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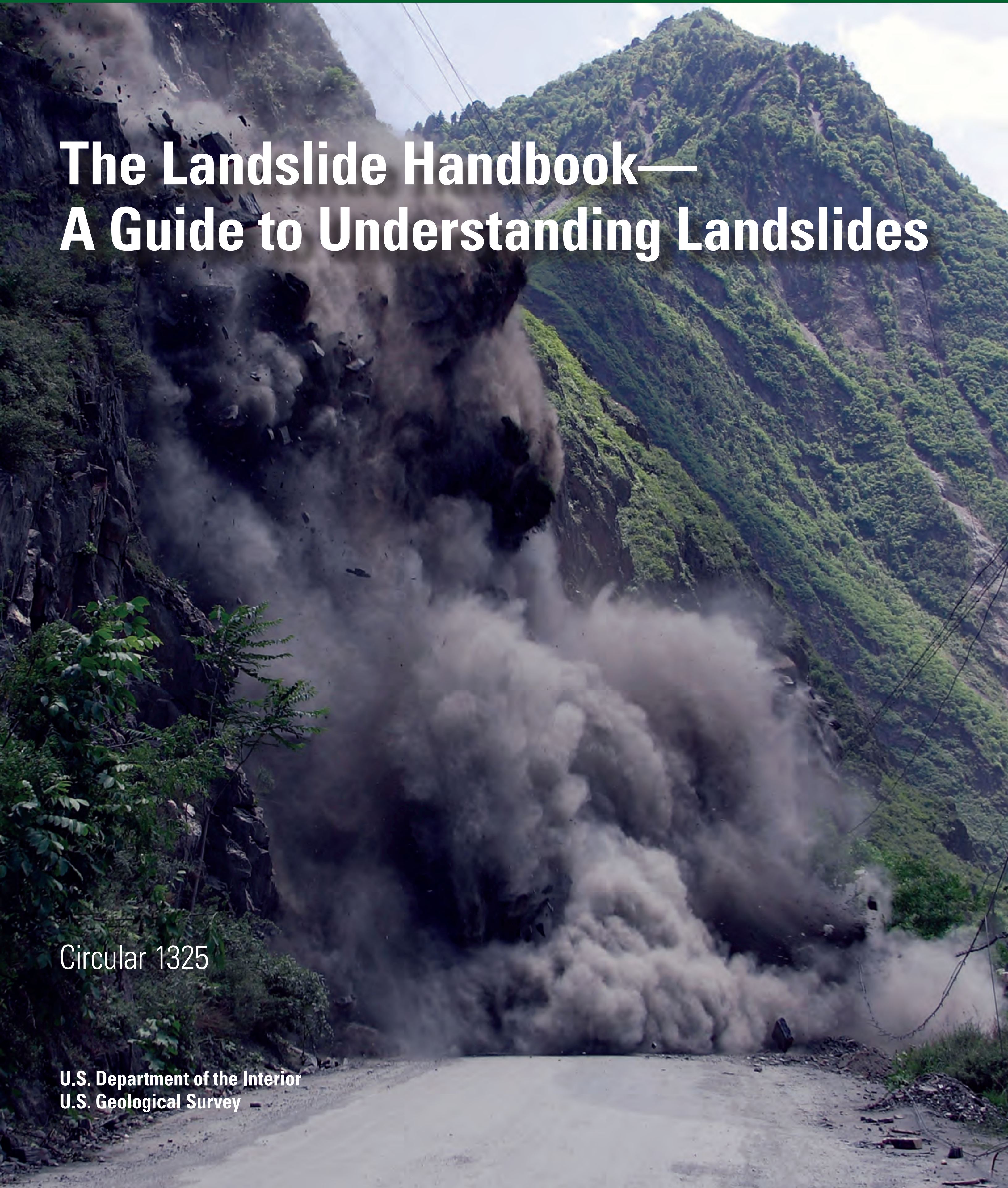

The Landslide Handbook— A Guide to Understanding Landslides

Circular 1325

U.S. Department of the Interior
U.S. Geological Survey

Cover: The threat of landslides like this have made the long drive to Wenchuan a risky affair for rescuers and aid delivery teams as they tried to reach the epicenter of the Wenchuan, China, earthquake of May 12, 2008. This photograph shows a landslide that sealed the entrance and exit to Wenchuan on May 23, 2008. (Photograph by Chua Chin Hon, Straits Times, Singapore.)

The Landslide Handbook—
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By Lynn M. Highland, United States Geological Survey, and
Peter Bobrowsky, Geological Survey of Canada

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Earthquake-induced landslides,
Sichuan Province, China, May 12, 2008.
Photograph courtesy of Dr. Yin Yueping,
China Geological Survey,
Ministry of Land and Resources, China.

Contents

Figures

How to read this guide

This guide consists of three primary sections with a series of extensive appendixes and an index. This style provides the most flexibility for users with considerable differences of interest and level of detail. Much of the detailed and expanded explanatory information can be found in the appendixes, including a ***Glossary of Landslide Terms***. References are provided for more information.

Please note

- For ease of reading, references are numbered at the end of sections and are not embedded within the text. The user may also contact either the United States Geological Survey or the Geological Survey of Canada for further guidance and assistance.
- Web sites are used as references for this book; however, Web site addresses (URLs) can change over time, and the Internet links given in this publication may become inactive or erroneous. It is suggested that users consult a Web-based keyword search engine if links are no longer accessible.

The Donghekou landslide, caused by the May 2008 Wenchuan Earthquake in Sichuan County, China. This extremely large landslide buried hundreds of people and caused a landslide dam to form in the Dong He River. Photograph by Lynn Highland, U.S. Geological Survey.

The Landslide Handbook—A Guide to Understanding Landslides

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Peter Bobrowsky, Geological Survey of Canada

Introduction

This handbook is intended to be a resource for people affected by landslides to acquire further knowledge, especially about the conditions that are unique to their neighborhoods and communities. Considerable literature and research are available concerning landslides, but unfortunately little of it is synthesized and integrated to address the geographically unique geologic and climatic conditions around the globe. Landslides occur throughout the world, under all climatic conditions and terrains, cost billions in monetary losses, and are responsible for thousands of deaths and injuries each year. Often, they cause long-term economic disruption, population displacement, and negative effects on the natural environment.

Outdated land-use policies may not always reflect the best planning for use of land that is vulnerable to landslides. The reasons for poor or nonexistent land-use policies that minimize the perceived or actual danger and damage potential from geologic hazards are many and encompass the political, cultural, and financial complexities and intricacies of communities. Landslides often are characterized as local problems, but their effects and costs frequently cross local jurisdictions and may become State or Provincial or national problems.

Growing populations may be limited in their geographic expansion, except to occupy unstable, steep, or remote areas. Often, stabilizing landslide-scarred areas is too costly, and some inhabitants have no other places to relocate. Fortunately, simple, “low-tech” precautions and actions can be adopted to at least ensure an individual’s immediate safety, and this handbook gives a brief overview of many of these options. We strongly suggest that, where possible, the assistance of professional engineers/geologists or those experienced in the successful mitigation of unstable slopes be consulted before actions are taken. This handbook helps homeowners, community and emergency managers, and decisionmakers to take the positive step of encouraging awareness of available options and recourse in regard to landslide hazard.

We provide a list of references, available in print or on the World Wide Web (Internet), that can be used for further knowledge about landslides. We recommend this handbook to managers and decisionmakers in communities in the hope that the information will be disseminated by such officials to other members of those communities. In response to the differing levels of literacy around the globe, we have emphasized visual information through the use of photographs and graphics. We plan to translate the handbook into additional languages as funding permits to further facilitate its use.

We welcome comments and critiques and have provided our contact information and the names and addresses of our respective agencies.

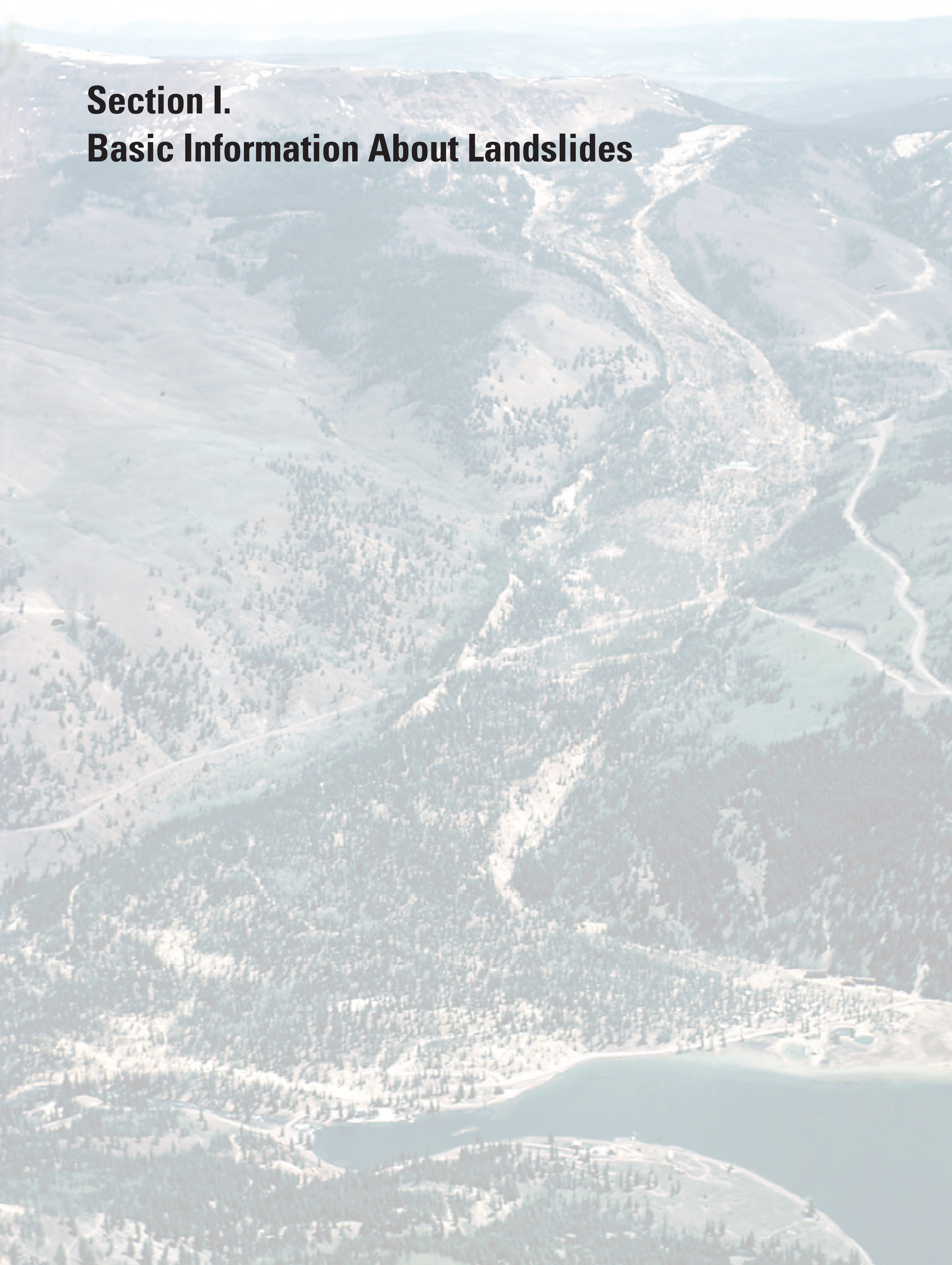
For more information

For questions on the content of this book or other inquiries regarding landslide issues, please be aware that the U.S. Geological Survey (USGS) National Landslide Information Center (NLIC), in Golden, Colorado, USA, is available as a resource to answer questions, help with interpretations, or otherwise support users of this book in providing additional information. Please contact the center by telephone, email, or written inquiry.

United States Geological Survey
Landslide Program and National Landslide Information Center
Mail Stop 966, Box 25046, Denver Federal Center
Denver, Colorado, 80225 USA
Web address: *http://landslides.usgs.gov/*
Telephone: 1-800-654-4966, or 1-303-273-8586
Highland@usgs.gov

Geological Survey of Canada
Landslides and Geotechnic Section
601 Booth Street
Ottawa, Ontario, Canada KIA 0E8
Web address: *http://gsc.nrcan.gc.ca/landslides/index_e.php*
Telephone: 1-613-947-0333
pbobrows@nrcan-rncan.gc.ca

Section I.
Basic Information About Landslides



Part A. What is a Landslide?

Geologists, engineers, and other professionals often rely on unique and slightly differing definitions of landslides. This diversity in definitions reflects the complex nature of the many disciplines associated with studying landslide phenomena. For our purposes, landslide is a general term used to describe the downslope movement of soil, rock, and organic materials under the effects of gravity and also the landform that results from such movement (please see figure 1 for an example of one type of landslide).

Varying classifications of landslides are associated with specific mechanics of slope failure and the properties and characteristics of failure types; these will be discussed briefly herein.

There are a number of other phrases/terms that are used interchangeably with the term “landslide” including mass movement, slope failure, and so on. One commonly hears such terms applied to all types and sizes of landslides.

Regardless of the exact definition used or the type of landslide under discussion, understanding the basic parts of a typical landslide is helpful. Figure 2 shows the position and the most common terms used to describe the unique parts of a landslide. These terms and other relevant words are defined in the Glossary of Landslide Terms included in Appendix A.

Figure 1. This landslide occurred at La Conchita, California, USA, in 2005. Ten people were killed. (Photograph by Mark Reid, U.S. Geological Survey.)

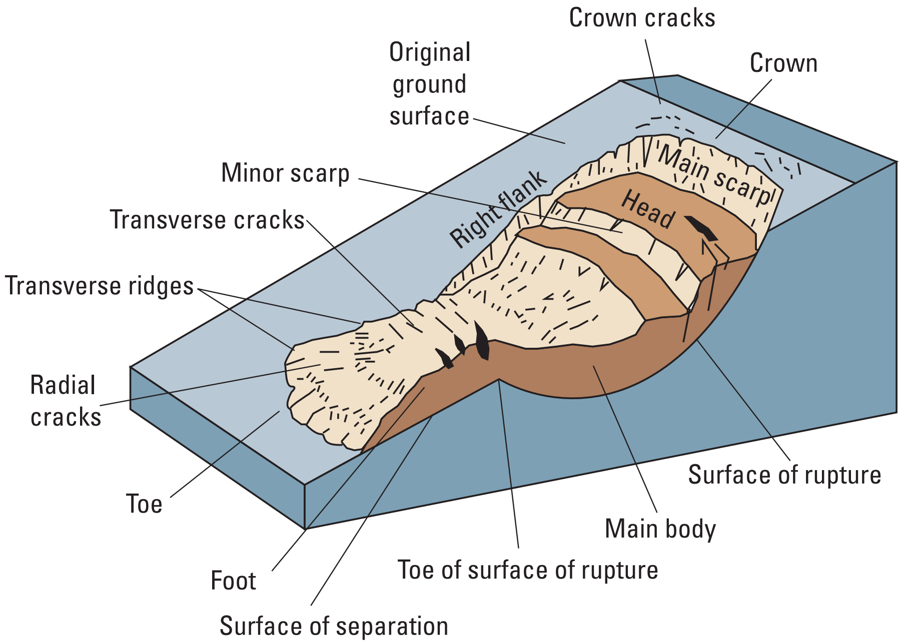


Figure 2. A simple illustration of a rotational landslide that has evolved into an earthflow. Image illustrates commonly used labels for the parts of a landslide (from Varnes, 1978, Reference 43).

Part B. Basic Landslide Types

A landslide is a downslope movement of rock or soil, or both, occurring on the surface of rupture—either curved (rotational slide) or planar (translational slide) rupture—in which much of the material often moves as a coherent or semicoherent mass with little internal deformation. It should be noted that, in some cases, landslides may also involve other types of movement, either at the inception of the failure or later, if properties change as the displaced material moves downslope.

This section provides descriptions and illustrations of the various types of landslides. Understanding the characteristics of the specific type of landslide hazard in your area is vitally important to consider when planning or adopting appropriate mitigative action to lessen the risk of loss and damage. The type of landslide will determine the potential speed of movement, likely volume of displacement, distance of run-out, as well as the possible effects of the landslide and the appropriate mitigative measures to be considered.

Landslides can be classified into different types on the basis of the type of movement and the type of material involved (please see References 9 and 39). In brief, material in a landslide mass is either ***rock*** or ***soil*** (or both); the latter is described as ***earth*** if mainly composed of sand-sized or finer particles and ***debris*** if composed of coarser fragments. The type of movement describes the actual internal mechanics of how the landslide mass is displaced: ***fall***, ***topple, slide, spread,*** or ***flow.*** Thus, landslides are described using two terms that refer respectively to material and movement (that is, rockfall, debris flow, and so forth). Landslides may also form a complex failure encompassing more than one type of movement (that is, rock slide—debris flow).

For the purposes of this handbook we treat "type of movement" as synonymous with "landslide type." Each type of movement can be further subdivided according to specific properties and characteristics, and the main subcategories of each type are described elsewhere. Less common subcategories are not discussed in this handbook but are referred to in the source reference.

Direct citations and identification of sources and references for text are avoided in the body of this handbook, but all source materials are duly recognized and given in the accompanying reference lists.

Falls

A fall begins with the detachment of soil or rock, or both, from a steep slope along a surface on which little or no shear displacement has occurred. The material subsequently descends mainly by falling, bouncing, or rolling.

Rockfall

Falls are abrupt, downward movements of rock or earth, or both, that detach from steep slopes or cliffs. The falling material usually strikes the lower slope at angles less than the angle of fall, causing bouncing. The falling mass may break on impact, may begin rolling on steeper slopes, and may continue until the terrain flattens.

Occurrence and relative size/range

Common worldwide on steep or vertical slopes—also in coastal areas, and along rocky banks of rivers and streams. The volume of material in a fall can vary substantially, from individual rocks or clumps of soil to massive blocks thousands of cubic meters in size.

Velocity of travel

Very rapid to extremely rapid, free-fall; bouncing and rolling of detached soil, rock, and boulders. The rolling velocity depends on slope steepness.

Triggering mechanism

Undercutting of slope by natural processes such as streams and rivers or differential weathering (such as the freeze/thaw cycle), human activities such as excavation during road building and (or) maintenance, and earthquake shaking or other intense vibration.

Effects (direct/indirect)

Falling material can be life-threatening. Falls can damage property beneath the fall-line of large rocks. Boulders can bounce or roll great distances and damage structures or kill people. Damage to roads and railroads is particularly high: rockfalls can cause deaths in vehicles hit by rocks and can block highways and railroads.

Corrective measures/mitigation

Rock curtains or other slope covers, protective covers over roadways, retaining walls to prevent rolling or bouncing, explosive blasting of hazardous target areas to remove the source, removal of rocks or other materials from highways and railroads can be used. Rock bolts or other similar types of anchoring used to stabilize cliffs, as well as scaling, can lessen the hazard. Warning signs are recommended in hazardous areas for awareness. Stopping or parking under hazardous cliffs should be warned against.

For further reading:
References 9, 39, 43, and 45

Predictability

Mapping of hazardous rockfall areas has been completed in a few areas around the world. Rock-bounce calculations and estimation methods for delineating the perimeter of rockall zones have also been determined and the information widely published. Indicators of imminent rockfall include terrain with overhanging rock or fractured or jointed rock along steep slopes, particularly in areas subject to frequent freeze-thaw cycles. Also, cut faces in gravel pits may be particularly subject to falls. Figures 3 and 4 show a schematic and an image of rockfall.

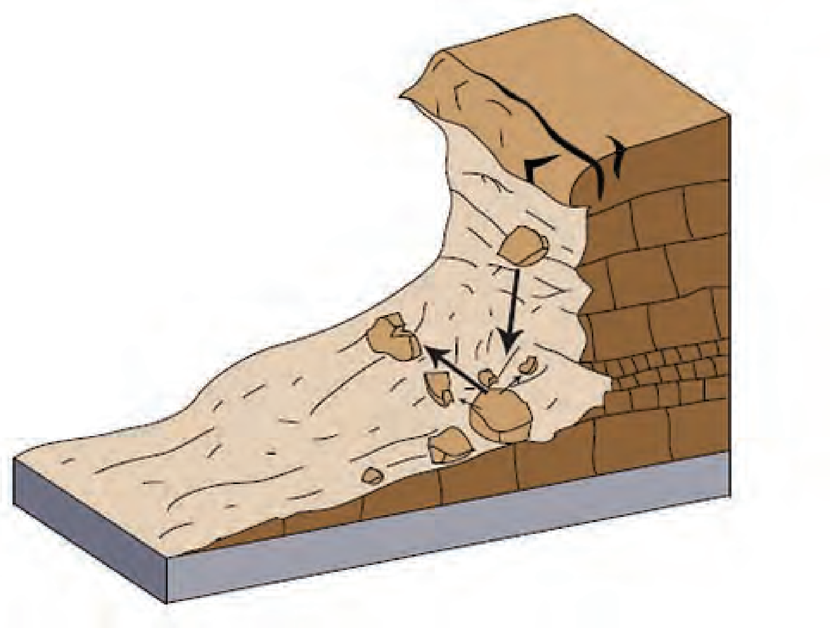


Figure 3. Schematic of a rockfall. (Schematic modified from Reference 9.)

Figure 4. A rockfall/slide that occurred in Clear Creek Canyon, Colorado, USA, in 2005, closing the canyon to traffic for a number of weeks. The photograph also shows an example of a rock curtain, a barrier commonly applied over hazardous rock faces (right center of photograph). (Photograph by Colorado Geological Survey.)

Topple

A topple is recognized as the forward *rotation* out of a slope of a mass of soil or rock around a point or *axis* below the *center of gravity* of the displaced mass. Toppling is sometimes driven by gravity exerted by the weight of material upslope from the displaced mass. Sometimes toppling is due to water or ice in cracks in the mass. Topples can consist of rock, debris (coarse material), or earth materials (fine-grained material). Topples can be complex and composite.

Occurrence

Known to occur globally, often prevalent in columnar-jointed volcanic terrain, as well as along stream and river courses where the banks are steep.

Velocity of travel

Extremely slow to extremely rapid, sometimes accelerating throughout the movement depending on distance of travel.

Triggering mechanism

Sometimes driven by gravity exerted by material located upslope from the displaced mass and sometimes by water or ice occurring in cracks within the mass; also, vibration, undercutting, differential weathering, excavation, or stream erosion.

Effects (direct/indirect)

Can be extremely destructive, especially when failure is sudden and (or) the velocity is rapid.

Corrective measures/mitigation

In rock there are many options for the stabilization of topple-prone areas. Some examples for reinforcement of these slopes include rock bolts and mechanical and other types of anchors. Seepage is also a contributing factor to rock instability, and drainage should be considered and addressed as a corrective means.

Predictability

Not generally mapped for susceptibility; some inventory of occurrence exists for certain areas. Monitoring of topple-prone areas is useful; for example, the use of tiltmeters. Tiltmeters are used to record changes in slope inclination near cracks and areas of greatest vertical movements. Warning systems based on movement measured by tiltmeters could be effective. Figures 5 and 6 show a schematic and an image of topple.

For further reading:
References 9, 39, 43, and 45

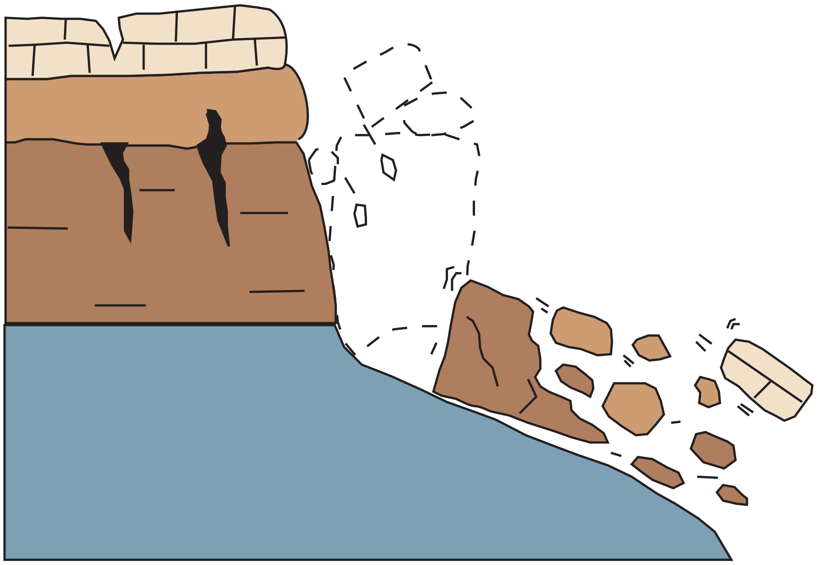


Figure 5. Schematic of a topple. (Schematic from Reference 9.)

Figure 6. Photograph of block toppling at Fort St. John, British Columbia, Canada. (Photograph by G. Bianchi Fasani.)

Slides

A slide is a downslope movement of a soil or rock mass occurring 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.

Rotational Landslide

A landslide on which the surface of rupture is curved upward (spoon-shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope. The displaced mass may, under certain circumstances, move as a relatively coherent mass along the rupture surface with little internal deformation. The head of the displaced material may move almost vertically downward, and the upper surface of the displaced material may tilt backwards toward the scarp. If the slide is rotational and has several parallel curved planes of movement, it is called a slump.

Occurrence

Because rotational slides occur most frequently in homogeneous materials, they are the most common landslide occurring in “fill” materials.

Relative size/range

Associated with slopes ranging from about 20 to 40 degrees. In soils, the surface of rupture generally has a depth-to-length ratio between 0.3 to 0.1.

Velocity of travel (rate of movement)

Extremely slow (less than 0.3 meter or 1 foot every 5 years) to moderately fast (1.5 meters or 5 feet per month) to rapid.

Triggering mechanism

Intense and (or) sustained rainfall or rapid snowmelt can lead to the saturation of slopes and increased groundwater levels within the mass; rapid drops in river level following floods, ground-water levels rising as a result of filling reservoirs, or the rise in level of streams, lakes, and rivers, which cause erosion at the base of slopes. These types of slides can also be earthquake-induced.

Effects (direct/indirect)

Can be extremely damaging to structures, roads, and lifelines but are not usually life-threatening if movement is slow. Structures situated on the moving mass also can be severely damaged as the mass tilts and deforms. The large volume of material that is displaced is difficult to permanently stabilize. Such failures can dam rivers, causing flooding.

Mitigation measures

Instrumental monitoring to detect movement and the rate of movement can be implemented. Disrupted drainage pathways should be restored or reengineered to prevent future water buildup in the slide mass. Proper grading and engineering of slopes, where possible, will reduce the hazard considerably. Construction of retaining walls at the toe may be effective to slow or deflect the moving soil; however, the slide may overtop such retaining structures despite good construction.

Predictability

Historical slides can be reactivated; cracks at tops (heads) of slopes are good indicators of the initiation of failure. Figures 7 and 8 show a schematic and an image of a rotational landslide.

For further reading:
References 9, 39, 43, and 45

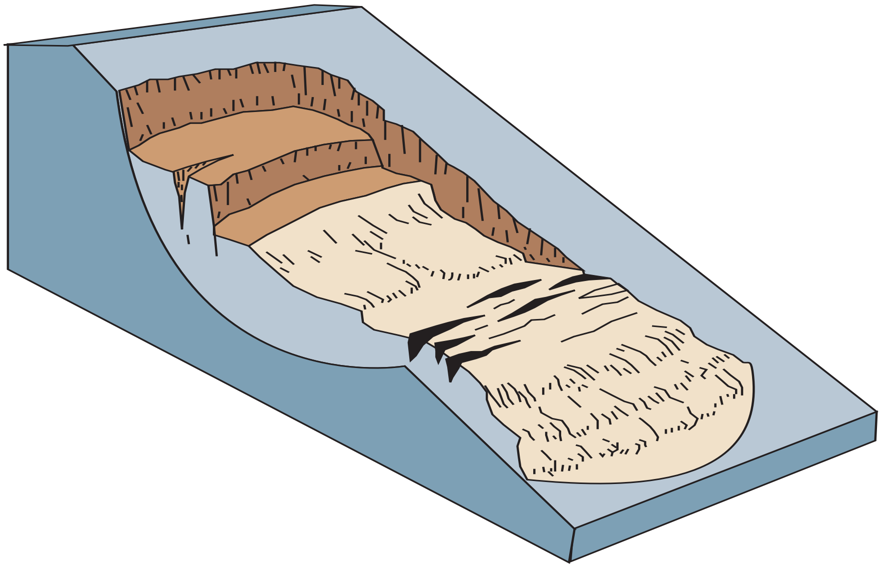


Figure 7. Schematic of a rotational landslide. (Schematic modified from Reference 9.)

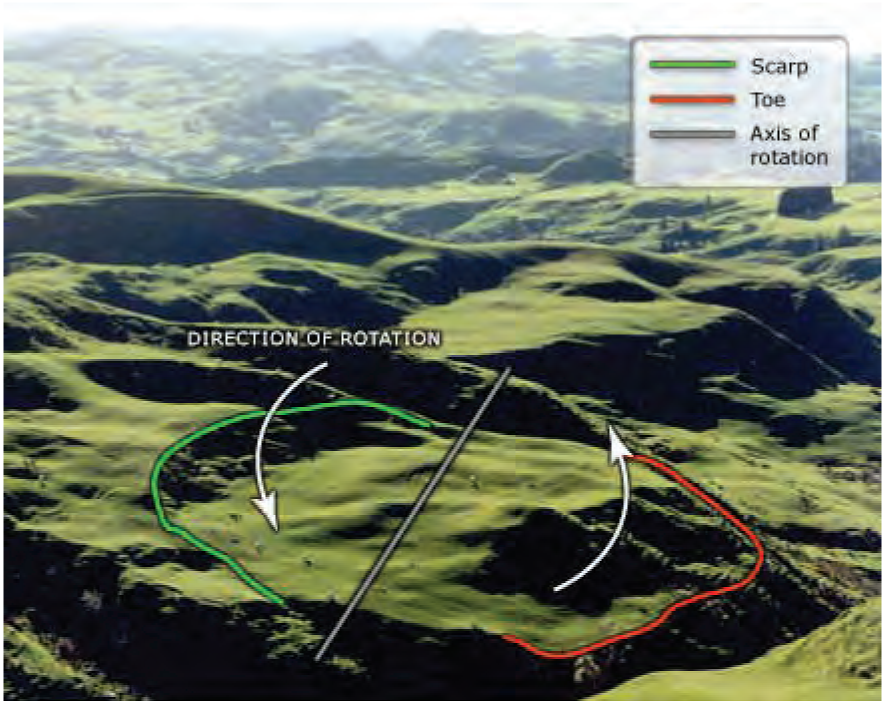


Figure 8. Photograph of a rotational landslide which occurred in New Zealand. The green curve at center left is the scarp (the area where the ground has failed). The hummocky ground at bottom right (in shadow) is the toe of the landslide (red line). This is called a rotational landslide as the earth has moved from left to right on a curved sliding surface. The direction and axis of rotation are also depicted. (Photograph by Michael J. Crozier, Encyclopedia of New Zealand, updated September 21, 2007.)

Translational Landslide

The mass in a translational landslide moves out, or down and outward, along a relatively planar surface with little rotational movement or backward tilting. This type of slide may progress over considerable distances if the surface of rupture is sufficiently inclined, in contrast to rotational slides, which tend to restore the slide equilibrium. The material in the slide may range from loose, unconsolidated soils to extensive slabs of rock, or both. Translational slides commonly fail along geologic discontinuities such as faults, joints, bedding surfaces, or the contact between rock and soil. In northern environments the slide may also move along the permafrost layer.

Occurrence

One of the most common types of landslides, worldwide. They are found globally in all types of environments and conditions.

Relative size/range

Generally shallower than rotational slides. The surface of rupture has a distance-to-length ratio of less than 0.1 and can range from small (residential lot size) failures to very large, regional landslides that are kilometers wide.

Velocity of travel

Movement may initially be slow (5 feet per month or 1.5 meters per month) but many are moderate in velocity (5 feet per day or 1.5 meters per day) to extremely rapid. With increased velocity, the landslide mass of translational failures may disintegrate and develop into a debris flow.

Triggering mechanism

Primarily intense rainfall, rise in ground water within the slide due to rainfall, snowmelt, flooding, or other inundation of water resulting from irrigation, or leakage from pipes or human-related disturbances such as undercutting. These types of landslides can be earthquake-induced.

Effects (direct/indirect)

Translational slides may initially be slow, damaging property and (or) lifelines; in some cases they can gain speed and become life-threatening. They also can dam rivers, causing flooding.

Mitigation measures

Adequate drainage is necessary to prevent sliding or, in the case of an existing failure, to prevent a reactivation of the movement. Common corrective measures include leveling, proper grading and drainage, and retaining walls. More sophisticated remedies in rock include anchors, bolts, and dowels, which in all situations are best implemented by professionals. Translational slides on moderate to steep slopes are very difficult to stabilize permanently.

Predictability

High probability of occurring repetitively in areas where they have occurred in the past, including areas subject to frequent strong earthquakes. Widening cracks at the head or toe bulge may be an indicator of imminent failure. Figures 9 and 10 show a schematic and an image of a translational landslide.

For further reading:
References 9, 39, 43, and 45

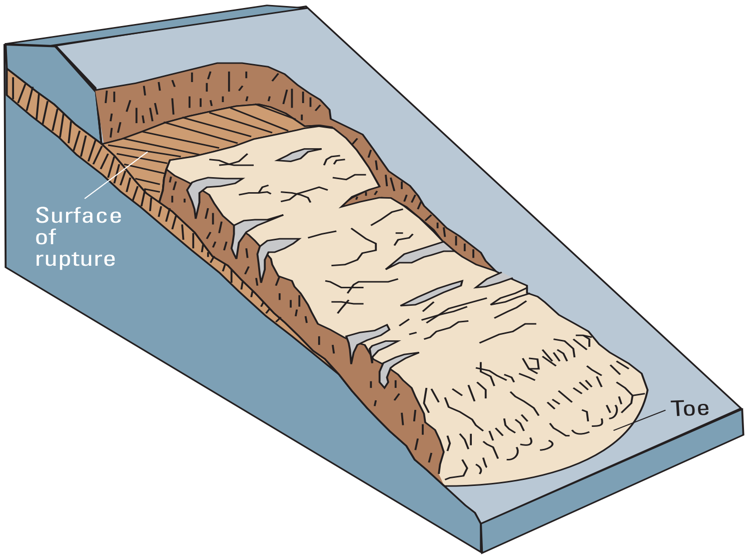


Figure 9. Schematic of a translational landslide. (Schematic modified from Reference 9.)

Figure 10. A translational landslide that occurred in 2001 in the Beatton River Valley, British Columbia, Canada. (Photograph by Réjean Couture, Canada Geological Survey.)

Spreads

An extension of a cohesive soil or rock mass combined with the general subsidence of the fractured mass of cohesive material into softer underlying material. Spreads may result from liquefaction or flow (and extrusion) of the softer underlying material. Types of spreads include block spreads, liquefaction spreads, and lateral spreads.

Lateral Spreads

Lateral spreads usually occur on very gentle slopes or essentially flat terrain, especially where a stronger upper layer of rock or soil undergoes extension and moves above an underlying softer, weaker layer. Such failures commonly are accompanied by some general subsidence into the weaker underlying unit. In rock spreads, solid ground extends and fractures, pulling away slowly from stable ground and moving over the weaker layer without necessarily forming a recognizable surface of rupture. The softer, weaker unit may, under certain conditions, squeeze upward into fractures that divide the extending layer into blocks. In earth spreads, the upper stable layer extends along a weaker underlying unit that has flowed following liquefaction or plastic deformation. If the weaker unit is relatively thick, the overriding fractured blocks may subside into it, translate, rotate, disintegrate, liquefy, or even flow.

Occurrence

Worldwide and known to occur where there are liquefiable soils. Common, but not restricted, to areas of seismic activity.

Relative size/range

The area affected may start small in size and have a few cracks that may spread quickly, affecting areas of hundreds of meters in width.

Velocity of travel

May be slow to moderate and sometimes rapid after certain triggering mechanisms, such as an earthquake. Ground may then slowly spread over time from a few millimeters per day to tens of square meters per day.

Triggering mechanism

Triggers that destabilize the weak layer include:

- Liquefaction of lower weak layer by earthquake shaking
- Natural or anthropogenic overloading of the ground above an unstable slope
- Saturation of underlying weaker layer due to precipitation, snowmelt, and (or) ground-water changes
- Liquefaction of underlying sensitive marine clay following an erosional disturbance at base of a riverbank/slope
- Plastic deformation of unstable material at depth (for example, salt)

Effects (direct/indirect)

Can cause extensive property damage to buildings, roads, railroads, and lifelines. Can spread slowly or quickly, depending on the extent of water saturation of the various soil layers. Lateral spreads may be a precursor to earthflows.

Mitigation measures

Liquefaction-potential maps exist for some places but are not widely available. Areas with potentially liquefiable soils can be avoided as construction sites, particularly in regions that are known to experience frequent earthquakes. If high ground-water levels are involved, sites can be drained or other water-diversion efforts can be added.

Predictability

High probability of recurring in areas that have experienced previous problems. Most prevalent in areas that have an extreme earthquake hazard as well as liquefiable soils. Lateral spreads are also associated with susceptible marine clays and are a common problem throughout the St. Lawrence Lowlands of eastern Canada. Figures 11 and 12 show a schematic and an image of a lateral spread.

For further reading:
References 9, 39, 43, and 45

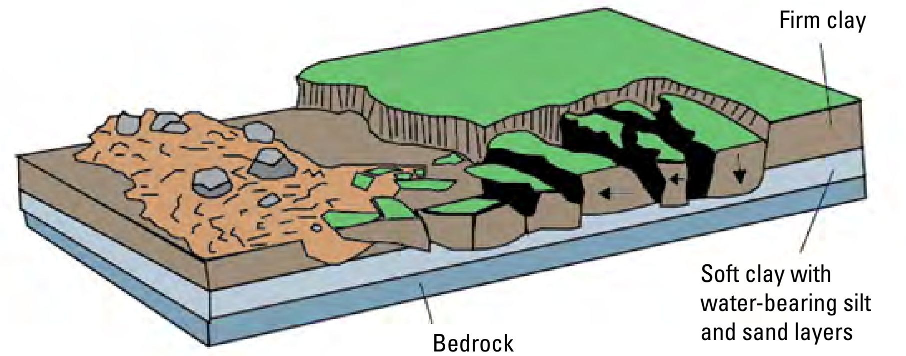


Figure 11. Schematic of a lateral spread. A liquefiable layer underlies the surface layer. (Schematic modified from Reference 9.)

Figure 12. Photograph of lateral spread damage to a roadway as a result of the 1989 Loma Prieta, California, USA, earthquake. (Photograph by Steve Ellen, U.S. Geological Survey.)

Flows

A flow is a spatially continuous movement in which the surfaces of shear are short-lived, closely spaced, and usually not preserved. The component velocities in the displacing mass of a flow resemble those in a viscous liquid. Often, there is a gradation of change from slides to flows, depending on the water content, mobility, and evolution of the movement.

Debris Flows

A form of rapid mass movement in which loose soil, rock and sometimes organic matter combine with water to form a slurry that flows downslope. They have been informally and inappropriately called "mudslides" due to the large quantity of fine material that may be present in the flow. Occasionally, as a rotational or translational slide gains velocity and the internal mass loses cohesion or gains water, it may evolve into a debris flow. Dry flows can sometimes occur in cohesionless sand (sand flows). Debris flows can be deadly as they can be extremely rapid and may occur without any warning.

Occurrence

Debris flows occur around the world and are prevalent in steep gullies and canyons; they can be intensified when occurring on slopes or in gullies that have been denuded of vegetation due to wildfires or forest logging. They are common in volcanic areas with weak soil.

Relative size/range

These types of flows can be thin and watery or thick with sediment and debris and are usually confined to the dimensions of the steep gullies that facilitate their downward movement. Generally the movement is relatively shallow and the runout is both long and narrow, sometimes extending for kilometers in steep terrain. The debris and mud usually terminate at the base of the slopes and create fanlike, triangular deposits called debris fans, which may also be unstable.

Velocity of travel

Can be rapid to extremely rapid (35 miles per hour or 56 km per hour) depending on consistency and slope angle.

Triggering mechanisms

Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes. Debris flows also commonly mobilize from other types of landslides that occur on steep slopes, are nearly saturated, and consist of a large proportion of silt- and sand-sized material.

Effects (direct/indirect)

Debris flows can be lethal because of their rapid onset, high speed of movement, and the fact that they can incorporate large boulders and other pieces of debris. They can move objects as large as houses in their downslope flow or can fill structures with a rapid accumulation of sediment and organic matter. They can affect the quality of water by depositing large amounts of silt and debris.

Mitigation measures

Flows usually cannot be prevented; thus, homes should not be built in steep-walled gullies that have a history of debris flows or are otherwise susceptible due to wildfires, soil type, or other related factors. New flows can be directed away from structures by means of deflection, debris-flow basins can be built to contain flow, and warning systems can be put in place in areas where it is known at what rainfall thresholds debris flows are triggered. Evacuation, avoidance, and (or) relocation are the best methods to prevent injury and life loss.

For further reading:
References 9, 39, 43, and 45

Predictability

Maps of potential debris-flow hazards exist for some areas. Debris flows can be frequent in any area of steep slopes and heavy rainfall, either seasonally or intermittently, and especially in areas that have been recently burned or the vegetation removed by other means. Figures 13 and 14 show a schematic and an image of a debris flow.

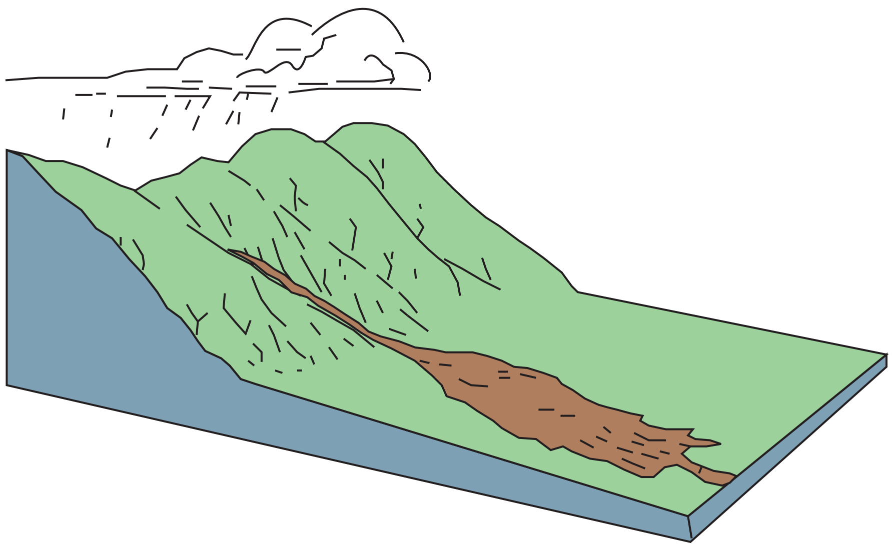


Figure 13. Schematic of a debris flow. (Schematic modified from Reference 9.)

Figure 14. Debris-flow damage to the city of Caraballeda, located at the base of the Cordillera de la Costan, on the north coast of Venezuela. In December 1999, this area was hit by Venezuela's worst natural disaster of the 20th century; several days of torrential rain triggered flows of mud, boulders, water, and trees that killed as many as 30,000 people. (Photograph by L.M. Smith, Waterways Experiment Station, U.S. Army Corps of Engineers.)

Lahars (Volcanic Debris Flows)

The word “lahar” is an Indonesian term. Lahars are also known as volcanic mudflows. These are flows that originate on the slopes of volcanoes and are a type of debris flow. A lahar mobilizes the loose accumulations of tephra (the airborne solids erupted from the volcano) and related debris.

Occurrence

Found in nearly all volcanic areas of the world.

Relative size/range

Lahars can be hundreds of square kilometers or miles in area and can become larger as they gain speed and accumulate debris as they travel downslope; or, they can be small in volume and affect limited areas of the volcano and then dissipate downslope.

Velocity of travel

Lahars can be very rapid (more than 35 miles per hour or 50 kilometers per hour) especially if they mix with a source of water such as melting snowfields or glaciers. If they are viscous and thick with debris and less water, the movement will be slow to moderately slow.

Triggering mechanism

Water is the primary triggering mechanism, and it can originate from crater lakes, condensation of erupted steam on volcano particles, or the melting of snow and ice at the top of high volcanoes. Some of the largest and most deadly lahars have originated from eruptions or volcanic venting which suddenly melts surrounding snow and ice and causes rapid liquefaction and flow down steep volcanic slopes at catastrophic speeds.

Effects (direct/indirect)

Effects can be extremely large and devastating, especially when triggered by a volcanic eruption and consequent rapid melting of any snow and ice—the flow can bury human settlements located on the volcano slopes. Some large flows can also dam rivers, causing flooding upstream. Subsequent breaching of these weakly cemented dams can cause catastrophic flooding downstream. This type of landslide often results in large numbers of human casualties.

Mitigation measures

No corrective measures are known that can be taken to prevent damage from lahars except for avoidance by not building or locating in their paths or on the slopes of volcanoes. Warning systems and subsequent evacuation work in some instances may save lives. However, warning systems require active monitoring, and a reliable evacuation method is essential.

Predictability

Susceptibility maps based on past occurrences of lahars can be constructed, as well as runout estimations of potential flows. Such maps are not readily available for most hazardous areas. Figures 15 and 16 show a schematic and an image of a lahar.

For further reading:
References 9, 39, 43, and 45

Figure 15. Schematic of a lahar. (Graphic by U.S. Geological Survey.)

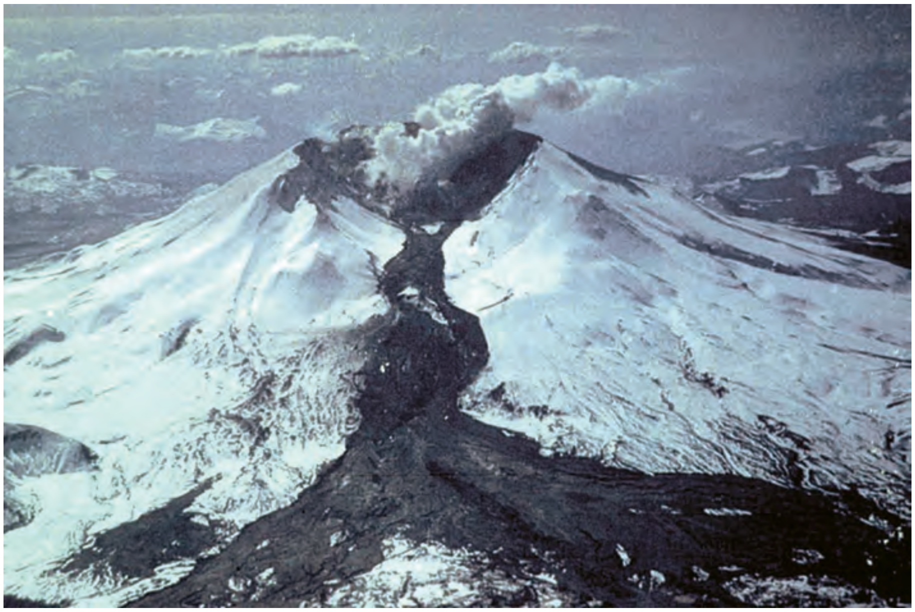


Figure 16. Photograph of a lahar caused by the 1982 eruption of Mount St. Helens in Washington, USA. (Photograph by Tom Casadevall, U.S. Geological Survey.)

Debris Avalanche

Debris avalanches are essentially large, extremely rapid, often open-slope flows formed when an unstable slope collapses and the resulting fragmented debris is rapidly transported away from the slope. In some cases, snow and ice will contribute to the movement if sufficient water is present, and the flow may become a debris flow and (or) a lahar.

Occurrence

Occur worldwide in steep terrain environments. Also common on very steep volcanoes where they may follow drainage courses.

Relative size/range

Some large avalanches have been known to transport material blocks as large as 3 kilometers in size, several kilometers from their source.

Velocity of travel

Rapid to extremely rapid; such debris avalanches can travel close to 100 meters/sec.

Triggering mechanism

In general, the two types of debris avalanches are those that are “cold” and those that are “hot.” A cold debris avalanche usually results from a slope becoming unstable, such as during collapse of weathered slopes in steep terrain or through the disintegration of bedrock during a slide-type landslide as it moves downslope at high velocity. At that point, the mass can then transform into a debris avalanche. A hot debris avalanche is one that results from volcanic activity including volcanic earthquakes or the injection of magma, which causes slope instability.

Effects (direct/indirect)

Debris avalanches may travel several kilometers before stopping, or they may transform into more water-rich lahars or debris flows that travel many tens of kilometers farther downstream. Such failures may inundate towns and villages and impair stream quality. They move very fast and thus may prove deadly because there is little chance for warning and response.

Corrective measures/mitigation

Avoidance of construction in valleys on volcanoes or steep mountain slopes and real-time warning systems may lessen damages. However, warning systems may prove difficult due to the speed at which debris avalanches occur—there may not be enough time after the initiation of the event for people to evacuate. Debris avalanches cannot be stopped or prevented by engineering means because the associated triggering mechanisms are not preventable.

Predictability

If evidence of prior debris avalanches exists in an area, and if such evidence can be dated, a probabilistic recurrence period might be established. During volcanic eruptions, chances are greater for a debris avalanche to occur, so appropriate cautionary actions could be adopted. Figures 17 and 18 show a schematic and an image of a debris avalanche.

For further reading:
References 9, 39, 43, and 45

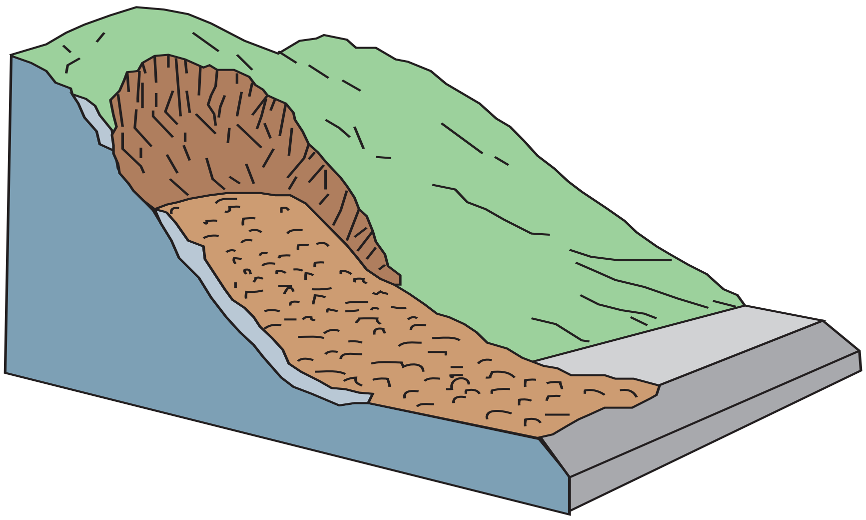


Figure 17. Schematic of a debris avalanche. (Schematic modified from Reference 9.)

Figure 18. A debris avalanche that buried the village of Guinsaugon, Southern Leyte, Philippines, in February 2006. (Photograph by University of Tokyo Geotechnical Team.) Please see figure 30 for an image of another debris avalanche.

Earthflow

Earthflows can occur on gentle to moderate slopes, generally in fine-grained soil, commonly clay or silt, but also in very weathered, clay-bearing bedrock. The mass in an earthflow moves as a plastic or viscous flow with strong internal deformation. Susceptible marine clay (quick clay) when disturbed is very vulnerable and may lose all shear strength with a change in its natural moisture content and suddenly liquefy, potentially destroying large areas and flowing for several kilometers. Size commonly increases through headscarp retrogression. Slides or lateral spreads may also evolve downslope into earthflows. Earthflows can range from very slow (creep) to rapid and catastrophic. Very slow flows and specialized forms of earthflow restricted to northern permafrost environments are discussed elsewhere.

Occurrence

Earthflows occur worldwide in regions underlain by fine-grained soil or very weathered bedrock. Catastrophic rapid earthflows are common in the susceptible marine clays of the St. Lawrence Lowlands of North America, coastal Alaska and British Columbia, and in Scandinavia.

Relative (size/range)

Flows can range from small events of 100 square meters in size to large events encompassing several square kilometers in area. Earthflows in susceptible marine clays may runout for several kilometers. Depth of the failure ranges from shallow to many tens of meters.

Velocity of travel

Slow to very rapid.

Triggering mechanisms

Triggers include saturation of soil due to prolonged or intense rainfall or snowmelt, sudden lowering of adjacent water surfaces causing rapid drawdown of the ground-water table, stream erosion at the bottom of a slope, excavation and construction activities, excessive loading on a slope, earthquakes, or human-induced vibration.

Effects (direct/indirect)

Rapid, retrogressive earthflows in susceptible marine clay may devastate large areas of flat land lying above the slope and also may runout for considerable distances, potentially resulting in human fatalities, destruction of buildings and linear infrastructure, and damming of rivers with resultant flooding upstream and water siltation problems downstream. Slower earthflows may damage properties and sever linear infrastructure.

Corrective measures/mitigation

Improved drainage is an important corrective measure, as is grading of slopes and protecting the base of the slope from erosion or excavation. Shear strength of clay can be measured, and potential pressure can be monitored in suspect slopes. However, the best mitigation is to avoid development activities near such slopes.

Predictability

Evidence of past earthflows is the best indication of vulnerability. Distribution of clay likely to liquefy can in some cases be mapped and has been mapped in many parts of eastern North America. Cracks opening near the top of the slope may indicate potential failure. Figures 19 and 20 show a schematic and an image of an earthflow.

For further reading: References 9, 39, 43, and 45

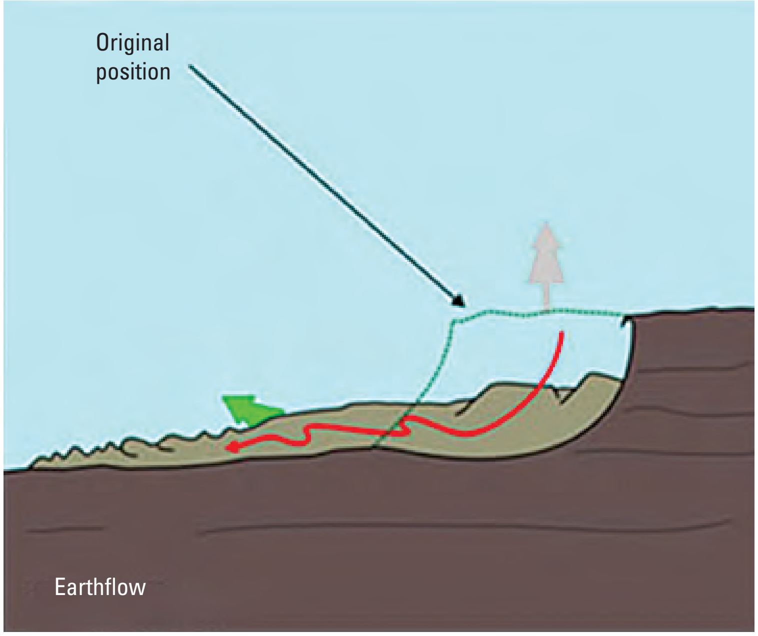


Figure 19. Schematic of an earthflow. (Schematic from Geological Survey of Canada.)

Figure 20. The 1993 Lemieux landslide—a rapid earthflow in sensitive marine clay near Ottawa, Canada. The headscarp retrogressed 680 meters into level ground above the riverbank. About 2.8 million tons of clay and silt liquefied and flowed into the South Nation River valley, damming the river. (Photograph by G.R. Brooks, Geological Survey of Canada.)

Slow Earthflow (Creep)

Creep is the informal name for a slow earthflow and consists of the imperceptibly slow, steady downward movement of slope-forming soil or rock. Movement is caused by internal shear stress sufficient to cause deformation but insufficient to cause failure. Generally, the three types of creep are: (1) seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and temperature; (2) continuous, where shear stress continuously exceeds the strength of the material; and (3) progressive, where slopes are reaching the point of failure for other types of mass movements.

Occurrence

Creep is widespread around the world and is probably the most common type of landslide, often preceding more rapid and damaging types of landslides. Solifluction, a specialized form of creep common to permafrost environments, occurs in the upper layer of ice-rich, fine-grained soils during the annual thaw of this layer.

Relative size/range

Creep can be very regional in nature (tens of square kilometers) or simply confined to small areas. It is difficult to discern the boundaries of creep since the event itself is so slow and surface features representing perceptible deformation may be lacking.

Velocity of travel

Very slow to extremely slow. Usually less than 1 meter (0.3 foot) per decade.

Triggering mechanism

For seasonal creep, rainfall and snowmelt are typical triggers, whereas for other types of creep there could be numerous causes, such as chemical or physical weathering, leaking pipes, poor drainage, destabilizing types of construction, and so on.

Effects

Because it is hard to detect in some places because of the slowness of movement, creep is sometimes not recognized when assessing the suitability of a building site. Creep can slowly pull apart pipelines, buildings, highways, fences, and so forth, and can lead to more drastic ground failures that are more destructive and faster moving.

Corrective measures/mitigation

The most common mitigation for creep is to ensure proper drainage of water, especially for the seasonal type of creep. Slope modification such as flattening or removing all or part of the landslide mass, can be attempted, as well as the construction of retaining walls.

Predictability

For further reading:
References 9, 39, 43, and 45

Indicated by curved tree trunks, bent fences and (or) retaining walls, tilted poles or fences, and small soil ripples or ridges on the surface. Rates of creep can be measured by inclinometers installed in boreholes or by detailed surface measurements. Figures 21 and 22 show a schematic and an image of creep.

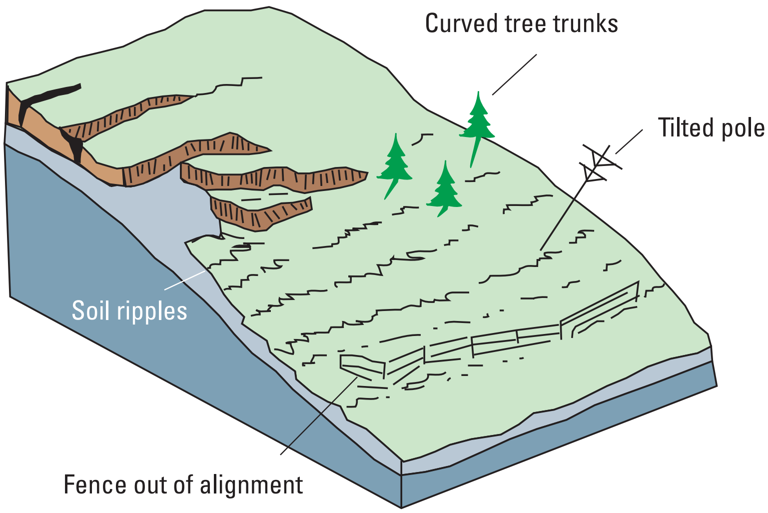


Figure 21. Schematic of a slow earthflow, often called creep. (Schematic modified from Reference 9.)

Figure 22. This photograph shows the effects of creep, in an area near East Sussex, United Kingdom, called the Chalk Grasslands. Steep slopes of thin soil over marine chalk deposits, develop a ribbed pattern of grass-covered horizontal steps that are 0.3 to 0.6 meter (1 to 2 feet) high. Although subsequently made more distinct by cattle and sheep walking along them, these terraces (commonly known as sheep tracks) were formed by the gradual, creeping movement of soil downhill. (Photograph by Ian Alexander.)

Flows in Permafrost

Failures in permafrost conditions involve the movement of fine-grained, previously ice-rich soil and can occur on gentle slopes. Seasonal thaw of the upper meter of frozen ground melts ground ice and results in oversaturation of the soil, which in turn loses shear strength and initiates flows. Solifluction, a form of cold environment creep, involves very slow deformation of the surface and forms shallow lobes elongated downslope. Active layer detachments, also known as skinflows, involve rapid flow of a shallow layer of saturated soil and vegetation, forming long, narrow flows moving on the surface but over the underlying permanently frozen soil. This type of movement may expose buried ice lenses, which when thawed may develop into retrogressive thaw flows or possibly debris flows. Retrogressive thaw flows are larger features with a bimodal shape of a steep headwall and low-angle tongue of saturated soil. This type of feature will continue to expand through headscarp retrogression until displaced vegetation buries and insulates the ice-rich scarp.

Occurrence

Flows are common in ice-rich permafrost soils in northern latitudes and high altitudes (cold environments).

Relative size/range

Flows are generally small but can increase in size through headscarp retrogression. They may evolve into a larger debris flow.

Velocity of travel

Very slow (solifluction); slow (retrogressive thaw flow); rapid (active layer detachment).

Triggering mechanisms

Above-average summer temperatures, frost wedges, wildfire, and anthropogenic disturbances to insulating peat layer. Such landslides are particularly likely in warming climates.

Effects (direct/indirect)

Damage to pipelines and roads and other structures can be severe.

Corrective measures/mitigation

Infrastructure designs that have minimal effect on the surface peat layer or temperature of the active layer and avoidance, when possible, of ice-rich soils when planning roads and other infrastructure, can reduce risk. Ice content of the upper soil can be readily tested.

Predictability

If ice-rich soil thaws, it will flow. In some areas, ice content has been mapped; in other areas, ice content can be estimated on the basis of specific mapped units shown on surficial geology maps. Figures 23 and 24 show a schematic and an image of permafrost-related flow.

For further reading:
References 2, 9, 39, 43, and 45

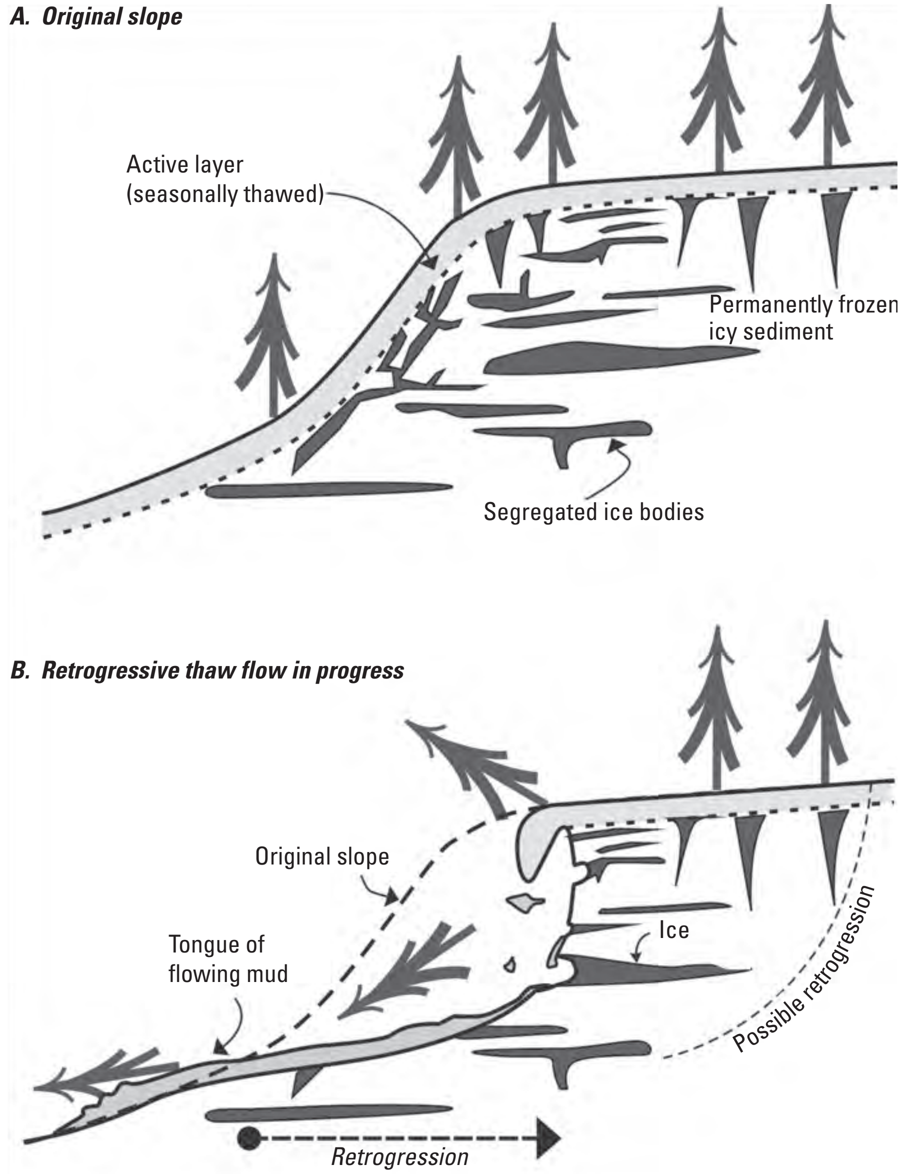


Figure 23. Schematic of a retrogressive thaw flow slide. (Schematic by Jan Aylsworth, Geological Survey of Canada.)

A note about complex landslides:
These are landslides that feature components of two or more of the basic types of landslides and can occur either simultaneously or at different times during the onset of slope failure.

Figure 24. Photograph of a retrogressive thaw flow in the Northwest Territories, Canada. Wildfire has likely contributed to the size of the flow by means of damage to an insulating moss layer, resulting in the thickening of the active layer, which is thawing permafrost. (Photograph by Marten Geertsema, Ministry of Forests, British Columbia, Canada.)

Part C. Where Do Landslides Occur?

A surprising fact to many people is that landslides can occur virtually anywhere in the world. The traditional viewpoint that landslides are restricted to extremely steep slopes and inhospitable terrain does not accurately reflect the real nature of the problem. Most countries in the world have been affected in some manner by landslides. The reason for such wide geographic coverage has much to do with the many different triggering mechanisms for landslides.

For further reading:
Reference 2

Excessive precipitation, earthquakes, volcanoes, forest fires and other mechanisms, and more recently, certain dangerous human activities are just some of the key causes that can trigger landslides. See "*Part D*. What Causes Landslides?" for more information on triggering mechanisms. Figure 25 shows an example of lateral spreading, a type of ground failure often associated with earthquakes.

Similarly, landslides are known to occur both on land and under water; they can occur in bedrock or on soils; cultivated land, barren slopes and natural forests are all subject to landslides. Both extremely dry areas and very humid areas can be affected by slope failures, and most important, steep slopes are not a necessary prerequisite for landslides to occur. In some cases, gentle slopes as shallow as 1–2 degrees have been observed to fail.

Bearing in mind that landslides can happen virtually anywhere around the world, we do, however, recognize certain patterns in their occurrence. At the national scale in countries such as Canada and the United States, the association of hilly terrain such as the Rocky Mountains with certain types of landslides is clear. Other geographic trends in landslide distribution can be linked to natural patterns of climate and weather, wildfires, and stream/river courses or human patterns involving the clearing of vegetation, modification to slopes, and other urban and rural practices. In each of these cases, it is important to recognize that landslide types vary in relation to the local and regional conditions.

Debris torrents require channels and ravines to occur, whereas rockfalls will happen only where steep, exposed faces of bedrock or boulder-rich deposits are present. Geology itself figures prominently in the occurrence of many landslides. The correlation of seismic and volcanic activity to landslides is of paramount importance, so specialists often approach the evaluation of hazards from a multi-hazard perspective, which by definition takes into account most of the factors discussed previously.

For further reading:
References 8, 16, 19, 25, 30, and 45

Figure 25. Lateral spreading damage. Photograph shows the Puget Sound area in Washington, USA, after the 2001 Nisqually earthquake. (Photograph courtesy of the Seattle Times.)

Part D. What Causes Landslides?

There are two primary categories of causes of landslides: natural and human-caused. Sometimes, landslides are caused, or made worse, by a combination of the two factors.

Natural Occurrences

This category has three major triggering mechanisms that can occur either singly or in combination —(1) water, (2) seismic activity, and (3) volcanic activity. Effects of all of these causes vary widely and depend on factors such as steepness of slope, morphology or shape of terrain, soil type, underlying geology, and whether there are people or structures on the affected areas. Effects of landslides will be discussed in more detail in Part E.

Landslides and Water

Slope saturation by water is a primary cause of landslides. Saturation can occur in the form of intense rainfall, snowmelt, changes in ground-water levels, and surface-water level changes along coastlines, earth dams, and in the banks of lakes, reservoirs, canals, and rivers. Landslides and flooding are closely associated because both are related to precipitation, runoff, and the saturation of ground by water. Flooding may cause landslides by undercutting banks of streams and rivers and by saturation of slopes by surface water (overland flow). In addition, debris flows and mudflows usually occur in small, steep stream channels and commonly are mistaken for floods; in fact, these two events often occur simultaneously in the same area. Conversely, landslides also can cause flooding when sliding rock and debris block stream channels and other waterways, allowing large volumes of water to back up behind such dams. This causes backwater flooding and, if the dam fails, subsequent downstream flooding. Moreover, solid landslide debris can “bulk” or add volume and density to otherwise normal streamflow or cause channel blockages and diversions, creating flood conditions or localized erosion. Landslides also can cause tsunamis (seiches), overtopping of reservoirs, and (or) reduced capacity of reservoirs to store water. Steep wildfire-burned slopes often are landslide-prone due to a combination of the burning and resultant denudation of vegetation on slopes, a change in soil chemistry due to burning, and a subsequent saturation of slopes by water from various sources, such as rainfall. Debris flows are the most common type of landslide on burned slopes (for a description and images of a debris flow, see “*Part B.* Basic Landslide Types” in Section I). Wildfires, of course, may be the result of natural or human causes. Figure 26 shows a devastating landslide caused by rainfall, and possibly made worse by a leaking water pipe, which added even more water to the soil.

Figure 26. The Mameyes, Puerto Rico, landslide, 1985. This landslide destroyed 120 houses and killed at least 129 people. The catastrophic slide was triggered by a tropical storm that produced extremely heavy rainfall. Contributing factors could also have included sewage saturating the ground in the densely populated area, and a leaking water pipe at the top of the landslide. (Photograph by Randall Jibson, U.S. Geological Survey.)

Landslides and Seismic Activity

Many mountainous areas that are vulnerable to landslides have also experienced at least moderate rates of earthquake activity in recorded times. Earthquakes in steep landslide-prone areas greatly increase the likelihood that landslides will occur, due to ground shaking alone, liquefaction of susceptible sediments, or shaking-caused dilation of soil materials, which allows rapid infiltration of water. For instance, the 1964 Great Alaska earthquake in the United States caused widespread landsliding and other ground failure, which led to most of the monetary loss attributed to the earthquake. Other areas in North America, such as the State of California, the Puget Sound region in Washington, and the St. Lawrence lowlands of eastern Canada, have experienced landslides, lateral spreading, and other types of ground failure classified as landslides, due to moderate to large earthquakes. Rockfalls and rock topples can also be caused by loosening of rocks or rocky formations as a result of earthquake ground shaking. Figure 27 shows damage from a landslide that was triggered by an earthquake. There is also a great danger of landslide dams forming in streams and rivers below steep slopes, a result of rock and earth being shaken down by the earthquake. These landslide dams often completely or partially block the flow of water, causing water to back up behind the landslide dam, flooding areas upriver. As these dams are often unstable, they may erode either quickly or over a period of time and fail catastrophically, unleashing the backed up water as a rapid deluge below the dam. This deluge is capable of causing a great deal of damage downriver.

Figures 32, 42, C53, C54, and C55 show examples of large landslide dams that still exist

Figure 27. Earthquake-induced landslide damage to a house built on artificial fill, after the 2004 Niigata Prefecture earthquake in Japan. (Photograph by Professor Kamai, Kyoto University, Japan.)

Landslides and Volcanic Activity

Landslides due to volcanic activity represent some of the most devastating types of failures. Volcanic lava may melt snow rapidly, which can form a deluge of rock, soil, ash, and water that accelerates rapidly on the steep slopes of volcanoes, devastating anything in its path. These volcanic debris flows (also known as lahars, an Indonesian term) can reach great distances after they leave the flanks of the volcano and can damage structures in flat areas surrounding the volcanoes. Volcanic edifices are young, unconsolidated, and geologically weak structures that in many cases can collapse and cause rockslides, landslides, and debris avalanches. Many islands of volcanic origin experience periodic failure of their perimeter areas (due to the weak volcanic surface deposits), and masses of soil and rock slide into the ocean or other water bodies, such as inlets. Such collapses may create massive sub-marine landslides that may also rapidly displace water, subsequently creating deadly tsunamis that can travel and do damage at great distances, as well as locally. Figure 28 shows a collapse of the side of a volcano and the resulting devastation.

Figure 28. The side of Casita Volcano in Nicaragua, Central America, collapsed on October 30, 1998, the day of peak rainfall as Hurricane Mitch moved across Central America. This lahar killed more than 2,000 people as it swept over the towns of El Porvenir and Rolando Rodriguez. (Photograph by K.M. Smith, U.S. Geological Survey.)

Human Activities

Populations expanding onto new land and creating neighborhoods, towns, and cities is the primary means by which humans contribute to the occurrence of landslides. Disturbing or changing drainage patterns, destabilizing slopes, and removing vegetation are common human-induced factors that may initiate landslides. Other examples include oversteepening of slopes by undercutting the bottom and loading the top of a slope to exceed the bearing strength of the soil or other component material. However, landslides may also occur in once-stable areas due to other human activities such as irrigation, lawn watering, draining of reservoirs (or creating them), leaking pipes, and improper excavating or grading on slopes. New construction on landslide-prone land can be improved through proper engineering (for example, grading, excavating) by first identifying the site's susceptibility to slope failures and by creating appropriate landslide zoning.

See Appendix A for an expanded, detailed list of causes/triggering mechanisms of landslides.

For further reading:
References 16, 19, 32, 38, 39, 43, and 45

Part E. What are the Effects and Consequences of Landslides?

Landslide effects occur in two basic environments: the built environment and the natural environment. Sometimes there is intersection between the two; for example agricultural lands and forest lands that are logged.

Effects of Landslides on the Built Environment

Landslides affect manmade structures whether they are directly on or near a landslide. Residential dwellings built on unstable slopes may experience partial damage to complete destruction as landslides destabilize or destroy foundations, walls, surrounding property, and above-ground and underground utilities. Landslides can affect residential areas either on a large regional basis (in which many dwellings are affected) or on an individual site basis (where only one structure or part of a structure is affected). Also, landslide damage to one individual property's lifelines (such as trunk sewer, water, or electrical lines and common-use roads) can affect the lifelines and access routes of other surrounding properties. Commercial structures are affected by landslides in much the same way residential structures are affected. In such a case, consequences may be great if the commercial structure is a common-use structure, such as a food market, which may experience an interruption in business due to landslide damage to the actual structure and (or) damage to its access roadways.

Note: In many areas of the world that provide private disaster insurance, damage from landslides is not covered in these insurance policies, and the costs of damages must be borne by the individual homeowner.

Fast-moving landslides such as debris flows are the most destructive type of landslide to structures, as they often occur without precursors or warnings, move too quickly for any mitigation measures to be enacted, and due to velocity and material are often very powerful and destructive. Fast-moving landslides can completely destroy a structure, whereas a slower moving landslide may only slightly damage it, and its slow pace may allow mitigation measures to be enacted. However, left unchecked, even slow landslides can completely destroy structures over time. Debris avalanches and lahars in steep areas can quickly destroy or damage the structures and lifelines of cities, towns, and (or) neighborhoods due to the fact that they are an extremely fast-moving, powerful force. The nature of landslide movement and the fact that they may continue moving after days, weeks, or months preclude rebuilding on the affected area, unless mitigative measures are taken; even then, such efforts are not always a guarantee of stability.

One of the greatest potential consequences from landslides is to the transportation industry, and this commonly affects large numbers of people around the world. Cut and fill failures along roadways and railways, as well as collapse of roads from underlying weak and slide-prone soils and fill, are common problems. Rockfalls may injure or kill motorists and pedestrians and damage structures. All types of landslides can lead to temporary or long-term closing of crucial routes for commerce, tourism, and emergency activities due to road or rail blockage by dirt, debris, and (or) rocks (fig. 29). Even slow creep can affect linear infrastructure, creating maintenance problems. Figure 29 shows a landslide blocking a major highway. Blockages of highways by landslides occur very commonly around the world, and many can simply be bulldozed or shoveled away. Others, such as the one shown in figure 29, will require major excavation and at least temporary diversion of traffic or even closure of the road.

As world populations continue to expand, they are increasingly vulnerable to landslide hazards. People tend to move on to new lands that might have been deemed too hazardous in the past but are now the only areas that remain for a growing population. Poor or nonexistent land-use policies allow building and other construction to take place on land that might better be left to agriculture, open-space parks, or uses other than for dwellings or other buildings and structures. Communities often are not prepared to regulate unsafe building practices and may not have the legitimate political means or the expertise to do so.

Figure 29. A landslide on the Pan American Highway in El Salvador, Central America, near the town of San Vicente, in 2001. (Photograph by Ed Harp, U.S. Geological Survey.)

Effects of Landslides on the Natural Environment

Landslides have effects on the natural environment:

- The morphology of the Earth's surface—mountain and valley systems, both on the continents and beneath the oceans; mountain and valley morphologies are most significantly affected by downslope movement of large landslide masses;
- The forests and grasslands that cover much of the continents; and
- The native wildlife that exists on the Earth's surface and in its rivers, lakes, and seas.

Figures 30, 31, and 32 show the very large areal extent of some landslides and how they may change the face of the terrain, affecting rivers, farmland, and forests.

Forest, grasslands, and wildlife often are negatively affected by landslides, with forest and fish habitats being most easily damaged, temporarily or even rarely, destroyed. However, because landslides are relatively local events, flora and fauna can recover with time. In addition, recent ecological studies have shown that, under certain conditions, in the medium-to-long term, landslides can actually benefit fish and wildlife habitats, either directly or by improving the habitat for organisms that the fish and wildlife rely on for food.

The following list identifies some examples of landslides that commonly occur in the natural environment:

- ***Submarine landslide*** is a general term used to describe the downslope mass movement of geologic materials from shallower to deeper regions of the ocean. Such events may produce major effects to the depth of shorelines, ultimately affecting boat dockings and navigation. These types of landslides can occur in rivers, lakes, and oceans. Large submarine landslides triggered by earthquakes have caused deadly tsunamis, such as the 1929 Grand Banks (off the coast of Newfoundland, Canada) tsunamis.
- ***Coastal cliff retreat***, or ***cliff erosion***, is another common effect of landslides on the natural environment. Rock-and-soil falls, slides, and avalanches are the common types of landslides affecting coastal areas; however, topples and flows also are known to occur. Falling rocks from eroding cliffs can be especially dangerous to anyone occupying areas at the base of cliffs, or on the beaches near the cliffs. Large amounts of landslide material can also be destructive to aquatic life, such as fish and kelp, and the rapid deposition of sediments in water bodies often changes the water quality around vulnerable shorelines.
- ***Landslide dams*** can naturally occur when a large landslide blocks the flow of a river, causing a lake to form behind the blockage. Most of these dams are short-lived as the water will eventually erode the dam. If the landslide dam is not destroyed by natural erosional processes or modified by humans, it creates a new landform—a lake. Lakes created by landslide dams can last a long time, or they may suddenly be released and cause massive flooding downstream. There are many ways that people can lessen the potential dangers of landslide dams, and some of these methods are discussed in the safety and mitigation sections of this volume. Figure 32 shows the Slumgullion landslide one of the largest landslides in the world—the landslide dam it has formed is so large and wide, that it has lasted 700 years. Figures C53, C54, and C55 (in Appendix C) also show aspects of another large landslide dam.

See Appendix C for more information on mitigating the effects of landslide dams.

For further reading:
References 4, 11, 14, 16, 19, 31, 35, 36, 39, and 43

Figure 30. The active volcano, Mount Shasta in California, USA. Note the landforms in the foreground, caused by a debris avalanche that occurred about 300,000 years ago. The debris avalanche traveled great distances from the volcano and produced lasting landform effects that can still be seen today. (Photograph by R. Crandall, U.S. Geological Survey.)

Figure 31. View looking downstream at the confluence of the Río Malo (flowing from lower left) and the Río Coca, northeastern Ecuador, in South America. Both river channels have been filled with sediment left behind by debris flows triggered by the 1987 Reventador earthquakes. Slopes in the area had been saturated by heavy rains in recent days before the earthquake. Debris/earth slides, debris avalanches, debris/mudflows, and resulting floods destroyed about 40 kilometers of the Trans-Ecuadorian oil pipeline and the only highway from Quito. (Photograph by R.L. Schuster, U.S. Geological Survey; information from Reference 32.)

Figure 32. The Slumgullion landslide, Colorado, USA. This landslide (formally referred to also as an earthflow) dammed the Lake Fork of the Gunnison River, which flooded the valley and formed Lake Cristobal. (Photograph by Jeff Coe, U.S. Geological Survey.)

Part F. Interrelationship of Landslides with Other Natural Hazards—The Multiple Hazard Effect

Natural hazards such as floods, earthquakes, volcanic eruptions, and landslides can occur simultaneously, or one or more of these hazards can trigger one or more of the others. Landslides are often the result of earthquakes, floods, and volcanic activity and may in turn cause subsequent hazards; for example, an earthquake-induced landslide can cause a deadly tsunami if sufficient landslide material slides into a body of water to displace a large volume of water. Another example would be a volcanic eruption-induced or earthquake-induced landslide that blocks a river, causing water to back up behind the mass and flood the upstream area. Should the dam fail, the impounded water will be suddenly unleashed to cause flooding downstream. This flooding can then add to riverbank and coastal erosion and destabilization through rapid saturation of slopes and undercutting of cliffs and banks. It is therefore imperative, when evaluating an area's vulnerability to landslides, to examine all other possible natural hazards. At this time, few maps exist that show multiple-hazard susceptibilities; for most areas, if hazards are mapped at all, only a single hazard is mapped.

Figures 33–35 show multi-hazard events involving landslides.

For further reading:
References 17, 20, 35, 39, 43, and 45

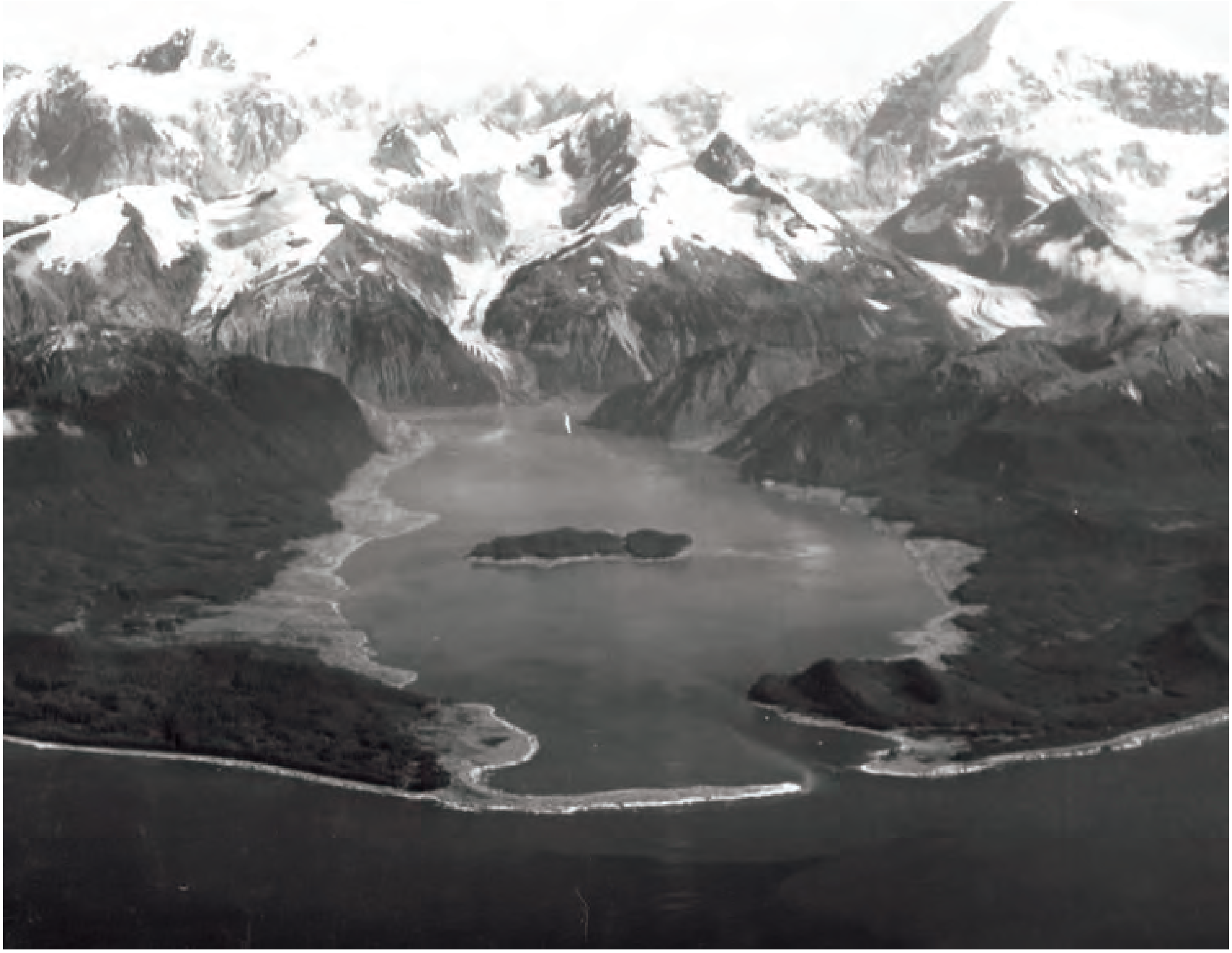


Figure 33. An example of a multi-hazard event. Photograph shows an aerial view of Lituya Bay, Alaska, USA. On July 9, 1958, an earthquake occurred which caused a landslide to enter the bay. The landslide in turn, caused a tsunami wave that had a run-up of 174 meters on the opposite shore, and a 30-meter wave passed beyond Lituya Bay. It is the largest landslide-generated wave ever documented. Note the extent of the nonforested areas of land lining the shore of the bay, which marks the approximate reach of the tsunami wave. (Photograph by D.J. Miller, U.S. Geological Survey.)

Figure 34. The 1999 multi-hazard event in Tanaguarena, in coastal Venezuela, South America. The floods and landslides were triggered by heavy rains. (Photograph by Matthew Larsen, U.S. Geological Survey.)

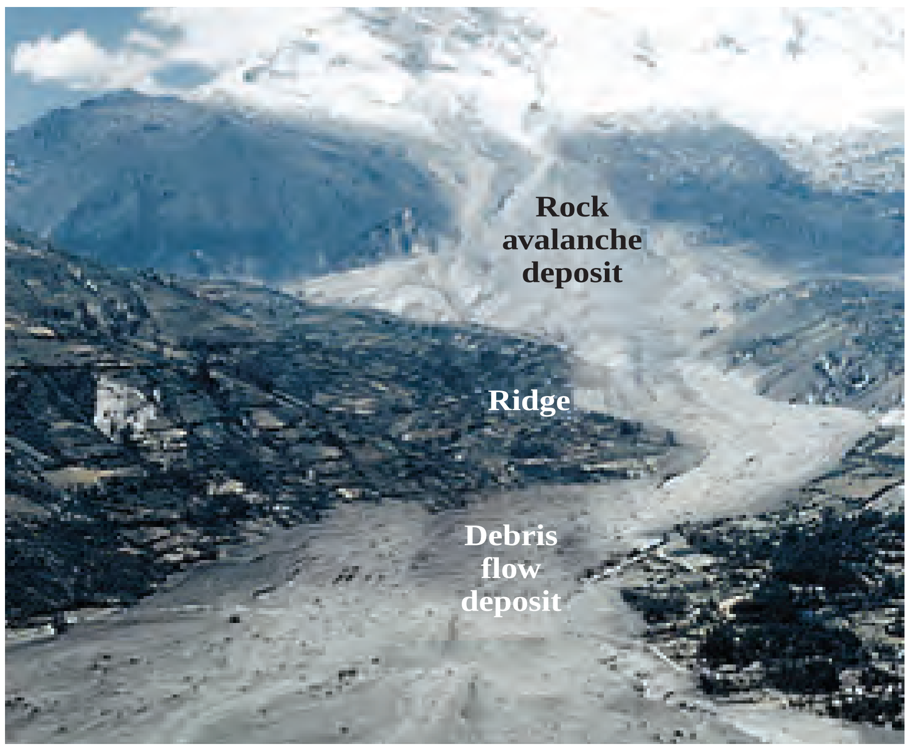


Figure 35. This is a photograph showing the aftereffects of a multi-hazard event. It is an aerial view showing part of the Andes Mountains and Nevado Huascaran, the highest peak in Peru, South America. A massive avalanche of ice and rock debris, triggered by the May 31, 1970, earthquake, buried the towns of Yungay and Ranrahirca, killing more than 20,000 people, about 40 percent of the total death toll of 67,000. The avalanche started with a sliding mass of glacial ice and rock about 1,000 meters (3,000 feet) wide and 1.6 kilometers (one mile) long that swept downslope about 5.4 kilometers (3.3 miles) to Yungay at average speed of more than 160 kilometers per hour. The ice picked up morainal material of water, mud, and rocks. (Photograph by Servicio Aerofotográfico National, graphics by George Plafker, U.S. Geological Survey.) Photograph and information from the U.S. Geological Survey Photographic Archives: *http://libraryphoto.cr.usgs.gov/*

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For more information concerning this publication, contact:
Team Chief Scientist, USGS Geologic Hazards
Box 25046, Mail Stop 966
Denver, CO 80225
(303)273-8579

Or visit the Geologic Hazards Team Web site at:
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