175 to 210 mph). They reported strong evidence that the extremely high velocity and low friction of the flow were due, at least in part, to lubrication by a cushion of air entrapped beneath the debris. Pautre, Sabarly, and Schneider (*2.122*) suggested that the mass may have ridden on a cushion of steam. A sketch of the area affected is shown in Figure 2.27, taken from a paper by Cluff (*2.24*) on engineering geology observations. Crandell and Fahnestock (*2.29*) cited evidence for an air cushion beneath one or more rock fall-debris flows that occurred in December 1963 at Little Tahoma Peak and Emmons Glacier on the east flank of Mt. Rainier volcano, Washington.

Such flows probably cannot be produced by a few thousand or a few hundred thousand cubic meters of material. Many millions of megagrams are required; and, when that much material is set in motion, perhaps even slowly, predictions of behavior based on past experience with small failures become questionable. The mechanics of large, extremely rapid debris flows, many of which appear to have been nearly dry when formed, have come under much recent study. The large prehistoric Blackhawk landslide (Figure 2.28) shows so little gross rearrangement within the sheet of debris of which it is composed that Shreve (*2.148*) believed the broken material was not fluidized but slid on an ephemeral layer of compressed air. He reported, similarly, that the large landslide that was triggered by the Alaska earthquake of 1964 and fell onto the Sherman Glacier showed little large-scale mixing and did not flow like a viscous fluid but instead slid like a flexible sheet (Shreve, *2.149*). On the other hand, Johnson and Ragle (*2.77*) reported,

Many rock-snow slides that followed from the Alaska earthquake of March 27, 1964, illustrated a variety of flow mechanics. The form of some slides suggests a complete turbulence during flow, while the form of others gives evidence for steady-state flow or for controlled shearing.

From a detailed analysis of the kinematics of natural rock fall-debris flows and from model studies, Hsü (*2.66*) disputed Shreve's hypothesis that some slid as relatively undeformed sheets on compressed air and concluded, rather, that they flowed.

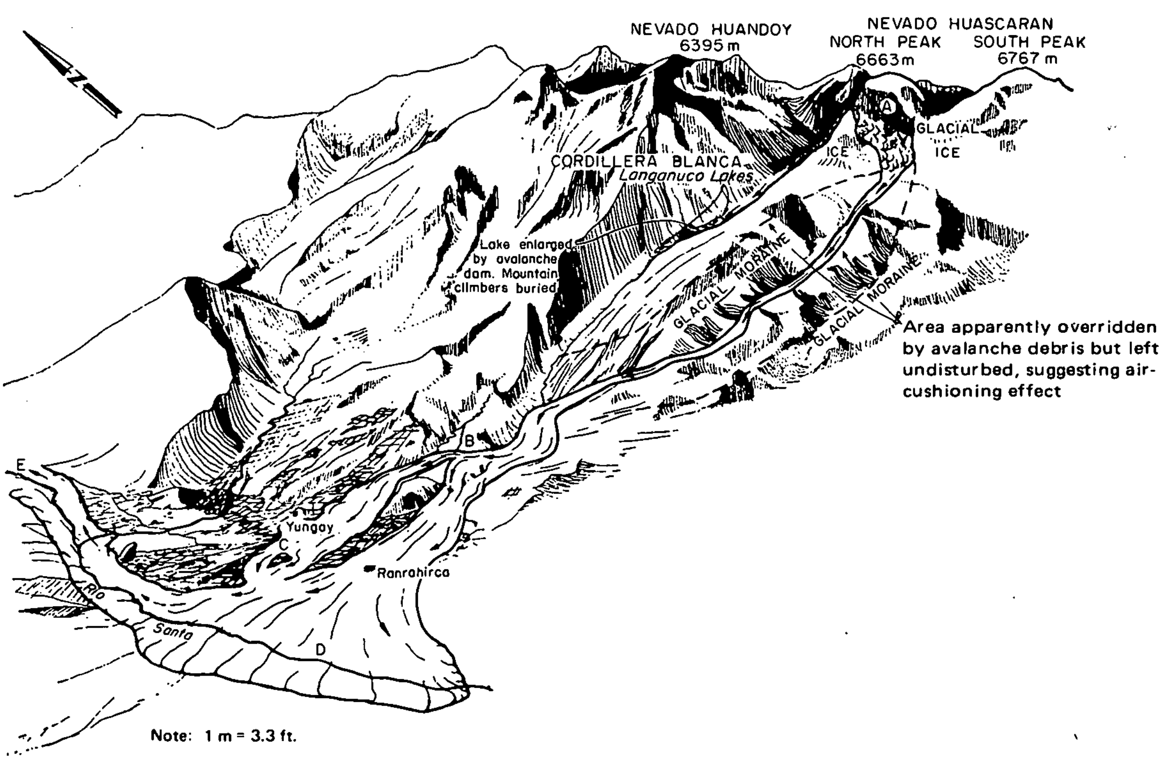
Obviously, there is much yet to be learned about these processes, particularly as similar features indicating mass movements of huge size have been recognized in Mariner 9 photographs of the surface of Mars (Sharp, *2.145*), where it is yet uncertain that significant amounts of either liquid or gas were available for fluidization.

Getting back to Earth, we note self-explanatory examples of complex movements in Figure 2-1: slump-topple in Figure 2.1s2, rock slide-rock fall in Figure 2.1s3, and the common combination of a slump that breaks down into an earth flow in its lower part in Figure 2.1s5.

The illustration of cambering and valley bulging in Figure 2.1s4 is adapted from the classical paper by Hollingworth and Taylor (*2.65*) on the Northampton Sand Ironstone in England, their earlier paper on the Kettering district (*2.64*), and a sketch supplied by J. N. Hutchinson. The complex movements were described by Hutchinson (*2.68*) as follows:

Cambering and Valley Bulging. These related features were first clearly recognized in 1944 by Hollingworth, Taylor, and Kellaway (see reference in Terzaghi, 1950) in the Northampton Ironstone field of central England, where they are believed to have a Late Pleistocene origin. The ironstone occurs in the near-horizontal and relatively thin Northampton Sands, which are the uppermost solid rocks in the neighborhood. These are underlain, conformably, by a great thickness of the Lias, into which shallow valleys, typically 1200 to 1500 meters wide and 45 meters deep, have been eroded. Excavations for dam trenches in the valley bottoms have shown the Lias there to be thrust strongly upward and contorted, while opencast workings in the Northampton Sands

Figure 2.27. Area affected by May 31, 1970, Huascarán debris avalanche, which originated at point A (*2.24*). Yungay was protected from January 10, 1962, debris avalanche by 180 to 240-m (600 to 800-ft) high ridge (point B), but a portion of May 31, 1970, debris avalanche diverted from south side of canyon wall, topped "protective" ridge, and descended on Yungay below. Only safe place in Yungay was Cemetery Hill (point C), where some 93 people managed to run to before debris avalanche devastated surrounding area. Moving at average speed of 320 km (200 mph), debris arrived at point D, 14.5 km (9 miles) distant and 3660 m (12 000 ft) lower, within 3 to 4 min after starting from north peak of Huascarán. Debris flowed upstream along course of Rio Santa (point E) approximately 2.5 km (1.5 miles). Debris continued to follow course of Rio Santa downstream to Pacific Ocean, approximately 160 km (100 miles), devastating villages and crops occupying floodplain.



occupying the interfluves reveal a general valleyward increase of dip of "camber" of this stratum, often passing into dip and fault structure, suggesting corresponding downward movements along the valley margins. In adjusting to these movements, the rigid cap-rock has been dislocated by successive, regularly spaced fissures which parallel the valley and are known as "gulls." Similar features have been recognized in other parts of England and in Bohemia. The mechanisms by which cambering and valley bulging have been formed remain to be established.

Hutchinson (*2.70*) also pointed out that Sharpe's definition of flow (*2.146*), which requires zero relative displacement at the boundary of the flow (flow adheres to the stable material), does not fit the observed distribution of velocities at Beltinge, where a mud flow developed in a temperate climate on a 30-m-high (98-ft) coastal cliff of stiff, fissured London clay subject to moderate marine erosion. Here the mud flow was bounded both on the sides and on the bottom by discrete surfaces along which shear displacements occurred. For these kinds of movements Hutchinson and Bhandari (*2.72*) proposed the term mudslides. These can be regarded as complex movements in which the internal distribution of velocities within the moving mass may or may not resemble that of viscous fluids, but the movement relative to stable ground is finite discontinuous shear. It would seem that the material of the sliding earth flow is behaving as a plastic body in plug flow, as suggested by Hutchinson (*2.69*, pp. 231-232) and as analyzed in detail by Johnson (*2.75*).

Sequence or Repetition of Movement

The term retrogressive has been used almost consistently for slides or flow failures that begin at a local area, usually along a slope, and enlarge or retreat opposite to the direction of movement of the material by spreading of the failure surface, successive rotational slumps, falls, or liquefaction of the material. Kojan, Foggin, and Rice (*2.87*, pp. 127-128) used the term for failure spreading downslope.

On the other hand, the term progressive has been used to indicate extension of the failure (a) downslope (Blong, *2.13*; Kjellman, *2.84*; Ter-Stepanian, *2.170, 2.171*; Thomson and Hayley, *2.177*), (b) upslope (but not specifically upslope only) (Seed, *2.143*; Tavenas, Chagnon, and La Rochelle, *2.168*), and (c) either upslope or downslope, or unspecified (Terzaghi and Peck, *2.176*; Bishop, *2.7*; Romani, Lovell, and Harr, *2.135*; Lo, *2.100*; Frölich, *2.51*; Ter-Stepanian and Goldstein, *2.173*, and many others).

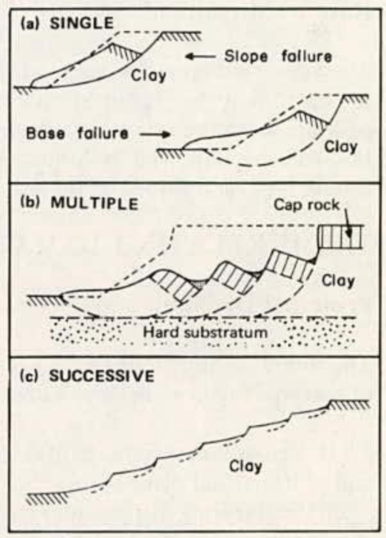
I suggest that the term progressive be used for failure that is either advancing or retreating or both simultaneously, that the term retrogressive be used only for retreating failures, and that failures that enlarge in the direction of movement be referred to simply as advancing failures.

The terms complex, composite, compound, multiple, and successive have been used in different ways by various authors. I suggest the following definitions.

1. Complex refers to slope movements that exhibit more than one of the major modes of movement. This is the sense of the meaning suggested by Blong (*2.14*). The term is synonymous with composite, as used by Prior, Stephens, and

Figure 2.28. Blackhawk landslide (*2.147*). Upslope view, southward over lobe of dark marble breccia spread beyond mouth of Blackhawk Canyon on north flank of San Bernardino Mountains in southern California. Maximum width of lobe is 3.2 km (2 miles); height of scarp at near edge is about 15 m (50 ft).

Figure 2.29. Main types of rotational slide (*2.68*).



Archer (*2.128*) to describe sliding mud flows.

2. Compound refers to movements in which "the failure surface is formed of a combination of curved and planar elements and the slide movements have a part-rotational, part-translational character" (Skempton and Hutchinson, *2.154*).

3. Multiple refers to manifold development of the same mode of movement. As applied to retrogressive rotational sliding, the term refers to the production of "two or more slipped blocks, each with a curved slip surface tangential to a common, generally deep-seated slip sole [Figure 2.29]. Clearly, as the number of units increases, the overall character of the slip becomes more translational, though in failing, each block itself rotates backwards" (Hutchinson, *2.68*). Leighton (*2.97*) distinguished two types of multiple slide blocks: superposed, in which each slide block rides out on the one below, and juxtaposed, in which adjacent

moving units have a common basal surface of rupture, as shown in Figure 2.30.

4. Successive refers to any type of multiple movements that develop successively in time. According to Skempton and Hutchinson (*2.154*), "Successive rotational slips consist of an assembly of individual shallow rotational slips. The rather sparse data available suggest that successive slips generally spread up a slope from its foot." Hutchinson (*2.67*) states,

Below a slope inclination of about 13° [in London Clay], *rotational slips of type R are replaced by successive rotational slips (type S). These probably develop by retrogression from a type R slip in the lower slope. Each component slip is usually of considerable lateral extent, forming a step across the slope. Irregular successive slips, which form a mosaic rather than a stepped pattern in plan are also found.*

Figure 2.31 (*2.67*) shows the main types of landslides in London clay.

Figure 2.30. Two types of multiple slide blocks (*2.97*).

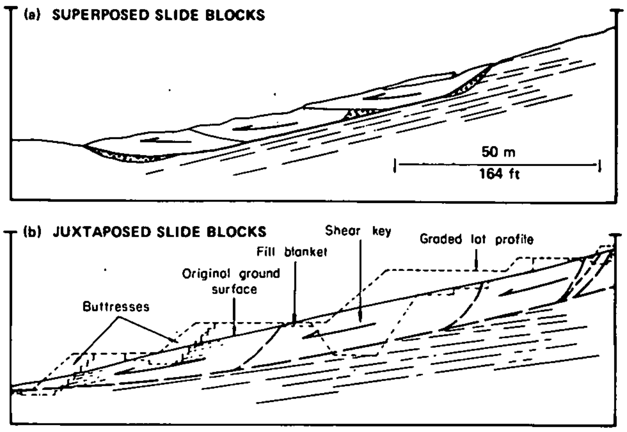
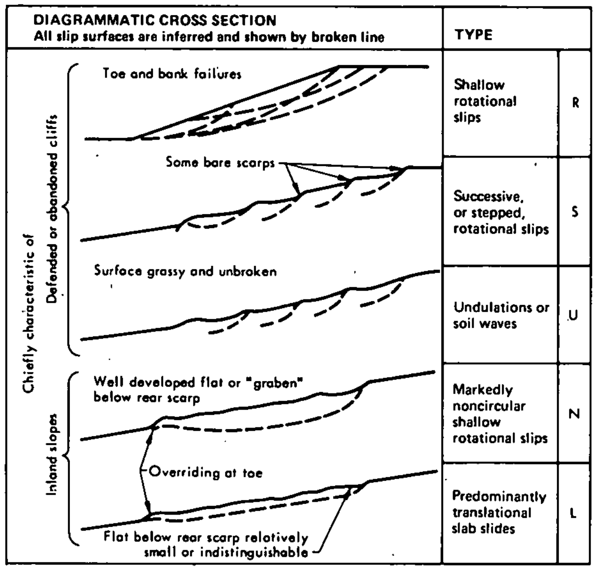


Figure 2.31. Main types of landslides in London clay (*2.67*).



Landslides that develop one on top of another are called multistoried by Ter-Stepanian and Goldstein (*2.173*). Figure 2.32 shows their illustration of a three-storied landslide in Sochi on the coast of the Black Sea.

Rate of Movement

The rate-of-movement scale used in this chapter is shown at the bottom of the classification chart in Figure 2.1u. Metric equivalents to the rate scale shown in the 1958 classification have been derived by Yemel'ianova (*2.190*), and these should now be regarded as the primary definitions.

TERMS RELATING TO MATERIAL

Principal Divisions

The following four terms have been adopted as descriptions of material involved in slope movements.

1. Bedrock designates hard or firm rock that was intact and in its natural place before the initiation of movement.

2. Engineering soil includes any loose, unconsolidated, or poorly cemented aggregate of solid particles, generally of natural mineral, rock, or inorganic composition and either transported or residual, together with any interstitial gas or liquid. Engineering soil is divided into debris and earth.

a. Debris refers to an engineering soil, generally surficial, that contains a significant proportion of coarse material. According to Shroder (*2.150*), debris is used to specify material in which 20 to 80 percent of the fragments are greater than 2 mm (0.08 in) in size and the remainder of the fragments less than 2 mm.

b. Earth (again according to Shroder) connotes material in which about 80 percent or more of the fragments are smaller than 2 mm; it includes a range of materials from nonplastic sand to highly plastic clay.

This division of material that is completely gradational is admittedly crude; however, it is intended mainly to enable a name to be applied to material involved in a slope movement on the basis of a limited amount of information.

Water Content

By modifying the suggestions of Radbruch-Hall (*2.130*), we may define terms relating to water content simply as (a) dry, contains no visible moisture; (b) moist, contains some water but no free water and may behave as a plastic solid but not as a liquid; (c) wet, contains enough water to behave in part as a liquid, has water flowing from it, or supports significant bodies of standing water; and (d) very wet, contains enough water to flow as a liquid under low gradients.

Texture, Structure, and Special Properties

As amounts of information increase, more definite designation can be made about slope movements. For example, a bedrock slump may be redesignated as a slump in sandstone

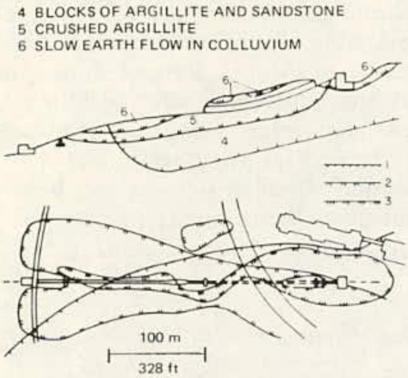


Figure 2.32. Three-storied landslide in Sochi on coast of Black Sea, USSR (*2.173*). Boundaries of three stories of sliding are shown in section and plan by three types of lines.

Figure 2.33. Shallow translational slide that developed on shaly slope in Puente Hills of southern California (*2.147*). Slide has low D/L ratio (note wrinkles in surface).

over stiff-fissured clay shale, or an earth slide may be given more precise definition as a block slide in moist sensitive clay.

TERMS RELATING TO SIZE OR GEOMETRY

A rather large body of descriptive terms has been built up relating to the size, shape, and morphology of slope movements and their deposits. Some of these have already been mentioned, such as the relation of rotational slides to curved surfaces of rupture and translational slides to planar surfaces of rupture. The close association between the morphology of a slope movement and its dominant genetic process, which is evident in a qualitative way from the foregoing text and illustrations, has been tested quantitatively through the use of refined measures of the parts and geometric attributes of landslides by Crozier (*2.32*) and by Blong (*2.14, 2.15*). These authors, together with Snopko (*2.157*), Klengel and Pašek (*2.85*), Shroder (*2.150*), and Laverdière (*2.94*), have made available a terminology that is adequate to describe almost any feature of a slump earth flow. In addition, Skempton and Hutchinson (*2.154*) used the ratio of D/L, where D is the maximum thickness of the slide and L is the maximum length of the slide upslope. From Skempton's figures showing original use of this ratio (*2.152*), it seems probable that the intended length is that of a chord of the rupture surface (L_c), rather than the total length (L), as shown in Figure 2.1t. Skempton and Hutchinson gave a range of D/L_c values of 0.15 to 0.33 for rotational slides in clay and shale, and they stated that slab slides, which commonly occur in a mantle of weathered or colluvial material on clayey slopes, rarely if ever have D/L_c ratios greater than 0.1. Figure 2.33 illustrates such a shallow slab slide. In a statistical study of the forms of landslides along the Columbia River valley, Jones, Embody, and Peterson (*2.79*) made extensive use of the horizontal component (HC) or distance from the foot of the landslide to the crown, measured in a longitudinal section of the landslide, and the vertical component (VC) or difference in altitude between the foot and crown, measured in the same section.

TERMS RELATING TO GEOLOGIC, GEOMORPHIC, GEOGRAPHIC, OR CLIMATIC SETTING

The classification of landslides proposed by Savarensky (*2.140*) and followed to some degree in eastern Europe makes the primary division of types on the basis of the relation of slope movements to the geologic structure of the materials involved. Accordingly, asequent slides are those in which the surface of rupture forms in homogeneous material; consequent slides are those in which the position and geometry of the surface of rupture are controlled by preexisting discontinuities such as bedding, jointing, or contact between weathered and fresh rock; and insequent slides are those in which the surface of rupture cuts across bedding or other surfaces of inhomogeneity. The Japanese have used a classification of landslides separated into (a) tertiary type, involving incompetent tertiary sedimentary strata (Takada, *2.167*); (b) hot-spring-volcanic type, which is in highly altered rocks; and (c) fracture-zone type, which occurs in fault zones and highly broken metamorphic rocks. Sharpe (*2.146*, pp. 57-61) distinguished three types of mud flows: semiarid, alpine, and volcanic, to which Hutchinson (*2.68*) has added a fourth variety, temperate.

Types of landslides are sometimes identified by the geographic location at which the type is particularly well developed. For example, Sokolov (*2.159*) refers to block slides of the Angara type (similar to that shown in Figure 2.1m2), of the Tyub-Karagan type (similar to that shown in Figure 2.1m3), and of the Ilim and Crimean types, all named after localities. Reiche (*2.133*) applied the term Toreva-block (from the village of Toreva on the Hopi Indian Reservation in Arizona) to "a landslide consisting essentially of a single large mass of unjostled material which, during descent, has undergone backward rotation toward the parent cliff about a horizontal axis which roughly parallels it" (Figure 2.1g). Shreve (*2.149*), in summarizing data on landslides that slid on a cushion of compressed air, referred to these landslides as being of the Blackhawk type, from the rock fall-debris slide-debris flow at Blackhawk Mountain in southern California (*2.148*). Although the use of locality terms may occasionally be a convenience, it is not recommended as a general practice, for the terms themselves are not informative to a reader who lacks knowledge of the locality.

TERMS RELATING TO AGE OR STATE OF ACTIVITY

Active slopes are those that are either currently moving or that are suspended, the latter term implying that they are not moving at the present time but have moved within the last cycle of seasons. Active slides are commonly fresh; that is, their morphological features, such as scarps and ridges, are easily recognizable as being due to gravitational movement, and they have not been significantly modified by surficial processes of weathering and erosion. However, in arid regions, slides may retain a fresh appearance for many years.

Inactive slopes are those for which there is no evidence that movement has taken place within the last cycle of seasons. They may be dormant, in which the causes of failure remain and movement may be renewed, or they may be stabilized, in which factors essential to movement have been removed naturally or by human activity. Slopes that have long-inactive movement are generally modified by erosion and weathering or may be covered with vegetation so that the evidence of the last movement is obscure. They are often referred to as fossil (Záruba and Mencl, *2.193*; Klengel and Pašek, *2.85*; Nossin, *2.118*) or ancient (Popov, *2.127*) landslides in that they commonly have developed under different geomorphological and climatic conditions thousands or more years ago and cannot repeat themselves at present.

FORMING NAMES

The names applied to slope movements can be made progressively more informative, as more data are obtained, by building up a designation from several descriptor words, each of which has a defined meaning. For example, a slow, moist, translational debris slab slide means material moving along a planar surface of a little-disturbed mass of fragmented material having a D/L_c ratio of 0.1 or less, containing some water but none free, and moving at a rate between 1.5 m/month and 1.5 m/year (5 ft/month or year). Once all these particulars are established in the description, the movement could be referred to thereafter simply as a debris slide.

CAUSES OF SLIDING SLOPE MOVEMENTS

The processes involved in slides, as well as in other slope movements, comprise a continuous series of events from cause to effect. An engineer faced with a landslide is primarily interested in preventing the harmful effects of the slide. In many instances the principal cause of the slide cannot be removed, so it may be more economical to alleviate the effects continually or intermittently without attempting to remove the cause. Some slides occur in a unique environment and may last only a few seconds. The damage can be repaired, and the cause may be of only academic interest unless legal actions are to be taken. More often, however, landslides take place under the influence of geologic, topographic, or climatic factors that are common to large areas. The causes must then be understood if other similar slides are to be avoided or controlled.

Seldom, if ever, can a landslide be attributed to a single definite cause. As clearly shown by Zolotarev (*2.196*), the process leading to the development of the slide has its beginning with the formation of the rock itself, when its basic physical properties are determined, and includes all the subsequent events of crustal movements, erosion, and weathering. Finally, some action, perhaps trivial, sets a mass of material in motion downhill. The last action cannot be regarded as the only cause, even though it was necessary in the chain of events. As Sowers and Sowers (*2.161*, p. 506) point out,

> *In most cases a number of causes exist simultaneously and so attempting to decide which one finally produced failure is not only difficult but also incorrect. Often the final factor is nothing more than a trigger that set in motion an earth mass that was already on the verge of failure. Calling the final factor the cause is like calling the match that lit the fuse that detonated the dynamite that destroyed the building the cause of the disaster.*

In this connection, however, the determination of all the geologic causes of a landslide should not be confused with determination of legal responsibility. The interrelations of landslide causes are lucidly and graphically presented by Terzaghi (*2.175*). His work, that of Sharpe (*2.146*), Ladd (*2.92*), and Bendel (*2.6*), and that of more recent researchers, such as Záruba and Mencl (*2.193*), Skempton and Hutchinson (*2.154*), Krinitzsky and Kolb (*2.90*), Rapp (*2.131*), and Legget (*2.96*) were used in the preparation of this section.

All slides involve the failure of earth materials under shear stress. The initiation of the process can therefore be reviewed according to (a) the factors that contribute to increased shear stress and (b) the factors that contribute to low or reduced shear strength. Although a single action, such as addition of water to a slope, may contribute to both an increase in stress and a decrease in strength, it is helpful to separate the various physical results of such an action. The principal factors contributing to the sliding of slope-forming materials are outlined in the following discussion. The operation of many factors is self-evident and needs no lengthy description; some factors are only discussed briefly, or reference is made to literature that gives examples or treats the subject in detail.

Factors That Contribute to Increased Shear Stress

Removal of Lateral Support

The removal of lateral support is the commonest of all factors leading to instability, and it includes the following actions:

1. Erosion by (a) streams and rivers, which produce most natural slopes that are subject to sliding (Hutchinson, *2.67*; Jones, Embody, and Peterson, *2.79*; Eyles, *2.43*; Fleming, Spencer, and Banks, *2.48*; California Division of

Highways, *2.19*), (b) glaciers, which have deeply cut and oversteepened many valleys in mountainous regions that have been the sites of large slides and debris flows (Plafker, Ericksen, and Fernandez Concha, *2.126*), (c) waves and longshore or tidal currents (Wood, *2.189*; Ward, *2.186*; Hutchinson, *2.71*; Koppejan, Van Wamelon, and Weinberg, *2.89*), and (d) subaerial weathering, wetting and drying, and frost action;

2. Previous rock fall, slide (Kenney and Drury, *2.81*), subsidence, or large-scale faulting that create new slopes; and

3. Work of human agencies in which (a) cuts, quarries, pits, and canals (Van Rensburg, *2.181*; Piteau, *2.124*; Patton, *2.121*; Cording, *2.26*) are established, (b) retaining walls and sheet piling are removed, and (c) lakes and reservoirs are created and their levels altered (Müller, *2.112*; Jones, Embody, and Peterson, *2.79*; Lane, *2.93*; Dupree and Taucher, *2.39*).

Surcharge

Surcharge also results from both natural and human agencies. The surcharge from natural agencies may be

1. Weight of rain, hail, snow, and water from springs;
2. Accumulation of talus overriding landslide materials;
3. Collapse of accumulated volcanic material, producing avalanches and debris flows (Francis and others, *2.50*);
4. Vegetation (Gray, *2.53*; Pain, *2.120*); and
5. Seepage pressures of percolating water.

The surcharge from human agencies may be

1. Construction of fill;
2. Stockpiles of ore or rock;
3. Waste piles (Bishop, *2.8*; Davies, *2.35*; Smalley, *2.156*);
4. Weight of buildings and other structures and trains; and
5. Weight of water from leaking pipelines, sewers, canals, and reservoirs.

Transitory Earth Stresses

Earthquakes have triggered a great many landslides, both small and extremely large and disastrous. Their action is complex, involving both an increase in shear stress (horizontal accelerations may greatly modify the state of stress within slope-forming materials) and, in some instances, a decrease in shear strength (Seed, *2.143*; Morton, *2.110*; Solonenko, *2.160*; Lawson, *2.95*; Hansen, *2.57*; Newmark, *2.117*; Simonett, *2.151*; Hadley, *2.55*; Gubin, *2.54*). Vibrations from blasting, machinery, traffic, thunder, and adjacent slope failures also produce transitory earth stresses.

Regional Tilting

A progressive increase in the slope angle through regional tilting is suspected as contributing to some landslides (Terzaghi, *2.175*). The slope must obviously be on the point of failure for such a small and slow-acting change to be effective.

Removal of Underlying Support

Examples of removal of underlying support include

1. Undercutting of banks by rivers (California Division of Highways, *2.19*) and by waves;
2. Subaerial weathering, wetting and drying, and frost action;
3. Subterranean erosion in which soluble material, such as carbonates, salt, or gypsum is removed and granular material beneath firmer material is worked out (Ward, *2.186*; Terzaghi, *2.174*);
4. Mining and similar actions by human agencies;
5. Loss of strength or failure in underlying material; and
6. Squeezing out of underlying plastic material (Záruba and Mencl, *2.193*, pp. 68-78).

Lateral Pressure

Lateral pressure may be caused by

1. Water in cracks and caverns,
2. Freezing of water in cracks,
3. Swelling as a result of hydration of clay or anhydrite, and
4. Mobilization of residual stress (Bjerrum, *2.9*; Krinitzsky and Kolb, *2.90*).

Volcanic Processes

Stress patterns in volcanic edifices and crater walls are modified by general dilation due to inflation or deflation of magma chambers, fluctuation in lava-lake levels, and increase in harmonic tremors (Tilling, Koyanagi, and Holcomb, *2.178*; Moore and Krivoy, *2.109*; Fiske and Jackson, *2.47*).

Factors That Contribute to Low or Reduced Shear Strength

The factors that contribute to low or reduced shear strength of rock or soil may be divided into two groups. The first group includes factors stemming from the initial state or inherent characteristics of the material. They are part of the geologic setting that may be favorable to landslides, exhibit little or no change during the useful life of a structure, and may exist for a long period of time without failure. The second group includes the changing or variable factors that tend to lower the shear strength of the material.

Initial State

Factors in the initial state of the material that cause low shear strength are composition, texture, and gross structure and slope geometry.

Composition

Materials are inherently weak or may become weak upon change in water content or other changes. Included especially are organic materials, sedimentary clays and shales, decomposed rocks, rocks of volcanic tuff that may weather to clayey material, and materials composed dominantly of soft platy minerals, such as mica, schist, talc, or serpentine.

Texture

The texture is a loose structure of individual particles in sensitive materials, such as clays, marl, loess, sands of low density, and porous organic matter (Aitchison, *2.2*; Bjerrum and Kenney, *2.11*; Cabrera and Smalley, *2.17*). Roundness of grain influences strength as compressibility and internal friction increase with angularity.

Gross Structure and Slope Geometry

Included in gross structure and slope geometry are

1. Discontinuities, such as faults, bedding planes, foliation in schist, cleavage, joints, slickensides, and brecciated zones (Skempton and Petley, *2.155*; Fookes and Wilson, *2.49*; Komarnitskii, *2.88*; St. John, Sowers, and Weaver, *2.138*; Van Rensburg, *2.181*; Jennings and Robertson, *2.74*; Bjerrum and Jørstad, *2.10*);
2. Massive beds over weak or plastic materials (Záruba and Mencl, *2.193*; Nemčok, *2.113*);
3. Strata inclined toward free face;
4. Alternation of permeable beds, such as sand or sandstone, and weak impermeable beds, such as clay or shale (Henkel, *2.59*); and
5. Slope orientation (Rice, Corbett, and Bailey, *2.134*; Shroder, *2.150*).

Changes Due to Weathering and Other Physicochemical Reactions

The following changes can occur because of weathering and other physicochemical reactions:

1. Softening of fissured clays (Skempton, *2.153*; Sangrey and Paul, *2.139*; Eden and Mitchell, *2.41*);
2. Physical disintegration of granular rocks, such as granite or sandstone, under action of frost or by thermal expansion (Rapp, *2.131*);
3. Hydration of clay minerals in which (a) water is absorbed by clay minerals and high water contents decrease cohesion of all clayey soils, (b) montmorillonitic clays swell and lose cohesion, and (c) loess markedly consolidates upon saturation because of destruction of the clay bond between silt particles;
4. Base exchange in clays, i.e., influence of exchangeable ions on physical properties of clays (Sangrey and Paul, *2.139*; Liebling and Kerr, *2.99*; Torrance, *2.179*);
5. Migration of water to weathering front under electrical potential (Veder, *2.184*);
6. Drying of clays that results in cracks and loss of cohesion and allows water to seep in;
7. Drying of shales that creates cracks on bedding and shear planes and reduces shale to chips, granules, or smaller particles; and
8. Removal of cement by solution.

Changes in Intergranular Forces Due to Water Content and Pressure in Pores and Fractures

Buoyancy in saturated state decreases effective intergranular pressure and friction. Intergranular pressure due to capillary tension in moist soil is destroyed upon saturation. Simple softening due to water and suffusion and slaking are discussed by Mamulea (*2.101*).

Changes can occur because of natural actions, such as rainfall and snowmelt, and because of a host of human activities, such as diversion of streams, blockage of drainage, irrigation and ponding, and clearing of vegetation and deforestation.

Crozier (*2.30, 2.31*), Shroder (*2.150*), and Špůrek (*2.163*) discuss the general effect of climate; Temple and Rapp (*2.169*) Williams and Guy (*2.188*), Jones (*2.78*), and So (*2.158*), catastrophic rainfall; Conway (*2.25*), Denness (*2.38*), and Piteau (*2.124*), effect of groundwater; Gray (*2.53*), Bailey (*2.4*), Cleveland (*2.22*), Rice, Corbett, and Bailey (*2.134*), and Swanston (*2.165*), deforestation; Peck (*2.123*) and Hirao and Okubo (*2.60*), correlation of rainfall and movement; and Shreve (*2.148*), Voight (*2.185*), Kent (*2.82*), and Goguel and Pachoud (*2.52*), gaseous entrainment or cushion.

Changes in Structure

Changes in structure may be caused by fissuring of shales and preconsolidated clays and fracturing and loosening of rock slopes due to release of vertical or lateral restraints in valley walls or cuts (Bjerrum, *2.9*; Aisenstein, *2.1*; Ferguson, *2.45*; Matheson and Thomson, *2.102*; Mencl, *2.106*). Disturbance or remolding can affect the shear strength of materials composed of fine particles, such as loess, dry or saturated loose sand, and sensitive clays (Gubin, *2.54*; Youd, *2.191*; Smalley, *2.156*; Mitchell and Markell, *2.108*).

Miscellaneous Causes

Other causes of low shear strength are (a) weakening due to progressive creep (Suklje, *2.164*; Ter-Stepanian, *2.172*; Trollope, *2.180*; Piteau, *2.124*) and actions of tree roots (Feld, *2.44*) and burrowing animals.

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