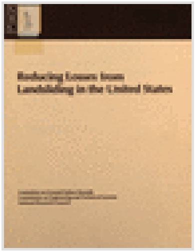

Reducing Losses From Landsliding in the United States (1985)

Pages
52

Size
8.5 x 10

ISBN
0309322561

Committee on Ground Failure Hazards; Commission on Engineering and Technical Systems; National Research Council

Reducing Losses from Landsliding in the United States

Committee on Ground Failure Hazards
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1985

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This study was supported by the U.S. Geological Survey, Grant 14-08-0001-G883; the Federal Emergency Management Agency, Contract EMW-84-C-1676; the Office of Surface Mining, Department of the Interior, Contract J5130137; and the Department of Transportation, Purchase Order DTFH61-84-P-00873.

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FOREWORD

The Committee on Ground Failure Hazards is charged to (1) survey ongoing geologic and engineering research relating to landslides, subsidence, and other ground failure hazards, (2) define nationwide research needs and research priorities, (3) publish accounts of ongoing research and recent research results, and (4) foster the exchange of information within the United States and abroad.

In this, its first report, the committee discusses the context in which landslide research is carried out and the gaps that now exist, in the United States, between the conduct of landslide research and the successful reduction of landslide losses.

During the period in which this report was prepared, the committee's activities were supported by the U.S. Geological Survey and the Office of Surface Mining, which are both within the Department of the Interior, by the Department of Transportation, and by the Federal Emergency Management Agency.

EXECUTIVE SUMMARY

In the United States, losses from landslides, subsidence, and other ground failures exceed the losses from all other natural hazards combined. This first report from the Committee on Ground Failure Hazards addresses landsliding; subsidence and other forms of ground failure will be covered in subsequent reports.

Landsliding in the United States causes at least $1 to $2 billion in economic losses and 25 to 50 deaths each year. Despite a growing geologic understanding of landslide processes and a rapidly developing engineering capability for landslide control, losses from landslides are continuing to increase. This is largely a consequence of residential and commercial development that continues to expand onto the steeply sloping terrain that is most prone to landsliding.

Landsliding occurs in every state in the nation and is an economically significant natural hazard in more than half the states. While landslides can and do occur as individual local events, as much as one third of the nation's annual landslide loss is associated either with heavy rains or with the melting of winter snows. Landsliding of this sort often extends beyond the boundaries of any single state or local governmental entity. Because of this, and because effective measures for reducing landslide losses require the cooperation of federal, state, local, and private entities, reduction of landslide losses should be viewed as a national goal requiring national leadership.

Successful and cost-effective national landslide mitigation programs can be implemented, and such programs exist in other countries (e.g., Japan). In the United States, although there have been some impressive and successful local demonstrations of landslide control, information about these activities has not been widely disseminated. There has been no recognized national leadership and no systematic basis for the exchange of information among governmental entities, scientists, and engineers.

Compared with the amounts spent on other geologic hazards, U.S. expenditures for landslide research and mitigation programs are very low. Yet practical application of corrective measures, based on appropriate research and enforced by local regulations, can lead to dramatic reductions in landslide losses. This has been demonstrated in the Los Angeles area, where reductions in losses of more than 90 percent have been achieved for new construction.

Appropriate land use management, effective building and grading codes, the use of well-designed engineering techniques for landslide control and stabilization, the timely issuance of emergency warnings, and the availability of landslide insurance can significantly reduce the catastrophic effects of landslides. All of these approaches require, as a starting point, the identification of areas where landslides are either statistically likely or immediately imminent, and the representation of these hazardous locations on maps.

In the United States, reduction of landslide losses is viewed primarily as a local responsibility. While the federal government plays a key role in research, in the development of mapping techniques, and in landslide management on federal lands, the reduction of landslide losses through land use management and the application of building and grading codes is essentially a function of local government. The programs undertaken by localities across the nation vary considerably, and there are no widely accepted procedures or regulatory approaches for taking landslide hazards into account in community planning and land use management.

The same applies to building and grading codes. These are the primary regulatory vehicles through which local governments ensure proper design and construction practices. While some localities (especially in California) have developed and implemented strong building and grading codes, and while Chapter 70 (Excavation and Grading) of the Uniform Building Code provides a model, the majority of construction and land surface modification in this country, both public and private, is carried out without reference to a major design code.

The physical method of landslide control most commonly used in the United States, both by private landowners and developers and by governmental agencies, is the control of ground and surface water in landslide-prone areas. Surface water is diverted from landslide-prone areas by ditches, and groundwater is collected and removed by underground drainage systems and pumping wells.

Other techniques used to prevent slope movement or to minimize damage are modification of the ground surface by removal of all or part of the material driving the landslide, construction of large earth buttresses at the toes of slides, and the use of retaining walls, piles, caissons, or rock anchors to stabilize earth masses on slopes. In some locales, structural debris barriers are used to divert mudflows and debris flows away from critical areas, and debris storage basins are built behind check dams to collect landslide debris prior to its hitting critical areas. These structures, which are major, expensive engineering works, are mostly found in parts of the western United States where debris flows are a common and hazardous form of landsliding.

Although some techniques for predicting landslides have been developed, there has been insufficient research in this area. The use of recurrence interval techniques and other temporal descriptions of risk has essentially been unexplored. Some research has been carried out on the use of early warning systems to alert the public to individual local landslides, and there have been a few successful demonstrations of such techniques. But there has never been extensive implementation of an early warning system in the United States or elsewhere.

Insurance is in principle a viable option for mitigating losses from landsliding. Insurance not only redistributes losses among the population, thereby reducing their catastrophic impact, but can also be used to encourage risk-reducing managerial decisions. However, to implement an effective insurance program requires a degree of specification of risk that is not generally thought to be possible for landslides. At present, very few companies in the United States offer landslide coverage, and then only for certain areas. A particular problem of landslide insurance is the potential for adverse selection by the insured population. Landslide risk is not uniformly distributed throughout the population or throughout a region. Rather, it is associated with certain distinctive physical features. The homeowner living on a flat surface has no interest in buying landslide insurance and sharing the risk and cost with the homeowner living on a steep hillside. Landslide insurance is virtually unavailable today in this country, with the exception of the insurance coverage provided for a single type of landslide (mudslides) under the National Flood Insurance Program.

The development of landslide mapping methodologies in the United States has received substantial effort, but much of the country's landslide-prone area remains insufficiently mapped. Rectifying this situation will require a program of landslide hazard mapping supplemented by other techniques such as aerial photointerpretation. Landslide susceptibility has been mapped for the United States as a whole, but at a scale that is not useful for regional or local planning. The appropriate scale for regional maps is between 1:125,000 and 1:500,000, while maps for site-specific purposes may require scales as large as 1:2,000.

A wide variety of federal, state, and local mapping programs have been carried out in the United States. All of this mapping has been done in the absence of universal (or even widely accepted) standards of accuracy, comprehensiveness, scale, symbols, or format. There are no guidelines available to assist in the preparation of these maps (except for examples such as the U.S. Geological Survey series). The technical capability with which landslide susceptibility maps are prepared varies widely, and the value of the final products is extremely variable.

There is much that can be done to reduce landslide losses in the United States. There are obvious needs for geologic and engineering research, for the development of new mapping techniques, for more widespread adoption and enforcement of appropriate building and grading codes, for more effective land use planning and management, for wider dissemination of information about landslide risk and landslide loss reduction, and for serious examination of the feasibility of landslide insurance.

The greatest need, however, is not for new knowledge or new engineering methods but for more effective implementation of the capabilities we have today. To achieve this will require focused, national leadership that today is almost totally lacking. This leadership need not come from the federal government. It could be provided by a consortium of research and engineering institutions or professional societies, by a national public interest organization, or by a U.S. national committee composed of representatives of government, industry, academia, and the professional societies. What is essential is to provide a continuing context for the development and effective implementation of loss reduction techniques and for the exchange of technical information that will enable private and local organizations to take steps that will effectively reduce landslide-related costs.

An effective program to reduce landslide losses in the United States can be undertaken today. Existing knowledge about landslide processes and loss reduction practices in a few U.S. communities and in some other countries can provide a basis for more widespread and effective implementation of the loss reduction techniques now available. At the same time, research should be undertaken to develop better loss reduction techniques than those that are in hand today.

A national landslide loss reduction program should center on the following activities:

- Adoption by local governments of regulations requiring the identification and mapping of landslide-prone lands.
- Adoption by local governments of land use regulations that restrict the purposes for which landslide-prone land can be developed.
- Adoption by local agencies of design, building, and grading codes that will ensure construction practices appropriate to the maintenance or enhancement of slope stability.
- Research to improve the technical base for the development of design, building, and grading codes applicable to landsliding.
- Landslide mapping activities by the federal government focusing on (1) the development of improved landslide mapping methodologies on a broad range of map scales, (2) the delineation of landslide hazards on a national scale, (3) demonstrations of landslide mapping on a regional scale, (4) landslide mapping on federal lands, and (5) landslide mapping in support of the missions of federal agencies.
- A nationwide program to provide information and technical assistance to state, local, and private organizations wishing to undertake landslide hazard mapping programs.
- Federally sponsored research on landslide processes, including landslide initiation and the mechanics of landslide transport and deposition.
- Research and technology transfer aimed at (1) using recently developed techniques in remote sensing, geophysics, hydrology, and geotechnics for the delineation of areas of landslide hazard, (2) assessing the effectiveness of ground improvement practices, such as soil drainage, for landslide control, (3) testing and evaluating innovative landslide engineering techniques, especially on public lands where the problem of legal liability is small, (4) monitoring recurrent landslides, and (5) instrumenting landslide-prone areas and establishing early warning systems.
- Research and data collection pertaining to landslide risk that can be used to provide a basis for decisions by private sector insurers concerning the feasibility of landslide insurance and for clarification by the federal government of its role in landslide insurance.

A program of this nature will require:

- Leadership at the national level drawing upon a number of professions and disciplines, including geology, civil engineering, planning, and economics, and involving federal, state, local, and private entities having responsibilities related to the reduction of landslide losses.
- An information dissemination and education effort spanning the spectrum from federal agencies through state and local agencies to the private sector.
- Legislation and funding at federal, state, and local levels, as needed.
- The active cooperation of the private sector.

1

THE LANDSLIDE PROBLEM

INTRODUCTION

The National Research Council's Task Group on Landslides and Other Ground Failures, whose report (National Research Council, 1981) led to the establishment of the Committee on Ground Failure Hazards, highlighted ground failures as the nation's most economically significant class of natural hazards. As the task group pointed out, although individual ground failures involving landsliding, subsidence, or expansive soils are generally neither so spectacular nor so costly as such natural disasters as earthquakes, volcanic eruptions, major floods, and tornadoes, they are far more frequent and widespread. In fact, the total financial losses from ground failure hazards in the United States are greater than the losses from all other natural hazards combined. During the period 1925-75, the combined losses (unadjusted for inflation) from floods, hurricanes, tornadoes, and earthquakes totaled nearly $20 billion. In contrast, ground failure of only two types, landslides and subsidence, caused at least $75 billion in losses during the same period.

This first report by the Committee on Ground Failure Hazards addresses the problem of landsliding in the United States. Subsidence and other forms of ground failure will be covered in subsequent reports.

LANDSLIDING IN THE UNITED STATES

Landslides, especially those caused in whole or in part by human activity, are often both predictable and preventable. Yet landslides cause staggering losses in the United States--typically $1 to $2 billion in economic losses and 25 to 50 deaths each year. The loss of life from landsliding is comparable to the total loss of life from floods, earthquakes, and hurricanes (Krohn and Slosson, 1976). The economic losses involve both public and private property. They include not only the direct costs of replacing and repairing damaged facilities but also the indirect costs associated with lost productivity and the disruption of utility and transportation systems. Much of the economic loss is borne by federal, state, and local agencies that are responsible for disaster assistance, flood insurance, and highway maintenance and repair. The indirect costs, including revenue losses that result from reduced property values and casualty loss deductions, may exceed the direct costs.

Landsliding is widely distributed in the United States and is not restricted to a few localized areas. Many different physiographic and climatic regions are subject to landslides, and in much of the United States landsliding is a dominant process of landscape alteration. Landslides can occur as isolated phenomena or in conjunction with heavy rains, earthquakes, and volcanic action. Landsliding is also a major problem along riverbanks.

Landslides also occur underwater, on lake and ocean floors, frequently in areas of extremely gentle slopes. Underwater landsliding occurs episodically due to a variety of triggering factors such as rapid sedimentation, earthquake shock, faulting, and storm-generated waves.

The number of damaging landslides has increased in the past two decades, largely because of the continuing expansion of the population into the vicinity of steeply sloping terrain. The building of residential and nonresidential structures, and the accompanying construction of infrastructure corridors and planting of irrigated landscaped areas, alters the hillslope configuration and upsets established equilibrium conditions. This compounds the natural instability of many slopes and can reactivate older landslides.

In addition, the use of offshore areas for oil and gas exploration and production, waste disposal, submarine communication, and military warning systems has increased dramatically in recent years. Many of these activities are severely affected by active submarine landsliding. Oil and gas production facilities off the Mississippi Delta and submarine cable systems off Hawaii have been damaged by underwater landslides.

The purposes of this report are to provide government and private decision makers with an overview of the landslide problem in the United States and to recommend approaches to reducing domestic landslide losses. The report is not intended to be a definitive analysis of the problem, nor does it offer a critical comparative evaluation of the options for loss reduction. The report makes five main points: (1) landsliding is a widely distributed and costly natural hazard in the United States and constitutes a national problem; (2) landslides are widespread and cause extensive damage in other countries as well; (3) landslide losses <u>can</u> be reduced, and successful national programs to reduce landslide losses are being carried out in some other countries; (4) what is most lacking in the United States is not geologic knowledge or technical capability but national leadership; and (5) it is possible to identify specific steps that could be taken to reduce landslide losses in the United States.

Figure 1 shows, in a qualitative way, the severity of the landslide problem in each state. The assignment of severity classes in this figure is relatively crude. It is based on admittedly incomplete records of past landslide losses and on assessments of the degree to which each state is prone to landslides as a consequence of its geology and physiography. The severity of landsliding within a particular state may change with time. If hillside development expands without proper

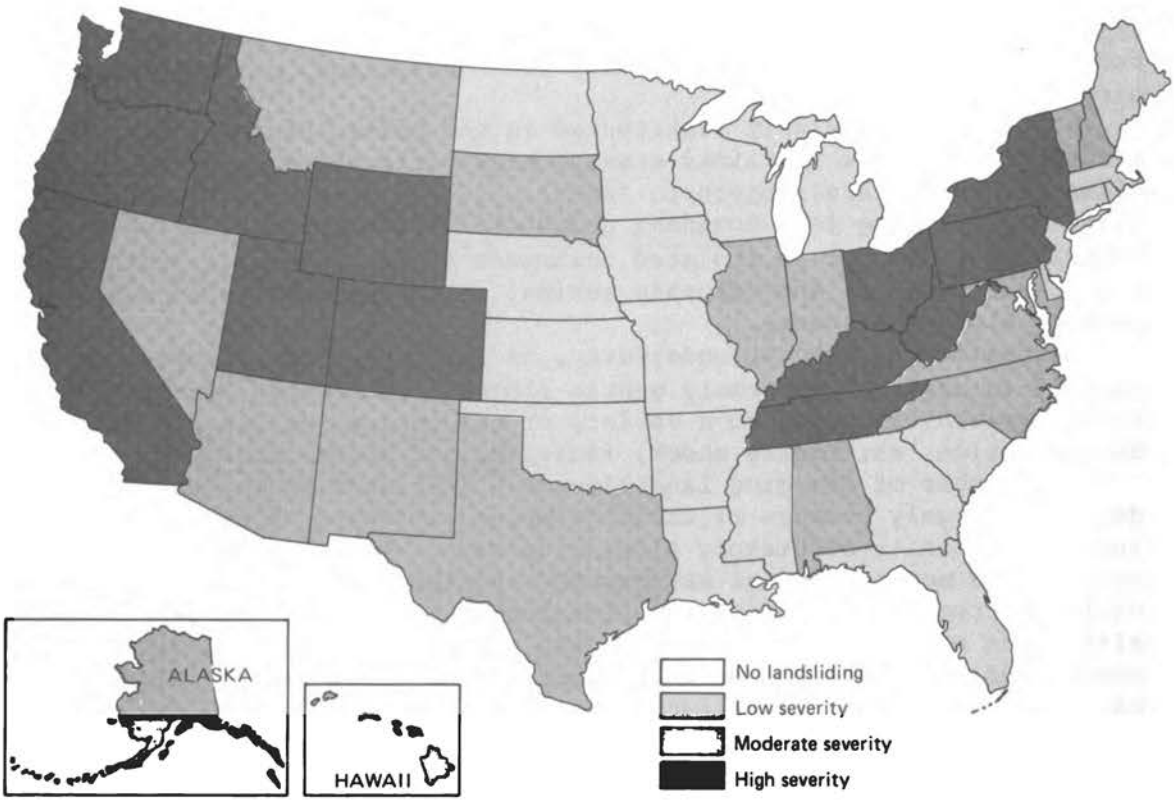

FIGURE 1 Qualitative indication of the severity of landsliding in the United States by state.

geotechnical measures to minimize loss, the severity may increase. Conversely, with proper planning and engineering, a state's landslide severity may diminish despite continued expansion of the population into landslide-prone terrain.

Figure 1 does not indicate the spatial variation of landsliding within each state. This variation can be quite large. In North Carolina, for example, the relatively flat eastern half of the state is virtually free of landslides while the mountainous western part of the state is almost entirely landslide-prone. Many excellent maps showing the detailed geographic distribution of landsliding based on physiographic and geologic considerations appear in the technical literature (e.g., Wiggins et al., 1978;* and Radbruch-Hall et al., 1982).

The purpose of Figure 1 is to display the number and locations of states in which landsliding is a serious or potentially serious source of economic loss. It is clear that no state is entirely free of landsliding, and that in more than half the states landsliding is a significant problem. While individual landslides can be widely scattered in space and time, a substantial portion--perhaps as much as one third--of the annual landslide loss is associated with major catastrophic events.

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*This map has also been reproduced in U.S. Geological Survey (1982).

Examples include the mudflows and mud floods of January 1982 in the San Francisco Bay region and the floods, landslides, debris flows, and mudflows that occurred along the Wasatch Front in Utah during the spring seasons of 1983 and 1984. In each of these instances, a single storm or sequence of climatic events produced extensive landsliding. Catastrophic events such as these can occur in many parts of the nation. The areas affected by such landslides often extend beyond the borders of individual states and individual governmental jurisdictions. Such events can overwhelm the local or state capability for response. The emergency response to catastrophic landslides therefore constitutes a national problem, and expediting this response should be a responsibility of the federal government.

Long-term landslide mitigation programs, on the other hand--including hazard mapping and delineation programs, building codes, and land use management programs--can be most effectively pursued at the state and local level. Local governments and the private sector must bear the major part of the long-term landslide cost and are in the best position to develop and enforce mitigation practices.

LANDSLIDE LOSSES IN THE UNITED STATES

Landslides can have both direct and indirect costs. Direct costs are a result of the actual damage sustained by buildings and property. Indirect costs include loss of tax revenues, reduced real estate values, loss of productivity, losses in tourism, and losses from litigation. Indirect costs are harder to measure than direct costs and may exceed them in magnitude.

Although no comprehensive cost-reporting mechanism is in use nationally, the U.S. Geological Survey has developed a method for estimating the cost of landslide damage (Fleming and Taylor, 1980). Application of this method suggests that incomplete and inaccurate records have resulted in reported costs that are much lower than those actually incurred. It also appears that losses are on the increase in most regions, despite an increased understanding of the causes of landslides and the development of improved methods for handling them. Thus the problem is growing at a faster pace than is the progress in applying solutions.

The three geographical areas that have experienced the greatest landslide damage are the Appalachian region, the Rocky Mountain region, and the Pacific Coast region.

Landslides are indigenous to much of the Appalachian Highlands, particularly southwestern Pennsylvania, southeastern Ohio, and northern West Virginia. More than two million mappable landslides are estimated to have occurred in the Appalachian Highlands from New England to the Gulf coastal plain. These include landslides in the portions of the highlands that extend into New England, New York, Maryland, Kentucky, Virginia, Tennessee, North Carolina, South Carolina, Georgia, and Alabama. The following examples illustrate the magnitude of landsliding:

- In Allegheny County, which surrounds Pittsburgh, Pennsylvania, damage from landslides in recent years has averaged over $4 million per year. Over 90 percent of the landslides in Allegheny County are attributable to human modification of hillslopes.

• In Hamilton County, Ohio, which includes the greater Cincinnati area, damage from landslides in recent years has averaged over $5.2 million per year. In Cincinnati a single landslide was responsible for $22 million in damage from 1974 to 1980.

• In eastern West Virginia in 1969, a single storm associated with Hurricane Camille resulted in 1,534 landslides in one small drainage basin, the Spring Creek watershed.

Much of the Rocky Mountain region is characterized by unstable slopes. Population growth, increasing development of energy and mineral resources, and increasing use of large areas for recreation in the Rocky Mountain states portend an increase of landslide-related losses in the next few decades. Two specific examples are:

• In Utah, landslides, debris flows, and debris floods caused upwards of $250 million in losses in 1983 and $50 million in 1984. Vast damage occurred to private and public works in populated areas along the mountain fronts, transportation routes were severed, and facilities in less populated areas were damaged.

• In Colorado, where landslides occupy about 8 percent of the area of the state, annual landslide damage to buildings is estimated to exceed $3 million, and damage to highways and railroads is estimated at several times that amount.

In the Pacific Coast region, California, Washington, and, to a lesser extent, Oregon have some of the most severe landslide problems in the United States. In this century, landslides have resulted in billions of dollars in losses in these states. It is estimated that losses due to landsliding will total almost $10 billion in California from 1970 to the year 2000 if no preventive action is taken (Alfors et al., 1973). Some examples of specific landslide situations are:

• In January 1982, 25 people were killed by landsliding in the nine-county San Francisco Bay area, with losses totaling $66 million.

• Between 1966 and 1981, Orange County, California, experienced 40 major bedrock landslides that resulted in a total economic loss of over $40 million. The 1978 Bluebird Canyon landslide in Laguna Beach destroyed 25 homes and accounted for $15 million of the $40 million total; providentially, no lives were lost.

• Storm-triggered landslides in the Los Angeles area during the winters of 1951-52, 1957-58, 1961-62, 1964-65, 1968-69, 1977-78, and 1978-79 produced an average loss of $500 million in each season of heavy storm activity.

• The Big Rock Mesa landslide west of Los Angeles is currently moving, with more than 300 homes in jeopardy in an area of high property values.

• Collapse of the northern part of the cone of Mount St. Helens, Washington, immediately before the May 18, 1980, eruption of that volcano, resulted in a debris avalanche of 2.8 billion cubic meters, the world's largest landslide in historical times. This huge landslide destroyed everything within an area of 60 km^2; however, because of evacuation of residents and visitors in anticipation of the eruption, only 5 to 10 people were killed by the landslide.

LANDSLIDE LOSSES IN OTHER COUNTRIES

Annual losses due to landslides in Japan, Italy, India, and a few other countries are of the same order of magnitude as those in the United States. N. Ohhira, Director General of the Japanese National Research Center for Disaster Prevention, has noted that annual losses in Japan from landslides total about $1.5 billion (personal communication, 1982). The unpublished results of a 1976 UNESCO survey of landslide effects indicate that annual landslide losses in Italy are about $1.1 billion (M. Arnould, personal communication, 1982). Landslide losses in other countries with significant landslide problems are not as well documented and are not thought to be as large as those noted above. However, landslides probably cause losses of more than $100 million a year in many countries, including Austria, France, and the Soviet Union. In addition, the urban area of Hong Kong has experienced extremely costly landslides.

Deaths due to catastrophic slope failures have occurred all over the world since people began to congregate in areas subject to such failures. The burgeoning population of the world in this century has worsened the problem. During the period 1971-74, an average of nearly 600 people per year were killed by slope failures worldwide (Varnes, 1981). Interestingly, about 90 percent of those deaths occurred within the Circum-Pacific region (i.e., in those areas in or on the margins of the Pacific Basin).

The greatest recorded loss of life in any single group of landslides occurred in Kansu Province, China, in 1920, when approximately 100,000 people were killed by earthquake-triggered loess landslides (Close and McCormick, 1922). A number of other landslides in this century have had large death tolls. In Peru, three major landslides during the past 20 years killed more than 20,000 people and destroyed villages, agricultural lands, and highways (Cluff, 1971; Kojan and Hutchinson, 1978; Plafker and Ericksen, 1978). The greatest landslide catastrophe in the Soviet Union occurred in 1949, when an earthquake in the Tien Shan Mountains of Soviet Tadzhikistan triggered a series of massive landslides that buried some 33 population centers, killing an estimated 12,000 to 20,000 people (Wesson and Wesson, 1975; Jaroff, 1977). In 1921 a large debris flow in Alma-Ata, the capital of the Kazakh Republic, killed 500 people and inflicted considerable damage to the city (Yesenov and Degovets, 1982). The most disastrous European landslide in recent time was the 1963 Vaiont Reservoir slide in Italy. This massive rockslide, with a volume of about 250 million cubic meters, slid into the reservoir at high velocity, sending a wave at least 100 meters high over the crest of the dam into the valley below that destroyed five villages and took 2,000 to 3,000 lives (Muller, 1964, 1968; Voight and Faust, 1982).

Among industrialized nations, Japan has probably suffered the greatest continuing loss of life and property from landslides. Casualties have been particularly high in heavily populated urban areas at the base of steep mountain slopes. In July 1938, Kobe, one of Japan's largest cities, was swept by debris flows generated by torrential rainfall, resulting in 450 to 600 deaths and the destruction of more than 100,000 houses (Nakano et al., 1974; Japan Ministry of Construction, 1983). In the city of Kure in 1945, 1,154 people were killed by debris flows generated by heavy rains accompanying a typhoon (Nakano et al., 1974). Data accumulated by the Japan Ministry of Construction (1983) indicate that landslides killed an average of 150 people per year in Japan from 1967 to 1982.

2

REDUCING LANDSLIDE COSTS

INTRODUCTION

Successful and cost-effective national landslide mitigation programs can be implemented. Such programs exist in other countries (e.g., Japan) but not in the United States. Although there have been some impressive and successful local demonstrations of landslide control programs within the United States, information about these programs has not been widely disseminated. This is characteristic of the state of landslide knowledge in this country, where such information tends to be scattered and diffused. There is no recognized national leadership or systematic basis for communication.

Compared with other ground failure hazards, the budgets for landslide research and mitigation programs are very low. Table 1 gives the committee's estimate of the annual national losses and annual federal research budgets for a number of ground failure hazards. Landsliding stands out as a severe and relatively underfunded hazard. Yet practical application of known corrective measures, based on appropriate research and enforced by local regulations, can lead to dramatic loss reductions. This has been demonstrated in the Los Angeles area, where reductions in losses of 92 to 97 percent have been achieved for new construction (Slosson and Krohn, 1982).

METHODS FOR REDUCING LANDSLIDE COSTS

There are two distinct components to reducing the costs of landsliding: emergency management and long-term hazard reduction.

Emergency management includes (1) the anticipation, prediction, and issuance of warnings of the occurrence of life- and property-threatening landslides, (2) the response that is required when landslides occur, and (3) the identification of landslide-prone areas and the planning, training, and other preparatory measures that are necessary to ensure that the warning and response will be effective. Emergency response focuses on minimizing property damage and loss of life and on restoring critical public facilities. It includes such activities as evacuation; rescue; provision of emergency food, water, shelter, clothing, health care, and waste disposal; and repair and restoration to service

TABLE 1 Estimated Annual Losses and Annual Research Funds for Selected Ground Failure Hazards in the United States

Hazard	Annual Loss of Life	Annual Economic Loss (millions of dollars)	Annual Research Funds (millions of dollars)
Landslides	25-50	1,000-2,000	3-5
Permafrost	0	20	2
Subsidence	*	500	10
Swelling soils	0	6,000	2
Frost action	0	*	*
Rock deformation	1	*	3
Earthquakes[a]	15	100	50
Volcanoes[a]	1	10	10

*Not available.

[a]A major earthquake or volcanic eruption affecting a large urban area could greatly affect the estimated annual losses from these hazards. The other hazards in the table are less episodic, and the estimates given are probably more reliable as estimates of future annual losses.

of roads, power lines, water and sewer lines, transportation and communication facilities, and homes, businesses, and public services. The emergency response to landslides is thus similar to the response to other disasters such as dam failures, floods, and major storms.

Long-term hazard reduction focuses on means for reducing the frequency with which landslides occur, reducing the likelihood that landslides will cause damage, and minimizing the damage when landslides do occur. Landslides can be caused by natural events such as heavy rain, erosion, and earthquakes. They can also be caused by human activities that change the nature of the ground surface or alter drainage patterns. Such activities as construction, clearing of vegetation, and watering of lawns can trigger landslides directly or make a location more prone to landsliding triggered by natural causes.

Landslide losses can be reduced in two ways. The first is to reduce the occurrence of landslides by requiring that excavation, grading, landscaping, and construction be carried out in ways that do not contribute to slope instability. The second is to minimize the damage when landslides do occur by (1) restricting development in landslide-prone terrain and (2) protecting buildings and other structures from landslide damage, either by designing them to be relatively damage-resistant or by erecting protective barriers that direct the moving rock and soil away from the vulnerable property.

There are four basic approaches to reducing the long-term losses from landsliding: avoidance; design, building, and grading codes; landslide control and stabilization; and insurance.

Avoidance involves eliminating or restricting development in landslide-prone terrain. While total avoidance, i.e., a total prohibition on the use of landslide-prone lands, is not possible, it is feasible to use these lands in a way that minimizes landslide losses. Thus, it is possible to use such land for recreational open spaces, watersheds, agriculture, and other activities for which the loss in the event of a landslide will be small. It is even possible to allow low-intensity physical development in such areas if appropriate precautions are taken. The principal issue in programs of avoidance is the lowering of land values associated with designation as a landslide-prone area. In the United States, restrictions on land use are generally imposed and enforced by local governments.

Design, building, and grading codes are regulatory tools available to local government agencies for achieving desired design and building practices. They can be applied to both new construction and preexisting buildings. In rare cases, such as those involving large offshore structures, the effect of landslides can be considered explicitly as part of the design, and the facility can be built to resist landslide damage. In some cases, existing structures in landslide-prone areas can be modified to be more accommodating to landslide movement. The extent to which this is successful depends on the type of landsliding to which the structure is exposed. Facilities other than buildings (e.g., gas pipelines and water mains) can also be designed to tolerate ground movement. Codes and regulations governing grading and excavation can reduce the likelihood that construction of buildings and highways will increase the degree to which a location is prone to landslides. Various codes that have been developed for federal, state, and local implementation can be used as models for landslide-damage mitigation. A fundamental concern with design and building codes is their enforcement in a uniform and equitable way.

The control and stabilization of landslides can dramatically reduce the likelihood of earth movement. The control of drainage on slopes and the building of walls and diversion and storage structures can be used to control landslides and to minimize the damage they do to developments and facilities. The principal difficulty with landslide control is the high cost involved.

Insurance works in two ways. It provides a means for distributing the cost of landslides over a larger population or a longer period of time. This redistributes costs and losses but does not reduce them. Insurance also can encourage managerial decisions that reduce risk, leading to real loss reductions. Landsliding presents essentially the same problems to an insurer as any other hazard. These problems include definition of the risk, the difficulty of adverse selection by the insured population, and the development of actuarial data.

Two basic capabilities constitute the starting point for both emergency management and long-term mitigation: a capability for identifying areas where landslides are either statistically likely or immediately imminent, and a capability for representing these hazardous locations on maps. Although some techniques for predicting landslides have been developed, research on landslide prediction has been insufficient. The use of recurrence interval techniques and other temporal descriptions of risk in landslide prediction is essentially unexplored. Some research has been carried out on the use of early warning systems to alert the public to individual local landslides, and there have been a few successful demonstrations of such techniques. However, there has never been extensive implementation of an early warning system in the United States or elsewhere.

Detailed landslide mapping is primarily the responsibility of state and local agencies and the private sector. The federal responsibility for mapping and hazard delineation has been limited to fundamental research, demonstrations of methodologies, and the mapping of federal lands. Considerable research has been done on mapping, and successful mapping programs have been implemented in parts of the United States and in many other countries with severe landslide problems.

PROGRAMS FOR REDUCING LANDSLIDE COSTS IN THE UNITED STATES AND OTHER COUNTRIES

In the United States, the responsibility for reducing the costs of landsliding is distributed among various elements of the public and private sectors, although the formal responsibilities of various agencies in the private and public sectors have not been defined. Table 2 presents some of these responsibilities in the context of the two principal types of cost reduction programs.

The federal role in landslide management had its origin in the Organic Act of 1879 (43 U.S.C. 31a) that created the U.S. Geological Survey. From the general mandate in this act, the Geological Survey has developed the institutional competence and the programs in research, hazard warning, technical assistance, and disaster response that now exist within that agency.

Other, more recent legislation has addressed a federal role in landsliding, at least indirectly, for the Geological Survey and other agencies. The Dam Inspection Act of 1972 includes responsibilities for the safety of dams that are affected by landslides in their abutments or foundations. Landslides into reservoirs are also recognized as a potentially serious threat to dam safety. Under the 1974 Disaster Relief Act and subsequent authorities, the Geological Survey was given specific responsibility for issuing warnings of potential natural disasters. Landslide hazards are included in this responsibility.

The Federal Emergency Management Agency (FEMA) has a number of responsibilities involving both emergency management and long-term mitigation of natural hazards, including landslides. Under the Disaster Assistance Program, FEMA is the federal coordinating agency for emergency response, disaster relief funding, and hazard mitigation planning. Disaster funding is made available to individuals and, on a cost-sharing basis, to state and local governments. FEMA takes the lead in activating hazard mitigation planning with the states after a disaster and in leading intergovernmental, interagency hazard mitigation teams. All of these disaster assistance activities are initiated when

TABLE 2 Partial Listing of Public and Private Roles in Reducing the Costs of Landsliding

Federal	State	Local	Private
Emergency Management			
Conduct research on real-time prediction of landslides, and develop techniques for monitoring and surveillance	Monitor landslides and landslide-prone areas	Issue warnings of imminent landslides	Cooperate with, and make resources available for, emergency operations
Provide expert advice to state and local governments during an emergency	Assess hazard and risk	Coordinate resources of private sector for emergency response	
Provide technical assistance, training assistance, and funds to state and local governments for emergency planning, training, and response	Mobilize resources and provide expert assistance for response and rescue operations	Manage emergency operations	
Long-Term Hazard Reduction			
Fund and undertake research on landslide mechanisms, and disseminate research results	Fund and undertake research on landslide problems in the particular state, and disseminate research results	Implement research results	Conduct research and use research results
Develop methods for inventorying landslides, and inventory landslides on federally managed lands	Inventory landslides within the state	Monitor landslides	Share information about potential landslide hazards and monitor landslides
Require federal agencies to avoid or design for landslides in federal construction programs	Require or provide disclosure of landslide hazards during real estate transactions	Require recognition, avoidance, or design for landslides as part of land use planning and development	Recognize, avoid, or design for landslide hazards in land acquisition, development, and construction
Improve design and construction techniques for minimizing landslide damage to federal buildings, highways, and other facilities	Require state agencies to avoid or design for landslides in state construction programs	Enact and enforce grading ordinances and building codes to minimize landslide occurence and damage	Incorporate geotechnical engineering advice in construction and management of buildings and facilities
Manage federal forest lands to minimize landslide damage	Establish special assessment districts to pay for landslide mitigation	Issue warnings and post signs to discourage entry and use of landslide-prone areas	Incorporate geotechnical engineering advice in investment and loan decisions
Provide financial incentives and disincentives to encourage making appropriate provisions for landslides in federally financed development activities	Establish landslide warning systems	Avoid construction of public facilities in landslide-prone areas, and relocate obsolete public facilities in landslide-safe areas	
	Require state geologist to designate landslide areas for special studies		
	Provide model ordinances and building codes to local governments for landslide mitigation		
	Provide information to local governments and to the public concerning landslide hazards		

the President declares a major disaster or emergency upon request of a state's governor in a situation beyond the capabilities of state and local forces.

Recently, FEMA has expanded the conditions under which disaster assistance funds may be used to supplement repairs to public facilities after landslides. If the stability of the natural site is in question, a feasibility study by the applicant may be approved to determine the practicability of replacing the facility at the original site. After stabilization of the landslide, which remains a responsibility of local government, FEMA restores the function of the damaged facility.

Under the National Flood Insurance Program, created by the Housing and Urban Development Act of 1968, FEMA provides insurance coverage for losses due to flooding. Amendments to that act in 1969 extended this coverage to include "mudslides;" however, implementation of this extension has been complicated by the absence of an accepted technical definition of a "mudslide" and an accepted engineering methodology for delineating mudslide hazard areas (National Research Council, 1982). Landslides other than mudslides are not covered under this program.

Other federal agencies directly involved with landslides are the Agricultural Research Service, the Forest Service, the Bureau of Reclamation, and the Corps of Engineers. Agencies less directly involved include the Department of Transportation and the Nuclear Regulatory Commission.

What is probably the world's most comprehensive program of landslide loss reduction is found in Japan, where a strong national program for landslide control has developed since the late 1940s (Japan Society of Landslides, 1980). Initially, Japanese landslide control activities were tied to other programs, such as river improvement, erosion control, and agricultural and forest land maintenance. The first programs in Japan devoted explicitly to landslides were created by the 1958 "Landslide Prevention Law." Other legislative measures have been adopted since 1958, culminating in 1969 with the "Law for the Prevention of Disasters Caused by the Collapse of Steep Slopes." This legislation authorizes the government to assume expenses and guide the recovery from natural disasters for which no individuals bear responsibility. These measures provide not only for the repair of damage and the restoration of property to its original form but also for construction efforts to prevent future slope failures. The estimated annual cost of this program is about $500 million (N. Ohhira, personal communication, 1982).

Japan has been a leader in mapping landslides. The 1:50,000-scale morphometrical map of large-scale landslide landforms in Kyushu by Hatano et al. (1974) is an outstanding example. Other maps in this series are currently being produced by the National Research Center for Disaster Prevention, Ministry of Construction (N. Oyagi, personal communication, 1983).

The Soviet Union has also developed programs to deal with landslide hazards. As early as 1924 the Soviet government set up a special commission to direct landslide control measures along the south coast of the Crimea (A. Sheko, personal communication, 1983). Over the next 40 years, landslide observation stations were created in many parts of the Soviet Union. In 1967, legislation entitled "On Measures to Protect

Soils from Wind and Water Erosion" was adopted by the Soviet government; this decree defined specific tasks in the field of mudflow and debris flow control in the mountainous regions of the Soviet Union. In 1978 the Soviet Council of Ministers passed a new law entitled "On Measures to Improve the Protection of Population Centers, Enterprises, and Other Properties and Lands Against Mudflows, Snow Avalanches, Landslides, and Rockfalls." State plans for the development of the Soviet national economy provide special allocations for the study and prediction of weather conditions and natural disasters, including landslides.

The study and prediction of landslides in the Soviet Union is carried out by many federal and regional ministries. As examples, the Ministry of Geology maps landslides and studies their regimes, the State Committee on Hydrometerology and the Environment conducts studies of mudflows and debris flows, and the Ministry of Melioration and Water Resources Management, together with the Ministry of Railroads and various provincial ministries of public utilities, conducts research on specific problems in landslide control and carries out the appropriate construction work. All scientific research on landslides is coordinated by the State Committee on Science and Technology.

To date, landslide prediction maps up to the year 2000 have been published for those areas of high landslide risk that are of greatest importance to the Soviet economy (the Black Sea coast of the Caucasus, Moldavia, the Baikal-Amur Railway zone, and the European part of the Soviet Union). Based on a 1978 decree of the Soviet Council of Ministers, plans are being formulated to map geologic hazards (including landslides) for the entire Soviet Union (A. Sheko, personal communication, 1983).

In France the ZERMOS (Zones Exposed to Risks of Movements of the Soil and Subsoil) plan provides for the production of landslide-hazard maps at scales of about 1:25,000 or larger. It also provides guidelines for selecting locations suitable for development and for identifying permissible land use (Porcher and Guilliope, 1979).

In 1978 the Swedish Geotechnical Institute, in cooperation with the Geological Survey of Sweden, was commissioned by the Swedish government to carry out general geologic mapping of areas of sensitive clays where a high risk of spontaneous landslides may exist. As of 1983, 14 maps at a scale of 1:50,000 had been completed; these maps show the extent of the clays and note where special attention should be paid to slope stability conditions (Cato and Engdahl, 1982).

In eastern Europe, Czechoslovakia has been a leader in landslide mapping. Maps produced at a scale of 1:10,000 represent the advanced state of the art in landslide hazard zonation (Mahr and Malgot, 1978). Romania has also fostered significant landslide mapping; of particular note has been a computer-processed geotechnical zonation mapping of land stability at a scale of 1:25,000 (Huma and Radulescu, 1978).

Information on land use regulation in countries other than the United States is sparse. However, in a summary of the responses to an international survey on landslides conducted by UNESCO, Arnould and Frey (1978) noted regulatory efforts by a few countries. As an example, the 1975 Forestry Law in Austria requires zonation of landslide risk before general planning. In France a 1970 decree pertaining to Plans of

Occupation requires the prevention of landslides in use of the land. Tasmania, Australia, has adopted a landslide zoning system for buildings in urban areas (Stevenson and Sloane, 1980). In cases of severe risk, proscriptive zones are established under Tasmanian statutes. The most restrictive of these prohibits all building, with some minor exceptions. A less restrictive zone controls buildings in respect to size, siting, drainage, earthworks, and the removal of trees.

Codes and associated regulations are not well developed in other countries, with a few exceptions. Japan and Canada practice some degree of grading regulation to control landslides, as do Sweden and England.

The physical methods of landslide control used in other countries are much the same as in the United States. These methods are most commonly used in heavily populated countries, such as Japan and Hong Kong, where land is very expensive. Japan probably leads the rest of the world in development of physical landslide control measures. Since the enactment of Japan's Sabo Law in 1897, preventive measures called sabo works (primarily check dams in gullies and on streams) have been promoted as public works to prevent debris flows and mudflows on mountain slopes and to reduce discharge into mountain streams. Although no estimates are available of the cost of construction and maintenance of sabo works and other physical protective measures in Japan, it probably represents the major part of the $500 million estimated as the total annual expenditure by the Japanese government for landslide mitigation and research. Check dams are also commonly used in other mountainous countries such as the Soviet Union and Indonesia.

New Zealand has a national insurance program that covers losses from landslides. This program assists homeowners whose dwellings have been damaged by landslides or other natural hazards that are not within the reasonable control of homeowners to prevent. This natural hazard insurance program is an outgrowth of the Earthquake and War Damage Act of 1944 (O'Riordan, 1974). A disaster fund, accumulated from a surcharge to the fire insurance program, reimburses property owners for losses.

3

LONG-TERM LANDSLIDE HAZARD MITIGATION IN THE UNITED STATES

INTRODUCTION

The four approaches to long-term hazard reduction--avoidance, design and building codes, landslide control, and insurance--are used, to varying extents and with varying degrees of effectiveness, in many parts of the United States today. An understanding of what is practiced now can provide a basis for recommendations concerning steps that can and should be taken to further reduce landslide losses in the United States.

AVOIDANCE

A program of landslide avoidance requires a process for effectively controlling land use. This process must be implemented by governmental decision makers with input from planners, geologists, and engineers. In the United States, experience with implementing land use planning for landslide control has been mixed. In some areas in California, land use programs by local governments to mitigate landslide damage have been extensive and successful. Across the nation, some individual private development projects have employed a very high standard of practice to avoid landslide damage. However, there are many examples where high standards have not been employed, and there has not been a consistent implementation of programs to mitigate landslide damage by avoidance. Furthermore, there are no widely accepted procedures or regulations for considering landslides as part of the land use and planning process.

DESIGN AND BUILDING CODES

Design, building, and grading codes are the regulatory vehicle through which governmental entities ensure proper design and construction practices. In the United States, many agencies at all levels of government apply design criteria for slope stability tailored to their specific needs. No uniform standard is applied. There is also no federal building code or federally sponsored design code that all governmental departments, or even all federal agencies, must use. While some private and governmental agencies have produced outstanding design criteria or documents that have served as guides for other agencies,* the majority of building and land surface modification throughout the country, both public and private, is carried out without any reference to a major design code.

A great deal of individual judgment is exercised when design criteria are established for specific projects. When professional engineering judgment is used alone, in the absence of standards--especially where there is pressure from owners and land developers--there is danger that the quality of design and construction will be low and will lack the consistency that would result from nationally accepted codes.

While the federal government has not generally participated directly in the formulation and enforcement of building codes, it has exerted influence on construction practices through the codes adopted by agencies responsible for government construction. The standards established and used for programs involving government financing for buildings have also been effective. In addition, federal standards for excavation--such as those established by the U.S. Army Corps of Engineers, the Soil Conservation Service, the Office of Naval Research, and the Bureau of Reclamation--are often used by private and public sector organizations.

In some states, certain cities and counties have developed and implemented strong building codes and grading regulations, often with encouragement and support from the state government. California, for example, has regulations concerning geologic hazards, and southern California communities have had experience with landslide mitigation codes for nearly 20 years. By publication and circulation of guidelines and reports, the California Division of Mines and Geology has established a standard for use throughout the state. The division is also actively involved in the review process for approval of various construction activities. By means of other legislation and regulation, California communities have established the nation's most extensive statewide program of codes and regulations designed to minimize landslide damage. While some other states have adopted similar regulations, these have not been extensive or coordinated. As a consequence, the implementation of landslide design codes at the local level is irregular throughout the nation.

Nevertheless, some of the most effective landslide regulations have been implemented by local governments. Examples of successful local programs include those in Los Angeles, Cincinnati, Prince Georges County in Maryland, and Fairfax County in Virginia. Local design and building codes are often patterned after Chapter 70 of the Uniform Building Code,

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*For example, the Grading and Geometric Design Criteria established by the American Association of State Highway and Transportation Officials are widely used as landslide design criteria. The U.S. Office of Naval Research Design Manual on Soil Mechanics, Foundations, and Earth Structures (NAVFAV DM-1971) is also used extensively as a guide for earthwork and slope stability.

"Excavation and Grading" (International Conference of Building Officials, 1979). This document provides a general statement about the requirements for design to control landslides and allows extensive interpretation or modification to suit the local user. In addition to the Uniform Building Code, many local or regional building codes have been developed through consultation with local professionals.

Two factors stand out concerning the experience with design and building codes in the United States. The first is the lack of uniformity and leadership in establishing codes applicable to landsliding. The second is the need to continue to add to the technological base for the development of codes. While there is considerable potential for reducing landslide losses through the adoption and effective enforcement of building codes based on today's technical understanding, it is clear that a greater understanding of landsliding processes would make it possible to develop codes that would provide an even greater capability for reducing landslide losses.

LANDSLIDE CONTROL

In the United States, the most commonly used physical method of landslide control is the control of ground and surface water in landslide-prone areas. The method is extensively used both by private landowners and developers and by governmental agencies. In general, surface water is diverted from landslide-prone areas by ditches, and groundwater is collected and removed by underground drainage systems and pumping wells.

Modification of the ground surface by removal of all or part of the material driving the landslide is another commonly used method of preventing slope movement. Large earth buttresses are often used to support the toes of slides, and in California this is the most common mechanical (as contrasted with hydrologic) method used to control landslides.

The most universal form of structural control for landslides is the retaining wall. Where walls will not suffice, other structural controls such as piles, caissons, or rock anchors are often used to stabilize earth masses on slopes. Structural debris barriers are used to divert mudflows and debris flows away from critical areas, and debris storage basins behind check dams collect landslide debris before it hits critical areas. These structures, which are major, expensive engineering works, are mostly found in parts of the western United States where debris flows are a common and hazardous form of landsliding. Landslide diversion structures, debris barriers, and debris basins have been built by governmental agencies at all levels, as well as by the private sector.

INSURANCE

Insurance is in principle a viable option for mitigating losses from landsliding; however, to implement an effective insurance program requires a degree of specification of risk that is not generally thought to be possible for landslides (although some recent studies by the U.S. Geological Survey, the Federal Emergency Management Agency, and some private consultants suggest otherwise). The history of landslide insurance in the United States indicates that the private sector is relatively uninterested at present in offering this coverage. This reluctance to provide landslide insurance is long-standing. Several highly publicized instances of landsliding, including the Portuguese Bend landslide in Los Angeles in 1956 and the extensive coastal landslides in California during the late 1960s, have contributed to this reluctance. At present, very few companies in the United States offer landslide coverage, and then only for certain areas.

A particular problem of landslide insurance is the potential for adverse selection by the insured population. Landslide risk is not uniformly distributed throughout the population or throughout a region. Rather, it is associated with certain distinctive physical features. The homeowner living on a flat surface has no interest in buying landslide insurance and sharing the risk and cost with the homeowner living on a steep hillside.

An alternative to private sector insurance would be a public insurance program, along the lines of the National Flood Insurance Program.

MAPPING

For all of the above approaches to landslide hazard mitigation, it is essential to know where the landslide-prone areas are and how serious the hazard is. This requires a program of landslide hazard mapping supplemented by other techniques such as aerial photointerpretation. Landslide susceptibility has been mapped for the United States as a whole (Radbruch-Hall et al., 1982), but at a scale that is not amenable to regional or local planning. The appropriate map scale for regional land use planning and hazard reduction programs is between 1:125,000 and 1:500,000. Mapping at this scale has been conducted in many locations throughout the nation. Local land use planning requires mapping at a scale of 1:24,000 or larger. Planning of individual projects requires mapping at a scale much larger than those noted above: map scales of 1:2,000 to 1:5,000 are used for individual projects. Some mapping at this scale has been carried out by local authorities and by private sector groups.

Landslide mapping at the federal level is conducted primarily by the U.S. Geological Survey. The Geological Survey has limited its landslide mapping to a few demonstration areas, to areas where problems are most severe, and to overview maps on a national scale. The Geological Survey and the Forest Service have also carried out extensive landslide mapping of federal lands. Other agencies (e.g., the Bureau of Reclamation) also do some landslide mapping and monitoring in connection with their missions.

Landslide mapping at the state level has generally been conducted by state geological surveys. The selection of areas to be mapped reflects the perception of the hazard. In general, mapping has been limited to extremely hazardous areas or areas experiencing rapid urbanization (Erley and Kockelman, 1981). In 1982 and 1983, landslide mapping was carried out by state geological surveys in selected areas of California, Idaho, New York, Pennsylvania, Virginia, and Wyoming with cooperative funding from the U.S. Geological Survey.

The greatest governmental involvement in landslide susceptibility mapping has been at the regional and local level. Maps are typically prepared for local governmental agencies by the U.S. Geological Survey, by state geological surveys, and by private consulting geologists.

Landslide susceptibility identification and mapping are also performed for private sector groups. This work is almost exclusively done as part of land development programs and is often a result of government codes or regulations. Consultants usually prepare these maps.

All of this mapping is carried out in the absence of universal (or even widely accepted) standards of accuracy, comprehensiveness, scale, symbols, or format. There are no guidelines available to assist in the preparation of these maps (except for examples such as the U.S. Geological Survey series). The technical capability with which landslide susceptibility maps are prepared varies widely, and the value of the final products is extremely variable.

4

RECOMMENDATIONS

INTRODUCTION

This report describes a situation that requires national attention at several different levels. The magnitude and extent of landslide damage in the United States can be reduced significantly by improvements in landslide engineering practice. These in turn will come about as a result of research and effective technology transfer. New concepts and approaches to forecasting, prevention, and remediation are urgently required. The costs and benefits of alternative mitigation strategies must be rigorously evaluated. Developing effective interaction among federal, state, and local agencies is imperative. The following recommendations are presented as a basis for addressing this problem.

LAND USE REGULATION

One of the most effective ways to reduce damage caused by landslides is to locate development on stable ground and leave unstable ground as open space or in low-intensity uses (although where land values are high, expensive engineering solutions for stabilization may be justified). Land use control programs are best carried out at the local level, but they require proper mapping and enabling legislation that may involve the participation of state and federal entities.

Recommendations

- The federal government should encourage the adoption and effective use, by state and local governments, of land use controls to mitigate landslide hazards.
- States should mandate or strongly encourage local governments to adopt regulations that will lead to the identification of landslides and their avoidance or control by developers.
- Local governments should require developers to map and disclose information about hazardous areas, and should allow design flexibilities so that hazardous areas can be usefully included within developments.

CODES

The development and implementation of design and building practices that minimize damage from landsliding in the United States is severely hampered by (1) geographic variations in the nature and degree of landslide risk, (2) insufficient numbers of trained geotechnical engineers assigned to code development and enforcement, and (3) inconsistent leadership. In spite of the wealth of experience with landsliding and landslide control, insufficient use is made of what has been learned. Greater emphasis needs to be placed on the use of existing engineering knowledge as a basis for code development. At the same time, further research should be undertaken to improve that technological base.

Recommendation

- Research should be undertaken, under national leadership, to improve the technical base for the development of design, building, and grading codes applicable to landsliding. At the same time, leadership in establishing appropriate design and building standards should be exercised at the national level. The codes themselves should be developed at state and local levels in response to regional and local conditions. Mechanisms for communication and standardization should be encouraged.

MAPPING

Landslide identification and delineation are fundamental to any hazard reduction or mitigation program. Mapping methodologies must be developed for application at a wide range of scales and coverage. The responsibilities for mapping programs must be identified, and there should be strong coordination at the national level. The private sector is a logical cooperator with state and local governmental agencies, a source of expertise in mapping and hazard delineation, and an obvious entrepreneur for the production and marketing of maps.

Recommendation

- The federal government should have specific but limited responsibilities for landslide mapping. These should include (1) the development of methodologies for landslide mapping on a variety of scales, (2) the delineation of landslide hazards on a national scale, (3) regional-scale mapping demonstrations, (4) landslide mapping on federal lands, and (5) landslide mapping in support of the missions of federal agencies. In addition, the federal government should work with other parties to provide cooperative support, information, and technical assistance to state, local, and private organizations wishing to implement effective hazard delineation programs to reduce landslide losses.

RESEARCH ON LANDSLIDE INITIATION AND LANDSLIDE PROCESSES

While there are practical working models of landslide initiation, and the mechanics of slope failure and the roles of the controlling variables are generally known, quantitative understanding of this process is limited and the time-dependent factors that influence landslides are not well understood.

Other aspects of landsliding, especially the mechanics of landslide transport and deposition, are even more poorly understood. For example, many flow-type landslides move greater distances and at different velocities than might be predicted by existing techniques. In addition, the mechanisms by which slides are transformed into debris flows and mudflows (a common occurrence in Utah in 1983 and 1984, for example) are not well understood. These limitations have direct consequences for programs of identification, avoidance, and control of landslide hazards.

Recommendations

• Field and laboratory research should be undertaken to establish quantitative relationships among the variables that control landslide initiation. This can only be achieved by controlled laboratory experiments dealing with the mechanics of failure and by careful field analysis and instrumentation of active and recent landslides. Long-term field measurements are essential to clearly define the influence of time-dependent factors and to fully understand the processes of landslide initiation under adverse conditions. Instrumentation for these types of studies is available and not excessively expensive, but field deployment is necessary for periods ranging from months to years.

• Examination of the three-dimensional structure of active and historical slope failures should be undertaken as a necessary first step in defining the mechanics of landslide transport and deposition. Laboratory analysis of the flow properties of various soil-water mixtures is also necessary to fully define the movement process in terms of variations of velocity and travel distance.

• Sponsorship of research to achieve these goals should be a responsibility of the federal government and should be carried out through (1) the support and maintenance of a research capability in universities through continuing National Science Foundation funding and (2) the maintenance of relevant interdisciplinary research in federal agencies with responsibilities related to landsliding, such as the U.S. Geological Survey, the Forest Service, the Agricultural Research Service, the Bureau of Reclamation, and the Corps of Engineers.

RESEARCH ON LANDSLIDE HAZARD DELINEATION, MAPPING, AND CONTROL

Field and laboratory research is needed to develop and test new methodologies, and to refine existing methodologies, for identifying and controlling landslides and for designing and building structures to resist landslide damage. For example, developments in geophysics, such as seismic profiling, can be applied to the identification of landslide areas. New methods in hydrology linking environmental factors to groundwater conditions are being developed and can be applied to the evaluation of landslide risk. Landslide incidence and landslide damage can be reduced by innovative application of drainage control measures and structural ground support. Automated data collection systems based on new electronic instrumentation are available for remote measurement of groundwater flow and landslide movement. Such systems can serve the dual roles of monitoring and early warning.

Recommendations

- Newly developed and currently accepted techniques in remote sensing, geophysics, hydrology, and geotechnics should be tested, adapted, and applied in as many different geologic and climatologic situations as possible to provide maximum correlations between effectiveness and site conditions. For example, new and proven geophysical methods have a high potential for rapidly defining landslide geometries and identifying potentially unstable subsurface conditions. Similarly, modern hydrologic techniques need to be tested and applied more widely to the identification of groundwater conditions that lead to landslide initiation. Advanced remote sensing techniques need to be explored more fully for their application to identifying unstable terrain, defining controlling parameters, and labeling and mapping downslope impact zones.
- Pilot studies of the effectiveness of various ground-improvement practices, such as drainage and engineered support structures, should be conducted in a variety of geologic and hydrologic environments to determine the adequacy of the design criteria and to identify suitable application practices in terms of costs and benefits.
- The behavior of recurrent landslides should be addressed by long-term monitoring programs to determine the magnitude and frequency of ground movement. Such information is necessary if an adequate analysis of landslide risk is to be developed for safety, insurance, zoning, and alternative land use purposes.
- Landslide-prone areas of particular significance to public safety should be instrumented to provide early warning of incipient hazards. Such early warning systems could also be used to identify areas for concentrated investigations and to provide a continuing measure of recurrence frequencies.
- Research in these areas should be carried out by federal agencies and by state and local governments through their own programs as well as through support and encouragement of private sector activities. Coordination of new activities with existing and planned public and private programs is essential.

TECHNOLOGY TRANSFER

At the present time, there is no effective vehicle for the transfer and dissemination of existing and new technologies applicable to the identification, analysis, and control of landslides. One issue involves liability. Increased liability associated with the use of pioneering techniques may tend to perpetuate the conservative and costly "tried and proven" methods of routine landslide engineering practice. Another issue is the absence of widespread knowledge of existing technologies developed in other geographic areas. For example, a number of techniques have been developed to identify landslides and to estimate the risk resulting from various natural and manipulative disturbances. Knowledge of these techniques is often limited outside their area of development, and research and development efforts are frequently duplicated. A third issue is the lack of perceived usefulness of existing technologies for landslide hazard mitigation. For example, new developments in remote sensing--including infrared imagery, side-looking radar, image enhancement procedures, and computer graphics--are not widely perceived as being useful in landslide identification.

Recommendations

- Experimental projects should be carried out in areas of low public risk to test and evaluate new procedures in landslide engineering practice in a context of low liability. Such testing and evaluation could be effectively pursued on remote areas of public land where liability is low and where the application of pioneering engineering techniques could provide substantial dollar savings to the federal government in terms of design, construction, and maintenance costs as well as reduced environmental damage from landslides. The Forest Service and the Bureau of Land Management are prime examples of rural land managers that have chronic landslide problems and could benefit from innovative mitigation techniques.
- A continuing education, training, and information dissemination program should be established to foster the use of existing and innovative landslide identification, analysis, and control techniques. This should include regional workshops and interagency cooperation and information exchange. It should also provide for dissemination of knowledge to a broad spectrum of user groups, ranging from private landowners to managers of state and local agencies.
- Partnerships between public and private sector groups should be encouraged.

INSURANCE

Insurance can be a viable mechanism for distributing landslide losses and encouraging risk-reducing actions. Implementing effective insurance programs requires a better understanding of (1) the landslide hazard in each area, (2) the likelihood of landslide occurrence, and (3) the risk of damage and loss of life. The virtual absence of private insurance coverage in the United States may not be justified, and with proper encouragement private coverage might be made available in selected locations. A public insurance program analogous to the National Flood Insurance Program should also be considered as an alternative to the present practice of providing insurance coverage for only one kind of landslide (mudslides) under the NFIP.

Recommendation

• A better understanding of landslide processes and risk should be developed to provide a basis for decisions by private sector insurers concerning coverage of landslide hazards. The federal involvement in landslide insurance should be clarified.

NATIONAL LEADERSHIP

Effective nationwide coordination of landslide research and mitigation programs is necessary. A national focus is appropriate as a basis for communication among the many federal, state, local, and private entities that are involved in landslide management. A national focus is also appropriate for interaction with landslide research and mitigation activities in other countries.

Recommendations

• A single organization drawing upon a number of professions and disciplines, including geology, civil engineering, planning, and economics, should have the responsibility for providing national leadership in reducing landslide losses within the United States. This organization could be a federal agency; it could be a consortium of private institutions, universities, or professional societies; it could be an independent scientific or technical institution of national stature; or it could be a U.S. national committee consisting of representatives from government, industry, academia, and the professional societies. Whatever the nature of the organization, the specific interests of federal, state, regional, and local agencies, as well as private institutions, having responsibility for various aspects of landsliding and landslide losses should be represented.

• The federal government should establish a mechanism for information exchange and program coordination among the federal agencies having responsibilities related to landsliding and landslide losses. An interagency task force or interagency coordinating committee might be an appropriate way to accomplish this purpose.

LEGISLATION

There exists a body of federal and state legislation addressing the problem of landslides. Some specific responsibilities for research, mitigation, hazard warning, disaster response, and insurance are defined in this legislation and in associated policy documents. On the other hand, some important issues are not addressed by existing legislation. In particular, no existing organization--governmental or private--has either the authority or the resources to effectively lead a comprehensive national program to reduce landslide losses.

Recommendations

- Existing legislated responsibilities for landslide loss reduction activities should be funded and carried out by the appropriate governmental bodies.
- New legislation to meet the recommendations proposed herein should be initiated as appropriate.

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APPENDIX:

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

GENEVIEVE ATWOOD is the Utah State Geologist and Director of the Utah Geological and Mineral Survey. She received her M.A. in the history of science from Bryn Mawr College in 1968 and her M.A. in geology from Wesleyan University in 1973. She worked as a field geologist in Honduras and as a staff geologist with the National Research Council's Environmental Studies Board, and then worked for six years with an engineering firm reclaiming disturbed lands (coal surface mines, uranium mill tailings, large construction sites). From 1974 to 1980 she served in the Utah House of Representatives. Since 1981 she has been director of the Utah Geological and Mineral Survey, which inventories the mineral resources of Utah and identifies the state's geologic hazards. Much of the Survey's emphasis in recent years has been on landslides. Her professional area of expertise is geomorphology, with practical emphasis on the reclamation of disturbed lands in Appalachia, the Midwest, the northern Great Plains, and Australia. Most recently she has advised policy makers on Utah's geologic hazards: landslides, earthquakes, poor soil conditions, rockfalls, high groundwater, and rising lakes. She is the coauthor of several professional publications as well as several pieces of state legislation.

DON U. DEERE is an international consultant in the fields of engineering geology and rock mechanics applied to hydroelectric projects. He is currently involved with 20 projects in 15 countries, working on dam foundations, pressure tunnels, underground powerhouse caverns, and landslide stabilization. He also is Adjunct Professor in the Department of Civil Engineering at the University of Florida, Gainesville. Formerly, he was a professor for 19 years at the University of Illinois in the departments of Civil Engineering and Geology. He received his B.S. in mining engineering from Iowa State University in 1943, his M.S. in geology from the University of Colorado in 1949, and his Ph.D. in civil engineering from the University of Illinois in 1955. He has published 50 papers and has served as a member or chairman of a number of national and international technical committees. He was elected to the National Academy of Engineering in 1966 and to the National Academy of Sciences in 1971.

ARTHUR G. KEENE is County Geologist for Los Angeles County. He heads a section of 10 engineering geologists in the Department of County Engineer--Facilities. He received his B.Sc. degree from the University of California at Los Angeles in 1950 and his M.Sc. from the University of Southern California in 1965. During the Korean conflict he served in the Engineer Research Development Laboratory of the U.S. Army Corps of Engineers, Fort Belvoir, Virginia. He was then employed by the Geophysical Laboratory, Carnegie Institute of Washington, D.C., doing research in silicate melts under Frank L. Schirer. His experience in engineering geology and groundwater began when he was a geologist with the Los Angeles County Flood Control District. In 1965 he transferred to the Department of County Engineer as County Geologist in charge of geologic clearance for building and grading permits throughout Los Angeles County and contract cities. He advises all County Departments on geologic hazards pertaining to existing roads, new road alignments, bridge abutments, beach erosion, active fault investigations, and landslide investigations. He also serves as expert witness for the County Counsel. He served as a member of the Land Use Planning Sub-committee on Seismic Safety between 1969 and 1974. He was Chairman of the Southern California Section of the Association of Engineering Geologists in 1976, a member of the Professional Affairs Committee, State Board of Registration for Geologists and Geophysicists, from 1973 to 1978, and has served on its Legislative Committee since 1978. He is the author and coauthor of several professional publications, including that of the Joint Committee on Seismic Safety, as well as various special publications of the Association of Engineering Geologists.

F. BEACH LEIGHTON is President of Leighton & Associates, a geotechnical consulting firm that he founded in 1960. He received his B.S. in engineering geology from the University of Virginia in 1946, his M.S. in geology from the California Institute of Technology in 1949, and his Ph.D. in geology from the California Institute of Technology in 1951. He was Chairman of the Department of Geology at Whittier College from 1951 to 1972 and is presently Adjunct Research Professor in that department. He is the principal author and coauthor of over 30 geotechnical papers and publications and received the Association of Engineering Geologists Claire P. Holdredge award in 1967 for his paper "Landslides and Hillside Development." He has served on the Engineering Geology Qualifications Boards of the City of Los Angeles and Los Angeles County, on the Geological Society of America Membership Committee, and on the National Earthquake Studies Advisory Panel. He was also State-of-the-Art Reviewer on Application of Earth Science to Urban Planning from 1972 to 1974.

GEORGE G. MADER is Vice-President of William Spangle & Associates, Inc., a city and regional planning consulting firm. He also is a Senior Lecturer in the School of Earth Sciences at Stanford University, where he has taught since 1970. He received his B.A. in geography from the University of California at Los Angeles in 1952 and his

Master of City Planning degree from the University of California at Berkeley in 1956. He is a member and past chairman of the California Seismic Safety Commission and a member of the Earthquake Hazard Mitigation Advisory Subcommittee to the National Science Foundation. He has a particular interest in the application of geologic and seismic information in land use planning and in connection with this interest has advised local governments, served on national and international committees, and been involved in international projects in China, Algeria, and Yugoslavia. He has written papers, conducted research under National Science Foundation and U.S. Geological Survey sponsorship, and spoken at numerous meetings on the earth sciences and land use planning.

NORBERT R. MORGENSTERN is University Professor in the Department of Civil Engineering at the University of Alberta, Edmonton, Canada. He received his B.A.Sc. in civil engineering from the University of Toronto in 1956 and his Ph.D. in soil mechanics from the University of London in 1964. Prior to assuming his present position, he was on the staff of the Department of Civil Engineering, Imperial College of Science and Technology, University of London. He has published numerous papers in geotechnical engineering and has acted as a consultant to industry and government for the past 25 years. He is a fellow of the Royal Society of Canada and has received awards from other professional organizations.

DAVID B. PRIOR, Professor in the Coastal Studies Institute of Louisiana State University, is an authority on marine geology, submarine slope instabilities, and various types of terrestrial landslides. He earned his B.A. in 1964 and his Ph.D. in 1968 at the Queen's University of Belfast, and has served on the faculty of the Queen's University of Belfast, Northern Ireland, Clark University, and Louisiana State University. Under recent contracts with the U.S. Geological Survey, the Bureau of Land Management, and the Office of Naval Research, and as a consultant to industry, he has been engaged in mapping and identifying shelf and continental slope geology and landslide features, particularly in the northern Gulf of Mexico and in the Atlantic. His work has involved considerable field experience with state-of-the-art marine survey systems and experience as chief scientist on numerous multisensor cruises. He has conducted field work in Ireland, France, Denmark, the Caribbean, Canada, Spitsbergen, and Greenland and has published approximately 80 scientific papers.

IRWIN REMSON is Barney and Estelle Morris Professor of Earth Sciences at Stanford University in California. He received his A.B. in physics from Columbia College in 1946 and his M.A. and Ph.D. from Columbia University in 1949 and 1954, respectively. Prior to his current appointment, he served as a geologist and hydraulic engineer with the U.S. Geological Survey, as Professor of Civil Engineering and Mechanics at Drexel Institute of Technology, and as Chairman of the Department of Applied Earth Sciences at Stanford University. He has coauthored two books, Numerical Methods in Subsurface Hydrology and Geology in Environmental Planning, as well as numerous journal articles on groundwater modeling, hydrologic optimization, solute transport, hydrogeology, and unsaturated flow. His consulting work has involved water supply, waste disposal, land instabilities, and environmental management.

DWIGHT A. SANGREY (Chairman) is Professor and Head of the Department of Civil Engineering at Carnegie-Mellon University. He received his Ph.D. in civil engineering from Cornell University in 1968 and also has degrees in civil engineering from Lafayette College and the University of Massachusetts. He has held several positions in industry and universities and was on the faculty of Cornell University for 10 years before joining Carnegie-Mellon in 1980. His major area of technical activity has been professional practice, teaching, and research in geotechnical engineering. Within this field he has been particularly concerned with problems involving dynamics, the stability of natural and man-made slopes, and engineering in offshore and frontier environments. He is the author of over 70 technical publications and proceedings, a member or fellow of several national and international professional societies, and a director of the Pittsburgh High-Technology Council. His current research interests include applications of robotics and artificial intelligence in civil engineering and construction. This work involves the development of expert systems as well as the design and evaluation of robotics in specific applications contexts. He is also actively involved in the development of innovative mechanisms for cooperative research between universities and industries.

ROBERT L. SCHUSTER is an engineering geologist with the U.S. Geological Survey. He received his B.S. in geology from Washington State College in 1950, his M.S. in geology from Ohio State University in 1952, M.S. and Ph.D. degrees in civil engineering from Purdue University in 1958 and 1960, and a diploma in soil mechanics from the Imperial College, University of London, in 1964. He was an Associate Professor and Professor in the Department of Civil Engineering, University of Colorado, from 1960 to 1967 and from 1967 to 1974 he was Professor and Chairman of the Department of Civil Engineering, University of Idaho. From 1974 to 1979 he was Chief of the Engineering Geology Branch of the U.S. Geological Survey. From 1979 to 1982 he was a member of the Executive Committee of the Geotechnical Engineering Division of the American Society of Civil Engineers, serving as Chairman in 1981. In 1982 he was elected to membership on the Management Board of the Engineering Geology Division of the Geological Society of America; in 1984-85 he will serve as Chairman of the Division. He is author and coauthor of over 100 scientific papers and coeditor of the 1978 National Academy of Sciences book Landslides: Analysis and Control.

DOUGLAS N. SWANSTON is Principal Research Geologist with the U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, Juneau, Alaska, and is currently Group Leader for Watershed Management Research in southeast Alaska. In addition to his duties in Alaska he is the coordinator for a West-Wide Soil Mass Movement Research Program dealing with the identification, prediction, and control of unstable terrain on national forest lands. He received his B.S. in geology from the University of Michigan in 1960, his M.A. in geology and geomorphology from Bowling Green State University in 1962, and his Ph.D. in geomorphology with a minor in soil mechanics and foundation engineering from Michigan State University in 1967. He has been instrumental in research and development of techniques for landslide identification, prediction, and control from steep forest lands in the West and is an authority on ground failure hazards along the North Pacific Coast. He has authored or coauthored 44 papers on this and related subjects.

BARRY VOIGHT is Professor of Geosciences at the Pennsylvania State University. He began research on mass movements under the guidance of Raymond Gutschick and colleagues at the University of Notre Dame, where he received three degrees in geology and civil engineering. In 1965 he received a Ph.D. in geology from Columbia University. Specializing in rock mechanics and tectonic geology, he has conducted field investigations in the Appalachians, the Rocky Mountains, and the Cascade Range and has annually led expeditions to Iceland since 1978. This work has led to numerous publications, many dealing with the subjects of mass movements or rock stress, and four books, including Rock Mechanics: The American Northwest (1974) and the two-volume work Rockslides and Avalanches (1978, 1979). Since 1980 he has served as an adjunct geologist for the U.S. Geological Survey at the Cascades Volcano Observatory. He has coauthored several papers that have received awards from the U.S. National Committee on Rock Mechanics (National Research Council) and has received the George Stephenson Medal from the Institution of Civil Engineers (London). He has been engaged as visiting professor at the Delft Technical University in the Netherlands, the University of Toronto, and the University of California at Santa Barbara and has served on various National Research Council committees dealing with rock mechanics and natural hazards.