Chapter Three

Landslide Types and Processes

David J. Varnes[3]

It is the purpose of this chapter to review the whole range of earth movements that may properly be regarded as landslides and to classify these movements according to factors that have some bearing on prevention or control.

As defined for use in this volume the term "landslide" denotes downward and outward movement of slope-forming materials composed of natural rock, soils, artificial fills, or combinations of these materials. The moving mass may proceed by any one of three principal types of movement: falling, sliding, or flowing, or by their combinations. Parts of a landslide may move upward while other parts move downward. The lower limit of the rate of movement of landslide material is restricted in this book by the economic aspect to that actual or potential rate of movement which provokes correction or maintenance. Normal surficial creep is excluded. Also, most types of movement due to freezing and thawing (solifluction), together with avalanches that are composed mostly of snow and ice, are not considered as landslides in the sense here intended, although they often pose serious problems to the highway engineer. Such movements are not discussed because they appear to depend on factors of weather, ice physics, and thermodynamics, rather than on principles of soil mechanics or geology, and hence lie outside the province of the committee.

[3] Publication authorized by the Director, U. S. Geological Survey.

Types of Landslides

Classification

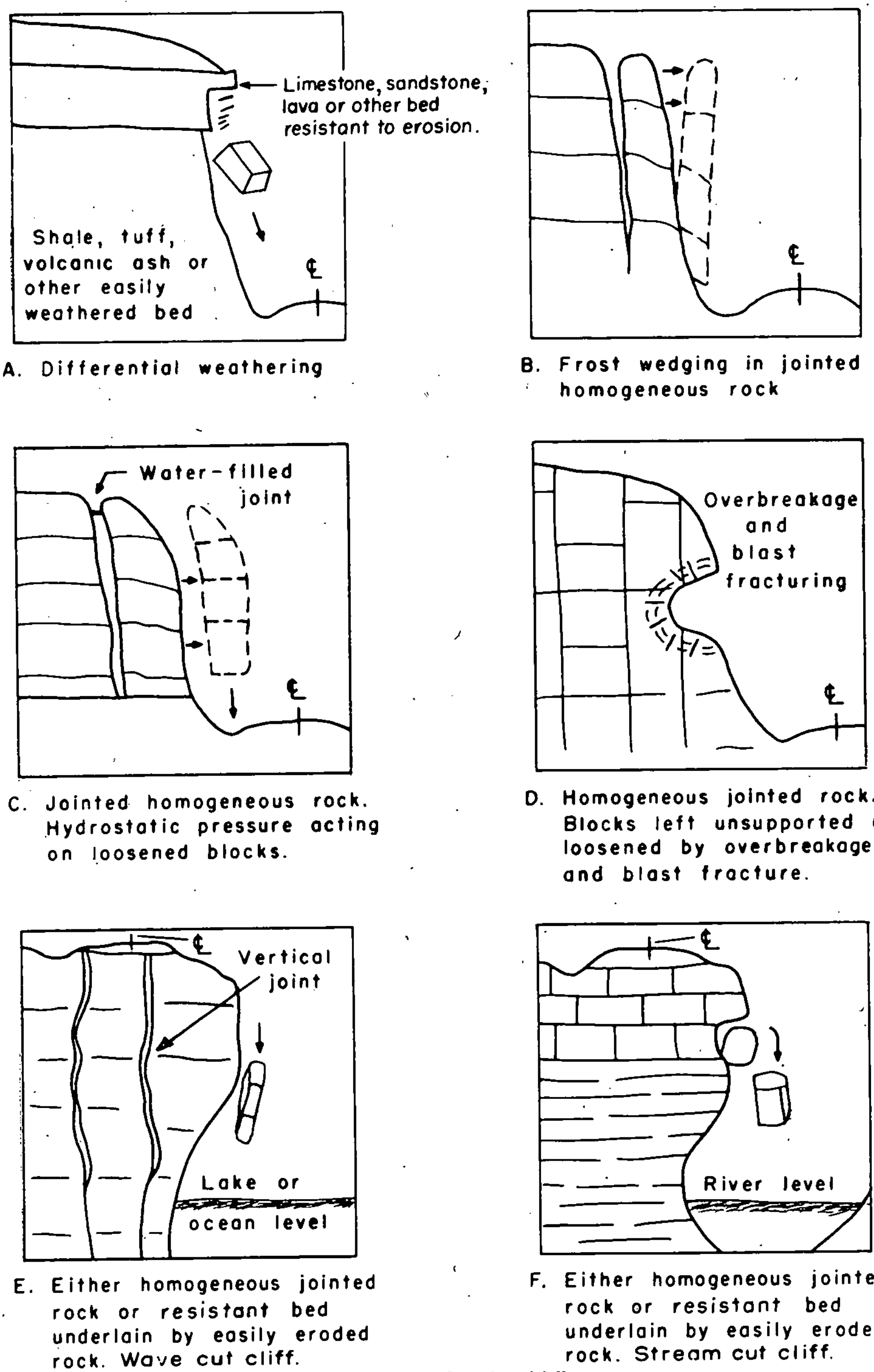
Many classifications have already been proposed for earth movements, based variously on the kind of material, type of movement, causes, and many other factors. There are, in fact, so many such schemes embedded with varying degrees of firmness in geological and engineering literature that the committee has approached the question of a "new" classification with considerable misgivings. As Terzaghi has stated (1950, p. 88), "A phenomenon involving such a multitude of combinations between materials and disturbing agents opens unlimited vistas for the classification enthusiast. The result of the classification depends quite obviously on the classifier's opinion regarding the relative importance of the many different aspects of the classified phenomenon." Each classification, including the one proposed in this volume, is best adapted to a particular mode of investigation, and each has its inherent advantages and disadvantages. However, as pointed out by Ward (1945, p. 172), "A classification of the types of failure is necessary to the engineer to enable him to distinguish and recognize the different phenomena for purposes of design and also to enable him to take the appropriate remedial or safety measures where necessary. The geographer and geologist need a classification so that they may interpret the past and predict the present trends of topography as revealed by their observations."

The classification adopted here is shown in Plate 1 and is further described in the following paragraphs. Definitions of the parts of a landslide appear in Plate 1-t. An abbreviated version, without diagrams and explanatory text, is shown in Figure 5. In preparing this classification of landslides, a deliberate effort has been made to set it up according to features that may be observed at once or with a minimum of investigation, and without reference to the causes of the slides. Two main variables are considered: (a) the type of material involved, which usually is apparent on inspection or preliminary boring; and (b) the type of movement, which usually may be determined by a short period of observation or by the shape of the slide and arrangement of debris. In its emphasis on type of movement the classification resembles, more than any other, that proposed by Sharpe (1938) for landslides and other related movements.

The chart (Pl. 1) shows examples of slides by small drawings. The type of material involved is indicated by the horizontal position of the drawing within the chart; the type of movement is indicated by the vertical position of the drawing. Water content of flow-type landslides is indicated by the relative vertical position of the drawing within the flow group. Each drawing also has a note giving the general range of velocity of movement of the landslide type, according to the scale of velocities at the bottom of the chart (Pl. 1-u).

<table>
<tr><td rowspan="2">TYPE OF MOVEMENT</td><td colspan="4">TYPE OF MATERIAL</td></tr>
<tr><td colspan="2">BEDROCK</td><td colspan="2">SOILS</td></tr>
<tr><td>FALLS</td><td colspan="2">ROCKFALL</td><td colspan="2">SOILFALL</td></tr>
<tr><td>SLIDES — FEW UNITS</td><td>ROTATIONAL
SLUMP</td><td>PLANAR
BLOCK GLIDE</td><td>PLANAR
BLOCK GLIDE</td><td>ROTATIONAL
BLOCK SLUMP</td></tr>
<tr><td>SLIDES — MANY UNITS</td><td></td><td>ROCKSLIDE</td><td>DEBRIS SLIDE</td><td>FAILURE BY LATERAL SPREADING</td></tr>
<tr><td rowspan="4">FLOWS</td><td>ROCK FRAGMENTS</td><td colspan="3">ALL UNCONSOLIDATED
SAND OR SILT — MIXED — MOSTLY PLASTIC</td></tr>
<tr><td>DRY: ROCK FRAGMENT FLOW</td><td>SAND RUN
LOESS FLOW</td><td></td><td></td></tr>
<tr><td></td><td>RAPID EARTHFLOW</td><td>DEBRIS AVALANCHE</td><td>SLOW EARTHFLOW</td></tr>
<tr><td>WET</td><td>SAND OR SILT FLOW</td><td>DEBRIS FLOW</td><td>MUDFLOW</td></tr>
<tr><td>COMPLEX</td><td colspan="4">COMBINATIONS OF MATERIALS OR TYPE OF MOVEMENT</td></tr>
</table>

Figure 5. Classification of landslides, abbreviated version (see plate 1 for complete chart with drawings and explanatory text).



A. Differential weathering

B. Frost wedging in jointed homogeneous rock

C. Jointed homogeneous rock. Hydrostatic pressure acting on loosened blocks.

D. Homogeneous jointed rock. Blocks left unsupported or loosened by overbreakage and blast fracture.

E. Either homogeneous jointed rock or resistant bed underlain by easily eroded rock. Wave cut cliff.

F. Either homogeneous jointed rock or resistant bed underlain by easily eroded rock. Stream cut cliff.

Figure 6. Examples of rockfalls.

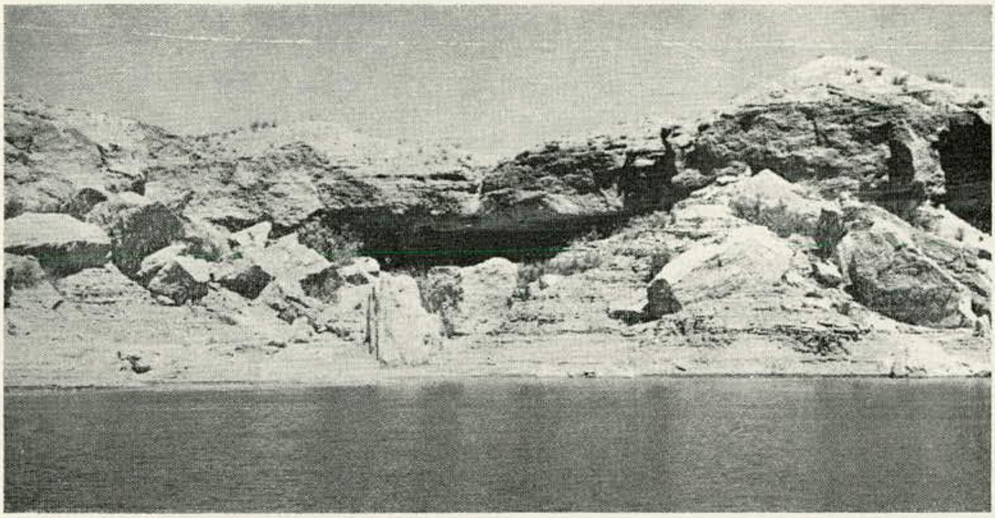


Figure 7. Rockfall due to undercutting along shore of Las Vegas Bay, Lake Mead, Nev. The rock is the Muddy Creek formation (Pliocene?) consisting here of siltstone overlain by indurated breccia. The movement is straight down by gravity, in contrast to rockslide, which slides on a sloping surface. (Photograph by U. S. Bureau of Reclamation, February 24, 1949)

Materials are classed, for falls and slides, into bedrock and soils. The term "soils" is used in the engineering sense and includes clastic material, rock fragments, sheared or weathered bedrock, and organic matter. Falls and slides involving bedrock are shown in the upper left part of the chart; those involving soils are shown in the upper right part of the chart. The materials of flows are grouped into various categories. Material is classified according to its state prior to initial movement, or, if the type of movement changes, according to its state at the time of the change to the new type of movement.

Types of movement are divided into three principal groups — falls, slides, and flows. A fourth group, complex slides, is a combination of any or all of the other three types of movement. There may be, of course, variations in the type of movement and in the materials from place to place, or from time to time, in an actual landslide, so that a rigid classification is neither practical nor desirable.

Type I — Falls

Falls are very common. In rockfall and soilfall, the moving mass travels mostly through the air by free fall, leaping, bounding, or rolling, with little or no interaction between one moving unit and another (Pl. 1-a, b). Movements are very rapid to extremely rapid (see rate of movement scale, Pl. 1-u) and may or may not be preceded by minor movements. Several varieties of rockfall are illustrated in Figures 6 and 7.

Type II — Slides

In true slides, the movement results from shear failure along one or several surfaces, which are either visible or may reasonably be inferred. Two subgroups of slides may be distinguished according to the mechanics of movement — those in which the moving mass is not greatly deformed (Type IIA), and those which are greatly deformed or consist of many small units (Type IIB). The Type IIA group includes the familiar slump or rotational shear types of slides; it includes also undeformed slides along more or less planar surfaces, for which the term "block glides" is here proposed. Type IIB slides include most rockslides, debris slides, and failures by lateral spreading.

A — Relatively Undeformed Material

Type IIA slides are made up of one or a few moving units. The maximum dimension of the units is greater than the relative displacement between units and is comparable to or greater than the displacement of the center of gravity of the whole mass. Movement may be structurally controlled by surfaces of weakness, such as faults, bedding planes, or joints.

Slumps. — The commonest examples of Type IIA or undeformed slides are slumps. Slumps, and slumps combined with other types of movement, make up a high proportion of the landslide problem facing the highway engineer. The movement in slumps takes place only along internal slip surfaces. The exposed cracks are concentric and concave toward the direction of movement. In many slumps the underlying surface of rupture, together with the exposed scarps, is spoon-shaped (see Fig. 8). 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 (see Fig. 9). In slumps the movement is more or less rotary about an axis that is parallel to the slope. The top surface of each unit tilts backward toward the slope (see Figs. 9, 10, 11, and 12, and Pl. 1-c and 1-h).

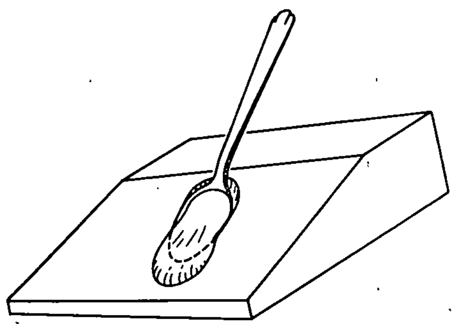


Figure 8. Spoon-shaped slope failure. Slope failures are often spoon-shaped, as in this sketch, or cylindrical as shown in Figure 9.

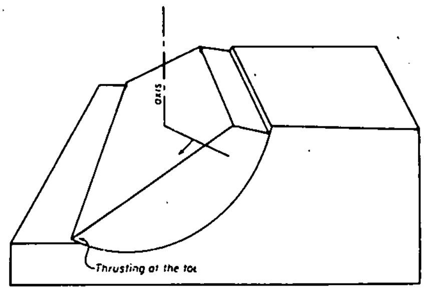


Figure 9. Rotational shear on cylindrical surface.

Figure 10 illustrates some of the commoner varieties of slump failure in various kinds of material. Figure 12 shows the backward tilting of strata exposed in a longitudinal section through a small slump in lake beds. Although the surface of rupture of slumps is a concave-upward curve, it is seldom a circular arc of uniform curvature. Often the shape of the curve is greatly influenced by faults, joints, bedding, or other preexisting discontinuities in the material. The influence of such structures must be considered very carefully when the engineer makes a slope stability analysis that assumes a certain configuration for the surface of rupture. Figures 12 and 13 illustrate 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 14.

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 at the crown of the slide similar to the original slump. Occasionally the scarps along the lateral margins of the upper part of the slide

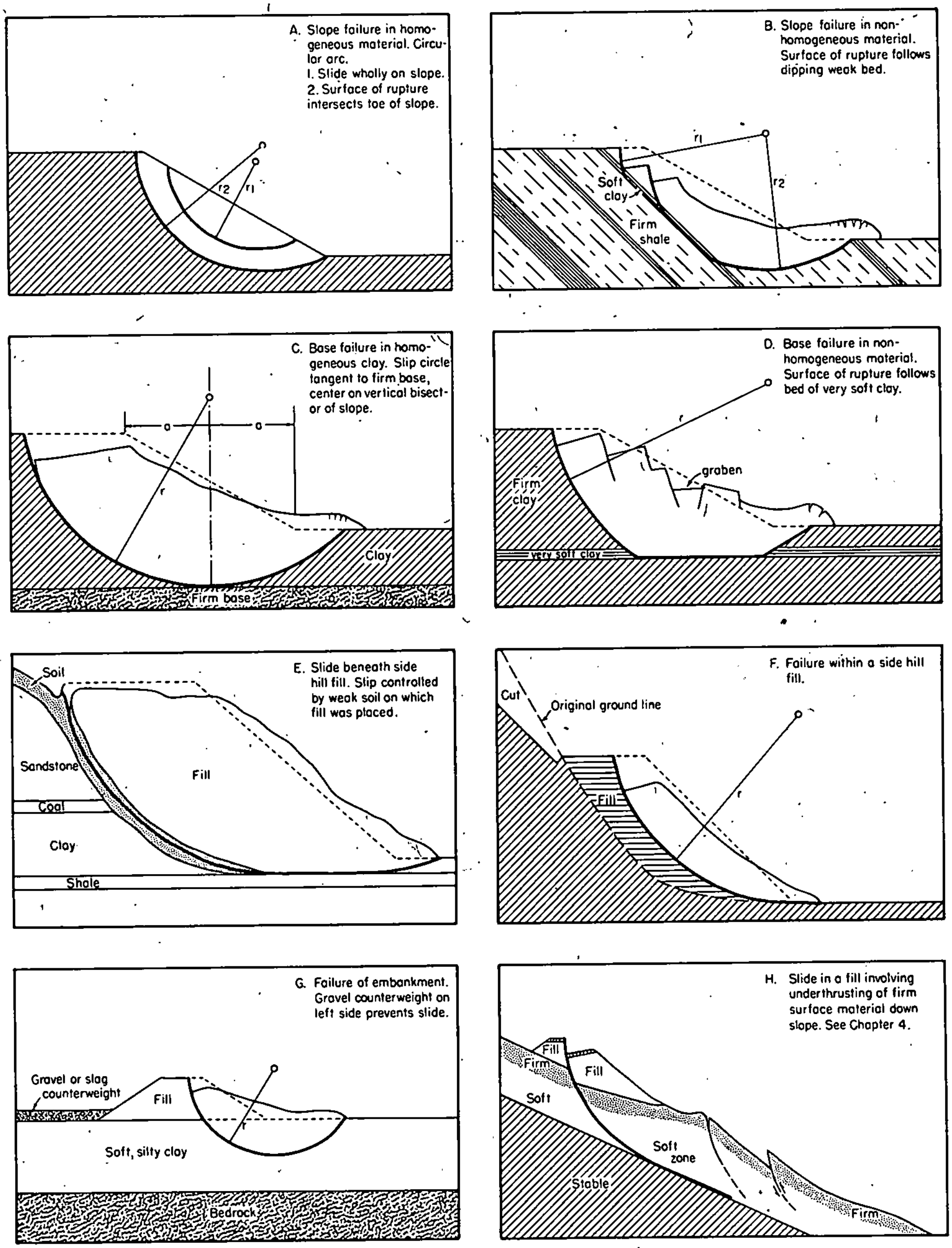


Figure 10. Some varieties of slump.

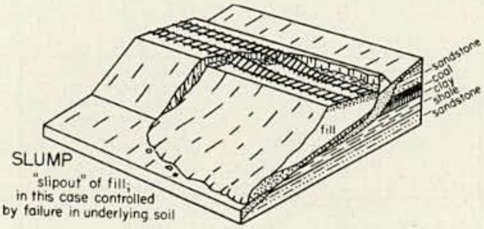


Figure 11. Slump. "Slipout" of fill; in this case controlled by failure in underlying soil.

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 15 shows, in plan, such an unusual type 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. Material in the lower parts of slumps may become so greatly broken or churned up that the toe advances as an earthflow or debris slide with a type of motion distinct from slumping at the head. The combination of slump and earthflow, as illustrated in Figures 16, 28, and 47, and Plate 1-h, occurs frequently. Slumping movement does not generally proceed with more than moderate velocity unless the toe is in water or unless flowing movements remove material as fast as it is brought down from above.

Block Glides. — Not all Type IIA slides have the characteristic form and

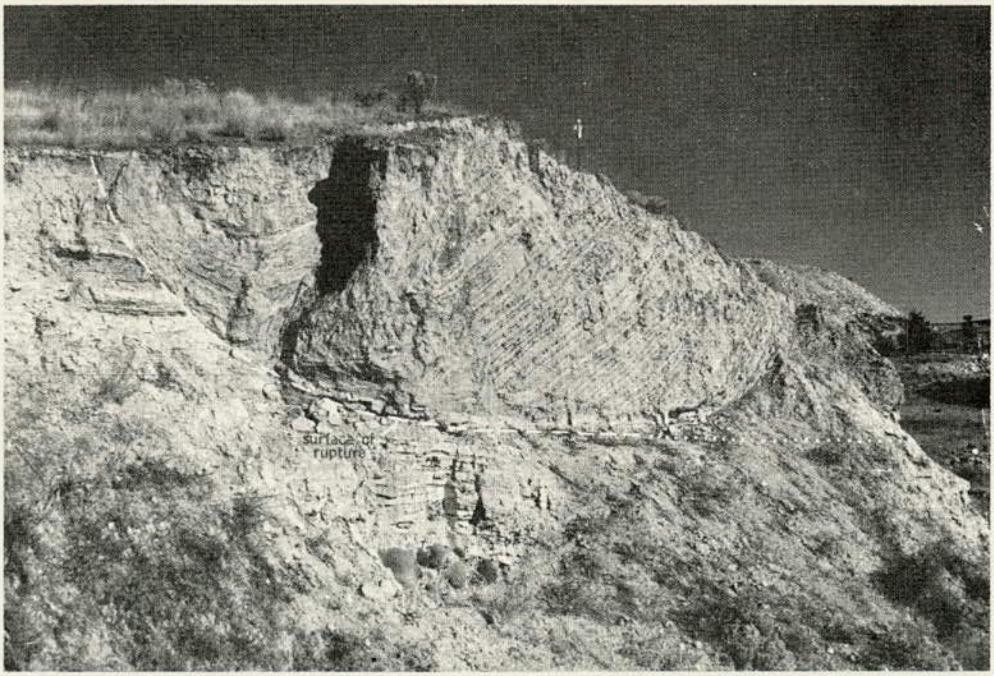


Figure 12. Slump in thinly bedded lake deposits of silt and clay in the Columbia River valley. Note backward tilting of beds above surface of rupture. (Photograph by F. O. Jones, U. S. Geological Survey)

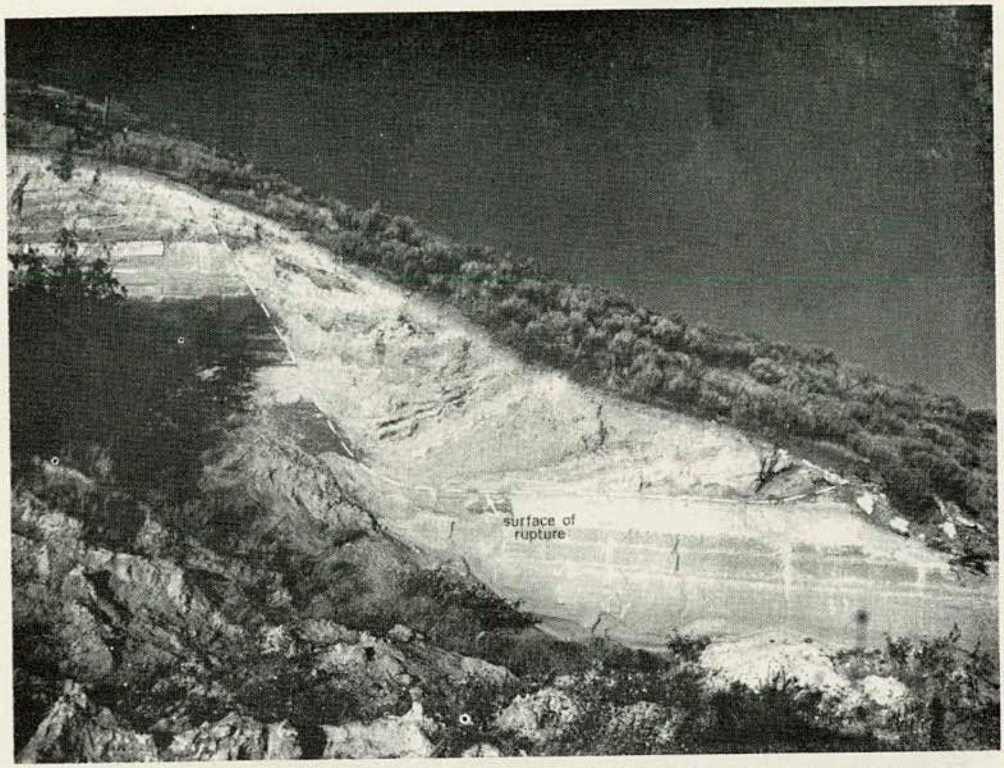


Figure 13. Slump in bedded lake deposits similar to those shown in Figure 12. Note how the surface of rupture follows a horizontal bedding plane for part of its length. (Photograph by F. O. Jones, U. S. Geological Survey)

rotary movement of a slump. In some, the mass progresses out, or down and out, as a unit along a more or less planar surface, without the rotary movement and backward tilting characteristic of slump. The moving mass may even slide out on the original ground surface. The term "block glide" is here applied to Type IIA slides of this kind. The need for distinguishing this type of slide from slump arises partly from restriction of slump to movement that is only along internal slip surfaces that are generally concave upward. But the distinction is useful also 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, therefore, decreases and the slide stops moving. A block glide, 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. Several examples of block glides are illustrated in Figures 17, 18, 19, and 38, and Plate 1-d, e, f, and g. Plate 1-g is an example suggested by the Iowa State Highway Commission. Block glides, alone or in combination with other types of movement, are probably quite common, although they seem to have attracted little attention in the literature.

B — Greatly Deformed Material

Type IIB landslides comprise those in which the movement is by sliding but the material is deformed or breaks up

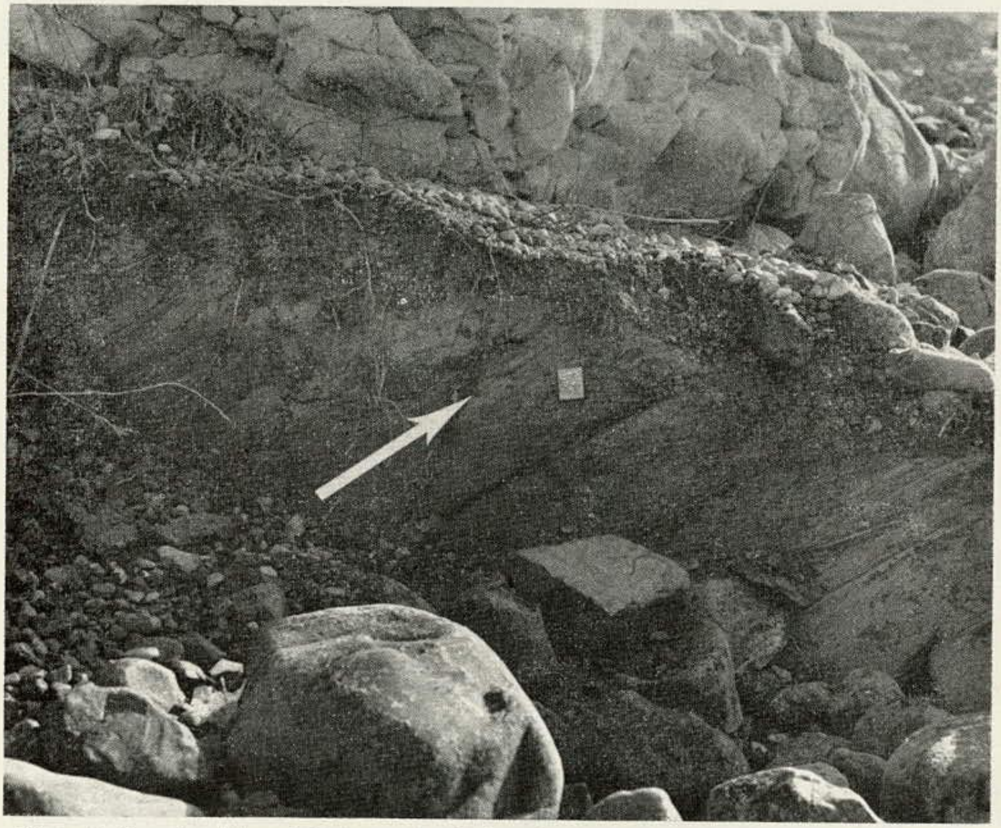


Figure 14. Upward and forward displacement at the lateral margin of the toe of a slump, right bank of the Columbia River downstream from Grand Coulee Dam, Wash. Slickensides are on the active toe, which consists of clay and silt overlain by river gravel. Arrow shows movement of toe relative to stable area in foreground. (Photograph by U. S. Bureau of Reclamation)

into many more or less independent units. With continued deformation and disintegration, especially if the water content or velocity — or both — increases, a Type IIB slide may change to a Type III flow. All gradations exist. The maximum dimension of the units is comparable to or less than the relative displacement between them, and generally much smaller than the displacement of the center of gravity of the whole mass. Movement is controlled, perhaps more frequently than in slumps, by pre-existing structural features, such as faults, joints, bedding planes, or variations in shear strength between layers of detritus. Movement often progresses beyond the limits of the original surface of rupture, so that parts of the mass may slide out over the original ground surface. Rate of movement ranges within wide limits among the several varieties of Type IIB slides and may vary greatly from one time to another in the development of a single slide.

Rockslides and Debris Slides. — Loose rockslides are a common variety of Type IIB slide consisting of many units (see Figs. 20, 41, and 94, and Pl. 1-i). Various kinds of slides involving natural soil, unconsolidated sedimentary material, and rock detritus are included as debris slides under Type IIB. Examples of these are illustrated in Figures 21, 22, and 23, and Plate 1-j. These slides are often limited by the contact between loose

Zone A. Movement chiefly by large-scale slumping along slip surfaces.
a, a', a" Principal slump units.
b, b' Narrow slump units with axes perpendicular to axes of main slump units and parallel with the length of the main slide.
c "Island" remaining after downward movement of unit d from area e.

Zone B. Zone of earthflow. Movement chiefly by flowage.

Zone C. Toe of slide area. Original form altered by railroad reconstruction work.

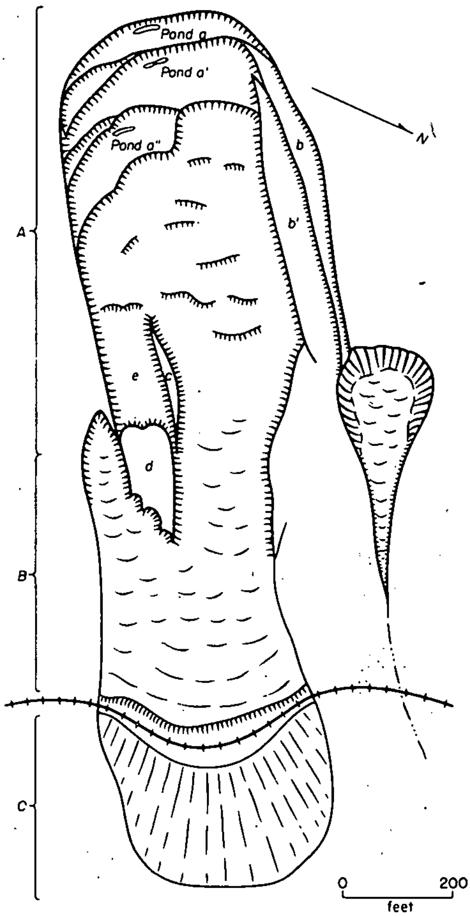


Figure 15. Ames slide near Telluride, Colo. This slump-earthflow landslide occurred in glacial till that overlies Mancos shale. Repeated slumping took place along the upper margins after the main body of material had moved down. Note that the long axes of slump blocks b and b' are parallel with rather than perpendicular to the direction of movement of the main part of the slide. Blocks b and b', however moved toward the left, rather than toward the observer. (See Varnes, Helen D., 1949)

material and underlying firm bedrock. With increase in water content or with increasing velocity, debris slides grade into the flowing movement of debris avalanches.

Failures by Lateral Spreading. — The slide shown in Plate 1-k is due to lateral spreading of soft clay from beneath firmer material. Related types of failure are described by Newland (1916) and by Terzaghi and Peck (1948, pp. 368-369, 401-404). In most places the failures take place along zones of high pore-water pressure in homogeneous clay or along partings of sand or silt in clay. The movement in these types of slides is usually complex, involving translation, breaking up of the material, some slumping, and some liquefaction and flow. These failures are arbitrarily classed with deformed slides rather than with flows because the material in motion generally slides out on a more or less planar surface, and in doing so it may break up into a number of semi-inde-

Figure 16. Aerial view of the Cedar Creek slide near Montrose, Colo. The landslide in the foreground is moving to the right and consists of slumps with earthflows at the toe. The material is Mancos shale overlain by 10 to 20 feet of gravel, which caps the mesa on the left. The original railroad alignment is completely destroyed and the new alignment is being covered by earthflows. (See Varnes, Helen D., 1949) (Photograph by R. W. Fender, Montrose, Colo.)

pendent units. The dominant movement is translation rather than rotation. If the underlying mobile zone is thick, the blocks at the head may sink downward

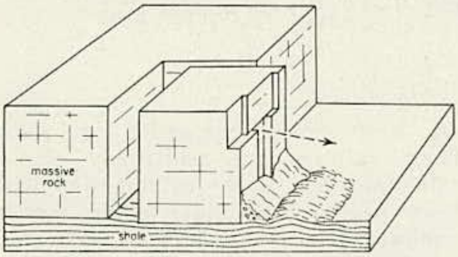


Figure 17. Block glide. Slide at a quarry face.

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 a rapid to very rapid velocity; but there are also some cases of slow movement (see Fig. 115), or of slow movement preceding sudden failure.

These kinds of slides appear to be members of a gradational series of landslide types in surficial materials extending from block glides at one extreme, in which the zone of flowage beneath the sliding mass may be very thin, to earthflows or completely liquefied mudflows at the other extreme, in which the zone of flowage includes the whole mass. The form taken depends upon local factors. Most of the larger landslides in glacial sediments of northern North America and Scandinavia lie somewhere within this series (see Fig. 3).

The large and sometimes disastrous landslides in Sweden and Norway have stimulated much excellent study. In a recent summary, W. Kjellman (1955) states that lateral spreading, although possible, has not been proved for any Swedish landslide. The slides are successive, however, in that they grow rapidly while moving. If the slide grows in the direction of its own motion it is termed "progressive." One that grows

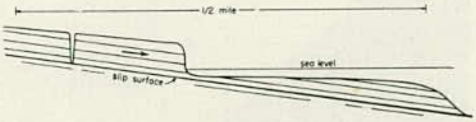


Figure 18. Block glide. Body of sliding bedrock at Point Fermin, Calif. (see also Figure 19). Maximum average rate of movement 0.1 foot per week. (From Miller, 1931)

in the opposite direction (headward) is called "retrogressive." Kjellman gives a step-by-step analysis of progressive failure. He discounts the statements that quick or sensitive clay — that is, a clay which loses practically all its shear strength if disturbed — is a main cause.

Figure 19. Block glide at Point Fermin, near Los Angeles, Calif. The photograph indicates minor slumping into the gap at the rear of the main mass and imminent rockfalls at the sea-cliff. The principal motion, however, is by gliding along gently seaward dipping strata. (Photograph by Spence Air Photos)

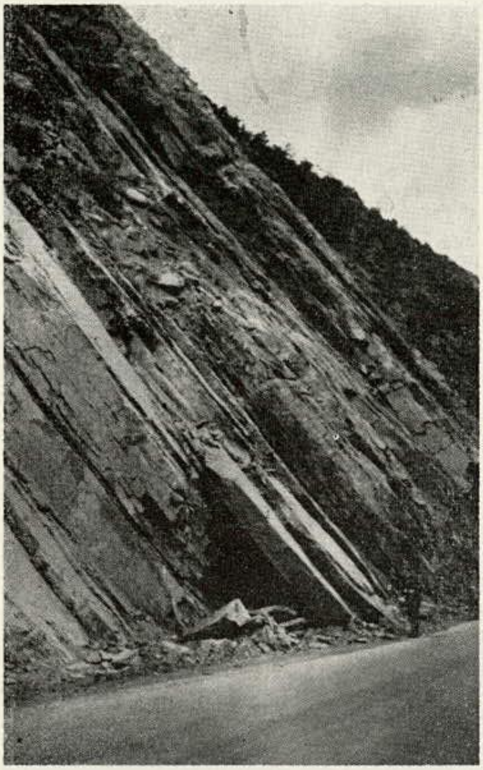


Figure 20. Small rockslide on dipping sandstone strata near Glenwood Springs, Colo. Slide controlled primarily by dip of beds toward road. (Photograph by D. J. Varnes, U. S. Geological Survey)

Odenstad (1951) gives an analysis of retrogressive failure in the landslide at Sköttorp on the Lidan River (see Fig. 24).

In a summary of Norwegian investigations, L. Bjerrum (1955) re-emphasizes the importance of sensitivity in leached marine clay and concludes that failure is not successive but instantaneous over the whole sliding surface.

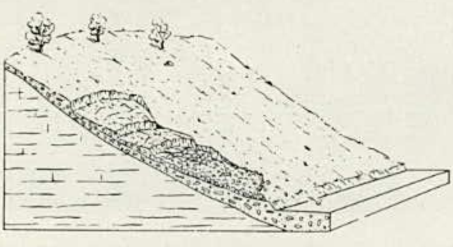


Figure 21. Debris slide of the soil disintegrating slip variety. (After Kesseli, 1943)

All investigators would agree that failures in glacial and marine sediments of Pleistocene age present some common and characteristic features. Among these are: sliding, which often exists for no apparent external reason; generally sudden failure (see Fig. 3); instability of very gentle slopes; dominant movement by translation; and importance of porewater pressure in creating instability. All degrees of disturbance of the masses have been observed; some slides consist almost entirely of one large slab or "flake," others liquefy almost entirely to small chunks or mud.

Type III — Flows

In flows, the movement within the displaced mass is such that the form taken by the moving material or the apparent distribution of velocities and displacements resembles those of viscous fluids. Slip surfaces within the moving mass are usually not visible or are short-lived, and the boundary between moving and stationary material may be sharp or it may be a zone of plastic flow. The material is, by necessity, unconsolidated at the time of flow but may consist of rock fragments, fine granular material, mixed debris and water, or plastic clay. As indicated in Plate 1, there is a continuous sequence from debris slide through debris avalanche to debris flow as solid material composed of mixed rock, soil, or detritus takes on more water. Earthflows in plastic or predominantly fine-grained material become mudflows at higher water content.

Dry Flows. — The word "flow" naturally brings water to mind, and some content of water is necessary for most types of flow movement. But there have been a surprising number of large and catastrophic landslides, which flowed according to the foregoing definition yet were nearly or quite dry. Therefore, the classification of flows on the chart indicates the complete range of water content from dry at the top to liquid at the bot-

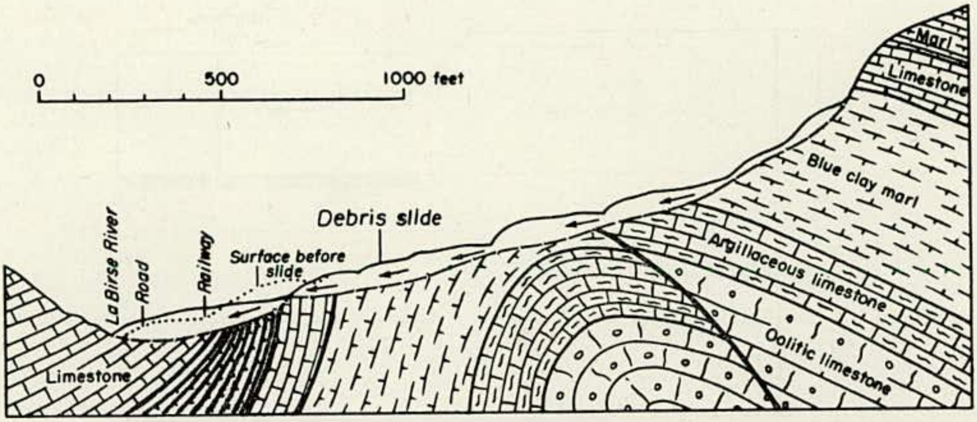


Figure 22. Debris slide, Moutier Court Gorges, Switzerland. Slide is composed of weathered blue clay marl, talus, and older slide material. (After Buxtorf and Vonderschmitt in Peter, A., 1938)

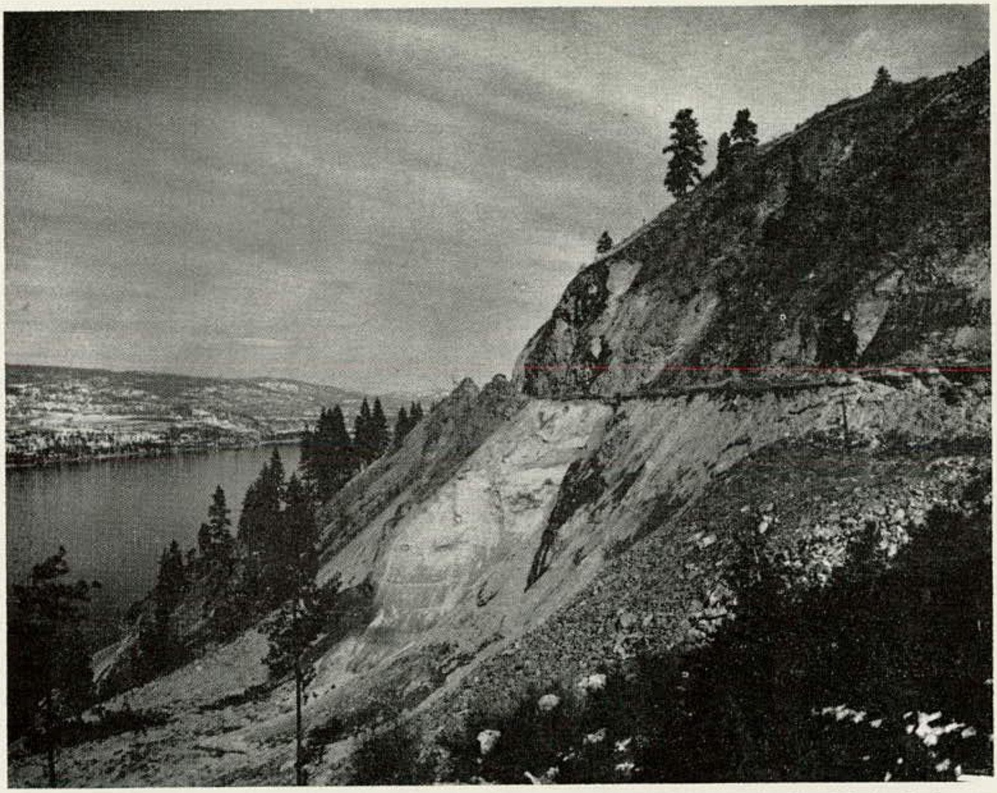


Figure 23. Debris slide along the Great Northern Railway near Kettle Falls, Wash. The slide involved unconsolidated sediments and talus and was limited by the contact between light-colored materials, exposed in the scarp at center of photo, and darker firm bedrock. The slide passed over the highway at the base of the slope and into Lake Roosevelt, creating a destructive wave. The slide has been corrected, at least temporarily, by clearing the roadway of fallen material; that is, partial excavation of the toe. (Photograph by F. O. Jones, U. S. Geological Survey)

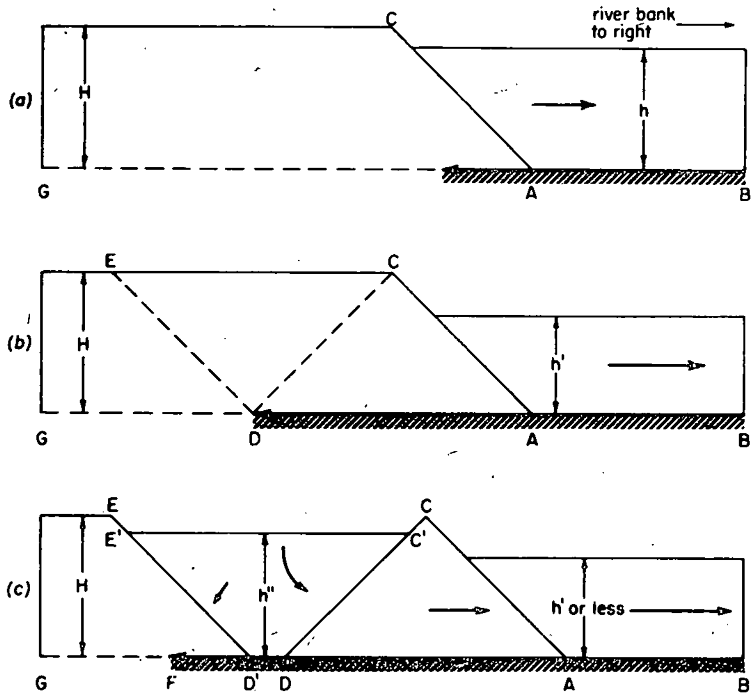


Figure 24. Retrogressive failure, landslide at Skottorp, Sweden, according to Odenstad (1951). Failure in sensitive clay began at the river bank and spread landward along a particularly weak surface BG at a depth H below ground surface. At the stage shown in drawing (a), a secondary slip surface has developed along AC, but the block to the left of A is still stable, being supported in part by the material to the right of A. Height h decreases as the material to the right of A moves out; also the failure surface continues to spread to the left, as in drawing (b). When height h has decreased to a critical value h′, complementary slip surfaces develop along CD and ED and wedge CDA moves to the right, drawing (c). Wedge E′C′DD′ deforms and moves down and to the right. The process is repeated when the height h″ of wedge E′C′DD″ decreases to the critical value h′.

tom. The horizontal position within the chart indicates the type of unconsolidated material, whether it is mostly rock fragments, sand, silt, or nonplastic material, mixed rock and soil, or mostly plastic. Blank spaces within this part of the chart indicate incompatible combinations, such as dry plastic material, or combinations for which there are no known examples of flows.

Dry flows that consist predominantly of rock fragments are here termed rock fragment flows. They may originate in two ways — by volcanic explosion, or by a large rockslide or rockfall turning into a flow. The latter two varieties are termed rockslide avalanche and rockfall avalanche, respectively. Clear-cut examples of rock fragment flows resulting from volcanic explosion are not known in North America. The "glowing cloud" or "nuée ardente" eruptions of very hot ash are not regarded as landslides. The remarkable flow at Bandaisan, Japan (Sekiya and Kikuchi, 1889, p. 109), appears to be, however, a true example of a volcanic rock fragment flow. The landslide that occurred in 1925 along the Gros Ventre Valley in Wyoming (Alden, 1928) is an example of a rockslide that turned into a flow.

Rockfall avalanches are most common in rugged mountainous regions. The disaster at Elm, Switzerland (Heim, 1932, pp. 84, 109-112), which took 115 lives, started with small rockslides at

Figure 25. Dry flow of silt. Material is lake bed silt of Pleistocene age from a high bluff on the right bank of the Columbia River, 2 1/2 miles downstream from Belvedere, Wash. 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 the base of the cliff. (Photograph by F. O. Jones, U. S. Geological Survey)

each side of a quarry on the mountainside. A few minutes later the whole mass of rock above the quarry crashed down and shot across the valley. The movement of the rock fragments, which had to this moment been that of rockslide and rockfall, now took 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 a mile at high velocity before stopping (see Pl. 1-l). About 13,000,000 cubic yards of rock descended an average of 1,450 feet vertically, in a total elapsed time of about 55 seconds. The kinetic energy involved must have been enormous. The flowing motion can perhaps be explained by assuming much internal interaction between the rock fragments and between them and entrapped highly compressed air, so that the whole mass became a density current of high gravity and unusual velocity. A similar and even larger rockfall avalanche occurred at Frank, Alberta, in 1903, also with great loss of life and property (McConnell and Brock, 1904). Such flows probably cannot be produced by a few thousand or a few hundred thousand cubic yards of material. Many millions of tons 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 very questionable. Perhaps the best way to study such

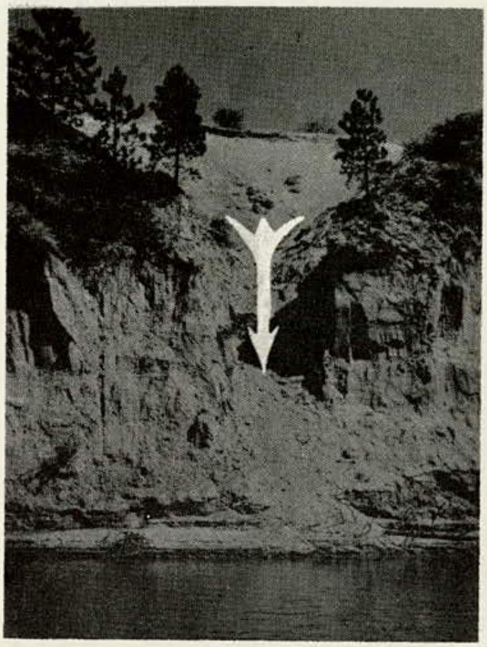


Figure. 26. Sand run. Material is sand over lake bed silt, Columbia River valley. Dry sand from upper part of terrace flowed like a liquid through notch in more compact sand and silt below. (Photograph by F. O. Jones, U. S. Geological Survey)

failures is by models, which are small enough to comprehend with the eye and mind, and constructed with due regard for the great decrease in the strength and other physical properties of the materials as required by scale factors determined through dimensional analysis.

From the meager accounts available, somewhat the same mechanism as operated at Elm produced the loess flows that followed the 1920 earthquake in Kansu Province, China (Close and McCormick, 1922), shown in Plate 1-n. 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. Small flows of dry silt, powdered by impact on falling from a cliff, have been recognized; but as far as is known, none have been studied in detail (see Fig. 25). The well-known fluidlike motion of dry sand, as illustrated in Plate 1-m and Figure 26, needs no comment.

Wet Flows. — Other types of flows, shown in Plate 1-o to s, require water in various proportions. The gradations between debris slide and debris flow reflect very largely the differences in water content, although material of a given water content may slide on a gentle slope but flow on a steeper slope. 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 rap-

Figure 27. Debris avalanche or debris flow, Franconia Notch, N. H. This landslide occurred June 24, 1948, after several days of heavy rainfall. Only soil mantle, 10 to 15 feet thick, which lay over bedrock on a slope of about 1:1, was involved. The slide scar is about 1,500 feet long. Note natural levees along sides of flow. U. S. Route 3 is in the foreground. (Photograph courtesy of New Hampshire Department of Public Works and Highways)

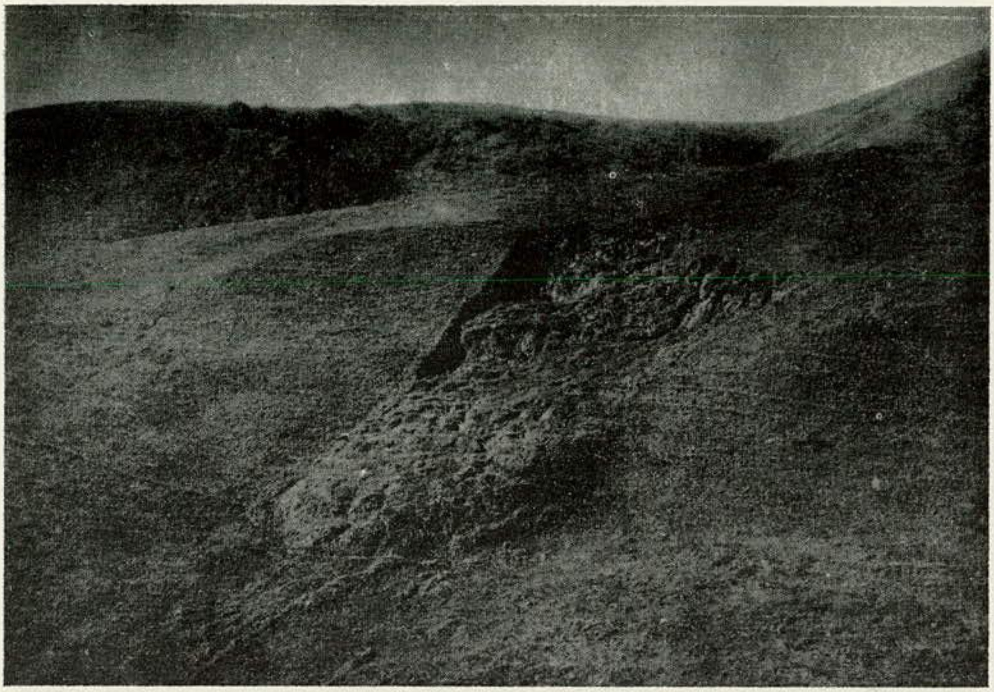


Figure 28. Earthflow developing from slump near Berkeley, Calif. (Photograph by G. K. Gilbert, U. S. Geological Survey)

id and the whole mass, either because it is quite wet or is on a steep slope, flows and tumbles downward, commonly along a stream channel, and advances 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 Figure 27, in contrast to the horseshoe-shaped scarp of a slump (see Fig. 104).

Debris flows, called mudflows in some other classifications, are here distinguished from the latter on the basis of particle size. That is, the term "debris flow" as used here denotes material that contains a relatively high percentage of coarse fragments, whereas the term "mudflow" is reserved for material with at least 50 percent sand, silt, and clay-size particles. Debris flows almost invariably result from unusually heavy precipitation or from sudden thaw of frozen soil. The kind of flow shown in Plate 1-r often occurs during torrential runoff following cloudbursts. It is favored by the presence of deep soil on mountain slopes from which the vegetative cover has been removed by fire or other means; but the absence of vegetation is not a necessary prerequisite. Once in motion, a small stream of water heavily laden with soil has transporting power out of all proportion to its size; and as more material is added to the stream by sloughing its size and power increase. These flows commonly follow pre-existing drainage ways, incorporating trees and bushes, and removing everything in their paths. Such flows are of high density, perhaps 60 to 70 percent solids by weight, so that boulders as big as an automobile 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 side to form a natural levee, while the more fluid part moves

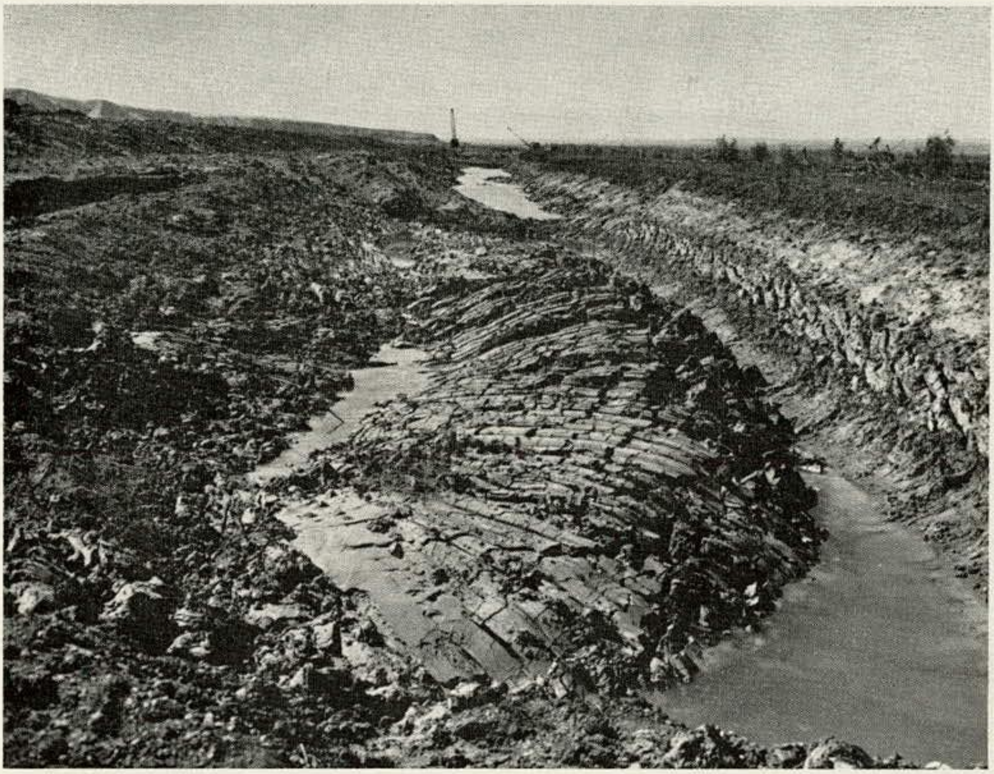


Figure 29. Upthrust toe of a slump-earthflow resulting from failure of a canal levee on Middle Rio Grande Project, N. Mex. The raised toe is about 5 feet high and 200 feet long. (Photograph by U. S. Bureau of Reclamation)

down the channel (see Fig. 27). Flows may extend many miles, until they drop their loads in a valley of lower gradient or at the base of a mountain front. Some debris flows and mudflows have been reported to proceed by a series of pulses in their lower parts; these pulses presumably are caused, in part, by periodic damming and release of debris.

An earthflow is a flow of slow to very rapid velocity involving mostly plastic or fine-grained nonplastic material. The slow earthflow shown in Figure 28 and Plate 1-p may be regarded as typical of an earthflow resulting from failure of a slope or embankment. The failure follows saturation and the building up of pore-water pressure so that part of the weight of the material is supported by interstitial water, with consequent decrease in shearing resistance. If relatively wet, the front of the mass bulges and advances either in more or less fluid tongues or, if less wet, by a gradual tumbling or rolling-over motion under the steady pressure of material behind and above. Many slowly moving earthflows form the bulbous or spreading toe of slump slides (see Fig. 16 and Pl. 1-h). Figure 29 shows the spreading, bulbous, upheaved toe of a slump-earthflow resulting from failure in a canal embankment.

Earthflows may continue to move slowly for many years under apparently small gravitational forces, until stability is reached at nearly flat slopes. At a higher water content the movement is faster, and what are here considered to be true mudflows are the liquid "end member" of the slump-earthflow series in dominantly fine-grained material.

The rapid type of earthflow illustrated in Figure 30 and Plate 1-q, called earthflow by Sharpe (1938, p. 50) and clay flow by Terzaghi and Peck (1948, p. 362), is different from the foregoing and is not easily classified because it shows some similarity to failure by lateral spreading. These flows usually take place in sensitive materials; that is, in those materials whose shear strength is decreased to a very small fraction of its former value on remolding at constant water content. Terzaghi and Peck state (1948, p. 361):

> During a slide in such a clay the moving mass breaks up into chunks that are lubricated by the remolded portion of the clay. The mixture of chunks and matrix is so mobile that it may flow like a stream for hundreds or even thousands of feet on an almost horizontal surface. . . . During the flow [at Riviere Blanche, Quebec] a roughly rectangular area having a length of 1,700 feet parallel to the river and 3,000 feet perpendicular to the river subsided 15 to 30 feet. Within several hours, 3,500,000 cubic yards of the underlying silty clay moved into the river channel through a gap 200 feet wide. The channel was blocked for over two miles, and the upstream water level was raised 25 feet.

Similar flows have occurred in other parts of Canada, in the state of Maine, and in the Scandinavian countries. The index properties of the soils which flow in this manner are not yet reliably known. The few data which are available indicate that the soils are either very fine rock flours or very silty clays of glacial origin with a natural water content high

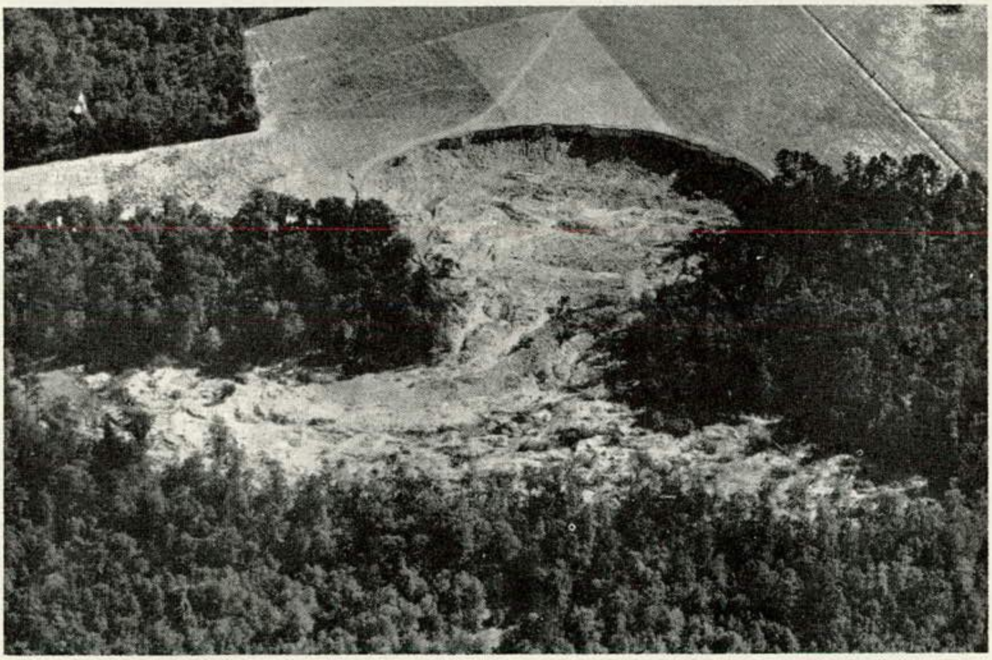


Figure 30. Earthflow near Greensboro, Fla. Material is flat-lying partly indurated clayey sand of the Hawthorn formation (Miocene). The length of the slide is 900 feet from scarp to edge of trees in foreground. Vertical distance from top to base of scarp is 45 feet and from top of scarp to toe is 60 feet. The slide occurred in April 1948 after a year of unusually heavy rainfall, including 16 inches during the 30 days preceding the slide. (Photograph from R. H. Jordan, 1949)

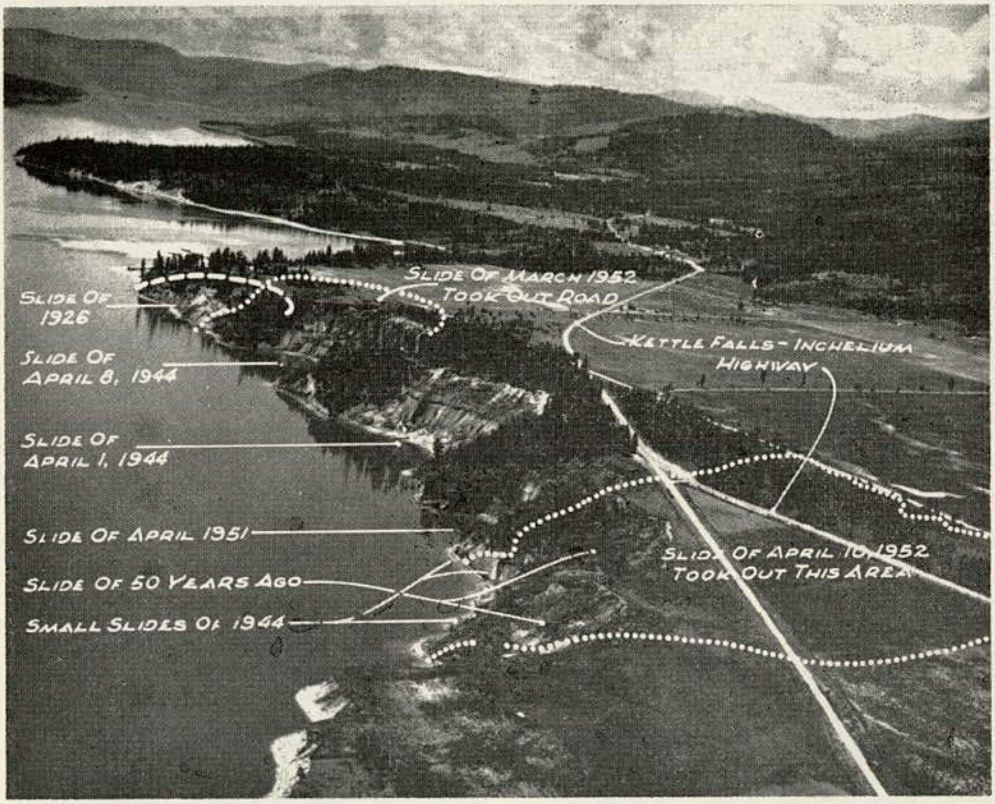


Figure 31. Reed Terrace area, right bank of Lake Roosevelt reservoir on Columbia River, near Kettle Falls, Wash., on May 15, 1951. The slide of April 10, 1952, involving about 15,000,000 cubic yards, took place by progressive slumping, liquefaction, and flowing out of glacio-fluvial sediments through a narrow orifice into the bottom of the reservoir. (Photograph by F. O. Jones, U. S. Geological Survey)

above the liquid limit. . . . The excessive water content, which seems to constitute a prerequisite, indicates a very high degree of sensitivity and possibly a well-developed skeleton structure.

The large slide on the Reed Terrace near Kettle Falls, Wash., shown in Figures 31 and 32, resembles in some respects the earthflow at Riviere Blanche shown in Plate 1-q. The lower part of the exposed section of the Reed Terrace slide is composed of laminated silty clays, similar to those described by Terzaghi and Peck in the foregoing. The terrace is capped by sand and gravel. The slide of April 10, 1952, involved about 15,000,000 cubic yards. According to F. O. Jones of the U. S. Geological Survey, who has made a study of slides along the Columbia River Valley,[4] it seems likely that the initial failure took place by lateral spreading of the fine-grained saturated sediments below water level. The sliding that followed the initial failure, however, was similar to slump-earthflow (Pl. 1-h), earthflow, and mudflow. Repeated sliding developed a group of interlocking alcoves, enlarging the slide laterally and landward and severing three roads. The slide had cut back 2,000 feet from the original shore by

[4] Jones, F. O., written communication.

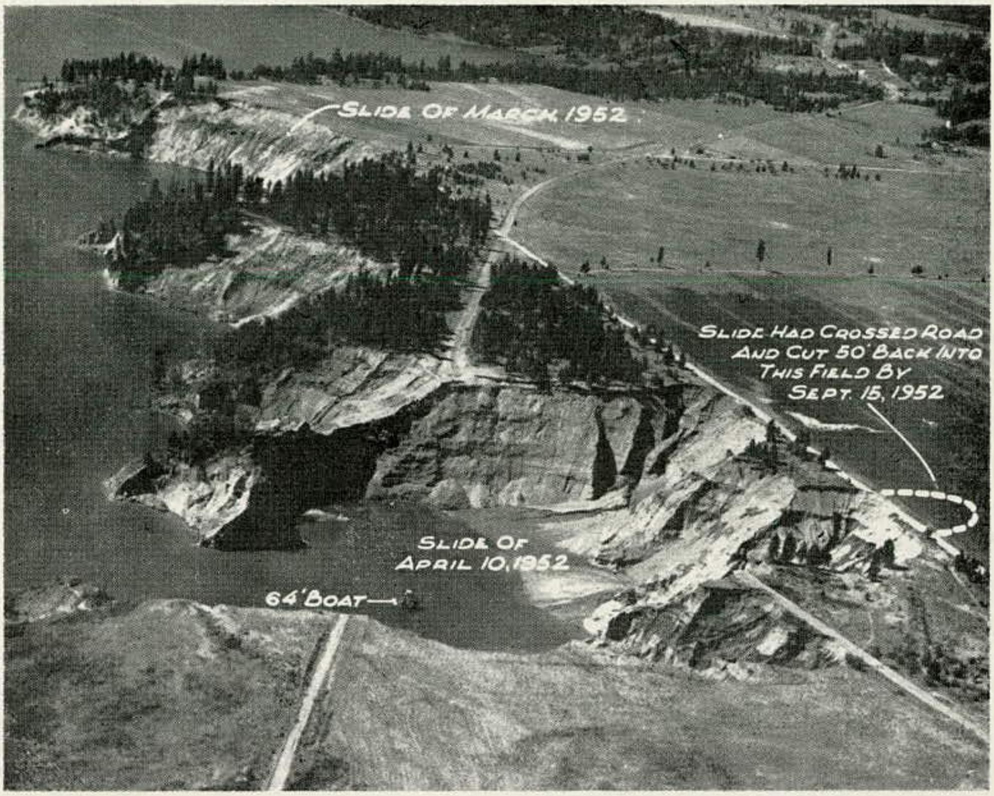


Figure 32. Reed Terrace area, Lake Roosevelt, Wash., after slide of April 10, 1952. (Photograph taken August 1, 1952, by F. O. Jones, U. S. Geological Survey)

April 13. A notable feature is the narrow orifice, which during the major movement was only 75 yards wide, and through which the slide material flowed out under water along the reservoir bottom.

Liquid sand or silt flows, such as illustrated in Plate 1-s, 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 due to rise and fall of the tide (Koppejan, Van Wamelon, and Weinberg, 1948; and Müller, 1898). When the structure of the loose sand breaks down along a section of the bank, the sand flows out rapidly upon the bottom, and, by repeated sloughing, the slide eats into the bank and enlarges the cavity. Sometimes the scarp produced is an arc, concave toward the water; sometimes it enlarges greatly, retaining a narrow neck or nozzle through which the sand flows.

Type IV — Complex Landslides

More often than not, any one landslide shows several types of movement within its various parts or at different times in its development. Most slides are therefore complex. Several shown on the chart, for example those drawn largely from actual slides (Pl. 1-h, k, and l), are complex, but each illustrates a dominant and characteristic type of movement and so can be fitted into the classification without too much difficulty.

Because the purpose of classifying landslides is to provide better data for use in controlling or avoiding them, it is of the greatest importance that for complex slides the classification be made at the time control or preventive measures are to be taken.

Landslide Processes

The process of landsliding is essentially a continuous series of events from cause to effect. An engineer faced with a landslide is primarily interested in curing 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 be over and done with in 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. These factors, these causes, must then be understood if other similar slides are to be avoided or controlled.

Very seldom, if ever, can a slide be attributed to a single definite cause. 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, until some action, perhaps trivial, sets a mass of it in motion downhill. The last action cannot be regarded as the one and only cause, even though it was necessary in the chain of events. As Sowers and Sowers (1951, p. 228) 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 (see Chapter Two).

The interrelations of landslide causes are very lucidly and graphically presented by Terzaghi (1950, p. 105-110). His work and that of Sharpe (1938, p. 83-87), Ladd (1935, p. 14-18), Bendel (1948, p. 268-337), and many others referred to elsewhere have been used extensively in the preparation of this section (see also Varnes, 1950).

All true slides (excluding falls) 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 high shear stress and (b) the factors that contribute to low shear strength. A single action, such as addition of water to a slope, may contribute both to an increase in stress and to decrease in strength. But it is helpful to separate mentally the various physical results of such an action.

The principal factors contributing to the instability of earth materials are outlined in the following. The operation of many factors is self-evident and needs no lengthy description; some factors are briefly discussed or reference is made to literature that gives examples or treats the subject in detail.

Factors That Contribute to High Shear Stress

A. Removal of lateral support

This is the commonest of all factors leading to instability and includes the actions of:

1. Erosion by:
    a. Streams and rivers in the production of most natural slopes. The literature on this subject

is vast. For introduction see Terzaghi (1936, 1950), Terzaghi and Peck (1948), Taylor (1948), Ladd (1935), Sharpe (1938), Ward (1945); bibliographies in these references and in Tompkin and Britt (1951).
   b. Glacier ice. Many valleys in mountainous regions were deeply cut by glaciers; when the ice retreated, landslides occurred on a large scale. See Howe (1909).
   c. Waves, and longshore or tidal currents. See the following: slides along coast of England, Ward (1945, 1948); coastal bluff at Santa Monica, Calif., Hill (1934); flow slides in Holland, Koppejan et al. (1948) and Müller (1898); along Mississippi River, Fisk (1944), Senour and Turnbull (1948).
   d. Subaerial weathering, wetting and drying, and frost action.
2. Creation of new slope by previous rockfall, slide, subsidence, or large-scale faulting.
3. Human agencies:
   a. Cuts, quarries, pits, and canals. Panama Canal, Binger (1948); MacDonald (1942?); National Academy of Sciences (1924); Wolf and Holtz (1948).
   b. Removal of retaining walls, sheet piling, etc.
   c. Draining of lakes or drawdown of reservoirs. See also seepage pressure under "Factors Contributing to Low Shear Strength."

B. Surcharge
1. Natural agencies:
   a. Weight of rain, hail, snow, and water from springs.
   b. Accumulation of talus overriding landslide material.
2. Human agencies:
   a. Construction of fill.
   b. Stockpiles of ore or rock. Hudson Valley, Terzaghi (1950, p. 105); Skempton and Golder (1948).
   c. Wastepiles. From strip mining, Savage (1950).
   d. Weight of buildings and other structures and trains.
   e. Weight of water from leaking pipelines, sewers, canals, reservoirs, etc.

C. Transitory earth stresses

Earthquakes have triggered a great many landslides, both small and very large and disastrous. Their action is complex, involving both increase in shear stress, and, in some examples, decrease in shear strength. They produce horizontal accelerations that may greatly modify the state of stress within slope-forming material. In the case of potential circular-arc failure, horizontal acceleration causes a moment about the center of the arc (Terzaghi, 1950, p. 89-91, and Taylor, 1948, p. 452), which when directed toward the free slope adds to its instability. Vibrations from blasting, machinery, and traffic also produce transitory earth stresses.

D. Regional tilting

Progressive increase in slope angle through regional tilting has been suspected as a contributing cause to some landslides (Terzaghi, 1950, p. 94). The slope must obviously be on the point of failure for such a small and slow-acting change to be effective.

E. Removal of underlying support
1. Undercutting of banks by rivers and waves.
2. Subaerial weathering, wetting and drying, and frost action.
3. Subterranean erosion.
   a. Removal of soluble material such as carbonates, salt, or gypsum; collapse of caverns. See Messines (1948), Buisson (1952).
   b. Washing out of granular material beneath firmer material. Terzaghi (1931), Ward (1945, p. 189-191).

4. Human agencies, such as mining.
5. Loss of strength in underlying material.
   a. Large masses of limestone over shale. At Frank, Alberta, and at Pulverhörndl in the Alps. Terzaghi (1950, p. 95-96).
   b. Compact till over clay. Terzaghi (1950, p. 96-97).
   c. Failure by lateral spreading. Newland (1916), Odenstad (1951), Ackermann (1948).

F. Lateral pressure due to
1. Water in cracks and caverns.
2. Freezing of water in cracks.
3. Swelling.
   a. Hydration of clay.
   b. Hydration of anhydrite. See also Messines (1948).

FACTORS THAT CONTRIBUTE TO LOW SHEAR STRENGTH

The factors that contribute to low shear strength of rock or soil may be divided into two groups. The first group includes factors deriving from the initial state or inherent characteristics of the material. They are part of the geologic setting that may be favorable to landsliding, and they change little or not at all during the useful life of a structure. They may exist for a long period without failure occurring. The second group (B, C, and D hereafter) includes the changing or variable factors that tend to lower shear strength of the material.

A. The initial state
1. Composition.
   Inherently weak materials, or those which may become weak upon change in water content or other changes as described in B, C, and D. Included especially are sedimentary clays and shales; decomposed rocks; rocks composed of volcanic tuff, which may weather to clayey material; materials composed dominantly of soft, platy minerals, such as mica, schist, talc, or serpentine; organic material.
2. Texture
   a. "Loose" arrangement of individual particles in sensitive clays, marl (von Moos and Rutsch, 1944), loess, sands of low density, and porous organic matter.
   b. Roundness of grains. See Chen (1948) on increase in compressibility and internal friction with increase in angularity.
3. Gross structure
   a. Discontinuities such as faults, bedding planes, foliation in schist, cleavage, joints, and brecciated zones. The effect of joints in rock is self-evident; the mechanism of progressive softening of stiff fissured clays is well described by Skempton (1948).
   b. Massive beds over weak or plastic materials.
   c. Strata inclined toward free face.
   d. Alternation of permeable beds, such as sandstone, and weak impermeable beds, such as shale or clay.

B. Changes due to weathering and other physico-chemical reactions
1. Physical disintegration of granular rocks such as granite or sandstone under action of frost, thermal expansion, etc. Decrease of cohesion.
2. Hydration of clay minerals. Absorption of water by clay minerals and decrease of cohesion of all clayey soils at high water contents. Swelling and loss of cohesion of montmorillonitic clays. Marked consolidation of loess upon saturation due to destruction of clay bond between silt particles (see American Society for Testing Materials, 1951, p. 9-34).
3. Base exchange in clays. Influence of exchangeable ions on physical properties of clays. See Grim (1949), Rosenqvist (1953), Proix-Noe

(1946), Tchourinov (1945), and American Society for Testing Materials (1952).

4. Drying of clays. Results in cracks and loss of cohesion and allows water to seep in.
5. Drying of shales. Creates cracks on bedding and shear planes. Reduces shale to chips, granules, or smaller particles.
6. Removal of cement by solution. Removal of cement from sandstone reduces internal friction.

C. Changes in intergranular forces due to pore water (see especially Taylor, 1948, Chap. 16)

1. Buoyancy in saturated state decreases effective intergranular pressure and friction.
2. Intergranular pressure due to capillary tension in moist soil is destroyed upon saturation.
3. Seepage pressures of percolating ground water result from viscous drag between liquid and solid grains.

D. Changes in structure

1. Fissuring of preconsolidated clays due to release of lateral restraint in a cut (Skempton, 1948).
2. Effect of disturbance or remolding on sensitive materials such as loess and dry or saturated loose sand. The great loss of shear strength of sensitive clays has been tentatively attributed to breakdown of a loose structure (Rosenqvist, 1953), but this has not been demonstrated. See also Skempton and Northey (1952).

References

Ackermann, E., "Quickerden und Fleissbewegungen bei Erdrutschen." Zeits. der Deutschen Geolog. Gesellschaft, B. 100, s. 427-466, 1948.

Alden, W. C., "Landslide and Flood at Gros Ventre, Wyoming." Am. Inst. Min. and Met. Eng., Tech. Pub. No. 140; Trans., v. 76, p. 347-361, 1928.

American Society for Testing Materials, "Symposium on Consolidation Testing of Soils." Am. Soc. Testing Materials Spec. Tech. Pub. 126, 1951.

American Society for Testing Materials, "Symposium on Exchange Phenomena in Soils." Am. Soc. Testing Materials Spec. Tech. Pub. 142, 1952.

Bendel, Ludwig, "Ingenieur-geologie, ein Handbuch für Studium und Praxis." v. 2, Springer-Verlag, Vienna, 1948.

Binger, W. V., "Analytical Studies of Panama Canal Slides." Proc. of 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 2, p. 54-60, 1948.

Bjerrum, L., "Stability of Natural Slopes in Quick Clay." *Geotechnique*, v. 5, no. 1, p. 101-119, 1955.

Buisson, M. M., "Les Glissements de la Falaise de Sainte-Adresse." *Annales de L'Institut Technique du Batiment et des Travaux Publics*, no. 59, p. 1131-1146, 1952. Translation No. 33 by Séverine Britt available from U. S. Geol. Survey.

Chen, Liang-Sheng, "An Investigation of Stress-Strain and Strength Characteristics of Cohesionless Soils by Triaxial Compression Tests." Proc. of 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 5, p. 43, 1948.

Close, U., and McCormick, E., "Where the Mountains Walked." *Nat. Geog. Mag.*, v. 41, p. 445-464, 1922.

Fisk, H. N., "Geological Investigation of the Alluvial Valley of the Lower Mississippi River." Mississippi River Comm., Corps of Eng., U. S. Army, Vicksburg, Miss., 1944.

Grim, R. E., "Mineralogical Composition in Relation to the Properties of Certain Soils." *Geotechnique*, v. 1, no. 3, p. 139-147, 1949.

Heim, A., "Bergsturz und Menschenleben." Fretz and Wasmuth, Zurich, 1932.

Hill, R. A., "Clay Stratum Dried Out to Prevent Landslips." *Civil Eng.*, v. 4, p. 403-407, 1934.

Howe, Ernest, "Landslides in the San Juan Mountains, Colorado." U. S. Geol. Survey Prof. Paper 67, 1909.

Jordan, R. H., "A Florida Landslide." *Jour. Geology*, v. 57, no. 4, p. 418-419, 1949.

Kesseli, J. E., "Disintegrating Soil Slips of the Coast Ranges of Central California." *Jour. Geology*, v. 51, no. 5, p. 342-352, 1943.

Kjellman, W., "Mechanics of Large Swedish Landslips." *Geotechnique,* v. 5, no. 1, p. 74-78, 1955.

Koppejan, A. W., Van Wamelon, B. M., and Weinberg, L. J. H., "Coastal Flow Slides in the Dutch Province of Zeeland." Proc. of 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 5, p. 89-96, 1948.

Ladd, G. E., "Landslides, Subsidences and Rockfalls." *Am. Ry. Eng. Assoc. Proc.,* v. 36, p. 1091-1162, 1935.

MacDonald, D. F., "The Third Locks Project, Panama Canal Slides." The Panama Canal, Special Engineering Division, Balboa Heights, Canal Zone, 1942 (?).

McConnell, R. G., and Brock, R. W., "Report on the Great Landslide at Frank, Alberta." App. to Rept. Supt. Mines, Canada Dept. Interior, Ann. Rept. 1902-1903, Pt. 8, 17 p., 1904.

Messines, Jean, "Les Éboulements dans les Gypses: Inefficacité des Travaux de Reboisement (Landslides in Gypsum: Ineffectiveness of Reforestation)." *Comptes Rendus des Séances de L'Academie des Sciences,* Paris, tome 226, no. 16, p. 295-296, 1948. Translation No. 14 by Séverine Britt available from U. S. Geol. Survey.

Miller, W. J., "The Landslide at Point Fermin, California." *Sci. Monthly,* v. 32, p. 464-469, 1931.

Moos, A. von, and Rutsch, R. F., "Über Einen durch Gefügestörung Verursachten Seeufereinbruch (Gerzensee, Kt. Berne)." *Eclogae Geologicae Helvetia,* Zurich, v. 37, no. 2, p. 385-400, 1944. Translation No. 17 by Séverine Britt available from U. S. Geol. Survey.

Müller, Fr., "Das Wasserwesen der Niederlandischen Provinz Zeeland." Ernst and Son, Berlin, 1898.

National Academy of Sciences, "Report of the Committee of the National Academy of Sciences on Panama Canal Slides." *Nat. Acad. Sci. Mem.,* v. 18, 84 p., 51 pls., 19 figs., 1924.

Newland, D. H., "Landslides in Unconsolidated Sediments; with Description of Some Occurrences in the Hudson Valley." New York State Mus. Bull. 187, p. 79-105, 1916.

Odenstad, Sten, "The Landslide at Sköttorp on the Lidan River." Royal Swedish Geotechnical Inst. Proc., no. 4, 1951.

Peter, A., "Glissement de Terrain dans les Gorges de Moutier-Court." *La Route et la Circulation Routiere,* no. 10, p. 165-172, 206-208, Solothurn, Switzerland, 1938.

Proix-Noe, Marthe, "Etude d'un Glissement de Terrain dû à la Présence de Glauconie." *Comptes Rendus Hebdomadaires des Séances de l'Académie des Sciences,* v. 222, no. 7, p. 403-405, 1946. Translation No. 6 by Séverine Britt available from U. S. Geol. Survey.

Rosenqvist, I. Th., "Considerations on the Sensitivity of Norwegian Quick-Clays." *Geotechnique,* v. 3, no. 5, p. 195-200, 1953.

Savage, C. N., "Earthflow Associated with Strip Mining." *Mining Eng.,* v. 187, no. 3, p. 337-339, 1950.

Sekiya, S., and Kikuchi, Y., "The Eruption of Bandaisan." *Jour. Coll. Sci. Imp. Univ. Tokyo,* v. 3, pt. 2, p. 91-172, 1889.

Senour, Charles, and Turnbull, W. J., "A Study of Foundation Failures at a River Bank Revetment." Proc. of 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 7, p. 117-121, 1948.

Sharpe, C. F. S., "Landslides and Related Phenomena." Columbia University Press, New York, N. Y., 1938.

Skempton, A. W., "The Rate of Softening in Stiff Fissured Clays, with Special Reference to London Clay." Proc. of 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 2, p. 50-53, 1948.

Skempton, A. W., and Golder, H. Q., "Practical Examples of the $\phi = 0$ Analysis of Stability of Clays." Proc. of 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 2, p. 63-70, 1948.

Skempton, A. W., and Northey, F. D., "The Sensitivity of Clays." *Geotechnique,* v. 3, no. 1, p. 30-53, 1952.

Sowers, G. B., and Sowers, G. F., "Introductory Soil Mechanics and Foundations." The Macmillan Co., New York, N. Y., 1951.

Taylor, D. W., "Fundamentals of Soil Mechanics." John Wiley & Sons, New York, N. Y., 1948.

Tchourinov, M. P., "Modifications par Altération dans la Composition, la Structure et les Propriétés des Argiles du Crétacé Inférieur." *Comptes Rendus (Doklady) de l'Académie des Sciences de l'URSS,* v. 49, no. 5, p.

364-368, 1945. Translation No. 15 by Séverine Britt available from the U. S. Geol. Survey.
Terzaghi, Karl, "Earth Slips and Subsidences from Underground Erosion." *Eng. News-Record,* v. 107, p. 90-92, 1931.
Terzaghi, Karl, "Stability of Slopes of Natural Clay." Proc. of 1st Internat. Conf. on Soil Mech. and Found. Eng., Harvard University, v. 1, p. 161-165, 1936.
Terzaghi, Karl, "Mechanism of Landslides." In "Application of Geology to Engineering Practice." Berkey Volume, Sidney Paige, Chairman; Geol. Soc. America, p. 83-123, 1950.
Terzaghi, Karl, and Peck, R. B., "Soil Mechanics in Engineering Practice." John Wiley & Sons, New York, N. Y., 1948.
Tompkin, J. M., and Britt, S. H., "Landslides." A selected annotated bibliography. Highway Research Board Bibliography 10, Washington, D. C., 1951.
Varnes, D. J., "Relation of Landslides to Sedimentary Features." In "Applied Sedimentation," P. D. Trask, editor, p. 229-246, John Wiley & Sons, New York, N. Y., 1950.
Varnes, H. D., "Landslide Problems of Southwestern Colorado." U. S. Geological Survey Circ. 31, 1949.
Ward, W. H., "The Stability of Natural Slopes." *Geog. Jour.*, London. v. 105, no. 5-6, p. 170-197, 1945.
Ward, W. H., "A Coastal Landslip." Proc. of 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 2, p. 33-38, 1948.
Wolf, W. H., and Holtz, W. G., "Slope Stability Studies for the Delta-Mindota Intake Canal." Proc. of the 2d Internat. Conf. on Soil Mech. and Found. Eng., Rotterdam, v. 3, p. 268-274, 1948.