GOALS, STRATEGIES, PRIORITIES AND TASKS

OF A

NATIONAL LANDSLIDE HAZARD-REDUCTION PROGRAM

By

U.S. Geological Survey

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Open-file Report

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PREFACE

Increased national concern about hazardous natural events expressed by Congress in Public Law 93-288 (1974) and strengthened by such disasters as the floods and landslides in southern California during 1980 prompted several U.S. Geological Survey scientists to express the need for a national program to cope with the problems. In order to formulate such a program and to solicit a wide variety of opinions from different disciplines within the Geological Survey, a workshop was convened in Denver, Colorado on January 28-29, 1981, attended by 53 scientists and administrators representing all of the interested divisions and offices of the Geological Survey. Workshop participants prepared three documents--a short summary for internal distribution, a longer document that is being edited and revised for a Circular, and a still longer document represented by this report. Inasmuch as this report contains many details that will interest some members of the earth sciences community, it is being released despite such problems as internal inconsistencies and uneveness of style because of the large number of authors involved. The report is the only one now available that discusses the goals, strategies, priorities and tasks of a national program to reduce ground failure hazards and, as such, may serve as a stimulus for discussion.

Although the title of the workshop implied that all ground failures were discussed, the focus of the January workshop was on landslide hazards. Nearly all the participants at the workshop either prepared written material or contributed ideas during the discussions. In this sense, they are all authors. However, few of them had a chance to review the manuscript and some may object to certain parts, although the views expressed in the manuscript are believed to be a general consensus.

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January 28-29, 1981

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INTRODUCTION

Ground failures caused by landslides, subsidence, swelling clay shales, permafrost thaw, and construction-induced rock deformation cause about $4 billion in property losses and an average of 25 deaths in the United States each year. Together, these losses exceed by many times the annual combined losses from floods, earthquakes, hurricanes, and tornadoes. Losses from landslides and subsidence alone amount to at least $1.5 billion per year, and losses from swelling clay shales to more than $2 billion. Such damage continues year after year, but only sporadic catastrophes attract nationwide attention.

The required information on hazardous geologic processes for the country as a whole is not being obtained, transmitted, and acted upon at a rate that can keep pace with current development. Losses continue as housing and engineering construction are undertaken without adequate assurance of long-term stability. Although the cost to American taxpayers is high, there is no national program in the Federal Government that deals with ground-failure problems, nor are such programs underway in individual States, although a few State and local governments have conducted mapping and topical research studies. However, state concern is growing; for example, legislation has recently been proposed to the California legislature that a systematic assessment be made of the distribution of potential geologic hazards in that State.

Although major reductions in these staggering losses can be achieved through applying state-of-the-art geologic and engineering practice to land-use planning and to standards for grading and construction, considerable research still needs to be undertaken. Reductions of as much as 90 percent have been achieved in a few communities. Many communities, however, view the presently available procedures as too expensive, too time-consuming, and too unreliable. Effective mitigation in many parts of the country, therefore, requires an accelerated program of earth sciences research focused on:

- Rapid, comprehensive, and reliable assessment of the distribution of potential hazards, and of the natural frequency of occurrence of hazardous events

- Development of more precise measurements of engineering parameters affecting quantitative slope stability evaluations and more reliable analytical models for anticipating the kind and degree of physical and chemical changes that can lead to failure

Needed research involves (1) the coordinated work of geologists, geophysicists, geochemists, hydrologists, and engineers, planners and mathematicians in (2) examining large areas, as well as in research into specific geologic conditions, with (3) support from exploration and laboratory testing, (4) the collection and analysis of past experience and new information and (5) the effective transfer of this information to users. Such activities can best be carried out in coordinated national effort, as has been successfully demonstrated by programs in other countries for example, Japan, Italy, and France. Japan is a world leader in engineering for landslide mitigation, expending hundreds of millions of dollars each year.

PROPOSED NATIONAL PROGRAM FOR GROUND-FAILURE RESEARCH

ROLE OF THE U.S. GEOLOGICAL SURVEY

USGS research in ground-failure hazards is currently less than 15 man-years per year, chiefly spread among programs for Construction and Ground Failures, Energy Lands, Reactor Hazards, and Earthquake Hazards Reduction. Although several of these studies are resulting in tangible benefits toward hazard reduction, many others are largely spin-offs of regional mapping projects and are not part of an integrated program having well-defined overall objectives. Such an integrated program does not exist, nor is the scope or rate of progress of present activity commensurate with the scale of the problem.

Research utilizing the multi-displinary skills of the U. S. Geological Survey should be brought to bear on the needs for improved, more rapid, less costly means of reducing ground failure losses. High-quality geologic, geotechnical, geophysical, geochemical and hydrologic mapping and process-oriented data are required to achieve effective regional assessments of ground failure hazards and to develop effective means of anticipating where and when failures are likely to occur.

The Geologic Division should take the lead in the development of a program designed to augment ongoing efforts and expand the scope of research on ground failure processes and assessment of regional hazards. The program should provide for coordination with and active participation of the Water Resources Division, (WRD), the National Mapping Division, (NMD), the Conservation Division, (CD), and the Office of Earth Sciences Applications, (OESA).

GOALS OF A NATIONAL PROGRAM

The workshop concluded that a national program to reduce the hazards to life and property, mitigate human suffering and economic losses, and minimize disruptions of business, government, and private activities from ground failures should include the following research goals:

- Provide a better basis for land-use decisions to avoid potential hazards or, if necessary to proceed, to do so in full awareness of the potential risks to people and property from ground-failure.

- Provide methods for warning people of times and places of probable future ground failures, especially those having a particularly high risk to personal safety.

- Provide regional geologic information needed to evaluate and protect critical structures from slope failures.

- Develop methods to determine the best engineering technologies to minimize, prevent, or remedy the effects of ground failures.

STRATEGIES FOR U.S. GEOLOGICAL SURVEY PARTICIPATION

Within the framework of a national program, USGS efforts in an expanded Construction and Ground-Failure Hazards Program should focus on research to recognize and delineate the regional distribution of potentially hazardous areas, and to evaluate the relative potential for ground failures through improved understanding of the mechanisms of failures and better measurements of the rock and soil conditions that contribute to failure. Research elements should include:

- Delineation on maps of regional distributions of potentially hazardous soil and rock conditions.
- Development and testing of consistent quantitative methods for rapid preparation of maps showing relative potential hazards.
- Recognition and delineation of areas that are most susceptible to failure during specific triggering events such as earthquakes and rainstorms.
- Evaluation of models of failure mechanisms and measurements of rock and soil parameters by detailed studies at selected natural sites and by laboratory procedures.
- Assisting the engineering profession in the evaluation of the performance of state-of-the-art engineering designs by detailed studies at selected construction sites.
- Establishment of a nationwide exchange for technical information on landslides and other ground failure hazards.

The plan within the U. S. Geological Survey is to divide the program into three major segments. One segment, landslide mapping and risk evaluation, should focus on preparing areal assessments of likelihood of ground failure for areas containing weak or landslide-susceptible materials. The second segment, processes and prediction, should develop techniques to predict slope movements and to understand the slope movements in terms of the failure processes. The third segment should contain facilities for providing information and technical assistance to individuals and areas experiencing damages from ground failure.

The workshop on ground failure hazard reduction prepared summaries of needed research for each of the three segments of the program. These summaries are contained in the following three sections of this report.

DEFINITIONS

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 in any of the following ways: by falling, toppling, sliding, spreading, flowing, or by their combinations. 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, as outlined in figure 1. These different types of slope movements have widely varying impact on man and his works. Some are large, very rapid, and can take many lives in a matter of minutes; some are slow, seldom causing injury but vastly destructive of property; some types are rare, some are common. In the United States few

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	Earth flow
				(soil creep)	
COMPLEX			Combination of two or more principal types of movement		

Figure 1.--Classification of slope movements (abbreviated version from Varnes, 1978.

areas of any 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 problems determined by the geology, topography, climate, and characteristics. Moreover, each kind of landslide process requires its own kind of response to recognize, avoid, or mitigate the problem.

In this report the term zonation applies in a general sense to division of the land surface into areas and the ranking of these areas according to degrees of actual or potential hazard from landslides or other mass movements on slopes. It does not necessarily imply legal restriction or regulation by zoning ordinances or laws.

Many hundreds of maps of landslides or of their deposits, old or new and active, have been made throughout the world, and to a certain degree they often indicate areas susceptible to future problems. But emphasis is placed here on the far fewer number of studies that go farther and attempt to assign degrees of hazard to mapped areas.

GOALS FOR LANDSLIDE-HAZARD MAPPING AND RISK EVALUATION

The objective of landslide-hazard mapping and risk evaluation is to determine the areal extent, timing, and severity of landslide processes in selected high-priority areas of the United States, including adjacent ocean floor areas, where such knowledge will provide the greatest benefit to government officials, consulting engineering firms, and the general public in avoiding the landslide hazard or in mitigating the losses.

Significant progress has been made during the past 10 years in determining the areal extent and kind of landslide processes operating in the United States. Several different types of landslide and slope stability maps can now be developed by the application of the experience and knowledge currently available.

STRATEGIES FOR MAPPING HAZARDS ON NATURAL SLOPES

Landslide hazard is evaluated most effectively when an orderly sequence of progressively more detailed steps is followed. In this way, the general distribution of hazardous areas is described, so that the hazard, though poorly defined, is recognized. Subsequently more detailed work defines and quantifies the hazardous conditions. The approaches discussed below should generally be followed in the order presented, although reconnaissance may not be necessary if only small areas are under consideration.

Reconnaissance Approaches--Simple Inventories

Reconnaissance maps show areas that appear to have failed by landslide processes. They are commonly prepared by interpreting aerial photographs, with a minimum of field checking. Features on aerial photographs that aid in the recognition of landslides include: (1) small isolated ponds, lakes, and other closed depressions, (2) many natural springs, (3) abrupt and irregular changes in slope and drainage patterns, (4) hummocky and irregular surfaces, (5) smaller landslide deposits that are commonly younger and form within older and larger landslide deposits, (6) steep curved scarps at the upper edge of the deposit, (7) irregular soil and vegetation patterns, (8) disturbed vegetation, and (9) interspersed, discontinuous flat areas. In general, fewer of these characteristics will be noted in small deposits. 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/or 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 be readily identified in a simple inventory. Experienced interpreters can complete a simple landslide inventory of a standard U.S. Geological Survey 7.5-min. quadrangle (about 150 km^2) in about 7 days. Figure 2 shows a simple landslide inventory for the Pittsburgh-Antioch area 50 km east of San Francisco, California.

A simple landslide inventory has the following advantages:

1. It can be prepared for a large area in a short time by few people at relatively small cost.

2. It shows the distribution of past landsliding and may show where landslide activity is most severe.

3. The data shown are generally understood by most decisionmakers.

4. It can be used to regulate or prevent future development in landslide areas.

A simple landslide inventory has the following disadvantages:

1. It is commonly incomplete, especially in wooded areas.

2. It is not as accurate as inventories accompanied by detailed ground or historic studies.

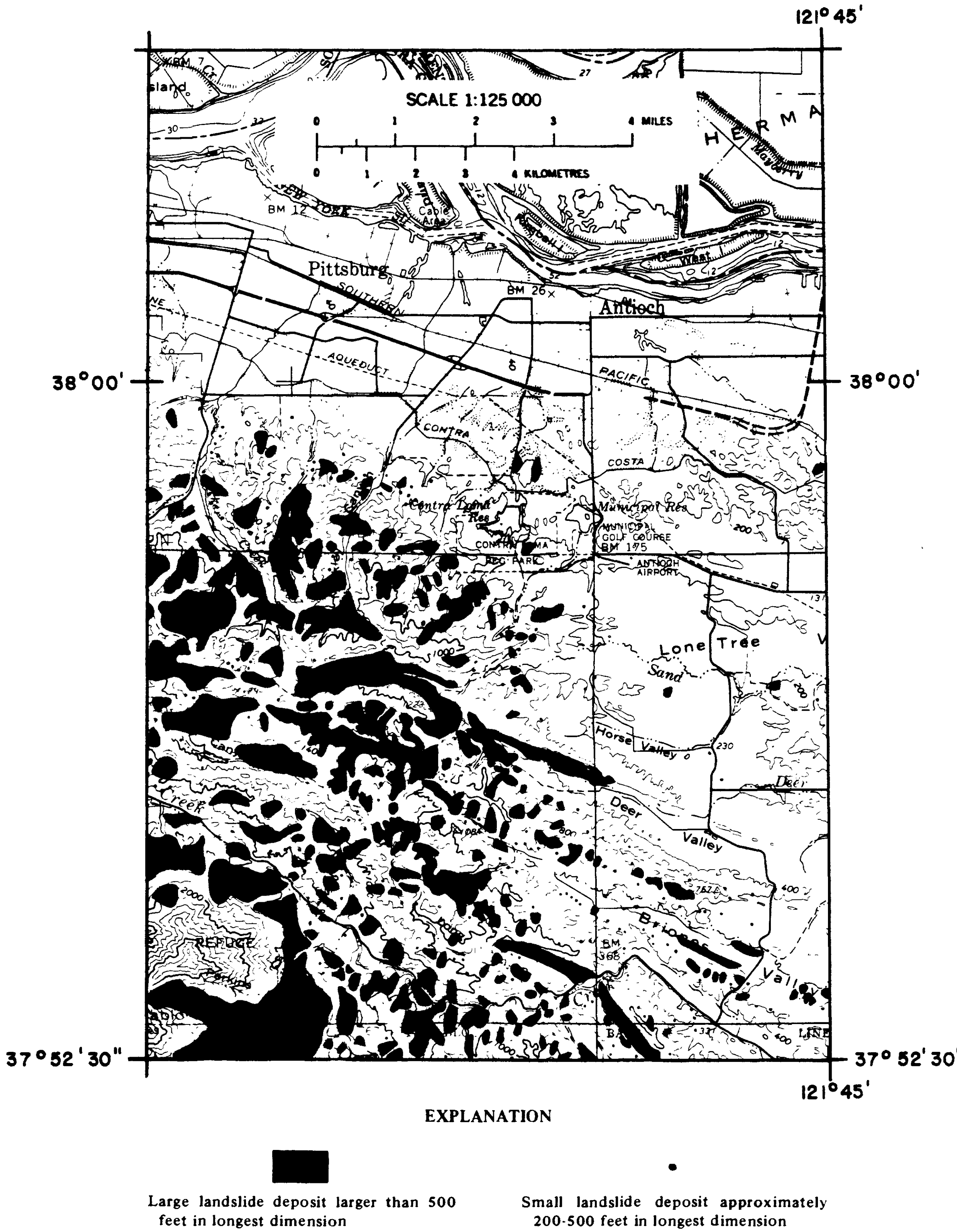


Figure 2.--A simple inventory of landslide deposits in part of northeastern Contra Costa County, California, near San Francisco. From Nilsen and others (1979, fig. 44).

3. It does not provide an understanding of the different landslide processes involved in an area.

4. It is not adequate for determining the safety of any particular site.

5. It does not generally indicate slope stability in areas where slides have not been identified.

Intermediate Types of Landslide Inventories

Intermediate types of landslide inventory maps show deposits and areas that appear to have failed because of landslide processes (fig. 3). In addition

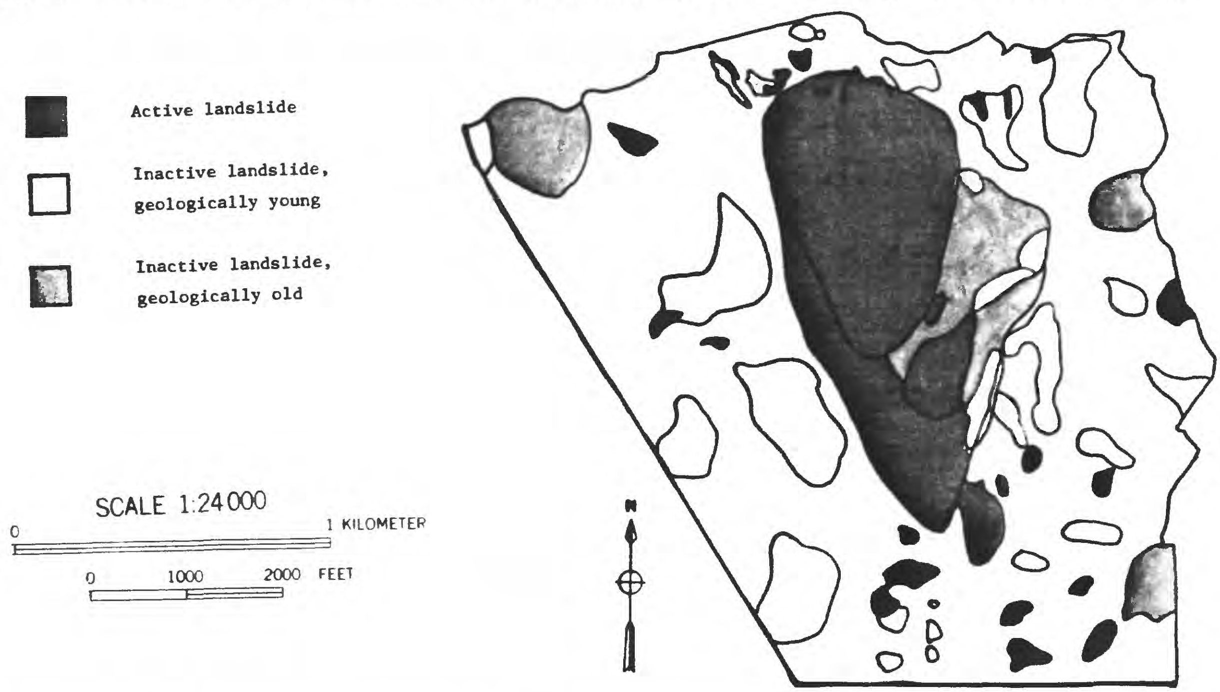


Figure 3.--An intermediate landslide inventory of the Congress Springs area, Santa Clara County, California. Reduced and generalized from a map at 1:2,000 scale by Cotton and Associates (1977, pl. 1).

they distinguish active from old landslides, 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 aerial photos of the area are also helpful to lessen the number of slides missed because they were masked by vegetation, farms, and other surface alterations. Field check is minimal but an additional check of manmade features is required. The additional observations and aerial photo interpretation requires substantially more (perhaps 50 percent more) time than for a simple inventory.

The intermediate type of landslide inventory map has the following advantages:

1. It can be prepared for a large area in a relatively short time, with few people, at small cost.

2. It shows the extent of both the natural and manmade problems and may show where the problems are greatest.

3. It can be used when remedial measures are being considered because certain types of landslides are indicated.

4. It provides some understanding of the different landslide processes that are operating in an area.

5. It provides a better foundation for the preparation of derivative maps of slope stability.

The intermediate landslide inventory map has the following disadvantages

1. It is commonly incomplete, especially in wooded areas.

2. It provides only a partial understanding of different landslide processes involved in an area.

3. It is not adequate for determining slope stability in areas where slides have not been identified.

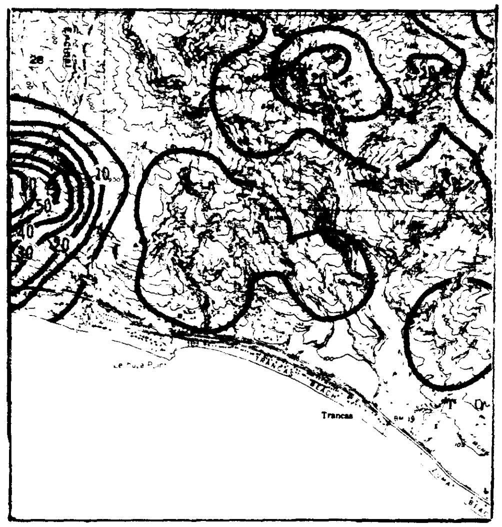
4. It is not as accurate as detailed inventories.

Detailed Inventories

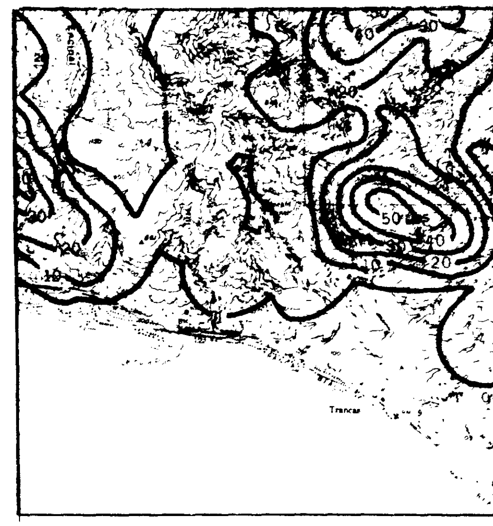
A detailed inventory map would show each landslide and classify it as to type along with a delineation of scarps, limits of the zone of accumulation, and other pertinent data on depth and kind of materials involved in the sliding. Active and old landslides are distinguished. The geologic age of the landslide and the rate of landslide movement would be included. In addition, the inventory would 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 would 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 information in Appendix 1 of the report by the U.S. Army Corps of Engineers (1976) is one example; another is shown on figure 4. Some of the information can be obtained from aerial photographs; new quad-centered color (false infrared) photos now becoming available will greatly increase the number of landslides that can be identified and classified. However, much of the data must be obtained in the field by closely spaced traverses and detailed geologic mapping.

A complex, detailed landslide inventory has the following advantages:

1. It provides a better understanding of the different landslide processes operating in an area.

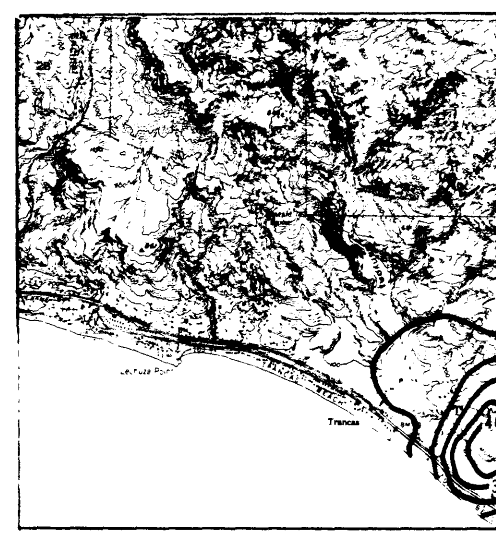


Group I - Isopleths on landslide deposits that are characterized by movement parallel to topographic slope (rockfalls and topples, soilfalls and topples, debris slides, and soil slips).



Group II - Isopleths on landslide deposits that are characterized by rotational sliding movement, concave upward with respect to topographic slope (bedrock slump and soil slump; includes most unclassified landslides).

Group III - Isopleths on landslide deposits that are characterized by translational sliding movement on pre-existing geologic surfaces such as bedding, faults, and joints (bedrock block glide, bedrock lateral spreading).



Group IV - Isopleths on landslide deposits that are characterized by movement as flowing slurries (debris flows).

0 1 MILE

0 1 KILOMETER

EXPLANATION OF FIGURES 1-4

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Isopleth, showing percentage of area covered by landslide deposits in each of an infinite number of overlapping 92-acre circles. That is, any given point identifies the center of a 92-acre circle, and the numerical value of the point, as read from the isopleth interval, identifies the percentage of that circle that is covered by landslide deposits (see Campbell, 1973).

Figure 4.--Maps showing different types of landslide processes near Los Angeles, California. The maps are derived by Campbell (1980) from an intermediate landslide inventory which shows the type of landslide, parent material, geometry of the landslide surface, transport mechanism, and characteristics of the scar and landslide deposits.

2. It provides a better foundation for preparing derivative maps of slope stability and hazards.

3. It can be used to regulate or prevent development in landslide areas and to provide guidance to engineers for coping with slope stability problems.

A complex detailed landslide inventory has the following disadvantages:

1. It is time consuming and expensive to prepare.

2. It requires extensive field study.

Terrain Analyses

The existing landscape is the aggregate product of various kinds of natural constructive and destructive processes. Examples of destructive processes include landslides, downslope creep, and movement by running water which, in eroding various kinds of earth materials, sculpt distinctive landforms. These landforms are recognized and appropriate units of the terrain mapped from small-scale (high-altitude) aerial photographs. Slope processes in each are determined by mapping in detail small areas representative of each unit. The result (fig. 5) is a map of terrain units each representing the kind of topography undergoing erosion by a common set of processes and each having an explanation that describes the kinds of landslides and their specific habitats within the unit.

Terrain analysis has the following advantages:

1. It is a method of regional reconnaissance study that treats the whole of the landscape and requires little preexistng data.

2. It distinguishes the kinds of landslides and the hazards they pose, and hence can specify the engineering effects and defenses for these hazards.

3. It includes small landslides that may be missed in landslide inventories.

4. It is both a form of landslide inventory and a zonation of landslide hazard.

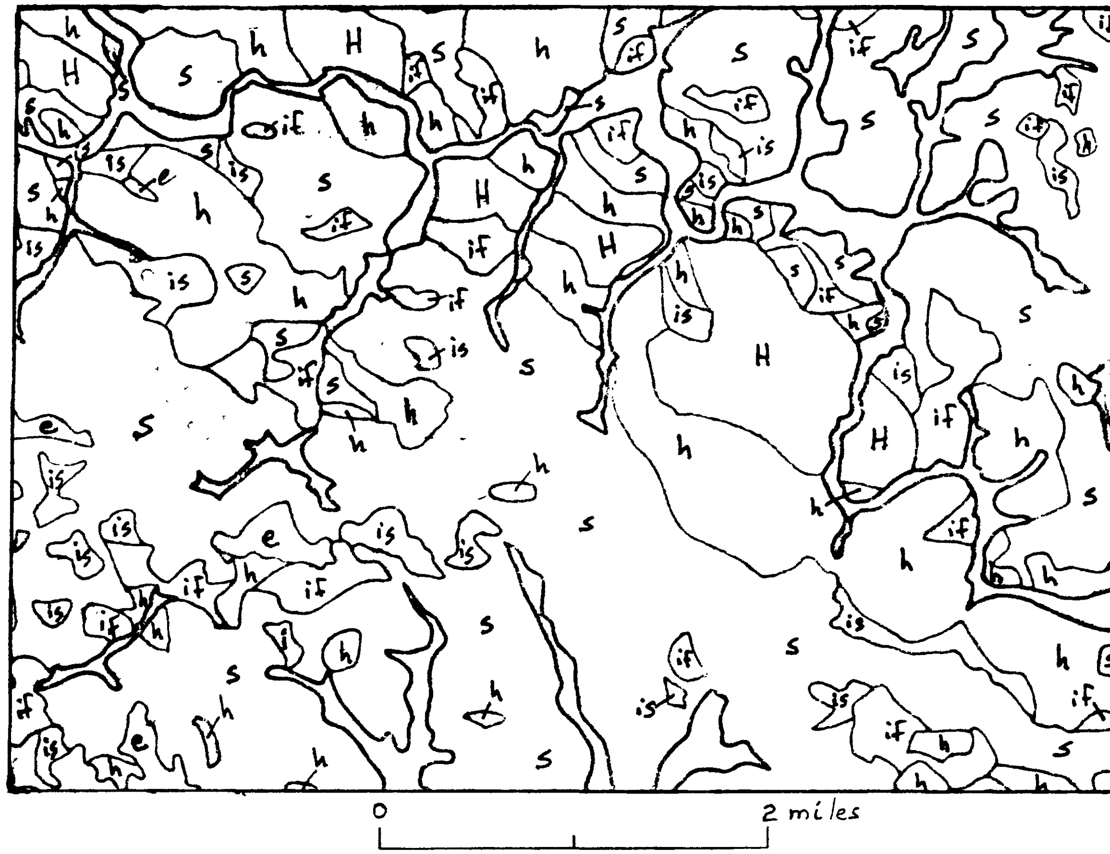
5. It stimulates consideration of the causes and triggers of landslides, and thus promotes a better understanding.

Terrain analysis has the following disadvantages:

1. It specifies the location of individual landslides only through a description of habitats (except for landslides so large that separate terrain units are needed), although the analysis can readily be combined with an inventory of larger landslides.

2. It requires that relics of past climatic or erosional regimes be distinguished (as do all historic approaches, including landslide inventories).

3. It requires further development before being generally applicable.



EXPLANATION OF PRINCIPAL MAP UNITS

Map Unit	Terrain form developed over Franciscan bedrock	Inferred types of shallow landslide 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 up to several meters thick.	Debris 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, though 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 up to several meters thick. 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.

Figure 5.--Terrain units for part of Marin County, California, and example of descriptions of landslide styles, habitats, and hazards (Ellen and others, in press).

4. It is potentially subjective and results may depend largely on the skill of the investigator.

Slope Stability Maps

Slope stabilty maps distinguish areas that have different potentials for landsliding. They predict where new landslides are likely to occur. Most slope stability maps indicate the relative stability of slopes rather than making absolute predictions of stability or instability.

A simple slope stability map can be made in areas where only one 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 geologic units are landslide-prone, and then using a geologic map to extrapolate this information and delineate the units, as shown on figure 6. Addition of other attributes, such as slope inclination and aspect, can improve the assessment of relative stability.

Areal distribution of landsliding in most 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 map 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 the likelihood of different types of landslide can be constructed. 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 7-10 are examples of relative slope stabilty maps prepared for various areas in the United States.

Using more detailed data, slope stabilty maps can be devised that predict the absolute (rather than the relative) stability of slopes, or the likely numbers and areal extent of failures over a given time period. The reliability of such predictions depends to a large extent on knowlege of the factors that control the initiation of landslides in the area.

Landslide Hazard Maps

Landslide hazard (zoning) maps are probably 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 the velocity and mass of the moving material. With this information it is possible to predict the 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 with regard to probability, requires extensive studies. A landslide project in the Appalachians calls for about 17 "optimum" hazard maps to be produced at a scale of 1:24,500 during the next 2 or 3 years. The specifications for such maps call for four categories of injury and damage modified by six probability factors.

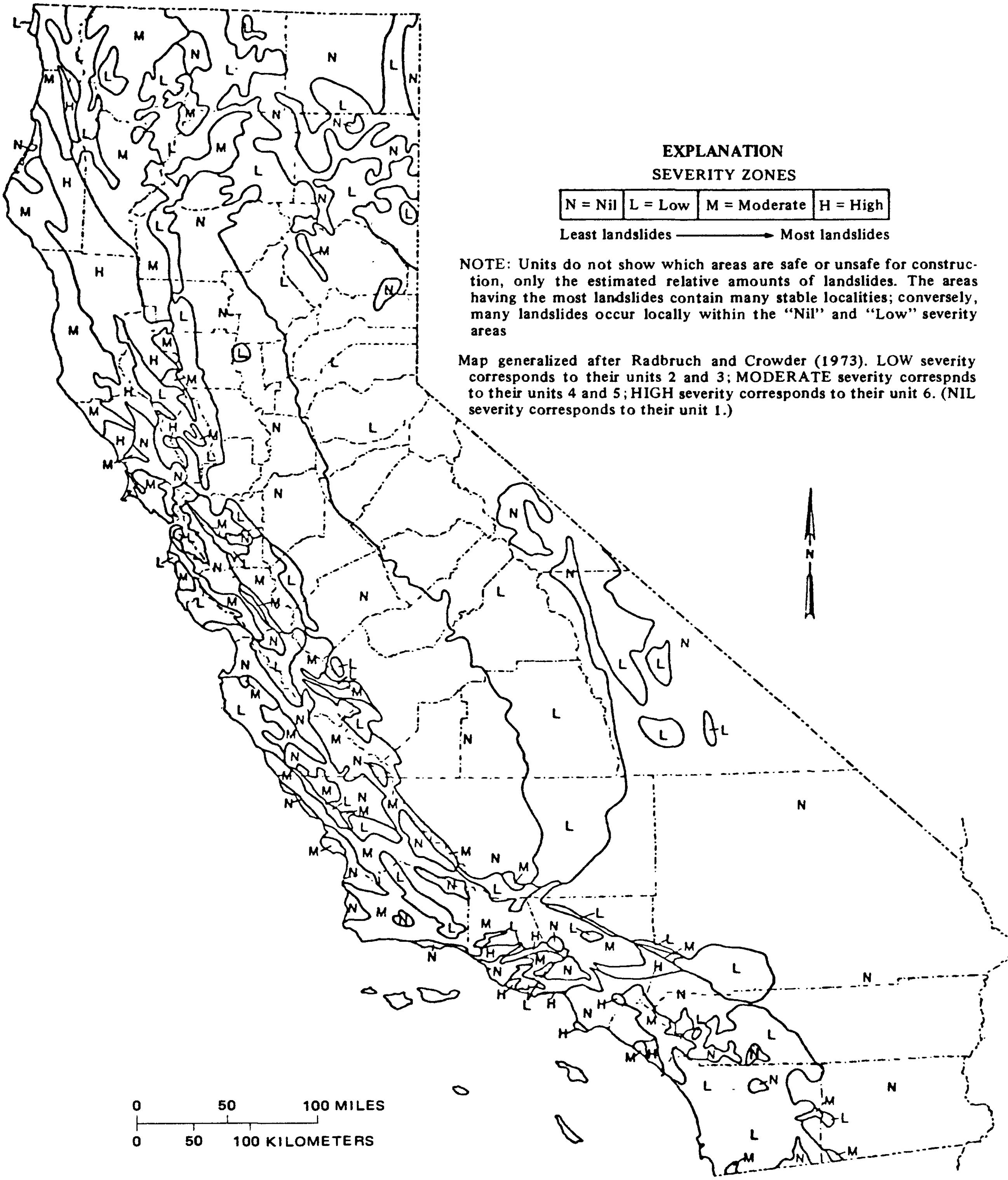


Figure 6.--A simple slope stability map of California. This map was originally published by Radbruch and Crowthers (1973) to show relative amounts of landslides. It was generalized and the severity zones were added by Alfors and others (1973).

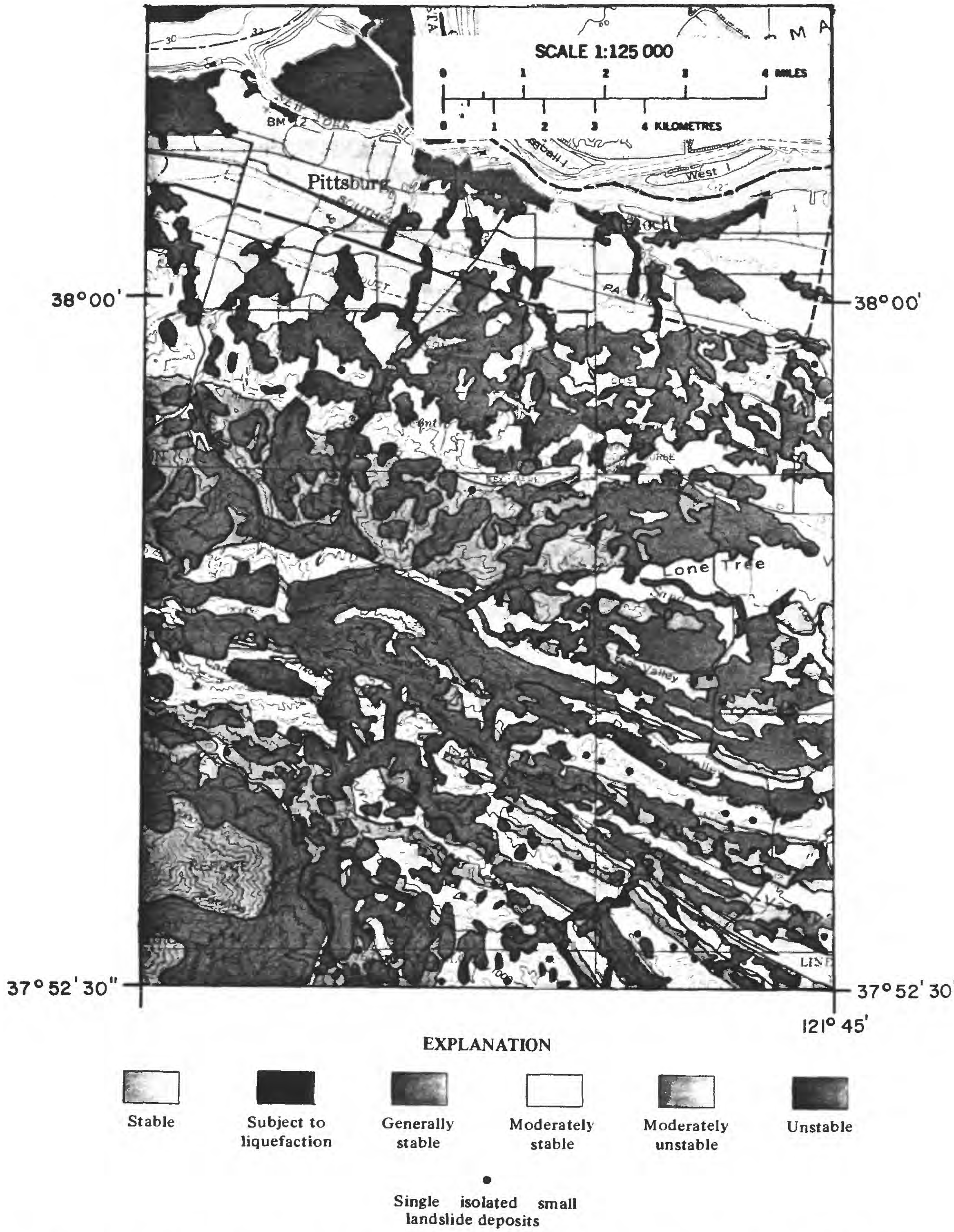
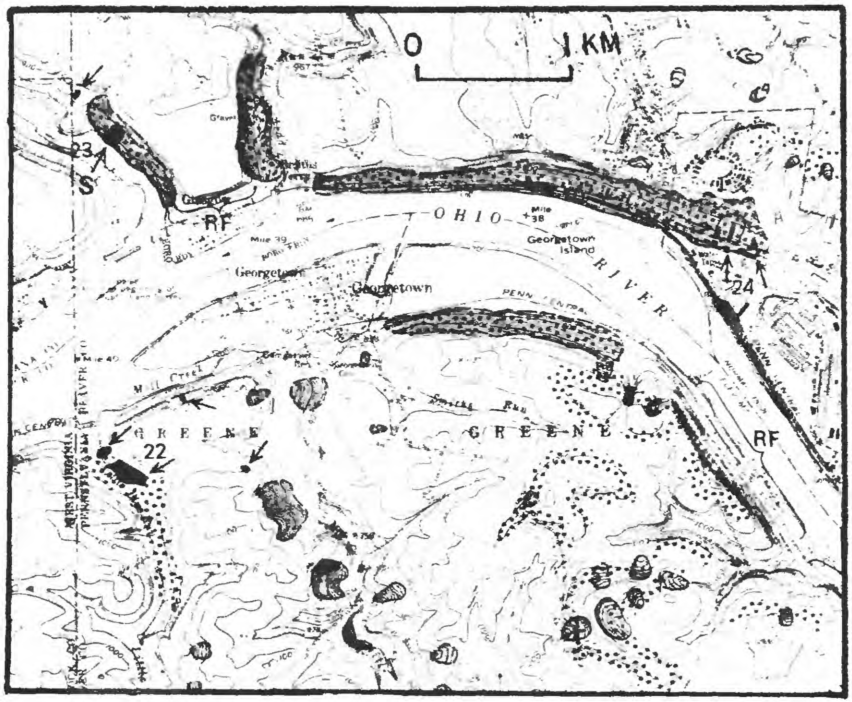


Figure 7.--Relative slope stability of part of northeastern Contra Costa County, California, near San Francisco. From Nilsen and others (1979, fig. 50). The distribution of landslides, the strength of materials inferred from a geologic map, and slope were the principal factors used in making this map. The map is part of a larger set of maps that show the slope stability of the entire San Francisco Bay region, about 20,000 km^2. The regional map is based on larger scale, more detailed information. The map and supporting information are appropriate for use by city, county, regional, state, and private planners and decisionmakers for land-use planning and development.



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. Number refers to locality discussed in table 1

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

NOTE: This map and accompanying text contain data usable in the identification of areas involving slope stability, but these cannot be used as a substitute for detailed geological engineering investigations of specific sites.

Figure 8.--Landslides in Beaver County, Pennsylvania. From Pomeroy (1979). Areas most susceptible to landsliding, stippled on the map, are places where weathered shales, mudstones and underclays occur on steep slopes.

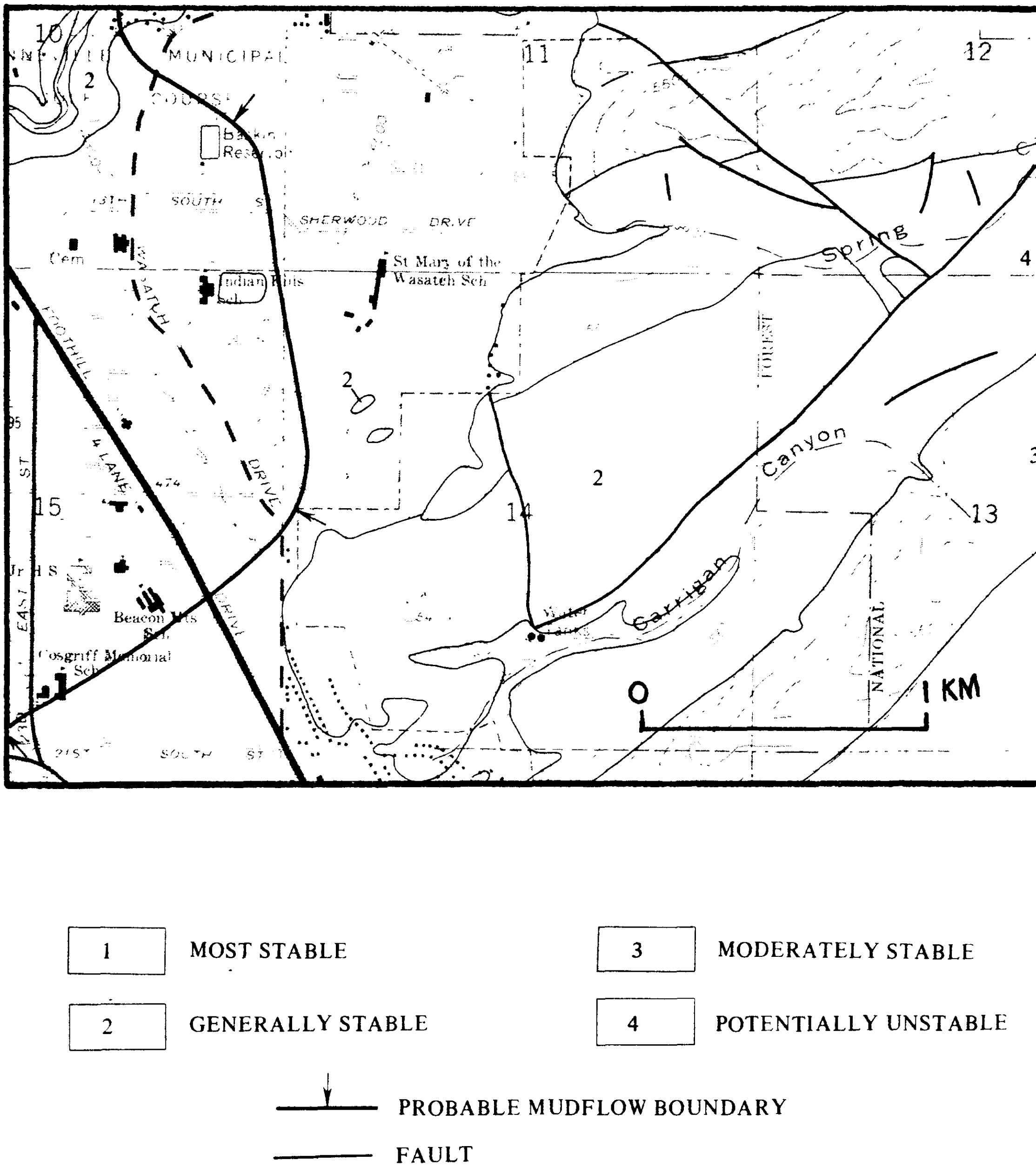
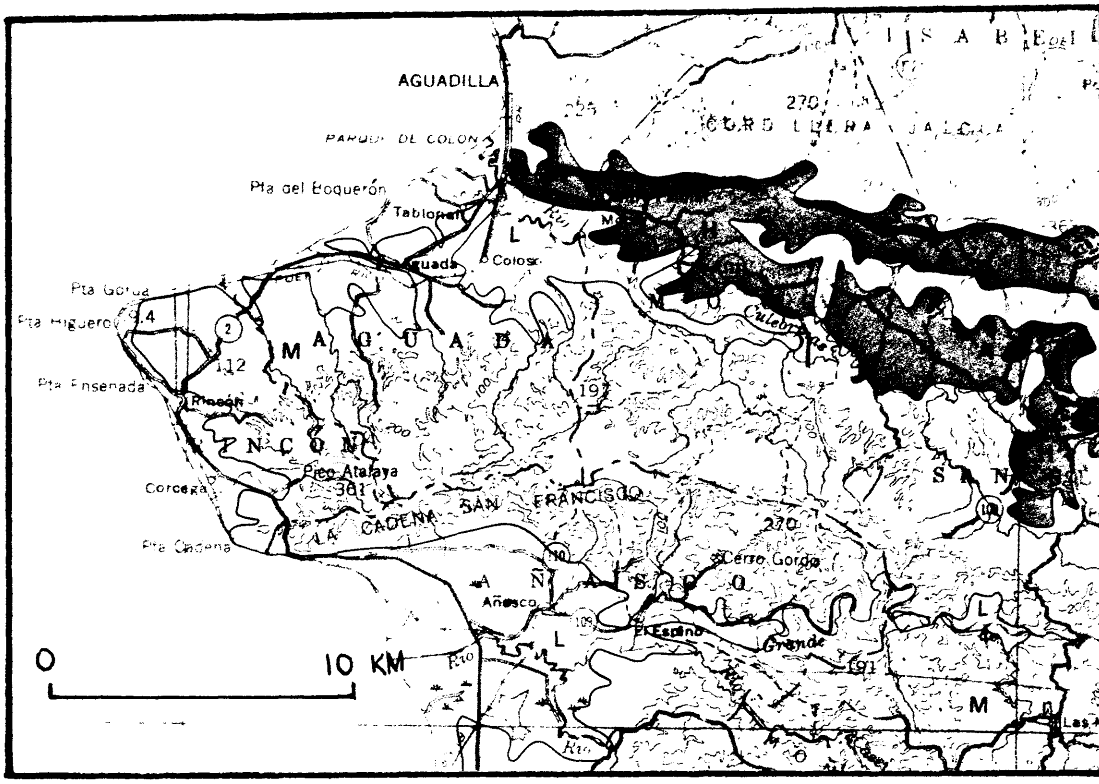


Figure 9.--Landslide susceptibility near Salt Lake, Utah. From Van Horn (1972). "The features considered in preparing the relative slope stability map include: steepness of slope, type of rock or surficial deposit, and locations of bedrock faults, springs, and former marshes. These features were evaluated according to their relation to known landslide deposits and talus accumulatons, to the observed deterioration of buildings in the area, and, in small part, to plausible predictions."



EXPLANATION

(black)	Area of highest susceptibility to landsliding—Includes active or recent slides; only landsliding having a diameter greater than 250 meters can be shown at this map scale
(stippled)	Area of high susceptibility to landsliding
M	Area of moderate susceptibility to landsliding
L	Area of low susceptibility to landsliding
———	Contact—Approximately located

Figure 10.--Landslide susceptibility in Puerto Rico. From Monroe (1979). Distribution of landslide deposits, landslide-prone rock formations and slope were the principal factors considered in making the map.

Landslide hazard maps have the following advantages:

1. They provide planners, engineers, and the general public with detailed guidance as to the extent and degree of the landslide hazard as well as the probability of landslide occurrences.

2. They can be used to regulate development.

3. They provide guidance in locating and designing structures.

Hazard maps have the following disadvantages:

1. They are very costly in time and money to gather and evaluate the data. Maximum investigation of the area is involved using borings, trenching, extensive laboratory work, chronology techniques, and production of extensive historic records.

2. Probability factors are not generally understood by users.

3. Large areas must be studied by experienced personnel.

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, combined with knowledge of the hazard itself. For example, the risk of landslide damage to a toolshed is far less than the risk of damage to a hospital by the same landslide. Table 1 provides the general framework for determining different levels of landslide risk as applied to regions, counties, and specific sites. Techniques for preparing risk maps have not been significantly developed in the United States, largely because landslide problems are commonly solved by more direct means.

Land-use Maps

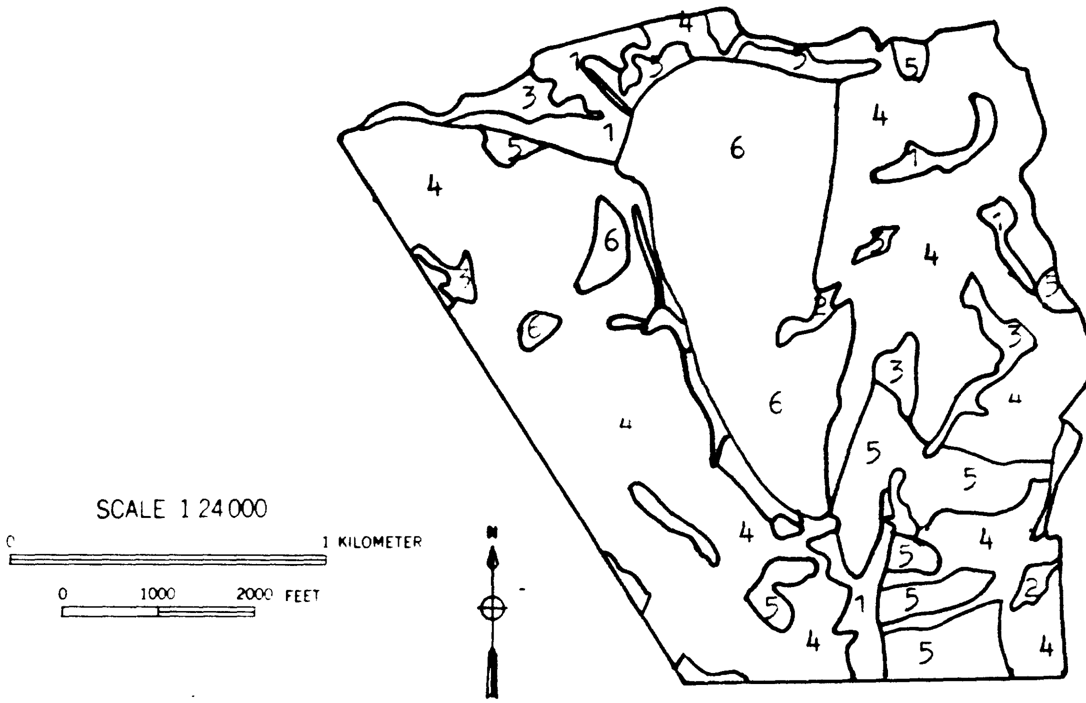
Land-use planning maps usually incorporate many additional attributes in addition to landslides and other geologic hazards. A few specialized maps of land-use with respect to landslide hazards have been made in California; figures 11 and 12 are representative. Guidelines for low-risk land-use are usually provided by geologists in consultation with engineers and planners, based on their experience and the experience of others as reported in the scientific literature.

Map Scales

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 1:27,000,000 when problems in the entire conterminous United States needs to be shown at page size. Most geologists plot landslides 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 also been published at 1:62,500, 1:63,360, 1:100,000 and 1:125,000 scales, again to take advantage of

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.
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 stabilily of bedrock, should be obtained for preparing the comprehensive plan, as deemed necessary by 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 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.

Table 1.--Levels of landslide risk. From Nilsen and others (1979, p. 59).



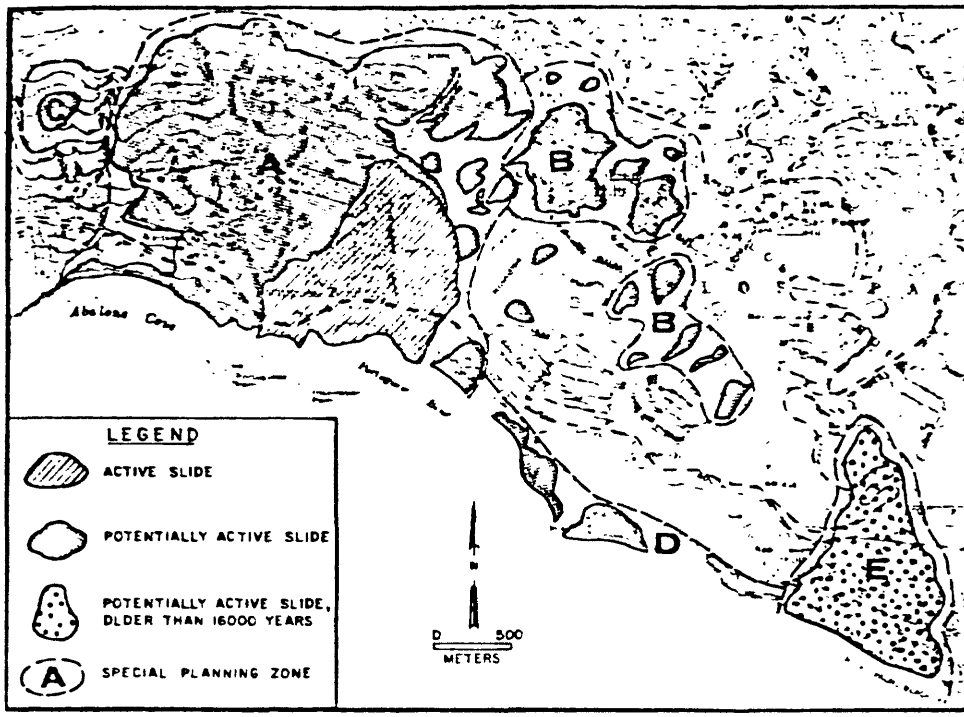
RELATIVE STABILITY	MAP AREA	GEOLOGIC CONDITIONS	RECOMMENDED LAND USE Houses	Roads Public	Roads Private
Most Stable	1	Flat or gentle slopes; subject to local shallow sliding, soil creep and settlement	Yes	Yes	Yes
	2	Gentle to moderately steep slopes in older stabilized landslide debris; subject to settlement, soil creep and shallow and deep landsliding	Yes*	Yes*	Yes*
	3	Steep to very steep slopes; subject to mass-wasting by soil creep, slumping and rock fall activities	Yes*	Yes*	Yes*
	4	Gentle to very steep slopes in unstable material subject to landsliding, slumping and soil creep	No*	No*	No*
	5	Moving shallow (<10 feet) landslide	No*	No*	No*
Least Stable	6	Moving deep landslide, subject to rapid failure by slumping or rock fall	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 11.--Potential ground movement and recommended land use for the Congress Springs area, Santa Clara County, California. 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). See figure 3 for the landslide inventory of the same area.



Slide area	Slide designation	Risk level	Former or existing land use	Suitable land use
A	Portuguese Bend	High	Subdivision	Open space; low intensity recreational use
B	Rolling Hills cluster	Medium-high	Subdivision and open	Open space, horse corrals, hiking trails
C	Rancho Palos Verdes	Medium-high	Open	Greenbelt scenic corridor
D	Setback from sea cliff	Moderate	Subdivision	Beach uses; view corridor
E	South Shores	Low	Subdivision on part	Mobile-type development and golf course

Figure 12.--A post-disaster planning map in the Palos Verdes area near Los Angeles indicating how recognition of the varying degrees of landslide risk before the area was subdivided could have greatly reduced landslide damage. From Leighton (1976, p. 56).

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 involved.

Present State of Techniques

In the United States, landslide inventory mapping is of two general types. General maps at scales of 1:500,000 or smaller have been produced for a few states, such as the one for Colorado, figure 13. Such maps identify areas where slides have been readily identified from aerial photos or geomorphic evidence shown on topographic maps. These maps serve an excellent purpose by indicating the extent of the landslide problem. Extensive large-scale mapping of landslides has been done primarily in California, Colorado, and the Appalachians. In contrast, large-scale maps have also been made in small areas around urban developments where slope stability problems exist. The large-scale maps vary greatly in the data shown. Some show landslide areas without distinguishing between active and older slides. Others make this distinction, and some include interpretations as to susceptibliity. Most of the maps in California and Colorado are of this type.

The most detailed inventory maps now being produced classify landslides as to type, activity, susceptibility, and cover for both natural and manmade slopes and include the conditions involved in landsliding. This intermediate landslide inventory mapping is mainly in the Appalachians. Very few detailed inventory maps have been produced.. The few that have been made are for limited areas such as the Pacific Palisades in California. Landslide hazard maps just beginning to be undertaken, and at this point data have been accumulated in only a few areas to permit such mapping.

STRATEGIES FOR MAPPING MAN-INDUCED LANDSLIDES

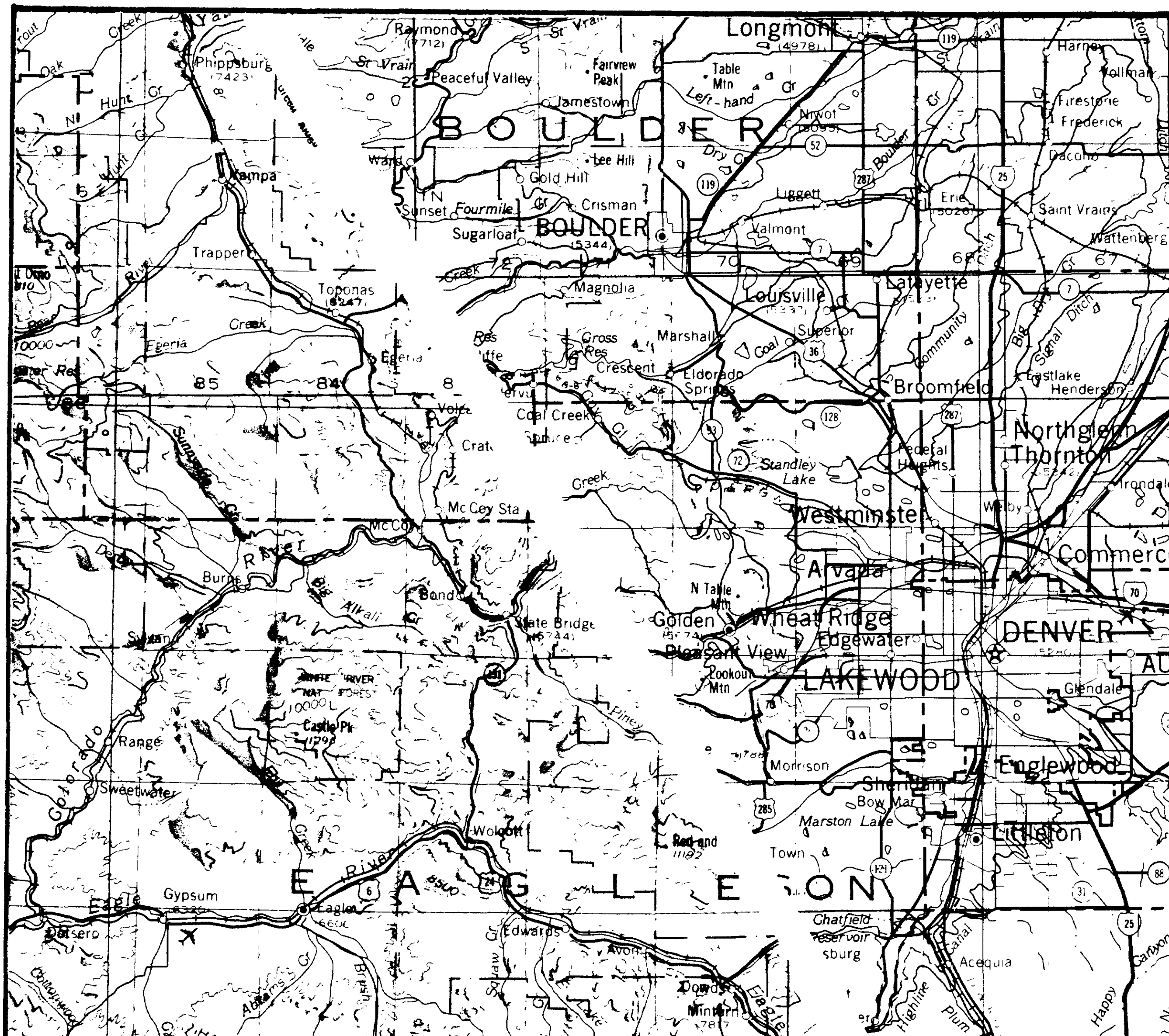
Landslide movement in many places is triggered by activities of man such as grading for roads or buildings, cutting trees, or additing water to slopes from septic tanks, leaky pipes or swimming pools, or lawns sprinklers. Predicting the effects of such activities on the stability of slopes is different from predicting landslides on natural slopes as discussed above. However, some methods of prediction follow those used in analyzing the stability of natural slopes.

Simple Inventories

The location of man-induced landslides can be predicted in a general way from simple landslide inventory maps because most landslide deposits, if not active, are commonly metastable. Hence, the landslide deposits mapped by simple inventory methods may indicate areas that are likely to fail when stability is decreased by grading or the addition of water. More detailed landslide inventory maps refine this information by describing the types of landslide deposit that are particularly susceptible to modification by man.

Slope Stability Maps

Detailed slope stability maps may be useful in predicting the occurrence of man-induced landslides, but less detailed or simple slope stability maps may



SCALE 1:500 000

0 10 MILES

0 10 KILOMETRES

Figure 13.--Part of the landslide inventory for Colorado. From Colton and others (1976).

be misleading for this use because different types of landslides are influenced to a greater or lesser degree by particular manmade modifications. For example, very deep-seated landslides are commonly less influenced by minor grading than are shallower landslides. Slope stability maps describing the absolute stability of sloping ground should be highly accurate predictors of man-induced landslides because the effect of man-induced decrease in stability can be measured directly against the stability before modification.

Studies of the Underlying Material

Because different materials respond differently to the removal of support by grading, the character of the slope-forming materials can be used to estimate the areal occurrence of failures on cut slopes. This approach requires detailed data on the physical properties of the underlying materials of the area, as well as an understanding the of factors responsible for failure. This method has been used to predict the stability of cut slopes in the Washoe City area of Nevada and in San Mateo County, California. The data on the underlying materials will soon be available for the entire San Francisco Bay region.

STRATEGIES FOR SUBMARINE LANDSLIDES

Literature Survey

During the last 15 years, increasing awareness of and concern about submarine landslides has resulted in shipborne surveys for the purpose of finding, locating, and determining the areal extent of these features. Results published have attempted to explain their origin and age, their susceptibility to further movement, and their impact on offshore operations for energy development, mining and communications. The published literature describes landslides principally in the Gulf of Mexico, the Atlantic Ocean (U.S. Atlantic Margin, Brazilian Margin, slope off South Africa, northwest Africa) and sections of the Mediterranean Sea. 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 and volume of materials affected, and causative factors.

The second step in such inventory is the re-examination of seismic reflection profiles and possibly sonographs, especially those that are in the proprietary domain. Although uncertainties exist in the interpretation of ground failure zones from seismic profile data, it is 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 little studied margins (except for the southern California borderland, the Mississippi River delta area, and the Gulf of Alaska) should receive early attention.

In 1929, turbidity currents associated with a major submarine landslide on Grand Banks, thought to have been triggered by an earthquake, severed many submarine telephone cables. Since then, other cable breaks and, in areas of petroleum exploration, several pipeline breaks have been documented, although the data are proprietary. The third step in the inventory should unearth these data as most relevant to historical documentation of submarine soil movement.

Collection of Off-Shore Data

A next-level of approach to submarine landslide mapping incorporates data of a more complex nature. By utilizing existing data and collecting new data where necessary, maps of offshore areas could be prepared showing 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 methods and by high-resolution geophysical (acoustic) profiling.

An overlay on these maps could give a qualitative assessment of the principal triggering forces for submarine landslides. For example, storm-wave forces, whose cyclic pressure variations perturbate certain weak sediments and elevate their pore pressures, could be mapped by conventional methods of refraction and bottom-energy dissipation to indicate where their forces might be concentrated. The cyclic loads imposed on the seafloor by earthquake accelerations could also be mapped by extrapolating ground motion parameters from historical earthquake data onto sensitive seafloor areas. Tectonic tilting, which might trigger submarine slides, could be approximated by indicating areas of active faulting or diapiric uplift. Other environmental processes which might contribute to undercompaction, such as areas of active biologic generation of methane and areas of rapid sedimentation, could also be entered on the overlay.

Hazard Mapping

To determine existing or potential failure features, quantitative studies could be made to identify the possible failure mechanisms involved and the probability of occurrence of each. The results could be used for interpreting the probability of failure on a regional basis using data supplemented, if necessary, with measurements on a regional basis. Quantitative information required for specific features include:

Forces--Rates of sediment accumulation and scour, rates and magnitudes of local tectonic deformation, and character and magnitude of cyclic stresses induced by storm-wave and earthquake loading.

In situ conditions--Detailed character and distribution of materials within and adjacent to existing or potential failure features, including the state of consolidation of each material, pore-pressure magnitudes and distribution throughout materials within and adjacent to the failure features, and the variation during dynamic loading.

Engineering properties--Stress-deformation and strength parameters of the materials, their geometric variation, and their variation with the magnitudes and duration of dynamic deformations induced by waves and earthquakes.

PRIORITIES FOR MAPPING LANDSLIDES

TERRESTRIAL AREAS

Population Centers with Rapid Urban Growth

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

Two data sets have been used to locate areas of greatest hazard: the Rand McNally (1979) statistics on population increases during the 1970-1979 period, and the Bureau of Census (1980) report on municipalities reporting the greatest net increase in land area from 1970-1979. The Rand McNally statistics indicate that cities in the western states may be the most vulnerable (fig. 14), as well as a few cities in New England and the Gulf Coast. If increase in urban land area is considered, a somewhat different set of priorities emerges, as shown on figure 15. A more detailed study of the various regions is needed before these results can be properly interpreted.

Figure 14.--Landslide map of the United States showing rapidly expanding metropolitan areas located in areas of high landslide incidence or susceptibility (dots). The 25 metropolitan areas shown are from a total of 53 listed in the 1979 Rand McMally commercial atlas. The map of landslide incidence and susceptibility is reduced from the map by Radbruch-Hall and others (1976).

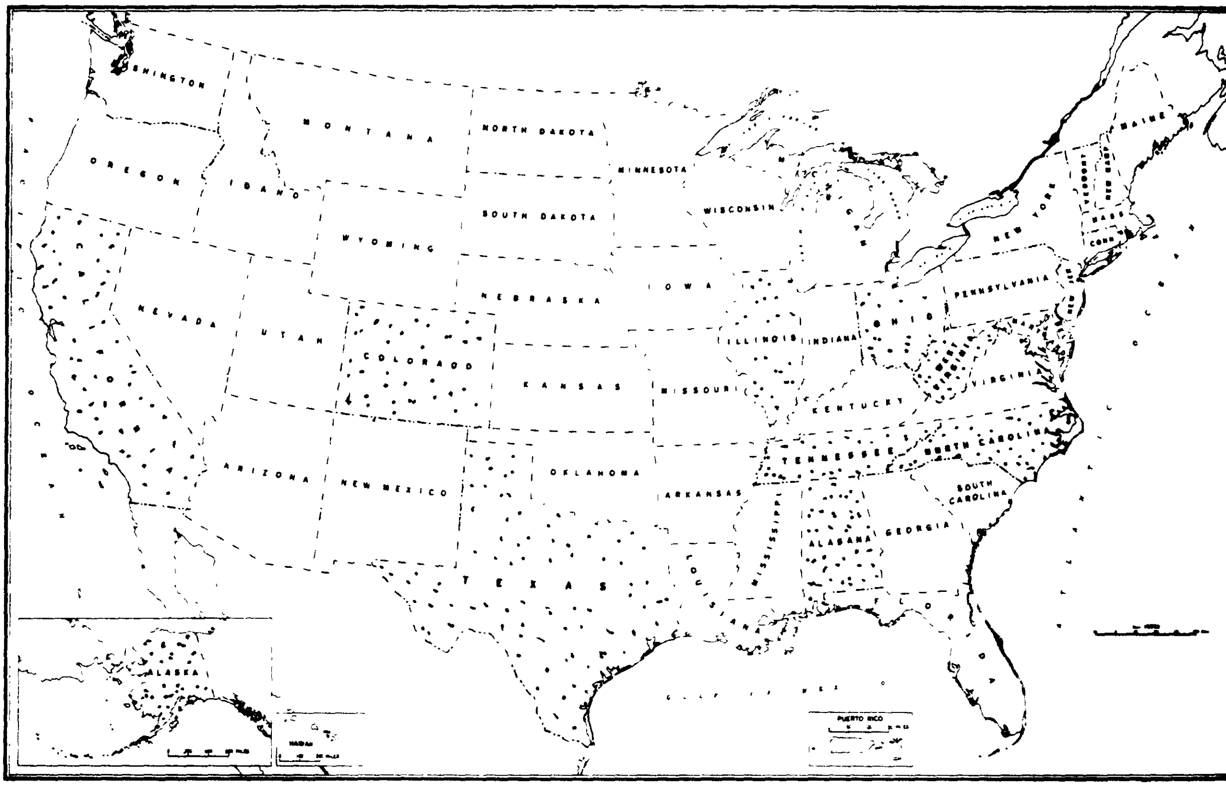


Figure 15.--Ten states having the largest number of municipalities expanding into landslide-prone areas. Data from the U.S. Bureau of Census, 1970-1979, and the landslide overview map of Radbruch-Hall and others (1976).

Regions 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 the mapping might be determined by the availability of data, by the severity of the local landslide problems, or by the density of populations. But the region as a whole should receive prompt attention. Intensive landslide studies have been carried out 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.

In the San Francisco Bay area, mapping could be extended from the U.S. Geological Survey core study. Inventories should be accompanied by detailed studies and by the preparation of intermediate maps. In the Puget Sound area mapping should be extended from the original USGS urban study area in response to the growth pattern. In the Los Angeles area the existing landslide inventory needs to be extended and several types of slope-stability studies initiated.

Appalachian Region

The Applachian region should be designated as second in priority. This region has a high incidence of landsliding and extensive areas of unstable slopes. However, except for a few major cities, the centers of population characteristic of the west coast are lacking. Some detailed studies have been completed in the Pittsburgh, Pa., area, and the inventory of landslides for all the plateau and much of the valley and ridge part of the region will be completed in 1981. Zonation maps are now being prepared on selected 7-1/2-minute quadrangles. This work should be expanded so that it can serve as an example for state geological surveys and consultants who can take over the work and complete it. Studies by the USGS should be expanded to cover more of the valley and ridge, the Piedmont, mountains of New England, and the anthracite area of Pennsylvania.

Rocky Mountain Region

The third priority should go to the Rocky Mountain region. Although the population is generally less dense, landslide incidence and susceptibility are very 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, 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, and the Rio Grand Valley (Albuquerque area).

In Alaska, areas near Anchorage, Fairbanks, and in southeast Alaska require study.

Studies should also be undertaken in areas of rapid urban growth near Dallas, Texas, Cincinnati/Columbus, Ohio, and Birmingham, Alabama. 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 also needed 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 can lead 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, which is great along parts of the Pacific Coast, should be mapped.

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, and southeastern Alaska.

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

Catastrophic Landslides

Landslides in China and Peru have killed tens to hundreds of thousands of people in a single event. Some research should be devoted to determining whether any of these cataclysmic landslides are possible in the United States and, if so, where they are likely to occur and how they can be prevented or avoided.

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, such as in harbors in a number of areas in Alaska and Puget Sound, Washington, they are not a direct threat to people. They are a hazard to offshore structures, however, and as such are responsible for annual losses of millions of dollars to oil-producing systems. Priorities for mapping submarine landslides will therefore depend upon the location of important offshore petroleum resources, and the risk of landslide 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 upper continental slope.

The Outer Continental Slope (OCS) of the Gulf of Mexico produces a substantial percentage of the total United States domestic oil and gas. The continental shelf and slope are 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 upwardly growing salt diapirs, and landslides are common. In this region, recent petroleum discoveries indicate a real need for landslide maps.

Southern California Coastal Area

Mapping of landslide hazards is required in areas where drilling platforms, pipeline facilities, and pumping stations are concentrated, particularly when they are to adjacent to seismically active faults and steep escarpments bordering uplifted areas.

Atlantic Coastal Area

Mapping of landslide hazards is required in areas of potential drilling and leasing particularly in the Baltimore Canyon area and off the New Jersey coast.

Alaska

Mapping of landslide hazards is needed in the Gulf of Alaska and Beaufort Sea. Both are regions of potential petroleum development.

Other areas

Other areas to be mapped as development proceeds, include the Washington, Oregon, and northern California regions.

Threats to Critical Facilities

Mapping of landslide hazards is important in areas of telephone cables and other important submarine communication systems. Military or other government facilities will require mapping of landslide hazards in areas where important submarine facilities are situated. Areas of major shipping channels, too, should be mapped.

Threats of Catastrophic Landslides

Mapping will be required in areas where tsumanis could be generated by major submarine landslides adjacent to populated coastal regions. Mapping will also be required in regions where other potentially catastrophic landslides may occur such as in areas adjacent to major active offshore faults, salt diapirs, and rapid sediment loading.

TASKS IN MAKING LANDSLIDE STUDIES

In making landslide studies the following one or more tasks need to be taken:

- Make an inventory of landslides
- Analyze the terrain
- Determine the age of the landslides
- Develop methods to delineate hazardous zones
- Study methods of controlling landslides
- Work out the causes of landslides

- Make zonation maps
- Establish guidelines for zoning
- Identify areas where catastrophic landslides may occur
- Examine secondary effects of large landslides
- Analyze and map landslide risk
- Make cost-benefit studies
- Investigate large landslides that have caused damage
- Establish a computer program to store and manipulate landslide data

In the following pages each one of these tasks is described in some detail. Many tasks in the section on process and prediction are also needed to make regional landslide studies and, for brevity, are not repeated here.

LANDSLIDE INVENTORIES

- Inventory existing landslide maps and review present types and techniques of landslide mapping in the U. S. and abroad to improve methodology.
- Develop a classification scheme for distinguishing and mapping scarps of landslides by photointerpretation. Most landslide mapping presently deals with only 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.
- Develop 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.
- Develop classifications of landslides for airphoto interpretation, including deposits, scars, and scarps. Develop criteria for recognition of landslide activity. Publish airphoto stereopair examples of landslide types from different parts of the United States and the world. Determine which kinds of photography (color, black and white, infrared, low sun angle), what scales, and what moisture conditions are most appropriate for recognizing and mapping landslides at various scales. Develop recommendations for stereoscope use--models, types, etc. Determine whether computer enhancement or processing of airphotos can aid photointerpretation of landslides.
- Determine the usefulness of radar and other remote sensing techniques for mapping landslides in areas with extensive tree cover.
- Make recommendations for topographic mapping that more accurately reflect landslide morphology.
- Develop techniques for use of orthophotoquads in mapping landslide processes.

- Devise methods for testing the accuracy, completeness, and usefulness of landslide inventory maps and apply to a variety of representative studies.
- Prepare landslide inventory maps of designated areas where they have not already been completed. This process will require ordering and acquiring aerial photographs if they are not already available.
- Apply landslide inventory, susceptibility, and zonation techniques developed in other countries to selected areas of the United States showing landslide deposits, scarps, and scars.
- In selected areas, find examples to provide control on method. Include information on type of landslides, whether simple or multiple, one type or a combination of types; kind of materials; geologic age; and information on rate of movement.

TERRAIN ANALYSES

- Develop 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 are not amenable to photointerpretation: disintegrating soil slips, rockfalls, snow avalanches, ice avalanches, mudflows, toppling, and creep.
- Expand the analyses to include larger, deep-seated landslides as well as shallow surficial slides.
- Make maps from high-altitude airphotos that show areas of probable landslide concentration by extrapolating from erosion and landform patterns that can be seen on these photos, where individual landslides cannot.

TIMING AND AGE OF LANDSLIDES

The steps for this category are mostly in the section on process and prediction. In addition;

- Do research on possible regional relationships between periods of increased landslide movement and geomorphic episodes as recorded in soil stratigraphies, alluvial histories, and landform evolution, in order to establish an efficient means of determining landslide ages, periods of increased landslide movement, and the interrelation between the landscape and the landslide hazard.

ZONATION STUDIES

Methods Used

- Develop methods for the rational planning of landslide-hazard zonation programs, at various scales and for various purposes. Develop 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 describe most effectively the character and degree of hazard; provide adequate data for derivative maps; provide information for engineers, planners and decision makers. Include development of symbols for use on landslide-hazard zonation maps.

Causes

- Make studies and prepare detailed maps showing the causes of landslide at large scales in selected areas as demonstration projects to define geologic and other parameters that become critical under certain specific conditions. These data can be extrapolated to other areas with similar conditions for landslide hazard, they can improve understanding of the causal relations for zonation, and they can be used to check the accuracy, completeness, and usefulness of less detailed studies of larger areas, such as inventory maps.

- Make detailed geologic maps showing bedrock distribution and character of materials and their geologic structure, and make detailed geologic maps showing the distribution and character of surficial materials. These two types of basic maps are essential to further studies of landslides.

Studies in Selected Areas

- Carry out preliminary studies of landslide hazard zonation in priority regions at a regional scale using available methods and data.

- Carry out state-of-the-art landslide hazard zonation for selected areas where especially high risk, exceptional data bases, or other opportunities or needs warrant it.

- Begin longer term hazard zonation of priority regions at appropriate scales to help define, and then to use, results of needed improvements in methods and areal information about the causes of landslides.

- Carry out hazard zonation by various methods and at different scales in the same areas in order to compare techniques and results.

Guidelines Required

- Establish guidelines for landslide hazard zonation to provide consistency in zoning throughout the nation, guidance for contractors, and to serve as a teaching tool.

- Address the differences in guideline requirements as determined by intended use, kind of landslide and terrain, and available or obtainable information on landslide distribution and causes.

- Establish guidelines for describing hazardous zones in probabilistic terms.

Studies of Catastrophic Events

- Identify landslides that might devastate whole towns or industries that lie in their path.

- Identify areas possibly subject to single catastrophic landslides (such as major rockfall avalanches and submarine delta-front slides) using present knowledge of their causes and locations.

- Using improved methods as they become available, progressively refine the assessment of areas and places that may be vulnerable to catastrophic landslides.

- Carry out field studies of areas at potentially high risk from catastrophic landslides to permit further refinement of the hazard zonation.

Zones of Secondary Risk

- 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 risk assessed.

Benefit-Cost Analysis

Much research is needed on the benefits derived from landslide maps as compared to other costs. Tasks involved in this research include:

- Determine the monetary benefits of landslide hazard zonation to society through its impact on land-use and zoning, construction practice, the financial and insurance sectors, and the decisions of individuals, businesses, and government and compare these with the costs of obtaining the information and implementing a loss-reduction program.

- Devise and apply methods of testing the accuracy, completeness, and usefulness of various kinds of landslide hazard zonations.

Risk Analysis and Mapping

- 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 studies and from landslide hazards 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 a variety of representative studies.

Post-landslide Investigations

- Organize teams to obtain the ephemeral data available soon after large or important landslide events.

- Determine causes and effects of landslides by investigating changes in specific geologic and geotechnical data as near failure time as possible.

- Organize similar teams with different support requirements to quickly investigate large or important submarine failures.

- Determine through continuing research the most critical data needed from fast-response teams for maximum understanding of landslide processes.

Computer Processing

The use of computers to store and manipulate data and produce graphic representation of that manipulation is essential to modern scientific investigations. Benefits include savings in time, money, and diversion of personnel. Computer techniques can be applied to landslide zonation studies in the following ways:

- Establish a standard set of digitization formats and resolutions tailored to the needs of computer storage and 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.

- Develop methods of concurrent map compilation and digitization from aerial photographs and other sources using state-of-the-art photogrammetric techniques and equipment.

- Conduct research on the application of computer methods, remotely sensed digital data, and photogrammetric methods to geologic mapping generally and landslide investigations specifically.

- Prepare for computer analysis the data on landslide size, type, age, geologic formation, type of shearing, jointing, fracturing, water conditions, slope, and other data that can be derived from maps, and develop methods for data storage, manipulation and combination of factors, and graphic production by computer equipment.

INFORMATION AND MATERIALS NEEDED FOR MAPPING LANDSLIDES

AERIAL PHOTOGRAPHS AND OTHER REMOTE SENSING DATA

Aerial photographs are the single most important tool for mapping landslides. They provide a way of recognizing, classifying, and mapping landslides over large areas in a short time. Stereoscopic viewing of the photographs provides a three-dimensional look at the terrain. The information on the photographs can be transferred either to a topographic map or an orthophotoquad.

Opinions vary as to the best scale of photography for mapping landslides, but 1:20,000 is commonly used. Photographs at 1:80,000 and 1:120,000 or even smaller scales may be useful in recognizing very large landslides; photographs at 1:10,000 scale or larger are used in small areas. Color and infrared photos and transparencies are helpful or even essential for recognizing some landslide features.

Several stages of photography are needed to establish the movement rate and activity of landslides. Older photographs are also essential in areas that are now urbanized because many of the features necessary for recognizing landslides are destroyed when houses or other structures are built on them.

Aerial photography is available for the entire United States, but the photographs are distributed among many Federal, State, and local agencies. A considerable effort would be needed just to determine where photographs could be obtained for a national landslide mapping program, although the U.S. Geological Survey's National Cartographic Information Center (NCIC) is establishing computer retrieval information about a large amount of photography held by governmental and private organizations. Even more effort would be needed to purchase, organize, and catalog the photographs. Some new photography, particularly color and infrared, would be needed.

Other remote sensing techniques, including multispectral scanner data, satellite and shuttle imagery, side-scan SONAR, and Side Looking Aperture Radar (SLAR), are also useful for a variety of landslide studies.

MAPS OF VARIOUS KINDS

Topographic and Bathymetric Maps

A U.S. Geological Survey quadrangle (1:24,000 or 1:25,000 scale) provides a convenient base on which to plot landslide data. The information may be transferred by the interpreter from photographs directly to the map or by using conventional photogrammetric instruments, such as a PG-2 plotter. Scale-stable and transparent material, such as Mylar, is needed for reproduction and printing of the landslide data. Topographic/bathymetric hybrid mapping is available from National Mapping Division at scales from 1:24,000 to 1:250,000 for use in the nearshore area. Bathymetric maps are also required in the offshore areas for use in mapping landslide hazards. These maps can be obtained from the National Ocean Survey (NOSA).

For large areas, such as counties and states, the landslide data are commonly reduced, generalized, and reproduced at scales ranging from 1:50,000 to 1:500,000. Topographic maps at 1:24,000 or 1:25,000 scale for all areas of the United States except Alaska will be available by 1985; figure 16 shows the current status of the mapping. Base maps at 1:50,000 to 1:125,000 scales are available for many areas, but some new base maps would be needed.

Digital Base Maps

The USGS National Mapping Division (NMD) has embarked on a program to develop a Digital Cartographic Data Base (DCDB) compatible with the 1:24,000 and 1:25,000 scale base maps. The DCDB consists of Digital Elevation Model (DEM) terrain data and Digital Line Graph (DLG) planimetric data and will, by the early 1990's, include all areas of the United States.

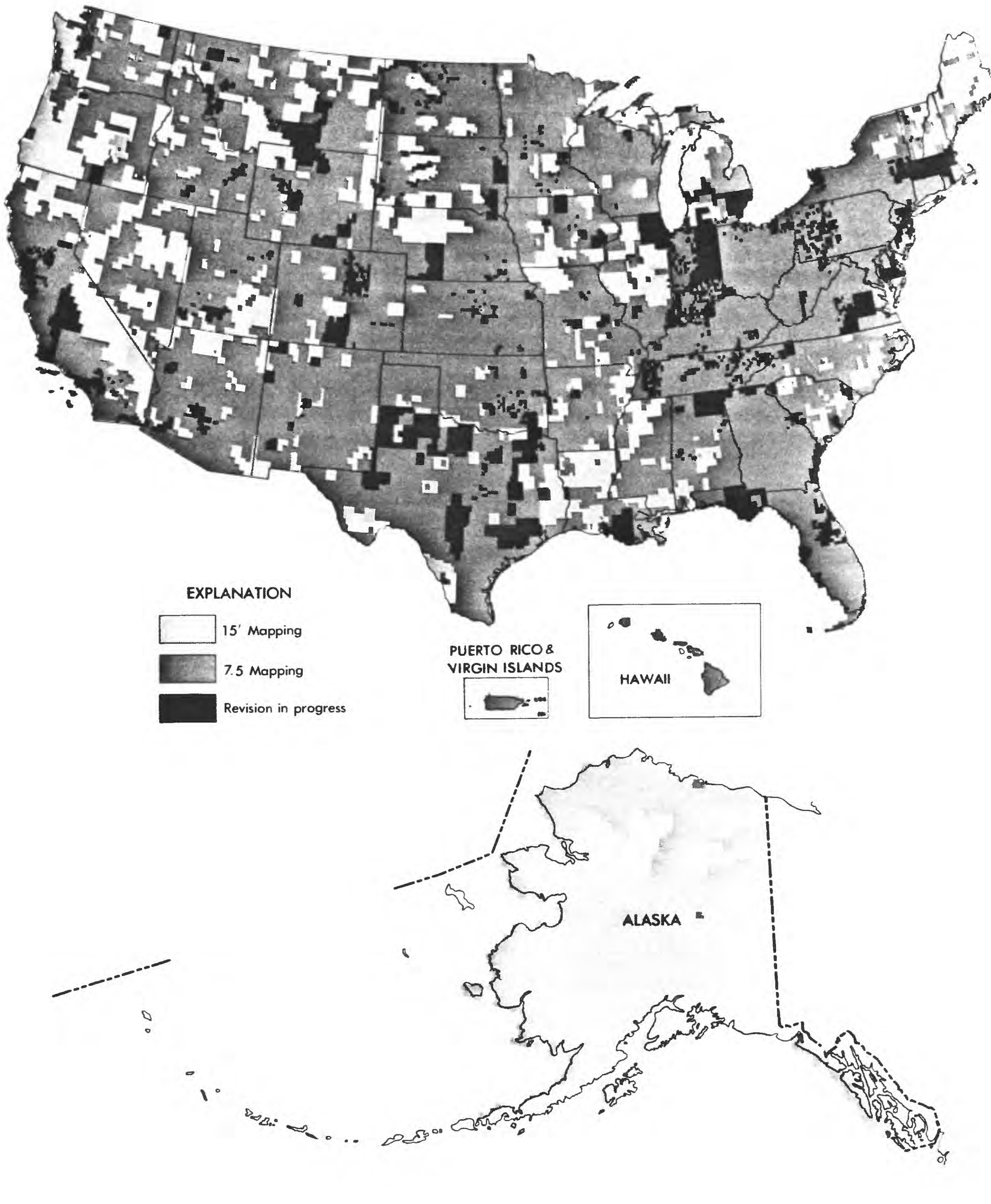


Figure 16.--Status of standard topographic mapping and revision. From U.S. Geological Survey Yearbook for fiscal year 1980.

Photographically interpreted landslide information may be collected using recently developed analytical stereoplotter technology and merged digitally with the base data from the DCDB. Automated cartographic and reproduction techniques are available for publication of the resulting landslide data.

Smaller scale products may be derived, either manually or digitally, from the resulting automated landslide data. Filtering techniques required to thin the resulting high-density data at the smaller scale are presently being developed by the NMD.

Orthophotoquads

Orthophotoquads are photographic images that match Geological Survey quadrangle format and scale. The distortion common to aerial photographs has been eliminated. Orthophotoquads provide a quick and inexpensive base on which to rapidly transfer landslide area from aerial photographs. Orthophotoquads are available as paper prints and as prints on stable-based material.

Figure 17 indicates that orthophotoquads are available or will soon be available for about 30 percent of the conterminous United States. Additional orthophotoquads will probably be needed in some areas selected for landslide hazard studies.

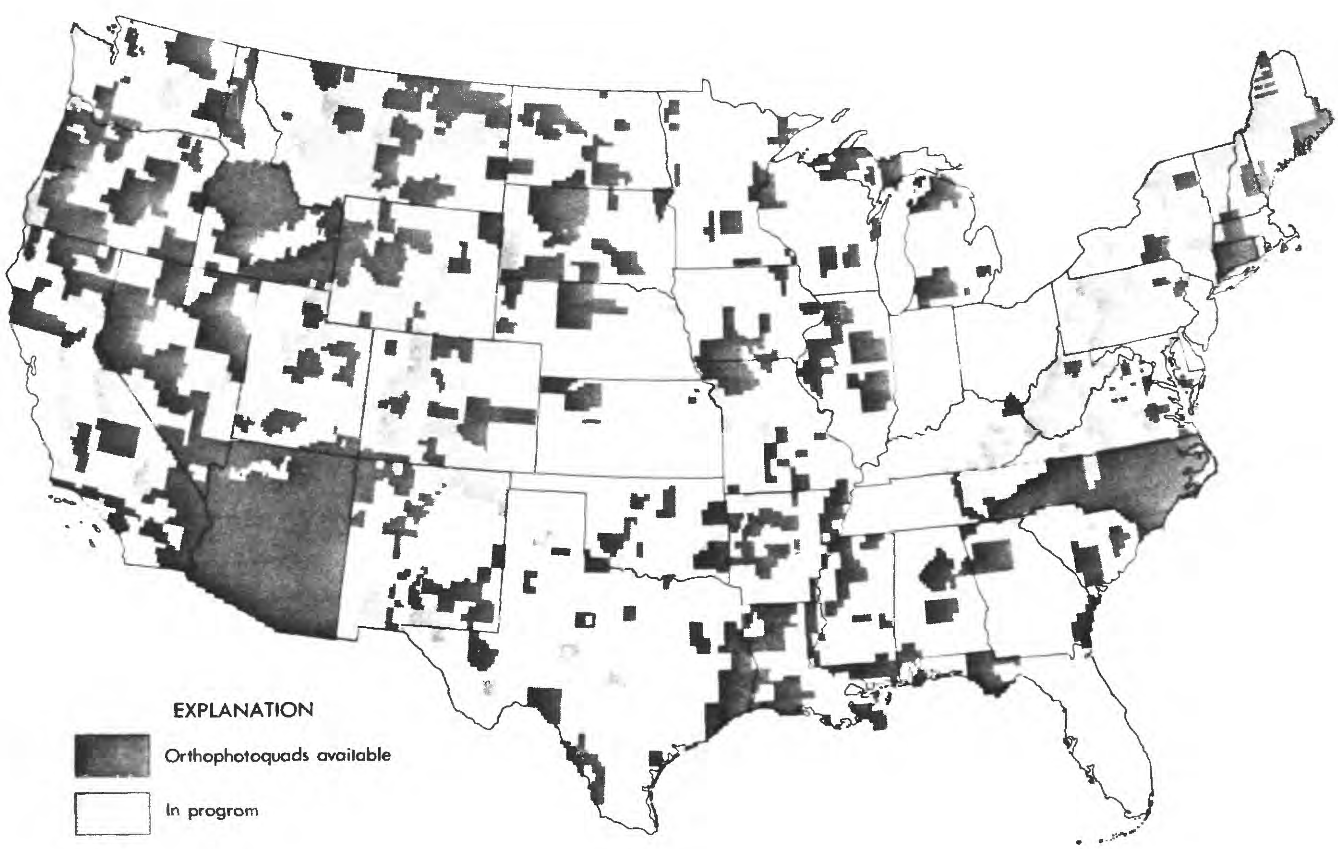


Figure 17.--Status of orthophotoquad production. From U.S. Geological Survey Yearbook for fiscal year 1980.

Geologic Maps

Geologic maps on a topographic base may provide, directly and indirectly, much information relative to slope stability, geometry of planes of weakness, relation between planes of weakness and slope, and the location of fault zones and other areas where the rocks may be brecciated and weak. In combination with a landslide inventory, the geologic map can be used to prepare a derivative map, such as figure 18, which shows geologic units susceptible to landsliding in an area near San Francisco.

Geologic maps less than 35 years old are available for about one-third of the United States. Almost none of these maps have all of the geologic information that would be needed to prepare regional slope stability maps. Among the most critical data missing are orientation and spacing of rock fractures, character and depth of weathering, and character and depth of colluvium.

Maps indicating the thickness and kinds of weathered rock products are needed in and around landslide areas in order to mitigate the landslide problem and help predict landslides.

Slope Maps

Steepness of slope may determine whether or not a geologic unit will fail by landsliding. Some geologic units, such as homogeneous and unweathered granite, are stable on very steep slopes whereas others, such as poorly consolidated surficial materials rich in clay, may fail on very gentle slopes. Slope maps, in combination with a landslide inventory, help to quantify this relationship.

Slope maps can be produced from U.S. Geological Survey contour maps by hand or by photomechanical processes. Figure 19 is an example of a combination of these methods for an area near San Francisco.

Slope maps can also be prepared by computer methods from digital elevation data. Tests are in progress to determine the relative costs and reliability of this method compared to slope maps prepared from contours.

Few areas of the United States have slope maps at scales sufficiently large to determine slope stability. The preparation of slope maps is apt to be an expensive and time consuming project, but the data would be of great value.

Vegetation Maps

The role of vegetation in the formation of landslides is not well understood. Some plant roots may hold the soil together and prevent it from moving downslope--the burning of this vegetation may lead to landsliding.

Vegetation maps are available for many areas of the United States but few studies have yet been made correlating vegetation with landslides.

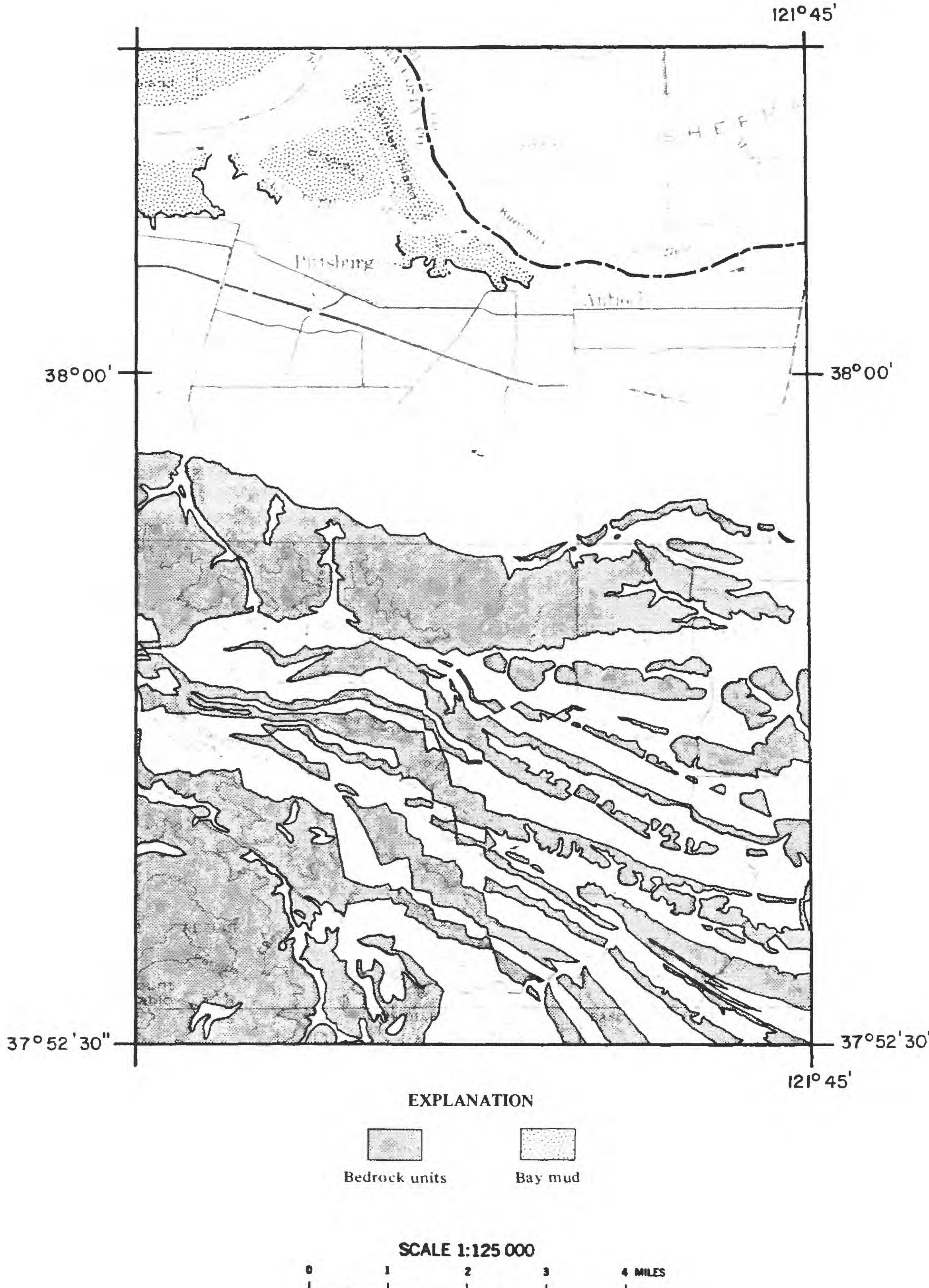
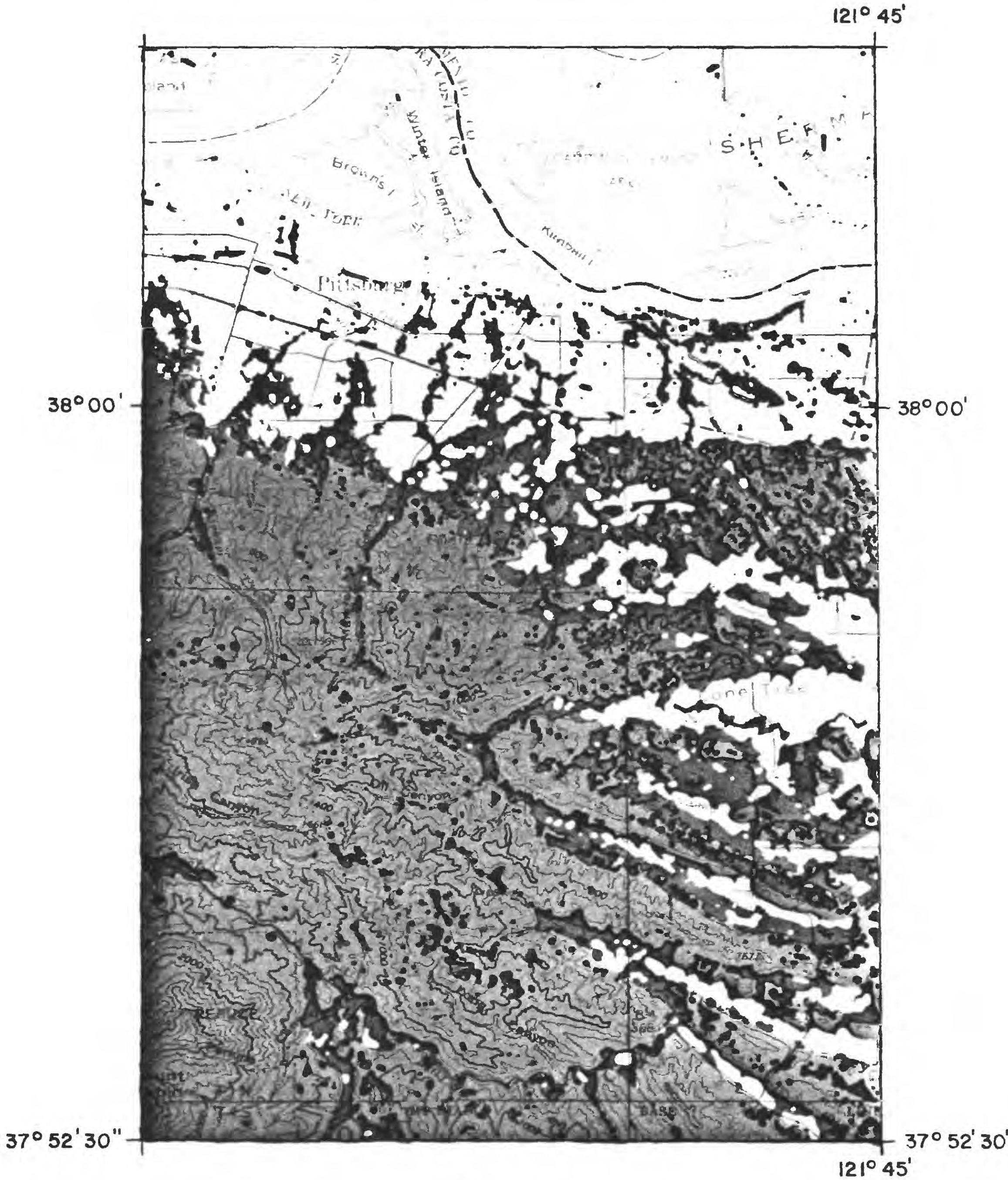


Figure 18.--Geologic units susceptible to landsliding in part of northeastern Contra Costa County, California, near San Francisco. From Nilsen and others (1979, fig. 48). Geology derived the the geologic map by Brabb, Sonneman, and Switzer (1971).



EXPLANATION

Percent of slope

0-5 5-15 >15

Figure 19.--Generalized slope map of part of northern Contra Costa and southern Solano Counties, California. From Nilsen and others (1979, fig. 44).

Land-Use Maps and Socioeconomic Data

In order to relate the existence of landslide hazards to the potential risks involved, an indication of the present and planned activities of man is required. Land-use maps and related socioeconomic data are valuable for such analyses.

Land-use maps at a scale of 1:250,000 are available for large portions of the United States through the National Mapping Division. This series of maps has been compiled from a variety of sources and will be updated and revised on a continuing basis. Such revision will help provide the chronological history of urban growth patterns needed to forecast potential risks.

Socioeconomic data are available from the Bureau of Census and other Department of Commerce agencies to assist further in risk analysis.

CLIMATIC DATA

The amount and variation of rainfall may determine whether or not landsliding will occur. Also, hourly and daily temperature means and extremes may influence landsliding. Long-term temperature and precipitation records are usually available only for major metropolitan areas so that extrapolation is required for the more isolated areas subject to landslides.

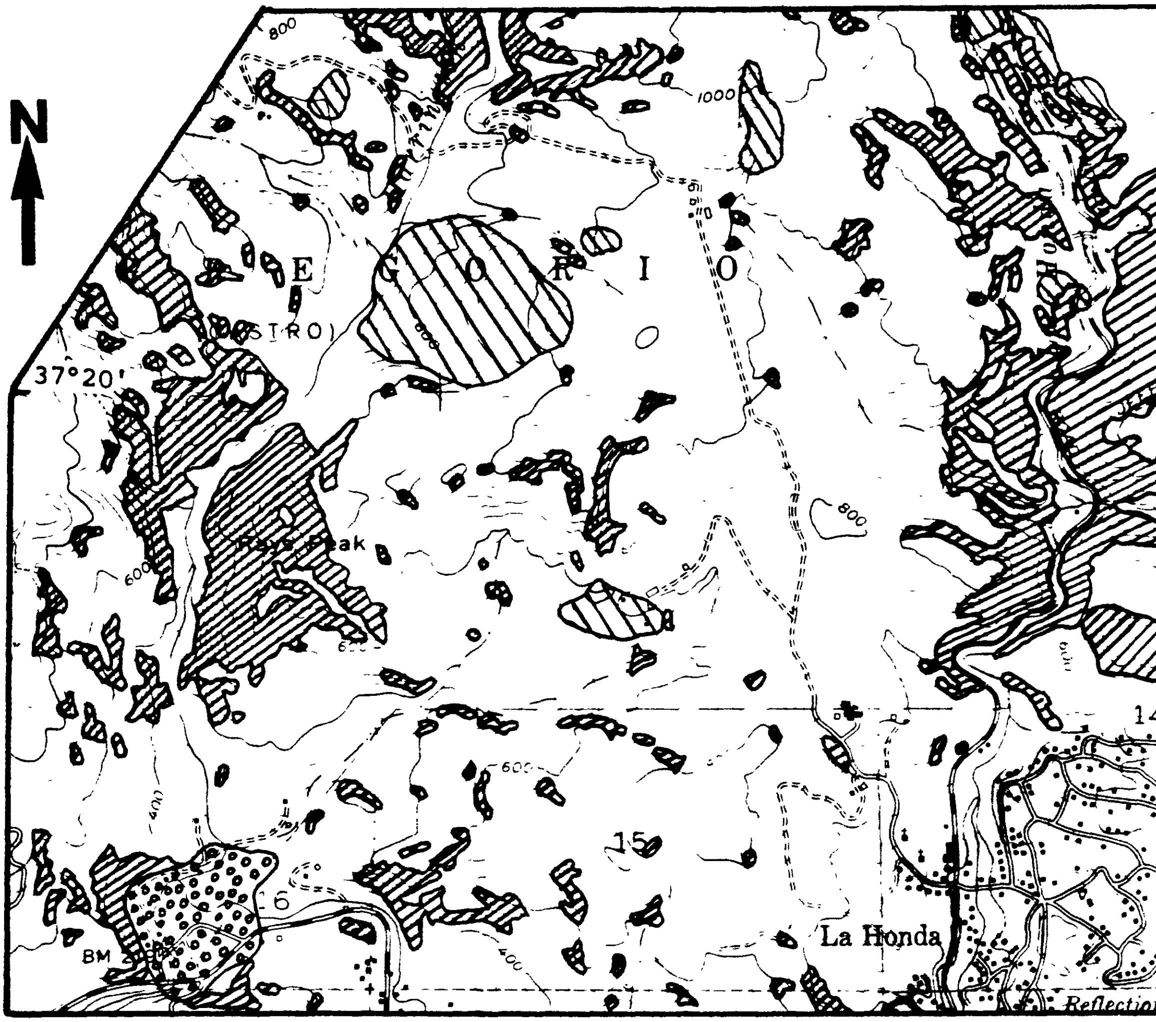
Knowledge of long-term climatic fluctuation may be essential in determining whether landslides in a particular region occured during a different climatic regime and, therefore, would not be likely to occur under present climatic conditions. The Geological Survey's Program in Climate Research is expected to provide at least some of these data.

DATA ON SUBSURFACE WATER

Changes in ground-water conditions caused by the infiltration of large quantities of rainwater into the ground may trigger many (if not most) landslides. Knowledge of the distribution of subsurface water is important in understanding the mechanism of ground failure and in planning measures to stabilize landslides. Data are needed to show the distribution of this water and the variation in level of the water in response to rainfall, seasonal fluctuations, and year-to-year changes.

SEISMIC DATA

Earthquakes, like rainfall, can also trigger landslides. In earthquake regions, the location of the earthquake-generating sources in relation to the potential landslide area may be important together with a consideration of ground response and earthquake frequency. When combined with geologic data, landslide occurrence, and slope data, predictive maps can be prepared showing which areas are likely to fail by landsliding during earthquakes (fig. 20). Vibrations, such as those caused by heavy trucks, heavy machinery, rocket blasts, quarry blasts, and large aircraft could also trigger landslides. A map showing the location of such sources of vibrations may be helpful in understanding landslide distribution and future potential movement.



CONTOUR INTERVAL 40 FEET

0 — 1 KILOMETER

0 — 1 MILE

ZONES OF HIGH SUSCEPTIBILITY TO SEISMICALLY INDUCED LANDSLIDES

SYMBOL	POSSIBLE LANDSLIDE TYPES	MAPPING CRITERIA
(dense diagonal hatching)	SOIL AVALANCHES; FALLS, SLUMPS, BLOCK SLIDES AND SHALLOW DISINTEGRATING SLIDES IN SOIL AND/OR ROCK	SLOPES STEEPER THAN 35°
(dots)	LATERAL SPREADS AND WET FLOWS	UNDERLAIN BY SATURATED SANDY AND SILTY HOLOCENE ALLUVIUM
(wide diagonal hatching)	SLUMPS AND BLOCK SLIDES IN SOIL AND/OR ROCK	ACTIVE AND RECENTLY ACTIVE LANDSLIDES

Figure 20.--Areas that may fail by landsliding during earthquakes (from Keefer, Wieczorek and Harp, 1979). The La Honda area is about 50 km south of San Francisco.

MARINE GEOPHYSICAL DATA

Landslides in marine sediments can only be studied by marine geophysical surveys and by the study of samples. Needed geophysical data can be purchased if available or contracted for if unavailable. Samples of seafloor materials will have to be collected and analyzed.

CHRONOLOGY DATA

The rate of the landslide process is the most critical factor in a predictive map relating landslide hazard to potential land use. If the landslides formed long ago under climatic conditions that no longer prevail they are not likely to move again unless disturbed by man. If movement takes place only after a storm with 8 in. of cumulative rainfall, and if the long-term rainfall rate can be established, then the chances for landslide movement in the future can be determined.

The collection of historical records (such as newspapers, state, county, or city records) in order to determine the age and recurrence of landsliding is necessary in order to prepare predictive maps which would indicate the landslide hazard or degree of risk. The study of ancient stable landslide deposits which formed under climatic conditions that no longer prevail can be facilitated by C^{14} dating and palynology. The study of long-term climatic data from tree rings or other data may indicate when renewed movement might be anticipated. The study of various vintages of aerial photography for a given area may indicate approximately when landslide deposits formed. Age of episodes of landsliding for each area is very important and should be obtained whenever possible and put on maps.

In practice, the age and movement rate of landslides in a region is difficult to determine.

COMPUTERIZATION

The application of automated data capture, processing, and output techniques to the analysis of landslide hazards is necessary in order to analyze the large volume of information available about landslide processes. The information needed in digital form includes data on geographic and elevation locations, climate, seismic sources, socioeconomics, land use, resource inventory, geology, and hydrology. Timely use of these data bases requires considerable investment in both hardware and software. Present hardware ranges from small stand-alone systems designed for a single purpose to medium-size general purpose systems providing access to several users and to large-scale multitask, multiuser systems. Real-time on-line access for modeling and decisionmaking is often necessary. Relatively high-quality graphic output will be required for production of reproducible quality maps depicting landslide hazards.

Considerable software exists for data basing activity and general analytical applications such as slope zone delineation, statistical analysis of data and overlay comparison of several categories, including creation of composite maps. However, a significant investment in software development will be required. Industry analysts project the typical cost of software required for scientific purposes at 1.5-2 times the cost of hardware. This ratio will undoubtedly increase as the price of hardware decreases and personnel costs rise. A nationwide shortage of trained software development talent exists and is expected to continue throughout the decade, further exacerbating the problem. Figures 21 and 22 are examples of computer generated maps that might not be attempted again if computer technology was not available to handle the large volume of data.

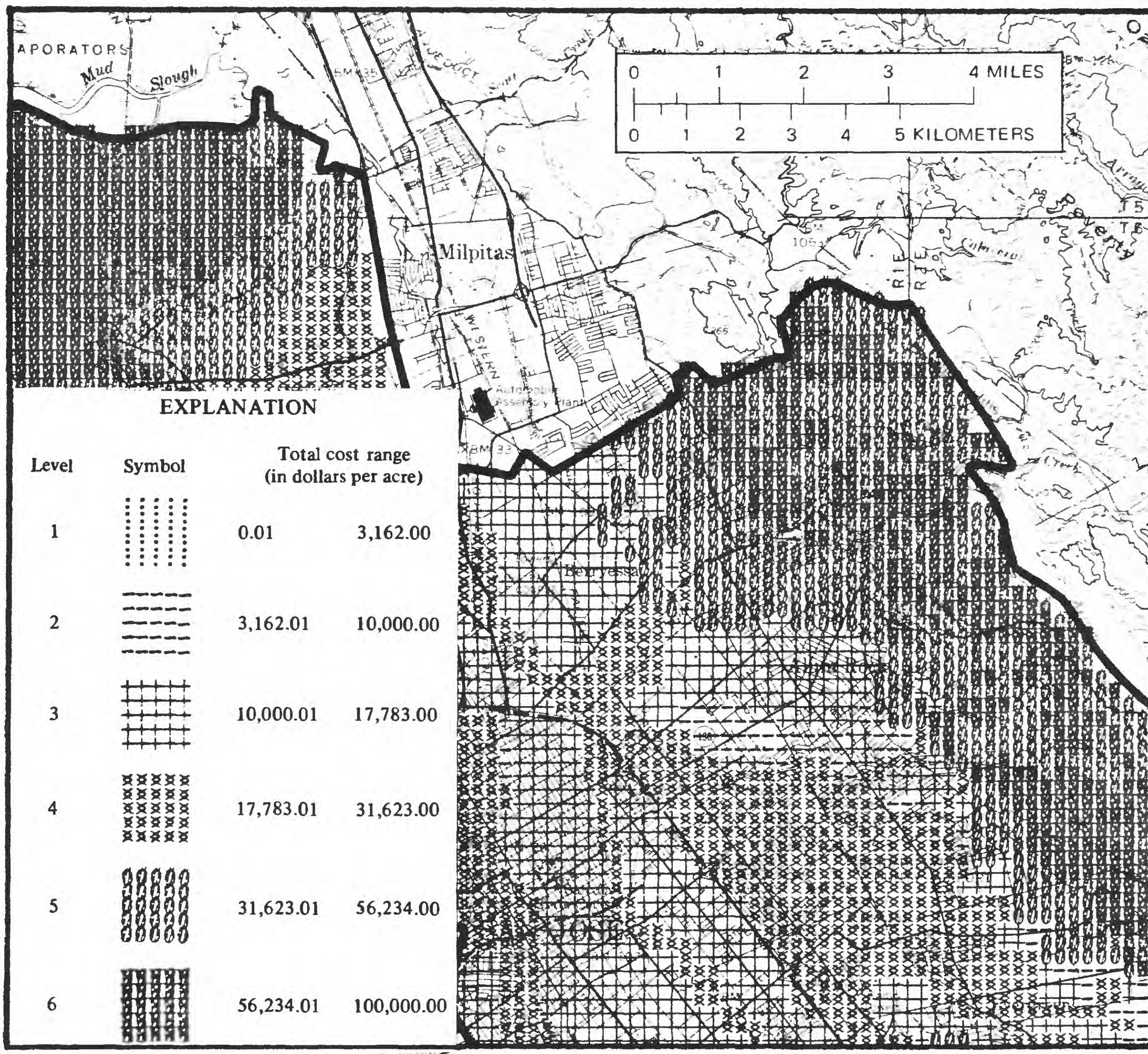


Figure 21.--Quantitative land capability map for single-family residentual use in the San Jose area, California. Estimates are made for additional expenses of land development, such as the cost of special engineering and construction practices necessary to prevent damage from slope failure and earthquakes, and loss of revenue if mineral resource areas are covered by housing or other developments. From Laird and others (1979, fig. 33).

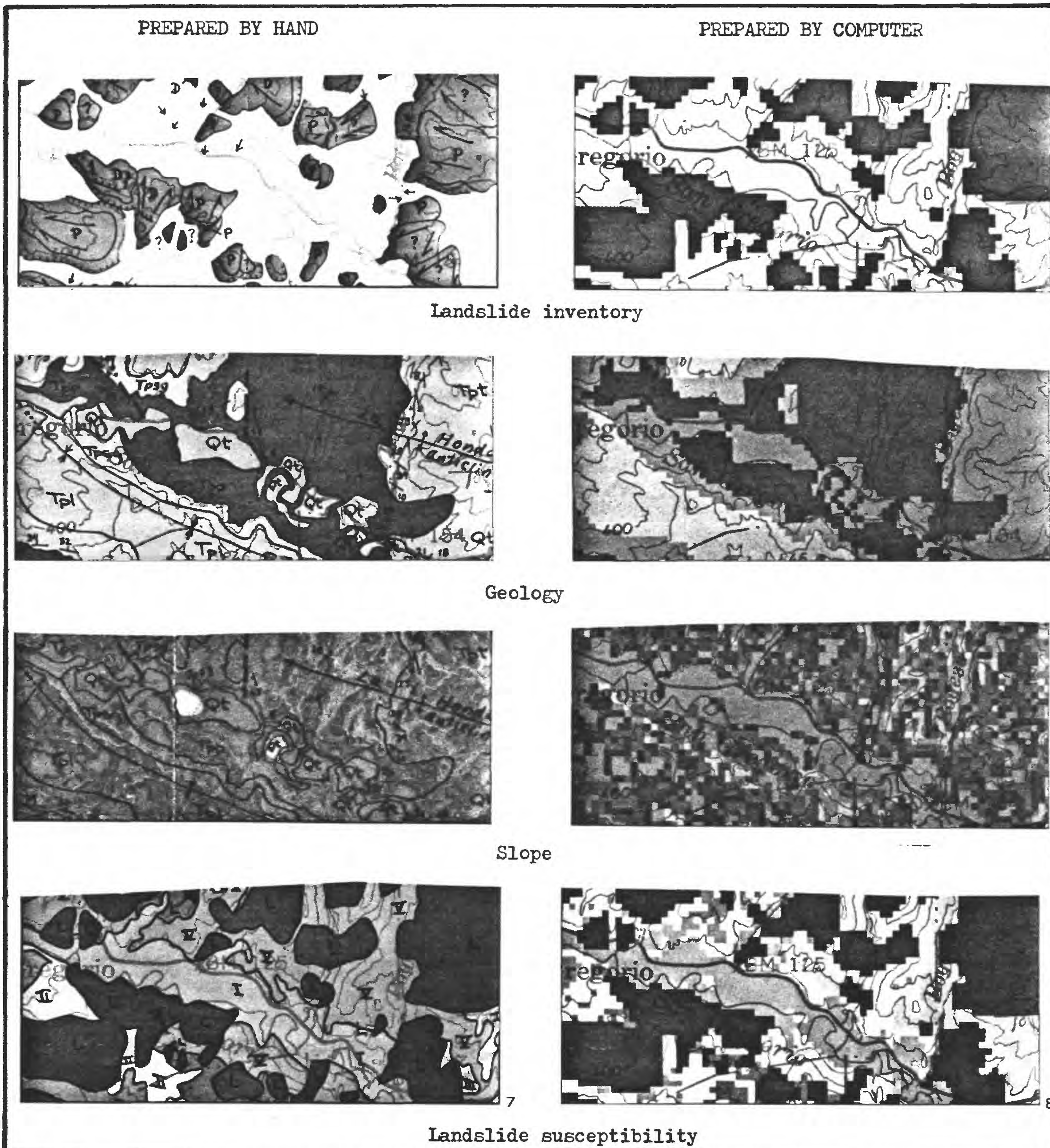


Figure 22.--Maps showing landslide inventory, geology, slope, and landslide susceptibility prepared by hand and computer methods (from Newman and Brabb, 1978). The area is about 50 km south of San Francisco, Scale 1:62,500.

PROCESSES AND PREDICTIONS

In order to prepare landslide hazard maps and to reduce the risk from landslides, the process must be sufficiently understood. Prediction about future movement of a landslide or a landslide-prone area requires knowledge of past and present geologic, geomorphic and hydrologic situations that have led to slope failures. Although the basic causes of slope instability are fairly well know from a number of case studies of specific failures, more research is needed to determine how these causes interact on a regional basis in a variety of geologic terrains.

With these basic ideas in mind, the goals of the landslide process and prediction segment of the Ground Failure and Construction Hazards Program 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 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 the capability to predict future failures.
- To develop new knowledge of slope failure processes and apply it to methods for avoiding, preventing, or mitigating damage.
- To present conclusions regarding hazardous slope processes in forms suitable to map and assess the degree of hazard.

STRATEGIES

The following steps are necessary to reach these goals:

1. Identify those slope processes that are hazardous. We are now able to identify the major slope processes that present hazards on land, even though we may not understand well their mechanisms. Offshore, the processes that affect seafloor stability--and hence the safety of oil-drilling platforms and pipelines--are less certain although our knowledge is developing 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 know some of the worst offenders. Others are widespread yet poorly recorded. A central body of information needs to be built up not only for the purpose of assigning priorities but also for obtaining a firm nationwide assessment of total annual costs in property and lives.

3. Identify gaps in our knowledge regarding:

a. Methods for recognizing unstable areas. Each type of landslide process occurs under particular environmnental conditions. Many landslides produce a particular landform or "signature" in the terrain. Some of the contributing environmental 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. An increased knowledge of processes will contribute to the 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 landslides. Prediction is the essential part of a hazard reduction program--and the most difficult. To be effective, the capability to predict 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 degrees of potential instability to mapped areas requires different procedures and has different meanings depending on whether the areas involved are 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 the necessary geotechnical information at the desired accuracy. The time of failure is similarly more and more uncertain as the prediction is limited in its time span. Climatic or seismic events, rather than the geological characteristics of a slope, may determine the time of failure. Predictions of time thus become linked with both short-term and long-term variations in weather, climate, or seismic activity. Thus, the effects of heavy rainfall may be immediate, if shallow failures of debris on slopes are involved, or delayed for months, if deep-seated failures of shales or other relatively impervious rocks are involved.

c. Determine what gaps in our knowledge affect the development of techniques to avoid, prevent, or mitigate landslide hazards and damage.

TYPES OF GROUND FAILURE 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. There are aspects of all the slope failure processes that 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 include debris flows and debris avalanches, rotational slides and slump-earth flows, rock falls and rock-fall avalanches, and liquefaction, lateral spreads, and quick clays. Each of these processes is described with a list of research tasks deserving high priority during the early phases of the program. A list of priority tasks for other ground failure processes will be developed during the early phases of the research program.

Debris Flows

Debris flows consist of a dense mixture of rock fragments, gravel, sand, mud, and water which behave as a viscous slurry (fig. 23). They are usually generated by heavy rainfall or snowmelt that causes the soil cover on a hillside to liquefy and flow downhill. Debris flows move very rapidly, carry large boulders, and are very destructive. They have been responsible for many

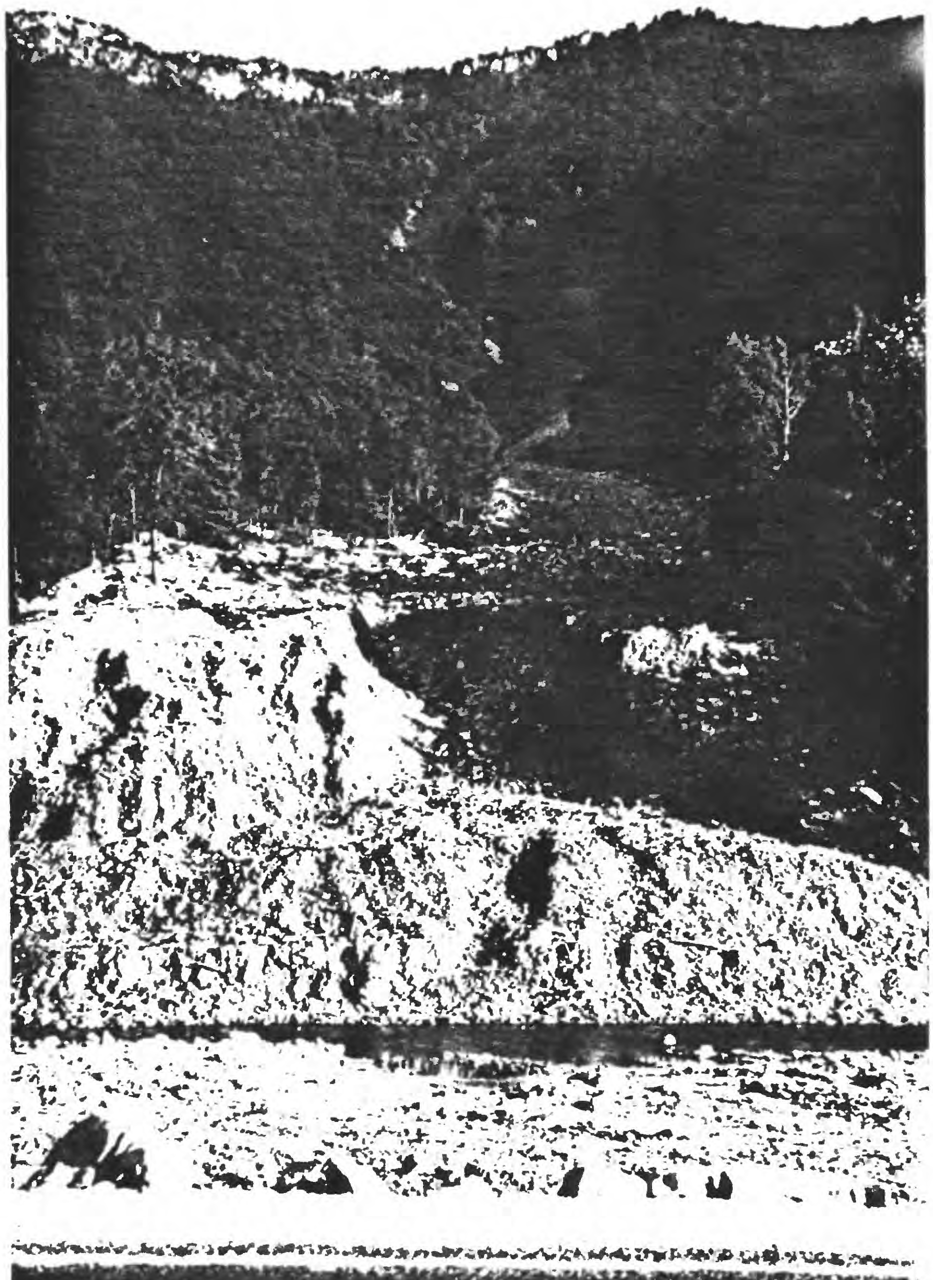


Figure 23.--Debris flow, Petersburg, West Virginia. Photograph by W. E. Davies, U.S. Geological Survey.

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 rains associated with hurricanes. They occur, however, in many other sections of the country and present probably the most serious of the landslide-type hazards with respect to loss of life.

Special types of debris flows generated on the flanks of volcanoes and associated with eruptions or heavy local rains have been under study for many years in a 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 of the Toutle River with perhaps the largest--and one of the most destructive--debris flows of modern times. This debris flow deposit is subject to further movement and its erosion remains a high priority item of study in terms of potential hazard.

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 are usually generated on moderate to steep slopes on which bedrock is overlain by a layer a few feet thick of soil and weathered rock. In regions where such conditions exist 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. However, the methods for determining the places most subject to failure and the meteorological events necessary to initiate such failure are not well developed. To improve our predictive capability, a coordinated combination of field, laboratory, analytical, and statistical studies should be undertaken.

Rotational Slides and Earth Flows

Rotational slides (slumps) are those in which movement takes place along a surface that is curved concavely upward (fig. 24). Such slides in both rock

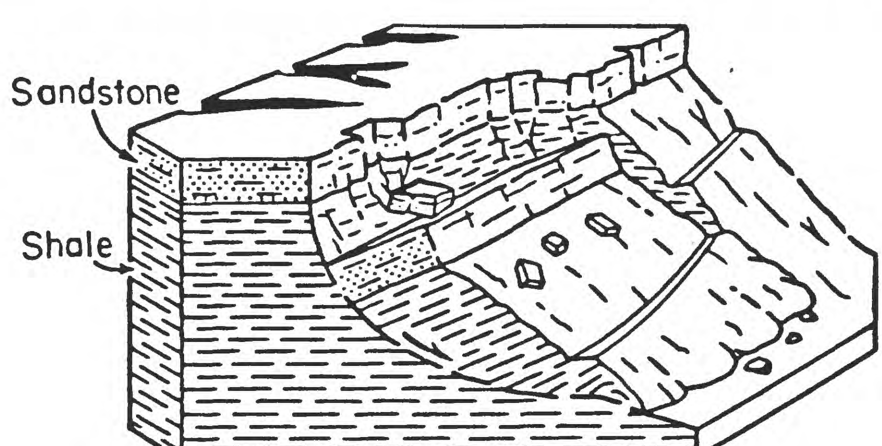


Figure 24.--Rotational slide in bedrock showing failure along a surface that is curved concavely upward.

and soil, often combined with flowage of disturbed material at the toe of the slide (fig. 25), make up a high proportion of the slope failure problems facing engineers, not only in the United States but all over the world. Owing

Figure 25.--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 alignment.

to the usually slow rate of movement of these slides, fatalities are rare; but movement may extend to considerable depth, the area involved may be relatively large, and damage to structures extensive (fig. 26). Remedial measures, where possible, are often costly, and may be of uncertain effectiveness if the geologic environment and geotechnical properties of the materials involved are not well understood (fig. 27).

Because they are so common both in natural slopes of clayey or shaly material and in manmade embankments, rotational slides have been the subject of more studies and analyses than any other type of slope failure. Yet there is still much that is not known concerning why, when, and where failures occur, the mechanisms of movement, the changes in material properties as movement progresses, and the most effective means for stabilization.

Figure 26.--Highway damaged by rotational slide near Cincinnati, Ohio. Photograph by W. E. Davies, U.S. Geological Survey.

Figure 27.--Unsuccessful use of pilings to correct a slump-earth flow in lake clays (Root, 1958; photograph by Massachusetts Department of Public Works).

Rock Falls and Rock-Fall Avalanches

Rock falls are masses of rock fragments which break away from a steep slope and travel mostly by free fall through the air (figs. 28 and 29). 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 outward from the base of the slope as a avalanche. Because the free-falling rocks reach high velocities and may remove large blocks of rock several meters in diameter, rock falls, and especially rock avalanches are very destructive. In the past 20 years, rock falls and avalanches have caused many fatalities in the United States as well as thousands of deaths in Peru, Guatemala, and Chili. For example, the Madison Canyon, Montana, rock-fall avalanche triggered by the Hebgen Lake earthquake in 1959 killed 26 people. In 1980 alone, rock falls in Yosemite National Park killed or seriously injured several people and caused the temporary closure of a large, privately owned campground.

Although we know that rock falls and rock avalanches occur on steep slopes, generally in areas of moderate to high relief, the distribution of highly susceptible rock-fall sites in the United States is not well known. This element of the program is aimed at developing criteria for delineating areas with a high potential for rock falls and rock avalanches in order to determine the extent and severity of these hazards. Potentially hazardous areas exist in the Appalachians, Rockies, Sierra Nevada, Cascades, Coast Ranges, several mountain ranges in Alaska, and other mountainous areas of the United States.

Liquefaction, Lateral Spreads, and Quick Clays

Liquefaction and lateral spreads are generally the product of rapid ground motion during earthquakes. Especially susceptible are saturated, relatively loose, cohesionless sediments, such as sands and silts. As described by Youd (1978):

"Liquefaction is the transformation of a cohesionless material 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 capacity. * * *

"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). They involve lateral displacements ranging up to several feet, and in particularly susceptible conditions several tens of feet, accompanied by ground cracks and differential vertical displacements.

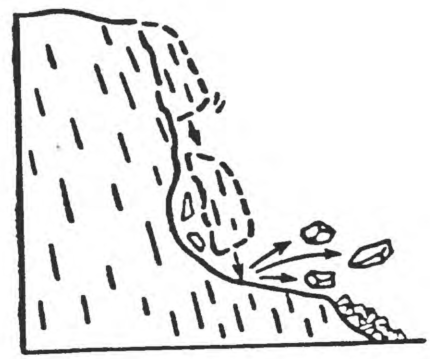


Figure 28.--Rock fall.

Figure 29.--Rock topple near Dingus, Kentucky. Rock topples are blocks that have rotated forward and may become a rock fall. Photograph by W. E. Davies, U.S. Geological Survey.

"These movements often disrupt the 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.

"Lateral spreads are particularly destructive to pipelines that pass through their slide masses. For example, 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."

Depositional environments favorable to the generation of liquefaction and lateral spreads include alluvial plains, 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, Charleston, S.C., area, and St. Lawrence Lowland. Urban construction in parts of San Francisco, Los Angeles, Seattle, Anchorage, Salt Lake City, Memphis, Paducah, Cairo, and Charleston has taken place in areas susceptible to the processes of liquefaction and lateral spreading. During past earthquakes in some of these areas, structures have been destroyed by liquefaction and lateral spreading.
Regarding quick clays, Youd (1978) further explained:

"Most clays lose strength when disturbed. 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. Most clays have sensitivities less than 4 and are termed insensitive. Clays with sensitivities greater than 8 are termed extra sensitive, and sensitivities greater than 40 have been reported for some very sensitive clays, often termed "quick clays." Clays with sensitivities greater than about 10, though rare, 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 soil 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 given in figure 4 (here reproduced as figure 30). The five landslides spread destruction into the downtown commercial area and residential areas, as well as disrupting many lifelines."

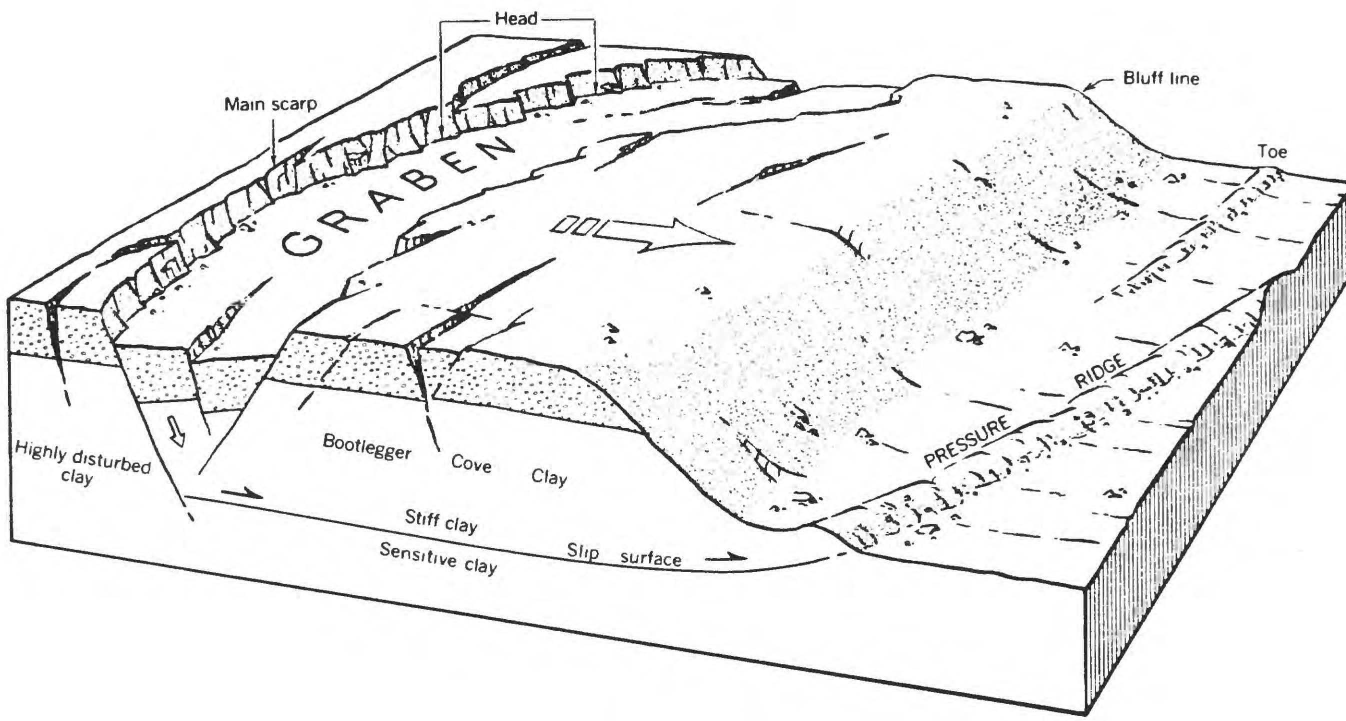


Figure 30.--During 1964 Alaska earthquake, five large translatory landslides passed through layers of Bootlegger Cove clay soil containing clay layers with sensitivities between 10 and 40. Factors contributing to failure were strength loss in sensitive clay layers and liquefaction of silt and sand lenses. Landslides disrupted 250 acres and caused $50 million in damages. This diagram shows features characteristic of the landslide movement (Hansen, 1965).

Ground Failures in Marine Environments

The search for and development of offshore oil and gas resources require that the drilling platforms and pipelines be placed on and in stable ocean-bottom materials. 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 by using a variety of underwater surveying techniques and field and laboratory methods to determine soil properties.

Disturbed areas on the sea bottom 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 producing head scarps and back-tilted blocks within the moved mass. Many resemble failures on land due to liquefaction and lateral spreading, with mobilization and transport of streams of muddy material down very gentle slopes. Some types of subaqueous failures are shown in figure 31.

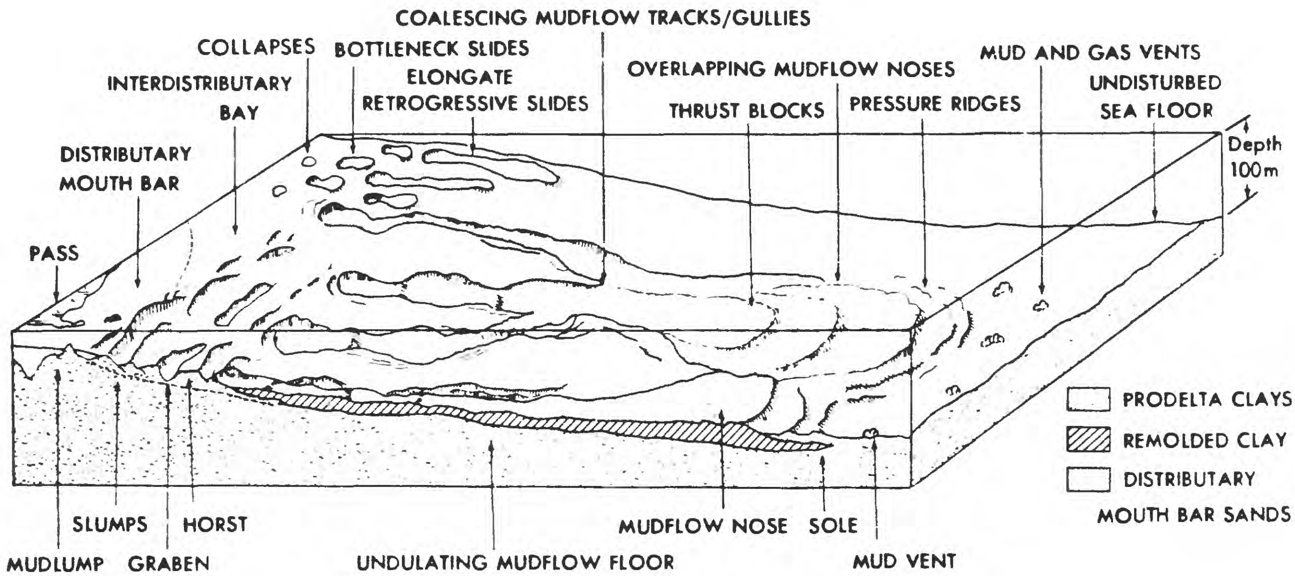


Figure 31.--Distribution and morphology of subaqueous landslides in part of the Mississippi delta front slope (Prior and Coleman, 1978).

Ground Failures Related to Frost Action and Permafrost

Freezing and thawing ground and permafrost present the chief geotechnical problems for manmade structures underlain by such materials. For example, thawing of permafrost and subsequent ground failure was the major geotechnical problem in the design and construction of the $12 billion Trans-Alaska hot oil pipeline. Frost heave is the chief problem engineers face in the design of the proposed chilled $31 billion Alaska Natural Gas Transportation System pipeline. Although permafrost-related problems have been studied for many years, we need to develop a fundamental understanding of the nature and physical behavior of frost action and permafrost in rock and soils as a basis for delineating the associated ground failures.

TASKS FOR RECOGNIZING AND REDUCING LANDSLIDE HAZARDS

Debris Flows

- Institute a program of detailed mapping (1:24,000) of selected areas in several regions of the United States (southern California, northern California, the Rockies, Great Basin, Appalachians) in order to evaluate the interaction of various sets of climatic, hydrologic, and geologic conditions under which debris flows occur.

- Develop analytic, numerical and laboratory physical models to help understand the generation and mechanical behavior of debris flows. In particular, model the unique multiphase characteristics of debris-flow slurries in order to predict their flow velocities.

- Undertake geotechnical investigations to classify hillside soils according to their potential as debris-flow source areas, and to determine which soil types are most susceptible to over saturation and mobilization under conditions of heavy precipitation, snowmelt, or thawing.

- Develop and install field instrumentation to monitor precipitation, ground-water levels, and movements in potential debris-flow source areas.

- Augment existing data bases and develop 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, timberclean cutting, etc.) on subsequent erosion and downstream sedimentation patterns as related to debris flows.

- Develop a history of climatic variation in the recent geologic past in the major climatic area, such as Alaska, the arid southwestern United States, the humid southeastern United States, and the temperate Appalachian region, and its relation to the occurrence of debris flows in these regions.

- Develop and improve techniques to date recent geologic features for the purpose of determining the timing and frequency of occurrence of debris flows.

- Conduct statistical studies on the recent rainfall histories of the selected mapping areas to investigate the effects of rainfall variations during drought and wet cycles.

Rotational Slides and Earth Flows

- Develop a better understanding of geologic, topographic, and climatic environments that are conducive to rotational sliding by thorough study of selected areas of failure. Such a study would include detailed mapping, physical exploration by trenching and drilling, 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 develop instrumentation for making measurements and 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 presssures 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.

- Develop 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.

- Develop 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 such failure is likely.

- Develop criteria for estimating the size of potential individual slides in an unstable area, the likelihood that they may enlarge or coalesce, and the area that may be affected by earthflows as the slump blocks disintegrate.
- Develop analytical and numerical models of unstable slopes using modern methods of finite element and probabilistic techniques.

- Develop models using centrifugal loading to investigate slope failures.

Rock Falls and Rock Fall Avalanches

- Prepare detailed geologic and topographic maps of selected areas to better define the geologic, topographic, and climatic environments in which rock falls occur. Particular attention should 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, and seismic activity on the incidence of rock falls.

- Develop field and laboratory techniques for characterizing the stress-strain properties of jointed rock masses.

- Develop analytical models for the processes by which large rock falls are converted to an extremely rapid and energetic flow of rock fragments. Develop criteria for predicting size, velocity, and extent of runout of rock-fall avalanches.

- Develop criteria for estimating the wave height to be expected from rock falls and avalanches that come into bodies of water.

Liquefaction, Lateral Spreads and Quick Clays

The reduction of hazards caused by liquefaction, lateral spreads, and 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 such hazards are defined. To attain this objective the following tasks are to be undertaken:

- Investigate the mechanism of lateral spreading. From case histories, laboratory and field studies, and analytical models determine the ground-motion 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 develop quantitative case histories in order to understand the mechanisms and develop predictive criteria.

- Map selected lateral spreads to quantify and locate ground effects, amounts of displacement, damage to structures, etc.

- Investigate the subsurface to determine its lithology, the 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.

- Perform laboratory tests to quantify material properties and classify materials. Such tests might include analyses of grain size, relative density, and dynamic strength.

- Instrument and monitor sites of newly created or probable future failures to determine pore-pressure development, ground displacement, and earthquake motions. These data are necessary to define mechanisms of failure and provide data for checking analytical models.

- Develop improved techniques for predicting sites likely to experience failure, and improve criteria for regional assessment of the hazards of liquefaction and lateral spreading.

- Investigate 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 by reviewing case histories of techniques used to stabilize areas suceptible to liquefaction and lateral spreading, and by evaluating the effectiveness of mitigation techniques following major earthquakes, and providing guidance to state and local officials on mitigation techniques.

Ground Failures in Marine Environments

Specific tasks for investigating ground failures in marine environment include:

- Investigate ground-failure mechanics in terms of tectonic, gravitational, and ocean dynamics, and the geotechnical properties of the bottom sediments as influenced by their composition of solid particles, organic material, and gas.

- Investigate the behavior of special sediment types, such as carbonates, volcanic ash, and ice-bonded materials, and the potential instabilities associated with each.

- Develop in situ and downhole instruments for measuring and monitoring geotechnical properties, stresses, and movements.

- Develop numerical and analytical models of critical stress-strain and soil-loading parameters that are difficult to measure in nature or are too expensive to investigate routinely.

Ground Failures Related to Frost Action and Permafrost

- Conduct laboratory and field studies to determine the extent, nature, characteristics, and formation of permafrost as it affects ground failure.

- Make detailed studies of selected areas to determine the effects of natural events, such as forest fires, and man's activities on the disturbance of permafrost and the active zone.

- Make laboratory and field studies on such frost-action processes as heaving, subsidence, and slope failures.

- Conduct field studies to determine ground movement, such as slump, flow, solifluction, and liquefaction when thawed permafrost soils are subjeced to stresses such as that from an earthquake.

- Conduct field mapping in selected areas of the northern U. S. to determine the capability of remote sensing techniques to delineate soils susceptible to frost heave.

- Make field, laboratory, and analytical studies to determine the effects of frost heave on the stability of manmade structures on susceptible soils and to develop criteria so that such areas will be avoided or stabilized.

- Compile and evaluate existing information on frost action and permafrost-related ground-failure problems.

- Make in situ measurements to improve our present knowledge of the depth, extent and temperature profile of permafrost.

- Provide the criteria for making maps of relative slope stability in areas underlain by permafrost and subject to frost action.

- Provide generalized geotechnical data necessary for planners and engineers to design resistant structures and develop mitigating measures.

TRANSFER AND USE OF LANDSLIDE-HAZARD INFORMATION

For the nation to avoid landslide hazards, and mitigate landslide losses, appropriate information must be communicated to, and used by, nongeologists, especially engineers, planners, and decisionmakers. The criteria and priorities for selecting specific landslide study areas 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: the users' interest, capabilities, and experience in hazard-related activities; enabling legislation authorizing Federal, State, and local hazard reduction activities; adequate, detailed information in a readily usable and understandable form; and the use of good communication techniques.

The goals of any successful national landslide reduction program must included:

- Identifying users and their needs
- Identifying potential uses
- Preparing usable and understandable information
- Communicating the information
- Evaluating the information and its use

Each of these goals is discussed below. The tasks suggested for accomplishing each goal must be tailored to the specific landslide study area.

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*The term "critical facilities" is used here to include:

(a) Lifelines such as major utility and transportation facilities and their connection to emergency facilities;

(b) Unique or large structures where failure might be catastrophic, for example, dams or buildings where explosive, toxic, and radioactive materials are stored or handled;

(c) High occupancy buildings, such as schools, hotels, offices, auditoriums, and stadiums; and

(d) Emergency facilities such as police and fire stations, hospitals, communications centers, and disaster-response centers.

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 are scientists and engineers who use the information directly; planners and decisionmakers who consider hazards among other land-use and development criteria; and educators and others who communicate information to interested citizens. Table 2 lists representative kinds of users. These people do not constitute a homogeneous group; they differ widely in the kinds of information they need and in their capacity to use that 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 that is required by geologists or practicing engineers is unsuitable for most state and local officials and probably unusuable by the vast majority of 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 curricula introduce students of planning or public administration to, or train them in, how to avoid natural hazards, or how to mitigate losses. Although many land-use planners and local officials have had some experience with natural hazards, such experience is generally related to flooding or soil problems according to the President's Office of Science and Technology Policy (OSTP, 1978, p. 170).

The effective use of landslide information to avoid damages or 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 region. For the cities and counties, only a few staff members 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 staff and two of the agencies employed geologists. These skills permitted a broader use of the technical materials, and the agencies were able to perform their own interpretations from the information for their own purposes. Similar findings were made by a Presidential working group on earthquake hazards reduction (OSTP, 1978, p. 170), by Wissel and others (1976, p. 2-5), and by the Council of State Governments (1975, p. 24; 1976, p. 15).

Users of landslide informaton must be able to understand landslide research products. Providing them with geologic information is not enough; the non-geologist user must have the skill to utilize it. Even professionals must continually update their skills in order to take advantage of new knowledge and technological advances. OSTP (1978, p. 63) suggests the establishment of planning grants to allow local governments to hire experts to draft and implement land-use regulations for earthquake hazard reduction. The first task should be to identify the key users or decisionmakers.

Table 2

Representative Users of Landslide-Hazard Information

Private Users
- Civic and voluntary groups
- Concerned citizens
- Construction companies
- Consulting geologists and engineers
- Financial institutions
- Landowners, developers, and real-estate persons
- News media
- Utilities

Community Users
- Mayors and council members
- Municipal engineers and planners
- Planning and zoning commissions
- Schools and colleges
- Town and county elected officials
- Tax assessors

Regional Users
- Multi-city and multi-county planning and development districts (including water and transportation)
- Multi-state planning and development districts
- Offices of emergency planning and response
- State departments of resource development
- State geological surveys
- State highway departments
- State legislatures
- University geology, civil engineering, architecture, urban and regional planning, and environmental 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 Administration 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

This task can be accomplished by the following procedures:

- o Identify and target those users from table 2 that have the greatest need and would use the landslide-hazard information most effectively
- o Consult with those users about their needs and priorities and identify the information most needed
- o Monitor and analyze the enactment of state and Federal laws or regulations and the landslide issues affecting users to anticipate and respond to their needs
- o Encourage planners and descisionmakers--both public and private--to develop an in-house capability to obtain and apply the information
- o Provide adequate training to potential users to enable them to understand and 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 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. Safety, although only one of several objectives in the land-use planning process, is a primary objective of government.

Prerequisites to making and implementing land-use plans are various planning studies, including benefit-cost studies. In such studies, the money saved by a reduction of landslide losses is compared with the costs of producing the landslide information and its collection, interpretation, and communication, as well as the costs connected with the enactment and enforcement of the regulations or the construction of protective engineering works. Typical uses of landslide hazard information, including studies, plans, and various hazard reduction techniques, are listed in table 3. Examples of many of these techniques are presented in a report by Erley and Kockelman (1981, p. 20-25).

Numerous techniques for reducing landslide hazards are available to planners and decisionmakers. Some of these techniques are well known in the engineering profession, such as structures to restrain landslides; or in the planning profession, such as public acquisition of hazardous areas. Others are obvious and practical, such as warning signs and regulations, 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 3 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. A prerequisite for the successsful use of any of these techniques is the availability of adequate, detailed information in a format and language understandable by nongeologists.

Table 3

Typical Uses of Information for Landslide Hazard Reduction

<u>Engineering and Planning studies</u>
- 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

<u>Development plans</u>
- 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

<u>Discouraging new development in hazardous areas</u>
- 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

<u>Regulating development in hazardous areas</u>
- Land-use zoning districts
- Special landslide-area use regulations
- Subdivision regulations
- Sanitary regulations
- Grading regulations

<u>Removing or converting existing development in hazardous areas</u>
- Public acquisitions
- Urban redevelopments
- Public-nuisance abatements
- Nonconforming uses
- Public facility reconstruction

<u>Protecting existing development in hazardous areas</u>
- Landslide restraints
- Mudflow diversions
- Monitoring, warning, and evacuations

The most economical method of reducing landslide losses is to discourage development in hazardous areas through 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. Requirements for landslide insurance, where available, and its cost might be an additional deterrent. 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.

Generally, landslide hazard areas can be restricted to such open-space uses as parks, grazing, or some types of agriculture, and to such roads and utilites as must be located in the areas. Techniques for prohibiting or regulating development in landslide areas include the establishment of zoning districts compatible with the hazards involved, and the incorporation of special use regulations in zoning, subdivision, sanitary, and grading ordinances. The success of the City of Los Angeles' landslide reduction program is discussed by Fleming, Varnes, and Schuster (1979, p. 434-437).

Recurrent damage from landslides can be avoided by permanently evacuating the hazard area. Structures can be removed or converted to some use that is less vulnerable to damage. The feasibility of such action depends on the value of the structures, whether they can be successfully reinforced, their potential for triggering landlides, and the level of citizen concern. Techniques for removal or conversion include public aquisition, urban redevelopment, abatement of a public nuisance, nonconforming-use provisions in zoning ordinances, and reconstruction of existing public facilites.

Development has occurred and will continue to occur in landslide areas. Such development can be protected by 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. Many descriptions of such remedial works appear in the engineering geology literature. For example, they may be found in "Reviews in Engineering Geology," edited by Coates (1977), "Landslides; Analysis and Control,", edited by Schuster and Krizek (1978), and "Landslide Remedial Measures" by Royster (1979). Some of the remedial works were evaluated and their construction costs analyzed by Martin Associates (1975) for the Allegheny County Department of Planning and Development.

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 up-slope often jeopardizes down-slope 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 <u>not</u> eligible for financial assistance, but that such work can be quite costly and may not produce the desired results.

Remedial public-works construction for landslide control, such as restraining structures, may encourage development in the area in an expectation that additional works will be forthcoming. The public may believe that the problem has been eliminated, rather than temporarily remedied. Also, earthquake-triggered landslides may not be prevented by such construction. Intelligent management and regulation in the hazardous areas is still required.

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 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 following tasks are recommended:

- Conduct benefit-cost studies of selected techniques for reducing landslide hazards in selected hazard areas (see table 3)
- Identify and target the most effective techniques
- Review and recommend those Federal programs or legislation from table 4 that could incorporate or require such techniques
- Develop and test innovative techniques

USABLE AND UNDERSTANDABLE MAPS AND REPORTS

A prerequisite for any successful landslide-hazard reduction program is the availability of adequate and reliable information about the hazard. The diverse groups of users need specific landslide information--location, susceptibility and magnitude--of a hazard shown on a map. Collecting such information is only the beginning of the process, because if nothing more were done with the information, it would be of little help in reducing hazards. Existing information about earthquake hazards including landslides is generally neither sufficiently detailed nor in a form that can be used for land-use planning or for implementing plans to avoid hazards, restrain landslides, or mitigate losses (OSTP, 1978, p. 157).

Ideally, reports and maps should be designed for one common user group--intelligent and interested citizens--thereby meeting almost all users' needs as to content, scale, detail, and interpretation and providing a common basis for discussion during public hearings. If the information is designed for this one common user group, it is not necessary to select target users and user groups or to depend on transfer agents for interpretation of the material. Simple maps--with a few "stop-light" colors--are the most effective and most frequently used. Examples of some of these kind of maps at various scales are listed in table 5.

Table 4

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 (OSTP, 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

Table 5

List of landslide-hazard maps and reports useful to nongeologists

Estimating the costs of landslide damage in the United States by Fleming and Taylor (1980) includes some of the costs of damage in California, Pennsylvania, Ohio, and Utah; and a discussion of hazard reduction techniques. See figure 32. This type of information is very useful in obtaining recognition of a national problem.

West Virginia landslides and slide-prone areas by Lessing and others (1976) includes 28 maps each with five susceptibility zones covering urban and urbanizing areas (figure 33) and advice for buyers, builders, and homeowners concerning danger signals. This type of report is very useful for obtaining recognition of a state problem and for town and county land use and development regulations.

Estimated relative abundance of landslides in the San Francisco Bay region by Radbruch and Wentworth (1971) includes six rankings of abundance. This information is very useful for recognition of a regional problem.

Relative slope stability and land-use planning by Nilsen and others (1979) includes a discussion of slope stability for land-use planning and a three-sheet map with four stability categories for hillsides, and two for flatlands. See figure 7. The map is based on larger scale, more detailed information. The map and supporting information are appropriate for use by city, county, regional, state, and private planners and decisionmakers.

Landslide susceptibility in San Mateo County, California by Brabb and others (1972) includes seven susceptibility categories and an explanation on how to use the map. See figure 22. The map is part of a county ordinance regulating general land-use and development.

Slope stability map of Fairfax County, Virginia by Obermeier (1979) includes diagrams of typical failures and descriptions of critical zones of weakening. The map has been used by civil engineers for establishing pre-construction investigation standards.

Feasibility and cost of using a computer to prepare landslide susceptibility maps by Newman and others (1978) includes a comparison of manual and computer-generated maps. See figure 22. Includes estimates of the time and cost for producing maps for 9 counties. This map is useful in similar geologic environments where geologic, slope, and landslide-inventory information is available.

Landsliding in Allegheny County by Briggs and others (1975) includes a discussion of actions to be avoided and what a homeowner should look for. See figures 34 and 35. This type of information has been found to be very useful by nongeologists.

Map of susceptibility to landsliding in Allegheny County, Pennsylvania by Pomeroy and Davis (1975) includes comments on 15 selected landslide localities. See figure 8. The need for site specific investigations by consulting geologists can be determined from this map.

Landslide damage maps of Northeastern San Jose, California, by Nilsen and Brabb (1972) includes suggestions to users. See figure 36. This type of large-scale demonstration map can be used as a basis for expert testimony needed in litigation.

Reducing landslide hazards by Erley and Kockelman (1981) includes an introduction to landslide causes, types, and hazards; site investigtions; grading controls; and examples for discouraging or regulating development in landslide areas, and for protecting, removing, or converting existing development. See table 3. The examples can be adapted by state and local governments for their hazard-reduction programs.

Seismic hazards and land-use planning by Nichols and Buchanan-Banks (1974) includes a discussion of ground failure and its implications for planning and land-use controls. This report is very useful for familiarizing planners and decisionmakers with seismic hazards including landslides.

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

DAMAGE SURVEY REPORT

FEDERAL DISASTER ASSISTANCE ADMINISTRATION

(See instructions on reverse of last copy)

3. DECLARATION NO. FDAA 5/16/73

4. INSPECTION DATE 5/1/73

1. TO ➧ REGION 9 FEDERAL DISASTER ASSISTANCE ADMINISTRATION (FDAA)

5. WORK ACCOMPLISHED BY ☒ CONTRACT ☐ FORCE ACCOUNT

2. APPLICANT *(State Agency, County, City, etc.)* County of Hawaii | PA NO P-1927

7. WORK CATEGORY *("X" Applicable Box)* ☐ EMERGENCY ☒ PERMANENT ☐A ☐B ☒C ☐D ☐E ☐F ☐G ☐H ☐I | ITEM NO. 22

6. PERCENTAGE OF WORK COMPLETED TO DATE 90 %

8. DAMAGED FACILITIES *(Location, identification and description)*

Mamalahoa Highway at Kolekole Gulch, Honokaa side of Kolekole Park. 28' roadway with 16' A.C. pavement and C.R.M. wall at down hill side.

9. DESCRIPTION OF DAMAGE

C.R.M. wall badly ruptured but still intact. Earth cracks and pavement cracks 110' long parallel to the road at downhill side of road.

10. SCOPE OF PROPOSED WORK

Relocate road closer to uphill side by cutting back at a 1:2 slope and surfacing the widened area. Patch all cracks and C.R.M. wall. Provide striping and delineators.

11. ESTIMATED COST OF PROPOSED WORK

QUANTITY (a)	UNIT (b)	MATERIAL AND/OR DESCRIPTION (c)	UNIT PRICE (d)	COST *(dollars)* (e)
696	c.y.	Unclassified Excavation	20.00	13,920.00
95	c.y.	Subbase	15.00	1,425.00
32	c.y.	Base Course	25.00	800.00
33	Tons	2" A.C. for widening	40.00	1,320.00
84	Tons	1-1/2" A.C. for Resurfacing	32.00	2,688.00
16	Each	RM-1 Delineators	75.00	1,200.00
1	Each	R-7-1 "No Parking At Any Time" sign	75.00	75.00
L/S		Striping	900.00	900.00
L/S		Repairing Existing C.R.M. Wall	1,000.00	1,000.00
		Construction Sub Total		23,328.00
		Surveying		150.00
		Engineering		250.00
		Drafting and Construction Engineering		650.00
12. EXISTING INSURANCE *(Type)* Not Covered		AMOUNT $	TOTAL	24,378.00

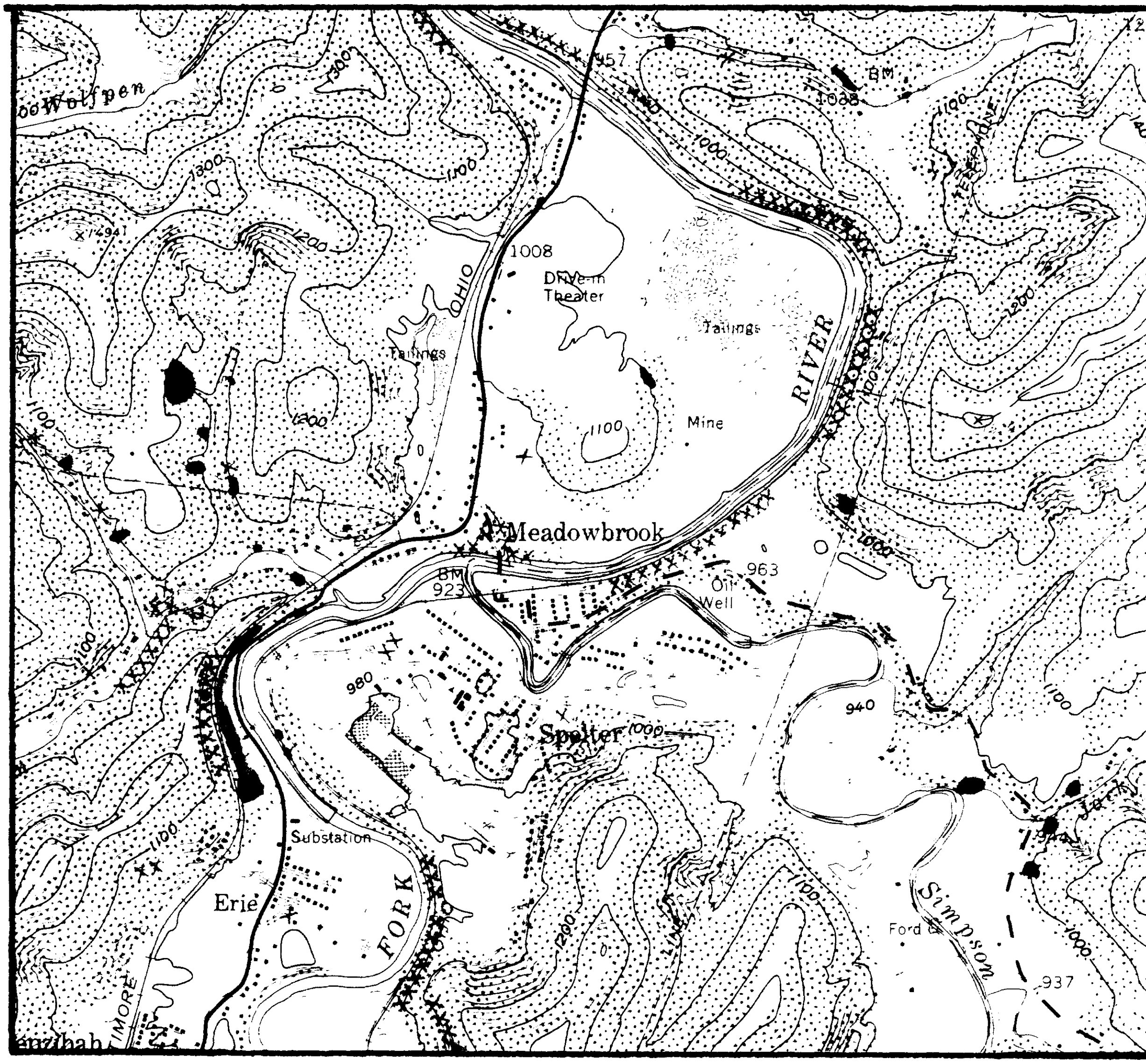
13. RECOMMENDATION BY FEDERAL INSPECTOR *(Signature, Agency, date)* | Eligible ☐ YES ☐ NO | ATTACHMENTS

14. CONCURRENCE IN REPORT BY STATE INSPECTOR *(Signature, Agency, date)* | ☐ YES ☐ NO | ATTACHMENTS

15. CONCURRENCE IN REPORT BY LOCAL REPRESENTATIVE *(Signature, Agency, date)* | ☐ YES ☐ NO | ATTACHMENTS

16. FEDERAL REVIEW *(Signature, Agency, date)* | FDAA REVIEW *(Initials and date)*

Figure 32.--Part of an application for federal disaster relief describing landslide damages and estimating restoration costs. From Fleming and Taylor (1980, p. 10). This type of information is very useful in obtaining public recognition of county and state landslide problems and their cost to taxpayers.



RECENT LANDSLIDES

Areas where landslides have been historically recorded or characterized by fresh scars and obvious recent movement.

OLDER LANDSLIDES

Areas lacking evidence of recent movement, but characterized by hummocky ground, slump blocks, flow structures, water seeps, or evidence from aerial photographs. Presently stable but can be reactivated easily.

0 0.5 1 Mile

ROCKFALLS

XXXX Areas where rocks have fallen or are highly likely to fall. Normally confined to very steep, natural or man-made slopes and cliffs.

SLIDE-PRONE AREAS

Areas judged to be unstable due to the occurrence of landslides, incompetent rock and soil, steep slope, or other evidence of instability.

RELATIVELY STABLE GROUND

Areas judged to have very low susceptibility to landslides and contain no known evidence of instability.

Figure 33.--Part of one of the 28 landslide and slide-prone area maps prepared by Lessing and others (1976) for the urban and urbanizing areas of West Virginia. This type of map is very useful for obtaining recognition of a state problem and for town and county land use and development regulations.

ACTIONS TO BE AVOIDED OR TO BE TAKEN ONLY WITH CAUTION

Most landslides in Allegheny County result from loading the tops or cutting into sensitive slopes, construction of fills on slopes, or altering water conditions of slopes. No significant actions should be taken without site investigations by competent technical personnel. Sketches in the margin of the companion map illustrate possible results from these actions. In the paragraphs below, the selected landslide localities referred to in parentheses are described later in this report and are located on the companion map.

Loading.—The most common loading (actually overloading) of a slope is by emplacing earth materials or slag as a fill, usually to extend the backyard of a house on the slope or on a ridgetop. Loading can cause the formation of surfaces of rupture in underlying soil and rock, resulting in failure. Structures also are loading factors. In most places they are set on bedrock, but when they are not, destruction may result —as occurred on Lawnwood Avenue (fig. 8; selected landslide locality 8).

Cutting into a slope.—Because valleys of the region are rather narrow, excavation of the foot of a slope to make more flat ground is very common. This can be disastrous, particularly if the cut is in the toe of an unidentified prehistoric landslide deposit, as happened during construction of Interstate 79 (selected landslide locality 2) and on West Smithfield Road (fig. 9; selected landslide locality 11).

Placing fills on slopes.—Proper construction of a fill on a slope involves engineering practice, and should be designed for the particular slope on which it is to be placed; it includes removal of natural vegetation before emplacement and lift-by-lift compaction. If vegetation is not removed, surfaces of rupture or slip planes can form on decaying vegetation between the new fill and the former natural slope; if fill is not compacted, failure can take place within it. The Painters Run (fig. 10) and Lawnwood Avenue (fig. 8) localities (selected landslide localities 5 and 8, respectively) are examples of fill failure, as are many other residential and backyard fills in Allegheny County.

Altering water conditions.—Natural slopes largely are protected from excessive infiltration of water by their vegetation; removal of vegetation can increase infiltration and thus increase susceptibility to landsliding. Faulty drainage systems, such as inadequate disposal of downspout water, also can affect slopes. Alteration of water conditions may have been a factor in the Baldwin Road, Robinson Township slide (selected landslide locality 3).

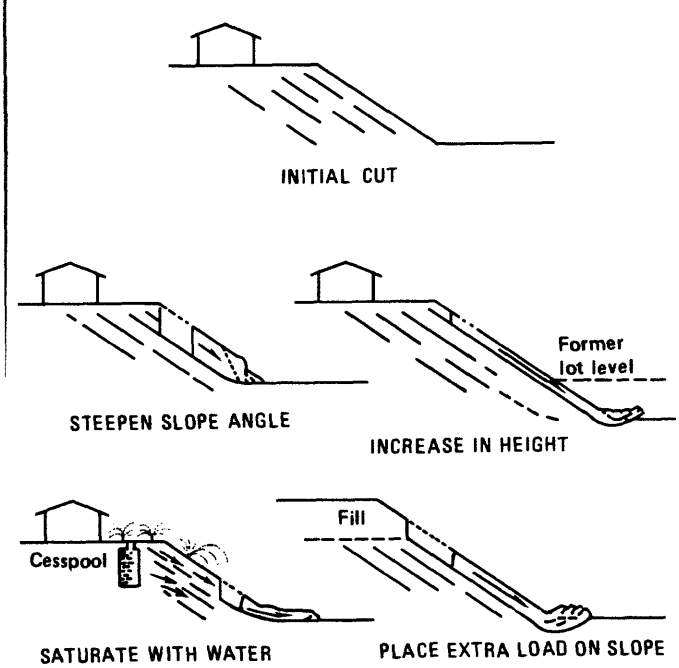


Figure 34.--A, Part of a report on landsliding in Allegheny County, Pennsylvania, prepared by Briggs and others (1975, p. 4). B, Diagram from Leighton (1966, fig. 10) showing four activities that would cause an unstable slope condition. This type of information has been found to be very useful by nongeologists.

WHAT THE BUYER, BUILDER, OR HOMEOWNER SHOULD LOOK FOR

The buyer, builder, or homeowner must always bear in mind that areas susceptible to landslides commonly are larger than most individual properties. Thus, it pays to look not only at the property in question but also at adjacent areas, particularly those upslope and downslope. If the property slopes more steeply than about 15 percent (15 feet of drop or rise vertically in 100 feet of horizontal distance), or if adjacent uphill or downhill slopes (or both) are significantly steeper than the slope of the property, site examinations should be made. In addition, if the property is on relatively flat ground on a ridge top or in a valley, but close to a fairly steep slope, an examination of the slope is recommended.

(1) *Cracks in buildings.*—Most older buildings have minor cracks, but these probably result largely from normal settlement. In general, the fact that a building is old and shows no significant damage is an indication that the building probably will remain undamaged by landsliding. Many or large cracks in newer structures are reasons for concern, although the cause of cracking may well be something other than landsliding. Major cracks commonly are repaired by owners, but evidence of repair usually is visible on close examination. Wet basements may be evidence of cracks in foundation.

(2) *Cracks in brick walls around yards and other outside brick and concrete features.*—Unlike buildings, which generally are set in bedrock, most yard walls and other ancillary features rest on soil. They thus are sensitive to creep which can cause cracking or can pull such features away from structures.

(3) *Doors and windows that jam.*—A door that sticks or otherwise does not seem to fit well or a sash window that jams may be evidence that the frame of a house has been warped.

(4) *Retaining walls, fences, curbs, gas meters, posts supporting porches, and other features out of plumb or not alined in a normal way.*

(7) *Tilted trees, grapevines, reeds.*—Trees are probably somewhat less reliable indicators of slope movement than are manmade objects, for trees on slopes tend to bend outward somewhat as they seek sunlight. However, trees leaning at appreciable angles (fig. 8) or numbers of trees leaning in different directions (fig. 9) strongly suggest areas of landsliding or strong creep. Many grapevines (fig. 11) and reeds have been observed on many prehistoric landslide deposits, perhaps as a result of water conditions within the deposits. They thus are general indicators of possible instability.

(8) *Tilted utility poles and taut or sagging wires.*—Most utility poles are more or less vertical and alined when new, and wires between poles usually sag uniformly, so appreciable tilting of poles and variations in amount of sag of wires between adjacent poles are abnormal and noteworthy.

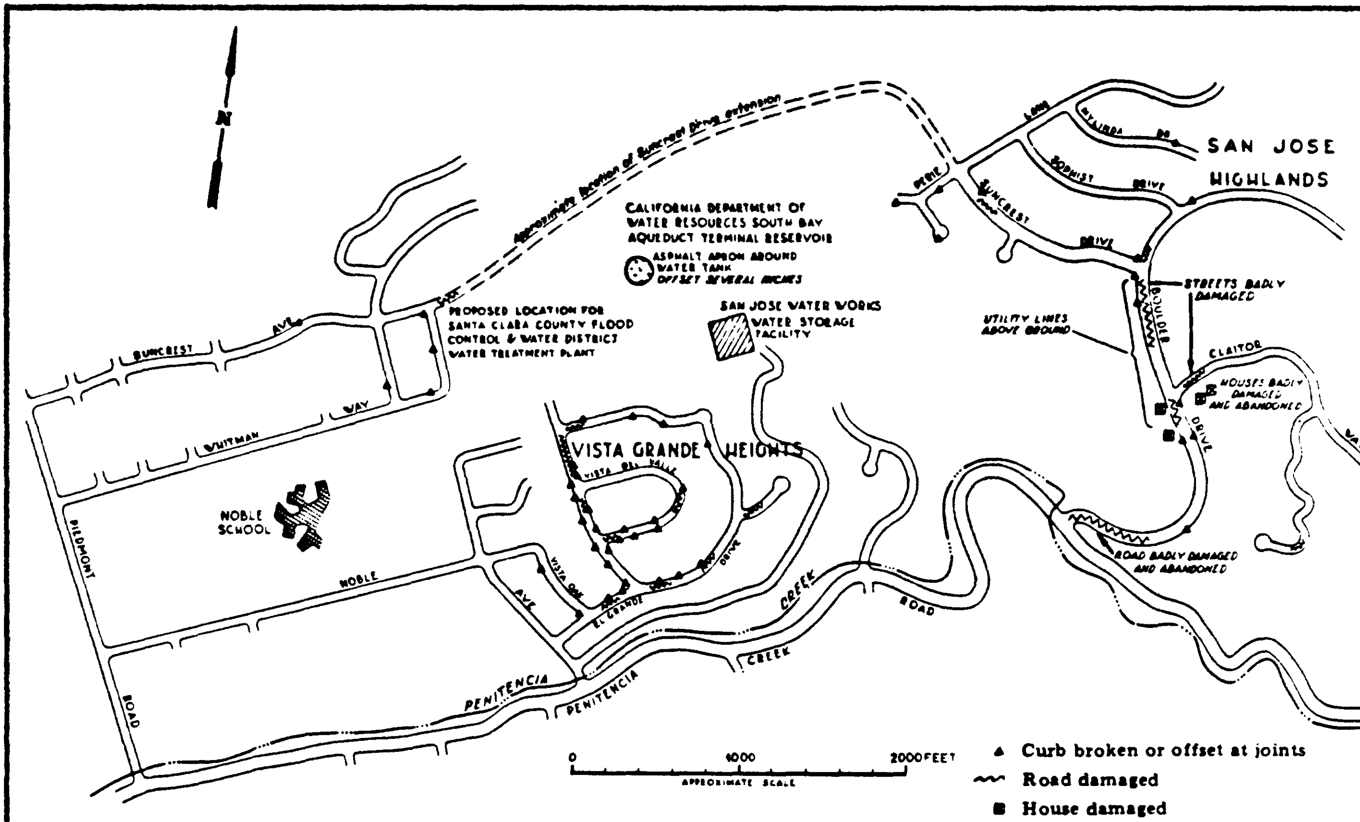
(9) *Cracks in the ground.*—Cracks more or less parallel (across) to a slope usually are indications that the slope is moving. Unusually wide cracks are shown in figure 12.

(10) *Steplike ground features.*—Slumping of ground usually results in steplike scarps (fig. 2) that may range from very low to many feet high. When relatively new, the "risers" of the scarps usually expose fresh earth (fig. 13). Older scarps may have subdued angles because of erosion and may be vegetated, making them more difficult to identify. Whether old or new, these features are evidence of unstable conditions.

(11) *Hummocky ground.*—Hummocks, low mounds, are common irregularly spaced features of the toes and lower ground surfaces of both prehistoric and recent landslides (fig. 9; fig. 13). They do not occur naturally on any other surfaces in Allegheny County.

(12) *Water seeps.*—Seeps and springs are very common at the toes of landslide deposits. Water from seeps on upper slopes may saturate the ground and so contribute to the mobility of downslope materials

Figure 35.--Excerpt from a report on landsliding for Allegheny County, Pennsylvania by Briggs and others (1975, p. 4-5). This type of information is useful for buyers, builders, and homeowners.



ACTIONS TAKEN BY AND FINANCED BY THE CITY OF SAN JOSE IN THE SAN JOSE HIGHLANDS AREA, 1968–71

Soils study and consultant fees	1968	$10,000
Soils study and consultant fees	1969	10,000
Consultant for new road	1970	30,000
Construct 1,400′ gravel-fill interception ditch (no water was apparently removed)	1969	15,000
Clean Hydraughers several times	--	3,000
Construct de-watering wells (deactivated after 1 year, no apparent help)	1969	25,000
Above-ground flexible aluminum sanitary sewer	1968	4,500
Sewer photo survey	1971	3,000
Replace sanitary sewer	1971	7,000
Aerial photography	--	2,000
Abandon 600′ of only access road and build 4,000′ of new access around landslide area	--	550,000
Winter and spring road maintenance to remove ground swells and increasing grade due to downward creep	1967	- 0 -
	1968	9,000
	1969	30,000
	1970	32,000
	1971	30,000
	Total	$760,500

Estimated value of city streets in San Jose Highlands (exclusive of new access road) ---- $750,000

Estimated value of city utilities (street lights and sewers) in San Jose Highlands ----- $300,000

Landslide damage to gas lines in San Jose Highlands totaled $20,000 by late 1970 (Pacific Gas and Electric Co., written commun., 11/18/70). Landslide damage to water lines has become progressively worse according to the following figures provided by the San Jose Highlands Water Company (written commun., 11/3/71):

1967–68 (1 repair)	$ 215
1968–69 (5 repairs)	$1,570
1969–70 (7 repairs)	$1,660
1970–71 (20 repairs)	$5,816

Figure 36.--Part of a map and table showing damage caused by landsliding in the northeastern San Jose area, California, by Nilsen and Brabb (1972). This type of large-scale demonstration map can be used as a basis for expert testimony in litigation.

Some of the simpler maps are derived from maps that portray landslides and landslide processes in far greater detail than is needed for land-use plans and their implementation; however, the detailed information can be made available upon request. Some users--consulting geologists or design engineers--may find that the original maps or the data from which they were compiled can better fill their needs. Some reports may go only to technical users, such as civil engineers, and therefore may not need to be simplified for nongeologists.

The scale of maps giving landslide information depends upon their potential use. If the map is to be used in hazard reduction, the scale should be at least as large as 1 inch equals 2,000 feet (1:24,000). Larger-scale or more detailed maps are required for permit regulations, site investigations, detailed plans, and project review and approval. If available maps are at scales smaller than 1 inch equals 2,000 feet, communities with landslide problems will probably find it necessary to prepare maps at larger scales. The smaller-scale or less detailed maps can be used to alert citizens, officials, and developers of the hazards and provide an authoritative source for local officials to cite support of regulations requiring on-site investigations, evaluation, and remedial measures.

A national hazard reduction program would include small-scale maps which can present national, regional, and community overviews and identify those localities which are most likely to have landslide problems. A wide variety of maps and reports ranging from highly technical documents to popular-type releases are required for a comprehensive program. Annotated bibliographies of landslide processes and damage reports, indexes to landslide inventory and hazard maps and directories of natural hazard data--sources similar to Lander, Alexander, and Downing 's 1979 inventory--are very helpful. Such material would not necessarily be produced by the U.S. Geological Survey, but the following tasks might be suitable for the Geological Survey to undertake:

- Produce maps and reports quickly for nongeologists from existing landslide information to orient potential users
- Identify the maps and reports needed
- Assure that new landslide information is prepared in the detail and at the scales needed and understood by most users (see table 2)
- Assure that landslide information (including discoveries, advances and innovative uses) is released promptly through appropriate communication channels (see table 7)
- Assist in developing 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. Information is a key to reducing the impact of hazards on society (OSTP, 1978, p. 61). Detailed landslide information must be provided in a readily usable format understandable by nongeologists, but providing such information is not sufficient in itself. It must be communicated or transferred to the user.

The information should be provided to various users at different stages in a carefully considered 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. Such groups would include key national, regional, and community decisionmakers, and representatives of the news media (OSTP, 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. Research workers must also attempt to understand the needs of potential users, such as State and local government officials and the private sector as well as the conditions under which the information is used. Since research workers and users tend to have divergent interests and needs, it may be necessary to interpret the research to make it helpful to the users. In any case, landslide information must be kept flowing between the research workers and the users.

Communicators of Information

A group composed of representatives of existing and potential users could be selected before designing, adopting or detailing any landslide- hazard reduction program. The group would not act as a coordinator or translator for the users, but would act as users communicating directly with the research workers or producers of the landslide information. The group or subgroups would also: help research personnel identify critical issues and user needs; collaborate in the design of the products; provide an immediate and receptive user market; encourage continued application of the material; and assist in avoiding duplication in the data collection.

Existing institutions should be utilized whenever possible to avoid duplication and reduce costs. Educational programs could be designed for public and private schools at all levels, for professional societies, and for professional schools such as schools of engineering, architecture, and law. Whenever possible, the communication of landslide information should be closely coordinated with the communication of other types of natural hazards, such as floods and earthquakes, again to avoid duplication and to reduce costs.

Table 6 lists some representative communicators of landslide hazard information. Many of the users listed in table 2 will also 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 listed in table 7, but to rely on them solely 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

Table 6

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, commentarors, 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)

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important components of the information transfer system, nothing replaces intensive producer-user interaction..."

State and local governments are primary users of landslide information and their early involvement should be encouraged. They should also be encouraged to provide feedback to the research workers. Groups in the private sector, such as voluntary associations, professional associations, and public-interest groups, which have not worked on natural-hazards information problems in the past, but nevertheless have the skills and resources to make a significant contribution, should be brought in to help communicate the information. Cooperation among Federal, state, and local agencies, professional societies, and other groups in the private sector has greatly improved the utilization of hazards information (OSTP, 1978, p. 65).

The news media can be a vital link between research workers, public officials, and the general public, enabling the officials to more easily release crucial information as to the kinds of hazard-reduction actions to take in the face of an imminent danger. The media can also play an effective role in the dissemination of general landslide information.

Table 7a

Typical Communication Techniques--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

Publishing and distributing a newsletter periodically to selected officials, professionals, and citizens in the project area

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 co-sponsoring conferences for planners and decisionmakers where the results of landslide studies are displayed and reported on to users

Participating and assisting in regional and national professional conferences directed to planners and decisionmakers, and cooperating in the publishing of the proceedings of the conference

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 products 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

Preparing and disseminating information to community and regional newspapers and radio and television stations on the landslide programs, products, and other activities in the project area

Guiding field trips to potentially hazardous sites

Preparing and distributing brochures, TV spots, films, and other visual materials to the news media

Table 7b

Typical Communication Techniques--Advisory Services

Preparing annotated and indexed bibliographies of landslide information

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 where 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 explanations or interpretations of landslide information for engineering, planning, and decisionmaking

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 on 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 forming of local, State, and Federal planning and plan-implementation programs so as to assure the proper and timely use of landslide hazard information

Explaining the techniques or methodology used in preparing landslide products or conducting landslide research

Incorporating appropriate land-use planning discussions and examples of hazard reduction techniques into major landslide products

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

Table 7c

Typical Communication Techniques--Review Services

Reviewing and commenting on proposed programs for collecting and interpreting landslide information

Reviewing and commenting on those studies and plans that are based upon landslide information

Reviewing and commenting on those proposed policies, procedures, ordinances, statutes, and regulations that cite landslide products

Reviewing and commenting on engineering or planning-consultant's reports that are based upon, interpret, or apply landslide information

Reviewing and commenting on local, State, and Federal policies, administrative procedures, and legislative analyses that have a direct effect on landslide information

Adapted from Kockelman (1976a)

Communication Techniques

Multiple ways of imparting information should be encouraged. A single exposure to new information, especially if the informaton is complex or differs from a user's previous knowledge, is often 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 (OSTP, 1978, p. 63).

Other group differences should be kept in mind when communication measures are being devised. For example, different strategies might be necessary depending on whether the people involved are recent or long-time residents of a community and which ethnic, socioeconomic, or age group they are in. The communication techniques must be tailored to project location, communicators available, information available, and user needs.

The most effective techniques should be selected jointly by the user and the research worker. Table 7 lists typical communication techniques under the headings of educational, advisory, and review services. Many of the uses, such as discloseure, monitoring, and warning, listed in table 3 are also excellent means of communication. Many techniques for communicating earthquake hazard reduction information can be seen in a report edited by Hays (1978, pp. 27, 47, 307, and 335). The information flow devices used in the San Francisco Bay region study may also be of interest (Hays, ed., 1978, p. 311).

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 would not supplant existing programs or activities of educational institutions, and would not replace services of private consulting firms or regional and community organizations, but instead would supplement them. The review services would not endorse or give approval to the documents reviewed. All services provided would be within the purview and capability of the producers or communicators. Educational, advisory, and review services would be provided only upon request. Many of these services have been recommended by Wissel and others (1976), USGS Publications Division staff, University of Wisconsin's Center for Geographic Analyses (1975, p. 24), the Council of State Governments (1975, p. 25; 1976, p. 17, 18), and A. D. Little, Inc. (1975, p. 82, 92).

Some of these services are already being provided 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). Some Survey scientists involved in the urban area studies have spent between 20 and 50 percent of their time working with users . 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) identifies the following additional benefits that will occur:

- Avoiding duplication in the collection and interpretation of landslide information, thereby conserving staff time and financial resources of research workers

- Developing a more acute awareness and understanding among scientific, engineering, and planning staffs of users' specific needs

- Assuring more correct and appropriate uses of landslide information

- Transferring the methods of collecting, interpreting, and presenting landslide information to users outside the project area

- Expediting the dissemination of critical landslide information needed on which to base urgent community, regional, and national decisions

- Increasing the familiarity of planners, decisionmakers, and citizens with landslide hazards

- Helping supply the information needed by users to comply with State and Federal statutes and regulations

- Improving the ability of local, district, State, and Federal planning and development agencies to understand and apply landslide information

Communication Tasks

The tasks that will be involved in communicating landslide-hazard information to users include:

- Design the research program in close cooperation with users in order to improve the likelihood of effective use

- Recommend or select the most effective communication techniques

- Prepare and adopt a formal program so that information can be rapidly 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. If the landslide information is not appropriate, not used, misused, or ineffectively used, the national objective of avoiding landslide hazards, restraining landslides, and mitigating losses will not be met.

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 where similar hazards exist, and where adequate landslide information is available. The adaption to, and adoption by, other jurisdictions depends on 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 agencies. Sponsors of similar hazard-reduction programs designed for planners and decisionmakers have performed self-evaluations on the usefulness of the programs (A. D. Little, Inc. 1975; Kockelman 1975, 1976b, 1979, and 1980; Downing, 1978; Wissel and others, 1976). Production and communication of any landslide hazard information is 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 preceeding tasks:

- Inventory selected public and private uses (see table 3) to identify and document the type and number of uses of each map or report
- Interview selected public and private users (see table 2) 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

CONCLUSIONS

The responsibility for providing landslide information suitable for land-use planning and its implementation is not clearly defined or evenly distributed between 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, restrain landslides, and 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, defining appropriate levels of detail for various users and uses, and conducting demonstration projects. The U.S. Geological Survey should continue to emphasize basic research and its use at state and local levels.

State geological surveys could be responsible for the bulk of the hazards mapping and continuing contact with district and local governments on how to apply the basic information. Geotechnical personnel in local and district government agencies could be primarily responsible for using the information. Costs could be shared, but a significant amount of the money could be derived from the Federal Government so that it could assign priority to those areas of the country with the highest risks. The U.S. Geological Survey, Federal Emergency Management Agency, and Department of Housing and Urban Development, together with professional planning and engineering organizations could develop guidelines for applying landslide-hazard information.

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. In many cases, failure of some of these facilities would increase the magnitude of the danger or lessen the capability of the community or region to recover from disasters.

It is particularly important 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 serve as examples to other units of government. The Federal Government has scientific, engineering, planning, and technical resources for undertaking landslide research, disseminating information, and 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 a success--involving adequate research, useful products, effective communication and proper use--according to Kockelman (1980, p. 74) its lasting 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 government attorneys
- 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 real-estate buyers and developers

In one of the most succinct and yet comprehensive reports on U.S. Geological Survey experience in disseminating earth-science information, T. F. Bates (1979, p. 28-29) concludes that:

> ... if earth science information is to be applied nationwide to the solution of land resource problems, the entire earth science community must mobilize to ...
>
> o Create nationwide awareness of earth science information needs and uses
>
> o Provide specialized, technical information in a form and language understandable to the intelligent citizen.
>
> o Engage in the educational, advisory, and review services necessary to assist the public and its representatives in making effective use of that information.

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