Chapter 3

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LANDSLIDE TYPES AND PROCESSES

1. INTRODUCTION

The range of landslide processes is reviewed in this chapter, and a vocabulary is provided for describing the features of landslides relevant to their classification for avoidance, control, or remediation. The classification of landslides in the previous landslide report (Varnes 1978) has been widely adopted, so departures from it have been minimized and the emphasis is on the progress made since 1978. Although this chapter is complete in itself, particular attention is drawn to changes and additions to the vocabulary used by Varnes in the previous report and the reasons for the changes.

The term *landslide* denotes "the movement of a mass of rock, debris or earth down a slope" (Cruden 1991, 27). The phenomena described as landslides are not limited either to the land or to sliding; the word as it is now used in North America has a much more extensive meaning than its component parts suggest (Cruden 1991). The coverage in this chapter will, however, be identical to that of the previous report (Varnes 1978). Ground subsidence and collapse are excluded, and snow avalanches and ice falls are not discussed.

This chapter also follows Varnes's expressed intention of (1978, 12) "developing and attempting to make more precise a useful vocabulary of terms by which . . . [landslides] . . . may be described." The terms Varnes recommended in 1978 are largely retained unchanged and a few useful new terms have been added. Eliot (1963, 194) noted:

> . . . Words strain,
> Crack and sometimes break, under the burden,
> Under the tension, slip, slide, perish,
> Decay with imprecision, will not stay in place,
> Will not stay still. . . .

Such displaced terms are identified in this chapter. Following Varnes (1978), the use of terms relating to the geologic, geomorphic, geographic, or climatic characteristics of a landslide has been discouraged, and the section in the previous report in which these terms are discussed has been deleted.

The viewpoint of the chapter is that of the investigator responding to a report of a landslide on a transportation route. What can be usefully observed and how should these observations be succinctly and unambiguously described?

The technical literature describing landslides has grown considerably since 1978. An important source of landslide information is the proceedings of the International Symposium on Landslides. The third symposium met in New Delhi, India (Swaminathan 1980), and the symposium has since met quadriennially in Toronto, Canada (Canadian Geotechnical Society 1984); in Lausanne, Switzerland (Bonnard 1988); and in Christchurch, New Zealand (Bell 1992); it is scheduled to meet in Trondheim, Norway, in 1996.

Among the other important English language texts and collections of descriptions of landslides have been those by Zaruba and Mencl (1982), Brunsden and Prior (1984), Crozier (1986), and

Costa and Wieczorek (1987). Eisbacher and Clague (1984) and Skermer's translation of Heim's *Bergsturz und Menschenleben* (1932) have made descriptions of the classic landslides of the European Alps more accessible to North Americans.

Important reviews of landsliding around the world were edited by Brabb and Harrod (1989) and Kozlovskii (1988). Kyunttsel (1988) reviewed experience with classification in the USSR and noted "considerable divergences of views between various researchers concerning the mechanisms underlying certain types of landslides. This applies particularly to lateral spreads."

A historical perspective has been added to the discussion of spreading to show that this type of landslide was recognized in North America over 100 years ago and is represented here by some extremely large movements. Both the size and the gentle slopes of these movements command particular attention.

Crozier commented:

> The two generalized classifications most likely to be encountered in the English speaking world are by J.N. Hutchinson (1968; Skempton and Hutchinson, 1969) and D.J. Varnes (1958; 1978). . . . Both authors use type of movement to establish the principal groups. . . . The major distinction between the two classifications is the difference accorded to the status of flow movements . . . slope movements which are initiated by shear failure on distinct, boundary shear surfaces but which subsequently achieve most of their translational movement by flowage . . . this dilemma depends on whether the principal interest rests with analyzing the conditions of failure or with treating the results of movement. Hutchinson's classification appears to be related more closely to this first purpose. . . . Both Hutchinson's and Varnes' classifications have tended to converge over recent years, particularly in terminology. . . . Whereas Varnes' scheme is perhaps easier to apply and requires less expertise to use, Hutchinson's classification has particular appeal to the engineer contemplating stability analysis. (Crozier 1986, Ch. 2)

The synthesis of these two classifications has continued. Hutchinson (1988) included topples, and this chapter has benefited from his comments. In Section 4 of this chapter particularly, which deals with landslide activity, many of Hutchinson's suggestions from the Working Party on the World Landslide Inventory (WP/WLI) have been adopted (WP/WLI 1993a,b).

Under Hutchinson's chairmanship, the International Association of Engineering Geology (IAEG) Commission on Landslides and Other Mass Movements continued its work on terminology. The declaration by the United Nations of the International Decade for Natural Disaster Reduction (1990–2000) prompted the IAEG Commission's Suggested Nomenclature for Landslides (1990) and the creation of the WP/WLI by the International Geotechnical Societies and the United Nations Educational, Scientific, and Cultural Organization (UNESCO). The Working Party, formed from the IAEG Commission, the Technical Committee on Landslides of the International Society for Soil Mechanics and Foundation Engineering, and nominees of the International Society for Rock Mechanics, published *Directory of the World Landslide Inventory* (Brown et al. 1992) listing many workers interested in the description of landslides worldwide. The Working Party has also prepared the *Multilingual Landslide Glossary*, which will encourage the use of standard terminology in describing landslides (WP/WLI 1993b). The terminology suggested in this chapter is consistent with the suggested methods and the glossary of the UNESCO Working Party (WP/WLI 1990, 1991, 1993a,b).

2. FORMING NAMES

The criteria used in the classification of landslides presented here follow Varnes (1978) in emphasizing type of movement and type of material. Any landslide can be classified and described by two nouns: the first describes the material and the second describes the type of movement, as shown in Table 3-1 (e.g., *rock fall, debris flow*).

The names for the types of materials are unchanged from Varnes's classification (1978): *rock*, *debris*, and *earth*. The definitions for these terms are given in Section 7. Movements have again been divided into five types: *falls*, *topples*, *slides*, *spreads*, and *flows*, defined and described in Section 8. The sixth type proposed by Varnes (1978, Figure 2.2), *complex landslides*, has been dropped from the formal classification, although the term *complex* has been retained as a description of the style of activity of a landslide. Complexity can also be indicated

Table 3-1
Abbreviated Classification of Slope Movements

	TYPE OF MATERIAL		
		ENGINEERING SOILS	
TYPE OF MOVEMENT	BEDROCK	PREDOMINANTLY COARSE	PREDOMINANTLY FINE
Fall	Rock fall	Debris fall	Earth fall
Topple	Rock topple	Debris topple	Earth topple
Slide	Rock slide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Rock flow	Debris flow	Earth flow

by combining the five types of landslide in the ways suggested below. The large classification chart accompanying the previous report (Varnes 1978, Figure 2.1) has been divided into separate figures distributed throughout this chapter.

Table 3-2
Glossary for Forming Names of Landslides

ACTIVITY			
STATE	DISTRIBUTION	STYLE	
Active	Advancing	Complex	
Reactivated	Retrogressive	Composite	
Suspended	Widening	Multiple	
Inactive	Enlarging	Successive	
Dormant	Confined	Single	
Abandoned	Diminishing		
Stabilized	Moving		
Relict			
DESCRIPTION OF FIRST MOVEMENT			
RATE	WATER CONTENT	MATERIAL	TYPE
Extremely rapid	Dry	Rock	Fall
Very rapid	Moist	Soil	Topple
Rapid	Wet	Earth	Slide
Moderate	Very wet	Debris	Spread
Slow			Flow
Very slow			
Extremely slow			
DESCRIPTION OF SECOND MOVEMENT			
RATE	WATER CONTENT	MATERIAL	TYPE
Extremely rapid	Dry	Rock	Fall
Very rapid	Moist	Soil	Topple
Rapid	Wet	Earth	Slide
Moderate	Very wet	Debris	Spread
Slow			Flow
Very slow			
Extremely slow			

NOTE: Subsequent movements may be described by repeating the above descriptors as many times as necessary.

The name of a landslide can become more elaborate as more information about the movement becomes available. To build up the complete identification of the movement, descriptors are added in front of the two-noun classification using a preferred sequence of terms. The suggested sequence provides a progressive narrowing of the focus of the descriptors, first by time and then by spatial location, beginning with a view of the whole landslide, continuing with parts of the movement, and finally defining the materials involved. The recommended sequence, as shown in Table 3-2, describes activity (including state, distribution, and style) followed by descriptions of all movements (including rate, water content, material, and type).

This sequence is followed throughout the chapter and all terms given in Table 3-2 are highlighted in bold type and discussed. Second or subsequent movements in complex or composite landslides can be described by repeating, as many times as necessary, the descriptors used in Table 3-2. Descriptors that are the same as those for the first movement may then be dropped from the name.

For instance, the very large and rapid slope movement that occurred near the town of Frank, Alberta, Canada, in 1903 (McConnell and Brock 1904) was a *complex, extremely rapid, dry rock fall–debris flow* (Figure 3-1). From the full name of this landslide at Frank, one would know that both the debris flow and the rock fall were extremely rapid and dry because no other descriptors are used for the debris flow.

As discussed in Section 4.3, the addition of the descriptor *complex* to the name indicates the sequence of movement in the landslide and distinguishes this landslide from a *composite rock fall–debris flow,* in which rock fall and debris flow movements were occurring, sometimes simultaneously, on different parts of the displaced mass. The

FIGURE 3-1
Slide at Frank, Alberta, Canada *(oblique aerial photograph from south).* About 4:10 a.m. on April 29, 1903, about 85 million tonnes of rock moved down east face of Turtle Mountain, across entrance of Frank mine of Canadian American Coal Company, Crowsnest River, southern end of town of Frank, main road from east, and Canadian Pacific mainline through Crowsnest Pass. Displaced mass continued up opposite side of valley before coming to rest 120 m above valley floor. Event lasted about 100 seconds.
PHOTOGRAPH NAPL T31L-213; REPRODUCED FROM COLLECTION OF NATIONAL AIR PHOTO LIBRARY WITH PERMISSION OF NATURAL RESOURCES CANADA

full name of the landslide need only be given once; subsequent references should then be to the initial material and type of movement, for example, "the rock fall" or "the Frank rock fall" for the landslide at Frank, Alberta.

Several noun combinations may be required to identify the multiple types of material and movement involved in a complex or composite landslide. To provide clarity in the description, a dash known as an "en dash" is used to link these stages, as in *rock fall–debris flow* in the example above. (An en dash is half the length of a regular dash and longer than a hyphen; it is used to remove ambiguity by indicating linkages between terms composed of two nouns.)

The full name of a landslide may be cumbersome and there is a natural tendency, particularly among geologists, to establish type examples with which other landslides may be compared. Shreve (1968), for instance, referred to the landslide in Frank, Alberta, as belonging to the *Blackhawk type*. It seems clear that type examples should be historic landslides that have been investigated in detail shortly after their occurrence and are of continuing interest to landslide specialists. In addition, for a type example to be useful, other landslides with the same descriptors should occur in similar material. The Blackhawk landslide (Figure 3-2) was a prehistoric landslide, and thus was not subject to investigation at its occurrence (Shreve 1968). It is therefore not a suitable type example; nevertheless, it may have been a Frank-type landslide.

Although Varnes (1978, 25) discussed "terms relating to geologic, geomorphic, geographic, or

FIGURE 3-2 Blackhawk landslide: view upslope to south over lobe of dark marble breccia spread beyond mouth of Blackhawk Canyon on north slope of San Bernardino Mountains in southern California. Maximum width of lobe is 2 to 3 km; height of scarp at near edge is about 15 m [Varnes 1978, Figure 2.28 (Shelton 1966)].

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climatic setting," he recommended against the practice of using type examples because the terms "are not informative to a reader who lacks knowledge of the locality" (1978, 26). Moreover, type examples are impractical because of the sheer number required to provide a fairly complete landslide classification. About 100,000 type examples would be required for all the combinations of descriptors and materials with all the types of movement defined in Table 3-2 and in the following sections, although admittedly some combinations may be unlikely. The inclusion of complex and composite landslides would increase the number of type examples to over a billion.

3. LANDSLIDE FEATURES AND GEOMETRY

Before landslide types are discussed, it is useful to establish a nomenclature for the observable landslide features and to discuss the methods of expressing the dimensions and geometry of landslides.

3.1 Landslide Features

Varnes (1978, Figure 2.1t) provided an idealized diagram showing the features for a *complex earth slide–earth flow*, which has been reproduced here as Figure 3-3. More recently, the IAEG Commission on Landslides (1990) produced a new idealized landslide diagram (Figure 3-4) in which the various features are identified by numbers, which are defined in different languages by referring to the accompanying tables. Table 3-3 provides the definitions in English.

The names of the features are unchanged from Varnes's classification (1978). However, Table 3-3 contains explicit definitions for the *surface of rupture* (Figure 3-4, *10*), the *depletion* (*16*), the *depleted mass* (*17*), and the *accumulation* (*18*) and expanded definitions for the *surface of separation* (*12*) and the *flank* (*19*). The sequence of the first nine landslide features has been rearranged to proceed from the crown above the head of the displaced material to the toe at the foot of the

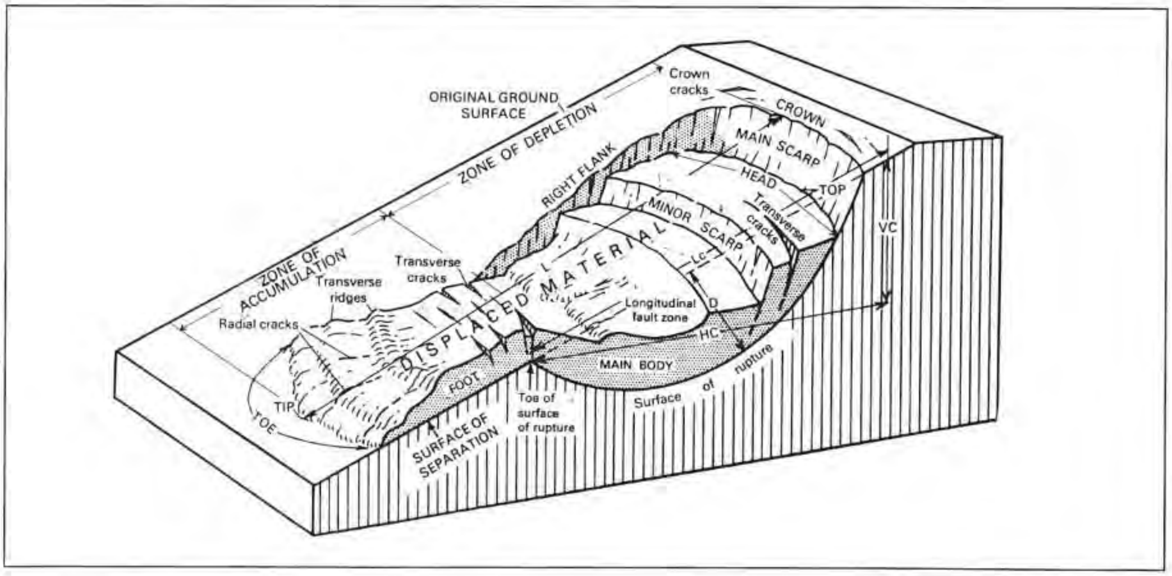


FIGURE 3-3 Block diagram of idealized complex earth slide–earth flow (Varnes 1978, Figure 2.1t).

displaced material. This sequence may make these features easier to remember.

It may also be helpful to point out that in the *zone of depletion* (*14*) the elevation of the ground surface decreases as a result of landsliding, whereas in the *zone of accumulation* (*15*) the elevation of the ground surface increases. If topographic maps or digital terrain models of the landslide exist for both before and after movements, the zones of depletion and accumulation can be found from the differences between the maps or models. The volume decrease over the zone of depletion is, of course, the depletion, and the volume increase over the zone of accumulation is the accumulation. The accumulation can be expected to be larger than the depletion because the ground generally dilates during landsliding.

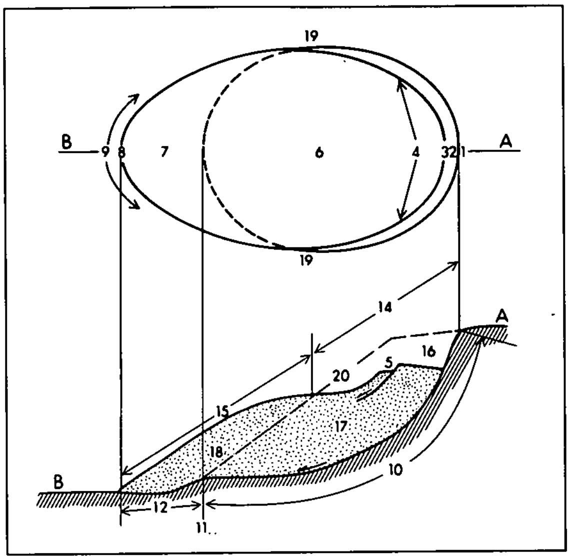


FIGURE 3-4
Landslide features: *upper portion,* plan of typical landslide in which dashed line indicates trace of rupture surface on original ground surface; *lower portion,* section in which hatching indicates undisturbed ground and stippling shows extent of displaced material. Numbers refer to features defined in Table 3-3 (IAEG Commission on Landslides 1990).

Table 3-3
Definitions of Landslide Features

NUMBER	NAME	DEFINITION
1	Crown	Practically undisplaced material adjacent to highest parts of main scarp
2	Main scarp	Steep surface on undisturbed ground at upper edge of landslide caused by movement of displaced material (*13*, stippled area) away from undisturbed ground; it is visible part of surface of rupture (*10*)
3	Top	Highest point of contact between displaced material (*13*) and main scarp (*2*)
4	Head	Upper parts of landslide along contact between displaced material and main scarp (*2*)
5	Minor scarp	Steep surface on displaced material of landslide produced by differential movements within displaced material
6	Main body	Part of displaced material of landslide that overlies surface of rupture between main scarp (*2*) and toe of surface of rupture (*11*)
7	Foot	Portion of landslide that has moved beyond toe of surface of rupture (*11*) and overlies original ground surface (*20*)
8	Tip	Point on toe (*9*) farthest from top (*3*) of landslide
9	Toe	Lower, usually curved margin of displaced material of a landslide, most distant from main scarp (*2*)
10	Surface of rupture	Surface that forms (or that has formed) lower boundary of displaced material (*13*) below original ground surface (*20*); mechanical idealization of surface of rupture is called *slip surface* in Chapter 13
11	Toe of surface of rupture	Intersection (usually buried) between lower part of surface of rupture (*10*) of a landslide and original ground surface (*20*)
12	Surface of separation	Part of original ground surface (*20*) now overlain by foot (*7*) of landslide
13	Displaced material	Material displaced from its original position on slope by movement in landslide; forms both depleted mass (*17*) and accumulation (*18*); it is stippled in Figure 3-4
14	Zone of depletion	Area of landslide within which displaced material (*13*) lies below original ground surface (*20*)
15	Zone of accumulation	Area of landslide within which displaced material lies above original ground surface (*20*)
16	Depletion	Volume bounded by main scarp (*2*), depleted mass (*17*), and original ground surface (*20*)
17	Depleted mass	Volume of displaced material that overlies surface of rupture (*10*) but underlies original ground surface (*20*)
18	Accumulation	Volume of displaced material (*13*) that lies above original ground surface (*20*)
19	Flank	Undisplaced material adjacent to sides of surface of rupture; compass directions are preferable in describing flanks, but if left and right are used, they refer to flanks as viewed from crown
20	Original ground surface	Surface of slope that existed before landslide took place

3.2 Landslide Dimensions

The IAEG Commission on Landslides (1990) utilized the nomenclature described in Section 3.1 (including Figure 3-4 and Table 3-3) to provide definitions of some dimensions of a typical landslide. The IAEG Commission diagram is reproduced here as Figure 3-5. Once again, each dimension is identified on the diagram by a number, and these numbers are linked to tables giving definitions in several languages. Table 3-4 gives the definitions in English.

The quantities L_d, W_d, D_d and L_r,W_r, D_r are introduced because, with an assumption about the shape of the landslide, their products lead to estimates of the volume of the landslide that are useful in remedial work. For instance, for many rotational landslides, the surface of rupture can be approximated by half an ellipsoid with semiaxes D_r, $W_r/2$, $L_r/2$. As shown in Figure 3-6(*a*), the volume of an ellipsoid is (Beyer 1987, 162)

$$VOL_{eps} = \frac{4}{3}\pi a \cdot b \cdot c$$

where *a*, *b*, and *c* are semimajor axes. Thus, the volume of a "spoon shape" corresponding to one-half an ellipsoid is

$$VOL_{ls} = \frac{1}{2}\frac{4}{3}\pi a \cdot b \cdot c = \frac{4}{6}\pi a \cdot b \cdot c$$

But as shown in Figure 3-6(*b*), for a landslide $a = D_r$, $b = W_r/2$, and $c = L_r/2$. Therefore, the volume of ground displaced by a landslide is approximately

$$VOL_{ls} = \frac{4}{6}\pi a \cdot b \cdot c = \frac{4}{6}\pi D_r \cdot W_r/2 \cdot L_r/2$$
$$= \frac{1}{6}\pi D_r \cdot W_r \cdot L_r$$

This is the volume of material before the landslide moves. Movement usually increases the volume of the material being displaced because the displaced material dilates. After the landslide, the volume of displaced material can be estimated by $\frac{1}{6}\pi D_d W_d L_d$ (WP/WLI 1990, Equation 1).

A term borrowed from the construction industry, the *swell factor*, may be used to describe the increase in volume after displacement as a percentage of the volume before displacement. Church (1981, Appendix 1) suggested that a swell factor of 67 percent "is an average figure obtained from existing data for solid rock" that has been mechan-

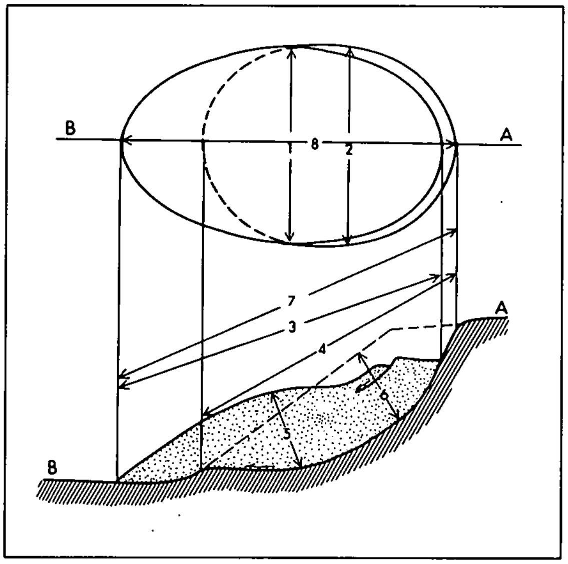


FIGURE 3-5
Landslide dimensions: *upper portion,* plan of typical landslide in which dashed line is trace of rupture surface on original ground surface; *lower portion,* section in which hatching indicates undisturbed ground, stippling shows extent of displaced material, and broken line is original ground surface. Numbers refer to dimensions defined in Table 3-4 (IAEG Commission on Landslides 1990).

Table 3-4
Definitions of Landslide Dimensions

NUMBER	NAME	DEFINITION
1	Width of displaced mass, W_d	Maximum breadth of displaced mass perpendicular to length, L_d
2	Width of surface of rupture, W_r	Maximum width between flanks of landslide perpendicular to length, L_r
3	Length of displaced mass, L_d	Minimum distance from tip to top
4	Length of surface of rupture, L_r	Minimum distance from toe of surface of rupture to crown
5	Depth of displaced mass, D_d	Maximum depth of displaced mass measured perpendicular to plane containing W_d and L_d
6	Depth of surface of rupture, D_r	Maximum depth of surface of rupture below original ground surface measured perpendicular to plane containing W_r and L_r
7	Total length, L	Minimum distance from tip of landslide to crown
8	Length of center line, L_{cl}	Distance from crown to tip of landslide through points on original ground surface equidistant from lateral margins of surface of rupture and displaced material

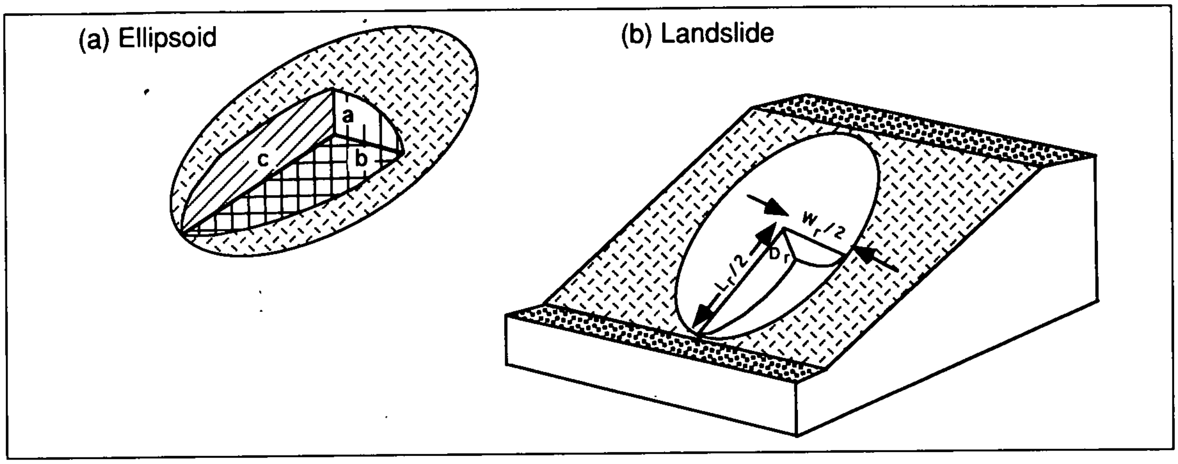


FIGURE 3-6 Estimation of landslide volume assuming a half-ellipsoid shape.

ically excavated. His estimates may approximate the upper bound for the swell due to landsliding. Nicoletti and Sorriso-Valvo (1991) chose an average dilation of 33 percent, so $4D_rW_rL_r \approx 3D_dW_dL_d$. More precise information is as yet unavailable.

The ground-surface dimensions of the displaced material, L_d, W_d, and of the surface of rupture, W_r, and the total length, L, of the landslide can be measured with an electronic distance-measuring instrument; a rangefinder may be sufficiently precise for a one-person reconnaissance. Measurement of the distance L_r may present problems because the toe of the surface of rupture is often not exposed. Its position can sometimes be estimated from graphical extrapolations of the main scarp supported by measurements of displacements within the displaced mass (Cruden 1986). Although D_d and D_r can also be estimated by these techniques, site investigations provide more precise methods of locating surfaces of rupture under displaced material (Hutchinson 1983).

The total length of the landslide, dimension L (5, Figure 3-5), is identical with length L, "the maximum length of the slide upslope," shown in Figure 3-3 (Varnes 1978); both are the straight-line distances from crown to tip. Readers are cautioned that several writers define the length of a landslide in terms of its horizontal extent and frequently use the letter L to define this horizontal distance in tabulations of observations and in calculations. This use of L is a source of potential confusion and inaccuracy, and readers should make certain that they can identify the dimension being specified by L in every case.

It should also be emphasized that it is unlikely that the displaced material at the tip has traveled from the crown despite the frequency of this assumption, originally due to Heim (1932). Material displaced from close to the landslide crown usually comes to rest close to the head of the landslide: Nicoletti and Sorriso-Valvo (1991) proposed that an estimate of the "overall runout" of a landslide be determined by measuring the length of a line constructed along the original ground surface equidistant from the lateral margins of the displaced material. However, such measurements may not have immediate physical significance and are also more difficult and imprecise than measurements of L. The length of the landslide measured through these central points is called the *length of center line*, L_{cl}. Note that L_{cl} will increase with the number of points surveyed on the center line, and the ratio L_{cl}/L will increase with the curvature of the center line in plan and section.

The difference in elevation between the crown and the tip of the landslide may be used to determine H, the height of the landslide. Combining estimates of H and L allows computation of the travel angle α, as shown by Figure 3-7. If the tip is visible from the crown, the travel angle can be mea-

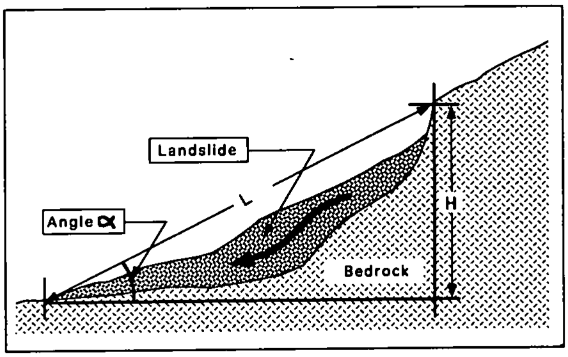


FIGURE 3-7 Definition of travel angle (α) of a landslide.

sured directly with a hand clinometer. The *H*-value may be conveniently estimated with an altimeter when tip and crown are accessible but not visible from each other. Hutchinson (1988) compiled data from several different types of debris flows to illustrate how debris-flow mobility appears to be related to the travel angle—and to the volume and lithology of the displaced material (Figure 3-8).

The measurements discussed above are adequate during reconnaissance for defining the basic dimensions of single-stage landslides whose displacement vectors parallel a common plane. Such landslides can be conveniently recorded on a landslide report such as that shown in Figure 3-9. Estimates of landslide volume determined by these methods are imprecise when topography diverts the displacing material from rectilinear paths. More elaborate surveys and analyses are then necessary (Nicoletti and Sorriso-Valvo 1991).

4. LANDSLIDE ACTIVITY

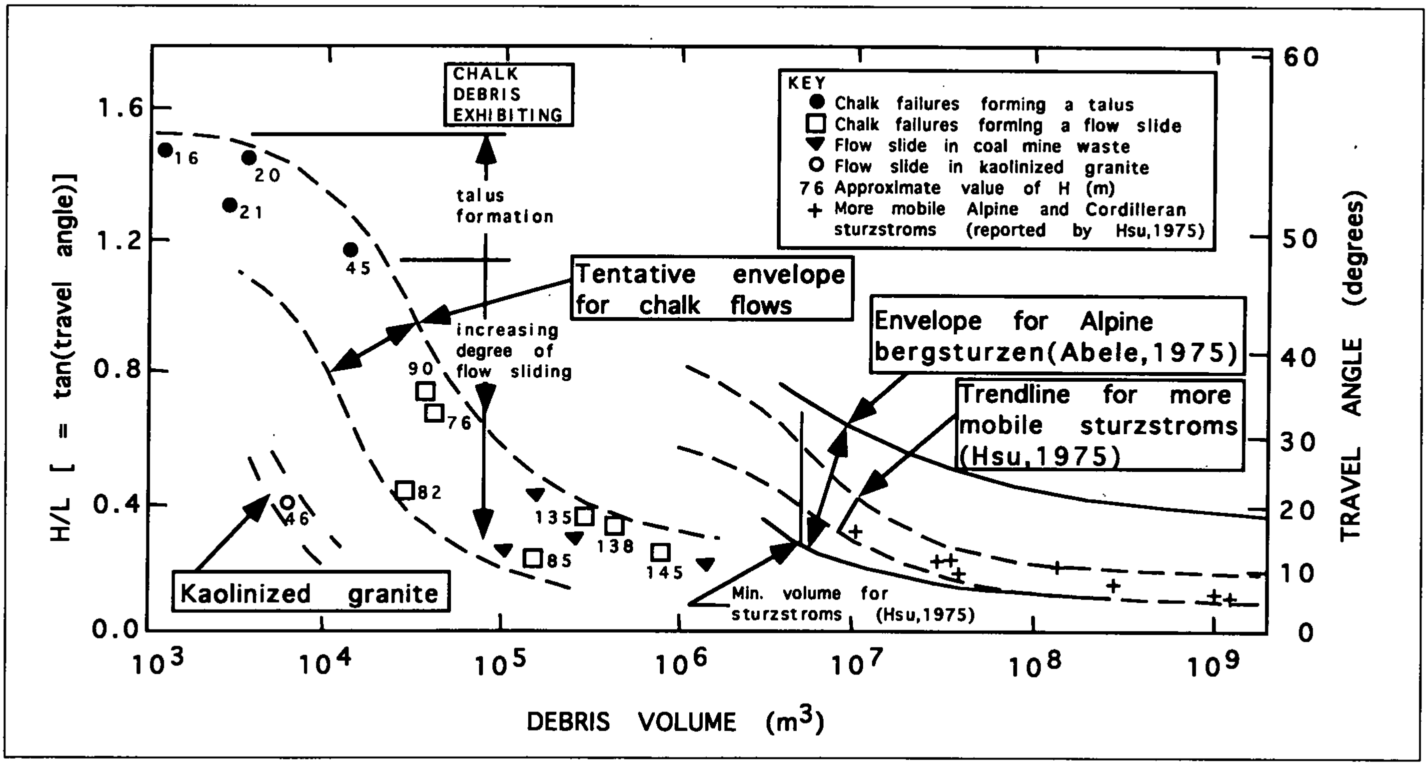
The broad aspects of landslide activity should be investigated and described during initial reconnaissance of landslide movements and before more detailed examination of displaced materials is undertaken. The terms relating to landslide age and state of activity defined by Varnes (1978) and some of his terms defining sequence or repetition of movement have been regrouped under three headings:

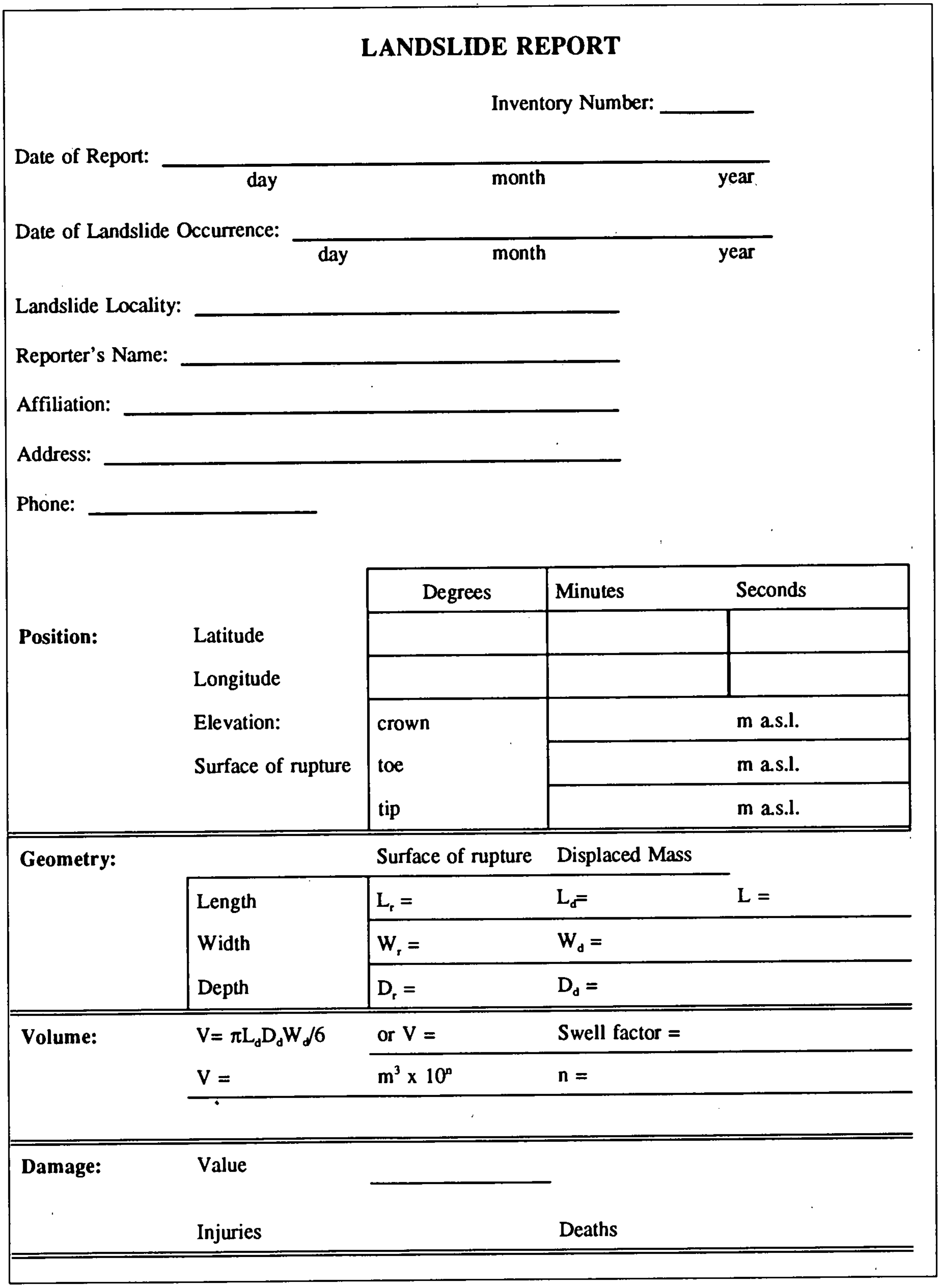
1. **State of Activity,** which describes what is known about the timing of movements;
2. **Distribution of Activity,** which describes broadly where the landslide is moving; and
3. **Style of Activity,** which indicates the manner in which different movements contribute to the landslide.

The terms used to define these three characteristics of landslide activity are given in the top section of Table 3-2 and are highlighted in bold type the first time they are used in the following sections.

The reader is cautioned that the following discussions relate to the terminology proposed by the UNESCO Working Party (WP/WLI 1990, 1991, 1993a,b) and given in Table 3-2. Other reports and authors may use classifications that apply different meanings to apparently identical terms. For example, in Chapter 9 of this report, a Unified Landslide Classification System is introduced that is based on landslide classification concepts presented by McCalpin (1984) and Wieczorek (1984). This sys-

FIGURE 3-8 Mobility of sturzstroms, chalk debris flows, and landslides in mine wastes related to travel angle (α) and debris volume (modified from Hutchinson 1988, Figure 12).





LANDSLIDE REPORT

Inventory Number: ________

Date of Report: ______________________________
day month year

Date of Landslide Occurrence: ______________________________
day month year

Landslide Locality: ______________________________

Reporter's Name: ______________________________

Affiliation: ______________________________

Address: ______________________________

Phone: ________________

		Degrees	Minutes	Seconds
Position:	Latitude			
	Longitude			
	Elevation:	crown		m a.s.l.
	Surface of rupture	toe		m a.s.l.
		tip		m a.s.l.

Geometry:		Surface of rupture	Displaced Mass	
	Length	$L_r =$	$L_d =$	$L =$
	Width	$W_r =$	$W_d =$	
	Depth	$D_r =$	$D_d =$	

Volume: $V = \pi L_d D_d W_d / 6$ or V = Swell factor =

V = $m^3 \times 10^n$ n =

Damage: Value ________________

Injuries Deaths

FIGURE 3-9
Proposed standard landslide report form.

tem is compared with a stability classification proposed by Crozier (1984). For further information on such alternative systems, the reader should refer to Tables 9-1, 9-2, and 9-6 and the associated text in Chapter 9.

4.1 State of Activity

Figure 3-10 illustrates the several states of activity by using an idealized toppling failure as an example. **Active** landslides are those that are currently moving; they include first-time movements and reactivations. A landslide that is again active after being inactive may be called **reactivated.** Slides that are reactivated generally move on preexisting shear surfaces whose strength parameters approach residual (Skempton 1970) or ultimate (Krahn and Morgenstern 1979) values. They can be distinguished from first-time slides on whose surfaces of rupture initial resistance to shear will generally approximate peak values (Skempton and Hutchinson 1969). Landslides that have moved within the last annual cycle of seasons but that are not moving at present were described by Varnes (1978) as **suspended.**

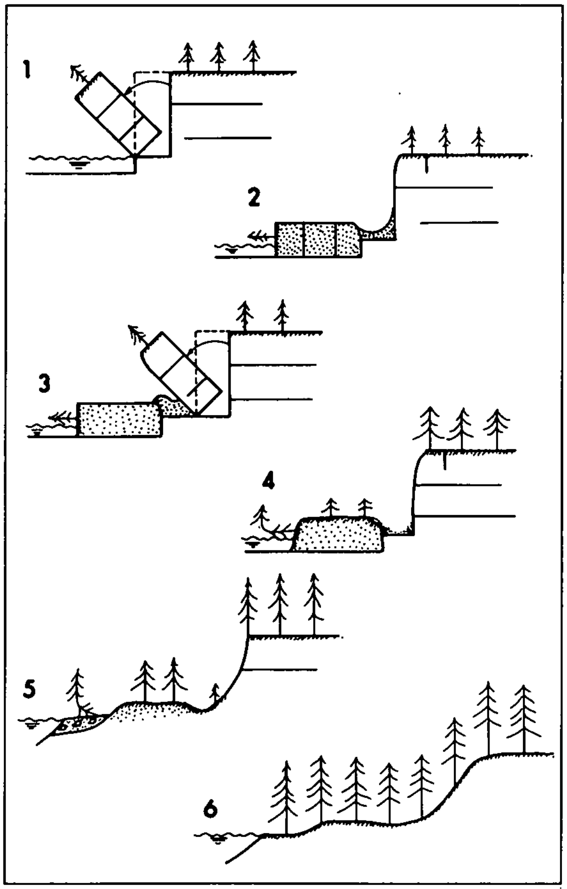


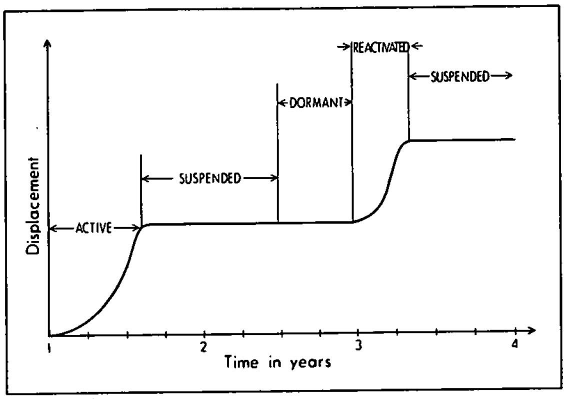
FIGURE 3-10 Sections through topples in different states of activity: (*1*) *active*—erosion at toe of slope causes block to topple; (*2*) *suspended*—local cracking in crown of topple; (*3*) *reactivated*—another block topples; (*4*) *dormant*—displaced mass begins to regain its tree cover and scarps are modified by weathering; (*5*) *stabilized*—fluvial deposition stabilizes toe of slope, which begins to regain its tree cover; and (*6*) *relict*—uniform tree cover over slope.

Inactive landslides are those that last moved more than one annual cycle of seasons ago. This state can be subdivided. If the causes of movement remain apparent, the landslide is **dormant.** However, if the river that has been eroding the toe of the moving slope changes course, the landslide is **abandoned** (Hutchinson 1973; Hutchinson and Gostelow 1976). If the toe of the slope has been protected against erosion by bank armoring or if other artificial remedial measures have stopped the movement, the landslide can be described as **stabilized.**

Landslides often remain visible in the landscape for thousands of years after they have moved and then stabilized. Such landslides were called *ancient* or *fossil* by Zaruba and Mencl (1982, 52), perhaps because they represent the skeletons of once-active movements. When these landslides have been covered by other deposits, they are referred to as *buried* landslides. Landslides that have clearly developed under different geomorphic or climatic conditions, perhaps thousands of years ago, can be called **relict.** Road construction in southern England reactivated relict debris flows that had occurred under periglacial conditions (Skempton and Weeks 1976).

Within regions, standard criteria might be developed to assist in distinguishing suspended landslides from dormant and relict landslides. These criteria would describe the recolonization by vegetation of surfaces exposed by slope movements and the dissection of the new topography by drainage. The rate of these changes depends on both the local climate and the local vegetation, so these criteria must be used with extreme caution. Nevertheless, it is generally true that when the main scarp of a landslide supports new vegetation, the landslide is usually dormant, and when drainage extends across a landslide without obvious discontinuities, the landslide is commonly relict. However, these generalizations must be confirmed by detailed study of typical slope movements under local conditions; Chapter 9 provides a systematic approach for such determinations. Figure 9-7 shows some idealized stages in the evolution of topographic features on suspended, dormant, and relict landslides.

The various states of activity are also defined by an idealized graph of displacement versus time (Figure 3-11). For an actual landslide, such a graph



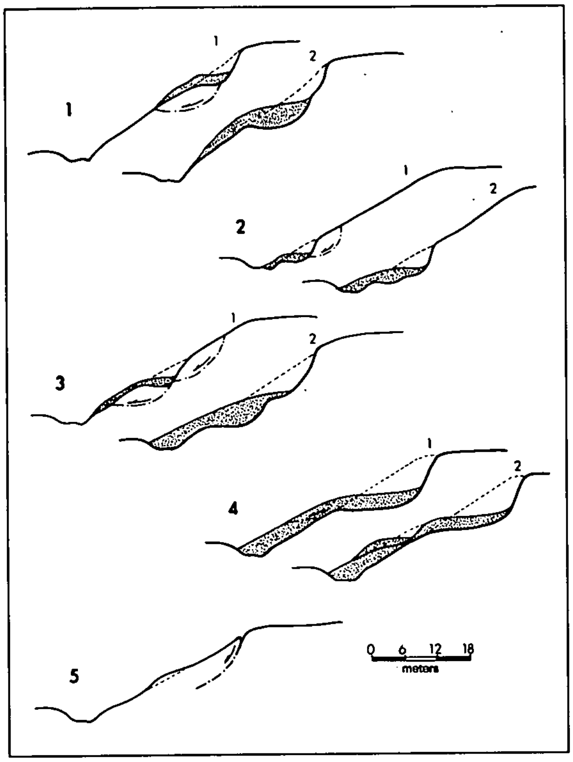


FIGURE 3-11 *(far left)* Displacement of landslide in different states of activity.

FIGURE 3-12 *(left)* Sections through landslides showing different distributions of activity: (*1*) *advancing,* (*2*) *retrogressing,* (*3*) *enlarging,* (*4*) *diminishing,* and (*5*) *confined.* In *1–4,* Section 2 shows slope after movement on rupture surface indicated by shear arrow. Stippling indicates displaced material.

can be created by plotting differences in the position of a target on the displacing material with time. Such graphs are particularly well suited to portraying the behavior of slow-moving landslides because they presuppose that the target is not displaced significantly over the time period during which measurement takes place. The velocity of the target can be estimated by the average rate of displacement of the target over the time period between measurements.

There is some redundancy in using the descriptions of activity state with those for rate of movement (see Section 5). Clearly, if the landslide has a measurable rate of movement, it is either active or reactivated. The state of activity might then be used to refer to conditions before the current movements of the landslide. If, for instance, remedial measures had been undertaken on a landslide that is now moving with moderate velocity, the landslide might be described as a *previously stabilized, moving, moderate-velocity landslide*. Landslides with no discernible history of previous movement would be described as active.

4.2 Distribution of Activity

Varnes (1978) defined a number of terms that can be used to describe the activity distribution in a landslide. Figure 3-12 shows idealized sections through landslides exhibiting various distributions of activity.

If the surface of rupture is extending in the direction of movement, the landslide is *advancing*, whereas if the surface of rupture is extending in the direction opposite the movement of the displaced material, the landslide is said to be *retrogressive*. If the surface of rupture is extending at one or both lateral margins, the landslide is *widening*. Movement may be limited to the displacing material or the surface of rupture may be *enlarging*, continually adding to the volume of displacing material. If the surface of rupture of the landslide is enlarging in two or more directions, Varnes (1978, 23) suggested the term *progressive* for the landslide, noting that this term had also been used for both advancing and retrogressive landslides. The term is also currently used to describe the process by which the surface of rupture extends in some landslides (*progressive failure*). The possibility of confusion seems sufficient now to abandon the term *progressive* in favor of describing the landslide as enlarging. Hutchinson (1988, 9) has drawn attention to *confined* movements that have a scarp but no visible surface of rupture in the foot of the displaced mass. He suggested that displacements in the head of the displaced mass are taken up by compression and slight bulging in the foot of the mass.

To complete the possibilities, terms are needed for landslides in which the volume of material being displaced grows less with time and for those landslides in which no trend is obvious. The term *diminishing* for an active landslide in which the volume of material being displaced is decreasing with time seems free of undesired implications. A landslide in which displaced materials continue to move but whose surface of rupture shows no visible changes can be simply described as *moving*. Several types of landslide may exhibit diminishing behavior. Movement may stop in parts of both rotational slides and topples after substantial displacements because the movements themselves reduce the gravitational forces on the displaced masses. Similarly, movements of rock masses may rapidly dilate cracks in the masses, cause decreases in fluid pore pressures within these cracks, and hence decrease rates of movement. However, it may be premature to conclude that the displacing material is stabilizing because the volume being displaced is decreasing with time. Hutchinson (1973) pointed out that the activity of rotational slides caused by erosion at the toe of slopes in cohesive soils is often cyclic.

4.3 Style of Activity

The style of landslide activity, or the way in which different movements contribute to the landslide, can be defined by terms originally established by Varnes (1978, 23). Figure 3-13 shows idealized sections through landslides exhibiting various styles of activity. Varnes defined **complex** landslides as those with at least two types of movement. However, it is now suggested that the term *complex* be limited to cases in which the various movements occur in sequence. For instance, the topple described by Giraud et al. (1990) and shown as Figure 3-13(*1*), in which some of the displaced mass subsequently slid, is termed a *complex rock topple–rock slide*. Not all the toppled mass slid, but no significant part of the displaced mass slid without first toppling. Some of the displaced mass may be still toppling while other parts are sliding.

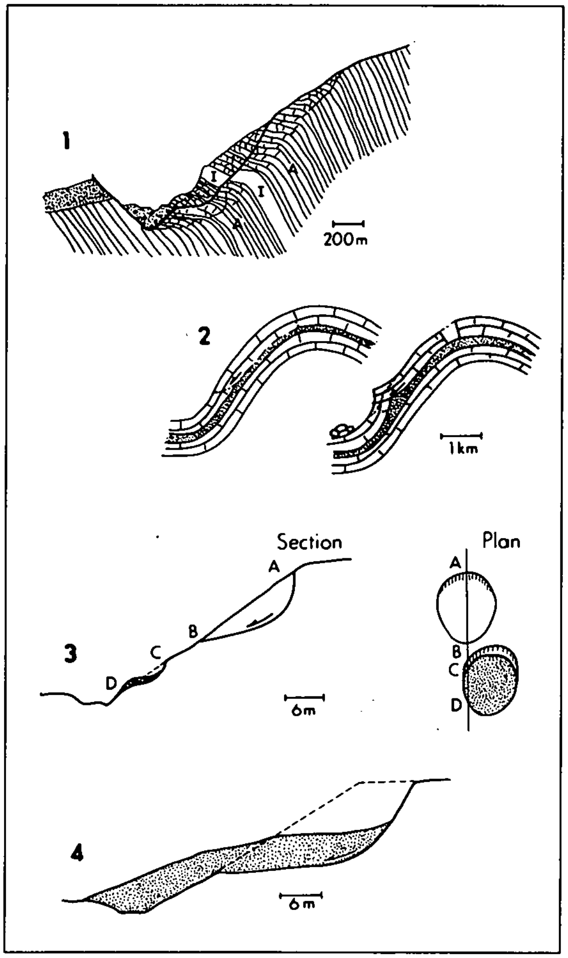


FIGURE 3-13 Sections through landslides showing different styles of activity. (*1*) *Complex:* gneiss (*A*) and migmatites (*I*) are forming topples caused by valley incision; alluvial materials fill valley bottom; after weathering further weakens toppled material, some of displaced mass moves by sliding (modified from Giraud et al. 1990). (*2*) *Composite:* limestones have slid on underlying shales, causing toppling failures below toe of slide rupture surface (modified from Harrison and Falcon 1934). (*3*) *Successive:* later landslide (*AB*) is same type as landslide *CD* but does not share displaced material or rupture surface. (*4*) *Single.*

The term **composite**, formerly a synonym for *complex*, is now proposed to describe landslides in which different types of movement occur in different areas of the displaced mass, sometimes simultaneously. However, the different areas of the displaced mass show different sequences of movement. For example, the structures shown in Figure 3-13(*2*), first described by Harrison and Falcon (1934, 1936), were called *slide toe topples* by Goodman and Bray (1976), but according to the classification proposed in this chapter, they are *composite rock slide–rock topples*. The term *composite* was introduced by Prior et al. (1968, 65, 76) to describe mudflows in which "slipping and sliding... occur in intimate association with flowing" and "the material... behaves as a liquid and flows rapidly between confining marginal shears." In the proposed naming convention, such movements are *composite earth slides-earth flows* and the convention of treating the topographically higher of the two movements as the first movement and the lower of the two movements as the second movement was adopted.

A **multiple** landslide shows repeated movements of the same type, often following enlargement of the surface of rupture. The newly displaced masses are in contact with previously displaced masses and often share a surface of rupture with them. In a *retrogressive, multiple rotational slide*, such as that shown in Figure 3-14, two or more blocks have each moved on curved surfaces of rupture tangential to common, generally deep surfaces of rupture (Eisbacher and Clague 1984).

A **successive** movement is identical in type to an earlier movement but in contrast to a multiple movement does not share displaced material or a surface of rupture with it [Figure 3-13(3)]. According to Skempton and Hutchinson (1969, 297), "successive rotational slips consist of an

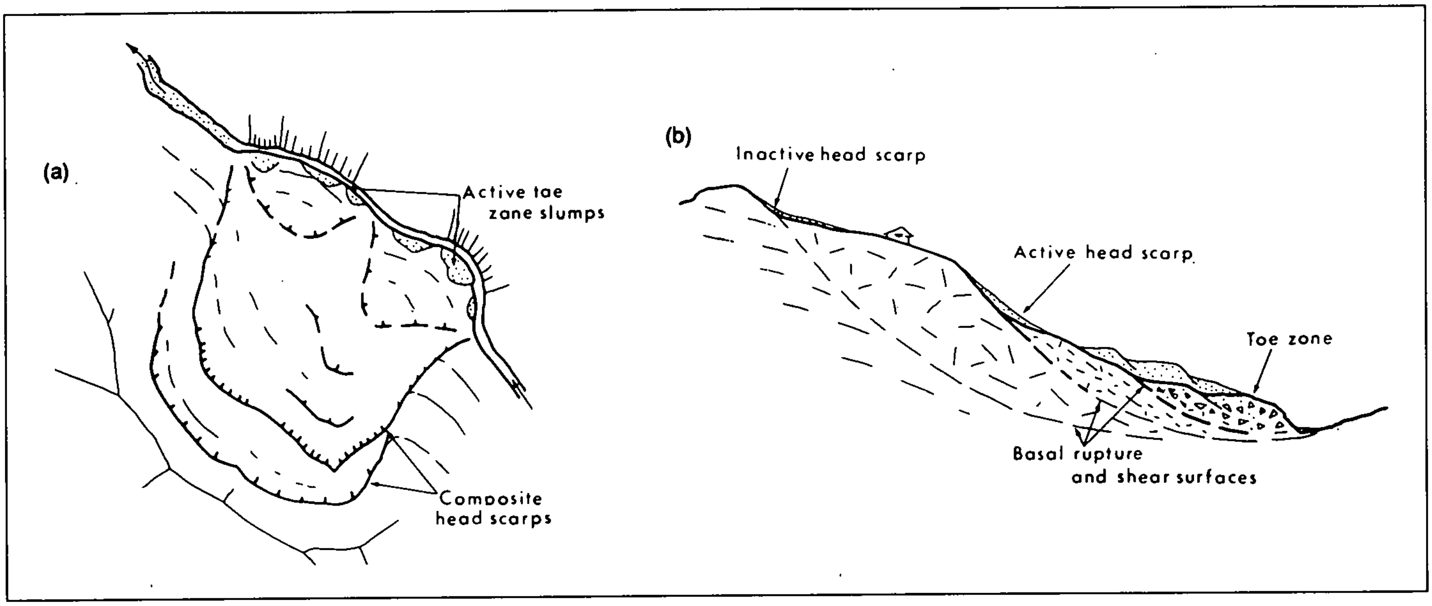


FIGURE 3-14 (*above*) (*a*) Map view and (*b*) cross section of typical retrogressive, multiple rotational slide (Eisbacher and Clague 1984, Figure 10).

assembly of individual shallow rotational slips." Hutchinson (1967, 116) commented that "irregular successive slips which form a mosaic rather than a stepped pattern in plan are also found."

Single landslides consist of a single movement of displaced material, often as an unbroken block [Figure 3-13(4)]. For instance, Hutchinson (1988) described single topples in which a single block moved and contrasted these with multiple topples (Figure 3-15). Single landslides differ from the other styles of movement, which require disruption of the displaced mass or independent movements of portions of the mass.

5. RATE OF MOVEMENT

The previous rate-of-movement scale provided by Varnes (1978, Figure 2.1u) is shown here as Figure 3-16. This scale is unchanged from Varnes's original scale (1958) except for the addition of the equivalent SI units, which range from meters per second to millimeters per year. Varnes (1958) did not discuss the divisions of the scale, then given in units ranging from feet per second to feet per 5 years; the scale probably represented a codification of informal practice in the United States at the time. Nem čok et al. (1972) suggested a fourfold division of a similar range of velocities.

Figure 3-17 presents a modified scale of landslide velocity classes. The divisions of the scale have been adjusted to increase in multiples of 100 by a slight increase in its upper limit and a decrease in its lower limit. These two limits now span 10 orders of magnitude. Interpretation of the scale was aided by Morgenstern's (1985) analogy to the Mercalli scale of earthquake intensity. He pointed out that the effects of a landslide can be sorted into six classes corresponding approximately to the six fastest movement ranges of Varnes's scale.

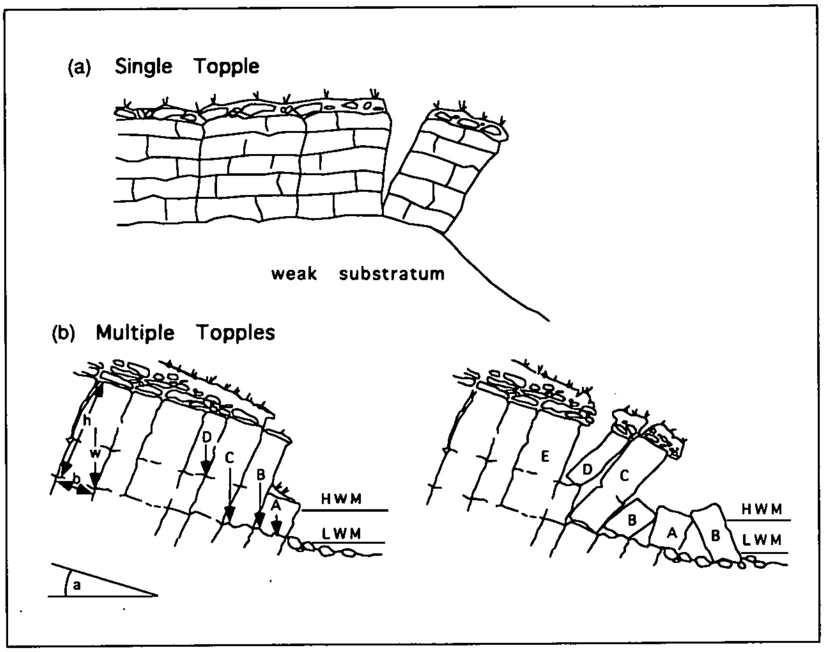


FIGURE 3-15
Comparison of (*a*) single topple (Hutchinson 1988) with (*b*) multiple topples [modified from Varnes 1978, Figure 2.1d1 (de Freitas and Watters 1973)].

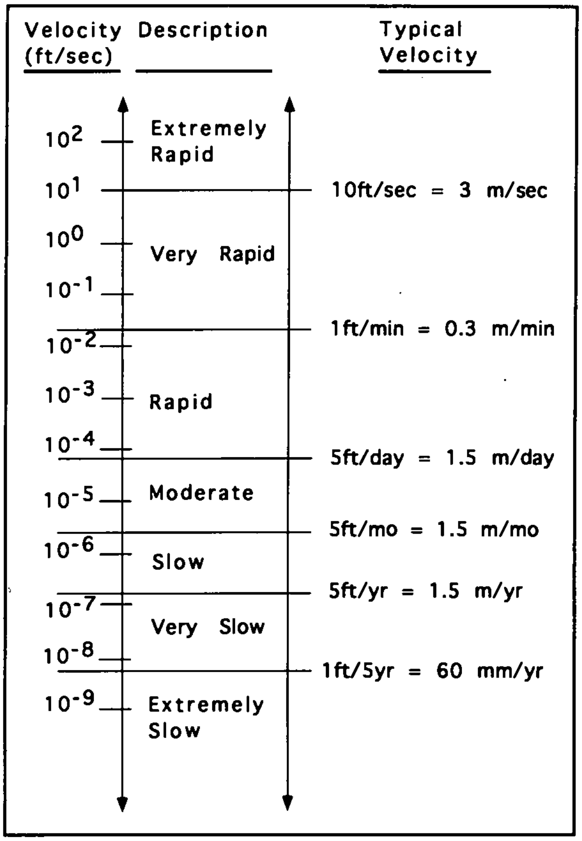


FIGURE 3-16 Varnes landslide movement scale (Varnes 1978, Figure 2.1u).

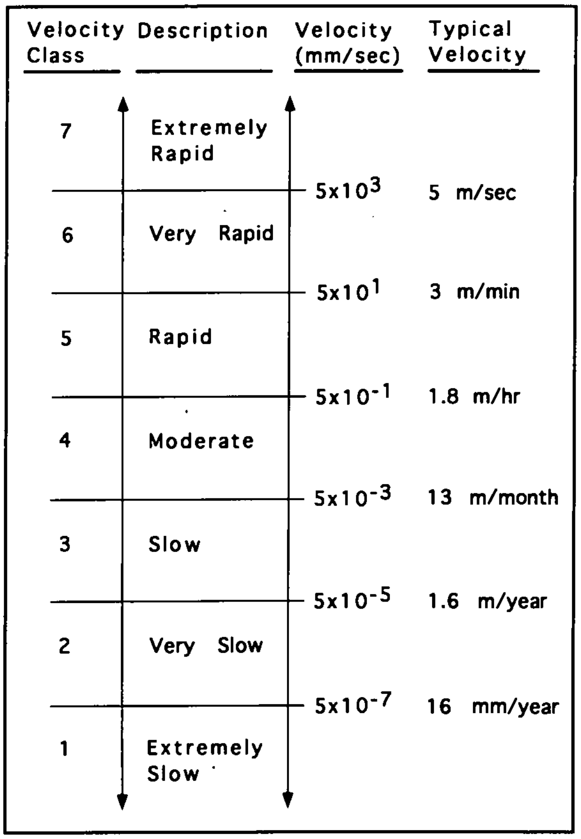


FIGURE 3-17 Proposed landslide velocity scale.

An added seventh class brings these effect classes into correspondence with the divisions of the velocity scale.

The Mercalli scale is based on descriptions of local effects of an earthquake; degrees of damage can be evaluated by investigating a house or a section of a street. Yet the intensity value can be correlated with the total energy release of the event because both local damage and the area affected are related to the magnitude of the earthquake. The situation is different for landslides. Small, **rapid** debris avalanches are known to have caused total destruction and loss of lives. In contrast, a large slope movement of **moderate** velocity can have much less serious effects because it can be avoided or the structures affected can be evacuated or rebuilt. It is suggested that a measure of landslide risk should include both the area affected and the velocity; the product of these two parameters is approximately proportional to the power release of the landslide.

Varnes (1984) drew attention to the United Nations Disaster Relief Organization terminology in which the specific risk, R_s, or the expected degree of loss due to landsliding or any other natural phenomenon, can be estimated as the product of the hazard (H) and the vulnerability (V). The hazard is the probability of occurrence of the phenomenon within a given area; the vulnerability is the degree of loss in the given area of elements at risk: population, properties, and economic activities. The vulnerability ranges from 0 to 1. In this terminology the vulnerability of the landslide might well increase with velocity because it can be expected that **extremely rapid** landslides would cause greater loss of life and property than **slow** landslides.

A parameter that is difficult to quantify is the internal distortion of the displaced mass. Structures on a moving mass generally are damaged in proportion to the internal distortion of their foundations. For example, the Lugnez slope in Switzerland (Huder 1976) is a 25-km^2 area moving steadily downward at a 15-degree angle at a velocity as high as 0.37 m/year. The movements have been observed by surveying since 1887. Yet in the six villages on the slope with 300-year-old stone houses and churches with bell towers, none of these structures have suffered damage when displaced because the block is moving without distortion. Damage will also depend on the type of landslide, and each type may require separate consideration.

Landslide velocity is a parameter whose destructive significance requires independent definition. Table 3-5 defines the probable destructive significance of the seven velocity classes on the new landslide velocity scale (Figure 3-17). Several case histories in which the effects of landslides on humans and their activities have been well described and for which the landslide velocities are also known are given in Table 3-6, which suggests a correlation between vulnerability and landslide velocity. An important limit appears to lie between **very rapid** and **extremely rapid** movement, which approximates the speed of a person running (5 m/sec). Another important boundary is between the **slow** and **very slow** classes (1.6 m/year), below which some structures on the landslide are undamaged. Terzaghi (1950, 84) identified as *creep* those slope movements that were "proceeding at an imperceptible rate. . . . Typical creep is a continuous movement which proceeds at an average rate of less than a foot per decade.

Table 3-5
Definition of Probable Destructive Significance of Landslides of Different Velocity Classes

LANDSLIDE VELOCITY CLASS	PROBABLE DESTRUCTIVE SIGNIFICANCE
7	Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
6	Some lives lost; velocity too great to permit all persons to escape
5	Escape evacuation possible; structures, possessions, and equipment destroyed
4	Some temporary and insensitive structures can be temporarily maintained
3	Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
2	Some permanent structures undamaged by movement
1	Imperceptible without instruments; construction possible with precautions

Table 3-6
Examples of Landslide Velocity and Damage

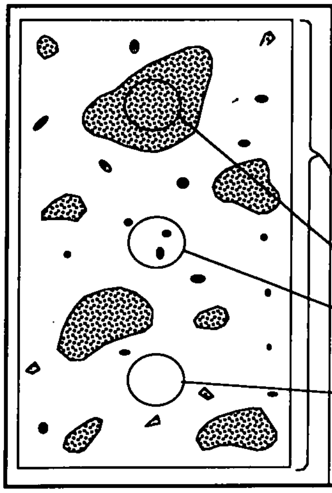
LANDSLIDE VELOCITY CLASS	LANDSLIDE NAME OR LOCATION	REFERENCE	ESTIMATED LANDSLIDE VELOCITY	DAMAGE
7	Elm	Heim (1932)	70 m/sec	115 deaths
7	Goldau	Heim (1932)	70 m/sec	457 deaths
7	Jupille	Bishop (1973)	31 m/sec	11 deaths, houses destroyed
7	Frank	McConnell and Brock (1904)	28 m/sec	70 deaths
7	Vaiont	Mueller (1964)	25 m/sec	1,900 deaths by indirect damage
7	Ikuta	*Engineering News Record* (1971)	18 m/sec	15 deaths, equipment destroyed
7	St. Jean Vianney	Tavenas et al. (1971)	7 m/sec	14 deaths, structures destroyed
6	Aberfan	Bishop (1973)	4.5 m/sec	144 deaths, some buildings damaged
5	Panama Canal	Cross (1924)	1 m/min	Equipment trapped, people escaped
4	Handlova	Zaruba and Mencl (1969)	6 m/day	150 houses destroyed, complete evacuation
3	Schuders	Huder (1976)	10 m/year	Road maintained with difficulty
3	Wind Mountain	Palmer (1977)	10 m/year	Road and railway require frequent maintenance, buildings adjusted periodically
2	Lugnez	Huder (1976)	0.37 m/year	Six villages on slope undisturbed
2	Little Smoky	Thomson and Hayley (1975)	0.25 m/year	Bridge protected by slip joint
2	Klosters	Haefeli (1965)	0.02 m/year	Tunnel maintained, bridge protected by slip joint
2	Ft. Peck Spillway	Wilson (1970)	0.02 m/year	Movements unacceptable, slope flattened

Higher rates of creep movement are uncommon." Terzaghi's rate is about 10^{-6} mm/sec. The limit of perceptible movements on the scale given in Figure 3-17 and Table 3-5 is conservatively lower than Terzaghi's. Still lower rates of movement can be detected with appropriate instrumentation (Kostak and Cruden 1990).

Varnes (1978, 17) pointed out that "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 the mechanics of materials; that is, creep is simply deformation that continues under constant stress." The term *creep* should be replaced by the appropriate descriptors from Figure 3-17, either **very slow** or **extremely slow,** to describe the rate of movement of landslides.

Estimates of landslide velocities can be made by repeated surveys of the positions of displaced objects (Thomson and Hayley 1975; Huder 1976), by reconstruction of the trajectories of portions of the displaced mass (Heim 1932; McConnell and Brock 1904; Ter-Stepanian 1980), by eyewitness observations (Tavenas et al. 1971), by instrumentation (Wilson 1970; Wilson and Mikkelsen 1978), and by other means. The Colorado Department of Transportation experimented with the use of time-lapse photography to document the movement of a relatively slow-moving but very large landslide. The estimates reported were usually the peak velocities of substantial portions of the displaced masses; these estimates are suitable for damage assessments. Rates of movement will differ within the displaced mass of the landslide with position, time, and the period over which the velocity is estimated. Such differences argue against very precise reports of landslide velocity in reconnaissance surveys.

FIGURE 3-18 Mudslide fabric and associated variability in water content (modified from Hutchinson 1988, Figure 9).



Location of water-content sample	Typical water-content values for London Clay	
	Site A (Beltinge)	Site B (Sheppey)
Overall Sample	43%	48%
Lump	41%	34%
General Matrix	46%	52%
True Matrix	?(>46%)	?(>52%)

6. WATER CONTENT

Varnes (1978) suggested the following modifications to terms first proposed by Radbruch-Hall (1978) to describe the water content of landslide materials by simple observations of the displaced material:

1. **Dry:** no moisture visible;
2. **Moist:** contains some water but no free water; the material may behave as a plastic solid but does not flow;
3. **Wet:** contains enough water to behave in part as a liquid, has water flowing from it, or supports significant bodies of standing water; and
4. **Very wet:** contains enough water to flow as a liquid under low gradients.

These terms may also provide guidance in estimating the water content of the displaced materials while they were moving. However, soil or rock masses may drain quickly during and after displacement, so this guidance may be qualitative rather than quantitative. Individual rock or soil masses may have water contents that differ considerably from the average water content of the displacing material. For example, Hutchinson (1988) noted that debris slides (which Hutchinson termed *mudslides*) generally were composed of materials that exhibited a fabric or texture consisting of lumps of various sizes in a softened clay matrix. Samples taken from different portions of this fabric had considerably different water contents, with lumps having much lower water contents than that of the matrix (Figure 3-18).

7. MATERIAL

According to Shroder (1971) and Varnes (1978), the material contained in a landslide may be described as either **rock,** a hard or firm mass that was intact and in its natural place before the initiation of movement, or **soil,** an aggregate of solid particles, generally of minerals and rocks, that either was transported or was formed by the weathering of rock in place. Gases or liquids filling the pores of the soil form part of the soil.

Soil is divided into earth and debris (see Table 3-1). **Earth** describes material in which 80 percent or more of the particles are smaller than 2 mm, the upper limit of sand-size particles recognized by most geologists (Bates and Jackson 1987). **Debris** contains a significant proportion of coarse material; 20 to 80 percent of the particles are larger than 2 mm, and the remainder are less than 2 mm. This division of soils is crude, but it allows the material to be named by a swift and even remote visual inspection.

The terms used should describe the displaced material in the landslide before it was displaced. The term *rock fall*, for instance, implies that the displacing mass was a rock mass at the initiation of the landslide. The displaced mass may be debris after the landslide. If the landslide is complex and the type of movement changes as it progresses, the material should be described at the beginning of each successive movement. For instance, a rock fall that was followed by the flow of the displaced material can be described as a *rock fall–debris flow*.

8. TYPE OF MOVEMENT

The kinematics of a landslide—how movement is distributed through the displaced mass—is one of the principal criteria for classifying landslides. However, of equally great importance is its use as a major criterion for defining the appropriate response to a landslide. For instance, occasional falls from a rock cut adjacent to a highway may be contained by a rock fence or similar barrier; in contrast, toppling from the face of the excavation may indicate adversely oriented discontinuities in the rock mass that require anchoring or bolting for stabilization.

In this section the five kinematically distinct types of landslide movement are described in the sequence **fall, topple, slide, spread,** and **flow** (Figure 3-19). Each type of landslide has a number of common modes that are frequently encountered in practice and that are described briefly, often with examples of some complex landslides whose first or initial movements were of that particular type. These descriptions show how landslides of that type may evolve.

8.1 Fall

A **fall** starts with the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place. The material then descends mainly through the air by falling, bouncing, or rolling. Movement is very rapid to extremely rapid. Except when the displaced mass has been undercut, falling will be preceded by small sliding or toppling movements that separate the displacing material from the undisturbed mass. Undercutting typically occurs in cohesive soils or rocks at the toe of a cliff undergoing wave attack or in eroding riverbanks.

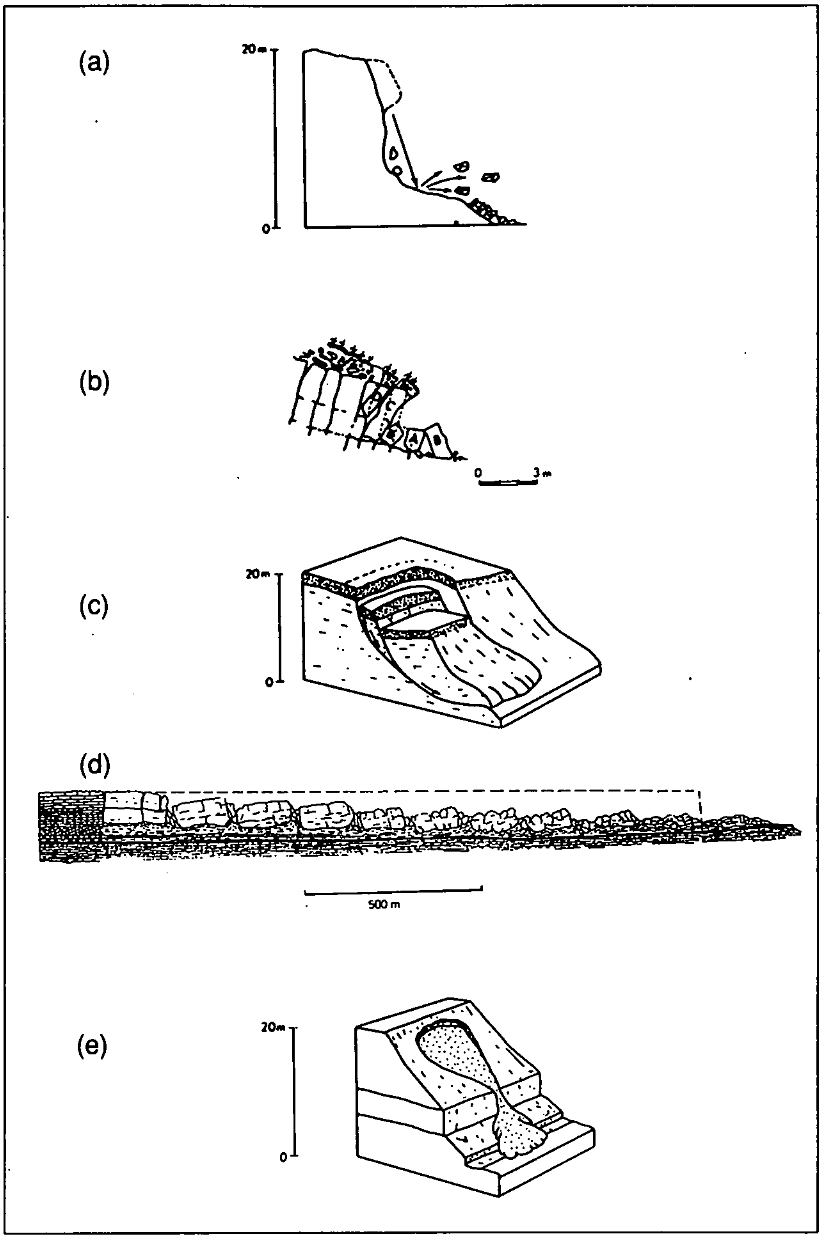


FIGURE 3-19
Types of landslides: (a) *fall*, (b) *topple*, (c) *slide*, (d) *spread*, (e) *flow*. Broken lines indicate original ground surfaces; arrows show portions of trajectories of individual particles of displaced mass [modified from Varnes 1978, Figure 2.1 (Zaruba and Mencl 1969)].

8.1.1 Modes of Falling

Observations show that the forward motion of masses of soil or rock is often sufficient for *free fall* if the slopes below the masses exceed 76 degrees

(0.25:1). The falling mass usually strikes a slope inclined at less than this angle (Ritchie 1963), which causes *bouncing*. Rebound from the impact will depend on material properties, particularly restitution coefficients, and the angle between the slope and the trajectory of the falling mass (Hungr and Evans 1988). The falling mass may also break up on impact.

On long slopes with angles at or below 45 degrees (1:1), particles will have movement paths dominated by *rolling*. There is a gradual transition to rolling from bouncing as bounces shorten and incidence angles decrease. Local steepening of the slope may again project rolling particles into the air, restarting the sequence of free fall, bouncing, and rolling (Hungr and Evans 1988).

8.1.2 Complex Falls

Sturzstroms are extremely rapid flows of dry debris created by large falls and slides (Hsu 1975). These flows may reach velocities over 50 m/sec. Sturzstroms have also been called *rock-fall avalanches* (Varnes 1958) and *rock avalanches* (Evans et al. 1989; Nicoletti and Sorriso-Valvo 1991). Two examples of historic sturzstroms in Switzerland, the Rossberg landslide of 1806 and the Elm landslide of 1881, are discussed in Chapter 1. Hsu (1975) suggested that 5 million m^3 is the lower limit of the volume of significant sturzstroms, but Hutchinson (1988) demonstrated that falls in high-porosity, weak European chalk rocks with volumes two orders of magnitude smaller have the same exceptional mobility because of collapse of the pores on impact and consequent high porewater pressures. Some of Hutchinson's data are reproduced in Figure 3-19.

The motion of sturzstroms probably depends on turbulent grain flow with dispersive stresses arising from momentum transfer between colliding grains. Such a mechanism does not require the presence of a liquid or gaseous pore fluid and can therefore explain lunar and Martian sturzstroms. Van Gassen and Cruden (1989) showed that the motion of the *complex, extremely rapid, dry rock fall–debris flow* that occurred near the town of Frank, Alberta, Canada, in 1903 (see Figure 3-1) could be explained reasonably well by momentum exchange between the moving particles and measured coefficients of friction.

8.2 Topple

A topple [Figure 3-19(*b*)] is the forward rotation out of the slope of a mass of soil or rock about a point or axis below the center of gravity of the displaced mass. Toppling is sometimes driven by gravity exerted by material upslope of the displaced mass and sometimes by water or ice in cracks in the mass. Topples may lead to falls or slides of the displaced mass, depending on the geometry of the moving mass, the geometry of the surface of separation, and the orientation and extent of the kinematically active discontinuities. Topples range from extremely slow to extremely rapid, sometimes accelerating throughout the movement.

8.2.1 Modes of Toppling

Flexural toppling was described by Goodman and Bray as

> occurring in rocks with one preferred discontinuity system, oriented to present a rock slope with semi-continuous cantilever beams. . . . Continuous columns break in flexure as they bend forward. . . . Sliding, undermining or erosion of the toe (of the displaced mass) lets the failure begin and it retrogresses backwards with deep, wide tension cracks. The lower portion of the slope is covered with disoriented and disordered blocks. . . . The outward movement of each cantilever produces interlayer sliding (flexural slip) and . . . back-facing scarps (obsequent scarps). . . . It is hard to say where the base of the disturbance lies for the change is gradual. . . . Flexural toppling occurs most notably in slates, phyllites and schists. (Goodman and Bray 1976, 203)

A flexural topple in the proposed classification is a *retrogressive, complex rock topple–rock fall*. Typical examples are shown in Figures 3-20(*a*) and 15-16.

In contrast, *block toppling* occurs

> where the individual columns are divided by widely-spaced joints. The toe of the slope with short columns, receives load from overturning, longer columns above. This thrusts the toe columns forward, permitting further toppling. The base of the disturbed mass is better defined than in the case of flexural toppling; it consists of a stairway generally rising from one layer to

> the next. The steps of this stairway are formed by cross-joints. . . . New rock breakage . . . occurs much less markedly than in flexural topples . . . . Thick-bedded sedimentary rocks such as limestones and sandstones, as well as columnar-jointed volcanics exhibit block-toppling. (Goodman and Bray 1976, 203)

Typical examples of block toppling are shown in Figure 15-16.

Chevron topples are block topples in which the dips of the toppled beds are constant and the change of dip is concentrated at the surface of rupture (Cruden et al. 1993). This mode was named from its resemblance to chevron folds (Ramsay 1967, 436). Chevron topples occur on steeper slopes than other block topples. The surface of rupture is often a sliding surface [Figure 3-20(*b*)] forming a *complex rock topple–rock slide*.

Block-flexure toppling is characterized by

> pseudo-continuous flexure of long columns through accumulated motions along numerous cross joints. Sliding is distributed along several joint surfaces in the toe [of the displaced mass] while sliding and overturning occur in close association through the rest of the mass. (Goodman and Bray 1976, 204)

Sliding occurs because accumulated overturning steepens the cross joints. There are fewer edge-to-face contacts than in block toppling but still enough to form "a loosened, highly open . . . disturbed zone [displaced mass]. . . . Interbedded sandstone and shale, interbedded chert and shale and thin-bedded limestone exhibit block flexure toppling" (Goodman and Bray 1976, 204). Typical block-flexure topple examples are shown in Figures 3-20(*c*) and 15-16.

8.2.2 Complex and Composite Topples

A *complex rock topple–rock slide* is shown in Figure 3-13(*1*). This cross section of the La Clapière landslide was described by Giraud et al. as follows:

> Several distinct movements may be identified as the phenomenon progresses, along with a modification of water flows within the rock mass, due to considerable changes in permeability over time and probably in space as a result of deformation of the massif. (Giraud et al. 1990, 250)

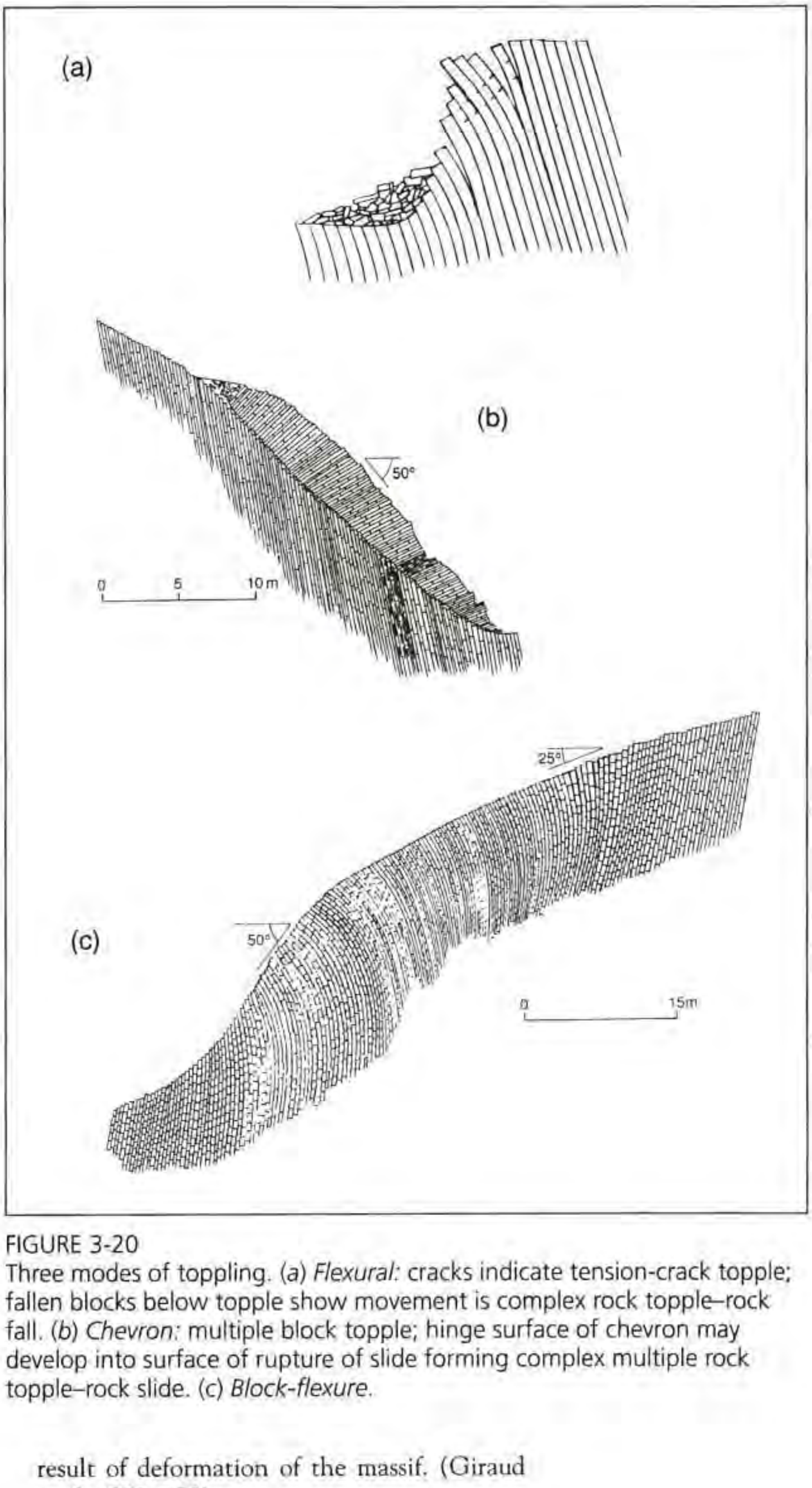


FIGURE 3-20
Three modes of toppling. (*a*) *Flexural:* cracks indicate tension-crack topple; fallen blocks below topple show movement is complex rock topple–rock fall. (*b*) *Chevron:* multiple block topple; hinge surface of chevron may develop into surface of rupture of slide forming complex multiple rock topple–rock slide. (*c*) *Block-flexure.*

Goodman and Bray (1976) identified four composite landslide modes in which toppling was caused by earlier sliding. These landslide conditions are discussed in detail in Chapter 15 and are illustrated in Figure 15-17. A *slide head topple* occurs as blocks from the crown of the slide topple onto the head of the displaced mass. According to the naming convention, such a landslide is a *composite rock slide–retrogressive rock topple.*

Rotational sliding of earth or debris above a steeply dipping sedimentary rock mass can cause *slide base toppling* as the sliding induces shear forces in the top of the rock mass (Goodman and Bray 1976). The resulting landslide is, according to the proposed naming convention, a *composite earth slide–advancing rock topple.*

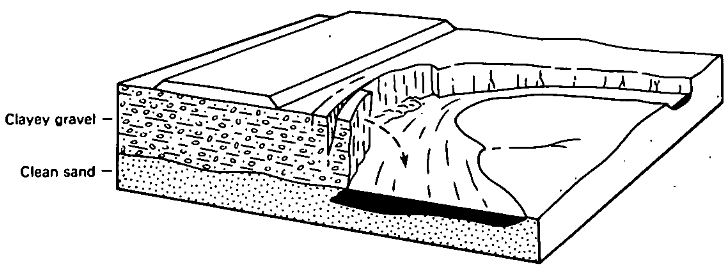
Toppling below the toe of the surface of rupture of a rock slide may be caused by load transmitted from the slide. Such a failure is called a *slide toe topple* (Goodman and Bray 1976). According to the proposed naming convention, it is a *composite rock slide–rock topple.*

The formation of extension cracks in the crown of a landslide may create blocks capable of toppling, or a *tension crack topple* (Goodman and Bray 1976). According to the proposed naming convention, this is a *retrogressive multiple topple*, perhaps forming part of a composite fall or slide. Such failures may also occur in cohesive soils being undercut along streambanks (Figure 3-21).

8.3 Slide

A slide is a downslope movement of a soil or rock mass occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain. Movement does not initially occur simultaneously over the whole of what eventually becomes the surface of rupture; the volume of displacing material enlarges from an area of local failure. Often the first signs of ground movement are cracks in the original ground surface along which the main scarp of the slide will form. The displaced mass may slide beyond the toe of the surface of rupture covering the original ground surface of the slope, which then becomes a surface of separation.

FIGURE 3-21
Debris topple
(Varnes 1978,
Figure 2.1e).



8.3.1 Modes of Sliding

Varnes (1978) emphasized the distinction between rotational and translational slides as significant for stability analyses and control methods. That distinction is retained in this discussion. Figure 3-22 shows two rotational slides and three translational slides. Translational slides frequently grade into flows or spreads.

Rotational slides (Figure 3-23) move along a surface of rupture that is curved and concave. If the surface of rupture is circular or cycloidal in profile, kinematics dictates that the displaced mass may move along the surface with little internal deformation. The head of the displaced material may move almost vertically downward, whereas the upper surface of the displaced material tilts backward toward the scarp. If the slide extends for a considerable distance along the slope perpendicular to the direction of motion, the surface of rupture may be roughly cylindrical. The axis of the cylindrical surface is parallel to the axis about which the slide rotates. Rotational slides in soils generally exhibit a ratio of depth of the surface of rupture to length of the surface of rupture, D_r/L_r (see Table 3-4 and Figure 3-5 for definitions of these dimensions), between 0.15 and 0.33 (Skempton and Hutchinson 1969).

Because rotational slides occur most frequently in homogeneous materials, their incidence in fills has been higher than that of other types of movement. Natural materials are seldom uniform, however, and slope movements in these materials commonly follow inhomogeneities and discontinuities (Figure 3-24). Cuts may cause movements that cannot be analyzed by methods used for rotational slides, and other more appropriate methods have been developed. Engineers have concentrated their studies on rotational slides.

The scarp below the crown of a rotational slide may be almost vertical and unsupported. Further movements may cause retrogression of the slide into the crown. Occasionally, the lateral margins of the surface of rupture may be sufficiently high and steep to cause the flanks to move down and into the depletion zone of the slide. Water finding its way into the head of a rotational slide may con-

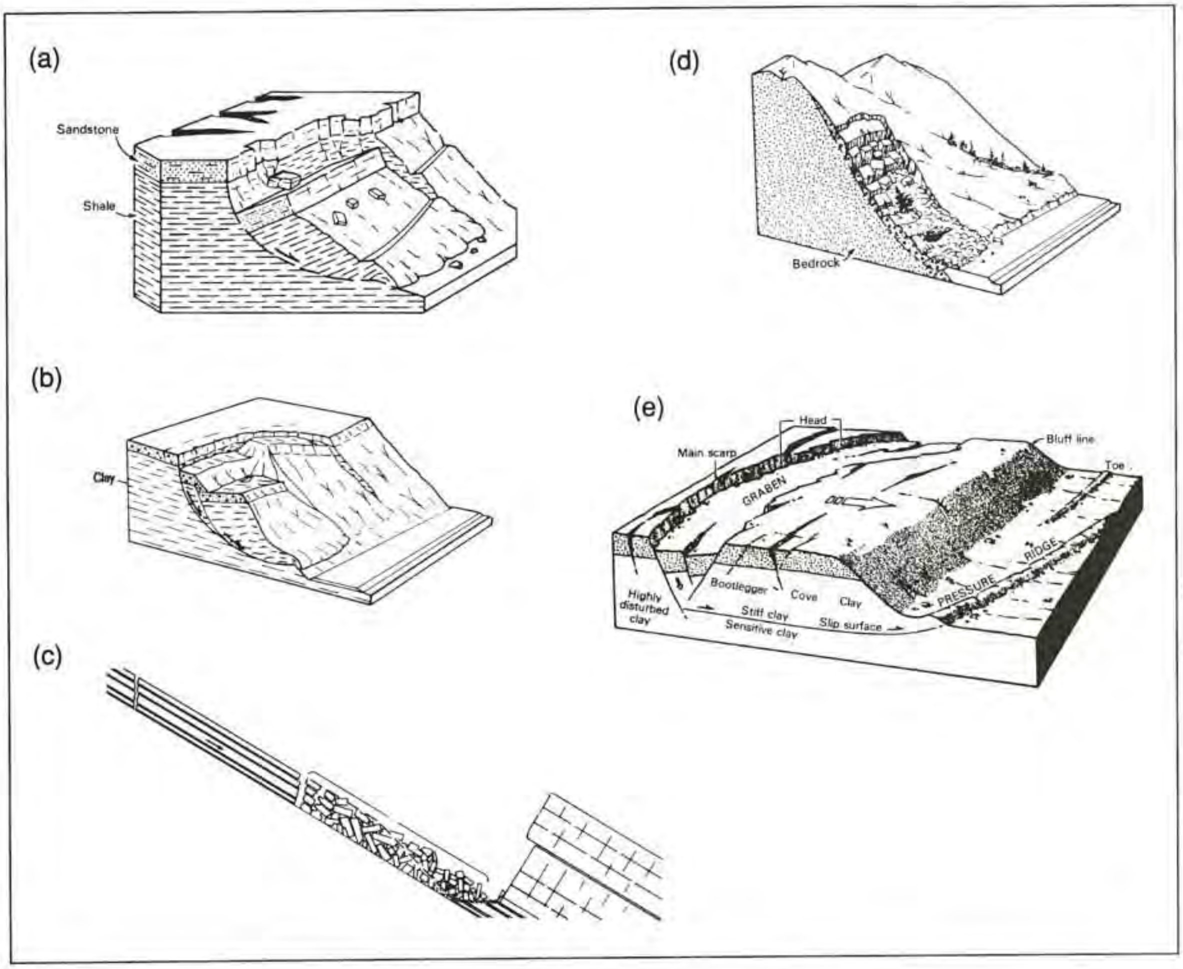


FIGURE 3-22
Examples of rotational and translational slides: (*a*) rotational rock slide; (*b*) rotational earth slide; (*c*) translational rock slide (upper portion is rock block slide); (*d*) debris slide; (*e*) translational earth block slide[Varnes 1978, Figures 2.1g, 2.1i, 2.1j2, 2.1k, 2.1l (Hansen 1965)].

tribute to a sag pond in the backward-tilted, displaced mass. This disruption of drainage may keep the displaced material wet and perpetuate the slope movements until a slope of sufficiently low gradient is formed.

In *translational slides* (Figures 3-22, 3-25, and 3-26) the mass displaces along a planar or undulating surface of rupture, sliding out over the original ground surface. Translational slides generally are relatively shallower than rotational slides. Therefore, ratios of D_r/L_r for translational slides in soils are typically less than 0.1 (Skempton and Hutchinson 1969). The surfaces of rupture of translational slides are often broadly channel-shaped in cross section (Hutchinson 1988). Whereas the rotation of a rotational slide tends to restore the displaced mass to equilibrium, translation may continue unchecked if the surface of separation is sufficiently inclined.

As translational sliding continues, the displaced mass may break up, particularly if its velocity or

FIGURE 3-23
Cut through rotational slide of fine-grained, thin-bedded lake deposits, Columbia River valley; beds above surface of rupture have been rotated by slide to dip into slope (Varnes 1978, Figure 2.7).

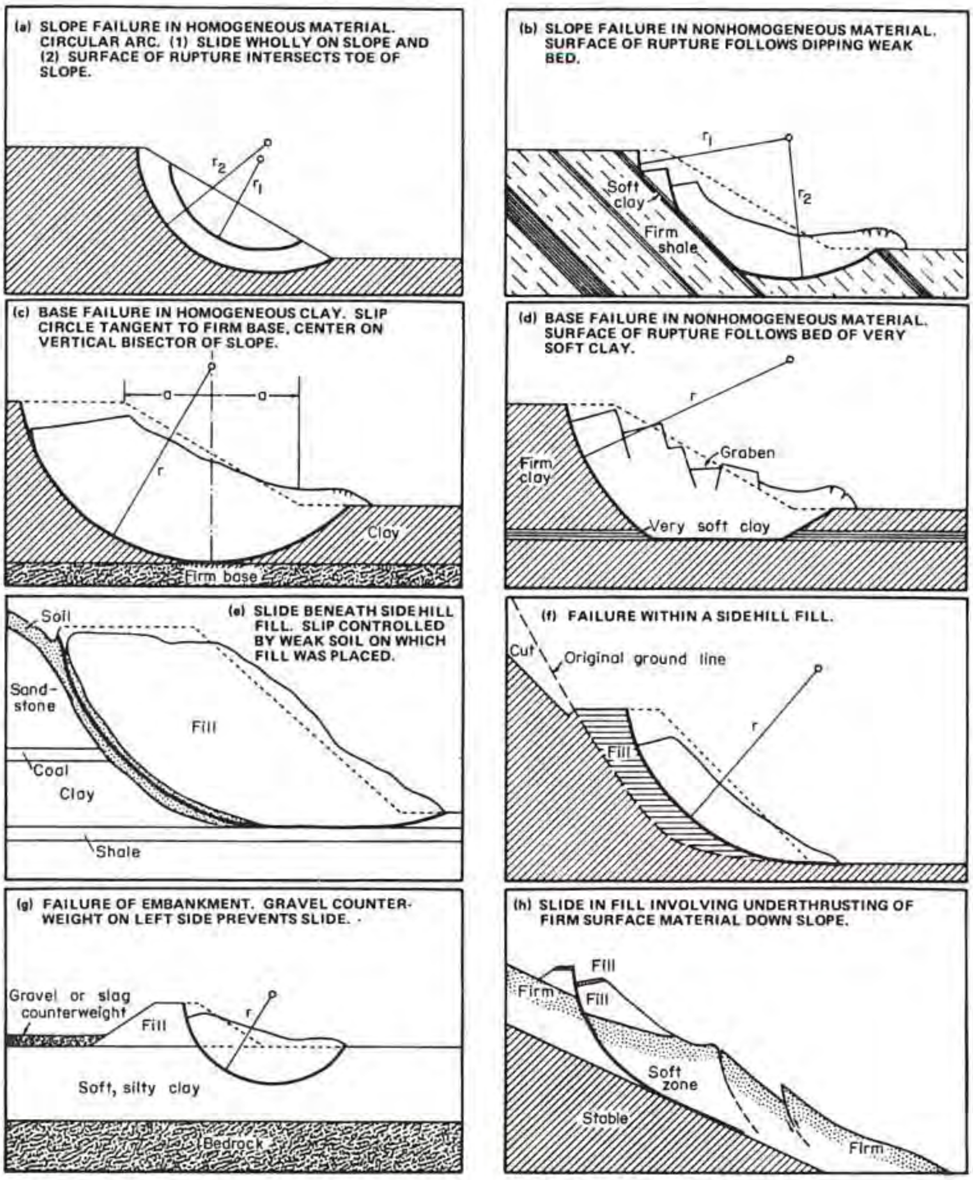


FIGURE 3-24 Rotational slides (Varnes 1978, Figure 2.5).

FIGURE 3-25 *(below)* Translational slide of colluvium on inclined metasiltstone strata along I-40, Cocke County, Tennessee (Varnes 1978, Figure 2.11).

water content increases. The disrupted mass may then flow, becoming a debris flow rather than a slide. Translational sliding often follows discontinuities such as faults, joints, or bedding surfaces or the contact between rock and residual or transported soils.

Translational slides on single discontinuities in rock masses have been called *block slides* (Panet 1969) or *planar slides* (Hoek and Bray 1981). As Hutchinson (1988) pointed out, there is a transition from rock slides of moderate displacement that remain as blocks on the surface of rupture to slides on steeper and longer surfaces that break up into debris or transform into sturzstroms. Where the surface of rupture follows a discontinuity that is parallel to the slope, the toe of the displaced mass may form a wedge that overrides or ploughs into undisplaced material causing folding beyond the toe of the surface of rupture (Walton and Atkinson 1978). *Composite rock slide–rock topples* [Figure 3-13(2)] or *buckles* and confined slides may result.

The surface of rupture may be formed by two discontinuities that cause the contained rock mass to displace down the line of intersection of the discontinuities, forming a *wedge slide* [Figure 3-27(*a*) and Chapter 15, Figures 15-8 through 15-14]. Similarly shaped displaced masses may be bounded by one discontinuity that forms the main scarp of the slide and another that forms the surface of rupture. The mode of movement depends on the orientations of the free surfaces relative to the discontinuities in the rock masses (Hocking 1976; Cruden 1978, 1984). Stepped rupture surfaces may result if two or more sets of discontinuities, such as bedding surfaces and some joint sets, penetrate the rock masses. As shown in Figure 3-27(*b*), one set of surfaces forms the risers of the steps and the other forms the treads, creating a *stepped slide* (Kovari and Fritz 1984).

Compound slides are intermediate between rotational and translational slides and their D_r / L_r ratios reflect this position (Skempton and Hutchinson 1969). Surfaces of rupture have steep main scarps that may flatten with depth [Figure 3-22(*e*)]. The toes of the surfaces of rupture may dip upslope. Displacement along complexly curved surfaces of rupture usually requires internal deformation and shear along surfaces within the displaced material and results in the formation of intermediate scarps. Abrupt decreases in downslope dips of surfaces of rupture may be marked by uphill-facing scarps in displaced masses and the subsidence of blocks of displaced material to form depressed areas, *grabens* [Figure 3-22(*e*)]. A compound slide often indicates the presence of a weak layer or the boundary between weathered and unweathered material. Such zones control the location of the surface of rupture (Hutchinson 1988). In single compound slides, the width of the graben may be proportional to the depth to the surface of rupture (Cruden et al. 1991).

FIGURE 3-26 *(above)* Shallow translational slide that developed on shaly rock slope in Puente Hills of southern California; slide has low D_r / L_r ratio; note wrinkles on surface [Varnes 1978, Figure 2.33; (Shelton 1966)]. COPYRIGHT JOHN S. SHELTON

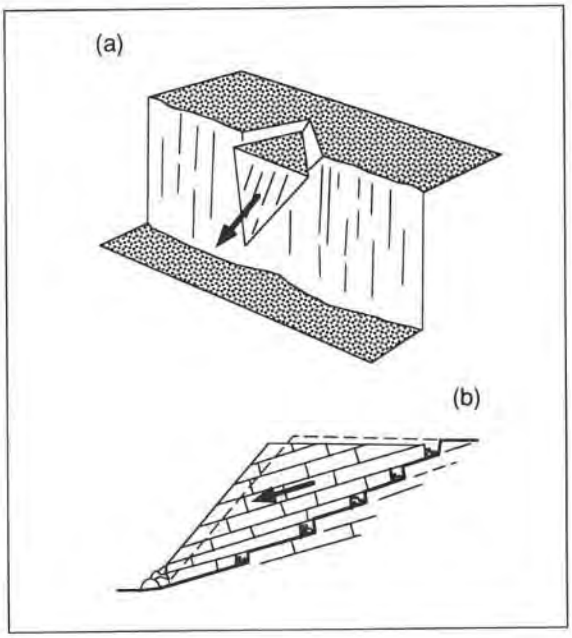


FIGURE 3-27 *(left)* (*a*) Wedge and (*b*) stepped translational slides.

8.3.2 Complex and Composite Slides

Complex and composite slide movements are common and the literature contains numerous references to a variety of specialized names. Two of these names, *mudslide* and *flowslide*, are believed to be imprecise and ambiguous, and therefore their use is not recommended.

According to Hutchinson, *mudslides* are

> slow-moving, commonly lobate or elongate masses of accumulated debris in a softened clayey matrix which advance chiefly by sliding on discrete, bounding shear surfaces. . . . In

> long profile, mudslides are generally bilinear with a steeper . . . slope down which debris is fed (by falls, shallow slides and mudslides) to a more gently-inclined slope. . . . Mudslides are especially well-developed on slopes containing stiff, fissured clays, doubtless because of the ease with which such materials break down to provide a good debris supply. (Hutchinson 1988, 12–13)

Evidently these movements begin in either weak rock or earth and retrogress by falls and slides while advancing by sliding. Hutchinson and Bhandari (1971) suggested that the displaced material, fed from above onto the mudslide, acted as an undrained load. Clearly mudslides are composite or perhaps complex both in style of activity and in the breakdown of displaced material into earth or debris. The displaced material is generally moist, though locally it may be wet. A mudslide is therefore often a *retrogressive, composite rock slide–advancing, slow, moist earth slide*. Other mudslide modes may include single earth slides (Brunsden 1984). The current use of *mudslide* for several different landslide modes suggests that more precise terminology should be used where possible.

The term *flowslide* has been used to describe sudden collapses of material that then move considerable distances very rapidly to extremely rapidly. As Hutchinson (1988) and Eckersley (1990) pointed out, at least three phenomena can cause this behavior: (*a*) impact collapse, (*b*) dynamic liquefaction, and (*c*) static liquefaction. Impact-collapse flowslides occur when highly porous, often-saturated weak rocks fall from cliffs, resulting in destruction of the cohesion of the material and the generation of excess fluid pressures within the flowing displaced mass. Clearly these are complex falls in which the second mode of movement is a *debris flow*; if the displaced material is dry debris, the movement may be a sturzstrom, previously defined in Section 8.1.2. This mode of movement can be recognized by both the materials involved and the topography of the flow.

If the structure of the material is destroyed by shocks such as earthquakes, saturated material may liquefy and then flow, sometimes carrying masses of overlying drier material with it. Such a movement is a flow or *liquefaction spread*, which is further defined in Section 8.4.1. Such movements are characteristic of loess, a lightly cemented aeolian silt. Landslides occurring in loosely dumped anthropogenic materials, both stockpiles and waste dumps, have also been termed *flowslides*. These loose, cohesionless materials contract on shearing and so may generate high pore-water pressures after some sliding (Eckersley 1990). Similar landslides may also occur in rapidly deposited natural silts and fine sands (Hutchinson 1988, 14). Since these movements involve both sliding and then flowage, they may be better described as *complex slide flows*.

Because these separate and distinguishable phenomena are comparatively distinct types of landslides that may be more accurately described by standard descriptors, the use of the term *flowslide* for all these types of movements is redundant, confusing, and potentially ambiguous.

In contrast, one form of compound sliding failure appears to warrant a special term. *Sags* (or *sackungen*) are deformations of the crests and steep slopes of mountain ridges that form scarps and grabens and result in some ridges with double crests and small summit lakes. Material can be displaced tens of meters at individual scarps. The state of activity, however, is generally dormant and may be relict. The term *sag* may be useful to indicate uncertainty about the type of movement visible on a mountain ridge.

Movement is often confined, and small bulges in local slopes are the only evidence of the toes of the displaced material. Detailed subsurface investigations of these features are rare, and classification should await this more detailed exploration. As Hutchinson (1988, 8) demonstrated, the geometry of the scarps (which often face uphill) may be used to suggest types of movement, which may include slides, spreads, and topples. The modes of sagging depend on the lithology of the displaced material and the orientation and strength of the discontinuities in the displacing rock mass. Varnes et al. (1989, 1) distinguished

1. "Massive, strong (although jointed) rocks lying on weak rocks,"
2. "Ridges composed generally of metamorphosed rocks with pronounced foliation, schistosity or cleavage," and
3. "Ridges composed of hard, but fractured, crystalline igneous rocks."

Sags of the first type are usually *spreads* (Radbruch-Hall 1978; Radbruch-Hall et al. 1976), which are discussed in Section 8.4. Sags in foliated metamorphic rocks are often topples, and thus are discussed in Section 8.2, although bedrock flow may also occur (see Section 8.5). Sags in crystalline igneous rocks (Varnes et al. 1989, 22) were modeled by a plasticity solution for "gravity-induced deformation of a slope yielding under the Coulomb criterion." Sags may thus be slides, spreads, or flows, depending on the extent and distribution of plastic flow within the deforming rock mass.

Sags are often associated with glacial features. The absence of Pleistocene snow and ice covers, and the resulting loss of the permafrost and high pore-water pressures these induced, may account for the present inactivity of many sags. Varnes et al. (1990) described an active sag in the mountains of Colorado. Earthquakes, however, can also produce uphill-facing scarps along reactivated normal faults. The surface features of sags require careful investigation before any conclusions can be drawn about the cause and timing of slope movement. Such investigations may be sufficient to allow the identification of sags as other types of landslides.

In many landslides, the displaced material, initially broken by slide movements, subsequently begins to flow (Figure 3-28). This behavior is especially common when fine-grained or weak materials are involved. These landslides have been termed *slump-earth flows*. *Slump* has been used as a synonym for a rotational slide, but it is also used to describe any movement in a fill. It is therefore recommended that this mode of movement be termed a *complex earth slide–earth flow* and that the use of the term *slump* be discontinued.

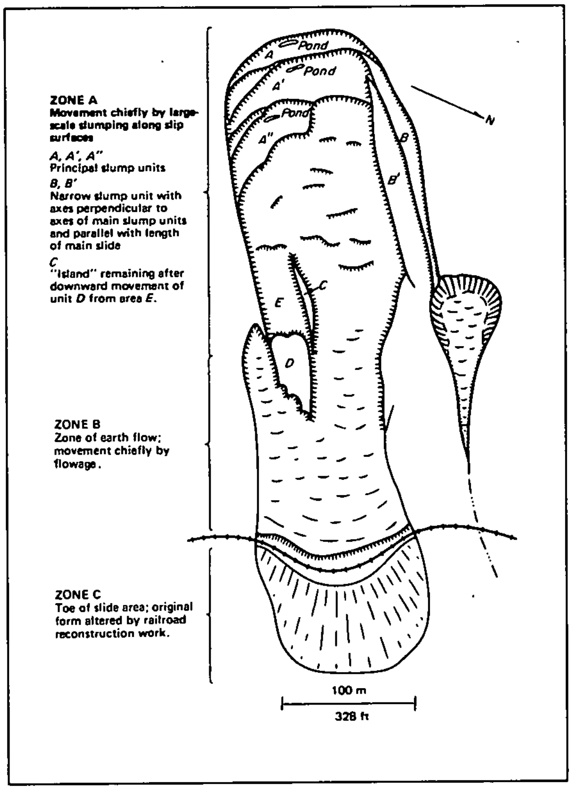


FIGURE 3-28
Plan of Ames slide near Telluride, Colorado. This enlarging complex earth slide–earth flow occurred in till overlying Mancos shale. Crown of slide retrogressed by multiple rotational slides after main body of displaced material moved. Surface of rupture also widened on left lateral margin [Varnes 1978, Figure 2.10 (modified from Varnes 1949)].

In permafrost regions, distinctive *retrogressive, complex earth slide–earth flows*, known as *thaw-slumps* (Hutchinson 1988, 21) and *bimodal flows* (McRoberts and Morgenstern 1974), develop on steep earth slopes when icy permafrost thaws and forms flows of very wet mud from a steep main scarp. These special landslide conditions are discussed in more detail in Chapter 25.

8.4 Spread

The term *spread* was introduced to geotechnical engineering by Terzaghi and Peck (1948) to describe sudden movements on water-bearing seams of sand or silt overlain by homogeneous clays or loaded by fills:

> It is characteristic . . . that a gentle clay slope which may have been stable for decades or centuries, moves out suddenly along a broad front. At the same time the terrain in front . . . heaves for a considerable distance from the toe. On investigation, it has invariably been found that the spreading occurred at a considerable distance beneath the toe along the boundary between the clay and an underlying water-bearing stratum or seam of sand or silt. (Terzaghi and Peck 1948, 366)

Recognition of the phenomenon is considerably older. One of the three types of landslides distinguished by Dana (1877, 74) occurs "when a layer of clay or wet sand becomes wet and softened by percolating water and then is pressed out laterally by the weight of the superincumbent layers." An early use of *spread* to describe this phenomenon is by Barlow:

> In a landslip [British term for some types of landslide], the spreading of some underlying bed which has become plastic through the percolation of water or for some other cause drags apart the more solid, intractable beds above and pro-

> duces fissures and fractures transverse to the direction of movement. (Barlow 1888, 786)

Spread is defined here as an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material. The surface of rupture is not a surface of intense shear. Spreads may result from liquefaction or flow (and extrusion) of the softer material. Varnes (1978) distinguished spreads typical of rock, which extended without forming an identifiable surface of rupture from movements in cohesive soils overlying liquefied materials or materials flowing plastically (Figure 3-29). The cohesive materials may also subside, translate, rotate, disintegrate, or liquefy and flow. Clearly these movements are complex, but they are sufficiently common in certain materials and geological situations that the concept of a spread is worth recognizing as a separate type of movement.

8.4.1 Modes of Spreading

In *block spreads*, a thick layer of rock overlies softer materials; the strong upper layer may fracture and separate into strips. The soft underlying material is squeezed into the cracks between the strips, which may also fill with broken, displaced material [Figure 3-29(*a*)]. Typical rates of movement are extremely slow.

Such movements may extend many kilometers back from the edges of plateaus and escarpments. The Needles District of Canyonlands National Park, Utah, is an example of a block spread (McGill and Stromquist 1979; Baars 1989). Grabens up to 600 m wide and 100 m deep stretch 20 km along the east side of Cataract Canyon on the Colorado River (Figure 3-30). The grabens extend up to 11 km back from the river. A 450-m-thick sequence of Paleozoic sedimentary rocks has been spread down a regional slope with a 4-degree dip by the flow of an underlying evaporite that is exposed in valley anticlines in the Colorado River and its tributaries (Potter and McGill 1978; Baars 1989). This approximately 60 km^3 of displaced material constitutes one of North America's largest landslides.

Liquefaction spreads form in sensitive clays and silts that have lost strength with disturbances that damaged their structure [Figures 3-29(*c*) and 3-31]. These types of landslides are discussed further in Chapter 24. Movement is translational and often retrogressive, starting at a stream bank or a shoreline and extending away from it. However, if the underlying flowing layer is thick, blocks may

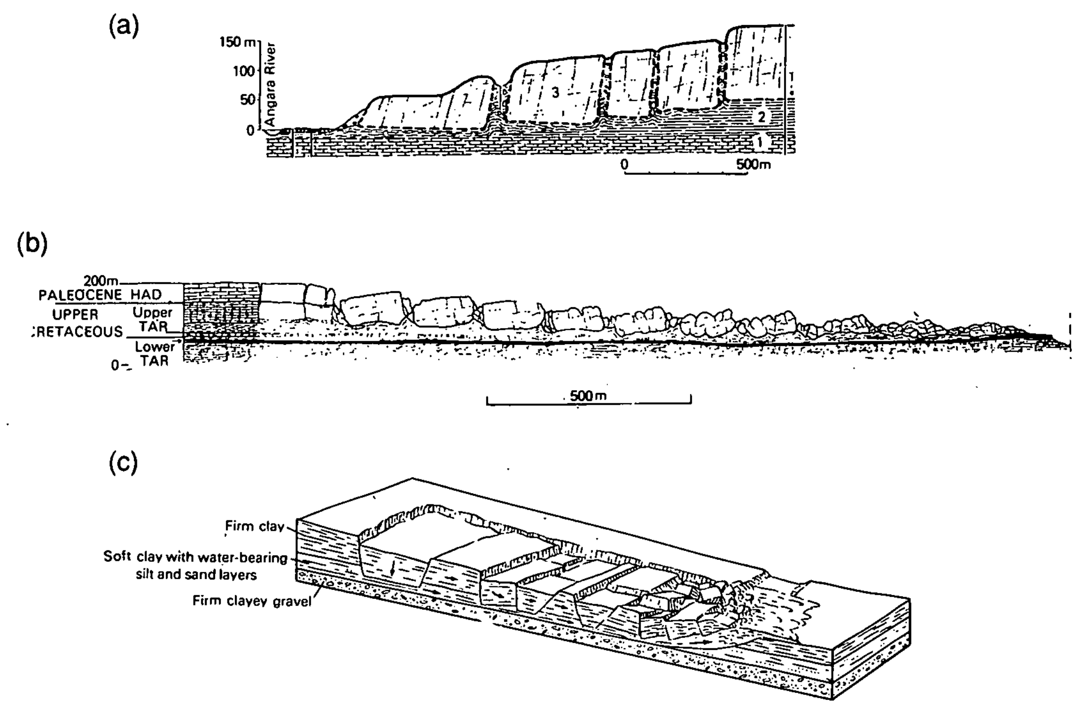


FIGURE 3-29
Rock and earth spreads: (*a*), (*b*) rock spreads that have experienced lateral extension without well-defined basal shear surface or zone of plastic flow [Varnes 1978, Figure 2.1m2 (Zaruba and Mencl 1969); Figure 2.1m3 (Ostaficzuk 1973)]; (*c*) earth spread resulting from liquefaction or plastic flow of subjacent material (Varnes 1978, Figure 2.1o).

sink into it, forming grabens, and upward flow can take place at the toe of the displaced mass. Movement can begin suddenly and reach very rapid velocities:

> Spreads are the most common ground failure during earthquakes. . . . [They] occur in gentler terrains (commonly between 0.5 per cent [0.3 degrees] and 5 percent [3 degrees]) with lateral movement of a few meters or so. . . . [S]preads involve fracturing and extension of coherent material owing to liquefaction or plastic flow of subjacent material. . . . [S]preads are primarily translational although some associated rotation and subsidence commonly occurs. (Andrus and Youd 1987, 16)

Van Horn (1975) described two movements of more than 8 km^2 in area on very gentle slopes in flat-lying beds of silty clay, clayey silt, and very fine sand deposited in prehistoric Lake Bonneville, Utah. The displaced material forms ridges parallel to the main scarp of the landslide; distinctive internal structures include gentle folds, shears, and intrusions of liquefied sediment.

8.4.2 Complex Spreads

Major deformations in rock strata were found along many valleys in north-central England during the construction of dams in the late 19th century. These deformations occurred where a nearly horizontal, rigid-jointed cap rock overlaid a thick layer of stiff-fissured clay or clay shale that in turn overlaid a more competent stratum. A bending, or *cambering*, of the rigid strata caused blocks of this stratum to dip toward the valley. This bending of the upper stratum was accompanied by severe deformation and bulging of the softer lower strata in the valley floor.

Hutchinson (1991) defined characteristic features of cambers and valley bulges as follows:

- Marked thinning of the clay substratum as a result of the transfer of clay into the valley bulge;
- Intense folding and distortion in the valley bulge itself as a result of the meeting of the clay masses moving in from beneath each valley side;
- Sympathetic flexuring of the superincumbent capping rocks, producing a valleyward camber, a valley marginal syncline, and an upturn against the flanks of the bulge; and

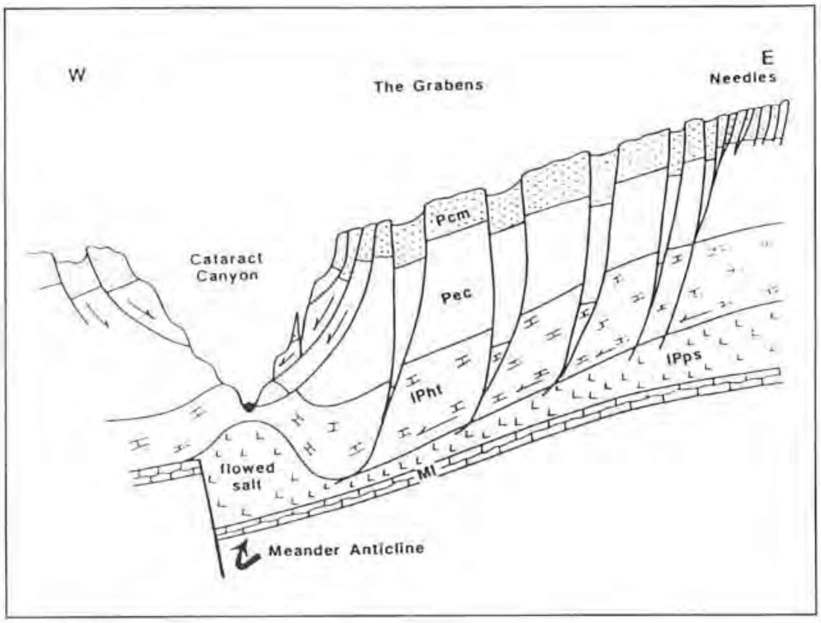


FIGURE 3-30
Geological cross section showing formation of The Grabens in Needles District of Canyonlands National Park, Utah. Colorado River has carved Cataract Canyon to within a few meters of top of Paradox Salt beds (*IPps*), undercutting inclined layers of overlying Honaker Trail (*IPht*), Elephant Canyon (*Pec*), and Cedar Mesa (*Pcm*) formations. These formations have broken up and are moving toward canyon by flowage within salt. Colorado River follows crest of Meander anticline, a salt-intruded fold located above a deep-seated fault zone (Baars 1989).

FIGURE 3-31
Earth spread–earth flow near Greensboro, Florida. Material is flat-lying, partly indurated clayey sand of Hawthorn Formation. Length of slide is 275 m from scarp to edge of trees in foreground. Vertical distance is about 15 m from top to base of scarp and about 20 m from top of scarp to toe. Landslide occurred in April 1948 after a year of unusually heavy rainfall, including 40 cm in the 30 days preceding landslide [Varnes 1978, Figure 2.19 (modified from Jordan 1949)].

- Extension and valleyward toppling of the capping rocks in the camber, resulting in opening of near-vertical joints to form wide-open fissures, termed *gulls*, in valleyward dips of the camber blocks and in the development of dip-and-fault structures between camber blocks as a consequence of their toppling.

The rotation of the dip of the rock blocks produces the slightly arched or convex form popularly called a camber. Rotation is made possible by the extension of "the cap-rock towards the valley producing widened joints (called gulls) often infilled by till" (Hutchinson 1988, 19). The cap rock has spread. The underlying clay exhibits

> a brecciated structure, probably frost-induced, in its upper parts, marked thinning as the valley is approached and intense generally-monoclinal folding in . . . the present valley bottom. . . . The dramatic internal structures appear to be the result principally of valleyward squeezing and extrusion made possible by the weakening of the clay stratum by multiple freezing and thawing. . . . These cambers and valley bulges are believed to be relict periglacial features. (Hutchinson 1988, 19)

Cambering and valley bulging affected slopes at Empingham, England, that were excavated during the construction of a dam (Horswill and Horton 1976). Figure 3-32(*a*) reproduces a portion of Figure 5 of Horswill and Horton (1976), which shows the details of the structures with a fourfold vertical exaggeration. Figure 3-32(*b*) is based on a diagram by Hutchinson (1991) that shows the same general section without vertical exaggeration and emphasizes that the displaced materials are found on slopes of less than 5 degrees. According to the proposed naming convention, a camber may be described as a *relict, complex rock spread–rock topple*.

Ward (1948) described as a landslide another complex spread in Britain in which stiff-fissured clays overlaid fine sands but qualified his description as follows:

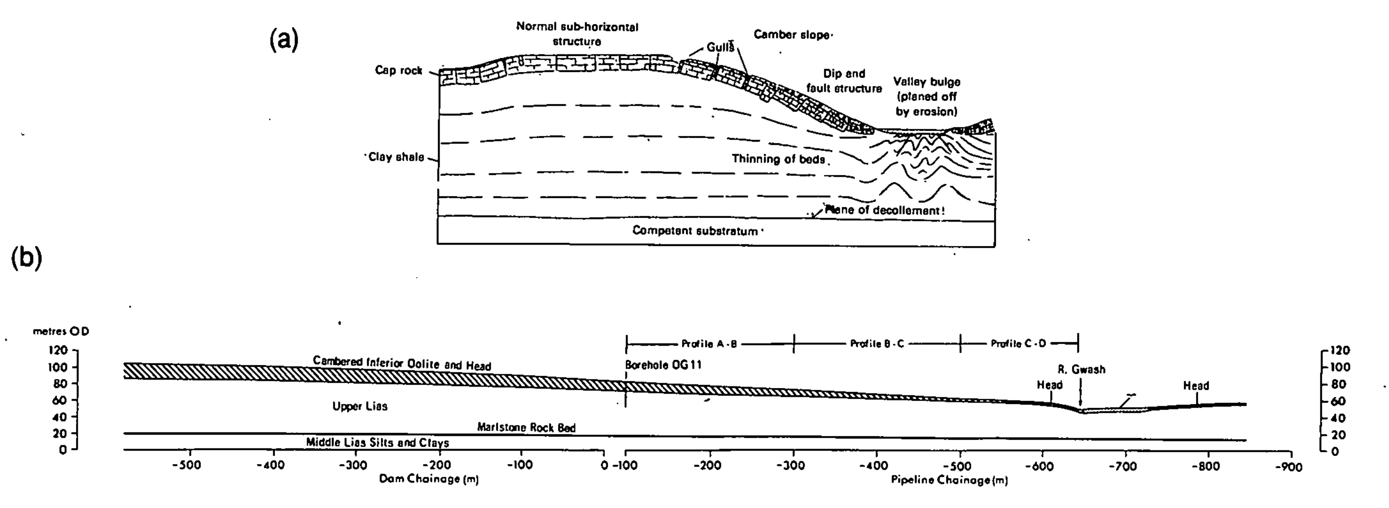
> So much movement of various types had occurred that it was difficult to trace the movement of the strata from the upper cliff until it arrived in the form of mud on the beach some 180 feet below. . . . The underlying fine sand is in a saturated, quick condition under the blocks when they become detached and they probably flounder forwards and tilt backwards. (Ward 1948, 36)

This description suggests that the clay was being spread by the flow of the sand and thus the movement was a type of *complex earth spread–debris flow*.

8.5 Flow

A **flow** is a spatially continuous movement in which surfaces of shear are short-lived, closely spaced, and usually not preserved. The distribution of velocities in the displacing mass resembles that in a viscous liquid. The lower boundary of the displaced mass may be a surface along which appre-

FIGURE 3-32 Cambering and valley bulging at Empingham, England: (*a*) detailed cross section with 4x vertical exaggeration (modified from Horswill and Horton 1976); and (*b*) generalized cross section drawn without vertical exaggeration (modified from Hutchinson 1991).



ciable differential movement has taken place or a thick zone of distributed shear (Figure 3-33). Thus there is a gradation from slides to flows depending on water content, mobility, and evolution of the movement. Debris slides may become extremely rapid debris flows or debris avalanches as the displaced material loses cohesion, gains water, or encounters steeper slopes (Figure 3-34).

Varnes (1978, 19–20) used the terms *earth flow* and *slow earth flow* [Figure 3-33(*a*)] to describe "the somewhat drier and slower earth flows in plastic earth . . . common . . . wherever there is . . . clay or weathered clay-bearing rocks, moderate slopes, and adequate moisture."

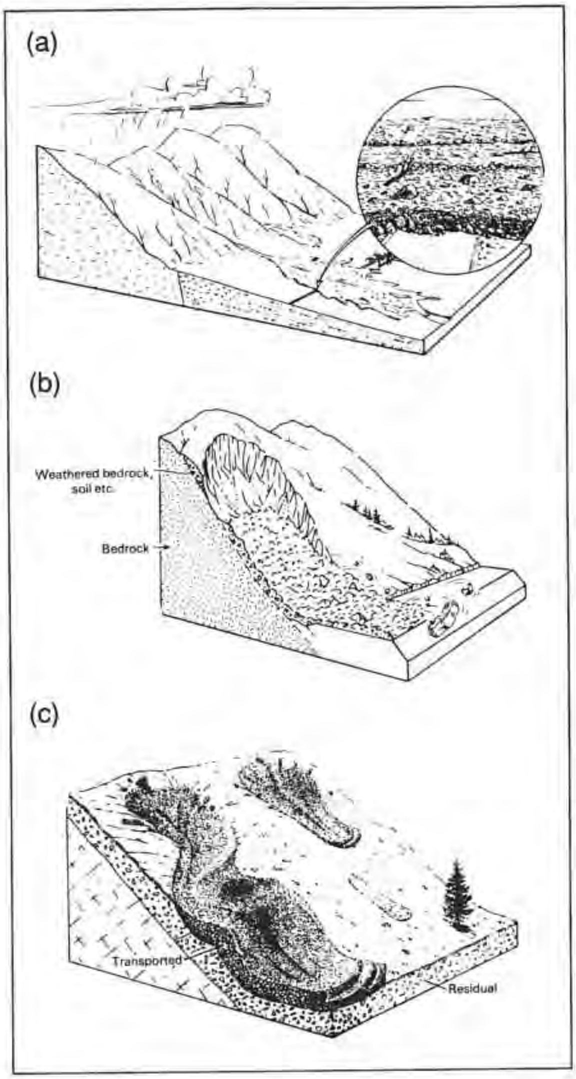


FIGURE 3-34 Channelized debris flows: (*a*) debris flow, (*b*) debris avalanche, and (*c*) block stream (Varnes 1978, Figures 2.1q1, 2.1q3, 2.1q5).

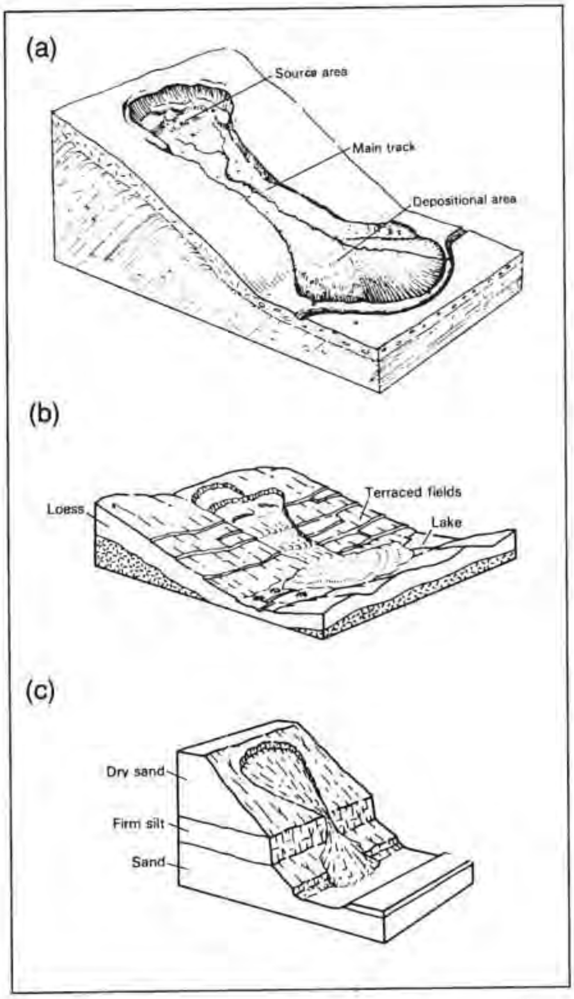


FIGURE 3-33 Examples of flows: (*a*) slow earth flow [Varnes 1978, Figure 2.1r3 (Zaruba and Mencl 1969)], (*b*) loess flow, and (*c*) dry sand flow (Varnes 1978, Figures 2.1r5 and 2.1r4).

Keefer and Johnson (1983) included detailed studies of the movement of earth flows in the San Francisco Bay area (Figure 3-35). They concluded (Keefer and Johnson 1983, 52): "Although some internal deformation occurs within earth flows, most movement takes place on or immediately adjacent to their boundaries." Their use of *earth flow* thus covers landslide modes from *slow earth flow* through *slow, composite earth slide–earth flow* to *slow earth slide*. When extensive, striated, or slickensided lateral margins or surfaces of rupture are visible, the landslide might well be called an *earth slide;* when the displaced mass is strongly deformed internally, the landslide is probably an *earth flow*. If the same landslide shows both modes of deformation, it is clearly a *composite earth slide–earth flow*.

While defining landslide processes in permafrost regions, McRoberts and Morgenstern (1974) used the term *skin flow* to describe a rapid to very rapid slope movement in which a thin layer, or skin, of thawed soil and vegetation flows or slides

FIGURE 3-35 Earth flow developing from initial rotational earth slide near Berkeley, California (Varnes 1978, Figure 2.22).

over the permafrost table, whereas Hutchinson (1988, 12) used the term *active-layer slide*. Seasonal thaw layers, or active layers, up to a meter or so in thickness may contain water originally drawn to the freezing front where it formed segregated ice. Melting of this ice may generate artesian pore-water pressures that greatly reduce the resistance of the active layer to movement. These landslide conditions are discussed in more detail in Chapter 25. Similar shallow failure may also occur in loess materials that become saturated or are subjected to earthquake shaking [Figure 3-33(*b*)].

Open-slope debris flows form their own path down a valley side onto the gentler slopes at the foot. Deposition of levees there may outline a more sinuous channel. The common, small dry flows of granular material may be channelized (Figure 3-36) or may extend as sheets for some distance across a slope [Figures 3-33(*b*) and 3-37].

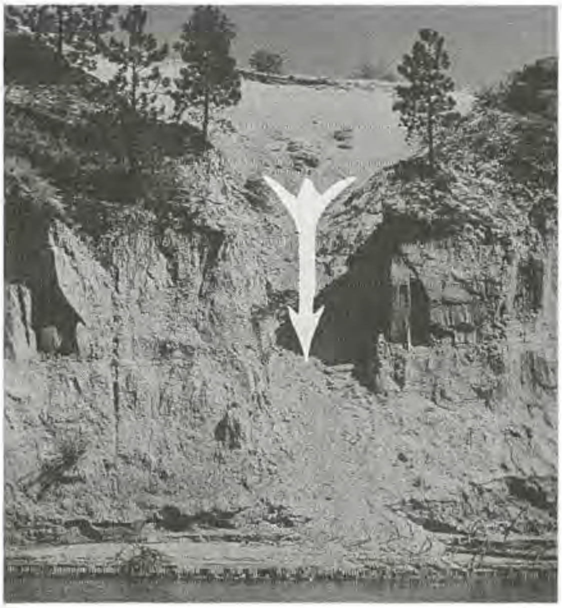


FIGURE 3-36 Dry sand flow in Columbia River valley; dry sand from upper terrace flowed through notch in cliffs of more compact sand and silt below (Varnes 1978, Figure 2.24).

Channelized flows follow existing channels (Figures 3-34 and 3-38). As shown in Figure 3-39, debris flows are often of high density, with over 80 percent solids by weight, and may exceed the density of wet concrete (Hutchinson 1988). They can therefore move boulders that are meters in diameter. The mode of flow shown in Figure 3-40 often occurs during torrential runoff following exceptional rainfalls. Soils on steep slopes unprotected by vegetation whose natural cover may have been destroyed by fire are prone to debris flows. Debris may be added to small surface streams by erosion or caving of their banks, increasing the power of the flows. Coarser material may form natural levees, leaving the fines in suspension to move down the channel. Flows can extend many kilometers before they drop their suspended loads upon entering lower-gradient channels. The movement may be in pulses, presumably caused by periodic mobilization of material or by the formation and bursting of dams of debris in the channel.

Pierson and Costa (1987) observed that the term *debris torrent* was misleading and gave two reasons:

> First, mountain torrent or debris torrent is used in European and Japanese literature to mean a very steep channel, not the material that flows in it. . . . Second, the term was coined to differentiate between coarse debris flows occurring in channels and flows occurring on open slopes . . . , a criterion that has no rheologic or other process-specific basis. We suggest that the usage of the term, debris torrent, be discontinued and the more general term, debris flow, be used instead with appropriate descriptive adjectives when specifics are required. (Pierson and Costa 1987, 10)

Debris avalanches are larger, extremely rapid, often open-slope flows [Figure 3-34(*b*)]. The Mt. Huascaran avalanche in Peru (Figure 3-41) involved 50 million m^3 to 100 million m^3 of rock, ice, snow, and soil that traveled at velocities of as much as 100 m/sec. In this case, steam and air cushions were suggested to account for the high velocity and long distance of the debris travel (Varnes 1978, 21). However, the contributions of snow and ice to the movement should also be considered.

FIGURE 3-37 Shallow dry sand flow along shore of Lake Roosevelt, Washington State; wave erosion or saturation of sediment by lake water caused thin skin of material to lose support and ravel off slope, formed on older terrace deposit [Varnes 1978, Figure 2.25 (modified from Jones et al. 1961)].

According to Varnes, *bedrock flows* include

> spatially continuous deformation and surficial as well as deep creep. . . . [They involve] extremely slow and generally nonaccelerating differential movements among relatively intact units. Movements may (1) be along many shear surfaces that are apparently not connected; (2) result in folding, bending, or bulging; or (3) roughly simulate those of viscous fluids in distribution of velocities. (Varnes 1978, Figure 2.1, V)

All the examples given by Varnes (1978) and reproduced as Figure 3-42 show movements that may have been initiated by sliding on the bedding or schistosity of the rock mass. These might all then be classified as complex slides. Further study may define the complex modes of movement to which these examples belong, in which sliding is followed by buckling (Hu and Cruden 1993). Clearly, further examples of bedrock flow should be explored in more detail before they can be more than tentatively classified.

A *lahar* is a debris flow from a volcano. The flow mobilizes the loose accumulations of tephra (airborne solids erupted from the volcano) on the volcano's slopes. Water for the flow may come from the ejection of crater lakes, condensations of erupted steam, the nucleation of water vapor on erupted particles and its precipitation, and the melting of snow and ice accumulated on a sufficiently high volcanic cone (Voight 1990).

9. LANDSLIDE PROCESSES

"The processes involved in slope movements comprise a continuous series of events from cause to effect" (Varnes 1978, 26). In some cases, it may be more economical to repair the effects of a landslide than to remove the cause; a highway on the crest of a slope may be relocated rather than armoring the toe of the slope to prevent further erosion. However, the design of appropriate, cost-effective remedial measures still requires a clear understanding of the processes that are causing the landslide. Although this understanding may require a

FIGURE 3-38 Old debris flow in altered volcanic rocks west of Pahsimeroi River in south central Idaho (Shaller 1991, Figure 8). COPYRIGHT JOHN S. SHELTON

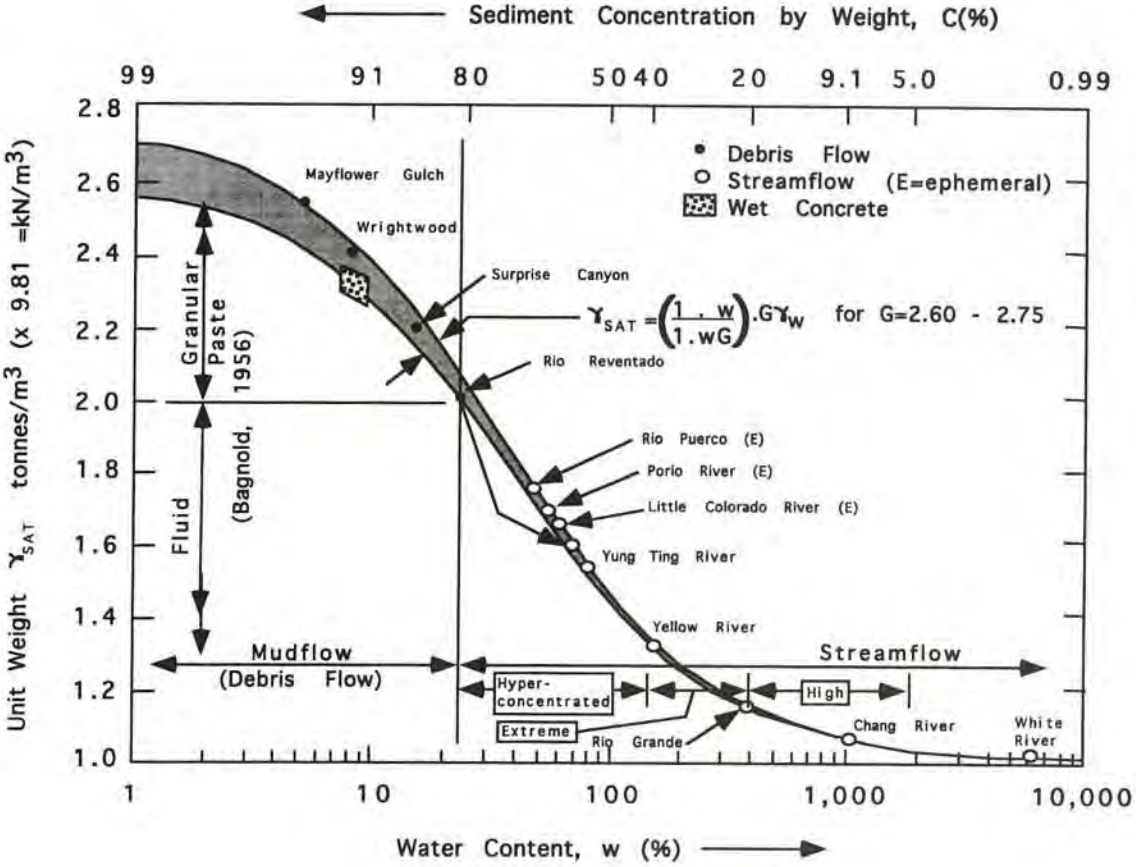


FIGURE 3-39 Continuous spectrum of sediment concentrations from sediment-laden rivers to debris flows (modified from Hutchinson 1988, Figure 15).

detailed site investigation, a reconnaissance of the landslide as soon as possible after its occurrence can allow important observations of the processes involved. These observations may guide both the site investigation and the remedial measures.

Although Varnes (1978) provided a list of the causes of slides, the aims in this section are less ambitious. The section follows Varnes's distinction that the three broad types of landslide processes are those that

1. Increase shear stresses (Section 9.1),
2. Contribute to low strength (Section 9.2), and
3. Reduce material strength (Section 9.3).

Common landslide triggering mechanisms are discussed at greater length in Chapter 4.

Processes and characteristics that contribute to landslides are summarized in a checklist of landslide causes arranged in four practical groups according to the tools and procedures necessary to begin the investigation (see p. 70). Ground causes

FIGURE 3-40 Very rapid debris flow, or debris avalanche, at Franconia Notch, New Hampshire, June 24, 1948, after several days of heavy rainfall. Colluvial soil up to 5 m thick moved down over bedrock along 450 m of a 45-degree slope. Levees appear at lateral margins. Flow covered US-3 (*foreground*) (Varnes 1978, Figure 2.17).

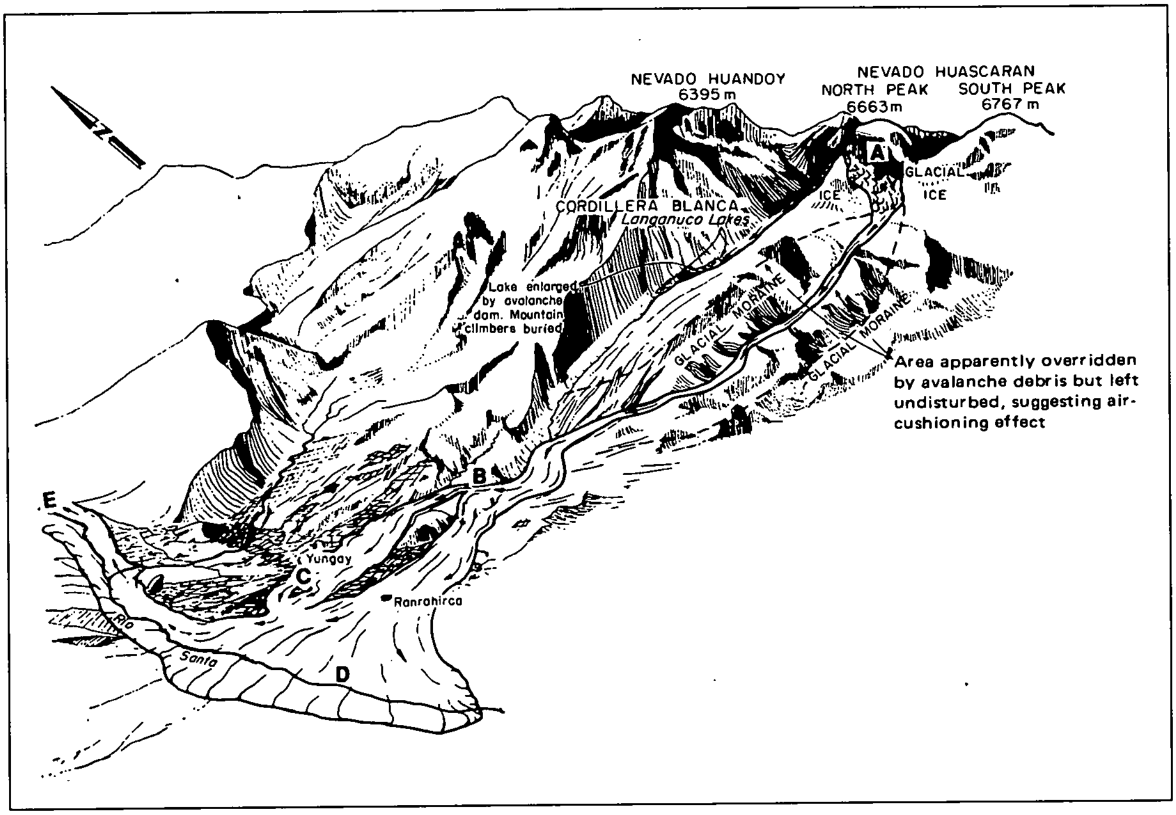


FIGURE 3-41
(top)
May 31, 1970, Huascaran debris avalanche (Peru) originated at *Point A*. Yungay had been protected from January 10, 1962, debris avalanche by ridge up to 240 m high (*Point B*), but portion of later avalanche overtopped protective ridge. Cemetery Hill (*Point C*) was only safe place in Yungay, some 93 people escaping to it before avalanche devastated surrounding area. Moving at an average speed of 320 km/hr, debris arrived at *Point D* on Rio Santa 14.5 km down 15-degree average slope within 3 to 4 min after starting from north peak of Huascaran (*Point A*). Debris flowed 2.5 km up Rio Santa (*Point E*) and continued 160 km downstream to Pacific Ocean, devastating villages and crops on its floodplain [Varnes 1978, Figure 2.27 (modified from Cluff 1971)].

can be identified with the customary tools of site reconnaissance and investigation. Changes in site morphology over time are apparent from the study of surveys, maps, and aerial photographs. Identification of causes of movement requires the collection of data over time from a variety of field instruments, including seismographs, rain gauges, flow gauges, and piezometers. Some changes in material and mass properties with time may, however, be inferred from gradual changes in the mass properties with distance. Anthropogenic causes can be documented by site records, plans, or other observations.

9.1 Increased Shear Stresses

Shear stresses can be increased by processes that lead to removal of lateral support, by the imposition of surcharges, by transitory stresses resulting from explosions or earthquakes, and by uplift or tilting of the land surface.

9.1.1 Removal of Support

The toe of a slope can be removed by erosion, steepening the slope. Typical agents are streams and

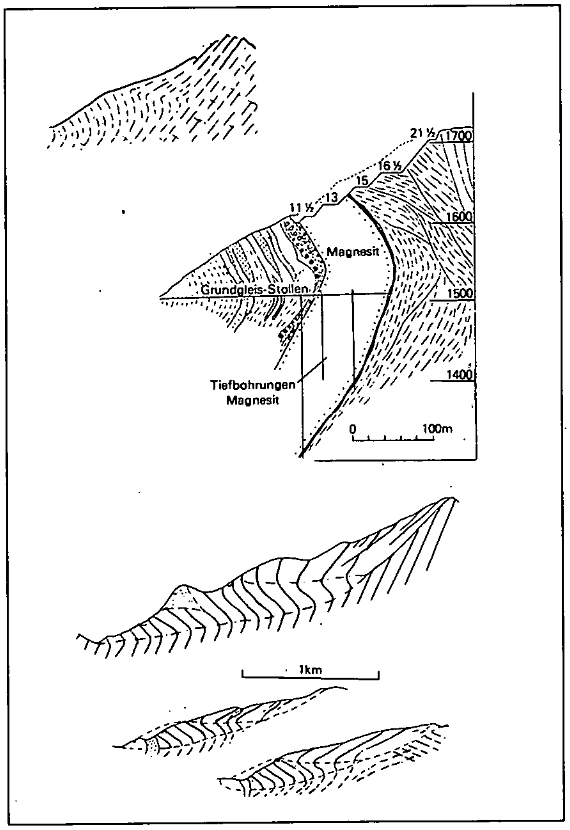


FIGURE 3-42
Examples of rock flows [Varnes 1978, Figure 2.1p1 (Nemčok et al. 1972; Zischinsky 1966)].

Checklist of Landslide Causes

1. Geological causes
   a. Weak materials
   b. Sensitive materials
   c. Weathered materials
   d. Sheared materials
   e. Jointed or fissured materials
   f. Adversely oriented mass discontinuity (bedding, schistosity, etc.)
   g. Adversely oriented structural discontinuity (fault, unconformity, contact, etc.)
   h. Contrast in permeability
   i. Contrast in stiffness (stiff, dense material over plastic materials)
2. Morphological causes
   a. Tectonic or volcanic uplift
   b. Glacial rebound
   c. Fluvial erosion of slope toe
   d. Wave erosion of slope toe
   e. Glacial erosion of slope toe
   f. Erosion of lateral margins
   g. Subterranean erosion (solution, piping)
   h. Deposition loading slope or its crest
   i. Vegetation removal (by forest fire, drought)
3. Physical causes
   a. Intense rainfall
   b. Rapid snow melt
   c. Prolonged exceptional precipitation
   d. Rapid drawdown (of floods and tides)
   e. Earthquake
   f. Volcanic eruption
   g. Thawing
   h. Freeze-and-thaw weathering
   i. Shrink-and-swell weathering
4. Human causes
   a. Excavation of slope or its toe
   b. Loading of slope or its crest
   c. Drawdown (of reservoirs)
   d. Deforestation
   e. Irrigation
   f. Mining
   g. Artificial vibration
   h. Water leakage from utilities

rivers, glaciers, waves and currents, and slope movements. Anthropogenic landslides can be caused by excavations for cuts, quarries, pits, and canals, and by the drawdown of lakes and reservoirs.

Removal of material from the lateral margins of the displaced mass can also cause movement. Material can be removed from below the landslide by solution in karst terrain, by piping (the transport of sediment in groundwater flows), or by mining. In some spreads, the loss of strength of the material at depth within the displacing mass results in its extrusion or, if the base of the spread has liquefied, in its outward flow. These issues as they relate to landslides in sensitive clay deposits are discussed in Chapter 24.

9.1.2 Imposition of Surcharges

The addition of material can result in increases of both the length and the height of the slope. Water can be added by precipitation, both rain and snow; by the flow of surface and groundwater into the displacing mass; and even by the growth of glaciers. Surcharges can be added by the movement of landslides onto the slope, by volcanic activity, and by the growth of vegetation. Anthropogenic surcharges include construction of fills, stockpiles, and waste dumps; structural weight; and water from leaking canals, irrigation systems, reservoirs, sewers, and septic tanks.

9.1.3 Transitory Stresses

The local stress field within a slope can be greatly changed by transitory stresses from earthquakes and explosions (both anthropogenic and volcanic). Smaller transitory changes in the stress field can result from storms and from human activity such as pile driving and the passage of heavy vehicles.

9.1.4 Uplift or Tilting

Uplift or tilting may be caused by tectonic forces or by volcanic processes. In either case, this type of increased shear stress may be associated with earthquakes, which themselves can trigger landslides (Section 9.1.3). The melting of the extensive Pleistocene ice sheets has caused widespread uplift in temperate and circumpolar regions.

Uplift of an area of the earth's surface generally causes steepening of slopes in the area as drainage responds by increased incision. The cutting of valleys in the uplifted area may cause valley rebound and accompanying fracturing and loosening of valley walls with inward shear along flat-lying discontinuities. The fractures and shears may allow the buildup of pore-water pressures in the loosened mass and eventually lead to landsliding.

9.2 Low Strength

Low strength of the earth or rock materials that make up a landslide may reflect inherent material characteristics or may result from the presence of discontinuities within the soil or rock mass.

9.2.1 Material Characteristics

Materials may be naturally weak or may become weak as a result of common natural processes such as saturation with water. Organic materials and clays have low natural strengths. Rocks that have decomposed to clays by chemical weathering (weathered volcanic tuffs, schists, and serpentinites, for example) develop similar properties.

Besides the nature of the individual particles of which the material is composed, the arrangement of these particles (the fabric of the material) may cause low material strengths. Sensitive materials, which lose strength when disturbed, generally have loose fabrics or textures.

9.2.2 Mass Characteristics

The soil or rock mass may be weakened by discontinuities such as faults, bedding surfaces, foliations, cleavages, joints, fissures, shears, and sheared zones (Chapters 12 and 14). Contrasts in bedded sedimentary sequences—such as stiff, thick beds overlying weak, plastic, thin beds or permeable sands (or sandstones) alternating with weak, impermeable clays (or shales)—are sources of weakness.

9.3 Reduced Shear Strength

Clays are particularly prone to weathering processes and other physicochemical reactions. Hydration of clay minerals results in loss of cohesion, a process often associated with softening of fissured clays. Fissuring of clays may be due to drying or to release of vertical and lateral restraints by erosion or excavation. The exchange of ions within clay minerals with those in the pore water of the clays may lead to substantial changes in the physical properties of some clays. Electrical potentials set up by these chemical reactions or by other processes may attract water to the weathering front.

The effects of extremes of temperature caused by severe weather are not confined to clays. Rocks may disintegrate under cycles of freezing and thawing or thermal expansion and contraction. Dry weather may cause desiccation cracking of weak or weathered rock along preexisting discontinuities, such as bedding planes. Wet weather may dissolve natural rock cements that hold particles together. Saturation with water reduces effective intergranular pressure and friction and destroys capillary tension.

10. SUMMARY

In the initial reconnaissance of a landslide, the activity and the materials displaced in that type of landslide would be described using terms from Table 3-2, the dimensions defined in Table 3-4 would be estimated, and some preliminary hypotheses would be chosen about the causes of the movements. A simple landslide report form is provided in Figure 3-9; its format would allow the creation of simple data bases suited to much of the data-base management software now available for personal computers. The information collected could be compared with summaries of other landslides (WP/WLI 1991) and used to guide additional investigations and mitigative measures. Further investigation would increase the precision of estimates of the dimensions and increase confidence in the descriptions of activity and material and in the hypotheses about the causes of movement. The new information would then be added to the data base to influence the analysis of new landslides. These data bases could form the foundations of expert systems for landslide mitigation.

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ABBREVIATIONS

IAEG	International Association of Engineering Geology
UNESCO	United Nations Educational, Scientific, and Cultural Organization
WP/WLI	Working Party on the World Landslide Inventory (International Geotechnical Societies and UNESCO)

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