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PART I

INTRODUCTION AND STATE OF THE ART

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1 Introduction

1.1 Landslide overview

Landslides are one of the most widespread and effective agents in sculpting the earth's surface (Eckel, 1958, p.1). They are ubiquitous in mountainous and hilly environments in all parts of the world and are an important mechanism for moving earth materials from uplands to river systems. The general term "landslide" is used to describe a wide range of gravity-driven mass movements both on the land surface and beneath bodies of water. Landslides include diverse slope movements such as rock fall and debris flows, which are described in more detail in Section 1.2.

Landslides are the failure of sloping earth materials. A hillslope fails when forces or stresses acting upon it overcome the strength of the earth materials. Some of the forces acting on a hillslope include gravity, pore-water pressure, tectonic uplift, and earthquake shaking. These forces act over time scales ranging from geologic to essentially instantaneous and over spatial scales that range from continental to the soil grain. The strength of hillslope materials is a function of geologic composition and stress state, and is modified by past movement, weathering, vegetation, and hydrologic processes. These concepts are discussed in detail in Chapters 3, 4, 5, 6, 7, and 8.

Processes leading to landslide occurrence are separated into "causes" and "triggers." Landslides can be caused by morphologic, geologic, and other factors that set the stage for a landslide to occur. Landslide triggers are the events that initiate landslide motion. The difference between a cause and a trigger is the time scale over which the processes take place. This range of time scales is obviously a continuum and often it is impossible to determine the precise trigger for a given slide. In other cases the trigger is easily identified, such as heavy rainfall, earthquake shaking, or volcanic eruption.

Landslides are also among the most costly natural hazards in terms of human life and economic loss. Because landslides occur over much of the land surface, and are generated by a range of processes, they frequently intersect human activities and the built environment, often with disastrous consequences. Statistics on losses associated with landslides are difficult to compile, in part because landslides often result from large earthquakes or coincide with large-scale flooding or tropical cyclones, which tend to capture the attention of the media and official inquiries. However, as human activities continue to expand into landslide-prone environments, the recognition of the scope and the magnitude of the hazard has increased.

To understand how landslides occur, it is useful to examine the geometry of a "typical" landslide body. Figure 1.1 is an idealized sketch showing the various parts of a rotational

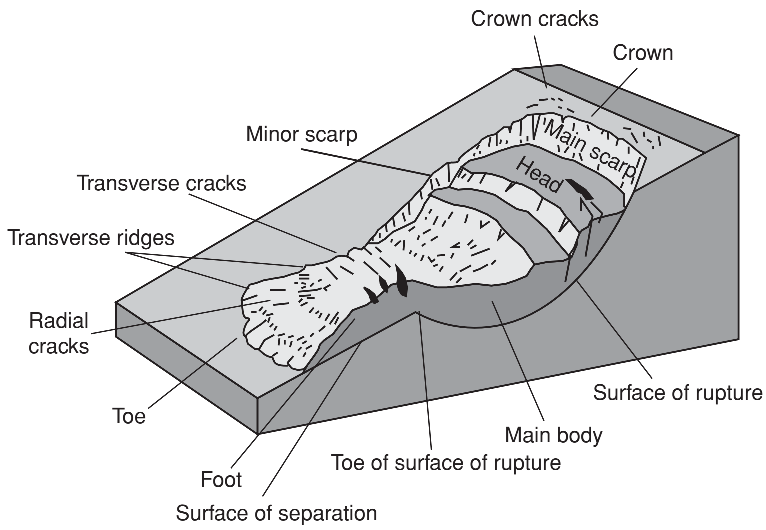

Figure 1.1 Diagram showing the location of the various parts of a landslide (after Varnes, 1978).

landslide, which are described in Table 1.1 (Varnes, 1978). A characteristic that distinguishes landslides from other mass movement processes such as saltation or grain-by-grain transport is the presence of a rupture surface. The rupture surface is the boundary between the relative motions of the landslide body and undisturbed ground around and beneath the slide. At the scale of the overall landslide, the shape of the rupture surface may range from planar to roughly circular. The upslope extent of the landslide is bounded by the main scarp, which is often a vertical or sub-vertical exposure of the hillside materials. The downslope extent of the landslide is referred to as the toe, and the lateral margins of the landslide are called flanks. Morphologic features, such as internal scarps, cracks, and ridges, are an expression of deformation in the landslide body and underlying topography (e.g., Baum *et al*., 1998; Coe *et al*., 2009).

While in general the geometry of a landslide body is complicated, it can be approximated as part of an ellipsoid such that the volume of a landslide shown in Figure 1.1 can be estimated by the following equation:

$$V = \frac{\pi}{6}\,(\text{length})\,(\text{width})\,(\text{depth}) \tag{1.1}$$

1.2 Landslide classification

The two most prominent English-language landslide classifications are by Hutchinson (Hutchinson, 1968, 1988; Skempton and Hutchinson, 1969; Hungr *et al*., 2001) and Varnes (Varnes, 1958, 1978; Cruden and Varnes, 1996). The two systems are generally similar but treat flows of earth materials somewhat differently. Hutchinson's classification emphasizes the results of movement whereas Varnes' tends to emphasize the conditions of slope

Table 1.1 Description of landslide parts (after Varnes, 1978)

Main scarp	A steep surface on the undisturbed ground around the periphery of the slide, caused by the movement of slide material away from undisturbed ground
Minor scarp	A steep surface on the displaced material produced by differential movements within the displaced mass
Head	The upper parts of the slide material along the contact between the displaced material and the main scarp
Toe	The margin of displaced material most distant from the main scarp
Main body	Part of the displaced material of the landslide that overlies the surface of rupture between the main scarp and toe of surface of rupture
Original ground surface	The surface of the hillslope that existed before the landslide occurred
Surface of rupture	Surface that forms the lower boundary of displaced material
Toe of surface of rupture	Intersection (usually buried) between the lower part of surface of rupture and original ground surface
Foot	The part of the displaced material that lies upslope from the toe of the surface of rupture
Crown	Practically undisplaced material adjacent to highest parts of main scarp
Flank	Undisplaced material adjacent to sides of surface of rupture, left and right refer to flanks as viewed from crown

Table 1.2 Abbreviated classification of slope movements (after Varnes, 1978)

			Type of material		
				Engineering soils	
Type of movement			Bedrock	Mostly coarse grained	Mostly fine grained
Falls			Rock fall	Debris fall	Earth fall
Topples			Rock topple	Debris topple	Earth slump
Slides	Rotational	Few units	Rock slump	Debris slump	Earth slump
	Translational	Many units	Rock slide	Debris slide	Earth slide
Lateral spreads			Rock spread	Debris spread	Earth spread
Flows			Rock flow	Debris flow	Earth flow
Complex combination of two or more types of movement					

failure (Crozier 1986; Hungr *et al*., 2001). The purpose of this book is the analysis of the mechanics and hydrology of slope failure, so the Varnes system is used. The Varnes (1958, 1978) scheme classifies landslides based on the type of movement and the material involved (Table 1.2).

The type of movement is separated into falls, topples, slides (rotational and translational), spreads, and flows. Another category of “complex” movements is used to describe a

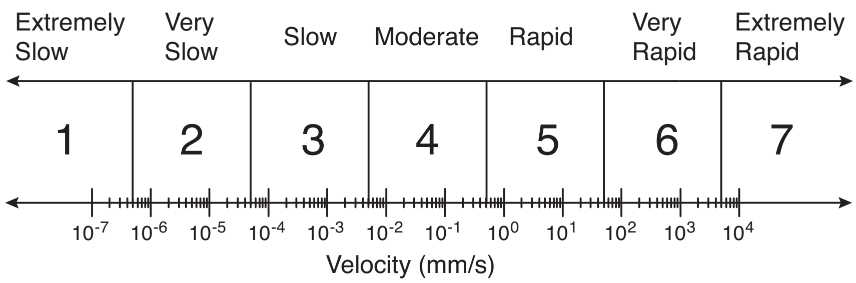

Figure 1.2 Landslide velocity scale (after Cruden and Varnes, 1996).

combination of any of these types of movements. Materials are separated into two classes, soil (in the engineering usage) and rock. Soil is differentiated from rock in that it is unconsolidated earth materials typically at the ground surface. Soil is subdivided into debris, which is predominantly coarse-grained in composition, and earth, which is predominantly fine-grained. The demarcation between debris and earth is arbitrary; debris is material in which 20–80% of the particles are greater than 2 mm in size, earth is material in which 80% of the particles are less than 2 mm (Shroder, 1971).

1.2.1 Landslide velocity

Landslides move at speeds ranging from a few millimeters per year to tens of kilometers per hour. The movement of the slowest slides is imperceptible to visual observation while the fastest may travel down mountain slopes in minutes or seconds. The state of landslide activity is classified as active, inactive, or fossil (Varnes, 1978). Active landslides are those that are currently moving or movement has been suspended, but they have moved within the last cycle of seasons. Deformation features such as scarps are typically distinct and easily identified. Inactive landslides are those for which no evidence of movement is detectable within the last cycle of seasons. Deformation features may be subdued by weathering and vegetation growth. Dormant slides are those in which movement has ceased, but changes in conditions may lead to renewed deformation. Reactivation of movement of dormant landslides is generally possible within the current climate. In contrast, fossil or relict landslides are slides in which movement has ceased and reactivation is not generally possible under the current precipitation climate unless human activities, such as reservoir construction, alter topographic or hydrologic conditions.

The destructiveness or hazard associated with landslides is proportional to their velocity. Cruden and Varnes (1996) provide a velocity ranking of landslides inspired by the Mercalli scale for earthquake damage (Figure 1.2). Extremely slow landslides that move less than a few tens of millimeters per year are likely to be undetected without instrumental observations. Properly engineered structures can be built on many such slides if the movement is recognized. Very slow landslides may move a few meters per year, and slow landslides move as much as 13 meters in a month (5×10^{-3} mm/s). Temporary and remedial structures can be maintained and built on such slides if episodic movements are limited. Landslides with moderate velocity, typically a few meters in an hour, are generally not a threat to human safety, but damage to buildings and other structures is common. Rapid landslides may move a few meters in minutes and potentially threaten human safety. Escape is generally possible; however, movement at this rate typically destroys buildings and property. Very rapid landslides move a few meters in a second. Lives are often lost if people are in the path of these landslides. Extremely rapid landslides move more than 5 meters per second. Escape from such landslides is unlikely and structures and buildings in their path are typically destroyed.

Figure 1.3 shows idealized sketches of various landslide types. The names describe either or both the style of movement and the materials involved. Styles of movement include *falls*, *topples*, *slides*, *spread*, and *flows* (Cruden and Varnes, 1996). *Falls* are a mass of rock or soil that is detached from a steep slope or cliff with little or no shear displacement along the failure surface. Under gravity, the mass then descends very rapidly to extremely rapidly by falling, bouncing, or rolling. *Topples* are the extremely slow to extremely rapid rotation of a mass of soil or rock out of the slope face. *Slides* are the downslope movement of soil or rock, in which the extremely slow to extremely rapid motion occurs primarily along a discrete surface of rupture. Sliding can occur in a variety of modes defined primarily by the shape of the rupture surface and the relative motion between the landslide body and the surrounding ground. Two distinct modes are translational and rotational slides. *Spread* is defined as the extension of a soil or rock mass combined with general subsidence of underlying material. The surface of rupture is not a zone of shear in such style of movement and movement rates are typically extremely slow to moderate. *Flows* are defined as spatially continuous movement in which shear surfaces are transient and short-lived and the moving mass takes the appearance of a viscous liquid. Flows can be extremely slow to extremely rapid and are often a secondary style of movement of a mass of soil or rock that initially fails as a fall or slide.

Because many flows move at great speed, they are potentially very destructive. This destructive potential has spurred the study of mass flows and driven the development of methods for hazard assessment and mitigation, as well as a rich vocabulary. Hungr *et al*. (2001) updated Hutchinson's (1968, 1988) classification of "debris movements of flow-like form" to further categorize the broad range of flows and conserve long-used terms. Post-failure movement is emphasized and classification of "landslides of the flow type" is based on the origin, character, and moisture condition of materials.

A widely used term from this classification is "flow slide." Flow slides are very rapid to extremely rapid flows of loose sorted or unsorted granular material involving excess pore pressures or liquefaction of material originating from the landslide source (Hutchinson, 1988; Hungr *et al*., 2001). The term "flow slide" was introduced by Casagrande (1936) and redefined by Hutchinson (1988). A flow slide is characterized by the collapse of the internal soil structure during sliding or as a result of earthquake shaking that reduces pore space and elevates pore pressures in moist materials. These landslides can be particularly hazardous in that they tend to travel at high speeds over long distances. This process is effective at generating debris flows (Iverson *et al*., 1997).

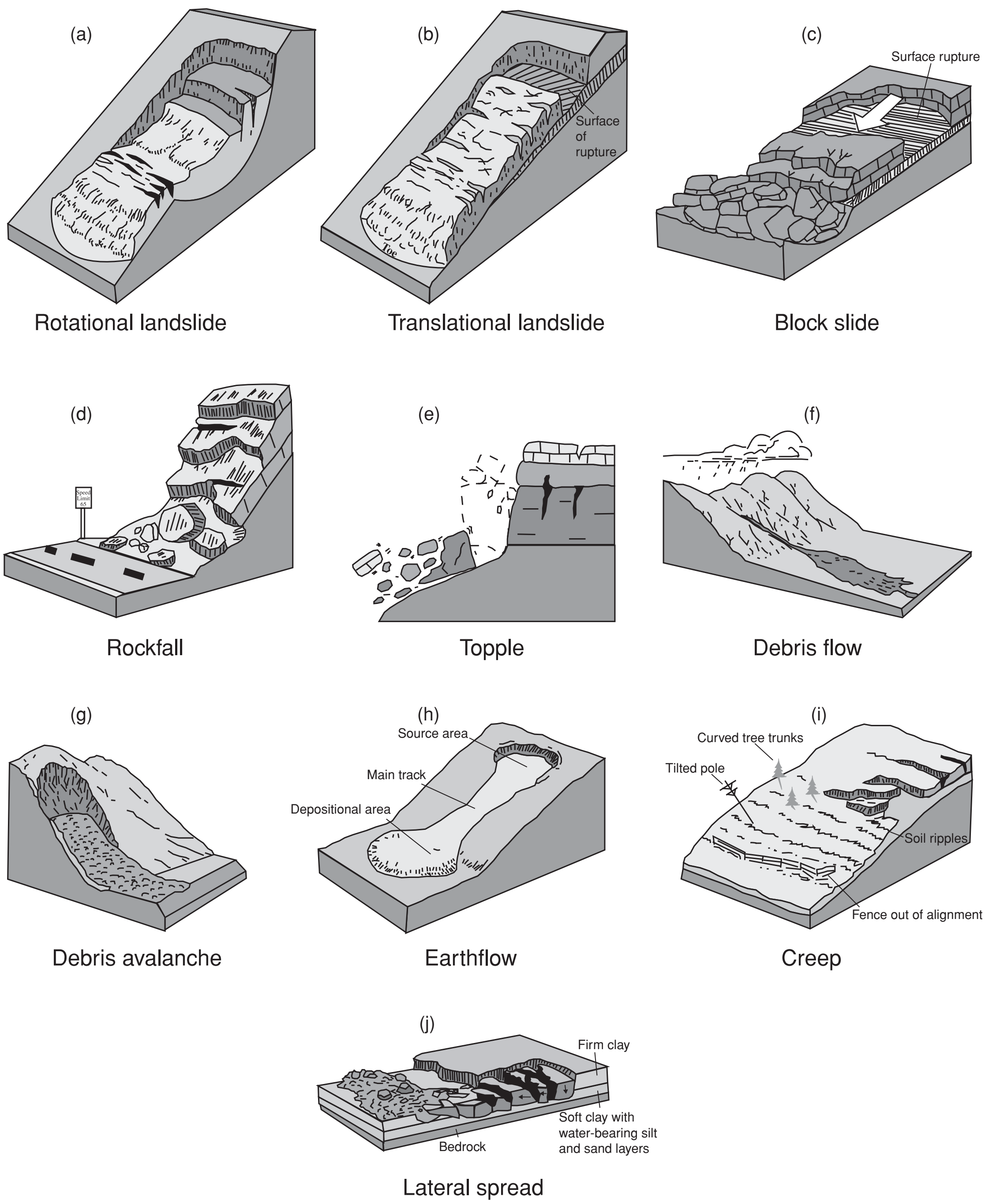

Figure 1.3 Idealized diagrams showing styles of landslide movement (after Varnes, 1978).

1.2.2 Illustration of landslide classification

The classification based on the type of movement and landslide materials is further illustrated below.

Rotational landslides (Figure 1.3a) move along an upwardly concave curved surface of rupture. In soil, the ratio of the depth (D_r) to length (L_r) of the surface of rupture D_r/L_r is typically between 0.15 and 0.33 (Skempton and Hutchinson, 1969).

Translational landslides (Figure 1.3b) move out and down a planar or undulating surface of rupture, often with a channel-shaped cross section that is parallel to the undisturbed ground. Rupture surfaces often coincide with discontinuities in earth materials such as bedding surfaces or the contact between rock and overlying soil. Translational slides are generally shallower than rotational landslides with D_r/L_r ratios of less than 0.1 (Skempton and Hutchinson, 1969). Translational landslides often mobilize as debris flows if slide velocity and pore-water pressures are sufficient (Iverson *et al*., 1997).

Block slides (Figure 1.3c) or planar slides (Hoek and Bray, 1981) are translational landslides that move on a single discontinuity in rock masses. With sufficient displacement, block slides may break up into debris or transform into rock avalanches (Hutchinson, 1988).

Rockfall (Figure 1.3d) is the detachment of particles from a rock mass typically along a steep or vertical surface. The particles then descend by falling, bounding, or rolling.

Topple (Figure 1.3e) is the forward rotation of a rock or soil mass out of the slopes that may result in falls or slides.

Debris flows (Figure 1.3f) are poorly sorted slurries of rock, soil, and mud that are saturated with water. Debris flows are distinguished from other slope movement processes such as rock avalanches in that both fluid forces and particle interactions affect motion (Iverson, 1997).

Debris avalanches (Figure 1.3g) or rock avalanches are distinguished from debris flows in that the debris or rock is not saturated with water.

Earthflows (Figure 1.3h) are slope movements in which the moving mass resembles a viscous liquid. The mass may be bounded by discrete shear surfaces (Hutchinson and Bhandari, 1971; Keefer and Johnson, 1983). These landslides are also known as mudslides (e.g., Hutchinson, 1988).

Creep (Figure 1.3i) is any extremely slow movement that tends to be diffuse rather than movement along a distinct surface of rupture.

Lateral spreads (Figure 1.3j) are the extension of cohesive soil or rock mass combined with subsidence of the moving mass into underlying material. Spreads may result from liquefaction of underlying material.

1.3 Landslide occurrence

1.3.1 Landslide triggering mechanisms

A wide range of geologic and meteorologic processes may trigger landslides including volcanic eruptions, earthquakes, and heavy precipitation (Wieczorek, 1996). Human activities,

Figure 1.4 Debris flow on the flank of Mt. St. Helens triggered by an eruption in March 1982 (photo by Tom Casadevall, USGS). See also color plate section.

such as slope excavation, reservoir operation, and irrigation, may also initiate landslides. In this section some of the more common natural landslide triggers are described.

Landslides initiated by volcanic eruptions are among the largest and most destructive. The 18 May 1980 eruption of Mt. St. Helens in Washington State was coincident with the occurrence of a 2.8 km^3 rock slide–debris avalanche from the north flank of the edifice that travelled 22 km down the North Fork of the Toutle River (Voight *et al.*, 1983). This landslide and other debris flows initiated by the eruption destroyed homes and transportation infrastructure in the area (Schuster, 1981). Debris flows from volcanoes are often described using the Indonesian term "lahar." Lahars can be initiated by volcanic eruption or other mechanisms. Figure 1.4 shows a lahar that swept down the flank of Mt. St. Helens in March of 1982 following one of the 17 eruptive episodes in the 6-year period following the 1980 event.

Strong ground shaking from earthquakes has triggered all types of landslides in a variety of physiographic settings. Large earthquakes in mountainous areas can generate landslides over very large regions and are often responsible for a significant part of the societal consequences (Keefer, 1984). Examples from Kashmir in 2005 and Sichuan, China, in 2008 highlight their effects in terms of human loss and damage to the built environment. Figure 1.5 shows rockslides triggered by the M7.9 Wenchuan, China, earthquake and the resulting damage to the town of Beichuan. Perhaps as many as 20% of the nearly 100,000 lives lost in the earthquake were the result of landslides (Yin *et al.*, 2009).

Heavy precipitation, either rainfall or melting snow, is the most common landslide trigger. Landslides triggered by heavy precipitation occur in all parts of the world in a wide variety of climatic, geologic, and topographic settings. Large storm systems or sequences of storms