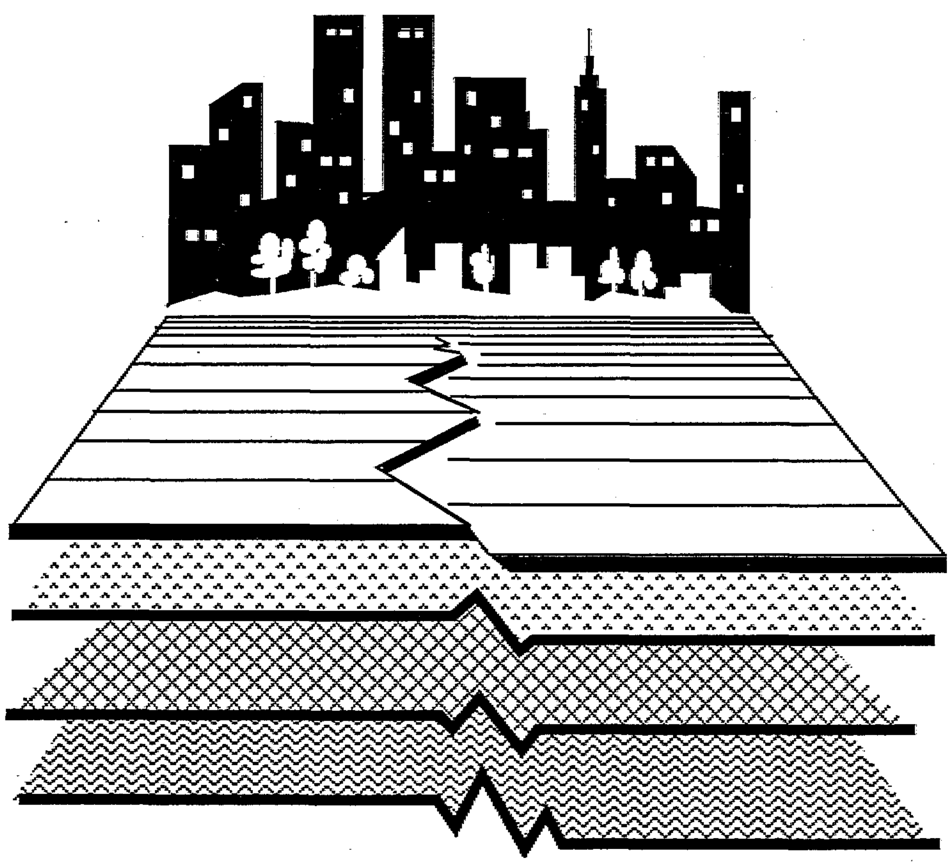
FEDERAL EMERGENCY MANAGEMENT AGENCY FEMA 182/August 1989

Landslide Loss Reduction:

A Guide for State and Local Government Planning



EARTHQUAKE HAZARDS REDUCTION SERIES 52

Issued by FEMA in furtherance of the Decade for Natural Disaster Reduction.

Landslide Loss Reduction:
A Guide for State and Local Government Planning

by:
Robert L. Wold, Jr.
Colorado Division of Disaster Emergency Services
and
Candace L. Jochim
Colorado Geological Survey

Contents

Contents Continued

Figures

Tables

Foreword

There is a need for a comprehensive program to reduce landslide losses in the United States that marshals the capability of all levels of government and the private sector. Without such a program, the heavy and widespread losses to the nation and to individuals from landslides will increase greatly. Successful and cost-effective landslide loss-reduction actions can and should be taken in the many jurisdictions facing landslide problems. The responsibility for dealing with landslides principally falls upon state and local governments and the private sector. The federal government can provide research, technical guidance, and limited funding assistance, but to meet their responsibility for maintaining the public's health, safety and welfare, state and local governments must prevent and reduce landslide losses through hazard mapping, land-use management, and building and grading controls. In partnership with public interest groups and governments, the private sector must also increase its efforts to reduce landslide hazards.

Dramatic landslide loss reduction can be achieved. The effective use of landslide building codes and grading ordinances by a few state and local governments in the nation clearly demonstrates that successful programs can be put into place with reasonable costs. Numerous examples of responsible landslide hazard planning and mitigation by private developers exist but are usually overshadowed by improper development that ignores the hazard.

Transfer of proven governmental and private sector landslide hazard mitigation techniques to other jurisdictions throughout the nation is one of the most effective ways of helping to reduce future landslide losses. This guide, prepared by the State of Colorado for the Federal Emergency Management Agency, builds upon the impressive efforts taken by Colorado state and local governments in planning for and mitigating landslide losses. The Federal Emergency Management Agency hopes that this guide and the accompanying plan for landslide hazard mitigation will stimulate and assist other state and local governments, private interests, and citizens throughout the nation to reduce the landslide threat.

Arthur J. Zeizel
Project Officer
Federal Emergency
Management Agency

Acknowledgments

This project was funded in part by the Federal Emergency Management Agency (FEMA), the Colorado Division of Disaster Emergency Services (DODES), the Colorado Geological Survey (CGS), and the U.S. Geological Survey (Grant No. 14–08–0001–A0420).

The document was written and prepared by **Robert L. Wold, Jr.** (DODES) and **Candace L. Jochim** (CGS). Staff contributors included: **William P. Rogers**, **Irwin M. Glassman**, and **John O. Truby**. Additional contributors included: **David B. Prior** of the Coastal Studies Institute of Louisiana State University and **William J. Kockelman** of the U.S. Geological Survey. Project management was provided by **Arthur Zeizel** (FEMA) and **Irwin Glassman** (DODES).

Other essential project personnel included: **Cheryl Brchan** (drafting and layout), **Nora Rimando** (word processing), and **David Butler** (editing).

Advisory Committee

John Beaulieu, *Deputy State Geologist, Oregon*

John P. Byrne, *Director, Disaster Emergency Services, Colorado*

William J. Kockelman, *Planner, U.S. Geological Survey, California*

Peter Lessing, *Environmental Geologist, West Virginia Geological Survey*

George Mader, *President, William Spangle and Associates, California*

Dr. Robert L. Schuster, *U.S. Geological Survey, Colorado*

Dr. James E. Slosson, *Chief Engineering Geologist, Slosson and Associates, California*

Darrell Waller, *State Coordinator, Bureau of Disaster Services, Idaho*

Chapter 1
Introduction

According to available information, landsliding in the United States causes an average of 25 to 50 deaths (Committee on Ground Failure Hazards, 1985) and $1 to $2 billion in economic losses annually (Schuster and Fleming, 1986). Although all 50 states are subject to landslide activity, the Rocky Mountain, Appalachian, and Pacific Coast regions generally suffer the greatest landslide losses (Figures 1a, b). The costs of landsliding can be direct or indirect and range from the expense of cleanup and repair or replacement of structures to lost tax revenues and reduced productivity and property values.

Landslide losses are growing in the United States despite the availability of successful techniques for landslide management and control. The failure to lessen the problem is primarily due to the ever-increasing pressure of development in areas of geologically hazardous terrain and the failure of responsible government entities and private developers to recognize landslide hazards and to apply appropriate measures for their mitigation, even though there is overwhelming evidence that landslide hazard mitigation programs serve both public and private interests by saving many times the cost of implementation. The high cost of landslide damage (Table 1) will continue to increase if community development and capital investments continue without taking advantage of the opportunities that currently exist to mitigate the effects of landslides.

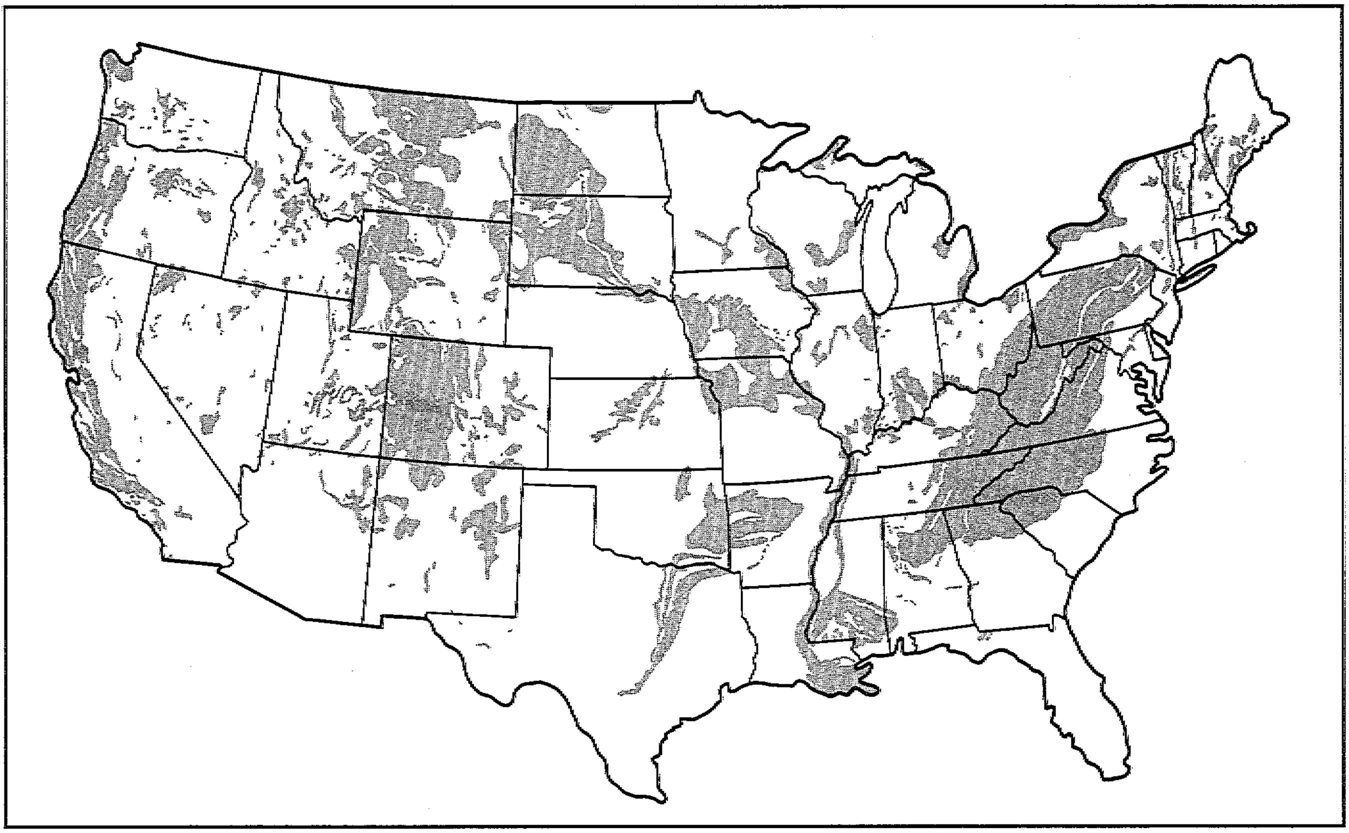


Figure 1a. Map showing relative potential of different parts of the conterminous United States to landsliding (U.S. Geological Survey, 1981a).

Table 1. Estimates of minimum amounts of landslide damage in the United States, 1973–1983, in millions of dollars. All figures are estimates. Figures queried are very rough estimates (adapted from Brabb, 1984).

	Damage 1973–1983			
State	State Roads ($M)	Priv. Prop. ($M)	Total ($M)	Ann. Avg. ($M)
Alabama	10.0	0.5	10.5	1.05
Alaska	10.0	0.0	10.0	1.0
Arizona	2.0	0.0	2.0	0.2
Arkansas	2.0	0.0	2.0	0.2
California	800.0 ?	200.0 ?	1000.0 ?	100.0 ?
Colorado	20.0	50.0	70.0	7.0
Connecticut	0.0	0.0	0.0	0.0
Delaware	2.0	0.0	2.0	0.2
Dist. of Columbia	0.1	0.1	0.01	0.8
Florida	0.0	0.0	0.0	0.0
Georgia	1.0 ?	0.0	1.0 ?	0.1 ?
Hawaii	4.0	0.5	4.5	0.45
Idaho	10.0 ?	1.0 ?	11.0 ?	1.1 ?
Illinois	1.0	1.0 ?	2.0 ?	0.2 ?
Indiana	10.0	1.0	11.0	1.1
Iowa	1.0	0.3	1.3	0.13
Kansas	1.0	0.3 ?	1.3 ?	0.13
Kentucky	180.0	10.0 ?	190.0 ?	19.0 ?
Louisiana	2.0	0.3	2.3	0.23
Maine	0.3	0.3	0.6	0.06
Maryland	20.0	0.0	20.0	2.0
Massachusetts	0.3	0.0	0.3	0.03
Michigan	0.1	0.0	0.1	0.01
Minnesota	7.0	0.0	7.0	0.7
Mississippi	3.0	0.5	3.5	0.35
Missouri	2.0 ?	1.0 ?	3.0 ?	0.3 ?
Montana	10.0 ?	1.0 ?	11.0 ?	1.1 ?
Nebraska	0.4	0.4 ?	0.8 ?	0.08 ?
Nevada	2.0 ?	0.5	2.5 ?	0.25 ?
New Hampshire	10.0	0.0	10.0	1.0
New Jersey	3.0	3.0	6.0	0.6
New Mexico	3.0	1.0	4.0	0.4
New York	20.0	50.0 ?	70.0 ?	7.0 ?
North Carolina	45.0	0.5	45.5	4.55
North Dakota	4.0	0.0	4.0	0.4
Ohio	60.0 ?	40.0	100.0 ?	10.0
Oklahoma	2.0 ?	0.0	2.0 ?	0.2 ?
Oregon	30.0	10.0	40.0	4.0
Pennsylvania	50.0	10.0 ?	60.0 ?	6.0
Rhode Island	0.0	0.0	0.0	0.0
South Carolina	0.0	0.0	0.0	0.0
South Dakota	16.0	2.0	18.0	1.8
Tennessee	100.0	10.0 ?	110.0 ?	11.0 ?
Texas	8.0	0.0	8.0	0.8
Utah	200.0 ?	10.0 ?	210.0 ?	21.0 ?
Vermont	3.0	0.5	3.5	0.35
Virginia	11.0	1.0	12.0	1.2
Washington	70.0 ?	30.0 ?	100.0 ?	10.0 ?
West Virginia	270.0	5.0	275.0	27.5
Wisconsin	0.2	0.5	0.7	0.07
Wyoming	4.0	0.0	4.0	0.4
Total (U.S.)	**2010.3**	**442.2**	**2452.5**	**245.25**

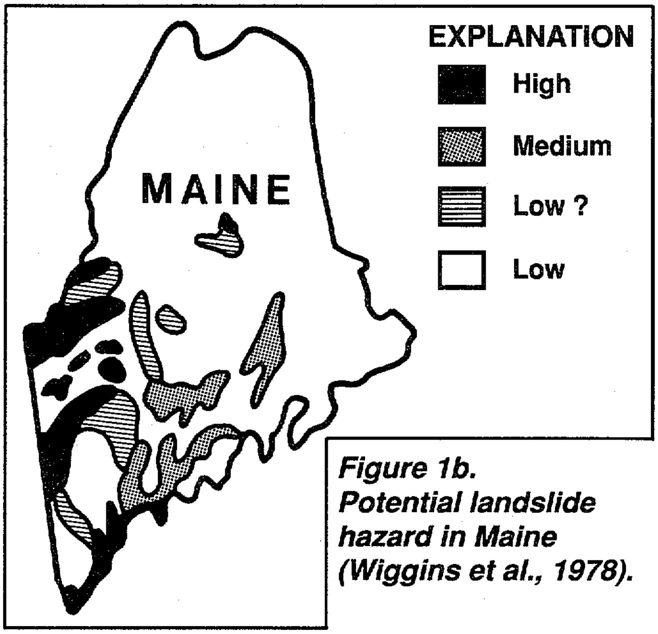


Figure 1b. Potential landslide hazard in Maine (Wiggins et al., 1978).

The widespread occurrence of landsliding, together with the potential for catastrophic statewide and regional impacts, emphasizes the need for cooperation among federal, state, and local governments and the private sector. Although annual landslide losses in the U.S. are extremely high, significant reductions in future losses can be achieved through a combination of landslide hazard mitigation and emergency management.

Landslide hazard mitigation consists of those activities that reduce the likelihood of occurrence of damaging landslides and minimize the effects of the landslides that do occur. The goal of emergency management is to minimize loss of life and property damage through the timely and efficient commitment of available resources.

Despite their common goals, emergency management and hazard mitigation activities have historically been carried out independently. The integration of these two efforts is most often demonstrated in the recovery phase following a disaster, when decisions about reconstruction and future land uses in the community are made.

> Emergency management, if well executed, can do much to minimize the loss and suffering associated with a particular disaster. However, unless it is guided by the goals of preventing or reducing long-term hazard losses, it is unlikely to reduce the adverse impact of future disasters

significantly. This is where mitigation becomes important (Advisory Board on the Built Environment, 1983, p. 9).

Purpose of this Guidebook

As mentioned above, the development and implementation of landslide loss-reduction strategies requires the cooperation of many public and private institutions, all levels of government, and private citizens. Coordinated and comprehensive systems for landslide hazard mitigation do not currently exist in most states and communities faced with the problem. In most states, local governments often take the lead by identifying goals and objectives, controlling land use, providing hazard information and technical assistance to property owners and developers, and implementing mitigation projects as resources allow. State and federal agencies play supporting roles—primarily financial, technical, and administrative. In some cases, however, legislation originating at the state or federal level is the sole impetus for stimulating effective local mitigation activity.

In many states there remains a need to develop long-term organizational systems at state and local levels to deal with landslide hazard mitigation in a coordinated and systematic manner. The development of a landslide hazard mitigation plan can be the initial step in the establishment of state and local programs that promote long-term landslide loss reduction.

The purpose of this guidebook is to provide a practical, politically feasible guide for state and local officials involved in landslide hazard mitigation. The guidebook presents concepts and a framework for the preparation of state and local landslide hazard mitigation plans. It outlines a basic methodology, provides information on available resources, and offers suggestions on the formation of an interdisciplinary mitigation planning team and a permanent state natural hazards mitigation organization. Individual states and local jurisdictions can adapt the suggestions in this book to meet their own unique needs.

Because of its involvement in identifying and mitigating landslide hazards, the state of Colorado was selected by the Federal Emergency Management Agency (FEMA) to produce a prototype state landslide hazard mitigation plan. The technical information contained in the plan was designed to be transferable to other states and local jurisdictions and suitable for incorporation into other plans. The planning process can also serve as an example to other states and localities dealing with landslide problems. The materials contained in the Colorado Landslide Hazard Mitigation Plan (Colorado Geological Survey et al., 1988) were intended to complement the information presented in this guidebook. In an effort to promote landslide hazard mitigation nationally, FEMA has provided for the distribution of these two documents to all states. ❑

Chapter 2
Landslide Losses and the Benefits of Mitigation

The Landslide Hazard

Landsliding is a natural process which occurs and recurs in certain geologic settings under certain conditions. The rising costs of landslide damages are a direct consequence of the increasing vulnerability of people and structures to the hazard. In most regions, the overall rate of occurrence and severity of naturally caused landslides has not increased. What has increased is the extent of human occupation of these lands and the impact of human activities on the environment. Many landslide damages that have occurred might have been prevented or avoided if accurate landslide hazard information had been available and used.

Economic and Social Impacts of Landsliding

Costs of Landsliding

The most commonly cited figures on landslide losses are $1 to $2 billion in economic losses and 25 to 50 deaths annually. However, these figures are probably conservative because they were generated in the late 1970s. Since that time, the use of marginally suitable land has increased, as has inflation. Furthermore, there are no exhaustive compilations of landslide loss data for the United States, so these figures are basically extrapolations of the available data.

The high losses from landsliding are illustrated in Table 1. Surveys indicate that damage to private property accounts for 30 to 50 percent of the total costs (U.S. Geological Survey, 1982). Examples of costs associated with individual landslide events from representative areas across the country include:

ALASKA—It has been estimated (Youd, 1978) that 60 percent of the $300 million damage from the 1964 Alaska earthquake was the direct result of landslides.

CALIFORNIA—In 1982 in the San Francisco Bay Region, 616 mm (24.3 in.) of rain fell in 34 hours causing thousands of landslides which killed 25 people and caused more than $66 million in damage (Keefer et al., 1987).

TEXAS—In Dallas in the 1960s, a toppling failure occurred in a vertical exposure of a geological formation known as the Austin Chalk. This closed two lanes of a major downtown thoroughfare for eight months. Costs of construction of remedial measures and construction delays amounted to about $2.8 million (Allen and Flanigan, 1986).

UTAH—In 1983, a massive landslide dammed Spanish Fork Canyon, creating a lake. The landslide buried sections of the Denver and Rio Grande Western Railroad and U.S. Highways 6, 50, and 89 and inundated the town of Thistle. The estimated total losses and reconstruction costs due to this one landslide range from $200 million (University of Utah, Bureau of Economic and Business Research, 1984) to $600 million (Kaliser and Slosson, 1988).

WEST VIRGINIA—In 1975, landslide movements in colluvial soil damaged 56 houses in McMechen, West Virginia, located on a hillside above the Ohio River. This landslide was attributed to above normal precipitation. Mitigation was accomplished by grading and surface and subsurface drainage (Gray and Gardner, 1977).

Impacts and Consequences of Landsliding

Economic losses due to landsliding include both direct and indirect costs. Schuster and Fleming (1986) define direct costs as the costs of replacement, repair, or maintenance due to damage to property or facilities within the actual boundaries of a landslide (Figure 2). Such facilities include highways, railroads, irrigation canals, underwater communication cables, offshore oil platforms, pipelines, and dams. The cost of cleanup must also be included (Figure 3). All other landslide costs are considered to be indirect. Examples of indirect costs given by Schuster and Fleming (1986) include:

(1) reduced real estate values,
(2) loss of productivity of agricultural or forest lands,
(3) loss of tax revenues from properties devalued as a result of landslides,
(4) costs of measures to prevent or mitigate future landslide damage,
(5) adverse effects on water quality in streams,
(6) secondary physical effects, such as landslide-caused flooding, for which the costs are both direct and indirect,
(7) loss of human productivity due to injury or death.

Other examples are:

(8) fish kills,
(9) costs of litigation.

In addition to economic losses, there are intangible costs of landsliding such as personal stress, reduced quality of life, and the destruction of personal possessions having great sentimental value. Because costs of indirect and intangible losses are difficult or impossible to calculate, they are often undervalued or ignored. If they are taken into account, they often produce highly variable estimates of damage for a particular incident.

Figure 2. Major damage to homes in Farmington, Utah as a result of 1983 Rudd Creek mudslide (photograph by Robert Kistner, Kistner and Associates).

Figure 3. Local volunteers form "bucket brigade" to help clean mud and debris from homes in Farmington, Utah in 1983 (photograph by Robert Kistner, Kistner and Associates).

Long–Term Benefits of Mitigation

Studies have been conducted to estimate the potential savings when measures to minimize the effects of landsliding are applied. One early study by Alfors et al. (1973) attempted to forecast the potential costs of landslide hazards in California for the period 1970-2000 and the effects of applying mitigative measures. Under the conditions of applying all feasible measures at state-of-the-art levels (for the 1970s), there was a 90 percent reduction in losses for a benefit/cost ratio of 8.7:1, or $8.7 saved for every $1 spent. Nilsen and Turner (1975) estimated that approximately 80 percent of the landslides in Contra Costa County, California are related to human activity. In Allegheny County, Pennsylvania, 90 percent are related to such activity according to Briggs et al. (1975).

Because most landslides triggered by man are directly related to construction activities, appropriate grading codes can significantly decrease landslide losses in urban areas. Slosson (1969) compared landslide losses in Los Angeles for those sites constructed prior to 1952, when no grading codes existed and soils engineering and engineering geology were not required, with losses sustained at sites after such codes were enacted. He found that the monetary losses were reduced by approximately 97 percent.

The Cincinnati, Ohio Study

In 1985, the U.S. Geological Survey, in cooperation with the Federal Emergency Managament Agency, conducted a geologic/economic development study in the Cincinnati, Ohio area. This study developed a systematic approach to quantitative forecasting of probable landslide activity. Landslide probabilities derived from a reproducible procedure were combined with property value data to forecast the potential economic losses in scenarios for proposed development and to quantitatively identify the potential benefits of mitigation activities.

The study area was divided into 14,255 grid cells of 100-square meters each. Information calculated for each cell included: probability of landslide occurrence, economic loss in the event of a landslide, cost of mitigation, and economic benefit of mitigation. This information was used to develop a mitigation strategy. In areas where both slope and shear strength information were available, the optimum strategy required mitigation in those cells with slopes steeper than 14 degrees or where materials had effective residual stress friction angles of less than 26 degrees. This strategy yielded $1.7 million in estimated annualized net benefits for the community. In areas where only slope information was used, the best strategy required mitigation in those cells where slopes were greater than 8 degrees. This yielded an estimated annualized net benefit of $1.4 million. Therefore, using regional geologic information in addition to slope information resulted in an additional $300,000 net benefit. The Cincinnati study cost only $20,000 to prepare (Bernknopf et al., 1985).

The Benefits of Mitigation in Japan

Japan has what is considered by many to be the world's most comprehensive landslide loss reduction program. In 1958, the Japanese government enacted strong legislation that provided for land-use planning and the construction of check dams, drainage systems, and other physical controls to prevent landslides. The success of the program is indicated by the dramatic reduction in losses over time (Figure 4). In 1938, 130,000 homes were destroyed and more than 500 lives were lost due to landslides in the Kobe area. However, since the Japanese program went into effect, losses have decreased dramatically. In 1976—one of Japan's worst years for landsliding—only 2000 homes were destroyed with fewer than 125 lives lost (Schuster and Fleming, 1986).

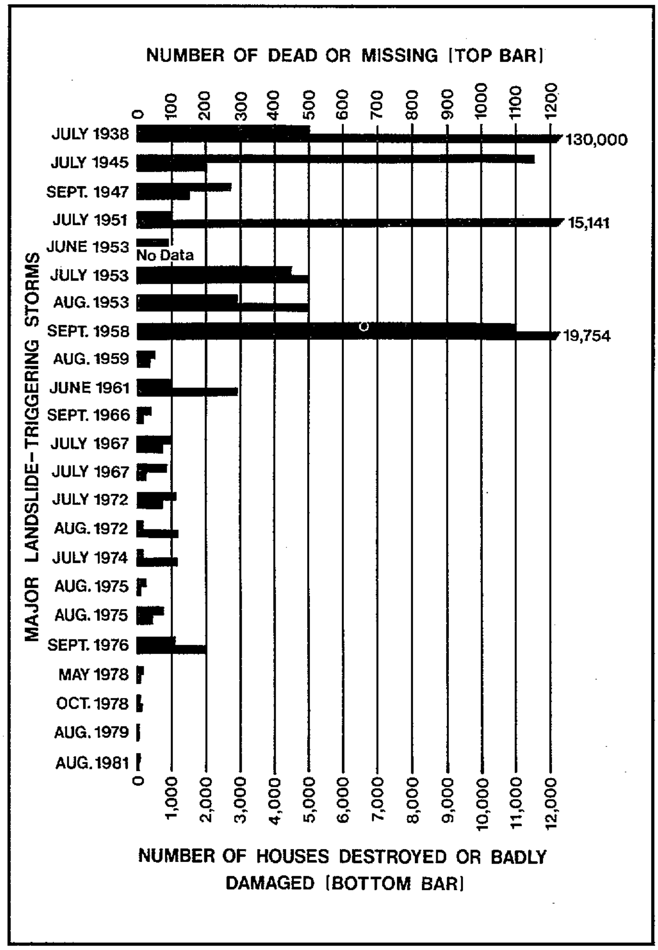


Figure 4. Losses due to major landslide disasters (mainly debris flows) in Japan from 1938–1981. All of these landslides were caused by heavy rainfall, most commonly related to typhoons, and many were associated with catastrophic flooding (data from Ministry of Construction, Japan, 1983).

Planning as a Means of Loss Reduction

The extent and severity of the landslide hazard in a particular area will determine the need for a landslide hazard mitigation plan.

> Communities that have landslide problems are encouraged to assess the costs of damage to public and private property and weigh those costs against the costs of a landslide reduction program. The prevention of a single major landslide in a community may more than compensate for the effort and cost of implementing a control program (Fleming and Taylor, 1980, p. 20).

Avoiding the costs of litigation is an additional incentive to undertaking a local program of landslide hazard mitigation.

When landslide disasters do occur, the existence of a program for loss reduction should help ensure that redevelopment planning takes existing geologic hazards into account.

In the U.S., only a few communities have established successful landslide loss reduction programs. The most notable is Los Angeles, where, as mentioned above, loss reductions of 97 percent have been achieved for new construction since the implementation of modern grading regulations (Slosson and Krohn, 1982).

In communities that have achieved loss reductions, decisions about building codes, zoning, and land use take into account identified landslide hazards. The U.S. Geological Survey (1982) has found that these communities have in common four preconditions leading to successful mitigation programs: (1) an adequate base of technical information about the local landslide problem, (2) an "able and concerned" local government, (3) a technical community able to apply and add to the technical planning base, and (4) an informed population that supports mitigation program objectives. While the technical expertise to reduce landslide losses is currently available in most states, in many cases it is not being utilized. Still, the success of loss reduction measures clearly depends upon the will of leaders to promote and support mitigation initiatives.

Local Government Roles

At the local government level, hazard mitigation is often a controversial issue. Staff and elected officials of local governments are usually subjected to diverse and sometimes conflicting pressures regarding land use and development. Local officials, as well as builders, realtors, and other parties in the development process, are increasingly being held liable for actions, or failures to act, that are determined to contribute to personal injuries and property damages caused by natural hazards. Consequently, a model community landslide hazard management planning process should encourage citizen participation and review in order to identify and address the perspectives and concerns of the various community groups affected by landslide hazards.

Because most landslide damages are related to human activity—mainly the construction of roads, utilities, homes, and businesses—the best opportunities for reducing landslide hazards are found in land-use planning and the administration and enforcement of codes and ordinances.

The vulnerability of people to natural hazards is determined by the relationship between the occurrences of extreme events, the proximity of people to these occurrences, and the degree to which the people are prepared to cope with these extremes of nature. The concept of a hazard as the intersection of the human system and the physical system, is illustrated in Figure 5. Only when these two systems are in conflict, does a landslide represent a hazard to public health and safety.

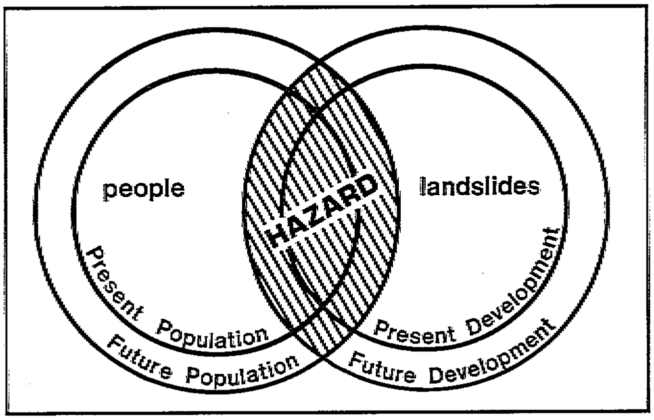


Figure 5. The relationship of people, landslides, and hazards (modified from Colorado Water Conservation Board et al., 1985).

The effectiveness of local landslide mitigation programs is generally tied to the ability and determination of local officials to apply the mitigation techniques available to them to limit and guide growth in hazardous areas. A list of 27 techniques that planners and managers may use to reduce landslide hazards in their communities is presented in Table 2. The key to achieving loss reduction is the identification and implementation of specific mitigation initiatives, as agreed upon and set forth in a local or state landslide hazard mitigation plan.

Table 2. Techniques for reducing landslide hazards (Kockelman, 1986).

Discouraging new developments in hazardous areas by:
- Disclosing the hazard to real-estate buyers
- Posting warnings of potential hazards
- Adopting utility and public-facility service-area policies
- Informing and educating the public
- Making a public record of hazards

Removing or converting existing development through:
- Acquiring or exchanging hazardous properties
- Discontinuing nonconforming uses
- Reconstructing damaged areas after landslides
- Removing unsafe structures
- Clearing and redeveloping blighted areas before landslides

Providing financial incentives or disincentives by:
- Conditioning federal and state financial assistance
- Clarifying the legal liability of property owners
- Adopting lending policies that reflect risk of loss
- Requiring insurance related to level of hazard
- Providing tax credits or lower assessments to property owners

Regulating new development in hazardous areas by:
- Enacting grading ordinances
- Adopting hillside-development regulations
- Amending land-use zoning districts and regulations
- Enacting sanitary ordinances
- Creating special hazard-reduction zones and regulations
- Enacting subdivision ordinances
- Placing moratoriums on rebuilding

Protecting existing development by:
- Controlling landslides and slumps
- Controlling mudflows and debris-flows
- Controlling rockfalls
- Creating improvement districts that assess costs to beneficiaries
- Operating monitoring, warning, and evacuating systems

Although certain opportunities for reducing landslide losses exist at the state government level (selection of sites for schools, hospitals, prisons, and other public facilities; public works projects that protect highways and state property), the greatest potential for mitigation is in the routine operations of local government: the adoption and enforcement of grading and construction codes and ordinances, the development of land-use and open-space plans, elimination of nonconforming uses, limitation of the extension of public utilities, etc. For this reason, state mitigation plans should emphasize mitigation activities that will essentially encourage and support local efforts. Local mitigation plans should provide guidelines and schedules for accomplishing local mitigation projects, as well as identify projects beyond local capability that should be considered in the state plan. ❑

Chapter 3
Causes and Types of Landslides

What is a Landslide?

The term "landslide" is used to describe a wide variety of processes that result in the perceptible downward and outward movement of soil, rock, and vegetation under gravitational influence. The materials may move by: falling, toppling, sliding, spreading, or flowing.

Although landslides are primarily associated with steep slopes, they also can occur in areas of generally low relief. In these areas landslides occur as cut-and-fill failures (highway and building excavations), river bluff failures, lateral spreading landslides, the collapse of mine-waste piles (especially coal), and a wide variety of slope failures associated with quarries and open-pit mines. Underwater landslides on the floors of lakes or reservoirs, or in offshore marine settings, also usually involve areas of low relief and small slope gradients.

Why Do Landslides Occur?

Landslides can be triggered by both natural and man-induced changes in the environment. The geologic history of an area, as well as activities associated with human occupation, directly determines, or contributes to the conditions that lead to slope failure. The basic causes of slope instability are fairly well known. They can be **inherent**, such as weaknesses in the composition or structure of the rock or soil; **variable**, such as heavy rain, snowmelt, and changes in ground-water level; **transient**, such as seismic or volcanic activity; or **due to new environmental conditions**, such as those imposed by construction activity (Varnes and the International Association of Engineering Geology, 1984).

Human Activities

Human activities triggering landslides are mainly associated with construction and involve changes in slope and in surface-water and ground-water regimes. Changes in slope result from terracing for agriculture, cut-and-fill construction for highways, the construction of buildings and railroads, and mining operations. If these activities and facilities are ill-conceived, or improperly designed or constructed, they can increase slope angle, decrease toe or lateral support, or load the head of an existing or potential landslide. Changes in irrigation or surface runoff can cause changes in surface drainage and can increase erosion or contribute to loading a slope or raising the ground-water table (Figure 6). The ground-water table can also be raised by lawn watering, waste-water effluent from leach fields or cesspools, leaking water pipes, swimming pools or ponds, and application or conveyance of irrigation water. A high ground-water level results in increased pore-water pressure and decreased shear strength, thus facilitating slope failure. Conversely, the lowering of the ground-water table as a result of rapid drawdown by water supply wells, or the lowering of a lake or reservoir, can also cause slope failure as the buoyancy provided by the water decreases and seepage gradients steepen.

Natural Factors

There are a number of natural factors that can cause slope failure. Some of these, such as long-term or cyclic climate changes, are not discernible without instrumentation and/or long-term record-keeping.

Climate

Long-term climate changes can have a significant impact on slope stability. An overall decrease in precipitation results in a lowering of the water table, as well as a decrease in the weight of the soil mass, decreased solution of materials, and less intense freeze-thaw activity. An increase in precipitation or ground saturation will raise the level of the ground-water

Figure 6.
Aerial view of the Savage Island landslide on the east shore of the Columbia River, Washington, 1981. This landslide was caused by irrigation water (photograph by Robert L. Schuster, U.S. Geological Survey).

table, reduce shear strength, increase the weight of the soil mass, and may increase erosion and freeze-thaw activity. Periodic high-intensity precipitation and rapid snowmelt can signifcantly increase slope instability temporarily (Figure 7).

Erosion

Erosion by intermittent running water (gully ing), streams, rivers, waves or currents, wind, and ice removes toe and lateral slope support of potential landslides.

Weathering

Weathering is the natural process of rock deterioration which produces weak, landslide-prone materials. It is caused by the chemical action of air, water, plants, and bacteria and the physical

Figure 7.
The remains of a house where three children died in a mudflow in Kanawha City, West Virginia. The movement was triggered by heavy rainfall from a cloudburst on July 9, 1973 (Lessing et al., 1976).

action brought on by changes in temperature (expansion and shrinkage), the freeze-thaw cycle, and the burrowing activity of animals.

Earthquakes
Earthquakes not only trigger landslides, but, over time, the tectonic activity causing them can create steep and potentially unstable slopes.

Rapid sedimentation
Rivers supply very large amounts of sediment to deltas in lakes and coastal areas. The rapidly deposited sediments are frequently underconsolidated, and have excess pore-water pressures and low strengths. Such deltaic sediments are often prone to underwater delta-front landsliding, especially where the sediments are rich in clay and/or contain gas from organic decomposition.

Wind-generated waves
Storm waves in coastal areas are known to trigger underwater landsliding in deltas by cyclically loading weak bottom sediments.

Tidal or river drawdown
Rapid lowering of water level in coastal areas or along river banks due to tides or river discharge fluctuations can cause underwater landsliding. The process in which weak river bank or deltaic sediments are left unsupported as the water level drops is known as "drawdown."

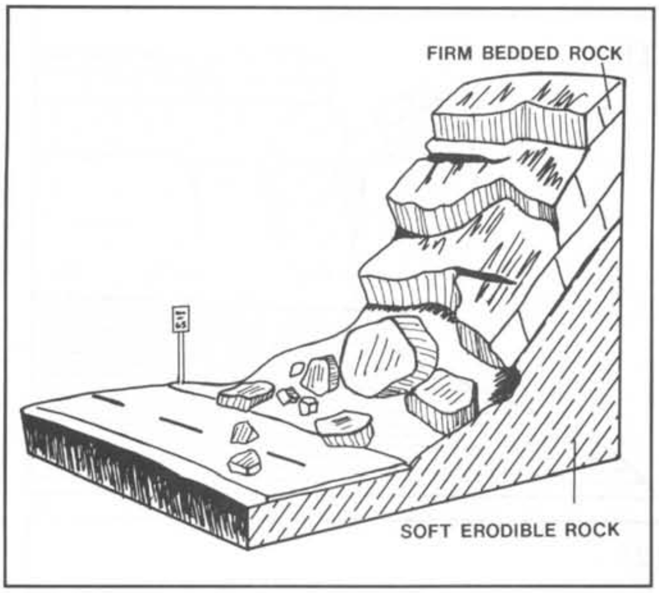


Figure 8a. Rockfall (Colorado Geological Survey et al., 1988).

Figure 8b. Rockfall on U.S. Highway 6, Colorado (photograph by Colorado Geological Survey).

Types of Landslides
The most common types of landslides are described below. These definitions are based mainly on the work of Varnes (1978).

Falls
Falls are abrupt movements of masses of geologic materials that become detached from steep slopes or cliffs (Figures 8a, b). Movement occurs by free-fall, bouncing, and rolling. Depending on the type of earth materials involved, the result is a rockfall, soilfall, debris fall, earth fall, boulder fall, and so on. All types of falls are promoted by undercutting, differential weathering, excavation, or stream erosion.

Topple
A topple is a block of rock that tilts or rotates forward on a pivot or hinge point and then separates from the main mass, falling to the slope below, and subsequently bouncing or rolling down the slope (Figures 9a, b).

Slides
Although many types of mass movement are included in the general term "landslide," the more restrictive use of the term refers to movements of soil or rock along a distinct surface of rupture which separates the slide material from more stable underlying material. The two major types of landslides are rotational slides and translational slides.

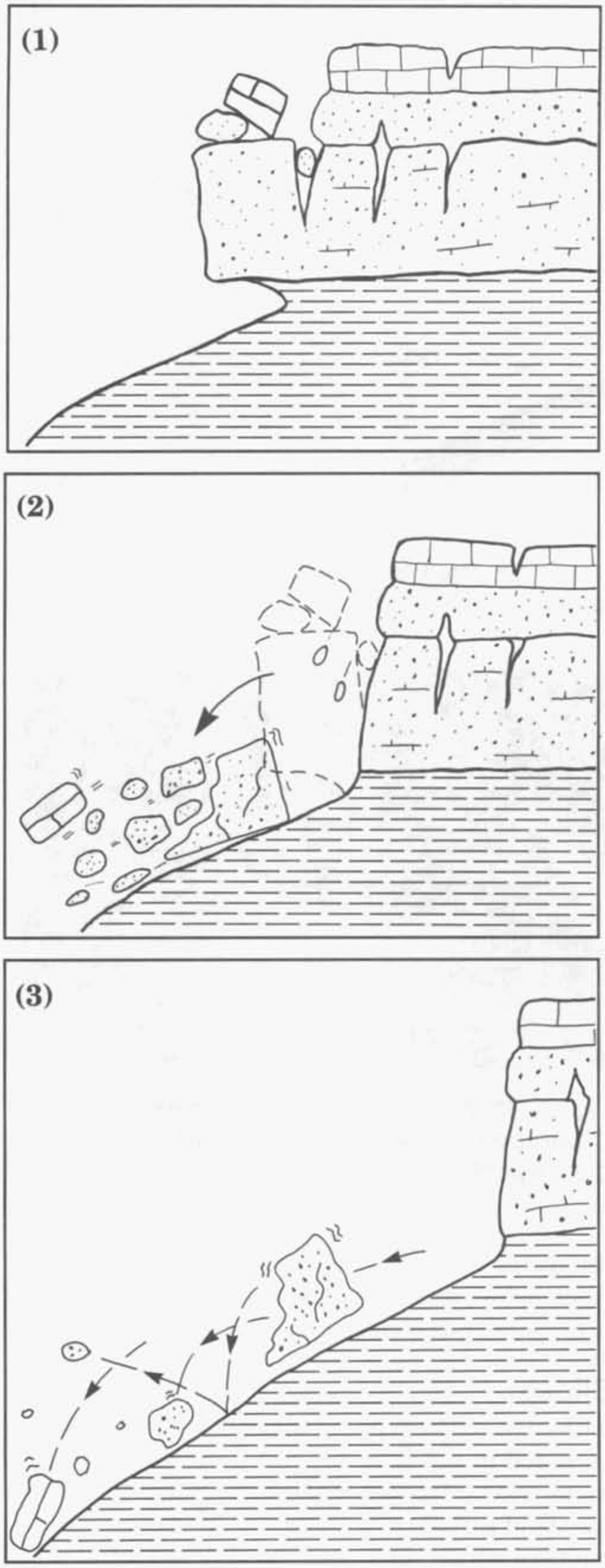


Figure 9a. Topple (Colorado Geological Survey et al., 1988).

Figure 9b. Topple, western Colorado (photograph by Colorado Geological Survey).

Rotational slide

A rotational slide is one in which the surface of rupture is curved concavely upward (spoon shaped) and the slide movement is more or less rotational about an axis that is parallel to the contour of the slope (Figures10a, b). A "slump" is an example of a small rotational slide.

Translational slide

In a translational slide, the mass moves out, or down and outward along a relatively planar surface and has little rotational movement or backward tilting (Figure 11). The mass commonly slides out on top of the original ground surface. Such a slide may progress over great

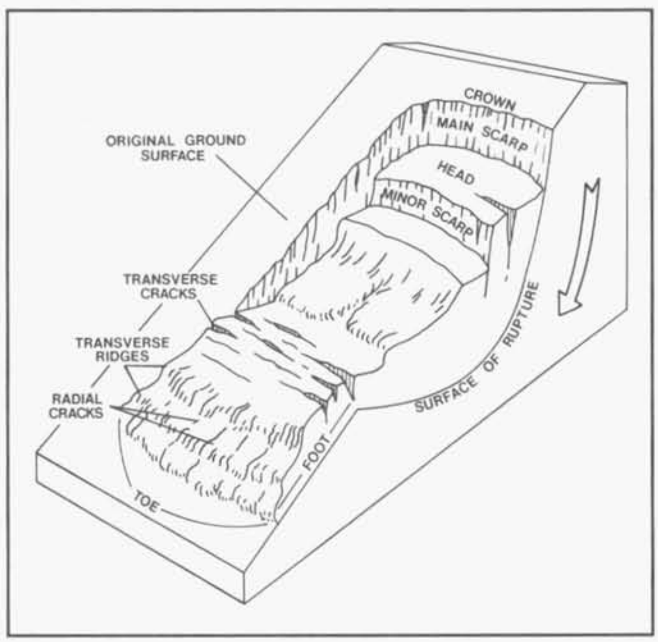


Figure 10a. Rotational landslide (modified from Varnes, 1978).

Figure 10b. Rotational landslide, Golden, Colorado (photograph by Colorado Geological Survey).

distances if conditions are right. Slide material may range from loose unconsolidated soils to extensive slabs of rock.

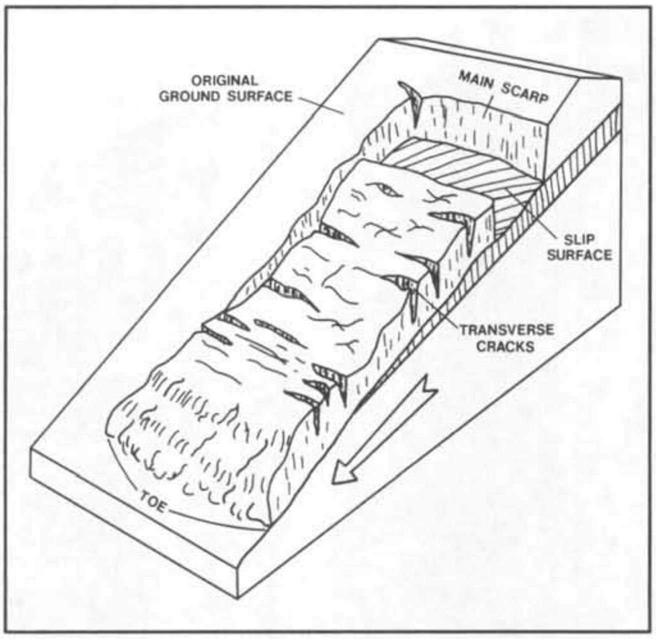


Figure 11. Translational slide (Colorado Geological Survey et al., 1988).

Block Slide. A block slide is a translational slide in which the moving mass consists of a single unit, or a few closely related units that move downslope as a single unit (Figure 12).

Lateral Spreads

Lateral spreads (Figures 13a, b) are a result of the nearly horizontal movement of geologic materials and are distinctive because they usually occur on very gentle slopes. The failure is caused by liquefaction, the process whereby saturated, loose, cohesionless sediments (usually sands and silts) are transformed from a solid into a liquefied state; or plastic flow of subjacent material. Failure is usually triggered by rapid ground motion such as that experienced during an earthquake, or by slow chemcal changes in the pore water and mineral constituents.

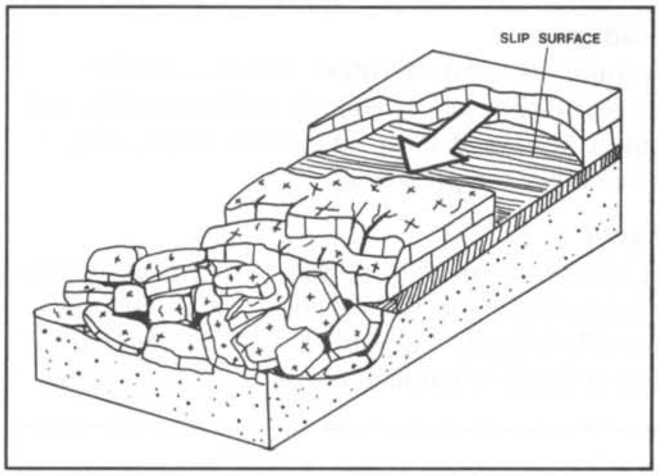


Figure 12 . Block slide (Colorado Geological Survey et al., 1988).

Flows

Creep

Creep is the imperceptibly slow, steady downward movement of slope-forming soil or rock. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or terracettes (Figures 14a, b).

Debris flow

A debris flow is a form of rapid mass movement in which loose soils, rocks, and organic matter combine with entrained air and water to form a slurry that then flows downslope. Debris-flow areas are usually associated with steep gullies. Individual debris-flow areas can usually be identified by the presence of debris fans at the termini of the drainage basins (Figure 15).

Debris avalanche

A debris avalanche is a variety of very rapid to extremely rapid debris flow.

Earthflow

Earthflows have a characteristic "hourglass" shape (Figures 16a, b). A bowl or depression forms at the head where the unstable material collects and flows out. The central area is narrow and usually becomes wider as it reaches the valley floor. Flows generally occur in fine-grained materials or clay-bearing rocks on moderate slopes and with saturated conditions. However, dry flows of granular material are also possible.

Mudflow

A mudflow is an earthflow that consists of material that is wet enough to flow rapidly and that contains at least 50 percent sand-, silt-, and clay-sized particles.

Lahar

A lahar is a mudflow or debris flow that originates on the slope of a volcano. Lahars are usually triggered by such things as heavy rainfall eroding volcanic deposits; sudden melting of snow and ice due to heat from volcanic vents; or by the breakout of water from glaciers, crater lakes, or lakes dammed by volcanic eruptions.

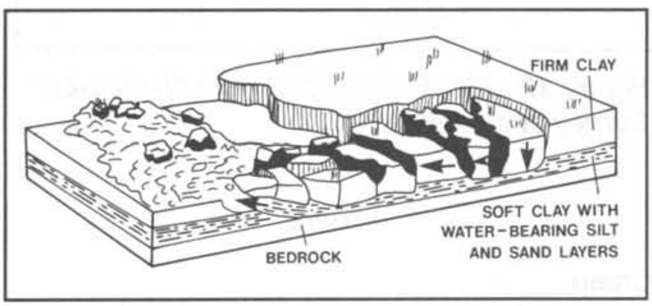


Figure 13a. Lateral spread (Colorado Geological Survey et al., 1988).

Figure 13b. Lateral spread, Cortez, Colorado. (Photograph by Colorado Geological Survey).

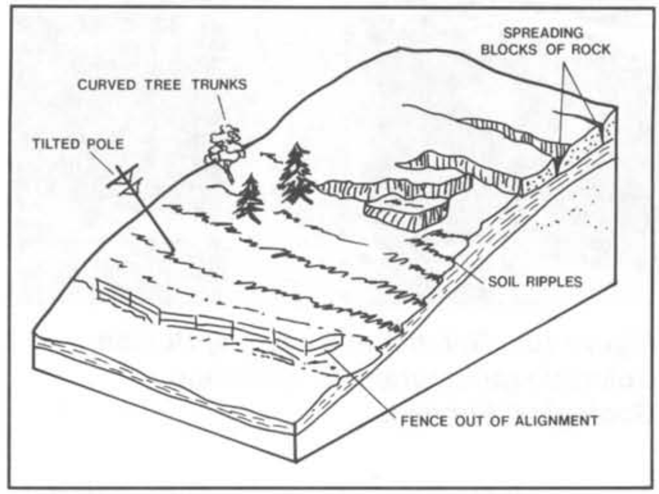


Figure 14a. Creep (Colorado Geological Survey et al., 1988).

Figure 14b. Creep, vicinity of Mt. Vernon Canyon, Jefferson County, Colorado (photograph by Colorado Geological Survey).

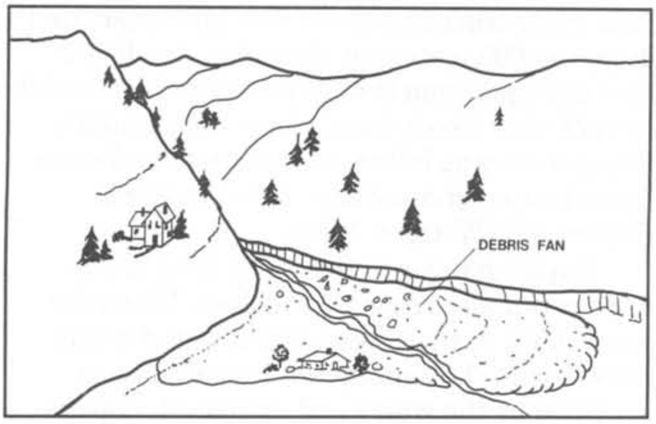


Figure 15. Debris fan formed by debris flows (Colorado Geological Survey et al., 1988).

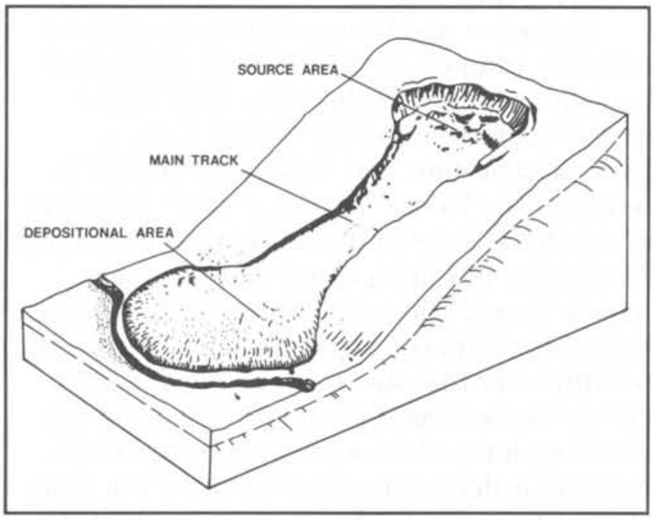


Figure 16a. Earthflow (modified from Varnes, 1978).

Figure 16b. Roan Creek earthflow near DeBeque, Colorado, 1985 (photograph by Colorado Geological Survey).

Subaqueous landslide *

Landslides which take place principally or totally underwater in lakes, along river banks, or in coastal and offshore marine areas are called subaqueous landslides. The failure of subaqueous slopes may result from a variety of factors acting singly or together, including rapid lacustrine or marine sedimentation, biogenic methane gas in sediments, surface water storm waves, current scour, water level drawdown, depositional oversteeping, or earthquake stresses. Many different types of subaqueous landslides have been identified in different locations, including rotational and translational slides, debris flows and mudflows, sand and silt liquefaction flows. There is also evidence that, in some circumstances, subaqueous landslides evolve into or initiate turbidity currents, which may flow underwater at high speeds for long distances. Subaqueous landslides pose problems for offshore and river engineering, particularly for the construction and maintenance of jetties, piers, levees, offshore platforms and facilities, and for sea-bed installations such as pipelines and telecommunications cables.

Interrelationship of Landsliding with Other Natural Hazards (The Multiple Hazard Concept)

Natural hazards often occur simultaneously or, in some cases, one hazard triggers another. For example, an earthquake may trigger a landslide, which in turn may block a valley causing upstream flooding. Different hazards may also occur at the same time as the result of a common cause. For example, heavy precipitation or rapid snowmelt can cause debris flows and flooding in the same area.

The simultaneous or sequential occurrence of interactive hazards may produce cumulative effects that differ significantly from those expected from any one of the component hazards.

Landsliding and Dam Safety

The safety of a dam can be severely compromised by landsliding upstream from the dam or on slopes bordering the dam's reservoir or abutments. Possible impacts include (1) the forma-

*Discussion by D.B. Prior

tion of wave surges that can overtop the dam, (2) increased sedimentation with resulting loss of storage, and (3) dam failure.

Flood surges can be generated either by the sudden detachment of large masses of earth into the reservoir, or by the formation and subsequent failure of a landslide dam across an upstream tributary stream channel. Waves formed by such failures can overtop the dam and cause serious downstream flooding without actually causing structural failure of the dam.

Landsliding into upstream areas or reservoirs can greatly increase the amount of sediment that is deposited in the reservoir, ultimately reducing storage capacity. This increases the likelihood that the dam will be overtopped during periods of excessive runoff, causing downstream flooding. Excessive sedimentation can also damage pumps and intake valves associated with water systems and hydroelectric plants.

Actual dam failure could be caused by landsliding at or near the abutments or in the embankments of earthen dams.

In 1983 a large mass of rock detached from Slide Mountain in Nevada. The mass slid into Upper Price Lake, an irrigation reservoir, displacing most of the water which overtopped and breached the dam, flowing into Lower Price Lake. This lake's dam was also breached. The water flowed into Ophir Creek where it collected large amounts of debris and became a debris flow. After traveling about four kilometers and dropping 600 meters in elevation, the debris flow emerged from the canyon onto the alluvial fan of Ophir Creek (total time—15 minutes). One person was killed, four injured, and numerous houses and vehicles were destroyed (Figure 17) (Watters, 1988).

Rapid changes in the water level of reservoirs can also trigger landslides. When the water level in the reservoir is lowered (rapid drawdown), the subsequent loss of support provided by the water and increased seepage pressure can initiate sliding (Figure 18). Alternatively, the increase in saturation caused by rising water can trigger landslides on slopes bordering the reservoir.

Eisbacher and Clague (1984) describe an excellent example of the potential impacts of landsliding on dam safety: the 1963 Vaiont dam disaster in Italy. The Vaiont Dam, a hydroelectric dam, was completed in 1960 to impound the Vaiont Torrent, a major tributary of the Piave River in the southern Alps of Italy. The dam is 261 m high and spans a steep narrow gorge. The southern wall of the valley behind the dam is a steep dip slope. Within two months after the reservoir was filled, a 0.7 x 10^6 m^3 mass of rock slumped away along the submerged toe of the southern embankment. Over time, deep-seated movement of the slope occurred in response to changing levels of the reservoir. As a result of these movements,

Figure 17. House destroyed by 1983 Slide Mountain, Nevada landslide (photograph by Robert J. Watters, University of Nevada, Reno).

Figure 18. Jackson Springs landslide on the Spokane arm of Franklin D. Roosevelt Lake, Washington, 1969. This landslide was triggered by extreme drawdown of the lake (photograph by the U.S. Bureau of Reclamation).

monitoring instruments were set up on the slope.In August and September of 1963, precipitation in the Piave Valley was three times higher than normal and infiltration of the precipitation into the slope probably contributed to its eventual failure. The day before the catastrophic slope failure creep rates of 40cm/day were registered.

On October 9–10, 1963, in the night, a large slab of the unstable slope failed and slipped into the reservoir. The volume of material was estimated to be 250 x 10^6 m^3 (a slab 250 m thick). A wall of water 250 m high surged up the opposite side of the valley, then turned and overtopped the dam. The concrete dam held, and the wall of water (30 x 10^6 m^3) dropped into the narrow gorge below, scouring loose debris as it went and destroying several communities below the dam. At least 1,900 people were killed.

The site of the dam has been left as it remained after the disaster, as a monument.

Landsliding and Flooding

Landsliding and flooding are closely allied because both are related to precipitation, runoff, and ground saturation. In addition, debris flows usually occur in small, steep stream channels and often are mistaken for floods. In fact, these events frequently occur simultaneously in the same area, and there is no distinct line differentiating the two phenomena.

Landslides and debris flows can cause flooding by forming landslide dams that block valleys and stream channels, allowing large amounts of water to back-up (Figure 19). This causes backwater flooding and, if the dam breaks, subsequent downstream flooding. Also, soil and debris from landslides can "bulk" or add volume to otherwise normal stream flow or cause channel blockages and diversions creating flood conditions or localized erosion. Finally, large landslides can negate the protective functions of a dam by reducing reservoir capacity or creating surge waves that can overtop a dam, resulting in downstream flooding (as described above).

In turn, flooding can cause landsliding. Erosion, due to rapidly moving flood waters, often undercuts slopes or cliffs. Once support is removed from the base of saturated slopes, landsliding often ensues.

Landsliding and Seismic Activity

Most of the mountainous areas that are vulnerable to landslides have also experienced at least moderate seismicity in historic times. The occurrence of earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur and increases the risk of serious damage far beyond that posed individually by the two processes. Landslide materials can be dilated by seismic activity and thus be subject to rapid infiltration during rainfall and snowmelt. Some areas of high seismic potential such as the New Madrid Seismic Zone of the lower Mississippi River valley may be subject to liquefaction and related ground failure.The Great Alaska Earthquake of March 27, 1964 caused an estimated $300 million in damages. As mentioned eariler, 60 percent of this was due to ground failure. Five landslides caused about $50 million damage in the city of Anchorage. Lateral spread failures damaged highways, railroads, and bridges, costing another $50 million. Flow failures in three Alaskan ports carried away docks, warehouses, and adjacent transportation facilities accounting for another $15

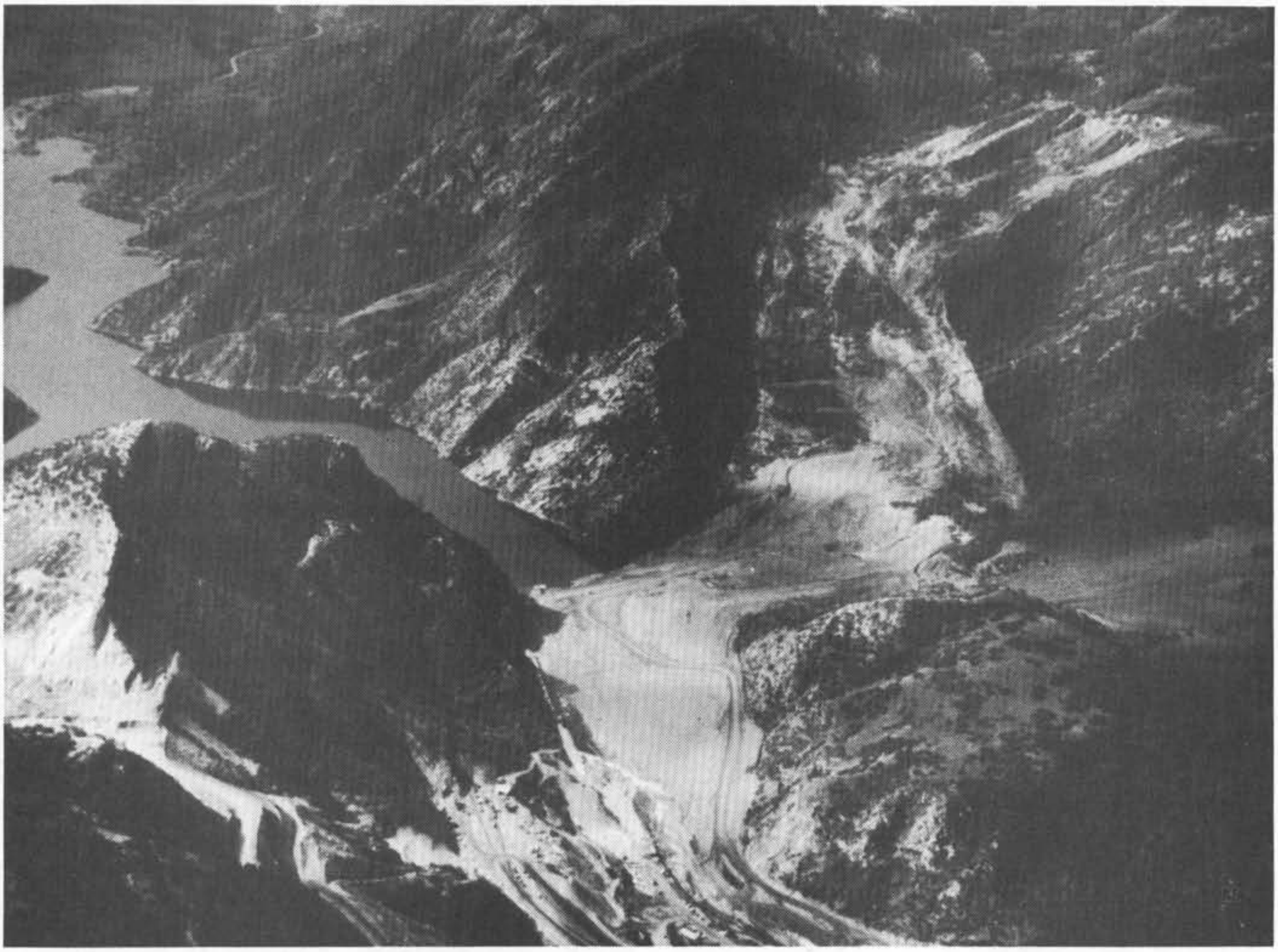


Figure 19. Aerial view of the Thistle landslide, Utah, 1983. This landslide dammed the Spanish Fork River creating a lake which inundated the town of Thistle and severed three major transportation arteries (photograph by Robert L. Schuster, U.S. Geological Survey).

million. Much of the landsliding was a direct result of the effect of the severe ground shaking on the Bootlegger Cove Formation. The shaking caused loss of strength in clays and liquefaction in sand and silt lenses (U.S. Geological Survey, 1981a).

Landsliding and Volcanic Activity

The May 18, 1980 eruption of Mount St. Helens in Washington state triggered a massive landslide on the north flank of the mountain. The volume of material moved was estimated to be 2.73 km^3. The landslide effectively depressurized the interior of the volcano; superheated waters turned into steam and magmatic gases also expanded, resulting in a giant explosion (U.S. Geological Survey, 1981b).

Because human activity had been restricted in the Mount St. Helens area due to predictions of an eruption, loss of life was minimized. However, the eruption devastated land as far as 29 km from the volcano. The resulting lateral blast, landslides, debris avalanches, debris flows, and flooding took 57 lives and caused an estimated $860 million in damage (Advisory Committee on the International Decade for Natural Hazard Reduction, 1987). ❑