GEOLOGICAL SURVEY CIRCULAR 880

Goals and Tasks of the Landslide Part of a Ground-Failure Hazards Reduction Program

Workshop on Ground-Failure Hazards, Golden, Colorado
January 28–29, 1981

Convenor: R. W. Fleming
Denver, Colo.

Group I (Scope and strategy)

R. L. Schuster, Denver, Colo. (Group Leader)
D. D. Bajema, Reston, Va.
R. H. Campbell, Reston, Va.
B. B. Hanshaw, Reston, Va.
Gerald Meyer, Reston, Va.
D. M. Morton, Reston, Va.
D. R. Nichols, Denver, Colo.
D. A. Seyler, Reston, Va.
P. G. Teleki, Reston, Va.
J. J. Travis, Reston, Va.
R. L. Wesson, Reston, Va.

Group II (Landslide hazard mapping and risk evaluation)

E. E. Brabb, Menlo Park, Calif. (Group Leader)
R. B. Colton, Denver, Colo.
W. E. Davies, Reston, Va.
S. D. Ellen, Menlo Park, Calif.
O. J. Ferrians, Jr., Menlo Park, Calif.
L. E. Garrison, Corpus Christi, Tex.
J. O. Maberry, Reston, Va.
J. T. McGill, Denver, Colo.
T. H. Nilsen, Menlo Park, Calif.
C. L. Pillmore, Denver, Colo.
J. R. Plasker, Denver, Colo.
D. H. Radbruch-Hall, Menlo Calif. Park, Calif.
R. B. Raup, Jr., Denver, Colo.
C. M. Wentworth, Jr., Menlo Park, Calif.

Group III (Processes and prediction)

D. J. Varnes, Denver, Colo., (Group Leader)
M. A. Hampton, Menlo Park, Calif.
E. L. Harp, Menlo Park, Calif.
Reuben Kachadoorian, Menlo Park, Calif.
D. K. Keefer, Menlo Park, Calif.
R. K. Mark, Menlo Park, Calif.
W. L. Newell, Reston, Va.
D. W. Rankin, Reston, Va.
F. S. Riley, Denver, Colo.
W. V. Sliter, Reston, Va.
D. E. Stuart-Alexander, Menlo Park, Calif.
R. C. Wilson, Menlo Park, Calif.
T. L. Youd, Menlo Park, Calif.

Group IV (Transfer and use of information)

W. J. Kockelman, Menlo Park, Calif. (Group Leader)
R. H. Alexander, Boulder, Colo.
R. M. Barker, Reston, Va.
J. S. Booth, Woods Hole, Mass.
W. R. Hansen, Denver, Colo.
K. W. King, Denver, Colo.
R. D. Jarrett, Denver, Colo.
R. H. Morris, Reston, Va.
J. S. Pomeroy, Reston, Va.
C. F. Shearer, Reston, Va.
H. E. Simpson, Denver, Colo.
J. C. Stephens, Reston, Va.
G. F. Wieczorek, Menlo Park, Calif.

Goals and Tasks of the Landslide Part of a Ground-Failure Hazards Reduction Program

By U.S. Geological Survey

GEOLOGICAL SURVEY CIRCULAR 880

1982

United States Department of the Interior

JAMES G. WATT, *Secretary*

Geological Survey

Dallas L. Peck, *Director*

First printing 1982

Second printing 1983

Free on application to Branch of Distribution, U.S. Geological Survey, 604 South Pickett Street, Alexandria, VA 22304

CONTENTS

ILLUSTRATIONS

TABLES

Goals and Tasks of the Landslide Part of a Ground-Failure Hazards Reduction Program

By U.S. Geological Survey

SUMMARY OF CONCLUSIONS

Ground failure in the form of landsliding in the United States results in damages in excess of $1 billion annually. And, although the most serious problems appear to be associated with the mountainous regions of the country, virtually every State has significant landslide problems.

National programs to reduce landslide losses in other countries of the world include national landslide insurance in New Zealand, hazard zonation with land-use controls in France, an extensive program of research and stabilization in Japan, and extensive programs of inventories and zonation in other European countries including Spain, Italy, Germany, and Czechoslovakia. In the United States, a few successful damage-avoidance and loss-reduction programs have been conducted by local governments. For example, in the City of Los Angeles, landslide damages to private property constructed since the 1963 enactment of a strong grading code have been reduced by more than 90 percent compared with private property constructed before the grading code. Using data such as these, geologists for the State of California (Alfors and others, 1973) have estimated that about 90 percent of their nearly $10 billion damages estimated for the period 1970–2000 can be avoided at a benefit-cost ratio of 9:1.

The U.S. Geological Survey proposes an expanded program of landslide studies to acquire the necessary technical data and to promote the effective utilization of the information. The proposed program consists of three separate but related parts—process and prediction studies, hazard mapping and risk evaluation, and transfer and use of the information. The types of investigations proposed for each part of the program are listed in detail in the text of this circular and are summarized at the end of this report into groups of similar types of studies.

The processes deserving the highest priority are those causing greatest damage or threat to human life and include debris flows, rock falls, slumps, lateral spreads, and submarine landslides of different types. The areas of highest priority, in addition to specific submarine areas, are the West Coast region, Appalachian region, Rocky Mountain region, and other small geographic areas that have serious landslide problems. Threats to lifelines, such as emergency evacuation routes and pipelines, and to critical facilities, such as nuclear reactors and high dams, also deserve special priority.

The success of a program to avoid landslide damages and to reduce losses will depend upon the continuing progress in technical investigations and the effective transfer and use of information.

PART 1—HISTORY AND SCOPE OF PROBLEM

INTRODUCTION

Ground failures caused by landslides, subsidence, swelling clays, and construction-induced rock deformation cause billions of dollars in property losses in the United States each year. Together, they have historically exceeded the annual combined losses from floods, earthquakes, hurricanes, and tornadoes by many times—those from landslides and subsidence alone amounting to at least $1.5 billion per year over the past 50 years (Jahns, 1978), and those from swelling clays more than $2 billion per year (Jones and Holtz, 1973). Yet, within the Federal Government, there is no coordinated program of research, application, and response to these geologic hazards that can avoid or reduce damages on a scale commensurate with the scope of the problem. Further, the necessary technical information is not being obtained now that will meet the future requirements for development of areas of marginal stability.

A national program committed to the reduction of losses from any of the kinds of ground failure just mentioned should address all aspects of the process including engineering analysis, structural design, scientific investigations of several types, and economic and sociological factors. Such a program requires skills that are clearly beyond the capacity of any single organization or agency. This statement is directed to the proposed role of the U.S. Geological Survey in the landslide part of a ground-failure hazards reduction program. Leonards (1982) has outlined some of the more engineering-oriented aspects of response to ground-failure problems.

The U.S. Geological Survey has proposed an expanded research program in ground-failure hazards for the past several years. A program of landslide-hazard reduction operated informally within the Geological Survey between 1977 and 1980. That program supported a few studies through research contracts, coordinated landslide studies within the Geological Survey, responded to requests for information and assistance from other agencies and recommended research tasks on topics of economical importance or technical promise. Beginning in fiscal year 1980, existing programs in engineering geology and arctic studies were combined into a formal program entitled Construction and Ground-Failure Hazards Reduction. The program has a research mission in landslides, subsidence, swelling clay-shales, and construction-induced rock deformation, and an applications mission in helping to avoid or to reduce losses from these geologic hazards. Emphasis during the early stages of the program will be on landslide studies.

A workshop on goals, strategies, and tasks of the Construction and Ground-Failure Hazards Reduction Program was held in Golden, Colo., on January 28–30, 1981. The focus of the workshop was on the part of the program that will be directed to landslide studies. Fifty-three participants from the U.S. Geological Survey, including scientists, engineers, application and information specialists, and representatives of major administrative units, met to discuss plans and priorities for the program. A list of participants, the authors of this report, is on the inside front cover of this circular. This report is a summary of the workshop and contains a discussion of (1) the scope of the landslide problem in the United States including costs of damages, (2) potential benefits of a program with selected examples, and (3) a summary of approaches and tasks for each of three major program elements—process and prediction studies, landslide-hazard mapping and risk evaluation, and information transfer and use.

SCOPE OF THE LANDSLIDE PROBLEM IN THE UNITED STATES

Ground failures in the form of different types of landslides are a significant problem in virtually all of the United States, the Commonwealth of Puerto Rico, and the Trust Territories of the Pacific region. Radbruch-Hall and others (1976) conducted a survey of the distributions of landslide deposits and materials susceptible to landsliding in the conterminous United States. Krohn and Slosson (1976) independently prepared a map of landslide potential as part of a comprehensive survey of natural hazards in the United States. Information from both maps was combined into a single map of landslide potential, shown here as figure 1 (Wiggins and others, 1978). Obviously the Pacific coastal region, Rocky Mountains, Appalachians, and northern Great Plains are more slide-prone than other areas. For smaller geographic areas, individual landslides can be mapped. Colton and others (1976) prepared an inventory of landslide deposits in Colorado and found that they comprised about 8 percent of the area of the State. A project to inventory landslide deposits in the Appalachians revealed that there are at least 2 million individual landslides large enough to be mapped from aerial photography (W. E. Davies, oral commun., 1979).

Submarine landslides likewise have been found in relative abundance in continental margins of the United States where energy-producing facilities, waste-disposal areas, and military installations are vital to the Nation's interest. Although no comprehensive mapping of large regions has been published, detailed mapping of selected areas demonstrates the magnitude of the problem (Coleman and others, 1980).

The costs of landslide damages are also significant, particularly in view of the fact that damages to private property are generally not recoverable through disaster-relief programs or insurance. Schuster (1978) conducted a survey of costs of landslide damages for the United States and concluded that they exceed $1 billion each year. More detailed surveys of smaller areas have produced information that suggests that costs of damages to private property amount to 30–50 percent of the total damages. Fleming and Taylor (1980) surveyed the cost of landslide damages for three major metropolitan areas including Cincinnati (Hamilton County), Ohio, Pittsburgh (Allegheny County), Pa., and the nine-county San Francisco Bay region. The damage costs obtained through interviews with public officials, consultants, and private citizens are minimum figures and are real monetary losses. Indirect losses such as inconvenience of road closures, lost time, costs of special police and (or) fire protection, or landslide damages that were not corrected were not included. The reported costs were for different periods of time between 1969 and 1978 and were unadjusted for inflation. The estimated annual costs of landslide damages are as follows: Allegheny County, Pa.—$4 million total or $2.50 per person per year; Hamilton County, Ohio—$5.2 million total or $5.80 per person per year; San Francisco Bay region—$5.9 million total or $1.30 per person per year. Based on data from other sources (Slosson, 1969), landslide damage to private property in the early 1970's in the City of Los Angeles was about $1.60 per person per year. Total annual costs of landslide damages to public and private property in Los Angeles were probably about $3 per person.

ANTICIPATED BENEFITS OF A PROGRAM FOR LANDSLIDE-DAMAGE REDUCTION

Other than the small program in the U.S. Geological Survey, there is no national program in the United States directed to reduction of losses from landslides. Without a well-directed, national program of research and applications, the costs of damages from landsliding will certainly increase. However, there is no point to an expenditure of national resources to reduce losses without a reasonable expectation of success. Expenditure of tax dollars for research and development of programs must produce reductions that are significantly greater than the costs of research and the costs of design and implementation of the loss-reduction programs. Fortunately, the experience in landslide-damage reduction in the United States and other countries suggests that dramatic reductions are attainable.

Successful damage reduction programs have operated at the local government level in a few communities in the United States through the energies of local officials and citizens. These programs are of different forms in different areas but have four common ingredients. All have (1) an adequate base of technical information about the landsliding, (2) an able and concerned local government, (3) a technical community able to apply and build on the technical data base, and (4) a citizenry that understands the value of programs that promote the health, safety, and general welfare of the community.

The best example of a successful local program to reduce landslide losses is in the City of Los Angeles. That program has been developed over the past 30 years, and the City has adopted grading regulations that are serving as a model to other communities. The regulations require specific evaluations of landslide potential by engineering geologists and geotechnical engineers before construction and also require inspections of the grading operations at seven key points during the construction process.

The Los Angeles program began in 1952 with adoption of a primitive grading code and was modified several times before being rewritten into nearly its present form in 1963. The modern code of 1963 has been refined to incorporate improvements in technology into the regulations. Although landslides still occur in the hillside areas of Los Angeles, the damages inflicted to developments built after the implementation of modern grading regulations are less than one-tenth of those to developments constructed with minimal regulations (Fleming and others, 1979; Slosson and Krohn, 1979). Leighton (1976) has estimated that, for developments in California, the technical information to reduce landslide damages by 95–99 percent is attainable through regional, community, and site investigations, with progressively greater detail obtained in the investigations of the smaller areas.

An alternative or supplement to the program of grading regulations adopted in the City of Los Angeles has been implemented by some local governments in the San Francisco Bay region. The town of Portola Valley, Calif., developed a set of criteria of permissible land use that is based on large-scale mapping (1:6,000) of susceptibility to landsliding (Hoexter and others, 1978). The permissible land uses for residences, roads, utilities, and water tanks are shown in table 1. The [Y] and [N] zones are provisional and can be de-

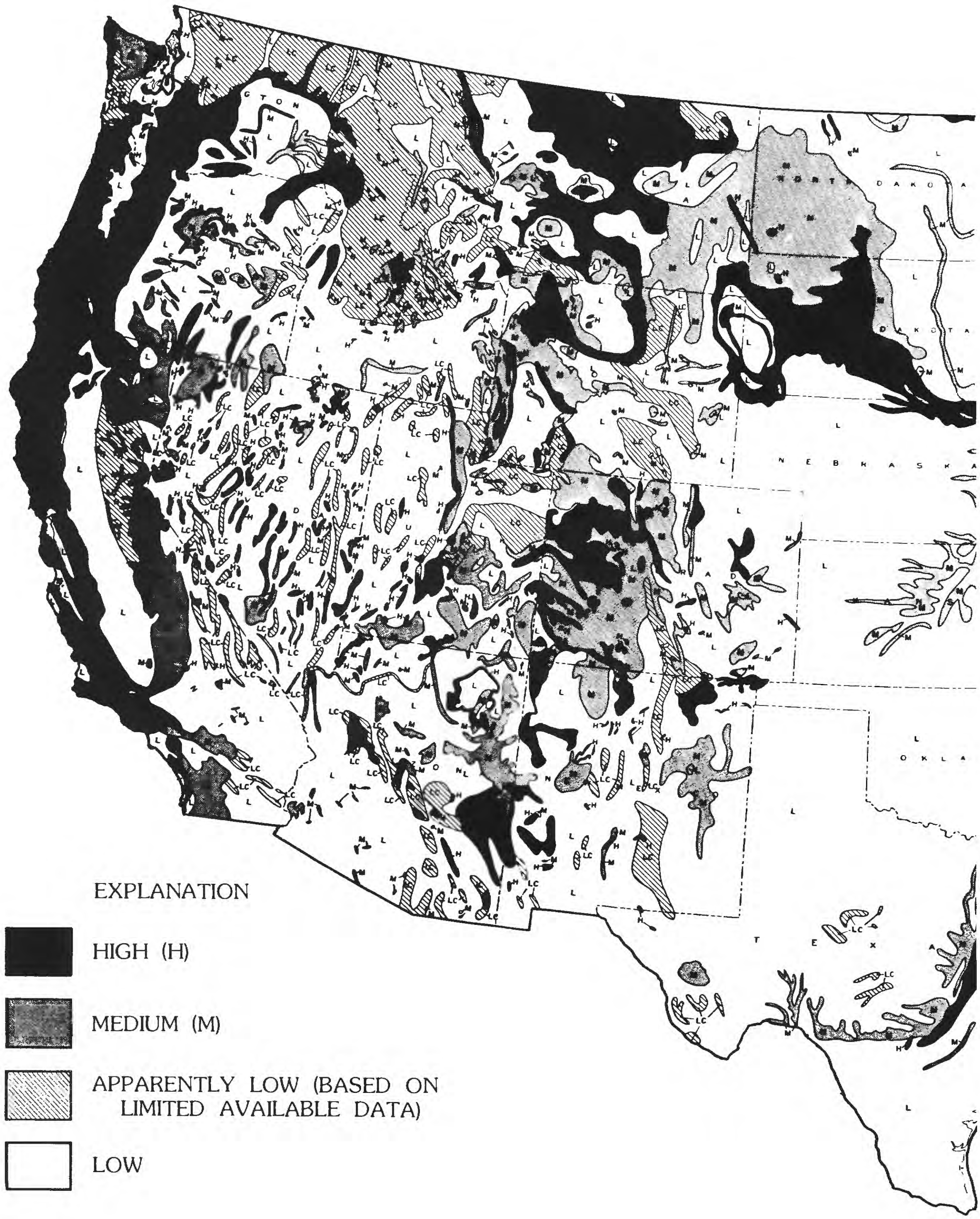
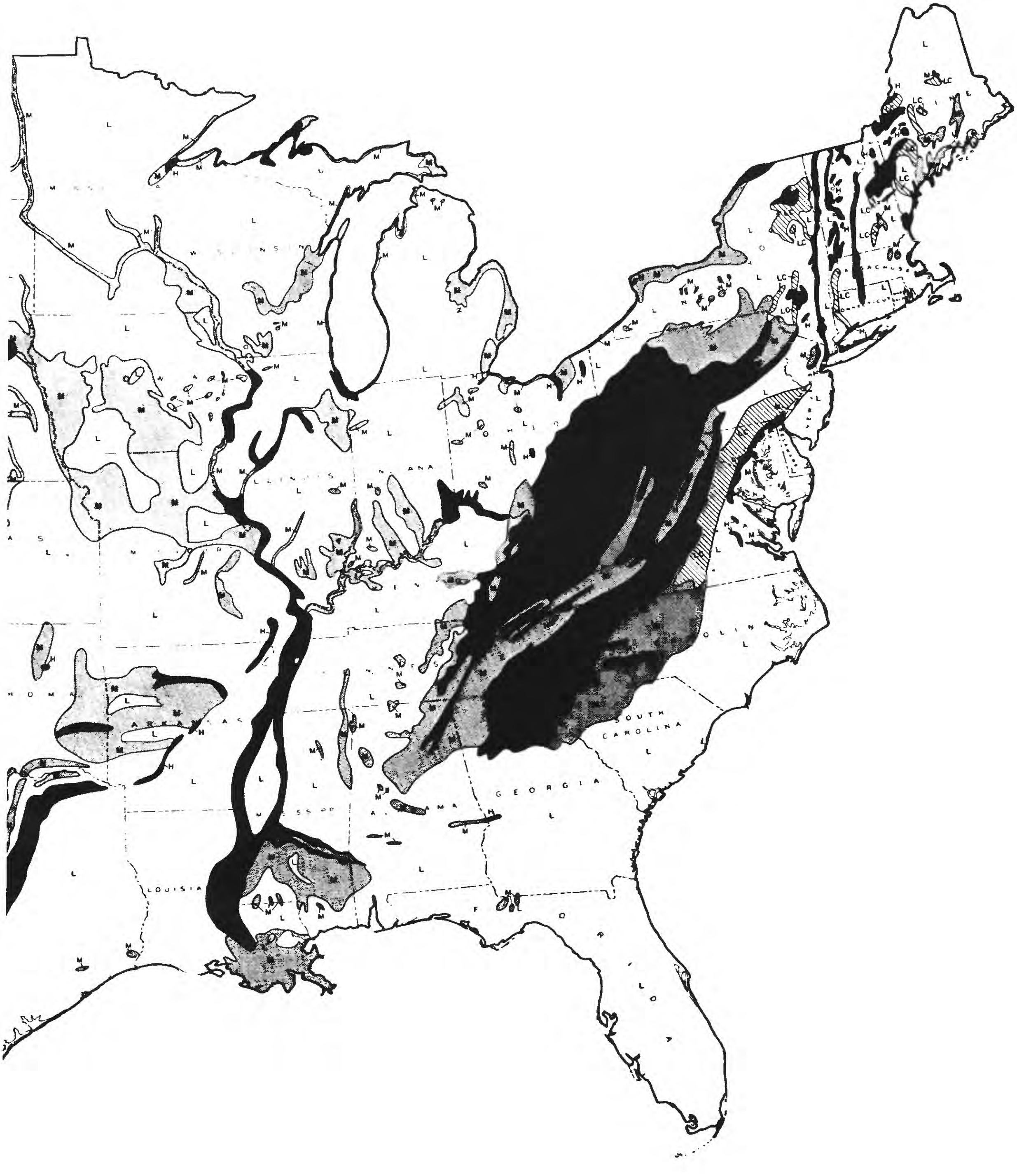


FIGURE 1.—Map showing relative potential of different parts of the



conterminous United States to landsliding (Wiggins and others, 1978).

TABLE 1.—*Criteria for permissible land use in Portola Valley, Calif. (from Mader, 1978)*

	Land stability symbol	Roads		Houses (parcel acreage)			Utilities	Water tanks
		Public	Private	1/4 Acre	1 Acre	3 Acres		
Most stable......	Sbr	Y	Y	Y	Y	Y	Y	Y
	Sun	Y	Y	Y	Y	Y	Y	Y
	Sex	[Y]	Y	[Y]	Y	Y	Y	[Y]
	Sls	[Y]	[Y]	[N]	[Y]	[Y]	[Y]	[N]
	Ps	[Y]	[Y]	[N]	[Y]	[Y]	[Y]	[N]
	Pmw	[N]	[N]	[N]	[N]	[N]	[N]	[N]
	Ms	[N]	[N]	N	N	N	N	N
	Pd	N	[N]	N	N	N	N	N
	Psc	N	N	N	N	N	N	N
	Md	N	N	N	N	N	N	N
Least stable	Pf	[Y]	[Y]	(Covered by zoning ordinance)			[N]	[N]

EXPLANATION OF SYMBOLS

Y Yes (construction permitted)
[Y] Normally permitted, given favorable geologic data and (or) engineering solutions
N No (construction not permitted)
[N] Normally not permitted, unless geologic data and (or) engineering solutions favorable

Land stability symbols (as used on geologic hazards map)

S Stable
P Potential movement
M Moving
br Bedrock within 3 ft of surface
d Deep landsliding
ex Expansive shale interbedded within sandstone
f Permanent ground displacement within 100 ft of active fault zone
ls Ancient landslide debris
mw Mass wasting on steep slopes, rock falls and slumping
s Shallow landsliding or slumping
sc Movement along scarps of bedrock landslides
un Unconsolidated material on gentle slope

veloped provided that detailed geologic and (or) geotechnical engineering studies reveal that the sites can be safely developed. Since enactment of the code in 1967, about 350 parcels have been developed. There reportedly has been one landslide in the area at a site where the owner insisted on building in opposition to recommendations (F. A. Taylor, oral commun., 1981).

In San Mateo County, Calif., a landslide susceptibility map (Brabb and others, 1972) was adopted as a zoning map that controls the permissible density of development on land of different susceptibility to landsliding. For areas in the highest category of susceptibility, only one structure is permitted on each 40 acres of land provided that geologic and engineering investigations show that a site exists in the parcel that can safely be developed. Since adoption of the zoning in 1975, there have been no landslides on 1,055 properties, about 370 of which were in hillside areas, developed under the program (F. A. Taylor, oral commun., 1981).

In Fairfax County, Va., a different approach is used. Maps have been prepared that outline varying degrees of hazard in the different materials (Obermeier, 1979). Developers are required to obtain professional engineering advice for sites developed in specific geologic materials. Site investigation reports and development plans that are also required by Fairfax County are reviewed by a peer review board of other consultants retained by the county. The result has been a "drastic reduction in landslides" (Dallaire, 1976, p. 77).

In the San Francisco Bay region, more than three-fourths of the local units of governments have made use of landslide-hazard information in various planning and decisionmaking activities including hazard studies; public safety, land use, and open-space plans; environmental analysis; critical facility siting; public site selection; and ordinances and their administration (Kockelman, 1975, 1976b).

In the offshore Mississippi River delta, landslide mapping and studies of the causes and mechanisms of submarine ground failure have been in progress since 1975. The results of this work have strongly influenced the subsequent development of petroleum resources by demonstrating potential hazards and providing information useful in the siting and design of offshore pipelines and production platforms (Garrison and Bea, 1977; Garrison and others, 1977; Teleki and others, 1979).

The State of California conducted a study of geologic problems and evaluated the potential benefits and costs of Statewide programs for mitigation. They investigated the costs of 10 different geologic hazards plus the loss of valuable mineral resources caused by urbanization. The losses were projected through the period 1970–2000 in terms of property damage, loss of life, and loss of mineral resources (Alfors and others, 1973). Landsliding, flooding, earthquakes, and loss of mineral resources were found to account for 98 percent of the projected $55 billion losses during the three decades. Projected losses attributed to landsliding during the period are $9.9 billion. The study further estimated that a reduction of damages of 90 percent could be attained with programs costing slightly more than $1 billion at a benefit-to-cost ratio of about 9 to 1.

National programs relating to landslide damages exist in other countries of the world. Some develop the technical data base necessary to recognize areas of differing likelihood of failure. For example, the ZERMOS (Zones Exposed to Risks of Movements of the Soil and Subsoil) plan in France is responsible for production of maps at scales of about 1:25,000 or larger. The maps portray degrees of risk of various types of slope failures and include activity, rate, and potential consequences (Humbert, 1977). Recently, the scope of the ZERMOS plan has been enlarged to provide guidelines for suitable locations of development and permissible land use (Porcher and Guillope, 1979).

Other countries have taken more comprehensive approaches to landslide loss reduction. In Japan, a national program for landslide control has been developing since World War II (Japan Society of Landslide, 1980). Initially, landslide control activities were tied to other legislation including erosion control, river improvement, and agricultural land maintenance, among others. The first program in Japan devoted exclusively to landslides began with the "1958 Landslide Prevention Law." Other legislative measures have been adopted since 1958 culminating in 1969 with the "Slope Failure Prevention Law." The legislation provides for governmental assumption of expenses and guidance for recovery for natural disasters for which no individuals bear responsibility. The measures provide not only for repair of damage and restoration of property to original form but also for work to prevent future landslides. The costs for the measures are divided between the Central Government and the local Prefectures. The estimated cost of the program was $600 million annually in 1980.

In New Zealand, a national insurance program assists homeowners when dwellings are damaged by landslides that are not within the reasonable control of homeowners to prevent. The landslide insurance is an outgrowth of the Earthquake and War Damage Act of 1944. A disaster fund, accumulated from a surcharge to the fire insurance premium for a property, reimburses property owners for losses caused by landslides (Arnould, 1976).

SUMMARY OF APPROACHES AND TASKS

Dramatic reductions in landslide damages can be achieved with the careful application of modern technology. However, the data necessary to achieve these reductions have been obtained for only a few areas. Further, the future need to utilize land of marginal stability will require an improvement in technology for safe development.

The proposed program of the U.S. Geological Survey for reduction of landslide losses can be divided into three major parts. Two of these parts, called (1) process and prediction studies, and (2) landslide-hazard mapping and risk evaluation, are intended to acquire the necessary technical information for loss reduction. The third major part of the program, transfer and use of landslide-hazard information, is intended to insure that the technical data will reach the appropriate user of the information in a form that is tailored to specific needs.

Participants in the ground-failure hazards workshop prepared a list of goals and tasks for each of the three major parts of the U.S. Geological Survey program just listed. This report is primarily a summary of goals and tasks of each of the three parts. A more complete description of the workshop proceedings is available (U.S. Geological Survey, 1981).

PART 2—PROCESS AND PREDICTION STUDIES

INTRODUCTION

The term landslide includes a wide variety of processes that result in the downward and outward movement of slope-forming materials composed of natural rocks, soil, artificial fill, or a combination of these materials. The mass may move by any of five principal types of motion: falling, toppling, sliding, spreading, or flowing, or combinations of these. As both the kind of material involved and the movements that occur are of importance in all phases of landslide investigation—from recognition to mitigation—these two factors are generally used to identify types of landslides (fig. 2).

These different types of slope movements have widely varying impact on man and his works. Some are large and very rapid, and can take many lives in a matter of minutes; some are slow, seldom causing injury, but are vastly destructive of property; some types are rare, some are common. In the United States, few areas of any considerable size are wholly free from the effects of one or another of these processes. Although widespread, landslides are not haphazard; each region has its distinctive suite of problems that are determined by the characteristic geology, topography, climate, and other factors of the area. Moreover, each kind of landslide process requires its own kind of response directed toward recognition, avoidance, or mitigation.

With these basic ideas in mind, the goals of the landslide process and prediction segment can be summarized as follows.

GOALS

* To determine the inherent geologic, topographic, and hydrologic conditions that set the stage for slope failures.
* To determine the factors, either natural, such as severe storms and earthquakes, or man-induced that lead to changes in stability.
* To analyze the time, physical setting, mechanism, rate, and extent of past failures in order to develop capability to predict future failures.
* To acquire new knowledge of slope failure processes that is applicable to methods for avoiding, preventing, or mitigating damage.
* To present conclusions regarding hazardous slope processes in forms suitable to devise methods to map and assess the degree of hazard in large or small areas.

APPROACH

The several steps that are necessary to reach these goals are as follows:

1. *Identify those slope processes that are hazardous.*—We are well along in being able to iden-

tify the major slope processes that present hazards on land, even though we may not understand well the mechanism of some. Offshore, our knowledge of processes that affect seafloor stability—and hence the safety of oil-drilling platforms and pipelines—is less certain although it is being acquired rapidly.

2. *Determine the relative degree of hazard and risk presented by the various processes of slope failure.*—To design an efficient and effective program of landslide-hazard reduction, we must know which processes are most damaging. We already are familiar with some of the worst offenders—and can start work on them . Others are so widespread, yet poorly reported, that a central body of information needs to be built up not only for the purpose of assigning priorities among processes but also, for the first time, to obtain a firm nationwide assessment of total annual costs in property and lives.

3. *Identify gaps in our knowledge regarding the following topics.*—

A. *Methods for recognition of unstable areas.* Each type of landslide process occurs under particular environmental conditions. Many that have occurred in the past produce a particular landform or "signature" in the terrain. Some of these contributing conditions—and the landforms that result from failure—are well known and can be recognized even from aerial photographs. Others are much less obvious, but are nonetheless significant. Here is where increased knowledge of processes will contribute to speed and accuracy of delineating unstable areas and assessing the degree of hazard they present.

B. *Prediction of place, extent, time, and potential damage of failures.* Prediction is the essential part of a hazard-reduction program—and the most difficult. But to be effective, predictive capability must be developed at several levels and at various degrees of statistical precision, depending upon the available information and the purpose of the prediction. For example, assigning various degrees of potential instability to mapped areas requires different procedures and has different meaning and accuracy depending on whether the areas involved are the size of States, counties, sections, or small developments, even though their physical environments are identical. In general, the smaller the area, the more precise the assessment must be, and the higher the cost per unit area in order to obtain necessary geotechnical information at the desired accuracy.

Likewise, the prediction of time of failure becomes more and more uncertain as the prediction is narrowed in its time span. Time of failure commonly depends on climatic or seismic events, rather than on the inherent geological characteristics of a slope. Predictions of time thus become linked with both short- and long-term variations in weather, climate, or seismic activity. Further, the effects of heavy rainfall may be immediate, if shallow failures of debris on slopes are involved, but may be delayed for months in deep-seated failures of shales or other relatively impervious rocks.

TYPE OF MOVEMENT			TYPE OF MATERIAL		
			BEDROCK	ENGINEERING SOILS	
				Predominantly coarse	Predominantly fine
FALLS			Rock fall	Debris fall	Earth fall
TOPPLES			Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	FEW UNITS	Rock slump	Debris slump	Earth slump
	TRANSLATIONAL		Rock block slide	Debris block slide	Earth block slide
		MANY UNITS	Rock slide	Debris slide	Earth slide
LATERAL SPREADS			Rock spread	Debris spread	Earth spread
FLOWS			Rock flow (deep creep)	Debris flow (soil creep)	Earth flow
COMPLEX			Combination of two or more principal types of movement		

FIGURE 2.—Classification of slope movements, abbreviated version (Varnes, 1978).

C. *Devise techniques to avoid, prevent, or mitigate landslide hazards and damage.* Such techniques range from engineering methods of structural restraint or drainage to a variety of land-use planning methods. Nonengineering techniques, principally planning alternatives, have not been widely adopted and may offer opportunities for dramatic progress. Improvements in engineering techniques have accompanied improvements in understanding landslide processes and have stabilized potentially hazardous areas.

PROCESSES CAUSING SIGNIFICANT HAZARDS

Our capability to predict the time, place, type, and consequences of a landslide event ranges from fair for certain processes to poor for others. Many aspects of all the slope-failure processes will require study to satisfy the goals of the program. However, some types of landslides are known to be particularly destructive or hazardous and deserve highest priority for research projects. These types include debris flows and debris avalanches, rotational slides and slump-earth flows, rock falls and rock-fall avalanches, and liquefaction, lateral spreads, and failures of quick clays. Each of these processes is described with a list of research tasks deserving high priority during the early phases of the program.

DEBRIS FLOWS AND DEBRIS AVALANCHES

Debris flows and their extreme velocity counterparts, debris avalanches, are dense mixtures of rock fragments, gravel, sand, mud, and water. They are usually generated by heavy rainfall or snowmelt that mobilizes soil cover on a hillside causing the soil to liquefy and flow downhill. They range in velocity from a few to many meters per second, can carry large boulders, and are extremely destructive. They have been responsible for many deaths and immense property damage. The areas most seriously affected have been the West Coast, particularly southern California during periods of heavy rainfall, and the Eastern United States, particularly the Appalachian region, during torrential rains, especially those associated with hurricanes. Debris flows occur, however, in many other sections of the country and present probably the most serious of landslide-type hazards with respect to human safety.

Debris flows and avalanches generated on the flanks of volcanoes and associated with eruptions or the attendant heavy local rains have been under study for many years in an evaluation of the volcanic hazards of the Cascade Range in the Pacific Northwest. The recent eruption of Mount St. Helens resulted in filling about 20 km of the North Fork Toutle River with perhaps the largest (2.8 km^3)—and one of the most destructive—debris avalanches of modern times. Assessment of the current hazards as this deposit is subjected to erosion remains a high-priority item of study.

The relation of debris flows to weather-related triggering events presents problems in predicting time and place that involve not only the local geologic and topographic setting but also regional and local meteorological conditions. Debris flows usually are generated on moderate to steep slopes on which bedrock is overlain by a layer a meter or two thick of soil and weathered rock. In a region of such conditions, widespread and sudden slope failures may occur when excessive rainfall or snowmelt saturates the surface layer of soil and weathered rock. The soil is stripped to bedrock and flows downhill, usually in a rather narrow path along a preexisting swale or watercourse, incorporating rocks and trees and damaging or destroying any structure in its path (fig. 3). However, the methods for determining the places most subject to failure and the meteorological events necessary to initiate failure are not well advanced. To improve our predictive capability a coordinated combination of field, laboratory, analytical, and statistical studies should be undertaken by the following specific tasks:

TASKS[1]

* Construct analytical, numerical, and laboratory physical models to help understand the generation and mechanical behavior of debris flows, particularly with respect to the unique multiphase characteristics of debris-flow slurries.
* Undertake geotechnical investigations to characterize hillside soils in potential debris-flow source areas to determine which soil types

[1]These lists of tasks are consolidated and are tabulated as summaries of tasks at the end of this paper.

FIGURE 3.—Source area and scar of debris flow near Johnstown, Pa. Photograph by J. S. Pomeroy.

are most susceptible to oversaturation and mobilization under heavy precipitation, snowmelt, or thawing of frozen ground.

* Provide instrumentation at field locations to monitor precipitation, ground-water levels, and movements in potential debris-flow source areas.
* Augment existing data bases and construct statistical models relating debris flows to mappable parameters such as bedrock lithology, soil type, slope, vegetation, and precipitation.
* Determine the effect of denudation of vegetation (due to forest fires, timber clear-cutting, and so forth) on subsequent erosion and downstream sedimentation patterns as related to debris flow.
* Reconstruct a history of climatic variation in the recent geologic record of a major climatic area, such as Alaska, the arid Southwestern United States, the humid Southern United States, and the temperate Appalachian region, and relate climatic variations to debris flows in these regions.
* Devise and improve techniques to date recent geologic features for the purpose of determining the timing and frequency of debris flows.
* Conduct statistical studies of recent rainfall histories of selected mapping areas to investigate effects of rainfall variations during drought-wet cycles.
* Organize teams of scientists and engineers to investigate major debris-flow events during and immediately after they occur.

ROTATIONAL SLIDES AND SLUMP-EARTH FLOWS

Rotational slides (slumps) are those in which movement takes place along a surface that is curved concavely upward (fig. 4). These types of slides in both rock and soil, often combined with flowage of disturbed material at the toe of the slide, make up a high proportion of the slope-failure problems facing engineers, not only in the United States but all over the world. Owing to the usually slow rate of movement, fatalities are rare; but movement may extend to considerable

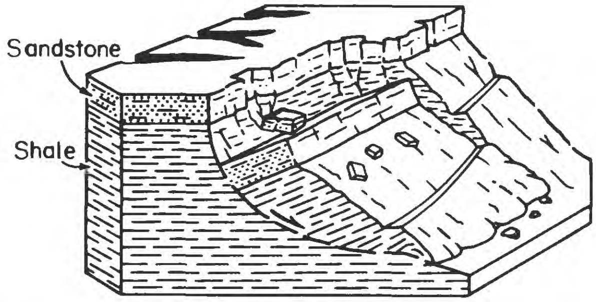


FIGURE 4.—Rotational slide in bedrock showing failure along a surface that is curved concavely upward.

depth, the area involved may be relatively large, and damage to structures may be extensive. Remedial measures are often costly, and may be of uncertain effectiveness if the geologic conditions and geotechnical properties of the materials involved are not well known. Figures 5 and 6 show examples of rotational slides that have damaged transportation routes.

Because they are so common both in natural slopes of clayey or shaly material and in man-made embankments, rotational slides have been studied and analyzed more than any other type of slope failure. Yet there is still much that is not known concerning (1) why failures occur where and when they do, (2) the mechanisms of movement, (3) the changes in material properties as

FIGURE 5.—Rotational slump in which the toe area has disintegrated into an earthflow. The original failure destroyed the railroad and the later flows have overrun the new alinement.

FIGURE 6.—Highway damaged by rotational slide near Cincinnati, Ohio. Photograph by W. E. Davies.

movement progresses, and (4) the most effective means for stabilization. Program tasks that will be directed toward some of these questions follow.

TASKS

* Develop a better understanding of geologic, topographic, and climatic environments that are conducive to rotational sliding by thorough study of selected areas of failure. Needed studies include detailed mapping, physical exploration by trenching and drilling, determining physical properties, monitoring movement and pore-water pressure by in situ instrumentation, and correlation of movement with records of rainfall, seismic disturbance, modification of the slope by cutting and filling, and other triggering events.
* Improve or design instrumentation for making measurements and for storing or transmitting the information to central offices for analysis. Types of information needed include measurement of displacements at the surface and at depth at known times, tilting, water pressures at various depths, stresses and stress changes, electrical potential changes, the location of acoustical events that may serve to identify areas at depth in which failure is occurring, and local rainfall, snowfall, and temperature.
* Devise techniques to recognize and monitor events that precede extensive failure such as cracks at the head of an incipient slide, bulges at the toe, tilt, distressed vegetation, slow displacements, and acoustic emissions.
* Improve methods of analysis of movement records in order to determine, from early slow movements, whether the movements are likely to accelerate into catastrophic failure and when failure is likely.
* Study regional relationships between periods of increased landslide movement and geomor-

phic episodes as recorded in soil stratigraphies, alluvial histories, and landform evolution, in order to establish a means for determining landslide ages, periods of increased landslide movement, and the interrelation between landscape and landslide hazard.

* Establish criteria for estimating the size of potential individual slides, the likelihood that they may enlarge or coalesce, and the area that may be affected by earth flows as the slump blocks disintegrate.
* Construct analytical and numerical models of unstable slopes using modern limit equilibrium, finite element, and probabilistic techniques.
* Build real physical models, using materials with scaled physical properties, to investigate slope failures using centrifugal loading.

ROCK FALLS AND ROCK-FALL AVALANCHES

Rock falls are masses of rock fragments that break away from a steep slope and that travel mostly by free fall through the air (fig. 7). The rock fragments may come to rest at the base of the slope as talus debris. Or, if the rock fragments acquire sufficient momentum, they may continue to travel in a stream outward from the base of the slope as an avalanche. Because the free-falling rocks reach high velocities, and may involve huge blocks of rock (several meters in di-

FIGURE 7.—Rock fall on Interstate 70 west of Denver, Colo., triggered by a severe storm on May 5–6, 1973. Photograph by W. R. Hansen.

ameter), rock falls, and especially rock avalanches, are highly destructive to any manmade structures in their path. Rock falls and avalanches have caused many fatalities in the United States, as well as thousands of deaths in Peru, Guatemala, Chile, and other countries in the past 20 years. For example, the Madison Canyon, Mont., landslide, a massive rock-fall avalanche triggered by the Hebgen Lake earthquake in 1959, killed 26 people. In 1980 alone, several rock falls in Yosemite National Park killed or seriously injured 10–12 people and caused the closure of a large, privately owned campground.

Although we know that rock falls and rock-fall avalanches occur on steep slopes, generally in areas of moderate to high relief, the distribution of sites highly susceptible to these failures in the United States is not well known. Therefore, this element of the program, which overlaps the mapping part of the program, is aimed at establishing criteria for delineating areas that have a high potential for rock falls and rock-fall avalanches to determine the extent and severity of these hazards. Potential hazardous areas exist in the Appalachians, Rockies, Sierra Nevada, Cascades, California Coast Ranges, Alaska, and other mountainous areas of the United States. High priority tasks for rock falls and rock-fall avalanches are as follows.

TASKS

* Prepare detailed geologic and topographic maps of selected areas to better define the geologic, topographic, and climatic conditions in which rock falls occur. Particular attention needs to be given to the influence of discontinuities in the rocks, such as bedding, joints, and faults and their relation to the orientation of the slope.
* Monitor selected sites of impending rock fall to determine the mechanics of failure, dilation of jointed rock masses preceding ultimate failure, and the influence of triggering events, such as heavy rains, freeze and thaw,

FIGURE 8.—Rock topple near Minefork, Morgan County, Ky. Rock topples are blocks that have rotated forward and may become a rock fall. Photograph by W. R. Outerbridge.

and seismic activity, on incidence of rock falls.

* Devise field and laboratory techniques for characterizing the stress-strain properties of jointed rock masses.
* Construct analytical models for the processes by which large rock falls are converted to the extremely rapid and energetic flow of fragments termed rock-fall avalanches. Establish criteria for predicting size, velocity, and extent of runout of rock-fall avalanches.
* Establish criteria for estimating the wave height to be expected from rock falls and avalanches that enter bodies of water.

LATERAL SPREADS CAUSED BY LIQUEFACTION AND FAILURE OF QUICK CLAYS

Lateral spreads are generally the product of rapid ground motion during earthquakes. Especially susceptible materials are saturated, relatively loose cohesionless sediments, usually sands and silts. Liquefaction occurs when cohesionless material is transformed from a solid state into a liquefied state as a consequence of increased pore pressure and reduced effective stress. Liquefaction by itself is not a failure, but where other conditions such as ground slope and extent of the liquefied zone are favorable, liquefaction commonly leads to ground failure. Three basic types of ground failure are associated with liquefaction: lateral spread, flow failure and loss of bearing strength (Youd, 1978).

Lateral spreads, the most common type of ground failure caused by liquefaction during earthquakes, involve lateral movement of surficial soil layers as the result of liquefaction and transient loss of strength in a subsurface layer. These failures generally develop on very gentle slopes (most commonly between 0.5 percent and 5 percent) and involve downslope displacements of as much as several feet, and, in particularly susceptible conditions, several tens of feet. These failures generally are accompanied by ground fissures and differential vertical displacements.

These movements commonly disrupt foundations of buildings or other structures built on or across the lateral spread, sever pipelines and other utilities placed within or through the spread, and compress structures astride the toe of failure. These failures have been particularly destructive during several past earthquakes (Youd, 1978). For example, more than 250 highway and railway bridges were damaged or destroyed by lateral spreads during the 1964 Alaska earthquake. Every major pipeline break in the City of San Francisco during the 1906 earthquake occurred in areas of lateral spreading. These pipeline breaks severely hampered efforts to fight the large fire that ignited during the earthquake. Thus, rather inconspicuous ground-failure movements of a few feet were in large part responsible for the devastating damage to that city.

Materials favorable to the generation of liquefaction and lateral spreads include saturated Holocene fluvial, alluvial, and aeolian deposits, deltaic and inner-tidal marine sediments, and glaciofluvial and glaciolacustrine sedimentary complexes. Manmade fill covering bogs, marshes, and lagoons is also susceptible. Liquefaction and lateral spreads are most commonly observed in the seismically active, west-coast region, including Alaska. They have also occurred in the upper Mississippi embayment and in the Charleston, S.C., area. Parts of the metropolitan areas of San Francisco, Los Angeles, Seattle, Anchorage, Salt Lake City, Memphis, and Charleston are areas that may contain sediments susceptible to liquefaction and lateral spreading.

Most clays lose strength when disturbed (Youd, 1978). If the strength loss is large, such soils are classed as sensitive, the sensitivity being defined as the ratio of the strength of an intact specimen of soil to the strength of the same soil specimen after severe disturbance such as by large shear deformation or remolding. Clays with sensitivities less than 4 are termed insensitive. Clays with sensitivities greater than 8 are termed extra sensitive; sensitivities greater than 40 have been reported for some extremely sensitive clays, often termed "quick clays." Clays with sensitivities greater than about 10, although rare in occurrence, may be prone to failure during strong seismic shaking. The mechanism of failure involves strength loss initiated by deformations caused by seismic shaking and continued at an accelerating rate by shear deformations generated during failure.

Examples of failures involving sensitive clays are the five large translatory landslides that disrupted parts of Anchorage during the 1964 Alaska earthquake. The failure zones of each of these slides passed through layers of Bootlegger

Cove Clay, a sediment containing clay layers with sensitivities between 10 and 40. Strength loss in these sensitive layers was a major factor contributing to these failures. Liquefaction of sand and silt lenses within the Bootlegger Cove Clay was also a contributing factor. A diagrammatic sketch of one of these failures is shown in figure 9. The landslides spread destruction into the downtown commercial area and residential areas of Anchorage, as well as disrupting many lifelines.

The reduction of hazards of lateral spreads caused by liquefaction and failure of quick clays must necessarily proceed from an understanding of where, how, and why these processes occur, what materials are susceptible, and the criteria by which hazardous areas may be defined. To attain this objective the following tasks are to be undertaken.

TASKS

* Investigate the mechanism of lateral spreading. From case histories, laboratory and field studies, and analytical models determine the static and dynamic factors and geotechnical properties of sediments that control the development of pore-water pressures in sediments, the onset of a liquefied condition, and the amount of shear deformation induced in a lateral spread, bearing failure, or other soil failure caused by liquefaction.
* Investigate selected lateral spreads to construct quantitative case histories for use in understanding mechanisms and establishing predictive criteria.

  a. Map selected lateral spreads to quantify and locate ground effects, amounts of displacement, damage to structures, and so forth.
  b. Perform subsurface investigations to determine subsurface lithology, material properties of sediment units, and depth to water table by soundings with static and dynamic penetrometers, drilling and sampling, and shear-wave velocity measurements.
  c. Perform laboratory tests to quantify material properties and to classify materials. Tests that might be used include grain-size analyses, relative density, and strength under dynamic loading.

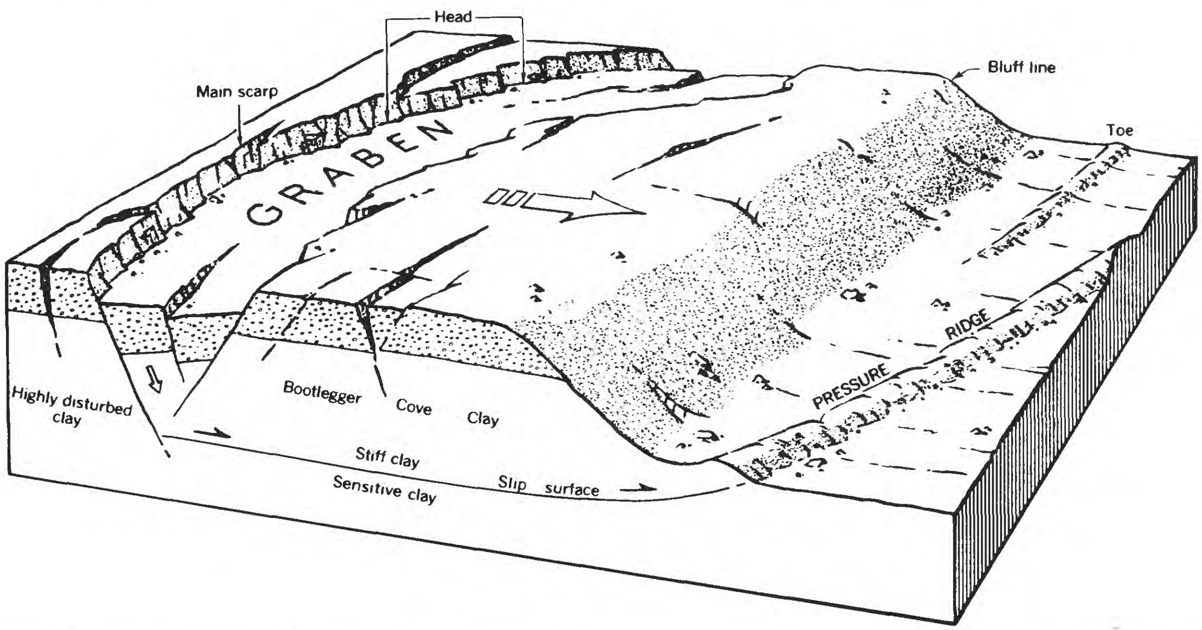


FIGURE 9.—During the 1964 Alaska earthquake, five large translatory landslides occurred in sensitive clay layers (sensitivities between 10 and 40) of Bootlegger Cove Clay. Factors contributing to failure were strength loss in sensitive clay layers and liquefaction of silt and sand lenses. Landslides disrupted 250 acres and caused $50 million in damages (Hansen, 1965).

* Provide instrumentation at sites of newly created or probable future lateral spreads to monitor pore-pressure development, ground displacement, and the generating earthquake motions. These data are necessary to define mechanisms of failure and to provide data for checking analytical models.
* Improve techniques for predicting sites likely to experience failure, and improve criteria for regional assessment of liquefaction and lateral spreading hazard.
* Investigate selected sites of quick-clay failures. Conduct sounding, drilling, and sampling investigations of documented quick-clay failures from earthquakes or other causes to determine subsurface lithology and to obtain samples for laboratory-index testing and static and cyclic tests to determine strengths and strength degradation.
* Evaluate effectiveness of mitigation techniques.
    a. Review case histories of techniques used to stabilize areas susceptible to liquefaction and lateral spreading or otherwise used to mitigate the hazard.
    b. Evaluate the effectiveness of mitigation techniques following major earthquakes.

FAILURE PROCESSES IN MARINE ENVIRONMENTS

The search for and development of offshore oil and gas resources requires that production platforms and pipelines remain in a stable condition in or on the seabed during the production life of a field. Yet there have been a number of failures of pipelines and some of drilling platforms due to movements of unconsolidated bottom sediments. Ground-failure hazards in areas of potential petroleum development are, therefore, being actively investigated using a variety of submarine surveying techniques and field and laboratory methods to determine soil properties.

Areas of disturbed sediment take a number of forms. Some are simply shallow depressions that appear to result from local loss of gas and pore water from bottom sediments. Others are clearly the result of rotational failures that have produced head scarps and back-tilted blocks within the moved mass. Many resemble failures due to liquefaction and lateral spreading as observed on land, with mobilization and transport of muddy material down very gentle slopes. Some types of subaqueous failures are shown in figure 10.

The investigations of marine ground-failure hazards by the U.S. Geological Survey provide regional information regarding resource leasing and management for Federal regulatory agencies, and pursue topical studies that improve the ability to predict occurrence of offshore failure events. For these investigations special facilities, equipment, and techniques are required.

Marine geologic studies have much in common with the U.S. Geological Survey's land-based Construction and Ground-Failure Hazards Reduction Program in terms of understanding the processes of failure of earth materials and predicting their occurrence. Hence, close coordination and sharing of personnel and facilities will help each program to most efficiently obtain its scientific and technological objectives. The following specific tasks are of joint interest to both programs.

TASKS

* Continue the task of mapping specific shelf environments and devote special attention to continental slope areas that are increasingly the focus of offshore activities such as waste disposal, energy production, mining, and seafloor military installations.
* Investigate ground-failure mechanics in terms of the initiating forces such as tectonic, gravitational, and ocean dynamics, and the geotechnical properties of the bottom sediments and the influence on these properties of variations in their composition of solid particles, liquid, and gas.
* Investigate the behavior of special marine-sediment types, such as clastic carbonates, volcanic ash, and ice-bonded materials, and the potential instabilities associated with each.
* Design in-place and downhole instruments for measuring and monitoring geotechnical properties, stresses, and sediment movements.
* Construct numerical and analytical models of critical stress-strain and soil-loading parameters that are difficult to measure in nature or that are too expensive to investigate routinely.

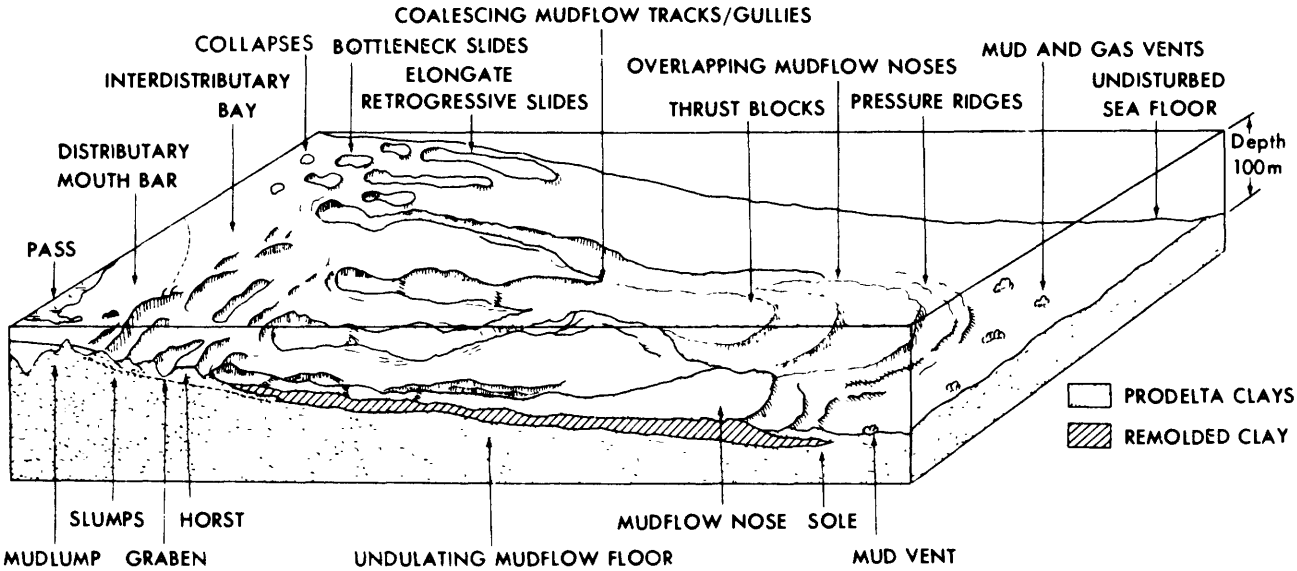


FIGURE 10.-Schematic distribution and morphology of subaqueous landslides in part of the Mississippi delta front slope (Prior and Coleman, 1978).

PART 3—LANDSLIDE-HAZARD MAPPING AND RISK EVALUATION

INTRODUCTION

A map is a useful, convenient, and readily understood form of presenting information about landslide hazards. Various physical attributes that contribute to landslide type and potential can be shown in different degrees of detail depending upon map scale and intended use. Maps have traditionally been the basic ingredients for planning and design of development. Presentation of landslide information in map form makes intended plans for land use readily comparable to the constraints on development imposed by many factors including landslides. Significant progress has been made during the past 10 years in preparing different types of maps related to landsliding in the United States. This experience and the results of mapping experiments from other countries can be applied to produce the landslide and slope-stability maps necessary for loss-avoidance and mitigation.

Part 3 is organized as follows: (1) a discussion of map scale and information and materials needed to prepare hazard-risk maps; (2) description and selected examples of different mapping strategies in terrestrial and marine environments; and (3) an analysis of priorities and tasks of the landslide-hazard mapping and risk evaluation part of the program.

GOALS

* To determine the areal extent, timing, and severity of landslide processes in selected high-priority areas of the United States, including adjacent submarine areas.
* To convey the hazard information on maps in a form that will provide the greatest benefit to government officials, consulting engineering firms, and the general public in order to avoid the landslide hazard or to mitigate the losses.
* To develop methods and produce clear and understandable risk evaluations of slope movements.

MAP SCALE

Users of regional landslide maps want the information at many different scales, from as large as 1:1,200 for city planning to as small as

TABLE 2.—*Information and materials needed for landslide-hazard mapping and risk evaluation*

Information or material needed	Uses	Availability
Geologic maps of bedrock and surficial materials.	Essential for understanding the causes of landslides and for predicting the density, severity, and frequency of landsliding in large areas. Can be used to extrapolate letailed information in small areas to large regions for which no landslide information is available.	Only about one-third of the United States has sufficiently detailed geologic maps for preparing slope-stability maps.
Aerial photography	Photographs enable recognition, classification, and mapping of landslides in a large area in a short time. Single most important tool for mapping landslides.	Aerial photography is available for the entire United States but is not consolidated in a single agency. Relatively new forms of imagery including color and infrared photography, satellite imagery, side-scan SONAR and Side-Looking Aperature Radar (SLAR) have application to landslide studies but limited availability has curtailed use.
Topographic and bathymetric maps.	Provides a base for plotting landslide information. Topographic form is used to identify landslides. Provides basic data for slope maps.	Generally available from Federal agencies for most areas at scales of 1:24,000 or smaller. Large scale, more detailed mapping has been completed for most urban areas by local agencies.
Digital base-map data	Enables automatic merger of information from aerial photographs with a base map to produce maps at lower cost.	Base maps that have been digitized are not available except for a few areas of the United States.
Orthophotoquads	Photographic images, produced to match U.S. Geological Survey quadrangle maps in format and scale, permit rapid and inexpensive transfer of landslide information to base maps.	Available for about 30 percent of the conterminous United States. Additional orthophotoquads may be needed in areas of high priority for inventories of landslides.
Slope maps	Used to prepare slope-stability maps that combine steepness, landsliding, and physical characteristics of different materials.	Can be prepared by hand, photomechanically, or by computer from a base map showing topography. They are expensive to produce and have been completed for only a few areas.
Climatic data................	Data from specific events and annual and long-term climate are needed for assessments of influence for case histories and probabilistic predictions.	Data are generally available for metropolitan areas, but may be lacking in remote areas. For offshore areas, data may be adequate to estimate ocean-wave heights for tropical storms and hurricanes.
Subsurface water............	Build-up of pore-water pressures in subsurface materials is a major cause of landsliding. Knowledge of the distribution of and changes in subsurface water levels are needed for predicting the initiation of specific landslides, and, coupled with climatic information, for predicting the probability of failure.	Records are available for a few areas as case histories. Data are not available for most hillside areas in which landslides are most prevalent.
Seismic data.................	To prepare maps of susceptibility to landsliding by earthquakes. (See, for example, Keefer and others, 1979.)	Because large earthquakes are widely scattered in time and place, the accuracy of earthquake-induced landslide mapping has not been tested. Data from previous earthquakes are sufficient to prepare prepare experimental maps.
Vegetation maps	Vegetation tends to support hillslopes by means of root strength and removal of subsurface water. The role of vegetation in stabilizing slopes has been studied in only a few areas with mixed results. A clear association exists between burning of vegetation and ensuing debris flows in California.	As special purpose maps similar to slope maps, they are generally unavailable for high-priority areas. Conceivably they can be produced from aerial photographs, but map-making techniques for slope stability studies are not well advanced.

TABLE 2.—Continued

Information or material needed	Uses	Availability
Weathering and weathering products.	Processes of weathering commonly result in loss of strength. Information on thickness and kinds of weathered-rock products can be used to estimate hillslope strength and landslide susceptibility.	Not generally available.
Marine geophysical surveys and sampling.	Geophysical surveys of the ocean floor serve the same function as aerial photography of terrestrial areas. They also provide information on structural features beneath the ocean floor.	Has been obtained for landslide studies in only a few areas. Can be purchased from contractors. Much of the needed information is proprietary data of energy companies.
Land-use maps and socioeconomic data.	Used to learn present and planned development for assessment of risk.	Large parts of the United States have been mapped at 1:250,000 scale. Larger scale mapping is available from State and local agencies. Socioeconomic data collected by U.S. Department of Commerce.
Chronology data	Used to determine past intensities of landsliding for comparison to climatic and human activity data. Involves use of historical records as well as various dating techniques.	Some data have been collected by the National Climate Program. Other needed data should be collected in conjunction with studies in specific areas.
Computerization	Data are collected, stored, and manipulated to check for sensitivity of different map parameters and to superimpose large data sets in different ways. (See, for example, Newman and others, 1978.)	Technology is well developed and can perform functions at the level needed. Large-volume use will require development of improved software.

1:27,000,000 (fig. 1) when problems in the entire conterminous United States need to be shown at page-size. Most previous mapping has been on standard 1:24,000 topographic maps to take advantage of the base materials available and because aerial photographs used in recognizing the landslides are commonly close to that scale. Several landslide and slope-stability maps have been published at 1:62,500, 1:63,360, 1:100,000, 1:125,000 and 1:250,000 scales, again to take advantage of standard base maps and also to convey the impression that the information is not as detailed or reliable as at large scales. *All landslide and slope stability maps are a compromise between detail and reliability and the difficulty and cost of preparation.*

INFORMATION AND MATERIALS NEEDED

The preparation of hazard maps and risk evaluations requires geologic and cartographic information as well as other basic materials. For all except the most simplified studies (such as outlining areas containing active landslides), knowledge is required of the distribution of different surficial and bedrock units. Implicit in the following discussion of strategies and tasks for hazard mapping and risk evaluation is the availability of these materials; some of the more important of which are listed in table 2.

STRATEGIES AND TASKS FOR HAZARD MAPPING AND RISK EVALUATION

APPROACHES FOR MAPPING HAZARDS IN TERRESTRIAL AREAS

Landslide hazard is evaluated in the most timely, efficient, and cost-effective manner when an orderly sequence of progressively more detailed approaches is followed. In this way, the general distribution of hazardous areas is described early in the program, so that the hazard, although not well defined, is recognized, whereas subsequently more detailed work better defines and quantifies the hazardous processes and conditions.

In general, strategies for landslide-hazard mapping and risk evaluation in terrestrial areas are applied to natural rather than to man-modified slopes. Landslide movement in many places is triggered by human activity such as grading for roads or building, cutting of trees, or altering subsurface water conditions. Prediction of the effects of such activities on the stability of slopes is somewhat different from the prediction of landslides on natural slopes, although some methods of prediction follow from methods used in analysis of stability of natural slopes.

Early recognition of a landslide hazard may be helpful in persuading developers to obtain the detailed geologic and engineering information needed to make certain that a particular site is safe, whereas the subsequent work is more likely to provide regional planners with the rationale for more effective land use. The following approaches should generally follow in the order presented, although reconnaissance approaches may not be necessary when only small areas are under consideration.

LANDSLIDE INVENTORIES

RECONNAISSANCE APPROACHES; SIMPLE INVENTORIES

Reconnaissance maps show areas that appear to have failed by landslide processes. These maps commonly are prepared by interpreting aerial photographs, with a minimum of field checking. Landslide deposits are usually more difficult to recognize in regions that have been extensively modified, such as urban areas, and in regions with exceptionally dense and tall vegetation where the ground surface cannot be seen on the photographs. Also, many landslide scars and deposits are highly altered or masked in a period of 1–15 years by rapidly growing vegetation and cannot readily be identified in a simple inventory. An experienced interpreter can complete a simple landslide inventory of a standard U.S. Geological Survey 7½-minute topographic quadrangle (about 150 km^2) in about 7 days. Figure 11 is an example of a simple landslide inventory for the Pittsburg-Antioch area 50 km east of San Francisco, Calif.

INTERMEDIATE TYPES OF LANDSLIDE INVENTORIES

Intermediate types of landslide inventory maps show landslide deposits and areas that appear to have failed by landslide processes. In addition, the maps distinguish active from old landslides (for example, fig. 12), and classify them as to whether the slides are single or multiple, one type, or a combination of types. They also show and classify slope failures in manmade features such as cuts, fills, and refuse deposits. Like simple landslide inventory maps, they can be prepared by the interpretation of aerial photographs, but sequential sets of photographs of the area are also helpful to identify landslides subsequently masked by growth of vegetation, farming, and other surface alterations. A limited field check of some landslides and manmade features is required. The inclusion of the limited field observations and aerial-photograph interpretation requires about 50 percent more time than for a simple inventory.

DETAILED INVENTORY

A detailed inventory map depicts each landslide classified as to type, as well as delineation of scarps, limits of the zone of accumulation, and other pertinent data on depth and kind of materials involved in sliding. Active and inactive landslides are distinguished. The geologic age of the landslide and the rate of landslide movement should be included. In addition, the inventory should include data on slope failures involving man's alteration of the terrain in a fashion similar to that outlined for the intermediate inventory. Location of excavations, trenches, and boreholes used in the study of landslides should be identified on the map. Few maps of this type have been made, in part because of the great time and expense needed to obtain the information, but the map by McGill (1973) in conjunction with his Appendix 1 of the report by the U.S. Army Corps of Engineers (1976) is a good example. Some of the information can be obtained from aerial photographs; new quadcentered color (false infrared) photographs now becoming available will greatly increase the number of landslides that can be identified and classified. However, much of the

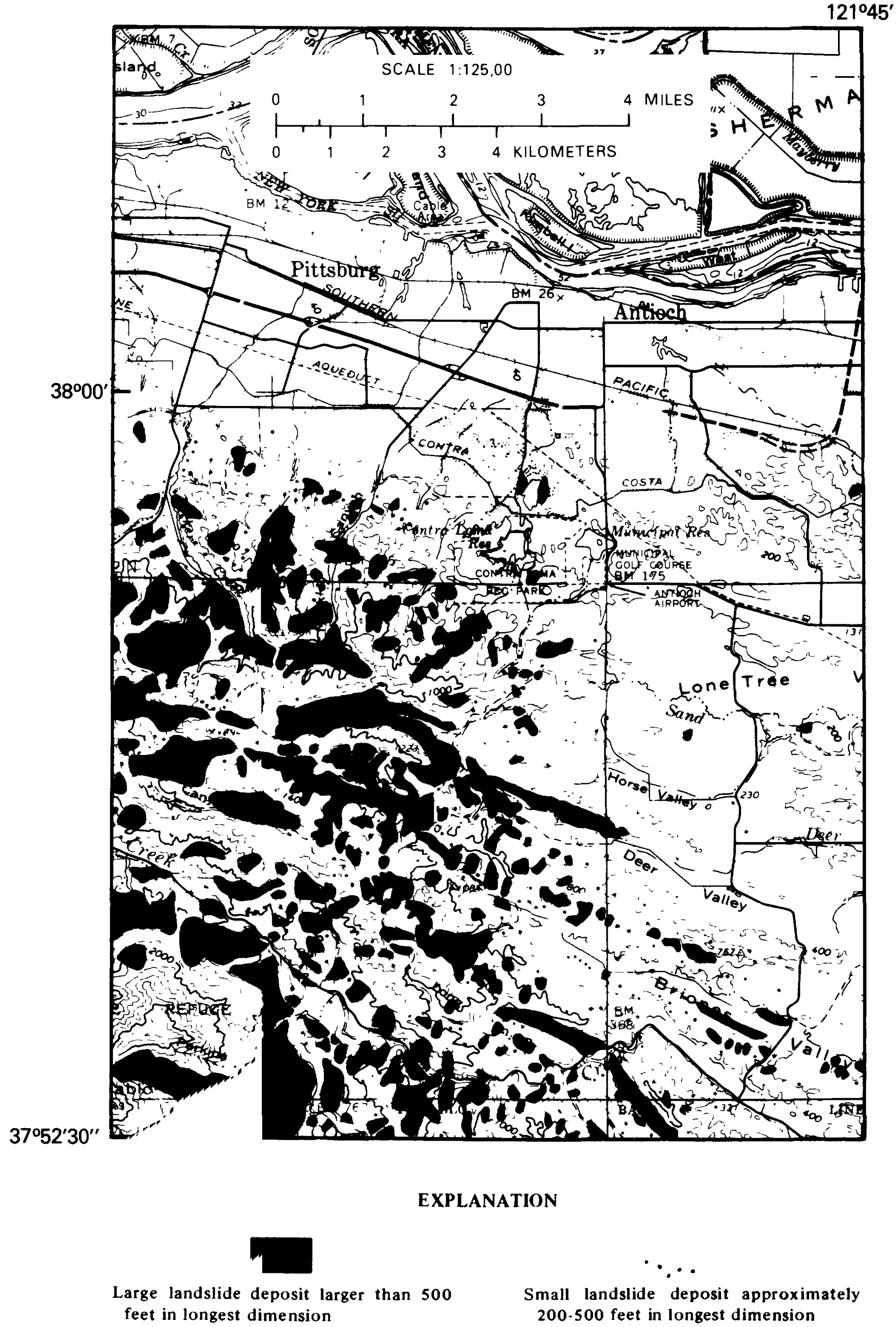


FIGURE 11.—A simple inventory of landslide deposits in part of northeastern Contra Costa County, Calif., near San Francisco. (From Nilsen and others, 1979, fig. 44.)

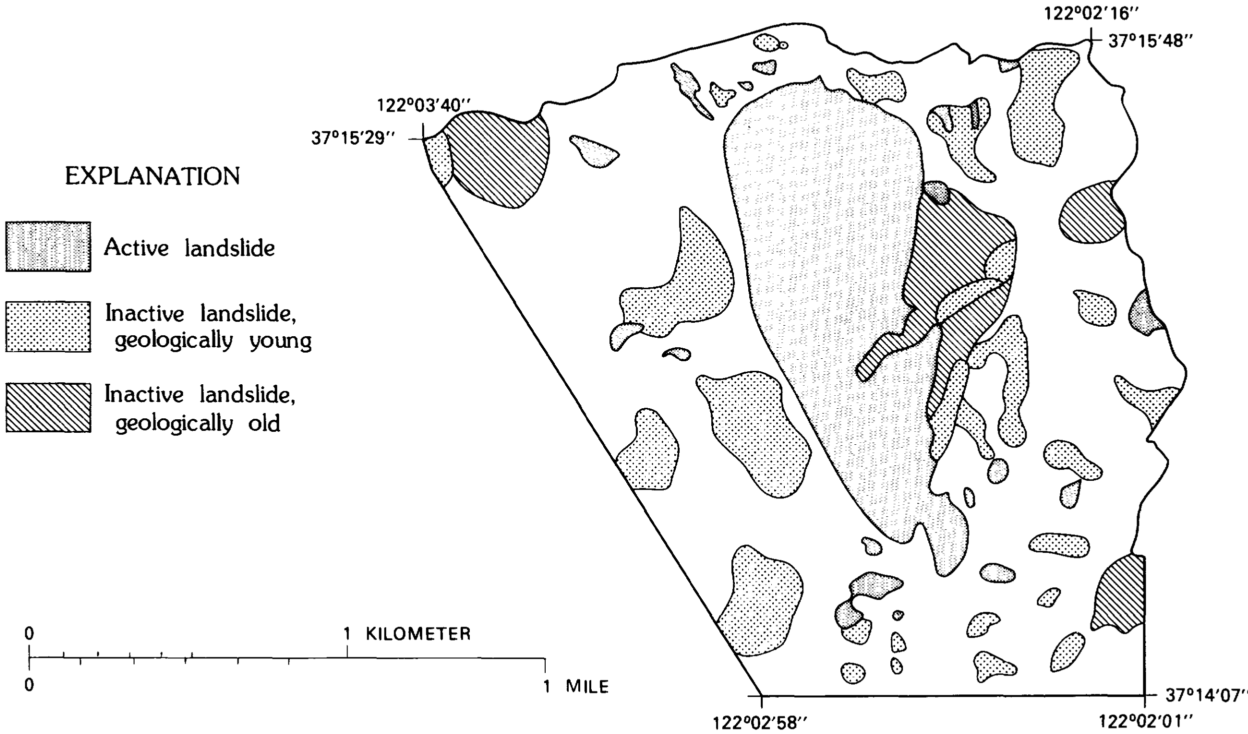


FIGURE 12.—An intermediate landslide inventory of the Congress Springs area, Santa Clara County, Calif. Reduced and generalized from a map at 1:2,000 scale by Cotton and Associates (1977, pl. 1).

data must be obtained in the field by closely spaced traverses. The cost of a detailed inventory is perhaps 10 times more than that of a simple inventory.

TASKS FOR LANDSLIDE INVENTORIES[2]

* Inventory existing landslide maps and review present types and techniques of landslide mapping in the United States and abroad to improve methodology.
* Devise a classification scheme for distinguishing and mapping scarps of landslides by photointerpretation. Most landslide mapping presently deals only with the deposit on the slide mass; photomapping of scarps will allow interpretation of the age and style of movement, and, hence, of the likelihood of renewed movement.
* Establish guidelines for various forms and levels (simple, complex) of landslide inventories in relation to the character of the area, available resources, map scales, and purposes or uses. Include use of aerial photographs, field reconnaissance and detailed study, laboratory testing, and maps.
* Prepare classifications of landslides for aerial-photograph interpretation, including deposits, scars, scarps, and activity. Determine the kinds of photography (color, black and white, infrared, low sun angle), the scales, and the moisture-vegetation conditions most appropriate for recognizing and mapping landslides.
* Determine the usefulness of radar and other remote-sensing techniques for mapping landslides in areas with extensive vegetation cover.
* Experiment with topographic mapping procedures to more accurately depict landslide morphology.
* Experiment with techniques for use of orthophotoquads and computer-enhanced images in mapping landslide features.

[2]These lists of tasks are consolidated and are tabulated as summaries of tasks at the end of this paper.

* Devise methods for testing the accuracy, completeness, and usefulness of landslide inventory maps and test selected maps.
* Prepare landslide inventory maps of designated areas for which they have not already been completed.
* Apply landslide inventory, susceptibility, and zonation techniques developed in other countries to selected areas of the United States.
* Select control areas for research on mapping methods. Experiment with mapping type of landslides, whether simple or multiple, one type or a combination of types; kind of materials; geologic age; rate of movement; thickness; change in morphology; and effect of external changes such as drought.
* Identify areas possibly subject to single catastrophic landslides (such as major rock-fall avalanches and submarine delta-front slides) using present knowledge of their causes and locations.
* Develop methods of concurrent map compilation and digitization from aerial photographs and other sources using advanced photogrammetric techniques and equipment.
* Conduct research on the application of computer methods, digital remote-sensing data, and photogrammetric methods to geologic mapping generally and to landslide investigations specifically.

TERRAIN ANALYSIS

The natural landscape is the aggregate product of various kinds of landslides, downslope creep, and movement by running water that, in eroding various kinds of earth materials, sculpts distinctive landform textures. These landforms are recognized and classified, and appropriate terrain units are defined from small-scale (high-altitude) aerial photographs. Slope processes in each terrain unit are determined by field mapping of small areas representative of each terrain unit. The result (fig. 13) is a map of terrain units, each of which represents a kind of topography that is being degraded by a common set of processes; an explanation for each unit describes the kinds of landslides and their specific habitats.

TASKS FOR TERRAIN ANALYSIS

* Establish guidelines for analyzing various types of terrain and distribution of landslides relative to character of area, available resources, map scales, and purposes or uses.
* Determine how to map potential hazards from the following processes that leave little record and that are not amenable to photointerpretation: disintegrating soil slips, rock falls, mudflows, toppling, and creep.
* Expand the analyses to include larger, deep-seated landslides as well as shallow surficial slides.
* Make experimental maps from high-altitude aerial photographs that show areas of probable landslide concentration by extrapolating from erosion and landform patterns that can be seen on these photographs, whereas individual landslides cannot. Test the accuracy of the maps with detailed studies of control areas.

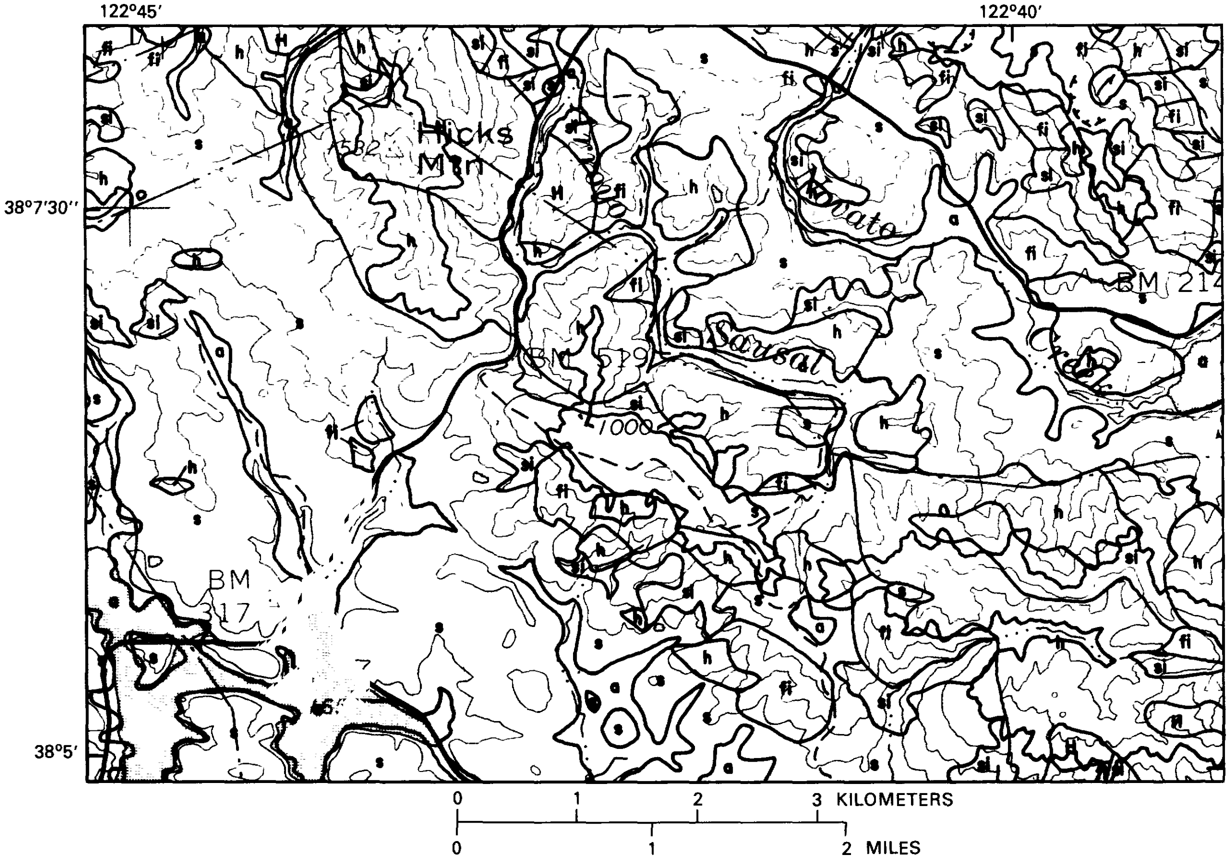
LANDSLIDE-HAZARD ZONATION

SLOPE-STABILITY MAPS

Slope-stability maps distinguish areas that have different potentials for landsliding. The maps predict where new landslides are likely to occur by a ranking of relative stability of slopes.

A simple form of slope-stability map can be made in areas where only a single geologic unit produces landslides. In such situations, a map showing the distribution of that unit shows the area of potential landsliding as well. Other simple slope-stability maps can be made of large areas in a short time by determining from the literature and (or) experience which mappable geologic units are landslide prone, and then using a geologic map to delineate slope-stability units, as shown on figure 14. Addition of other attributes, such as slope inclination and aspect, can improve the assessment of relative stability within specific geologic units.

Areal distribution of landsliding in most actual situations is more complex. In such situations, slope-stability maps may be constructed by a variety of means. One relatively simple method involves combining a landslide inventory with a geologic map. The combination will indicate which geologic units are most likely to fail by landsliding and where these units are located. If the landslide inventory used distinguishes types of landslides, then complex slope-stability maps showing likelihood of different types of landslide



EXPLANATION OF PRINCIPAL MAP UNITS

Map unit	Type of terrain formed over Franciscan bedrock	Inferred types of shallow landslides and hazards they pose	Habitat of landslides in the terrain
H	Very hard terrain: regularly spaced straight ribs between sharply incised flutes; sharp crests, steep slopes.	Debris-avalanche and debris-flow failures in granular material that are characterized by sudden, rapid movement during heavy rainfall. Hazard is impact by rapidly moving debris as thick as several meters.	Debris and avalanche is likely at heads of flutes and along lower slopes of ribs; possibly on upper slopes of ribs. Debris flow is likely from heads of flutes down drainages and out on to slopes below mouths of drainages; possible from lower slopes of ribs.
h	Hard terrain: ribs between sharply incised flutes are somewhat irregular in form or spacing; crests may be rounded, slopes steep.	Chiefly debris avalanche and debris flow, as characterized above for unit H. Local earth flow and slump-earth flow, as characterized below for unit s.	Debris avalanche and debris flow are likely in habitats described above for unit H. Earth flow and slump-earth flow are possible in places, particularly on aprons at the foot of fluted hill-slopes.
s	Soft terrain: lacks flutes, although includes irregular and poorly incised drainages; crests broadly rounded, gentle slopes.	Chiefly earth flow, earth-flow complex, and slump-earth flow, failures in clayey material that are characterized by slow movement lasting days to months during rainy season. Hazard is distortion of structures by slow movement of underlying or adjacent material as thick as several meters. Some debris avalanche and debris flow, as characterized above for unit H.	Earth flow, earth-flow complex, and slump-earth flow are likely in concave portions of terrain, possible throughout terrain. Debris avalanche and debris flow are possible in steep portions of terrain.

Other terrain units: a, alluvium; si, soft-intermediate; fi, fluted-intermediate.

FIGURE 13.—Map of slope-process terrain units for part of Marin County, Calif., with example descriptions of landslide styles, habitat, and hazard for map units H, h, and s. Descriptions for other map units not shown. (Ellen and others, 1981.)

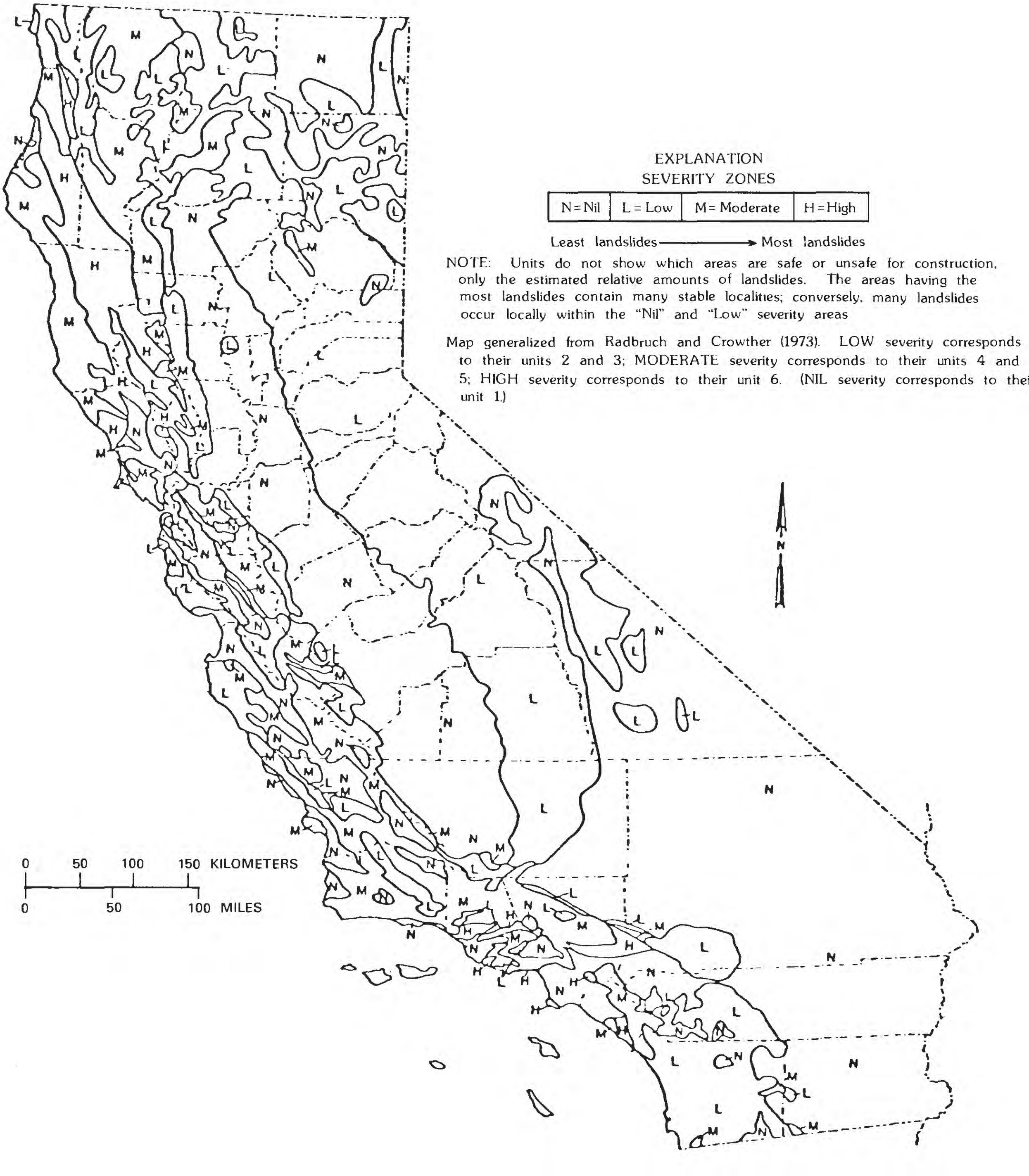


FIGURE 14.—A simple slope-stability map of California, originally published by Radbruch and Crowther (1973) to show relative amounts of landsliding, is shown here in generalized form with severity zones. (Alfors and others, 1973.)

can be constructed by this method. Large areas, such as counties, States, and even countries can be mapped in a short time using this general method where reliable geologic maps are available. Figures 15–16 are examples of relative slope-stability maps prepared by various means for areas in the United States. (For other examples, see Nilsen and others (1979) and Monroe (1979).)

Using more detailed data, slope-stability maps can be devised that, in theory, predict the absolute (rather than relative) stability of slopes, or the likely numbers or areal extent of failures over a given time period. The reliability of such predictions would depend to a large extent on how well the factors are known that control the initia-

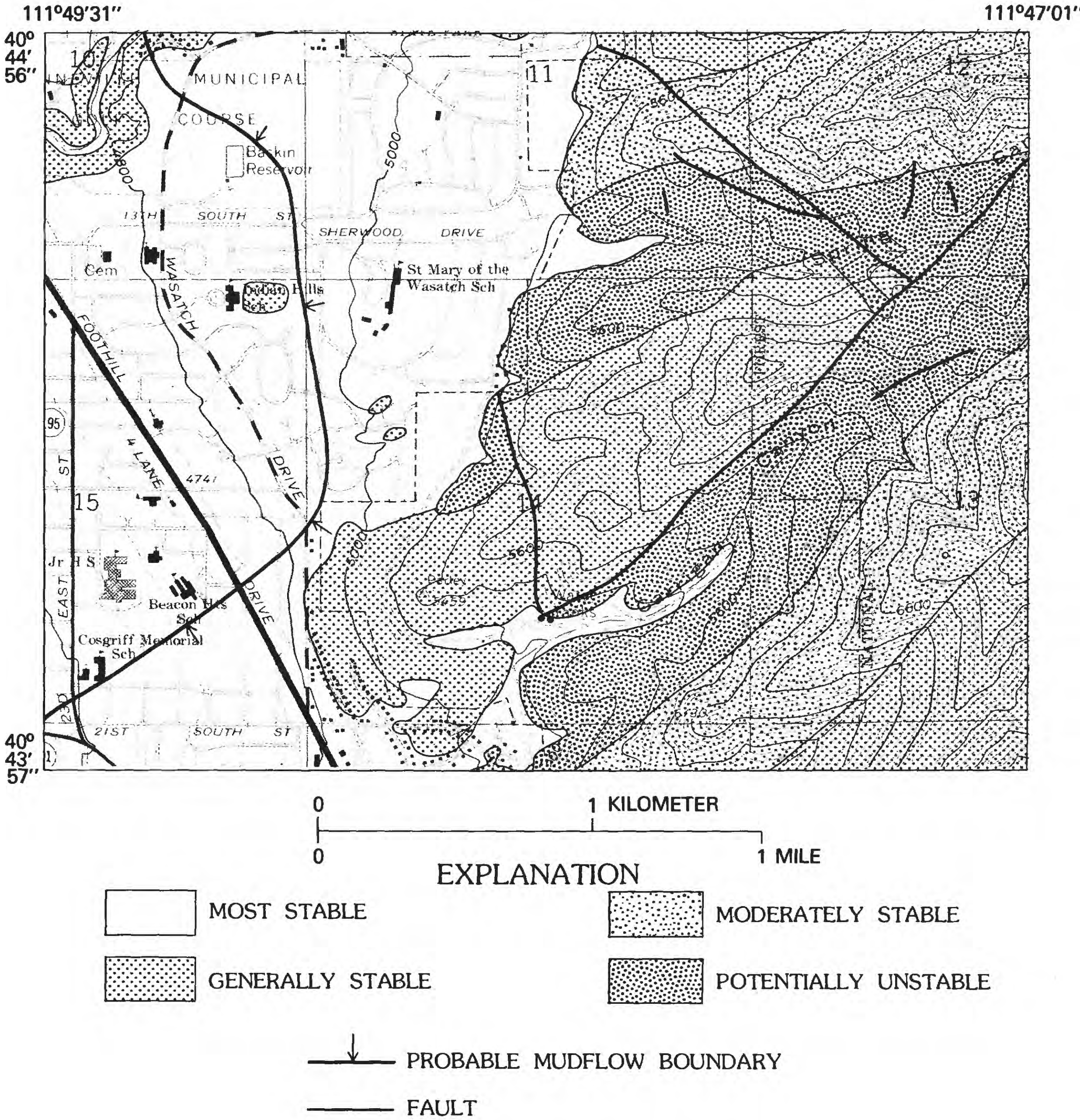
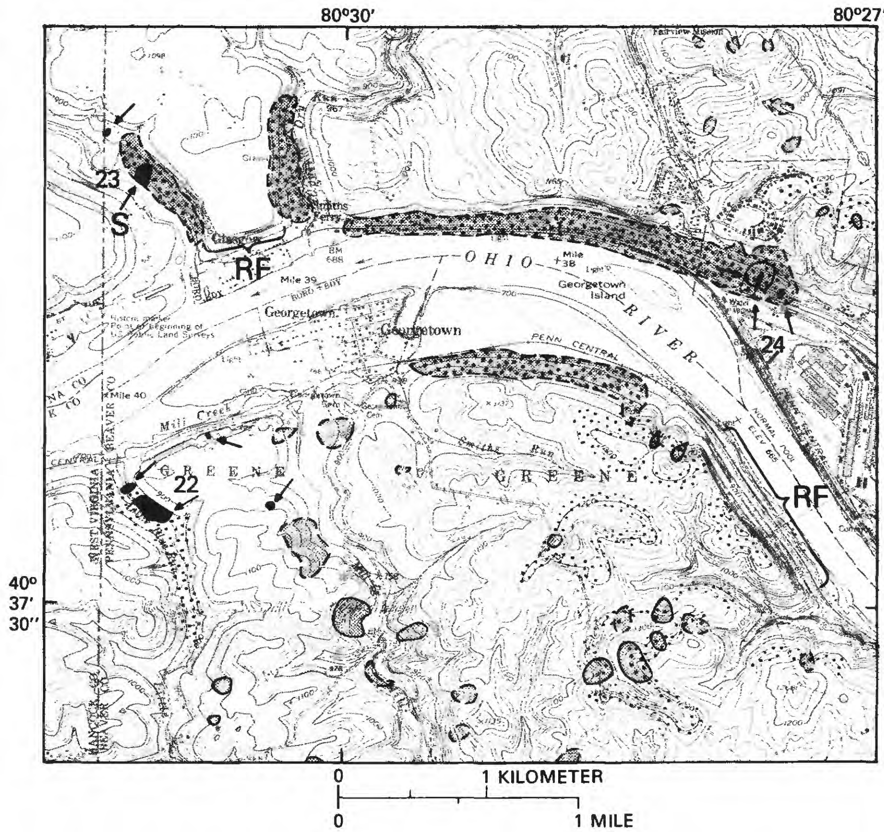


FIGURE 15.—Landslide susceptibility near Salt Lake City, Utah. From Van Horn (1972) "The features considered in preparing the relative slope stability map include: steepness of slope, type of rock or surficial deposit, and locations of bedrock, faults, springs, and former marshes. These features were evaluated according to their relation to known landslide deposits and talus accumulations, to the observed deterioration of buildings in the area, and, in small part, to plausible predictions."

tion of landslides in the map area. In general, slope-stability maps provide more information and include an assessment of potential for landsliding of the entire map area than do inventory maps. However, the increased information is obtained at the expense of more field work and more extensive background information.

LANDSLIDE-HAZARD MAPS

Landslide-hazard (zoning) maps are probably



EXPLANATION

(See text for additional information)

RECENT LANDSLIDES—Well-defined, characterized by fresh scars, may still be active. Selected examples of slump (S), fill slump (FS), earthflow (E), debris slide (DS), mining-related slide (M). Arrow used to point out symbol. Numbers refer to locality discussed in table 1 of Pomeroy (1979)

OLDER LANDSLIDES—Solid lines represent definite landslides, boundaries approximately located. Dashed lines represent indefinite landslides, fairly to poorly defined, boundaries inferred

AREAS MOST SUSCEPTIBLE TO LANDSLIDING—Underlain mostly by red mudstones of Conemaugh Group

STEEP SLOPES MOST SUSCEPTIBLE TO ROCKFALL—Bracket identifies steep, locally vertical, natural and manmade slopes and cliffs

FIGURE 16.—Landslides in Beaver County, Pa. (from Pomeroy, 1979). Areas most susceptible to landsliding are places where weathered shales, mudstones, and underclays occur on steep slopes.

the most sophisticated type of map that can be obtained with existing technology. These maps contain detailed information on the probable type of landslide, the extent of slope subject to failure, the probable maximum extent of ground movement, and the probable frequency of slope failure. Important in the classification of landslide type are data on velocity and mass of moving material. With this information, the risk can be estimated of varying degrees of injury to people and animals and damage to structures and real property that the landslide processes are capable of inflicting. Few such maps have been produced and procurement of data, especially in regard to probability, requires extensive studies.

RISK MAPS

Risk maps show the potential impact of landslide hazards on people or structures. Thus, evaluation of risk requires a knowledge of the structures or lives that can be affected by a given hazard, in combination with knowledge of the hazard itself. Table 3 provides the general framework for different levels of landslide risk in relation to regional, county, and site applications. Techniques for preparing risk maps have not been significantly developed in the United States. However, such maps will become necessary if landslide insurance is offered to mitigate damage costs.

LAND-USE MAPS

Land-use planning maps incorporate many things other than landslides and other geologic hazards. A few, more specialized maps that generally fit the category of land-use maps with respect to landslide hazards have been made in California; figure 17 is representative. Guidelines for low-risk land use usually are provided by geologists, in consultation with engineers and planners, based on their experience and the experience of others as reported in the scientific literature. Table 1 (from Mader, 1978), provides land-use guidelines based on mapping in Portola Valley, Calif., described by Hoexter and others (1978).

TASKS FOR HAZARD-ZONATION STUDIES

* Develop methods for the rational planning of landslide-hazard zonation programs, at various scales and for various purposes. Devise methods for preparation of landslide-hazard zonation maps at different scales, using several kinds of data for various purposes, including local and regional planning, site selection, and resource development.
* Explore methods of describing and displaying landslide hazards on zonation maps in order to: (1) describe most effectively the character and degree of hazard; (2) provide adequate data for derivative maps; and (3) provide information for engineers, planners and decisionmakers. Include design of symbols for use on landslide-hazard zonation maps.
* Devise mapping techniques that can be applied to progressively refine the assessment of stability of areas that may be vulnerable to catastrophic landslides.
* Carry out preliminary studies of landslide-hazard zonation in priority regions at a regional scale using available methods and data.
* Carry out detailed landslide-hazard zonation for selected areas where especially high risk, exceptional data bases, or other opportunities or needs warrant it.
* Experiment with hazard-zonation techniques by various methods and at different scales in the same areas in order to compare techniques and results.
* Begin longer term hazard zonation of priority regions at appropriate scales to help define, and then to use, improvements in methods about the causes of landslides.
* Study the interrelations between landslide hazard, structures and social vulnerabilities, and land-use patterns and inventories, and develop methods for evaluating landslide risk.
* Using data from the above-mentioned studies and from landslide-hazard maps, data on age and recurrence of landsliding, land-use maps, and constraints on land use, prepare landslide-risk maps and land-capability (cost of development) maps.
* Devise methods of testing the accuracy, completeness, and usefulness of various kinds of landslide-risk studies and landslide-risk maps and apply these methods to selected areas.
* Some noncatastrophic landslides can have catastrophic risks owing to secondary effects such as dam failures, seiches, and interruption or destruction of critical facilities. Areas should be identified and the risks assessed.

TABLE 3.—*Levels of landslide risk (from Nilsen and others, 1979, p. 59)*

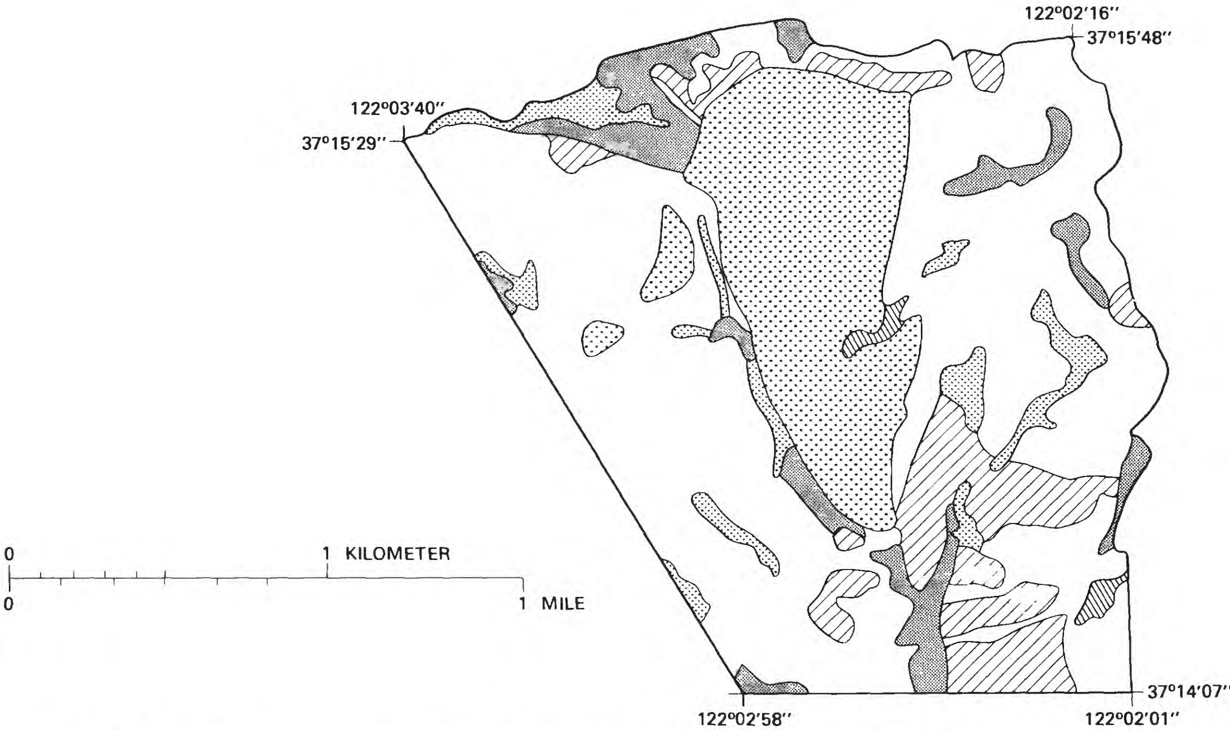
Low risk	Moderate risk	High risk
	Overall land-use potential	
Generally very few limitations to land use imposed by slope instability. The most intensive urban growth and development will be located in low risk areas. Local limitations may be imposed by soil conditions, susceptibility to flooding and seismic hazards.	Limitations to urban-type land use are present. However, much of the area can support urban growth and development if appropriate measures are taken to minimize risk to life and property. Local areas may be unsuitable for urban development without extensive grading and filling, or structures to ensure stability.	Urban development is usually inappropriate. These areas should be assigned lowest priority for urban growth and development. These areas may be designated as permanent open space for public health and safety or as regional parks. Unstable bay muds may be of value as wildlife refuges. Some areas may be suitable for low-density residential development making use of clustering techniques, on slopes of adequate stability.
	Regional	
1. No further slope-stability studies necessary for development of regional policies, standards, and criteria.	1. No further slope-stability study necessary for development of regional policies, standards, and criteria.	1. No further slope-stability study necessary for development of regional policies, standards, and criteria.
2. Slope stability is not critical factor in regional land-capability analysis.	2. Regional land-capability analysis must recognize that slope stability may be critical in local areas and plan on higher costs for studying and reducing hazards.	2. Regional land-capability analysis should reflect possible limits to urban land use imposed by slope instability throughout high-risk areas and costs of studying and reducing hazards. reducing hazards.
3. Regional planning policies and criteria should indicate need for more detailed studies of local bedrock geology, soils, flood-prone areas, and areas of seismic hazards and the impact of these factors on local slope stability.	3. Regional planning criteria and standards reflect lower priority for urban land uses, particularly critical facilities serving the region, as a result of potential slope instability.	3. Avoid locating critical facilities in high-risk areas, and consider designating such areas as regional open space.
	4. More slope-stability data may be required to evaluate impact of specific projects of regional significance.	4. More slope-stability data will be necessary to evaluate impact of specific projects with regional significance.
	County or city comprehensive plan and implementation regulations	
1. More detailed data on local conditions, particularly stability of bedrock, should be obtained for preparing the comprehensive plan, as deemed necessary by the geologist.	1. More detailed geologic hazard data, as determined in conjunction with the geologist, are essential to land-use decisionmaking within local planning area.	1. Detailed geologic data are essential to determine general potential for development and to establish the nature of more specific data that will be needed to ensure proper safeguards.
2. Detailed data are essential to define local slope-stability problems and as a basis for reducing risk.	2. On the basis of detailed data, the comprehensive plan provides guidance for the regulation of areas determined unsuitable for urban development. Methods of avoiding or reducing hazards are included in plan policy and proposals.	2. On the basis of detailed data, boundary of high-risk area may be modified to reflect local conditions more precisely.
3. Regulations should be based on detailed data and adopted comprehensive plan. Framework and guidelines for site-specific studies should be made part of implementing procedures in conjunction with the geologist.	3. Regulations should be developed in conjunction with the geologist indicating soils and engineering geologic studies to be required before approving specific projects.	3. High-risk areas are precluded from development in comprehensive plan and implementing regulations, both of which should be developed in conjunction with the geologist.
	Site-specific design and construction	
1. In almost every case, some site-specific studies will be necessary. In most cases, only soils studies will be needed.	1. Soils and preliminary engineering geologic studies will be necessary before approving specific projects unless waiver procedure is established in conjunction with the geologist.	1. High-risk boundaries should be modified in accordance with site-specific studies approved by the local jurisdiction and the geologist.
2. On the basis of data developed while preparing the comprehensive plan and implementing the regulations, specific engineering geologic studies may be required in local areas.	2. Where stability problems are noted in preliminary studies, more detailed analysis will be necessary as a basis for project design and construction.	2. Site-specific studies may show that low-density development is appropriate with adequate safeguards.
3. Only development conforming to recommendations from the approved site-specific investigation is to be permitted. Approval of the investigation is based on recommendations of the soils engineer or engineering geologist.	3. Only development conforming to recommendations from the site-specific study should be permitted. Approval of the study by the jurisdiction based on advice of the soils engineer or engineering geologist.	3. Only development conforming to the recommendations of the study should be permitted. Approval of the study by the jurisdiction is based on recommendations of the soils engineer or engineering geologist.

* Make field studies of areas at potentially high risk from catastrophic landslides to permit further refinement of the hazard zonation.
* Prepare for computer analysis the data on landslide size, type, age, geologic material, discontinuities, strength, water conditions, slope, and other data that can be derived from maps, and develop methods for storage, manipulation, and graphic production by computer equipment.
* Establish digitization formats and resolutions tailored to computer manipulation for hazard zonation and demonstrate their use in working with data sets relative to landslide incidence and frequency, possible causes, land use and vulnerability, hazard zonation, and risk analysis.

APPROACHES FOR MAPPING HAZARDS ON SUBMARINE SLOPES

LANDSLIDE INVENTORIES

During the last 15 years, increasing awareness of and concern about submarine landslides has in-



RELATIVE STABILITY	MAP AREA	GEOLOGIC CONDITIONS	RECOMMENDED LAND USE: Houses	Roads: Public	Roads: Private
Most Stable		Flat or gentle slopes; subject to local shallow sliding, soil creep and settlement	Yes	Yes	Yes
↑		Gentle to moderately steep slopes in older stabilized landslide debris; subject to settlement, soil creep, and shallow and deep landsliding	Yes*	Yes*	Yes*
		Steep to very steep slopes; subject to mass-wasting by soil creep, slumping and rock fall	Yes*	Yes*	Yes*
		Gentle to very steep slopes in unstable material subject to sliding, slumping, and soil creep	No*	No*	No*
↓		Moving, shallow (<10 ft) landslide	No*	No*	No*
Least Stable		Moving, deep landslide, subject to rapid failure	No	No	No

EXPLANATION

Yes*--The land use would normally be expected to be permitted, provided the geologic data and (or) engineering solutions are favorable. However, there will be instances where the use will not be appropriate

No*--The land use would normally be expected to not be permitted. However there will be circumstances where geologic data and (or) engineering solutions will permit the use.

FIGURE 17.—Potential ground movement and recommended land-use policies for the Congress Springs area, Santa Clara County, Calif. Somewhat generalized from Cotton and Associates (1977, pl. 3). The original map is on a topographic base at a scale of 1 in. equals 250 ft (1:3,000). Compare figure 17 with the inventory map of the same area (fig. 12).

itiated shipborne surveys for the purpose of finding, locating, and determining the areal extent of these features. Published results have described many major submarine landslides in terms of origin and age, susceptibility to further movement, and impact on offshore operations for energy development, mining, and communications (Moore, 1978; Prior and Coleman, 1979). The published literature describes slides principally in the Atlantic Ocean (U.S. Atlantic coastal margin, Brazilian coastal margin, continental slope off South Africa, northwest Africa) and sections of the Mediterranean Sea (Sangrey and Garrison, 1978).

In recent years, more detailed studies have appeared in the literature based on high-resolution seismic and side-scanning sonar data (Hampton and others, 1978; Field and Edwards, 1980; Prior and Coleman, 1980). The closely spaced survey lines in such studies have revealed large numbers of smaller landslide features on continental shelves and slopes that may prove significant in terms of potential damage to manmade structures.

In the offshore areas of the United States, investigations have concentrated on areas of potential or actual energy development. Innovative techniques have been devised that identify areas of previously failed material and of anomalous gas and water pressures. However, these techniques have not been applied in enough areas to understand all the physical settings and processes that lead to different failure types. Therefore, the strategies for submarine landslide studies are essentially an ordering of priorities for needed research. The first order of priority, hence, is inventory of the published literature aimed at a systematic categorization of submarine landslides in terms of geologic (morphologic, tectonic, sedimentary) settings, age of events, areal extent, volume of materials affected, and causative factors. The second priority is the reexamination of seismic reflection profiles and sonographs, especially those that are in the proprietary domain. Although uncertainties sometimes appear in the interpretation of ground-failure zones from seismic-profile data, such data are still the principal time-tested tool for this purpose. Other unpublished geophysical data should also be examined for the purpose of extending the data base. The relatively poorly examined continental margins (except for the southern California borderland, the Mississippi River delta area, and the Gulf of Alaska) should receive early attention.

A body of worldwide data exists that describes many of the local effects of submarine landslides such as sudden bathymetric changes, pipeline and communication-cable breaks, and tilting or other disturbance to offshore platforms. Although some of these data are proprietary, there is enough publicly available information to compile an historical documentation of submarine soil movements. The third step in the inventory should be to collect, analyze, and report these data.

SLOPE-STABILITY MAPPING

After the inventory studies, a program of submarine landslide mapping, utilizing existing data and collecting new data where necessary, would undertake to prepare maps of priority offshore areas. These maps would show the texture, composition, and thickness of the surficial sediment cover, superimposed on the seafloor slope gradient. Such data are routinely collected by standard sediment sampling and by high-resolution geophysical (acoustic) profiling. The quantity and quality of seafloor data can be enhanced with improvement in submarine remote-sensing techniques combined with adaptation of techniques of processing terrestrial and space remote-sensing data.

A qualitative assessment of the principal triggering forces for submarine landslides would be overlaid upon such maps. These forces include storm waves whose cyclic pressure variations perturb certain weak sediments and elevate their pore pressures, and the cyclic loads imposed on the seafloor by earthquake accelerations. Areas of tectonic tilting are associated with areas of active faulting or diapiric uplift. Other environmental processes that might contribute to undercompaction and low strength are operative in areas of active biologic generation of methane and areas of rapid sedimentation. The final superposition of these data sets should graphically designate the areas where submarine landslides are most likely to occur.

RISK MAPPING

Risk mapping, based on an understanding of submarine conditions and material properties, is a basis for development of preventive or stabilization techniques. Quantitative studies, which identify the possible failure mechanisms and the probability of occurrence of each mechanism, combined with slope-stability mapping could produce interpretations of probability of failure on a regional basis. The probability of failure, combined with the value of the energy or communication structure involved, provides an estimate of risk.

The types of information required to produce regional predictions of submarine landslides include (1) rates of sediment accumulation and scour, rates-magnitudes of local tectonic deformation, character and magnitude of cyclic stresses induced by storm-wave and earthquake loading; (2) detailed character and distribution of materials within and adjacent to existing or potential failure features, including consolidation state of each material, and pore-pressure gradients throughout materials within and adjacent to existing or potential failure features, and their variation during dynamic loading; and (3) stress deformation and strength parameters of the materials, their geometric variation, and their dynamic deformations induced by waves and earthquakes.

PRIORITIES FOR MAPPING

TERRESTRIAL AREAS

MAJOR POPULATION CENTERS OR AREAS OF RAPID URBAN GROWTH

Priorities for terrestrial landslide mapping on a national basis should be given to areas of greatest hazard to the largest number of people. Thus, the major population centers in regions of highest landslide incidence should be designated highest priority. Areas where cities are rapidly expanding into landslide-prone hillsides should also be mapped.

Two data sets have been used to locate areas of highest priority: the Rand McNally (1981) statistics on population increases in metropolitan areas during the 1970–79 period, and the U.S. Bureau of the Census (1980, table 4) report on municipalities reporting the greatest net increase in land area from 1970-79. The Rand McNally statistics indicate that cities in the Western United States may be the most vulnerable (fig. 18), as well as a few cities in Alaska, New England, and the Gulf Coast. Increase in urban land

TABLE 4.—*Representative users of landslide-hazard information*

Private users
Civic and voluntary groups
Concerned citizens
Construction companies
Consulting geologists and engineers
Financing and insuring institutions
Landowners, developers, and real-estate persons
News media
Utility companies
Community users
Mayors and council members
Other elected officials
Municipal engineers, planners, and administrators
Planning and zoning commissions
Schools
Tax assessors
Regional users
Multicity and multicounty planning and development districts (including water and transportation)
Multistate planning and development districts
Offices of emergency planning and response
State departments of resource development
State geological surveys
State departments of transportation
State legislatures
University geology, civil engineering, architecture, urban and regional planning departments
National users
Academy for Contemporary Problems
American Association of State Highway and Transportation Officials
American Public Works Association
Association of State Geologists
Council of State Governments
National Academy of Science (Transportation Research Board)
National Association of Counties
National Association of Insurance Commissioners
National Governors' Association
Natural Hazards Research and Applications Center, University of Colorado
National League of Cities
Professional and scientific societies (including geologic, engineering, architecture, and planning societies)
Smithsonian Center for Short-lived Phenomena
United States Conference of Mayors
Urban Consortium
Federal government users
National Science Foundation
Army Corps of Engineers
Bureau of Land Management
Bureau of Reclamation
Congress and Congressional staffs
Department of Agriculture
Department of Energy
Department of Housing and Urban Development
Department of Interior
Department of Transportation
Environmental Protection Agency
Farmers Home Administration
Federal Emergency Management Agency
Federal Housing Administration
Federal Power Commission
Forest Service
General Services Administration
National Park Service
Nuclear Regulatory Commission
Soil Conservation Service
Small Business Administration

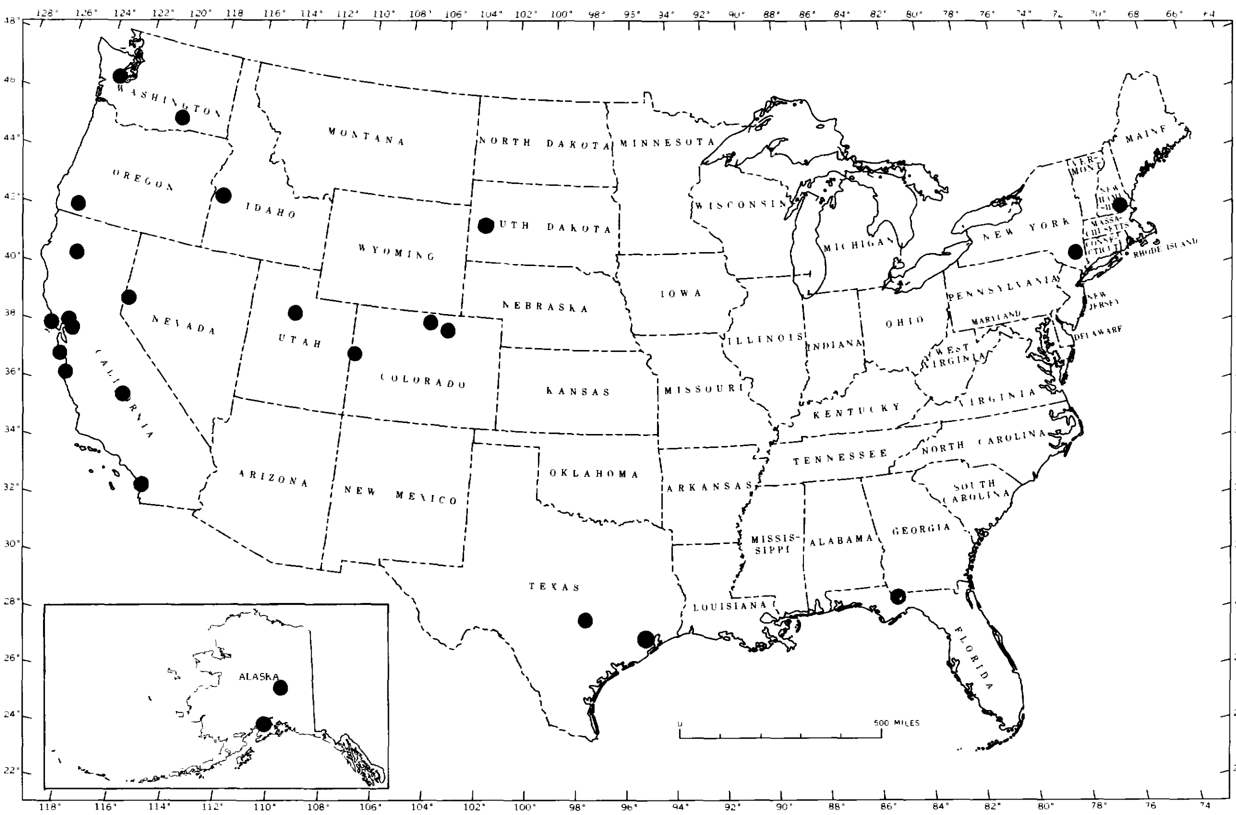


FIGURE 18.—Map of the United States showing rapidly expanding metropolitan areas located in areas of high-landslide incidence or susceptibility (solid circles). The 25 metropolitan areas shown are from a total of 53 listed in the 1981 Rand McNally commercial atlas.

area by States results in a somewhat different set of priorities as shown on figure 19. The following is a discussion of apparent priorities for landslide-hazard mapping and risk evaluation.

REGIONS IN THE UNITED STATES REQUIRING STUDY, IN ORDER OF NEED

WEST COAST REGION

Because of the combined influence of high-density population, active seismicity, and many unstable slopes, the West Coast should be given first priority for study. The sequence of mapping might be determined by the availability of data, the severity of local landslide probelms, or density of population. But the region as a whole should receive prompt attention. Intensive landslide studies have been made in many parts of this region; for example, in the San Francisco Bay area. Such studies can form the basis for the extension of mapping into adjacent areas.

APPALACHIAN REGION

This region should be designated second in priority because it has a high incidence of landsliding and extensive areas of unstable slopes. However, except for a few major cities, the centers of concentrated population characteristic of the West Coast are lacking. Some detailed studies have been completed by the U.S. Geological Survey in the area of Pittsburgh, Pa. The inventory of landslides for all the Appalachian Plateau and much of the Valley and Ridge part of the region is planned for completion in 1982. Inventory and slope-stability mapping has been completed for some parts of West Virginia by the West Virginia Geological and Economic Survey (Lessing and others, 1976). This work should be

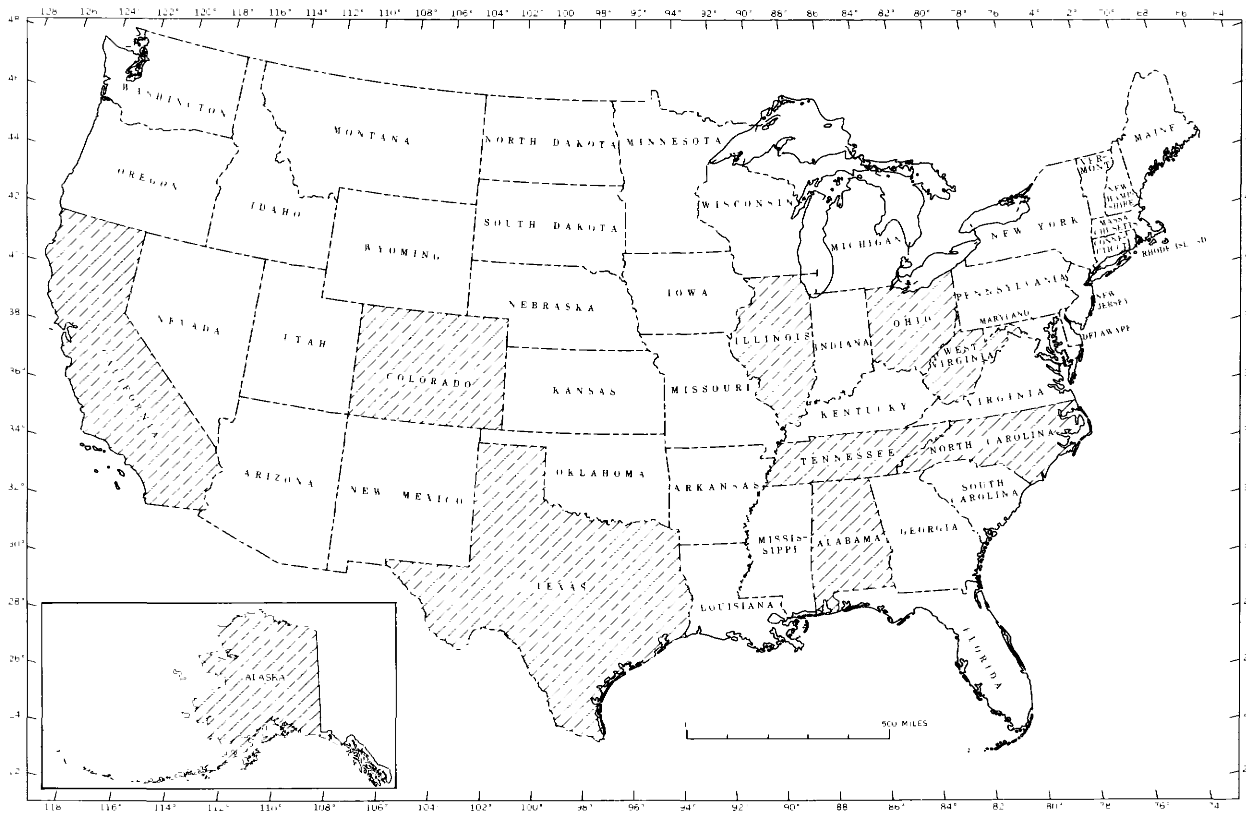


FIGURE 19.—Ten States having the largest number of municipalities that are expanding into landslide-prone areas. Data from U.S. Bureau of the Census (1980, table 4), and the landslide map of Radbruch-Hall and others (1976).

expanded so that it can serve as an example for others. Studies should also be expanded to cover more of the Valley and Ridge, the Piedmont, the mountains of New England, and the anthracite area of Pennsylvania.

ROCKY MOUNTAIN REGION

The third priority is the Rocky Mountain region. Although the population is generally not dense, landslide incidence and susceptibility are extremely high because of the steep mountain terrain characterized by unstable slopes. Additional reasons for this priority designation involve escalating energy development throughout much of the region and the high seasonal use of many areas for recreational purposes. In the Front Range urban corridor in Colorado, geologic and surficial studies at a scale of 1:100,000 form a good basis from which to extend work and focus on detailed studies.

OTHER AREAS

Other areas requiring study include Salt Lake City and the Wasatch Front, Utah; the Albuquerque, N. Mex., area; and Anchorage, Fairbanks, and southeast Alaska. Studies also should be undertaken in areas of rapid urban growth near Dallas, Tex., Cincinnati-Columbus, Ohio, and Birmingham, Ala. In addition, priority should be given to areas designated by State geologists or regional agencies for mapping landslide hazards.

THREATS TO LIFELINES AND OTHER CRITICAL FACILITIES

Landslides need to be mapped in transportation corridors in less populated areas that provide the only link between small population centers. Landslide maps are needed also for areas near major dams, reactor sites, aqueducts, airports, canals, energy-production centers, military sites, and other major Federal or local facilities.

THREATS TO NATURAL RESOURCES

Landslide hazards need to be mapped in recreation areas, such as national parks and mountainous terrain where intensive seasonal use has led to injury and death to vacationers and hikers. The shoreline areas of the country are also subject to intense seasonal use and pressure for development, and the landslide hazard should be mapped in areas of steep slopes and weak rocks.

Landslide hazards, both short-term (damage to roads and other facilities) and long-term (damage to soil and slopes that will prevent or delay the regrowth of forests), need to be mapped in many areas where extensive damage is being caused by timber harvesting, particularly in the Pacific Northwest, northern California, southeastern Alaska, and the Rocky Mountains.

Landslide hazards should be mapped for areas that supply critical energy resources and minerals, particularly those on Federal lands in the Western United States.

MARINE AREAS

Priorities for mapping submarine landslides are established, for the most part, in a different way from those on land. Except for the submarine landslides that generate large waves, they are not a direct threat to large numbers of people. They are a threat to offshore structures and to people that may be on them, however, and as such are responsible for annual losses of millions of dollars to offshore oil-producing systems. Priorities for mapping submarine landslides will, therefore, depend upon the location of important offshore petroleum resources, and the risk of landsliding in the vicinity.

REGIONS TO BE STUDIED

GULF OF MEXICO

Mapping of landslides is required in areas where drilling platforms are concentrated together with pipeline facilities and pumping stations. Many of these are located along the front of the Mississippi River delta and on the upper continental slope.

The continental shelf and upper slope in the Gulf of Mexico produce a substantial percentage of the total United States domestic oil and gas. The region is covered in many places by thick sections of rapidly deposited, underconsolidated sediments highly susceptible to landsliding. The Mississippi Delta front is perhaps one of the most carefully mapped seafloor areas in the world and, as such, could serve as the nucleus for expanded mapping in the same way as the San Francisco Bay area on land.

The upper slope of the Gulf is a region where thick sediments cloak the steep flanks of growing salt diapirs, and landslides are common. In this region, recent petroleum discoveries indicate an urgent need for landslide maps.

OTHER AREAS

Offshore energy projects in the continental shelf and upper slope areas off southern California and New Jersey, as well as those in the Gulf of Alaska and the Beaufort Sea, will require landslide mapping to assure safe development of resources.

CATASTROPHIC LANDSLIDES AND THREATS TO CRITICAL FACILITIES

Tsunamis generated by extremely large submarine landslides are a serious threat to thousands of people living in coastal regions. Areas in which these landslides can occur and areas of potentially catastrophic landslides in tectonically active areas should be systematically evaluated. Mapping of landslide hazards is important in areas of telephone cables and other critical submarine communication systems. Military or other government facilities will require mapping of landslide hazards in areas of shipping channels and where important submarine facilities are situated.

PART 4—TRANSFER AND USE OF LANDSLIDE-HAZARD INFORMATION

INTRODUCTION

The third major part of a program for landslide-hazard reduction is dedicated to transfer and use of the technical information obtained in the other parts of this program. The avoidance of landslide hazards and mitigation of landslide losses will require that appropriate information be communicated to, and used by, nongeologists, especially engineers, planners, and decisionmakers. The criteria and priorities for specific technical studies must include consideration of major urban and urbanizing areas, national environmental and energy resources, and critical facilities.

The selection of landslide areas or processes for study is only the first step of a national program of landslide-hazard reduction. If the information prepared is inadequate, inappropriate, undisseminated or unused, landslide hazards and losses will increase, thereby wasting public and private capital and creating demands on Federal, State, and local government agencies for costly engineering works, and for loans, grants, insurance, tax credits, or other subsidies.

The effective use of landslide information depends upon (1) the users' interest, capabilities, and experience in hazard-related activities; (2) enabling legislation authorizing Federal, State, and local hazard-reduction activities; (3) adequate, detailed information in a readily usable and understandable form; and (4) the use of good communication techniques.

GOALS

The goals of the information-transfer and use part of the program are as follows:

* To identify users and their needs,
* To identify potential uses,
* To prepare usable and understandable information,
* To communicate the information, and
* To evaluate the information and its use.

The challenges, strategies, and some of the tasks for accomplishing these goals are discussed next.

USERS OF LANDSLIDE-HAZARD INFORMATION

Potential users of landslide information include a vast array of people at national, regional, and community levels—both public and private. Three general categories can be identified. These categories are (1) scientists and engineers who use the information directly; (2) planners and decisionmakers who consider hazards among other land-use and development criteria; and (3) interested citizens, including educators and others. Table 4 lists representative kinds of users. These people do not constitute a homogeneous group. Rather, they differ widely in the kinds of information they need and in their capacities to use that information. Some groups produce certain landslide information as well as require other types of information. Engineers, architects, and professional planners have needs that differ from those of State and local government officials and private citizens. Thus, detailed scientific information prepared for geologists or practicing engineers is unsuitable for most State and local officials, and probably is unusable by most private citizens.

For example, most professional land-use planners and local officials do not have the training or experience to understand and directly apply scientific information. Few academic programs train students of planning or public administration to avoid hazards or mitigate losses from certain kinds of geologic processes. Although many land-use planners and local officials have some experience with natural hazards, such experience is generally related to flooding or soil problems (Office of Science and Technical Policy, 1978, p. 170).

The effective use of landslide information to avoid damages or to mitigate losses requires a considerable effort on the part of both the producers and the users of the information. Without specific tailoring of the scientific and engineering results, the effective user community is limited to other engineers and geologists. On the other extreme, if the users do not become proficient in interpreting and applying technical information, the information is likely to be misused or not used in the decisionmaking process. Kockelman (1975, 1976b, 1979) reported interviews with 91 city planning staffs, 8 county planning staffs, and 7 selected regional agencies in the San Francisco Bay area. For the cities and counties, only a few staff members had had any training in earth sciences or engineering. The most effective use of landslide information by the staffs was achieved when maps were provided that contained locations, susceptibilities, and magnitudes of the hazards. For the regional agencies, all had professional planners or engineers on their staffs and two of the agencies employed geologists. These skills permitted a broader use of the technical materials, and the agencies were able to make their own interpretations from the information for their own purposes.

The goal of identifying information users can be accomplished by the following procedures:

* Identify and target those users listed in table 4 that have the greatest need and that would use the landslide-hazard information most effectively.
* Consult with those users about their needs and priorities and identify the information most needed.
* Monitor and analyze the enactment of State and Federal laws or regulations and the landslide issues that affect users to anticipate and respond to their needs.
* Encourage planners and decisionmakers—both public and private—to develop an in-house capability to obtain and apply the information.
* Provide adequate training to potential users to enable them to understand and to use information effectively.

USES OF LANDSLIDE-HAZARD INFORMATION

Site or development plans prepared by engineers and land-use plans adopted by local units of government, if implemented, can be a most effective means for avoiding landslide hazards and for mitigating landslide losses if they include adequate landslide information. Responsibilities for land-use planning rest with all levels of government and are spelled out in various Federal acts, State statutes, and local ordinances. Land-use planning involves prescribing the best possible type, location, density, and arrangement of land uses while taking all relevant factors into account, including landslide hazards. Unfortunately, landslide information has not been widely incorporated into the planning process.

Numerous techniques for reducing landslide hazards (table 5) are available to planners and decisionmakers (Erley and Kockelman, 1981). Some of these techniques are well known in the engineering profession (for example, restraining structures); or in the planning profession (for example, public acquisition of hazardous areas). Others, such as warning signs and regulations are obvious and practical, but these require consistent enforcement. Still others are innovative when applied to landslides, but have been successfully used in solving flood and soil problems. These techniques are listed in table 5 under the headings of discouraging new development, regulating development, removing or converting existing development, and protecting existing development. The techniques may be used in a variety of combinations to help solve both existing and potential landslide problems.

The most economical method of reducing landslide losses is to discourage development in hazardous areas by means of public-information programs, erecting warning signs, public recording of the hazard, special assessments and tax credits, lenders' policies, public facility extension policies, and disclosure to property buyers. Historically, financial institutions fund projects in, developers build on, and people occupy, areas known to be hazardous. Usually they rebuild in the same manner and in the same location immediately following most disasters and often use government loans or other subsidies for the rebuilding. Government funding incentives or disincentives can be important techniques to discourage such development.

Such development can be protected by drainage, excavation, or building structures to restrain the landslides; by diverting mudflows; and by monitoring, warning, and evacuating residents if a landslide is imminent. Loss from landslides often leads to a demand for costly remedial public works to provide protection for existing developments. However, landslide restraint can be self-defeating. As construction in hazard areas continues, the number of occupants and the value of the property tend to increase at a rate faster than that at which remedial or protective works can be provided. Development upslope often jeopardizes downslope development. Grading, drainage improvements, paving, and watering, for example, may overload, or cause instability of a landslide and require public expenditures for restraint. The Federal Emergency Management Agency (1980, Sec. 205.75a. (17)) advises that not only is permanent work to stabilize a landslide not eligible for financial assistance, but that such work can be quite costly and may not produce the desired results.

It is costly to build public works for the protection of development, difficult to remove or convert existing development, and probably unrealistic to assume that all future development in hazard areas can be discouraged. Prohibiting and regulating uses in areas susceptible to landslide damage or capable of triggering slides can provide the most efficient and economical method for avoiding landslide hazards and reducing damage. The goal of identifying uses for the information can be accomplished by studies of the following types:

* Conduct benefit-cost studies of selected techniques for reducing landslide hazards in selected hazard areas (see table 5).
* Identify and target the most effective techniques for different situations.
* Review and recommend those Federal programs or legislation from table 6 that could incorporate or require such techniques.
* Devise and test innovative techniques.

USABLE AND UNDERSTANDABLE MAPS AND REPORTS

A prerequisite for a successful landslide-hazard reduction program is the production of adequate and reliable information about the hazard. The diverse groups of users need specific landslide information—location, susceptibility, and magnitude—of the hazard shown on a map. Reports and maps designed for one common user group—intelligent and interested citizens—serve user needs as to content, scale, detail, and interpretation and provide a common basis for discussion during public hearings. Simple maps—with a few "stop-light" colors—are the most effective and most frequently prepared for this user group.

Improvement in technology requires that geologists and engineers experiment with different methods of making hazard maps, risk evaluations and landslide predictions. The results of these studies will portray landslides and landslide processes in far greater detail than is needed for land-use plans and their implementation, but, over the longer term, will result in definitive assessments of landslide risk and hazard. Such products then, as now, can readily be simplified for nongeologists.

A wide variety of maps and reports ranging from highly technical documents to popular-type releases are required. Annotated bibliographies of landslide processes and damage reports, indexes to landslide inventory and hazard maps and directories of natural hazard data—sources similar to the inventory of Lander and others (1979)—are extremely helpful. Such material would not necessarily be produced by the U.S. Geological Survey, but achievement of the goal of producing usable and understandable information will require the following types of studies:

* Produce maps and reports quickly for nongeologists from existing landslide information to orient potential users.

TABLE 5.—*Typical uses of information for landslide-hazard reduction*

Engineering and planning studies
Structure and foundation design
Special hazard study zones
Environmental impact assessments and statements
Site-specific investigations
Early warning reconnaissance
Geologic hazards inventories
Benefit-cost studies
Development plans
General or master plans
Redevelopment plans
Circulation or transportation plans
Utility plans
Subdivision layout plans
Community facility plans
Seismic safety plans
Public safety plans
Land-use plans
Open-space plans
Natural hazards reduction plans
Neighborhood development plans
Discouraging new development in hazardous areas
Public information
Warning signs
Recording the hazard
Special assessments and tax credits
Lenders' policies
Funding incentives and disincentives
Public facility extensions
Disclosures
Insurance costs
Executive orders
Capital improvement programs
Regulating development in hazardous areas
Land-use zoning districts
Special landslide-area use regulations
Subdivision regulations
Sanitary regulations
Grading regulations
Removing or converting existing development in hazardous areas
Public acquisitions
Urban redevelopments
Public-nuisance abatements
Nonconforming uses
Public facility reconstruction
Protecting existing development in hazardous areas
Physical measures to improve stability
Mudflow diversions
Monitoring, warning, and evacuations

TABLE 6.—*Federal programs or legislation affecting land use that could be reviewed for possible amendment to encourage Federal, State, and local governments to adopt landslide-hazard reduction techniques (Office of Science and Technology Policy, 1978, p. 56)*

Agricultural Land Protection (S-106,1977)
Airport and Airway Development Act, as amended
Alaska Native Claims Settlement Act
Bankhead-Jones Farm Tenant Act of 1937
Bureau of Outdoor Recreation Act of 1962
Clean Air Act of 1970, as amended in June 1974
Coastal Zone Management Act of 1972, as amended
Concessions Policies Act of 1965
Disaster Relief Act of 1974
Estuarine Areas Act of 1968
Federal-Aid Highway Act, as amended
Federal-Aid in Wildlife Restoration Act of 1937
Federal Civil Defense Act of 1958
Federal Energy Administration Act of 1974
Federal Land Policy and Management Act of 1976
Federal Power Act of 1920
Federal Property and Administration Act of 1949
Federal Surplus Lands for Parks and Recreation Act
Federal Water Pollution Control Act Amendments of 1972
Federal Water Project Recreation Act of 1965
Fish and Wildlife Act of 1956
Fish and Wildlife Coordination Act of 1974
Flood Disaster Protection Act of 1973
Forest and Rangeland Renewable Resources Planning Act of 1974
Historic Preservation Acts
Housing and Community Development Act of 1974
Land and Water Conservation Fund Act of 1965
Multiple Use-Sustained Yield Act of 1960
National Environmental Policy Act of 1969, as amended
National Forest Management Act of 1976
National Trails System Act of 1968
National Wild and Scenic Rivers Act of 1968
National Wilderness Preservation Systems Act of 1964
Noise Control Act of 1972
Payments in Lieu of Taxes Act
Pickett Act of 1910
Public Works and Economic Development Act of 1965
Railroad Revitalization and Regulatory Reform Act of 1976
Solid Waste Disposal Act of 1965, as amended
Surface Mining Control and Reclamation Act of 1977
The Snyder Act of 1924 and Indian Reorganization Act of 1934
Trans Alaska Pipeline Authorization Act of 1973
Water Resources Planning Act of 1965

* Identify the maps and reports needed.

* Assure that new landslide information is prepared in the detail and at the scales needed and understood by the targeted users (see table 4).

* Assure that landslide information (including discoveries, advances and innovative uses) is released promptly through appropriate communication channels (see tables 7 and 8).

* Assist in preparing new interpretative reports to meet user needs.

* Make special efforts to present the information in a format and language suitable for use by engineers, planners, and decisionmakers.

METHODS OF COMMUNICATION

Before people can mitigate landslide hazards, they need certain kinds of information. They must know the nature of the hazard and what can be done to reduce it. The information should be communicated to various users at different stages in a carefully structured time sequence. For example, those groups in a position to influence policies and programs affecting large numbers of persons should be involved actively in two-way communication and should receive information on a first-priority basis. The groups include key national, regional, and community decisionmakers, and representatives of the news media (Office of Science and Technology Policy, 1978, p. 65).

Before collecting and interpreting landslide-hazard information, the required two-way communication must be established between research workers and users. If potential users are not aware of the research, they will not use it; they should be informed before, during, and after the research. This kind of communication is common practice among scientists and engineers already, but the needs of other potential users, such as State and local government officials and the private sector traditionally have been omitted from the process. Because research workers and some of the users tend to have divergent interests and needs, interpretation of the research may be necessary to make it helpful.

Table 7 lists some representative communicators of landslide-hazard information. Many of the users listed in table 4 also will be communicating such information. Of course, geologists and other landslide-research workers will be available to provide some of the educational, advisory, and review services, but to rely solely on these scientists would divert them from their work of collecting and interpreting landslide information. However, Bates (1979, p. 11) notes that "* * * although both the use of transfer agents and the education of planners in the earth sciences, * * * are increasingly important components of the information-transfer system, nothing replaces intensive producer-user interaction * * *."

TABLE 7.—*Representative communicators of landslide information*

American Institute of Architects/Research Corporation
Circuit riders (regional or project area)
City Management Association
Civic and voluntary groups
Community planning assistance programs (regional and county)
County extension agents
Educators (university, college, high school, and elementary school levels)
Hazard-information clearinghouses (national, regional, or project area)
Information-exchange groups (Federal, State, or local)
Journalists, commentators, and editors
Landslide researchers, interpreters, and mappers
Local professional and scientific societies
National Hazards Research and Applications Center at University of Colorado
Professional associations of media personnel
Public information offices (Federal and State)
Researchers, engineers, and planners
Speakers bureaus (regional or project area)
State geological surveys
United States Conference of Mayors
USDA Soil Conservation Service
The Urban Consortium
Users advisory committees (national, regional, or project area

COMMUNICATION TECHNIQUES

Multiple ways of imparting information should be encouraged. A single exposure to new information, especially if the information is complex or differs from a user's previous knowledge, often is insufficient. Repeated exposures in different formats and through different channels are needed. This technique is particularly successful when new information is provided by persons who are customarily looked to for guidance, such as members of the same professional group (Office of Science and Technology Policy, 1978, p. 63).

The most effective techniques should be selected jointly by the user and the research worker. Table 8 lists typical communication techniques under the headings of educational, advisory, and review services. Many of the uses, such as disclosure, monitoring, and warning, listed in table 5, are also excellent means of communication.

Educational, advisory, and review services should accompany any landslide-information collection and interpretation program designed for planners and decisionmakers. Educational services range from merely announcing the availability of landslide information, through the publishing and distributing of newsletters and brochures, to sponsoring, conducting, or participating in seminars and workshops for potential users.

Advisory services range from explaining or interpreting landslide reports and maps, through assisting in the design of regulations based upon the information, to giving expert testimony and depositions concerning the information.

Review services include review and comment on policies, procedures, studies, plans, statutes, ordinances, or other regulations, that are based upon, cite, interpret, or apply landslide information.

The educational and advisory services should not supplant existing programs or activities of

TABLE 8.—*Typical communication techniques (adapted from Kockelman, 1976a)*

Educational services
Assisting and cooperating with universities and their extension divisions in the preparation of course outlines, detailed lectures, casebooks, and display materials.
Contacting speakers and participating as lecturers in regional and community educational programs related to the application of landslide information.
Sponsoring, conducting and participating in topical and areal seminars, workshops, short courses, technology utilization sessions, cluster meetings, innovative transfer meetings, training symposia, and other discussions with user groups.
Releasing information needed to address critical landslide hazards early through oral briefings, seminars, map-type "interpretive inventories," open-file reports, reports of cooperating agencies, and "official use only" materials.
Sponsoring or cosponsoring conferences for planners and decisionmakers at which the results of landslide studies are displayed and reported on to users.
Providing speakers to government, civic, corporate, conservation, and citizen groups, and participating in radio and television programs to explain or report on landslide-hazard reduction programs and products.
Assisting and cooperating with regional and community groups whose intention it is to incorporate landslide information into school curricula.
Preparing and exhibiting displays that present landslide information and illustrate their use in hazard reduction.
Attending and participating in meetings with local, district, and State agencies and their governing bodies for the purpose of presenting landslide information.
Guiding field trips to potentially hazardous sites.
Preparing and distributing brochures, TV spots, films, and other visual materials to the news media.
Advisory services
Preparing annotated and indexed bibliographies of landslide information and providing lists of pertinent reference material to various users.
Assisting local, State, and Federal agencies in designing policies, procedures, ordinances, statutes, and regulations that cite or make other use of landslide information.
Assisting in recruiting, interviewing, and selecting planners, engineers, and scientists by government agencies for which education and training in landslide-information collection, interpretation, and application are criteria.
Assisting local, State, and Federal agencies in the design of their landslide-information collection and interpretation programs and in their work specifications.
Providing expert testimony and depositions concerning landslide-research information.
Assisting in the presentation and adoption of plans and plan-implementation devices that are based upon landslide information.
Assisting in the incorporation of landslide information into local, State, and Federal studies and plans.
Preparing brief fact sheets or transmittal letters about landslide products explaining their impact on, value to, and most appropriate use to, local, State, and Federal planning and decisionmaking.
Assisting users in the creation, organization, staffing, and formation of local, State, and Federal planning and plan-implementation programs so as to assure the proper and timely use of landslide-hazard information.
Preparing and distributing appropriate user guides relating to landslide processes, mapping, and hazard-reduction techniques.
Preparing model State landslide-safety legislation, regulations, and development policies.
Preparing model local landslide-safety policies, plan criteria, and plan-implementation devices.
Review services
Review of proposed programs for collecting and interpreting landslide information.
Review of local, State, and Federal policies, administrative procedures, and legislative analyses that have a direct effect on landslide information.
Review of proposed policies, procedures, and legal enactments that cite landslide information.
Review studies and plans based on landslide information.

educational institutions, or replace services of private consulting firms or regional and community organizations, but instead should supplement them. Educational, advisory, and review services would be provided only upon request and only as a service to improve communication and awareness. Many of these services have been recommended by Wissel and others (1976), University of Wisconsin's Center for Geographic Analyses (1975, p. 24), the Council of State Governments (1975, p. 25; 1976, p. 17, 18), and Arthur D. Little, Inc. (1975, p. 82, 92).

Some of these services are being provided already through cooperative agreements, map-sales offices, geologic-inquiries staff, public inquiries offices, and ordinary day-to-day contacts with the public by the producers of landslide-hazard information. In addition, many research workers have provided such services on a limited and informal basis (Kockelman, 1975, 1976a, 1976b, 1979). U.S. Geological Survey scientists involved in urban area studies are frequently called upon to assist users in interpretation of information. Such services should be formally recognized and included as a work element in any program for collecting and interpreting landslide information designed for nongeologists.

BENEFITS FROM COMMUNICATING INFORMATION

Providing educational, advisory, and review services to planners and decisionmakers will result in fuller and more effective use of landslide information in addressing critical community, regional, and national issues. In addition to avoiding landslide hazards and reducing losses, Kockelman (1976a) identified the following additional benefits that will accrue:

* Avoid duplication in the collection and interpretation of landslide information, thereby conserving staff time and financial resources of research workers.
* Develop a more acute awareness and understanding among scientific, engineering, and planning staffs of users' specific needs.
* Assure more correct and more appropriate uses of landslide information.
* Transfer the methods of collecting, interpreting, and presenting landslide information to users outside the study area.
* Expedite the dissemination of critical landslide information needed on which to base urgent community, regional, and national decisions.
* Increase the familiarity of planners, decisionmakers, and citizens with landslide hazards.

COMMUNICATION TASKS

The tasks required to effectively communicate landslide-hazard information to users include the following:

* Design the communications program following an assessment of users' needs in order to improve the likelihood of effective use.
* Recommend or select the most effective communication techniques.
* Prepare and tailor the communications program so that information can be rapidly and continuously disseminated.
* Inform users promptly of new landslide information by using the most effective communication techniques.
* Select the educational, advisory, and review services appropriate to the users and the project area.

EVALUATION OF LANDSLIDE INFORMATION AND ITS USE

A continuing, systematic evaluation should be part of any national program for landslide-hazard reduction. An inventory of uses made of the information, reports of interviews with the users, and an analysis of the results and responses will result in identifying new users, innovative uses, as well as any problems concerning the information and its communication.

The criteria, decisions, and methods used in applying the landslide research findings to planning and decisionmaking can be of value to other jurisdictions in which similar hazards exist, and for which adequate landslide information is available. The adaption to, and adoption by, other jurisdictions depends upon the presence of similar public awareness, enabling legislation, hazard issues, priorities, community interest, innovative decisionmakers, and staff capabilities.

The evaluation will be helpful—even necessary—to the funding, producing, and using individuals and agencies. Sponsors of hazard-reduction programs for hazards other than landslides that were designed for planners and decisionmakers have performed self-evaluations on the usefulness of the programs (Arthur D. Little, Inc. 1975; Kockelman 1975, 1976b, 1979, and 1980; Downing, 1978; Wissel and others, 1976). Production and communication of any landslide-hazard information are a prerequisite to any inventory of its uses or interviews with its users; therefore, the following tasks must await the initiation or completion of most of the preceding tasks:

* Inventory selected public and private uses (see table 5) to identify and document the type and number of uses of each map or report.
* Interview selected public and private users (see table 4) to identify problems with the information or the communication techniques.
* Collect and analyze examples of innovative uses.
* Analyze uses and problems and suggest improvements to the information or to the communication techniques.
* Conduct benefit-cost analyses of local programs to reduce landslide losses.

RESPONSIBILITY FOR USE

The responsibility for acquiring and using landslide information suitable for hazard avoidance and damage mitigation is neither clearly defined nor evenly distributed among the several governmental levels. Although it may be appropriate for the Federal Government to provide leadership in basic research, mapping, and dissemination of information, the States have shared and should continue to share this responsibility. The Federal Government could help define the roles of the different governmental levels and help communication by establishing standards for ways of obtaining, interpreting, and presenting landslide information.

The effort needed to assure the avoidance of landslide hazards, to restrain landslides, and to mitigate their damage exceeds the capabilities of any one level of government. Any program for reducing landslide hazards must be a multigovernmental concern, and the information must be disseminated through a partnership of Federal, State, and local governments. National standards should be established for collecting, interpreting, and disseminating landslide-hazard information, for defining appropriate levels of detail for various users and uses, and for conducting demonstration projects. The U.S. Geological Survey should continue to emphasize basic research and its use at State and local levels.

Techniques for reducing landslide hazards can be encouraged by a carefully conceived and firmly implemented program involving all levels of government. Each level is empowered and obligated to promote the health, safety, welfare, and prosperity of its people and their communities. Each level is directly involved in planning, financing, constructing, operating, or maintaining its own facilities, some of which may be located in areas with landslide hazards.

Particularly important is that the Federal Government make wise land-use and development decisions. Its own buildings and facilities should be located and constructed to avoid landslide hazards and should serve as examples to other units of government. The Federal Government has scientific, engineering, planning, and technical resources for undertaking landslide research, for disseminating information, and for monitoring State and local programs. Finally, the Federal Government is the largest unit of government, possesses the greatest resources, and is under great pressure to provide funds and manpower for disaster relief.

State governments have sovereign powers and duties to promote health, safety, welfare, and prosperity. Most State governments also have financial and technical resources and the power to require district and local units of government to avoid landslide hazards and to mitigate damage. Even if a hazard-reduction program is an initial success—involving adequate research, useful products, effective communication and proper use—according to Kockelman (1980, p. 74), its continuing effectiveness will depend upon many other factors outside the program including:

* Continued awareness and interest by the public.
* Careful revision of enabling legislation (as needed) by legislative bodies.
* Conscientious administration of regulations by inspectors.
* Consistent enforcement by responsible government officials.
* Sustained support of government officials by the political leaders.
* Judicious adjustment of regulations by administrative appeal bodies.
* Skillful advocacy (if challenged) and proper interpretation by the courts.
* Concern for individual, family, and community safety by home buyers and real-estate developers.

SUMMARY OF TASKS FOR THE THREE MAJOR PARTS OF THE PROGRAM

<table>
<tr><th>PROCESS AND PREDICTION</th><th>HAZARD MAPPING AND RISK EVALUATION</th><th>TRANSFER AND USE OF INFORMATION</th></tr>
<tr><td colspan="3">Investigate past landslides, their consequences, and lessons learned.
Organize quick-response teams to study different aspects of major landslide events.
Conduct a coordinated program of investigation of submarine landslides.
Provide timely information in a format and language usable by nongeologists.
Collect, evaluate, and transfer innovative approaches to landslide-hazard avoidance or loss reduction.
Monitor effectiveness of the program and incorporate changes in emphasis where changes would contribute to loss reduction.</td></tr>
<tr><td>Evaluate mitigation techniques.
Monitor active landslide areas.
Conduct numerical and scale modeling of landsliding.</td><td></td><td>Evaluate mitigation techniques including planning and regulatory alternatives.</td></tr>
<tr><td colspan="2">Measure and characterize the physical variables that control the occurrence and distribution of landslides.
Devise new and improved techniques for measuring and analyzing failure leading to the goal of predicting the time, size, and consequences of a landslide.
Conduct or promote investigations of high-hazard areas.</td><td></td></tr>
<tr><td></td><td>Inventory existing mapping data base.
Prepare landslide inventories, slope-stability maps, and landslide-risk maps.
Refine classification techniques to improve hazard or risk portrayals of areas.
Experiment with computer processing, different forms of imagery, and novel map types to improve hazard or risk categorization.</td><td></td></tr>
<tr><td></td><td colspan="2">Experiment with different mapping scales, strategies, and map units for providing different levels of information to potential user groups.</td></tr>
<tr><td colspan="2"></td><td>Provide education, advisory and review services to users.
Consult with potential users about their needs and priorities.
Conduct benefit-cost analyses of different reduction measures.</td></tr>
</table>

REFERENCES CITED

Alfors, J. T., Burnett, J. L., and Gay, T. E., Jr., 1973, Urban geology master plan for California; the nature, magnitude, and costs of geologic hazards in California and recommendations for their mitigation: California Division of Mines and Geology Bulletin 198, 112 p.

Arnould, M., 1976, Geological hazards—Insurance and technical aspects: International Association of Engineering Geology Bulletin 14, p. 263–274.

Arthur D. Little, Inc., 1975, An evaluation of the San Francisco Bay region environment and resources planning study: U.S. Department of Housing and Urban Development, Office of Policy Development and Research, 93 p. (Report prepared by Arthur D. Little, Inc., San Francisco, Calif.)

Bates, T. F., 1979 [1980], Transferring earth science information to decisionmakers—Problems and opportunities as experienced by the U.S. Geological Survey: U.S. Geological Survey Circular 813, 30 p.

Brabb, E. E., Pampeyan, E. H., and Bonilla, M. G., 1972, Landslide susceptibility in San Mateo County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-360, scale 1:62,500.

Coleman, J. M., Prior, D. B., and Garrison, L. E., 1980, Subaqueous sediment instabilities in the offshore Mississippi River delta, *in* Handley, L. R., ed., Environmental information on hurricanes, deep water technology, and Mississippi delta mudslides in the Gulf of Mexico: U.S. Bureau of Land Management Open-File Report 80–02, p. 1–49.

Colton, R. B., Holligan, J. A., Anderson, L. W., and Patterson, P. E., 1976, Preliminary map of landslide deposits in Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-964, scale 1:500,000.

Cotton, W. R., and Associates, 1977, Analysis of the geologic hazards of the Congress Springs study area: Unpublished report for Santa Clara County on file in Santa Clara County Planning Office, San Jose, Calif., 47 p., scale 1:3,000.

Council of State Governments, 1975, An evaluation of natural resources data products by state data users: Lexington, Ky., 113 p.

———1976, Natural resource data needs and recommendations: Lexington, Ky., 25 p.

Dallaire, Gene, 1976, Consultants reviewing plans of other consultants in Fairfax County, Virginia—Landslides greatly reduced: Civil Engineering, v. 46, no. 9, p. 77–79.

Downing, T. E., 1978, Use of the Front Range Urban Corridor studies: Boulder, Colo., University of Colorado, Institute of Behavioral Science, 69 p.

Ellen, Stephen, Peterson, D. M., and Reid, G. O., 1982, Hazards from shallow landslides on hillslopes in Marin County, California: U.S. Geological Survey Miscellaneous Field Investigations Map MF-1406, scale 1:62,500 [in press].

Erley, Duncan, and Kockelman, W. J., 1981, Reducing landslide hazards—A guide for planners: Chicago, Ill., American Planning Association Planning Advisory Service Report 359, 29 p.

Federal Emergency Management Agency, 1980, Disaster relief, public assistance: Federal Register, v. 45, no. 158, p. 53956 and following, August 13.

Field, M. E., and Edwards, B. D., 1980, Slopes of the southern California borderland; A regime of mass transport, *in* Field, M. E., Colburn, I. P., and Bouma, A. H., eds., Quaternary depositional environments of the Pacific Coast: Society of Economic Paleontologists and Mineralogists, Pacific Section, Los Angeles, Calif., p. 169–184.

Fleming, R. W., and Taylor, F. A., 1980, Estimating the costs of landslide damage in the United States: U.S. Geological Survey Circular 832, 21 p.

Fleming, R. W., Varnes, D. J., and Schuster, R. L., 1979, Landslide hazards and their reduction: American Planning Association Journal, v. 45, no. 4, p. 428–439, October.

Garrison, L. E., and Bea, R. E., 1977, Bottom stability as a factor in platform siting and design: Offshore Technical Conference, Houston, Tex., Paper no. 2893, p. 127–134.

Garrison, L. E., Tatum, T. E., Booth, J. S., and Casby, S. M., 1977, Geologic hazards of the upper continental slope of the Gulf of Mexico: Offshore Technical Conference, Houston, Tex., Paper no. 2733, p. 51–58.

Hampton, M. A., Bouma, A. H., Sangrey, D. A., Carlson, P. R., Molnia, B. M., and Clukey, E. C., 1978, Quantitative study of slope instability in the Gulf of Alaska: Offshore Technical Conference, Houston, Tex., Paper no. 3314, p. 2307–2318.

Hansen, W. R., 1965, Effects of the earthquake of March 27, 1964, at Anchorage, Alaska: U.S. Geological Survey Professional Paper 542–A, 68 p.

Hoexter, D. F., Holzhausen, Gary, and Sota, A. E., 1978, A method of evaluating the relative stability of ground for hillside development: Engineering Geology, v. 12, no. 4, p. 319–336.

Humbert, M., 1977, Risk-mapping of areas exposed to movements of soil and subsoil—French "ZERMOS" maps [in French with English summary]: International Association of Engineering Geology Bulletin, v. 16, p. 80–82.

Jahns, R. H., 1978, Landslides, in Geophysical predictions—Studies in geophysics: National Academy of Sciences, p. 58–65.

Japan Society of Landslide, 1980, Landslides in Japan: Japan Society of Landslide, National Conference of Landslide Control, 44 p.

Jones, D. G., Jr., and Holtz, W. G., 1973, Expansive soils—The hidden disaster: Civil Engineering, v. 43, no. 8, p. 49–51.

Keefer, D. K., Wieczorek, G. F., Harp, E. L., and Tuel, D. H., 1979, Preliminary assessment of seismically induced landslide susceptibility: U.S. Geological Survey Circular 807, p. 49–60.

Kockelman, W. J., 1975, Use of USGS earth-science products by city planning agencies in the San Francisco Bay region, California: U.S. Geological Survey Open-File Report 75–276, 110 p.

———1976a, Educational, advisory, and review services: U.S. Geological Survey administrative report, Menlo Park, Calif., 25 p.

———1976b, Use of USGS earth-science products by county planning agencies in the San Francisco Bay region, California: U.S. Geological Survey Open-File Report 76–547, 186 p.

———1979, Use of U.S. Geological Survey earth-science products by selected regional agencies in the San Francisco Bay region, California: U.S. Geological Survey Open-File Report 79–221, 173 p.

———1980, Examples of the use of earth-science information by decisionmakers in the San Francisco Bay region, California: U.S. Geological Survey Open-File Report 80–124, 88 p.

Krohn, J. P., and Slosson, J. E., 1976, Landslide potential in the United States: California Geology, v. 29, no. 10, p. 224–231.

Lander, J. F., Alexander, R. H., and Downing, T. E., 1979, Inventory of natural hazards data resources in the federal government: U.S. Department of Commerce, U.S. Department of Interior, and U.S. Government Printing Office, 122 p.

Leighton, F. B., 1976, Urban landslides—Targets for land-use planning in California: Geological Society of America Special Paper 174, p. 37–60.

Leonards, G. A., 1982, Investigations of failures: American Society of Civil Engineers, Journal of the Geotechnical Engineering Division, v. 108, GT2, p. 187–246.

Lessing, Peter, and others, 1976, West Virginia landslides and slide-prone areas: West Virginia Geological and Economic Survey Environmental Geology Bulletin 15, 64 p., 28 maps, scale 1:24,000.

Mader, George, 1978, Land use planning in Portola Valley, California, *in* Hays, W. W., ed., Proceedings of Conference V—Communicating earthquake hazard reduction information: U.S. Geological Survey Open-File Report 78–933, p. 27–46.

McGill, J. T., 1973, Map showing landslides in the Pacific Palisades area, City of Los Angeles, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-471, scale 1:4,800.

Monroe, W. H., 1979, Map showing landslides and areas of susceptibility to landsliding in Puerto Rico: U.S. Geological Survey Miscellaneous Investigations Map I-1148, scale 1:240,000.

Moore, D. G., 1978, Submarine slides, Chapter 16, *in* Voight, Barry, ed., Rockslides and avalanches, [v.] 1, Natural phenomena; Developments in Geotechnical Engineering, 14A: Amsterdam, Oxford, New York, Elsevier Scientific Publishing Co., p. 563–604.

Newman, E. B., Paradis, A. R., and Brabb, E. E., 1978, Feasibility and cost of using a computer to prepare landslide susceptibility maps of the San Francisco Bay region, California: U.S. Geological Survey Bulletin 1443, 27 p.

Nilsen, T. H., Wright, R. H., Vlasic, T. C., and Spangle, W. E., 1979, Relative slope stability and land-use planning in the San Francisco Bay region, California: U.S. Geological Survey Professional Paper 944, 96 p., 3 pls, scale 1:125,000.

Obermeier, S. F., 1979, Slope stability map of Fairfax County, Virginia: U.S. Geological Survey Miscellaneous Field Studies Map MF-1072, scale 1:48,000.

Office of Science and Technology Policy, 1978, Earthquake hazards reduction—Issues for an implementation plan: Washington, Executive Office of the President, 231 p.

Pomeroy, J. S., 1979, Map showing landslides and areas most susceptible to sliding in Beaver County, Pennsylvania: U.S. Geological Survey Miscellaneous Investigations Map I-1160, scale 1:50,000.

Pomeroy, J. S., and Davies, W. E., 1975, Map of susceptibility to landsliding, Allegheny County, Pennsylvania: U.S. Geological Survey Miscellaneous Field Studies Map MF-685-B, scale 1:50,000.

Porcher, M., and Guillope, P., 1979, Cartographie des risques ZERMOS appliquée á des plans d'occupation des sols en Normandie (Introduction par Ph. Gaudemer et M. Le Campion): Laboratoire Central des Ponts et Chaussées, Paris, Bulletin de liaison, no. 99, p. 43–54.

Prior, D. B., and Coleman, J. M., 1978, Submarine landslides on the Mississippi River delta-front slope: Geoscience and Man, v. 19, p. 41–53.

———1979, Submarine landslides—Geometry and nomenclature: Zeitschrift fur Geomorphologie, v. 23, no. 4, p. 415–426.

———1980, Sonograph mosaics of submarine slope instabilities, Mississippi River delta: Marine Geology, v. 36, p. 227–239.

Radbruch, D. H., and Crowther, K. C., 1973 [1974], Map showing areas of estimated relative amounts of landslides in California: U.S. Geological Survey Miscellaneous Investigations Map I–747, scale 1:1,000,000.

Radbruch-Hall, D. H., Colton, R. B., Davies, W. E., Skipp, B. A., Lucchita, Ivo, and Varnes, D. J., 1976, Preliminary landslide overview map of the conterminous United States: U.S. Geological Survey Miscellaneous Field Studies Map MF-771, scale 1:7,500,000.

Rand McNally & Company, 1981, 1981 Commercial atlas and marketing guide: Chicago, Ill., Rand McNally & Company, p. 78–89.

Rantz, S. E., 1971, Precipitation depth-duration-frequency relations for the San Francisco Bay region, showing annual precipitation: U.S. Geological Survey open-file report, scale 1:500,000.

Sangrey, D. A., and Garrison, L. E., 1978, Submarine landslides: U.S. Geological Survey Yearbook, Fiscal Year 1977, p. 53–63.

Schuster, R. L., 1978, Introduction, Chapter 1, *in* Schuster, R. L., and Krizek, R. J., eds., Landslides—Analysis and control: Transportation Research Board Special Report 176, National Academy of Sciences, p. 1–10.

Slosson, J. E., 1969, The role of engineering geology in urban planning, *in* The Governor's conference on environmental geology: Colorado Geological Survey Special Publication 1, p. 8–15.

Slosson, J. E., and Krohn, J. P., 1979, AEG building code review— Mudflow/debris flow damage; February 1978 storm—Los Angeles area: California Geology, v. 32, no. 1, p. 8–11.

Teleki, P. T., Garrison, L. E., and Hampton, M. A., 1979, Environmental hazards; Considerations for outer continental shelf development: Offshore Technical Conference, Houston, Tex., Paper no. 3654, p. 2579–2589.

U.S. Army Corps of Engineers, 1976, Report on landslide study, Pacific Palisades area, Los Angeles California: U.S. Army Corps of Engineers, Los Angeles District, Calif., 30 p., Appendix 1 prepared by J. T. McGill, 89 p., map scale 1:4,800.

U.S. Bureau of the Census, 1980, Boundary and annexation survey—1970–1979: Washington, U.S. Government Printing Office, Report GE-30-4.

U.S. Geological Survey, 1981, Goals, strategies, priorities and tasks of a national landslide hazard-reduction program: U.S. Geological Survey Open-File Report 81–937, 91 p.

University of Wisconsin, Center for Geographic Analysis, 1975, Data needs and data gathering for areas of critical environmental concern, [pt. 1]: Summary Report, 130 p.

Van Horn, Richard, 1972, Relative slope stability map of the Sugar House quadrangle, Salt Lake County, Utah: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-766-E, scale 1:24,000.

Varnes, D. J., 1978, Slope movement types and processes, *in* Schuster, R. L., and Krizek, R. J., eds., Landslides—Analysis and control: Transportation Research Board Special Report 176, National Academy of Sciences, p. 11–33.

Wiggins, J. H., Slosson, J. E., and Krohn, J. P., 1978, National hazards— Earthquake, landslide, expansive soil loss models: J. H. Wiggins Company Technical Report, Redondo Beach, Calif., 162 p.

Wissel, Peter, O'Connor, Robert, and Cigler, Beverly, 1976, Summary report—The use of geological information in the greater Pittsburgh area: Pennsylvania State University, Center for the Study of Environmental Policy, 23 p.

Youd, T. L., 1978, Major cause of earthquake damage is ground failure: Civil Engineering, v. 48, no. 4, p. 47–51.

U.S. GOVERNMENT PRINTING OFFICE: 676-041/17—1983