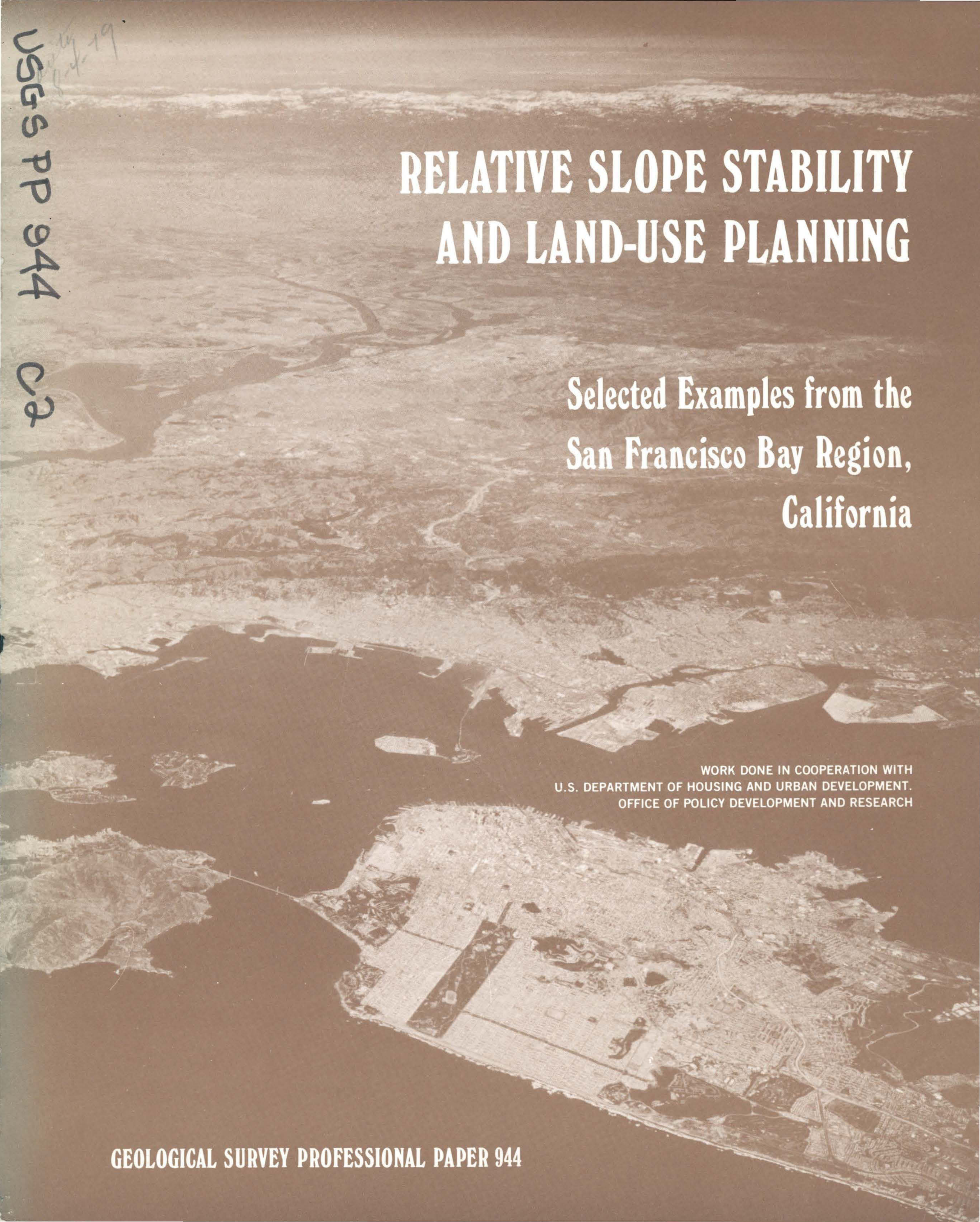

RELATIVE SLOPE STABILITY AND LAND-USE PLANNING

Selected Examples from the San Francisco Bay Region, California

WORK DONE IN COOPERATION WITH
U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT.
OFFICE OF POLICY DEVELOPMENT AND RESEARCH

GEOLOGICAL SURVEY PROFESSIONAL PAPER 944

USGS PP 944 C2

Relative Slope Stability And Land-use Planning In The San Francisco Bay Region, California

By TOR H. NILSEN *and* ROBERT H. WRIGHT, U.S. GEOLOGICAL SURVEY, *and* THOMAS C. VLASIC *and* WILLIAM E. SPANGLE, WILLIAM SPANGLE AND ASSOCIATES, CITY AND REGIONAL PLANNERS

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Jointly supported by the U.S. Geological Survey and the Department of Housing and Urban Development, Office of Policy Development and Research as a part of a program to develop and apply earth-science information in support of land-use planning and decisionmaking

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FOREWORD

This report is a product of the San Francisco Bay Region Environment and Resources Planning Study, an experimental study designed to facilitate the use of earth-science information in regional planning and decisionmaking. The study is jointly supported by the U.S. Geological Survey and the Office of Policy Development and Research, Department of Housing and Urban Development. The Association of Bay Area Governments participates in the study and provides liaison with other regional planning agencies and with county and local governments.

Although the study focuses on the nine-county, 7,400-square-mile (19,100 km^2) San Francisco Bay region, it bears on a complex issue that is of national concern: how best to accommodate orderly development and growth while conserving our natural resource base, insuring public health and safety, and minimizing degradation of our natural and manmade environment. The complexity of the problem can be greatly reduced if we understand the natural characteristics of the land, the processes that shape it, its resource potential, and its natural hazards. These subjects are chiefly within the domain of the earth sciences: geology, geophysics, hydrology, and the soil sciences. Appropriate earth-science information, if available, can be rationally applied in guiding growth and development, but the existence of the information does not assure its effective use in the day-to-day decisions that shape development. Planners, elected officials, and the public rarely have the training or experience needed to recognize the significance of basic earth-science information, and many of the conventional methods of communicating earth-science information are ill suited to their needs.

The study is intended to aid the planning and decisionmaking community by (1) identifying important problems that are rooted in the earth sciences and related to growth and development in the bay region; (2) providing the earth-science information that is needed to solve these problems; (3) interpreting and publishing findings in forms understandable to and usable by nonscientists; (4) establishing new avenues of communication between scientists and users, and (5) exploring alternate ways of applying earth-science information in planning and decisionmaking.

Since the study was started in 1970, more than one hundred reports and maps have been completed. These cover a wide range of topics: flood and earthquake hazards, unstable slopes, engineering characteristics of hillside and lowland areas, mineral and water resources management, solid and liquid waste disposal, erosion and sedimentation problems, bay water circulation patterns, and others. The methods used in the study and the results that have been produced have elicited great interest and have been widely applied by planners, government officials, industry, universities, and by the general public.

In this report, the results of several years of research on problems of slope stability are interpreted and summarized. Some of these results, derived chiefly from research and experience in the San Francisco Bay region, will be useful wherever the threat of slope failure complicates decisions on land use. For example, the report describes a method of evaluating slope stability. Based on a knowledge of geology, slope, and the incidence of landslide deposits, this method can help planners, elected officials, and developers anticipate and avoid problems where development is imminent. Maps that accompany the report illustrate the method as it has been used in the San Francisco Bay region. The maps also show a relation that is particularly important in planning for land use: slope stability varies throughout the region, but some large areas are relatively stable and others, equally large, are potentially unstable. Finally, the report discusses how a regionwide knowledge of relative slope stability may be used to improve both planning and day-to-day decisions on land use.

The maps that accompany the report are at a scale of 1:125,000 (1 inch = about 2 miles). This scale is a compromise between the need for abundant detail and precision, which are attainable on maps at large scales, and the need for regionwide coverage on map sheets of manageable size. Furthermore, at this scale, the maps provide uniform coverage of the entire nine-county region. They show that all nine counties and many of the 91 cities in the region contain potentially unstable slopes and that most slope-stability problems are not confined by political boundaries. The nonpolitical nature of landslides and other kinds of slope failure suggest a need for coordinated planning, whether it be regionwide or by the joint efforts of jurisdictions with common boundaries or agencies with overlapping responsibilities.

Robert D. Brown, Jr.

Robert D. Brown, Jr.
Project Director
San Francisco Bay Region Study

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DEFINITIONS OF TERMS

Alluvium. Unconsolidated clay, sand, or gravel deposited by running water.

Argillaceous. Rocks or sediments largely composed of clay.

Basalt. A fine grained, compact, dark-colored volcanic rock.

Colluvium. A loose mass of soil or rock fragments deposited largely by the force of gravity at the base of a steep slope or cliff.

Conglomerate. Pebbles, cobbles, and boulders larger than 2 mm in diameter set in a fine-grained matrix of sand, silt, or other cementing material. The rocks may vary in composition and size but they are usually rounded from transportation by water or waves.

Cretaceous. A period of geologic time extending from about 136 million years ago to 65 million years ago.

Diabase. A dark-gray to black fine-textured crystalline rock that was solidified from molten or partly molten rock material at depth in the Earth's crust.

Eocene. An epoch of geologic time extending from about 53 million years ago to about 38 million years ago.

Evapotranspiration. Loss of water from a land area through transpiration of plants and evaporation from the soil.

Expansive soils. Soils that increase in volume according to the amount of water they absorb.

Facies. A distinguishable part of a single geologic unit that differs from other parts in some general aspect such as appearance or composition. The term implies physical closeness and genetic relation or connection between the parts.

Franciscan rocks. A complex assortment of sandstone, shale, chert, volcanic rocks such as basalt and pillow lavas, and intrusive coarse-grained crystalline rocks such as gabbro and serpentine. Many of the Franciscan rocks have been intensely sheared. The rocks are Jurassic to Eocene in age and crop out in western California.

Geotrophic. A type of growth in which an organism turns or curves in response to gravity.

Glauconite. A dull-green earthy or granular mineral of the mica group found in marine sedimentary rocks. It indicates very slow sedimentation.

Graywacke. A very hard dark-gray or greenish-gray clayey impure sandstone generally formed in an environment in which erosion, transportation, deposition, and burial are rapid. Generally of marine origin.

Infrared photography. A type of aerial photography using a film more sensitive to infrared than to visible light rays, that is, to wavelengths just beyond the red end of the visual spectrum.

Isopleth map. A map that shows the distribution of a variable quantity by means of lines of equal value. For example, a map that shows the thickness of a rock unit throughout a geographic area.

Jurassic. A period of geologic time extending from about 190 million years ago to 136 million years ago.

Lithified. Changed from an unconsolidated sediment into a solid rock through such processes as cementation, crystallization, and compression.

Loess. A widespread unconsolidated blanket deposit, buff to light yellow, consisting largely of silt with lesser amounts of clay and sand. Generally believed to be windblown dust of Pleistocene age.

Melange. A heterogeneous mixture of rock materials consisting of a fine-grained sheared matrix thoroughly mixed with angular fragments, blocks, or slabs of diverse origin and age.

Metagraywacke. A graywacke that has been somewhat altered, or metamorphosed.

Metamorphic rocks. Rocks derived from preexisting rocks. Through changes in temperature, pressure, shearing stress, and chemicals, the original rocks have been wholly or partly transformed mineralogically, chemically, and structurally. Many metamorphic rocks contain prominent well-formed crystals set in a finer matrix. Most metamorphic rocks are characterized by well-marked foliation—thin, leaflike layers or laminae. The rocks tend to split along parallel planes or surfaces determined by the foliation.

Miocene. An epoch of geologic time extending from about 26 million years ago to 5 million years ago.

Oligocene. An epoch of geologic time extending from about 37 million years ago to 26 million years ago.

Paleocene. An epoch of geologic time extending from 65 million years ago to about 53 million years ago.

Phototrophic. A plant that is nourished entirely from its own organs.

Quaternary. A period of geologic time extending from 2 or 3 million years ago to the present.

Seismicity. The amount or degree of earthquake activity.

Serpentine. A green, greenish-yellow, or greenish-gray rock that is formed by alteration of other minerals. They are found in both igneous and metamorphic rocks. Their presence may indicate regional rock metamorphism.

Siltstone. A sedimentary rock composed of detrital particles smaller than very fine sand grains and larger than coarse clay. The particles, mechanically formed fragments of older rock, were transported from their source, deposited in water or from air, and consolidated to form the rock.

Syncline. Rock layers folded concave upward. The folding is usually produced by deformation, generally compression, and results in an undulating land surface.

Tectonics. A branch of geology dealing with the structural or deformational features of the upper part of the Earth's crust.

Tertiary. A period of geologic time extending from 65 million years ago to 2 or 3 million years ago.

RELATIVE SLOPE STABILITY AND LAND-USE PLANNING IN THE SAN FRANCISCO BAY REGION, CALIFORNIA

By Tor H. Nilsen, Robert H. Wright,[1] Thomas C. Vlasic, and William Spangle

ABSTRACT

Landslides and associated types of slope failure such as accelerated soil and rock creep have become a major geologic hazard in the San Francisco Bay region. As increasing development of hillside areas has taken place since the mid-1940's, the costs of damage from slope failures have steadily increased. More than $1 million in losses was documented from a single hillside development in the city of San Jose. For the entire San Francisco Bay region, more than $25 million of damage was caused by landslides during the rainy season of 1968–69 and more than $10 million in 1972–73. These losses can be greatly reduced by: (1) using geologic information to recognize, evaluate, and map those areas and slopes that are potentially unstable, and (2) applying this information in planning, designing, and organizing the use of hillside areas. For this report, we have prepared the first standardized relative slope-stability maps (scale 1:125,000) of the entire San Francisco Bay region, and we discuss the implications and uses of these maps in the regional land-use planning process.

We have divided the land area of the bay region into five categories and one subcategory of relative slope stability ranging from unstable to stable. The categories have been derived by analyses of the steepness of slope angles, the distribution of ancient landslide deposits, and the relative strength of bedrock and surficial geologic units. Previous studies have shown that most landslides in a given year occur on slopes greater than 15 percent (8°), in areas where landsliding has previously taken place, and in areas underlain by particular landslide-prone geologic units. Other secondary and related factors such as rainfall distribution, active seismicity, active faults, soil thickness and strength, and various effects of urbanization have not been specifically included in our analysis. However, most of these factors have already been incorporated in our analysis through the combined effects of slope, ancient landslide deposits, and landslide-prone geologic units.

The relative slope stability maps indicate that much of the San Francisco Bay region is relatively unstable and susceptible to natural slope failures. Unstable uplands are common in the Coast Ranges north of San Francisco Bay and in the Diablo Range east and southeast of San Francisco Bay, where steep slopes, abundant ancient landslide deposits, and weak, structurally deformed rocks of the Franciscan assemblage and Great Valley sequence and numerous poorly consolidated younger Tertiary siltstones and shales are very susceptible to landsliding. Large parts of the Santa Cruz Mountains southwest of San Francisco Bay, underlain by Tertiary sandstones and shales, are also highly unstable. More stable areas are located in interior valleys and along the gently sloping foothills of these upland areas. However, lowlands along the margins of San Francisco, San Pablo, Suisun, and Grizzly Bays and in the Sacramento-San Joaquin delta region, underlain by soft, moist, unconsolidated muds, are unstable and susceptible to lateral flowage, particularly during earthquakes.

The relative slope stability maps have a variety of potential uses in long-range regional land-use planning for purposes such as transportation and communication networks, nuclear reactor sites, open space, and urban growth. However, because of their regional scale, they are not intended to be used for specific site investigations; these should be undertaken by qualified engineering geologists and soils engineers. The maps are designed so that in future years, as more detailed and useful data are obtained for making more sophisticated slope-stability maps (perhaps in part using computer-based technologic improvements), they will form a data base to be incorporated in the next generation of maps.

For land-use planning purposes, the six relative slope stability categories and subcategories have been subdivided into three risk groups—low, moderate, and high. Each group suggests specific actions and data requirements. These actions and data needs have been examined for three different levels of governmental concern: (1) regional, (2) county and city, and (3) specific sites. Regional slope-stability analyses such as those described herein must be supplemented by more detailed information at levels (2) and (3). At all levels of government, effective planning and land-use decisions require a continuing exchange between earth scientists, planners, and engineers.

INTRODUCTION

By T. H. Nilsen, T. C. Vlasic, and W. E. Spangle

The recognition of landslide hazards in urban areas is essential if safe living environments are to be provided. Planners and earth scientists need to work together to achieve such safety. The earth scientist prepares data on slope stability that can be used by the land-use planner in formulating policy to reduce landslide hazards.

This study focuses on landslide conditions in the San Francisco Bay region and the procedures associated with collecting slope-stability information and applying it to land-use planning. The methods and examples that are described are also relevant to manage-

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ment of lands in other hillside areas where planning and governmental processes are similar.

Slope failures have caused millions of dollars worth of damage and losses in the San Francisco Bay region alone. The delineation of unstable areas and the prediction of landslide possibilities can mitigate the damage suffered by local communities as well as the adverse effects on terrain used for nonurban purposes, such as watershed, agricultural, and forest lands. In fact, land-use planning to reduce this risk to life and property is mandated, in one way or another, by Federal and State legislation.

Landslides are a local phenomenon, and slope stability varies from area to area. Consequently, detailed guides for planning agencies to follow in acquiring and applying slope-stability data are not presented in this study. General guidelines and some examples are provided, however, to assist jurisdictions in determining ways to reduce risk from landslide hazards. In making this determination, it is necessary to balance the costs of acquiring and interpreting adequate earth-science data against the benefits to be gained by reducing losses.

Another important objective of this report is communication between the earth scientist and the land-use planner. Therefore, we describe the activities and products of the two disciplines and their interrelations. Communication is essential if land-use planners and earth scientists are to be responsive to each other's ideas. The changing requirements of the planner need to be made clear to the earth scientist, so that earth scientists can prepare products that can be readily incorporated into the planning and decision-making process.

The first section of this report serves as a general introduction to planning for slope stability and includes a general description of the nationwide potential for landsliding. A description is also given of the losses resulting from landsliding in the major urban regions of California. In addition, the concept of "risk analysis" is described together with the relation of slope stability to land-use planning.

The second section presents a discussion of the relative slope stability of the San Francisco Bay region. A logical method for preparing regionwide slope-stability information is described in detail.

The third section provides a description of how slope-stability information can be applied to mitigate potential hazards and reduce risk to life and property. Ways of applying the relative slope-stability map of the bay region to planning at the regional and local level are discussed. In addition, Federal, State, and regional involvements are outlined, and basic guidelines, techniques, and examples are described.

The fourth section is a summary of major findings of the study. Recommendations are offered both for improving slope-stability mapping and for applying slope-stability data in planning and decisionmaking.

In the pocket of this report are three slope-stability maps that cover the entire San Francisco Bay region at a scale of 1:125,000. These maps divide the land area of the region into several categories and subcategories of relative slope stability on the basis of geologic analyses. The maps, which are a result of more than 5 years of data collection, assimilation, and analysis, present the major results of this study.

PLANNING FOR SLOPE STABILITY— AN OVERVIEW

Slope instability is, perhaps, potentially the most dangerous and damaging geologic hazard threatening residents of hillside areas. Experience has shown that failure to recognize slope-stability hazards during planning and development can result in catastrophic destruction. At the same time, geologists can determine the potential for landsliding through study of such factors as bedrock and soil conditions, slope of the land surface, earlier landslide deposits, and amount of rainfall. In addition, it has been found that in most cases, through sound planning and engineering, landslides can be controlled or avoided. Thus it is important for planners and geologists to work together to inform the general public and decisionmakers of ways to reduce problems and cost of slope instability.

Earth-science information from the geologist, such as is described later in this report, can be of great importance to the planner (as advisor to decisionmakers on appropriate actions in preparing, adopting, and implementing comprehensive plans) to ensure acceptable levels of risk to life and property. The land-use planner, by profession a generalist and coordinator, plays a key role in seeing that slope stability is considered as well as all other physical, social, and economic conditions that affect a region or community. The planner must also know what roles other planning agencies and governmental bodies, from the local to the Federal level, play in land-use planning.

To put planning for slope stability in context, the magnitude of the landslide problem, particularly as it exists in California, is described below. In addition, some general procedures for reducing landslide risk through sound planning and decisionmaking are discussed. To provide perspective on government involvement in planning for slope stability, land-use planning in the San Francisco Bay region is used as an example.

THE LANDSLIDE PROBLEM

Several studies have been made of the historic distribution and potential occurrence of landslides for all of the United States (Sorensen and others, 1975). Figure 1, showing landslide severity of the United States, was prepared by Baker and Chieruzzi (1958) using a regional concept of landslide occurrence based on physiographic divisions of the United States. Radbruch-Hall and others (1976) produced a preliminary landslide overview map of the conterminous U.S. A chart (table 1) contained in a report of the Federal Office of Emergency Preparedness (1972) relates types of landslides to major physiographic areas of the United States and describes their severity in terms of lives and property losses. Although these studies are of limited usefulness in land-use planning because they are so generalized, they clearly indicate that in many areas throughout the United States, landslides are a risk to life and property.

The severity of the landslide hazards can be judged from a review of slope failures that have occurred in California. Figure 2 is a generalized map of the State showing relative "severity zones" ranging from "least" to "most" landslides. Because of the scale of the map, the amount of detail is limited. Thus, the units shown on the map cannot be used to define local landslide conditions.

Landsliding in California causes damage to structures as well as loss of usefulness of the land itself (measured by cost of remedial measures). Past damage to urban areas in the State has been calculated in terms of millions of dollars (California Div. Mines and Geology, 1971). Although individual landslides may affect only a few houses and the amount of movement may be slight on many landslides, landslides are so numerous that the total annual loss is great.

Landslides that have occurred on "urbanized" hillsides of the State's two major populated areas—the

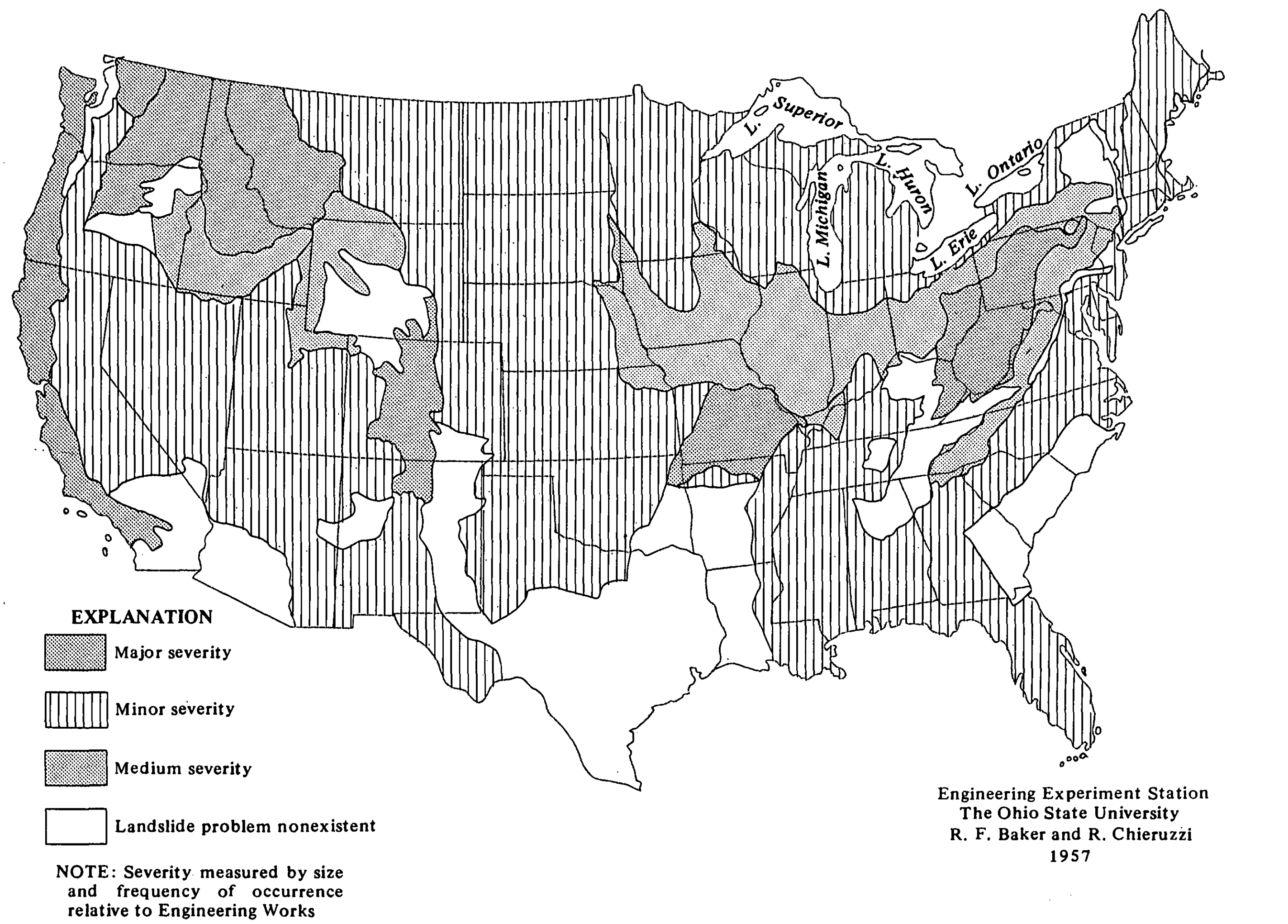


FIGURE 1.—Landslide severity in the United States (Baker and Chieruzzi, 1958).

TABLE 1.—*Distribution, frequency, and losses by landslide type in the United States*

[Office of Emergency Preparedness, 1972]

Type of slide	Major areas	Number of historical slides	Approximate Frequency per 100 miles (260 km²)	Approximate Frequency per 40,000 miles (103,600 km²)	Estimated property damage (million $ adjusted to 1971 values)	Recorded deaths
Rockslide and rockfall	White, Blue Ridge, Great Smoky, Rocky Mtns. and Appalachian Plateau	Several hundred	---	1 per 10 yr	30	42
Rockslump and rockfall	Widespread in central and west U.S.; prevalent in Colo. Plateau, Wyo., Mont., southern Calif., Oreg., and Wash.	Several thousand	10 per yr hill areas; 1 per yr plateaus	100 per yr. hill areas; 10 per yr. plateaus	325	188
	Appalachian Plateau	Several thousand	1 per 10 yr	70 per yr	350 (mainly in highway and railroad damage)	20
	Calif. Coast Ranges, Northern Rocky Mtns.	Several hundred	1 per 10 yr	10 per yr	30	--
Slump	Maine, Conn. River Valley, Hudson Valley, Chicago, Red River, Puget Sound, Mont. glacial lakes, Alaska	About 70	1 per 100 yr	1 per yr	140	103
	Long Island, Md., Va., Ala., S. Dak., Wyo., Mont., Colo.	Several hundred	1 per 50 yr	1 per yr	30 (mainly to highways and foundations	--
	Miss. and Mo. River valleys, eastern Wash., southern Idaho	Several hundred	1 per 10 yr	1 per yr	2	--
	Appalachian Piedmont	About 100	---	1 per yr	less than 1	--
Debris flow and mudflow	White (N.H.), Adirondack, and Appalachian Mountains	Several hundred	1 group slides, 10+ per group, per 100 yr in White Mtns. and North Carolina	1 group slides, 10+ per group, per 15 yr	100	89

Los Angeles and San Francisco Bay regions—are of special importance to Californians. Before World War II, hillside subdivisions were not uncommon; however, they were considerably different from postwar subdivisions in nature of development, scale, and amount of grading. Most of the earlier structures were individually built single-family houses without much grading. The postwar population migration into California with its accompanying demand for housing, particularly on view sites, resulted in increased development of hillsides, especially in the Los Angeles and San Francisco Bay areas. Mass grading operations were made possible by the use of heavy excavation equipment developed during the war, and initially, very few controls were placed on the operations. Grading was often done without adequate compaction, erosion control, or provision for drainage. As a result, major and minor landslides occurred subsequently, and homes were destroyed.

An unusually wet winter in 1951–52 caused erosion, settlement, subsidence, and major landsliding in many parts of Los Angeles; as a result losses were heavy (Yelverton, 1971). Consequently, in 1952 the first grading ordinance in Los Angeles was adopted, placing some control and supervision on all grading activities. However, despite these grading controls, losses due to landslides continued, and when such losses were combined with termination of landslide insurance by the insurance industry in the late 1950's, many hillside residents reached a state of "semi-hys-

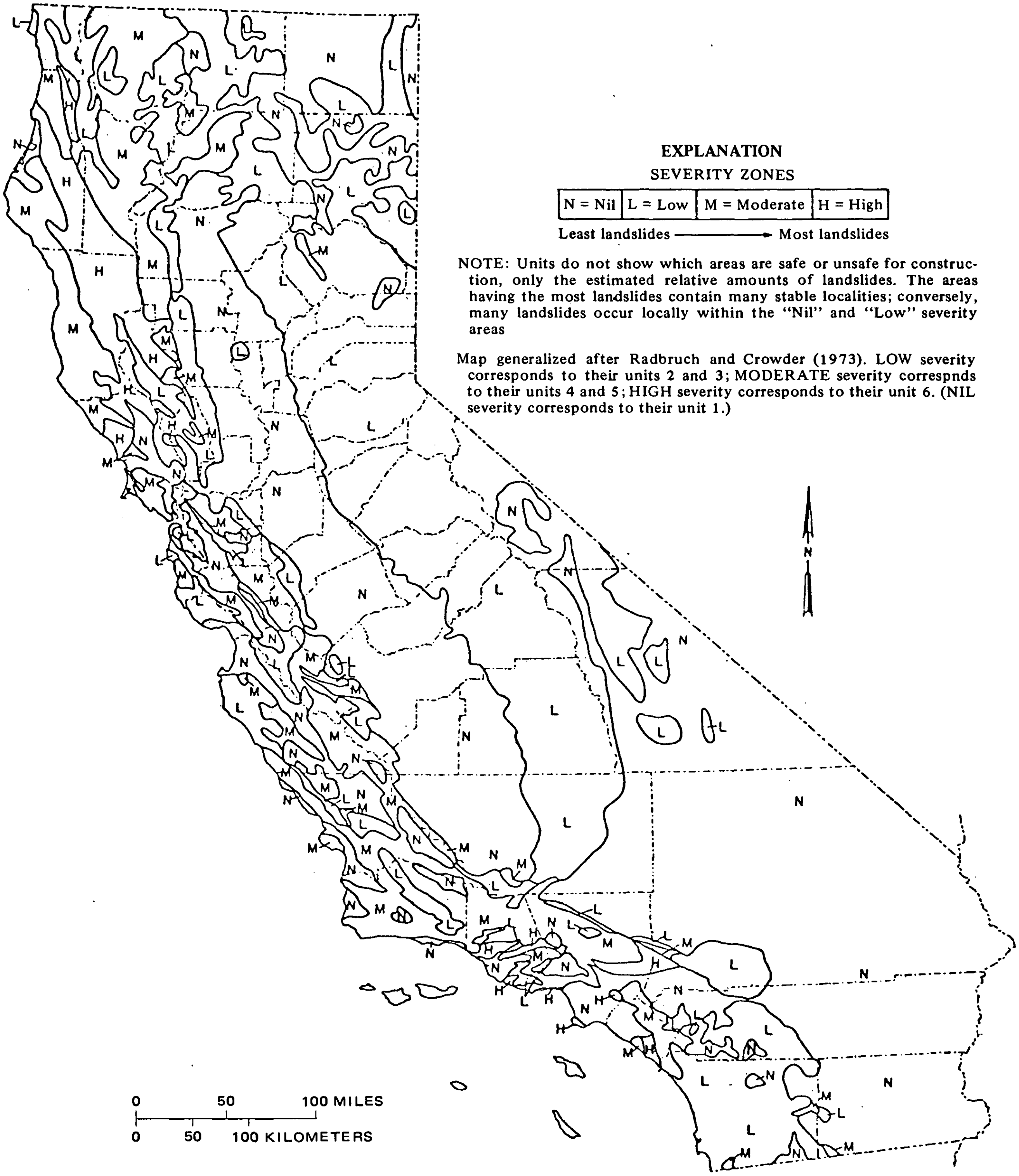


FIGURE 2.—Generalized map showing relative amounts of landsliding in California (from Alfors and others, 1973, as modified from Radbruch and Crowder, 1973).

teria" (Yelverton, 1971). During a heavy storm in the winter season of 1961–62, approximately 1,700 of the 60,000 hillside homes in Los Angeles were damaged (Gill, 1967; Alfors and others, 1973). The estimated cost of repairs ranged from $50 to over $100,000 per site. The total estimated cost was about $5,440,000, or an average of $3,200 for each of the 1,700 sites.

After the disasters that occurred in the rainy season of 1961–62, Los Angeles amended the 1952 grading ordinance, making it more stringent. Slope angles were regulated, and both soils and geologic reports were required, where necessary, before issuance of permits. All grading was to be supervised by engineering geologists and soils engineers.

The San Francisco Bay region (fig. 3) has also had its share of damaging landslides, and many counties and cities have adopted grading ordinances similar to those in Los Angeles. The history of landsliding in the bay region is discussed in more detail later. However, to provide insight to the slope-instability problems that geologists, planners, and decisionmakers in the San Francisco Bay region must face, data describing recent costs of landslides in the region are presented in table 2.

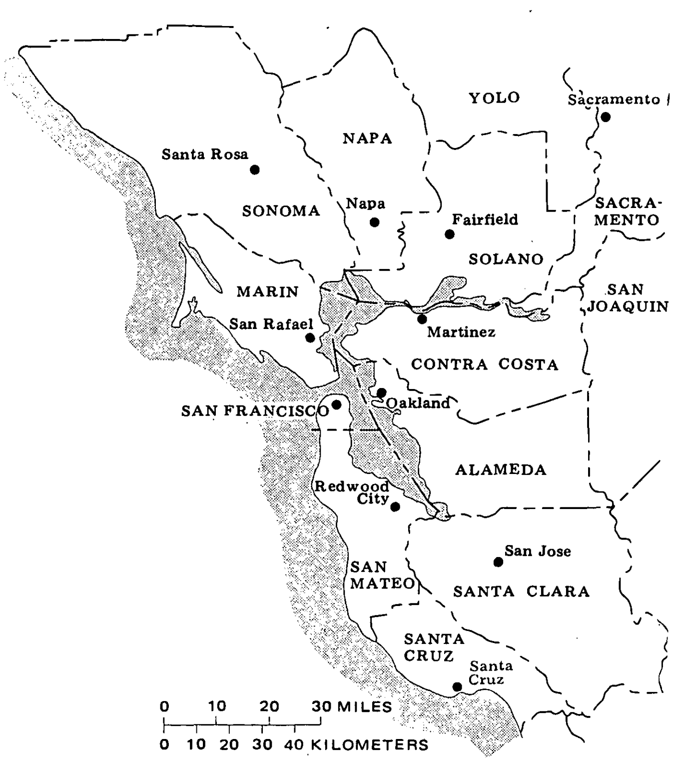


FIGURE 3.—Index map of San Francisco Bay region.

An indication of the magnitude of the landslide problem in the bay region can be obtained from the reports by Taylor and Brabb (1972) and Taylor, Nilsen, and Dean (1975). These reports present the locations of all recorded landslides and the public and private costs of these landslides for the entire region during the rainy seasons of 1968–69 and 1972–73, respectively. In a recent study of the natural conditions that control landsliding in the bay region, Nilsen, Taylor, and Dean (1976) compared the data from the 1968–69 and the 1972–73 rainy seasons. The purpose of the analysis was to compare modern landslides in the bay region to ancient landslide deposits, slope, bedrock geology, and the temporal distribution of precipitation. The landslide information reported in the study is summarized in tables 2 and 3. The study also showed that large numbers of landslides were triggered during storm periods with more than 6–8 inches (15–20 cm) of rain in areas where 10–15 inches (25–38 cm) of rain had previously fallen during the season.

One of the most important observations of Nilsen, Taylor, and Dean (1976) was that human activity in the hills marginal to San Francisco Bay has been a prime force in creating or adding to problems of slope stability. They also observed, however, that careful geologic mapping and slope-stability analysis (considering ancient landslide deposits, slope, bedrock geology, and rainfall patterns) can provide fairly reliable information about areas that are susceptible to slope failure. Use of such information in land-use planning can help minimize future landslide damage that would otherwise result from human activities.

Other conclusions were drawn on frequency of high rainfall and the nature of landslide damage that can be expected during unusually wet winters. Winters of heavy rainfall may occur every five to ten years. Most damage from landsliding triggered by rainfall during the wet winters will probably be to roads and private homes, with lesser damage to utilities, public buildings, parklands, dams, and other structures. Public and private costs will not necessarily be proportional to the number of landslides reported for any specific area, but costs will be related more directly to the type and location of landslide activity. Precautions can be taken to reduce potential landslide damage during especially wet winters, including installation of special drainage systems both in developed areas and as part of new development, and addition of vegetation to help stabilize slopes. More will be said about mitigating these hazards in later sections.

The hazard that landsliding represents to man and his works in the bay region is more specifically described in a study of the San Jose Highlands hillside development in the northeastern part of the city of

TABLE 2.—*Losses from landslides in 1968–69 and 1972–73 in the San Francisco Bay region*

Costs	Alameda	Contra Costa	Marin	Napa	San Francisco	San Mateo	Santa Clara	Solano	Sonoma	Totals
1968–69 RAINY SEASON[1]										
Public:										
State 5	$ 53,000	$1,970,000	$ 164,000	$ 48,000	$ 33,000	$ 735,000	$ 148,000	$ —	$1,844,800	$ 4,995,800
County:										
Roads and purchases	390,000	1,682,190	678,950	380,000	—	448,500	904,758	4,000	688,750	5,177,148
Tax loss	—	—	—	—	—	12,000	—	—	—	12,000
Private:										
Property depreciation	3,942,900	1,295,070	—	800,000	—	583,056	484,520	—	—	7,105,546
Other	986,800	145,000	82,000	—	100,000	662,462	7,000	—	—	1,983,262
Miscellaneous	24,000	90,000	130,000	250,000	—	1,158,000	355,000	—	[2]3,900,200	5,907,200
Total	5,396,700	5,182,260	1,054,950	1,478,000	133,000	3,599,018	1,899,278	[3]4,000	[3]6,433,750	[4]25,180,956
1972–73 RAINY SEASON[5]										
Public:										
State	$191,000	$ 40,243	$ 340,000	$ 87,000	$400,000	$2,182,500	$ 41,000	$ —	$ 195,000	$ 3,476,743
County	20,000	901,400	630,570	42,000	see "City"	50,000	?	8,750	?	1,652,720
City	57,500	—	967,150	—	90,000	49,000	30,543	200	1,000	1,195,393
Parks	—	10,845	—	300	—	—	4,000	—	4,250	19,395
Tax loss	2,345	22,140	32,820	—	—	29,810	—	—	?	87,115
Private	88,400	712,550	1,093,950	2,000	—	1,284,000	74,518	19,500	10,000	3,284,918
Total	359,245	1,687,178	3,064,490	131,300	490,000	3,595,310	150,061	28,450	210,250	9,716,284
COST BREAKDOWN, 1968–69 AND 1972–73[6]										
Population[7]	1,073,184	555,805	206,038	79,140	715,674	556,234	1,064,714	171,989	204,885	4,627,663
Cost per capita:										
1968–69	$ 5.03	$ 9.32	$ 5.12	$ $ 18.68	$ 0.19	$ 6.47	$ 1.78	$ 0.02	$ 12.37	
1972–73	0.33	3.04	14.87	1.66	0.68	6.46	0.14	0.17	1.03	
Average	2.68	6.18	10.00	10.17	0.44	6.47	0.90	0.10	6.70	avg. 4.85
Dwelling units	365,000	173,000	68,000	25,000	295,000	185,000	323,000	51,000	68,000	1,553,000
Cost per unit:										
1968–69	$ 14.79	$ 29.96	$ 15.51	$ 59.12	$ 0.45	$ 19.45	$ 5.88	$ 0.08	$ 37.26	
1972–73	0.98	9.75	45.07	5.25	1.66	19.45	0.46	0.56	3.09	
Average	7.89	19.86	30.29	32.19	1.06	19.45	3.17	0.32	12.06	avg. 14.03
Area of urban land (sq mi)	162	102	40	10	39	90	184	27	26	680
Cost per square mile:										
1968–69	$33,313	$50,806	$ 26,374	$147,800	$ 3,410	$ 39,989	$ 10,322	$ 148	$ 97,452	
1972–73	2,218	16,541	76,612	13,130	12,564	39,948	816	1,054	8,087	
Average	17,766	33,674	51,493	80,465	7,987	39,969	5,569	601	52,770	avg. 32,254.89

[1] From Taylor and Brabb (1972).
[2] Costs attributed to the Warm Springs Dam totaled $3,900,000 in 1968–69, but no costs were reported in 1972–73. This cost is anomalous and has been omitted from this comparison.
[3] These counties did not report a considerable part of their costs, hence these values will be lower than the actual amount.
[4] Total should include $213,000 damage reported by Pacific Gas and Electric for the entire region.
[5] From Taylor, Nilsen, and Dean (1975).
[6] From Nilsen, Taylor and Dean (1976).
[7] U.S. Census, 1970.

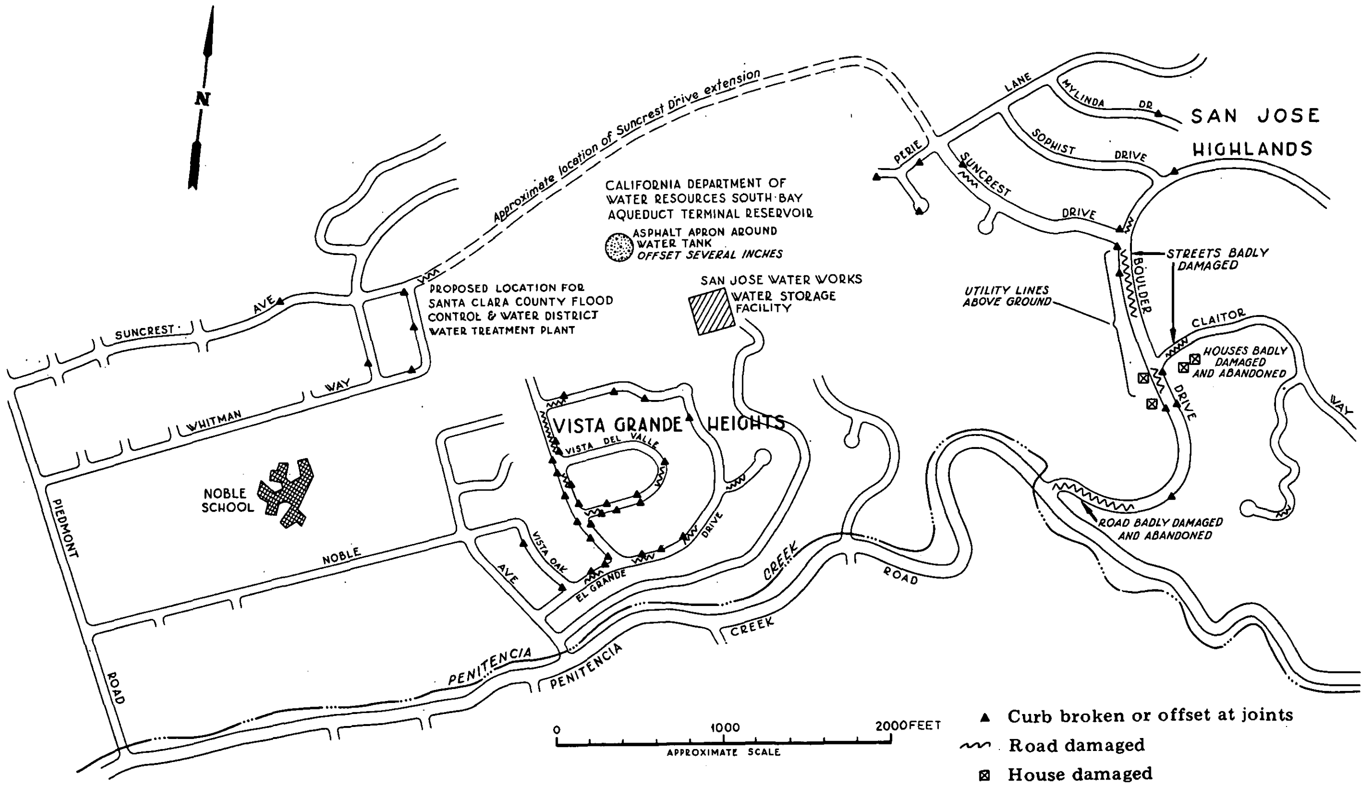
TABLE 3.—*Number and distribution of landslides that occurred during the 1968–69 and 1972–73 rainy seasons in the San Francisco Bay region*

[From Nilsen, Taylor, and Dean, 1976]

	1968–69	1972–73
Number of landslides reported	335	411
Landslides that took place within 2,000 ft (600 m) of an ancient landslide deposit (percent)	55	69
Landslides that took place on slopes steeper than 15 per cent (percent)	74	80
Landslides that took place in soils overlying or within bedrock geologic units generally considered to be highly susceptible to slope failure, as shown on plates 1–3 (per cent)	61	65

San Jose (Nilsen and Brabb, 1972). Landslide deposits in the area were mapped, and damage from landsliding to roads, curbs, utilities, and homes was noted (fig. 4). Nilsen and Brabb (1972) found the dollar loss as a result of development on these landslide deposits to be as follows:

The economic loss as a consequence of development on these landslide deposits is already large, will continue to grow, and will probably become significantly greater if additional development is permitted without thorough engineering geology investigations of the area. The estimated 1969–70 loss in market value for all houses in San Jose Highlands, for example, was $228,000, the loss for lots was $195,000, and the loss in valuation for specific landslide damage to certain houses was $61,520—a total loss of $484,520 (Santa Clara County Assessor's Office, written commun., 9/22/71). The cost data tabulated below, provided by the San Jose Department of Public Works (written commun., 9/28/71), reveal the variety and magnitude of expenses to a municipality when landslide activity takes place within a subdivision area:



The damage observed appeared to be, or in some cases definitely is, related to landslide movement. No comparable damage was observed outside of the area mapped as landslides. Several of the roads, curbs, and houses within the landslide areas were checked and had no apparent damage, but a more thorough survey must be made before the extent of the damage can be fully assessed.

Observations of damage were made during 2 days of field checks in July and September 1971. Damage repaired before those dates is not shown on the map.

FIGURE 4.—Map showing damage observed in the San Jose Highlands area in northeastern San Jose, Calif., in 1971 and preliminary photointerpretation map of landslide and other surficial deposits in the same area (from Nilsen and Brabb, 1972).

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

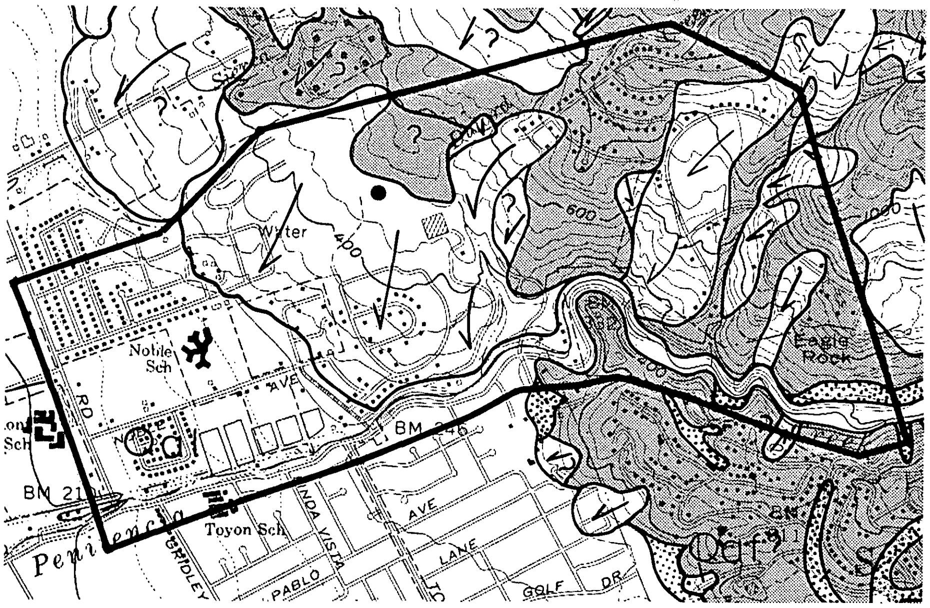
Soils study and consultant fees	1968	$10,000
Soils study and consultant fees	1969	10,000
Consultant for new road	1970	30,000
Construct 1,400′ gravel-fill interception ditch (no water was apparently removed)	1969	15,000
Clean Hydraughers several times	--	3,000
Construct de-watering wells (deactivated 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



SCALE 1: 24,000
CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 10 FOOT CONTOURS
DATUM IS MEAN SEA LEVEL

Qal — Alluvial deposits

Colluvial deposits and small alluvial fan deposits

Qaf — Artificial fill only one shown

Bedrock *(Queried where identification uncertain)*

Landslide deposits *(Arrows indicate general direction of downslope movements; queried where identification is uncertain)*

FIGURE 4.—Continued.

No information was obtained on the cost of landslide damage in the map area outside of the San Jose Highlands, but landslides were a substantial and presumably costly problem during and after construction of terminal facilities for the South Bay aqueduct.

An important aspect of this example is that some landslide deposits were shown on a map published by the California Division of Mines and Geology as early as 1951, well before the land was developed (Crittenden, 1951). This is a case where some basic earth-science data were available but were not effectively incorporated into land-use decisions. The result of this failure was costly to San Jose and catastrophic for those individuals who lost their homes.

COSTS OF LANDSLIDE DISASTERS

It is evident that landsliding in an urban area often results in substantial costs that are borne by both public agencies and private landowners. Dollar costs include replacement or reconstruction of public facilities or utilities, loss or reconstruction of private structures, decrease in land values, and public acquisition of damaged land with corresponding loss of tax income. Although complete dollar cost figures for each landslide disaster are not always immediately available, they are fairly easy to estimate because they can be based on prevailing construction costs, land costs, and costs of materials.

In their study of landsliding in the San Francisco Bay region during the 1968–69 rainy season, Taylor and Brabb (1972) determined dollar costs as follows:

Two categories of costs are reported—public and private. Public costs are dollars spent or lost by governmental agencies, costs ultimately paid by the taxpayer.

Public landslide costs include such emergency expenses as salaries for firemen, policemen, and others responsible for protecting health and safety. These costs are rarely available and are not included in this report. Most of the public landslide cost consists of the direct expense of repairing, restoring, or relocating roads. This figure includes expenses readily attributed to specific large landslides and an estimate for clearing up smaller slides (included in budgets for routine road maintenance and repair). Some expense for damage to sewer lines, street lighting, sidewalks, and other publicly owned facilities is included, but this is a small part of the total cost.

To protect public property or to repair existing landslides, it sometimes becomes necessary for a public agency to obtain title to privately owned land. In addition to the original cost of procurement, the agency assumes costs for erosion and weed control and minor repairs. It sometimes becomes more economical to obtain title to property and have it vacated than to attempt to maintain services that are continually disrupted by an active landslide.

Litigation results in further public costs. No figures were obtained on costs of preparing and conducting court proceedings, and only limited data were available on settlements of civil suits resulting from landslide damage.

Another public cost is lost tax revenue when land is transferred from private to public ownership and thereby removed from the tax rolls. Revenue loss also results from devaluation of private property because of landslide damage and a subsequent lowering of the tax.

Private costs are those resulting from loss of real property, improvements, and possessions. Of these three, the last two can be replaced if an individual is financially able. The first, real property, may be rendered unusable. In addition to the direct costs of repairs, property that has been damaged by landsliding often depreciates in value. A reappraisal by the tax assessor's office that shows a difference between the fair market values before and after a landslide represents a loss to the property owners.

No attempt was made to put a dollar value on inconveniences, such as time lost taking detours. Nor were costs explored that resulted from evacuating a home—for example, the cost of food and lodging.

Some costs could not be classified under state, county, or private categories, and were grouped as "miscellaneous." These were costs that might be specifically for one county, slide damage where responsibility is disputed, litigation costs not specifically attributed to a governing agency, and costs to the Federal Government, cities, utility companies, sanitation districts, and water districts.

More difficult to calculate than the costs outlined above are the socio-psychological "costs" of a landslide disaster, yet such costs may have significant and lasting effects. These costs can range from emotional shock brought about from living with the landslide threat to actual loss of home or life. There are many documented cases from various parts of the world of loss of life from landslide disasters. For example, on May 4, 1971, a landslide at St. Jean-Vianney in the Lake St. John district of Quebec, Canada, destroyed 40 homes in a residential development and was responsible for 31 deaths (Legget, 1973, p. 427).

ACTIONS TO REDUCE "RISK"

Thus, in general, landsliding can be a major threat to man and his works. Damage and casualties from landslides and demands for government relief will certainly recur because of ill-advised developments that have already been built on unstable slopes and future development in unstable areas where an adequate evaluation of geologic hazards has not been made. This potential for disaster creates a "risk" which, simply defined, is a chance of damage or injury to life and property occurring over a period of time.

By incorporating information on relative stability of slopes in land-use planning, the public agencies charged with regulating use of land can formulate and implement effective strategies to significantly reduce the risk to life and property. For example, the application of modern grading techniques in the city of Los Angeles, which require grading to be done in compliance with the professional analysis of information on soils and geology, has reduced slope failure damage from $330 per site developed prior to 1952, to $7 per site developed after 1963 (Slosson, 1969). From slope-stability information prepared by geologists, landslide risks associated with any potentital or existing planning program, project, or structure can be defined. Through comparative analyses, these risks can be evaluated against risks of alternatives, planning decisions can be made, and measures can be implemented to reduce the risk. Thus potential costs, both public and private, can be reduced over a given period of time.

Critical to such risk analysis is the determination on the part of the governmental jurisdiction of the point at which a risk becomes acceptable. Generally, acceptable risk will be defined primarily on awareness of the range of risk associated with various activities and conditions and by the level of risk the majority of citizens will accept without asking for governmental action to provide protection.

Often risks from landsliding can be effectively mitigated through techniques such as special grading, installation of drainage devices, and landscaping for slope stabilization. Of course, it will be necessary to consider the total cost for such risk mitigation, such as costs for detailed slope-stability studies, cost to mitigate identified hazards in conjuction with land development, environmental-impact costs (for example, visual impact of mass grading), and public-safety costs. At some point, the landslide hazard becomes so great that the cost of mitigation clearly overshadows the benefits of development, or the hazard will be so great that it cannot be practically contained.

In any case, sufficient earth-science information should be available so that decisionmakers will be informed about the effects of their action (or inaction) on risk to life, damage to public and private property, and risk of economic or social dislocation. In addition, whenever a risk has been defined, the public agency should assume the responsiblity to make each individual aware of the risk. Mader (1974) provides the following insight on risk and community responsibility.

***Where does the responsiblity lie for protecting people and property? An often-heard argument is that if an individual wants to take the risk of building in a hazardous area, he should be allowed to do so. The argument goes on that only he will suffer in the event of a failure. In an isolated location, this position might be acceptable. But in urban and suburban settings, land failure on an individual property usually has intense repercussions on the surrounding area. Decreased property values, possible fire hazards, costly public assistance, and possible physical impact on adjacent land are frequent major results.

Similarly, a developer often says he is willing to accept the risk in an unstable area. In the end, of course, that risk is passed on to purchasers in the development and to the public agency that assumes responsiblity for streets and other public improvements, for the developer is usually out of the picture by the time a failure occurs. Thus the burden is unfairly shifted to all the taxpayers in the community.

It becomes clear that geologic hazards are not private matters, but concern the public in general. It is therefore incumbent upon government to protect the public interest.

Alfors, Burnett, and Gay (1973) have identified statewide risk in terms of dollar loss due to the 10 greatest geologic hazards. Their report projects the total dollar loss of property and life in the State of California from 1970 to the year 2,000 at $55 billion, of which $10 billion will be the result of landsliding. Of greatest significance is their finding that $38 billion of the total estimated losses could be prevented. Thus the risk to life and property could be reduced by nearly 70 percent by applying the most advanced loss-prevention measures.

LAND-USE PLANNING AND REGULATION IN THE SAN FRANCISCO BAY REGION

In the bay region and throughout California, planning and regulation carried out at the local (city and county) level have had the greatest effect on actual distribution of land use. There is increasing awareness, however, that local planning decisions often have broader impact. Local powers and functions are more and more affected by the actions of other levels of government. Therefore, while slope-stability problems are largely local in nature, requirements or directives concerning them may well be initiated from other levels of government. Higher level agencies often preempt or affect the decisionmaking of lower level agencies through regulating planning programs and program funding, the content of local planning, standards of air and water quality, and through shared responsibility for specific functions such as transportation, air quality, and geologic mapping.

FEDERAL LEVEL

The Federal Government exerts its most significant influence on planning and regulation for slope stability through its funding requirements. The following Department of Housing and Urban Development (HUD) programs and requirements pertain to the problem:

1. Required Land Use Element of the Comprehensive Planning Assistance Program (HUD 701).
2. HUD Housing Production and Mortgage Credit/Minimum Property Standards.
3. Federal Disaster Assistance Administration (FDAA).

These programs and requirements are discussed in detail in later sections of this report.

Other agencies besides HUD that have significant interest in slope stability for land-use planning purposes are the U.S. Geological Survey (USGS) of the Department of the Interior and the Soil Conservation Service (SCS) of the Department of Agriculture. The USGS provides technical information on landsliding and the relative stability of slopes but has no powers other than review of Federal projects. The SCS has responsibility for developing and carrying out a national soil and water conservation program and, as a part of this program, provides information on soil stability.

STATE LEVEL

The primary influence exerted by the State of California regarding planning for slope stability is through the State law requiring open space, seismic safety, and safety elements of general (comprehensive) plans. Zoning and subdivision regulations must be consistent with such plans.

The required open-space element provides for preservation as open space of highly hazardous areas such as active landslides, which cannot be effectively controlled. The required seismic-safety element is to identify seismic hazards including appraisal of mudslides, landslides, and slope stabilty as necessary geologic hazards that must be considered simultaneously with other hazards such as possible surface ruptures from faulting, ground shaking, ground failure, and seismically induced waves. The required safety element is to provide for protection of the community from fires and geologic hazards.[2] The nature of these elements and related general-plan requirements and their relation to planning for slope stability are discussed in detail in a later section of this report. Significant State influence on the local planning process in California has also resulted from the adoption of the California Environmental Quality Act of 1970 by the State Legislature. This act requires that any "project," unless categorically exempt, requiring discretionary action by a government agency must be evaluated for its enviromental impact; a "project" thus includes almost all local land-use decisions and any action on a local general plan. The Resources Agency of California has published guidelines (section 15000 of the California Administrative Code) for interpretation of the act which, in part, require that a full environmental-impact investigation and report, meeting specified requirements, be completed for any project that could expose people or structures to major geologic hazards such as landsliding. The investigation and report must be approved by the local agency with project approval authority; the report findings are to guide the actions of the local decisionmakers.

REGIONAL LEVEL

Regional land-use planning and decisionmaking is a complex process involving interconnected responsibilities and functions of a bewildering array of public agencies and units of government. Agencies with regional jurisdiction (including at least parts of more than one county) attempt to solve problems of regional significance with powers either voluntarily ceded to them by city and county governments or conferred directly by Federal or State legislation. Decisionmaking authority at the regional level is diffused among more than 20 agencies with disparate responsiblities and jurisdictional boundaries. Five major agencies have limited approval and(or) regulatory authority over projects related to slope stability; the responsiblities of these agencies are briefly discussed below. The impact of slope stability on their land-use planning activites is discussed later.

[2] Because of the relation between the seismic-safety and safety elements, several bay region communities have chosen to combine the elements into one "seismic-safety/safety" element.

ABAG (the Association of Bay Area Governments) is a council of governments, established in 1961 to "meet regional problems through the cooperative action of its member cities and counties." At present, 86 of 92 cities and 8 of 9 counties in the bay area are members. ABAG is the areawide comprehensive planning agency for the bay area, and its approved regional plan provides a policy framework for regional planning of a variety of issues, including safety from geologic hazards. A key function of ABAG is formulating criteria for evaluating the regional significance of developments and activities or of special land areas having critical environmental concerns. ABAG implements its plans and policies primarily through project review and joint memorandums of agreement with other agencies for pursuit of planning objectives. The Federal Government has designated ABAG as the "clearing house agency" for the bay region. In this capacity, ABAG reviews requests for Federal funds available under more than 150 Federal programs. ABAG also reviews and comments on Federal development projects in the bay area and on environmental impact statements, required by Federal and State law for projects in the region.

The MTC (Metropolitan Transportation Commission) was established to coordinate development of regional transportation facilities. Its planning and project-review responsibilities and other duties are normally coordinated with ABAG. MTC is charged with preparing and adopting a Regional Transportation Plan, including proposals for major highways, mass transit, transbay bridges, airports, and harbors. It must also develop a transportation improvement program and a financial program for carrying out that program. MTC's approval is required for all applications from local governments or districts for State or Federal funds for any kind of transportation facility and certain applications from other government agencies. In addition to reviewing projects, MTC administers the public transit funds acquired from State and local sales taxes on gasoline. MTC needs slope-stability information in planning the location of transportation facilities and reviewing transportation proposals.

The BCDC (Bay Conservation and Development Commission) initially was authorized by the State Legislature to prepare a comprehensive plan for San Francisco Bay and its shores and to control development within its area of jurisdiction. The plan was subsequently adopted by the State Legislature, and BCDC became a permanent agency charged with carrying out the plan. The adopted plan has legal status and serves as a guide in the review of projects. BCDC shares jurisdiction over land-use decisions with the cities and counties, which retain normal land-use and building-permit controls. However, with certain minor exceptions, a permit from BCDC is required for all projects within its jurisdiction. An important consideration in BCDC's planning and regulatory activities is the effect of unstable bay muds on land-use proposals.

The CCZCC (California Coastal Zone Conservation Commission), working with six regional commissions, was created by initiative and was charged with preparing a plan for the future of the California coastal zone. While the plan was being prepared, the commissions controlled all development, through a permit process, to insure consistency with the objectives of the legislation and the emerging plan policies. The plan was presented to the Governor and Legislature in December, 1975 for adoption and implementation. In September 1976 the California Coastal Act of 1976 was enacted, establishing the California Coastal Commission and six regional commissions as successors to the previous commissions. Under the terms of the Act, the six regional commissions will expire 30 days after the last required local coastal program has been certified, but no later than January 1, 1981. Coastal areas of the bay region are represented by two regional commissions: Central (San Mateo County) and North Central (San Francisco, Marin, and Sonoma Counties). The Coastal Plan stresses the importance of considering natural earth processes, particularly landslides, in planning for conservation and development of the land within the coastal zone.

LOCAL LEVEL

Although California cities and counties are parts of the State, they exercise broad authority over most local concerns. However, the scope of local land-use planning is mandated to a large degree by State requirements for general plans, consistency of zoning and subdivision ordinances with general plans, and environmental-impact assessment.

In addition to State-mandated responsibilities for land-use planning and regulation, local jurisdictions find themselves responsible for such specific hazards as landsliding. The Sheffet decision (Los Angeles Superior Court Case No. 32487) declared that a public entity is liable for damages to adjacent property resulting from improvements planned, specified, or authorized by the public entity in the exercise of its governmental power. Also, the Los Angeles County Superior Court (Case No. 684595 and consolidated cases) found the county liable for damages which may have resulted from road work and the placement of fill by the county. This case concerned the Portuguese Bend landslide, in the Palos Verdes Hills in Los Angeles. As a direct result of these and similar cases, counsels to local government have advised local decisionmakers to give special attention to problems of slope stability

Although State requirements establish the framework for local planning, local agencies have some discretion in how the requirements are carried out. Many local agencies in California have been able to adapt the requirements (which have evolved in a piecemeal manner over a number of years, most often in response to crisis situations) into more comprehensive and creative planning strategies for decisionmaking.

SLOPE-STABILITY CONSIDERATIONS IN LAND-USE PLANNING

If landslide risk is to be reduced, it is essential that planning for mitigation of geologic hazards take place throughout the land-use planning process. Land-use planning is that part of comprehensive planning which deals with all aspects of the future growth and development of an area and requires the proper balance of economic, political, social, and physical factors. Land-use planning is concerned with the arrangement and types of land uses, their impact on the landscape, their relation to transportation and other community facilities and utilities, and the changes in these conditions and relations over time.

Although the form and content of land-use plans and implementing strategies vary across the United States and from jurisdiction to jurisdiction there is a strong similarity in the planning process. The planning process is composed of six conceptually distinct yet functionally related phases. Although these phases are generally followed in sequence, there is a great deal of "recycling" or interplay between them. The phases are: (1) issue identification and definition of objectives; (2) data collection and interpretation; (3) policy review and plan formulation; (4) impact evaluation; (5) plan review and adoption; and (6) plan implementation.

The planning process is shown in schematic form in figure 5. As shown by the arrows, each phase of the process is interrelated with all the others, and the sequence, while logical, often varies, especially in response to crises, political opportunities, or legal requirements. Interaction among the phases, however, usually is continuous. For example, plan formulation often indicates the need for additional information; additional information may alter the concept of the objectives and problems; and plan implementation may reveal the need for additional information or modification of the plan.

Public initiative and response are key parts of every phase of land-use planning. "Public" may refer to

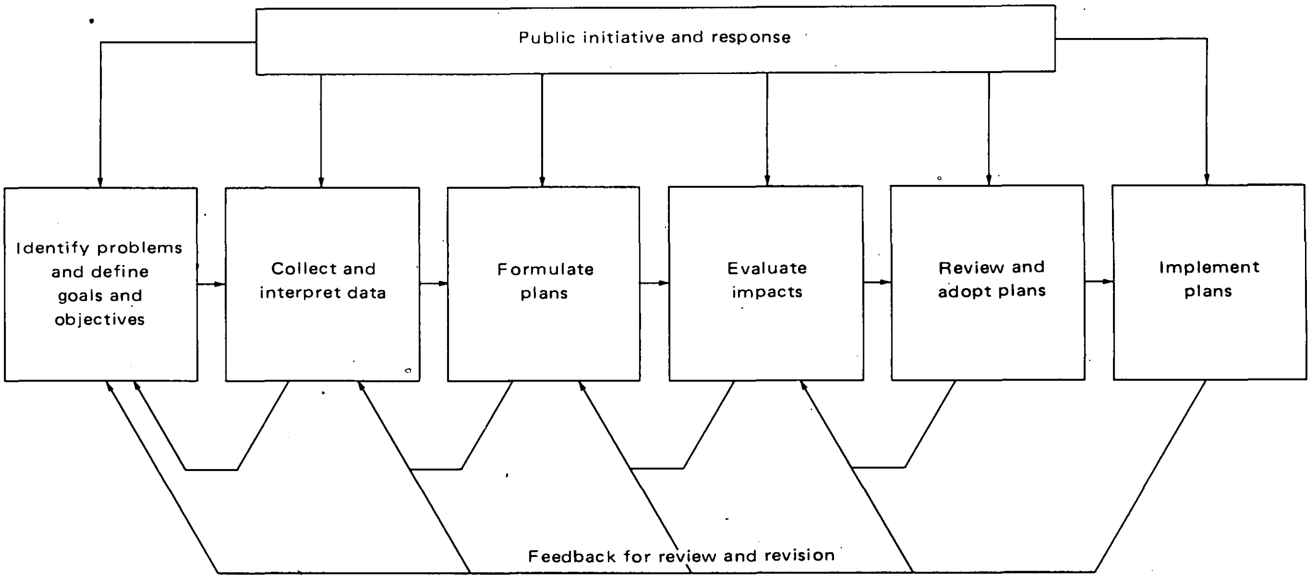


FIGURE 5.—The land-use planning process.

elective political bodies, special-interest groups, or interested individuals. Elected officials have final responsibility for most key policy decisions, although persons in nonelective positions actually make many important day-to-day decisons. Decisions range from the decision to engage in a planning effort, to the final approval of a plan and adoption of implementing regulations, programs, and procedures.

The phases of the land-use planning process are explained below with a brief description of how they relate to planning for slope stability:

1. *Issue identification and definition of objectives.*—Land-use concerns are identified and reviewed in relation to any existing land-use plans and policies, projected growth trends, and anticipated changes; a tentative set of goals and priorities is defined. Some issues are obvious because of their continuing impact on many people, for example the need for conveniently located quality low-cost housing; others are less obvious. However, earth-science concerns such as slope stability frequently do not become apparent until a disaster has occured. At the time an issue is identified, therefore, it is important that the planner assemble and review the available earth-science information so that appropriate objectives and priorities can be defined. A regional slope-stability map such as is contained in this report could be an essential part of this phase of land-use planning.

2. *Data collection and interpretation.*—A program for utilizing available data and compiling new data is developed in connection with the goals and priorities established in phase 1. The planner, together with the earth scientist, needs to determine what earth-science data are available and the most effective manner of using existing data and collecting and interpreting new data. Interpretive maps and text should be close in scale and detail to other basic planning information. The planner estimates the future demand for land, considering projections of population growth and distribution, economic activity, social and cultural needs, and transportation requirements. Preparation of land-capability maps, showing potential uses of specific areas, can be a significant part of this phase.

The slope-stability map in this report would be useful in helping define land capability at the regional level. In addition, it provides information needed to evaluate the regional significance of the slope-stability problem. The regional slope-stability map will provide the city or county planner with some indication of the local problem, but it will be necessary to work closely with an earth scientist to determine the requirements for additional slope-stability information to serve specific local needs.

3. *Policy review and plan formulation.*—On the basis of a land-capability study, appropriate projections, and environmental, economic, social, and political analyses, local or regional land-use strategies are considered. Alternative land uses can be evaluated, and the best uses and the best ways of guiding growth and managing land use can be selected. A land-use plan is then prepared, incorporating the policy and proposals necessary to serve as an effective basis for decisionmaking. In formulating plans for protection from slope failure, the slope-stability map will help to determine potential risk to life and property

from landsliding for each alternative use. Risk should be considered not only in terms of harm to the individual who occupies a particular area identified as unstable, but also in terms of impact on the public interest if damage should occur, including damage to adjoining public and private property. In addition, acceptable risk must meet Federal and State requirements, particularly when Federal or State funds are involved. Plans should consider all potential methods of implementation.

4. *Impact evaluation.*—Federal and State legislation in the late 1960's and early 1970's have focused considerable attention on "environmental impact evaluation," with the result that impact evaluation has become virtually a separate step in the planning process. Realistically, however, judging the effects of each alternative plan and land-use strategy is an integral part of plan formulation. As indicated in the discussion on plan formulation, development of land-use alternatives and management strategies is based on analysis of the environmental, economic, social, and political consequences of the various alternatives—that is, the impact evaluation of these various factors. In addition, impact evaluation is critical to analysis during implementation and particularly during review of land-development proposals.

5. *Plan review and adoption.*—The land-use plan, either separate or as part of a comprehensive plan, is prepared as a statement of city, county, or regional policy and as a commitment to a future course of action. The plan might be a series of policy statements establishing criteria for urban growth and land use and development, or it may take the form of a text containing policy and proposals accompanied by diagrams showing the desired or expected spatial distribution of land uses in the future. It is essential that policy-makers understand thoroughly the content, implications, and use in decisionmaking of any plan they adopt. They should also understand that the plan is a document that will change as new information becomes available. Most governing bodies are genuinely concerned about their constituency, the public, understanding the content and implications of plans prior to official adoption. It is highly desirable, therefore, that adequate information on the plans be made available as a part of the review and adoption process.

At the time of plan review, information should be available to provide background on how the plan was formulated. This information might include a description of data used to develop the plan proposals, among which might be a relative slope stability map and text. In addition, methods of implementation should be summarized, noting possible changes in regulations and implied expenditure of funds, environmental and economic impacts described, and social consequences analyzed.

Public review of plan proposals may bring recommendations for changing the plan. If this is the case, it will be necessary to repeat some of the earlier steps in the planning process.

6. *Plan implementation.*—After a plan is adopted, land-use regulations (for example, zoning, subdivision, and land development ordinances) and programs for land acquisition and capital improvement are prepared and adopted. Methods to implement slope-stability proposals can include partial or full acquisition of hazardous lands, open-space zoning of areas of great hazard, and establishment of special regulations to guide development in areas where unstable slopes require some limits on land use. Also, guidelines and procedures for conducting the earth-science studies needed to evaluate proposals should be established. Procedures should be developed and staff provided for reviewing soils and geology reports, environmental impact assessments, and project proposals.

The planning process is not finished with the completion of the six steps summarized above; it is an ongoing process that continually receives public input. Governments usually find that, by design or by circumstance, they are routinely revising their statement of goals, collecting and analyzing new information about their jurisdiction, revising statement of policy, updating plans, and enacting new strategies to implement their plans.

The foregoing generalized model of the planning process is necessarily idealized and simplified. Actual practices vary widely depending on the responsibility, authority, and financial position of the planning agency, the diversity of the planning area, the scope of the planning effort, and availability of data. For example, planning by regional councils of government is likely to emphasize the development of objectives, policies, and criteria for use in reviewing projects and plans, because the councils' Federally mandated power is that of review. Local planning, on the other hand, is more likely to emphasize the development of objectives, policies, and criteria to serve as a basis for public projects and land-use and development regulations—the latter traditionally a local responsibility. In addition, planning practices are not static. Planning is in a state of flux, with planners, legislators, and citizens searching for new ways to make the process more effective. The scope of planning is expanding and its role changing, fresh approaches are being tried, and new relationships—local, metropolitan-regional, State, and Federal—are emerging.

RELATIVE SLOPE STABILITY OF THE SAN FRANCISCO BAY REGION

By T. H. NILSEN and R. H. WRIGHT

One purpose of this report is to present a method of classifying the land surface of the San Francisco Bay region in terms of relative slope stability, or the relative susceptibility of the land surface to landsliding. The relative slope stability is portrayed in three maps that were prepared to indicate broad regional variations in relative slope stability at a scale of 1:125,000 (pls. 1, 2, and 3). The area is divided into five categories and one subcategory, ranging from stable areas, where landslides are highly unlikely to occur, to unstable areas, where landsliding is very likely to occur. The maps were prepared from an analysis of three of the more important factors that contribute to and control the generation of landslides—the nature of the underlying bedrock, the angle of slope of the land surface, and the presence or absence of earlier landslide deposits in the area.

Numerous studies and maps of relative slope stability have been made for different parts of the bay region at various scales and using different techniques. The entire region is covered in this report, and we have attempted to incorporate as many as possible of the previous concepts, ideas, and maps of slope stability in the bay region. However, as better data become available in the future, the maps presented herein should be revised and superseded by newer maps.

The nine counties bordering San Francisco Bay that make up the San Francisco Bay region cover a total land area of about 7,400 square miles (19,200 km^2) and include all or parts of 162 U.S. Geological Survey topographic quadrangle maps (fig. 6). The present population is about five million.

The region is extremely varied in topography, vegetation, relief, population density, geology, and local climate. It lies primarily within the central and northern Coast Ranges but includes part of the San Joaquin and Sacramento Valleys (Scott, 1959). The region is characterized by large flat areas that surround San Francisco Bay and extend into adjacent interior valleys (fig. 7). These valleys abut on rugged highlands that reach elevations of over 4,000 ft (1,200 m).

Population growth historically has been confined primarily to flat areas such as interior valleys and the margins of San Francisco Bay (Scott, 1959); however, in recent years, development has spread rapidly into upland areas, where slope-stability problems have become increasingly common. Though the damage from slope failures in the San Francisco Bay region may not be quite so destructive or so widespread as in some other parts of the world, for example, damage has been more severe in regions such as Calabria, Italy (Burton, 1970; Guida and others, 1974), urban centers such as Hong Kong (Lumb, 1975) and Rio de Janeiro (Jones, 1973), and along major highway networks in eastern Tennessee (Royster, 1973), Ohio (Marshall, 1969), and West Virginia (Long and Stinnet, 1969), nonetheless, landsliding is one of the major geologic problems and hazards in the bay region.

The geology of the bay region is very complex (Schlocker, 1968, 1970). Many different types of rocks and numerous active faults are present (Brown, 1970), and the structural and tectonic history has been complex. Local climates within the region are highly variable; the rainy season commences in October or November and ends in March or April. The total seasonal rainfall can be more than 40 in. (100 cm) in the redwood forests along the Pacific coast and less than 10 in. (25 cm) in the drier oak and grassland areas of the interior.

All the primary conditions responsible for landslides are present in the bay region: (1) steep, irregular slopes; (2) abundant and seasonally intense rainfall; (3) extensive human activity, including logging and the grading and cutting of slopes; (4) many weak and unconsolidated rock units that form unstable slopes, including extensively crushed and sheared Franciscan sedimentary complexes and unlithified upper Tertiary to Holocene sediments; (5) thick unconsolidated colluvial deposits and thick weathered zones on steep slopes; (6) many expansive clay soils; and (7) frequent and occasionally strong seismic activity. Because these and other factors are present, landsliding is a very costly problem at present and will continue to be one during the future growth of the region (Harding, 1969). Figures 8 through 17 illustrate the types of damage caused by landsliding in the bay area.

Damage is closely related to the type of landslide involved. A thin mudslide of low velocity will cause less damage than a large debris flow of high velocity or a debris slide or slump involving large blocks of material. Also, a landslide that falls on a road is usually far less expensive (involving only cleanup of debris) than a landslide that undermines a roadbed (requiring extensive work preparing a new foundation and roadbed). Mud and debris flows represent the greatest hazard to human life inasmuch as they occur rapidly and commonly without warning.

PREVIOUS WORK

Many studies of engineering geology, slope stability, and landsliding have been made in the bay region.

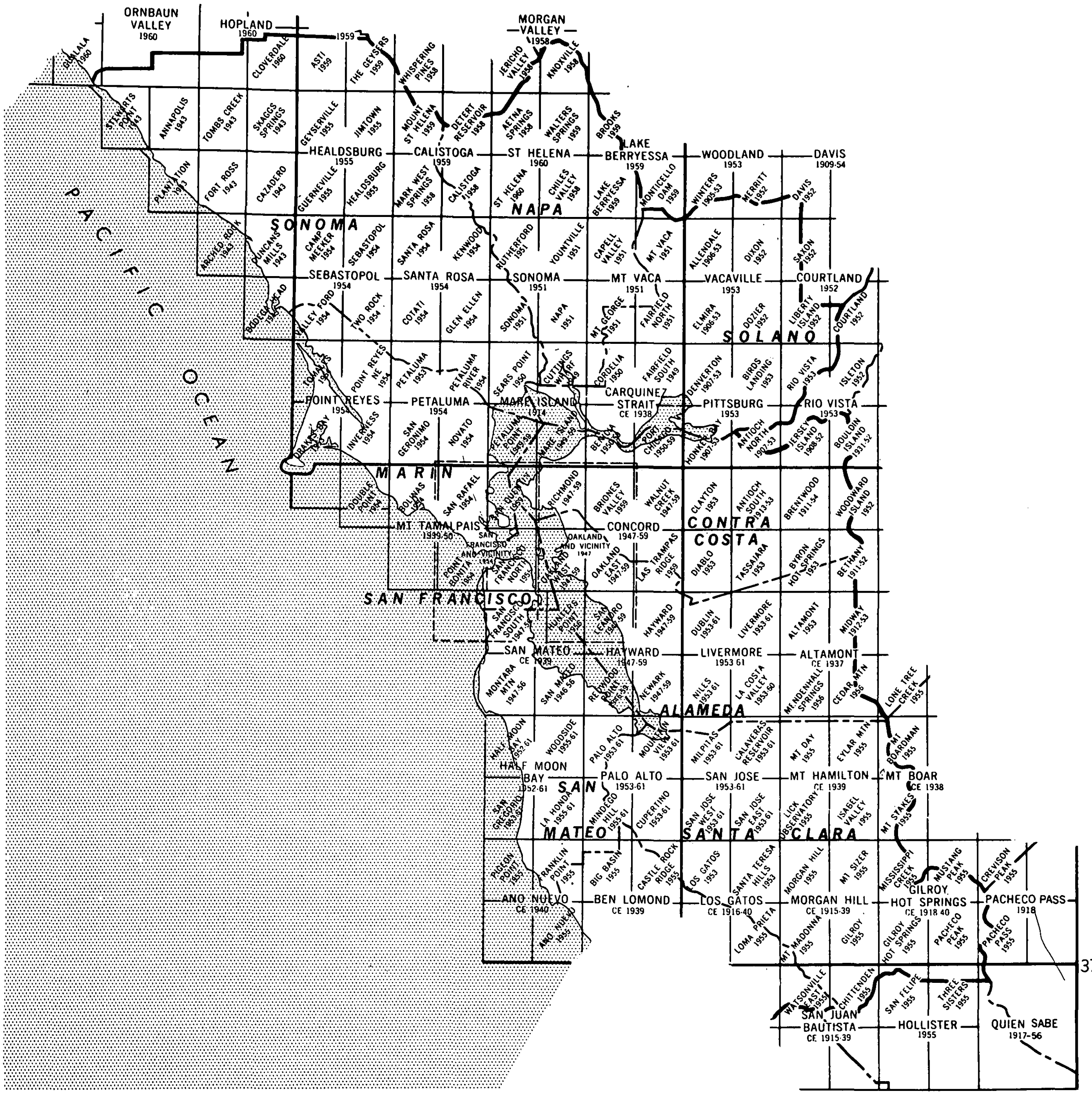


FIGURE 6.—Index map of U.S. Geological Survey quadrangle maps in the San Francisco Bay region.

Most of this work has been done by consulting engineering geologists and is unpublished. Some early papers and research studies of major interest that relate to present-day slope-stability problems include the analysis of landslides triggered during the 1906 San Francisco earthquake (Lawson, 1908; Anderson, 1908), an analysis of an induced landslide on Lone Mountain in San Francisco by Cogen (1936), a study of a major landslide near Gilroy (Krauskopf and others, 1939), a general study of landslides in the central Coast Ranges (Thomas, 1939), a discussion of soil slips by Kesseli (1943), and a general discussion of the causes of landslides in the bay region and ways of preventing them by Forbes (1947).

Publications in the 1950's dealt largely with particular aspects of the factors that controlled landsliding such as slope exposure (Beaty, 1956), landslides that resulted from the 1957 San Francisco earthquake

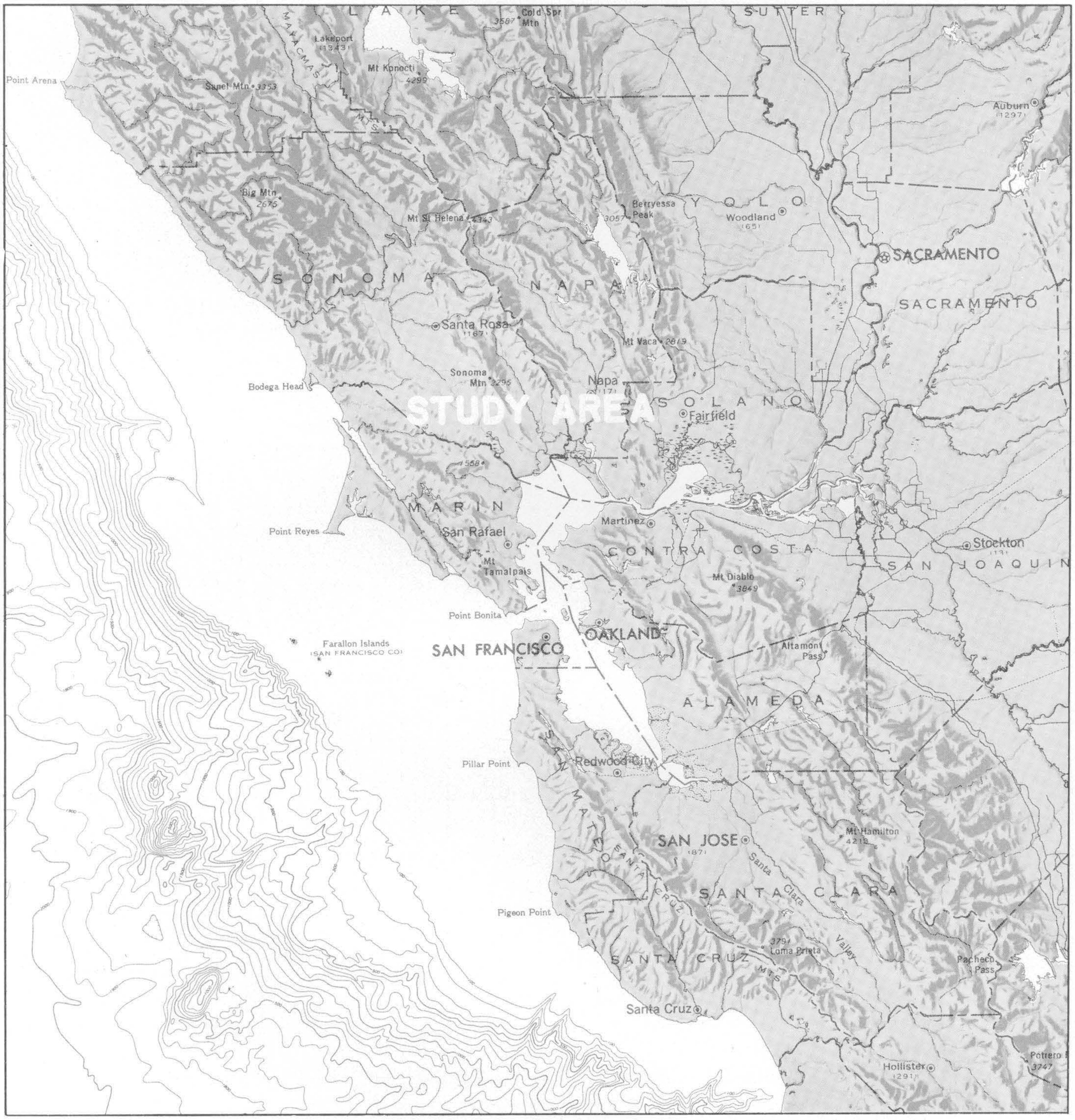
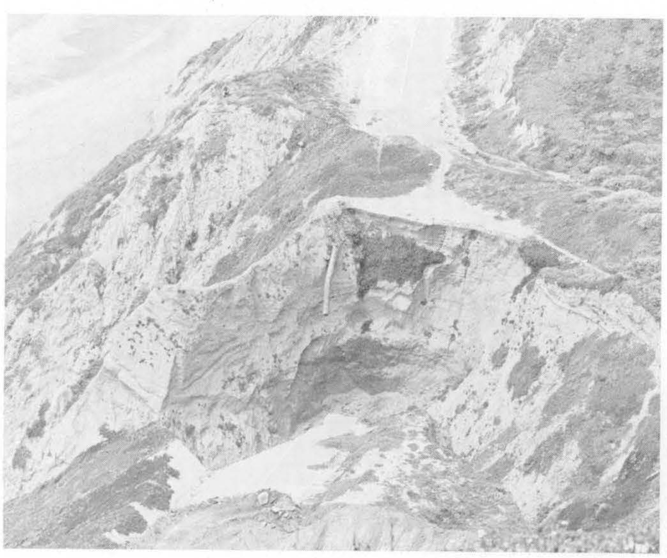


FIGURE 7.—Overall setting of the San Francisco Bay region.

(Bonilla, 1959), specific studies of individual landslides (Woods, 1958), and studies of slope stability at particular sites of development (Kachadoorian, 1956, 1959). Several geologic maps published during this decade incorporated much engineering geologic data and were forerunners of recent types of engineering geologic maps (Radbruch, 1957; Schlocker and others, 1958).

Numerous studies were completed in the 1960's, including an analysis of landslides in the San Francisco South quadrangle (Bonilla, 1960), a study of landslides in the Orinda Formation (Radbruch and Weiler,

FIGURE 8.—Landslide damage to a road north of Cloverdale in Sonoma County. Photograph by the California Division of Highways, 1970.



◀FIGURE 9.—Landslide damage to a coastal road near Thornton Beach, San Mateo County. Photograph by Fred A. Taylor, U.S. Geological Survey, 1971.

1963), engineering geologic mapping and landslide studies in the Oakland area (Radbruch and Case, 1967), slope stability studies in the town of Portola Valley (Johnson and Ellen, 1968; Johnson and Lobo-Guerrero, 1968) and in the Nicasio Valley (Twiss and others, 1970), a study of the mechanics of creep and rates of creep (Kojan, 1968), a study of landslides at Point Reyes National Seashore (Clague, 1969), and a summary of the environmental aspects of landsliding in the bay region (Harding, 1969).

The 1970's have seen a great increase in slope-stability studies in the bay region. The U.S. Geological Survey undertook extensive regional mapping of land-

FIGURE 10.—Landslide damage to Eastmore Drive in Daly City. Photograph by Eugene Gray.

slide deposits, analyses of the costs of damage produced by landsliding, preparation of regional slope maps, and preparation of slope-stability maps (summarized in part by Nilsen and Brabb, 1973, 1977). The California Division of Mines and Geology has also conducted numerous studies and prepared maps of slope stability, generally at scales of 1:12,000 and 1:24,000 (Rogers, 1971; Burnett, 1972; Huffman, 1971, 1972, 1973; Rice and Strand, 1972; Rice, 1973; Williams, 1973; Rogers and Armstrong, 1973; Saul, 1973; Bishop and Knox, 1973). Work by other groups has continued on certain types of landslides (Waltz, 1971), creep (Fleming and Johnson, 1975), state park areas (Frame, 1974; Anderson, 1974), and coastal regions (Leighton, 1972; Bedrossian, 1974; Sullivan, 1975; Williamson, 1975).

LANDSLIDES

GENERAL CLASSIFICATION

Landslides are defined for the purposes of this study as the "downward and outward movement of slope-forming materials composed of natural rock, soils, artificial fills, or combinations of these materials. The moving mass may proceed by any of three principal types of movement: falling, sliding, or flowing, or by their combinations" (Varnes, 1958). Landslide deposits consist of the mass of material that has moved downslope.

In detail, there are many types of landslides, and they vary greatly in size, shape, geometry, rate of movement, and type of materials involved. There are

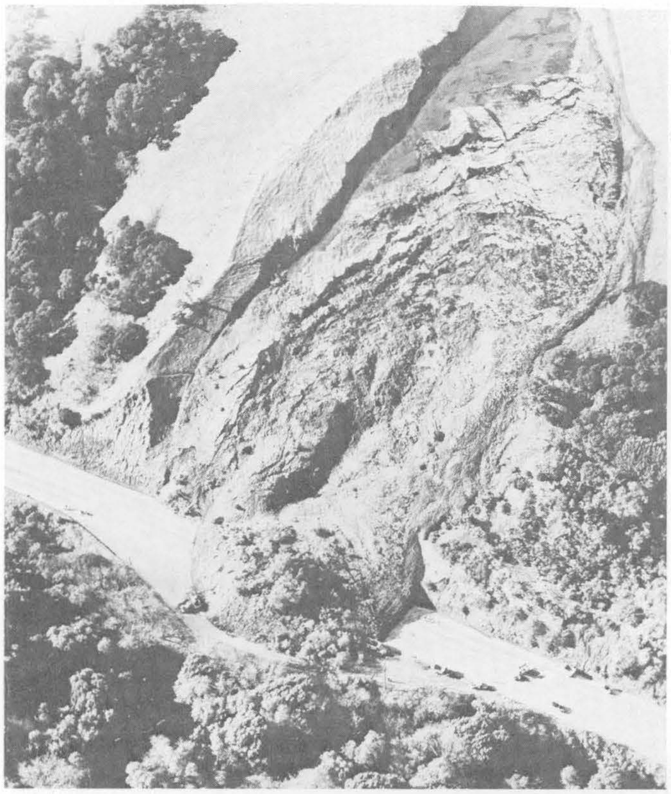


FIGURE 11.—A landslide on Highway 24 between Oakland and Orinda. Photograph from the Oakland Tribune, 1959.

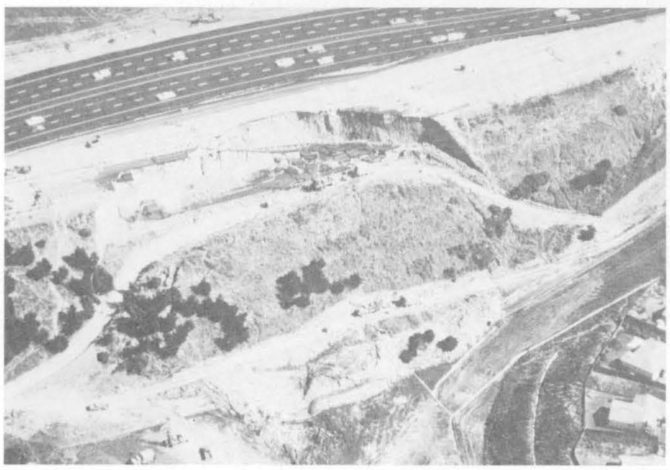


FIGURE 12.—Landslide damage to U.S. Interstate Highway 80 near Pinole. Photograph by Norman Prime, U.S. Geological Survey, May 1969.

also numerous classifications of landslides. The general shape and appearance of landslides and the nomenclature used are shown in figure 18. The four main types of landslide found in the San Francisco region are slides, slumps, falls, and flows. For a complete discussion of landslide types, the reader is referred to Varnes (1958).

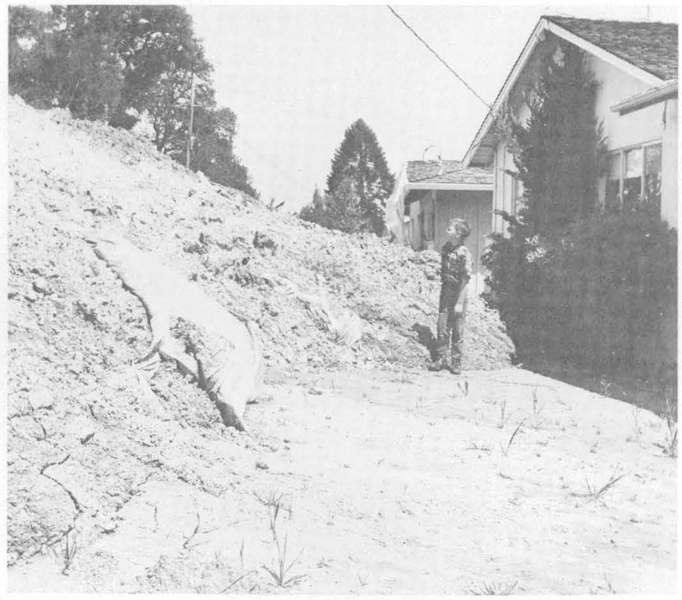


FIGURE 13.—Toe of landslide and damage to private homes in Redwood City. Photograph by Earl Pampeyan, U.S. Geological Survey, 1967.

FIGURE 14.—Landslide damage to a private home in Oakland. Photograph from Oakland Tribune, 1958.

The different types of landslides move downslope at a wide range of speeds (fig. 19). The more rapidly moving landslides may pose a greater hazard to life because they can destroy dwellings or damage roads quickly and with little warning. Slower moving landslides will gradually cause increasing amounts of damage, but the expected movements can be anticipated.

FALLS

Falls (figs. 20 and 21) do not commonly cause much damage in the bay region. A fall moves quite rapidly, most of the mass falling free or bouncing downslope

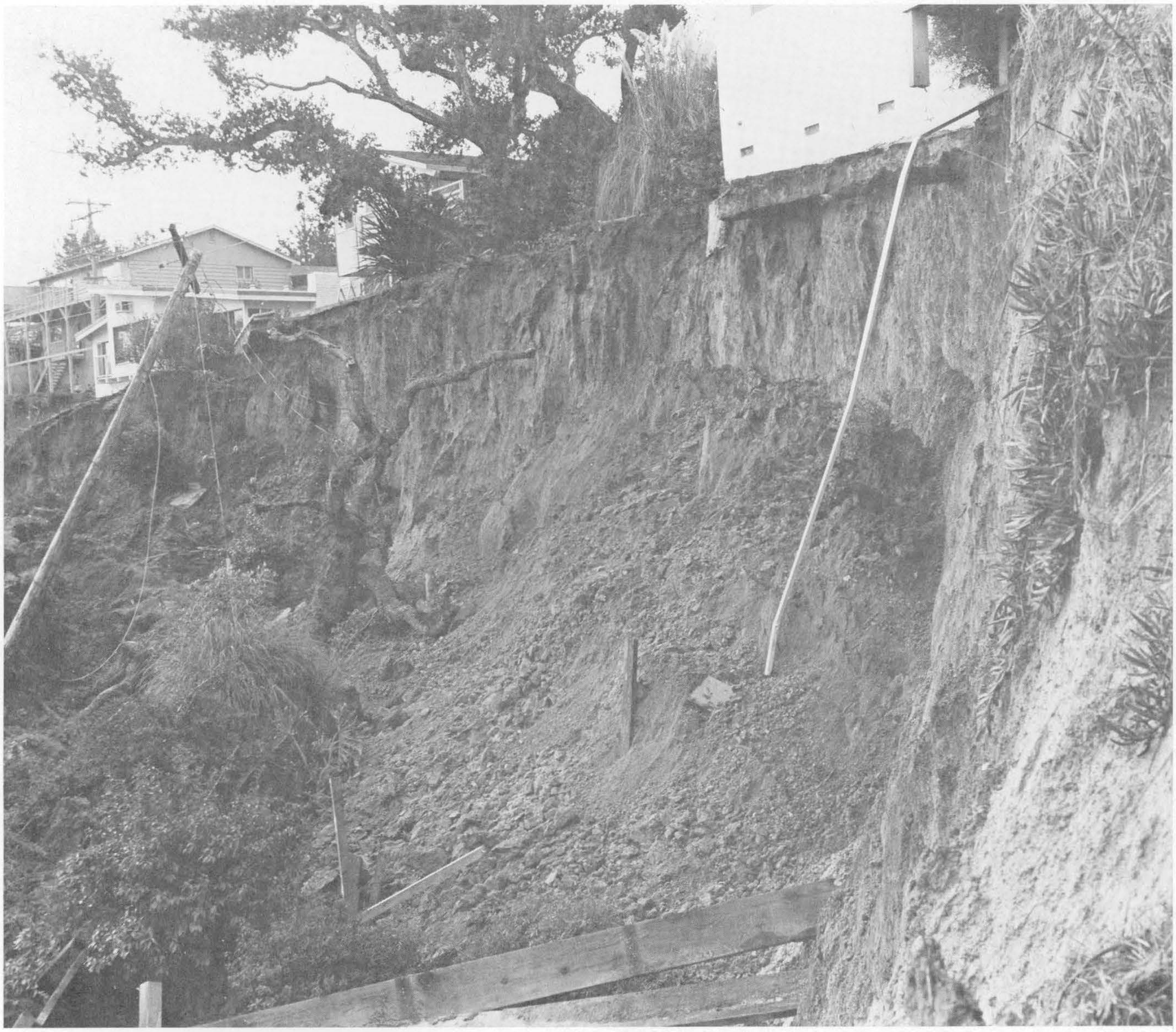


FIGURE 15.—Landslide damage to private homes in Redwood City in 1966. Photograph from Redwood City Fire Department file, by John Montenero.

with little interaction between individual parts of the mass. In the bay region, falls are typically restricted in area and involve the movement of relatively small amounts of material. They are most common along steep road or railroad cuts, along steep scarps formed either by landsliding or stream erosion, and along steeply undercut cliffs in coastal areas. Large individual boulders or blocks of rock can cause considerable damage to houses or roadways located at the base of the slope. Sheared rocks of the Franciscan assemblage, which characteristically contain large blocks of hard rock scattered within a softer fine-grained matrix, are particularly hazardous and susceptible to rock falls. Under certain conditions, trees, concrete, or other natural and manmade objects can be very destructive "projectiles" when they fall downslope. Tubbs (1974) reported that, during periods of landsliding along steep margins of flat terracelike surfaces in Seattle, Wash., tall trees with shallow root systems fell or bounced downslope into houses, causing considerable damage.

SLIDES

Slides result from shear failure along one or several surfaces. The slide materials can be broken up and de-

FIGURE 16.—Landslide damage to private homes on London Road in Oakland. Photograph by Fred A. Taylor, U.S. Geological Survey, 1970.

formed (figs. 22 and 23) or fairly cohesive and intact. A cohesive landslide is called a slump (figs. 24, 25, and 26). Movement in both slides and slumps is controlled primarily by preexisting structural features such as faults, joints, and bedding.

Slumps, perhaps the most common landslide type in the bay region, cause the most damage. Movement takes place primarily along internal slip surfaces and is usually rotational. The general form of the slip surface is concave upward or spoon shaped. This ideal form is seldom realized, however, because of the structural control mentioned above. A steep scarp and flanking walls (fig. 24) are commonly formed and water is ponded behind slump blocks (fig. 26), both of which promote further landsliding. Thus the surrounding area becomes prone to slope failure once the first slump has occurred.

The speed of movement ranges from very slow to extremely rapid for a slide and from slow to moderate

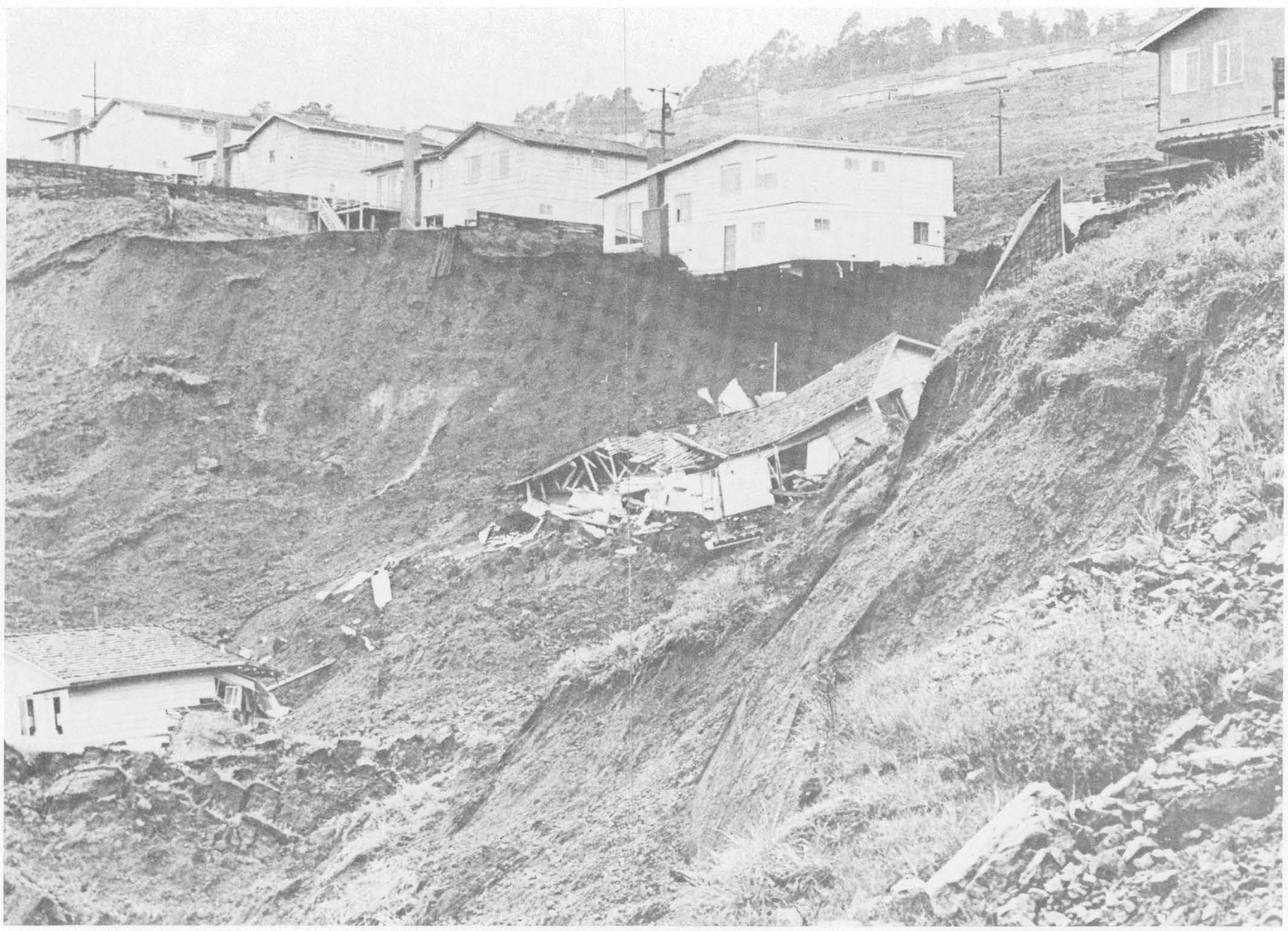


FIGURE 17.—Landslide damage to private homes on Van Cleave Way in Oakland. Photograph from the Oakland Tribune, 1958.

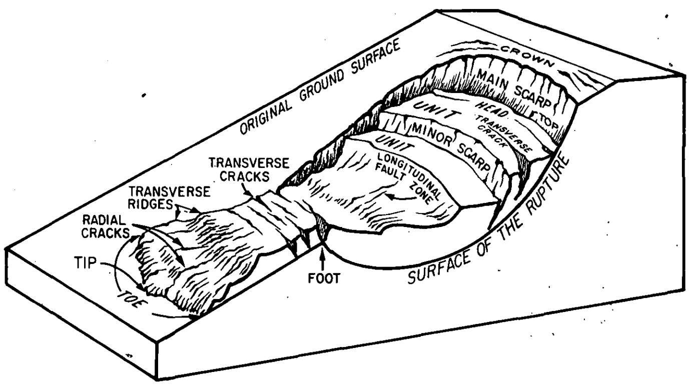


FIGURE 18.—General shape and appearance of a landslide and the nomenclature used (from Eckel, 1958, pl. 1).

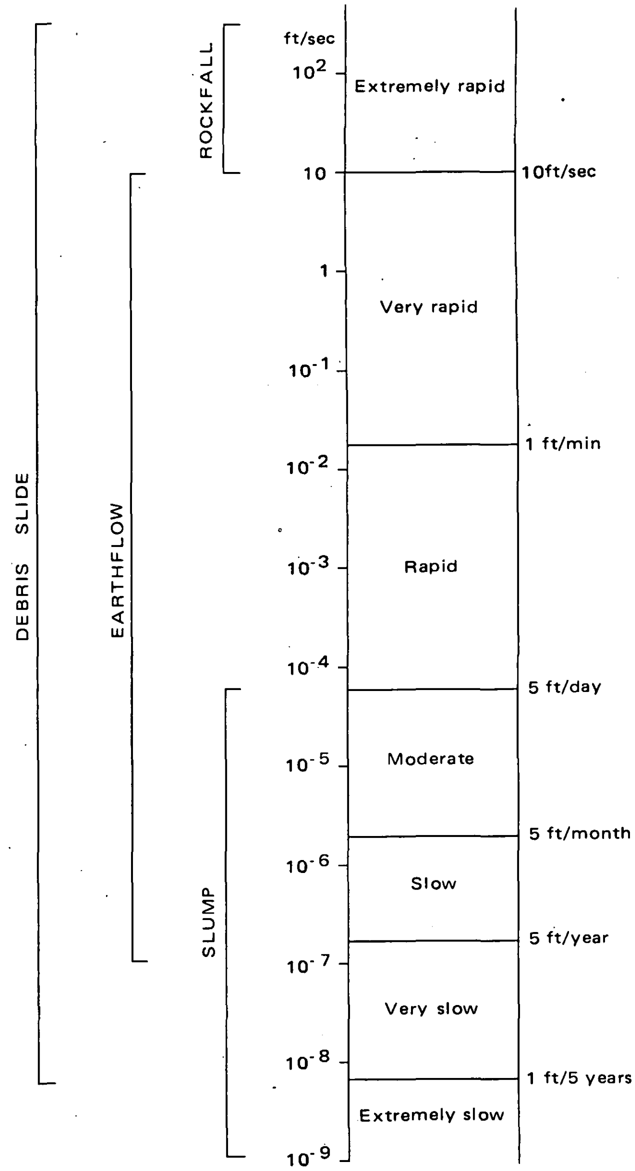
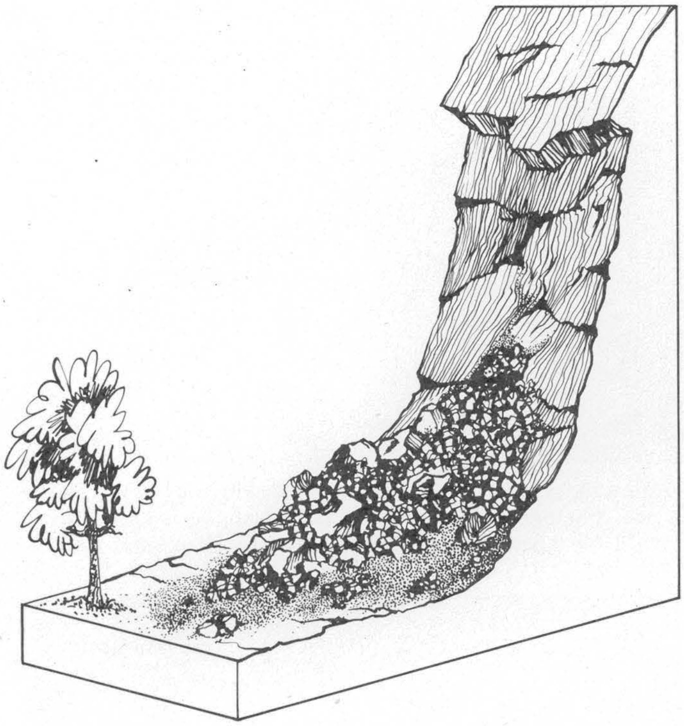


FIGURE 19.—Relative speeds of landslide movements (modified from Eckel, 1958, pl. 1).

for a slump (fig. 24). Large slump blocks are especially common along coastal areas where wave erosion and undercutting of seacliffs are rapid, in both the bay region (Clague, 1969; Bedrossian, 1974; Sullivan, 1975) and other areas (Minch, 1972; Minard, 1974; Tubbs, 1974). They are also common along major rivers or along the edges of terraces bounded by steep valley walls (Jones and others, 1961, Erskine, 1973; Yeend, 1973; Vallier and Miller, 1974) where meandering rivers are undercutting the banks. Paleoslumps have been recognized and described in considerable detail in ancient rocks (Williams and other, 1965; Laird, 1968; Laury, 1971).

LATERAL SPREADING

Lateral spreading is a special type of slide movement in which material generally slides along a somewhat planar, generally subhorizontal surface, thereby making it a slide rather than a flow. The movement is often very rapid but it can be slow. The margins of San Francisco Bay that are underlain by moist unconsolidated mud are especially susceptible to this type of failure (Youd, 1973; Youd and others, 1975) (fig. 27). Sliding usually takes place along the margins of tidal channels and levees, where slight differences in elevation and tidal erosion provide suitable conditions for



◀FIGURE 20.—Fall—masses of rock and (or) other material that have moved downslope primarily by falling or bouncing through the air.

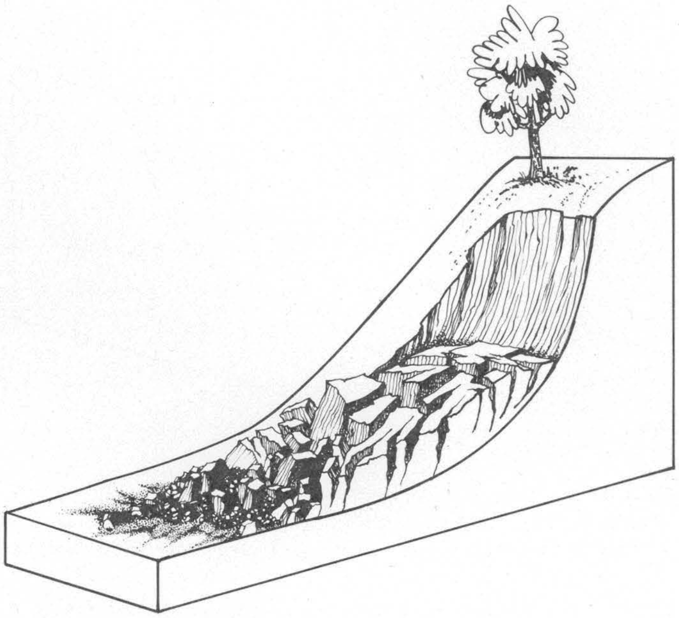
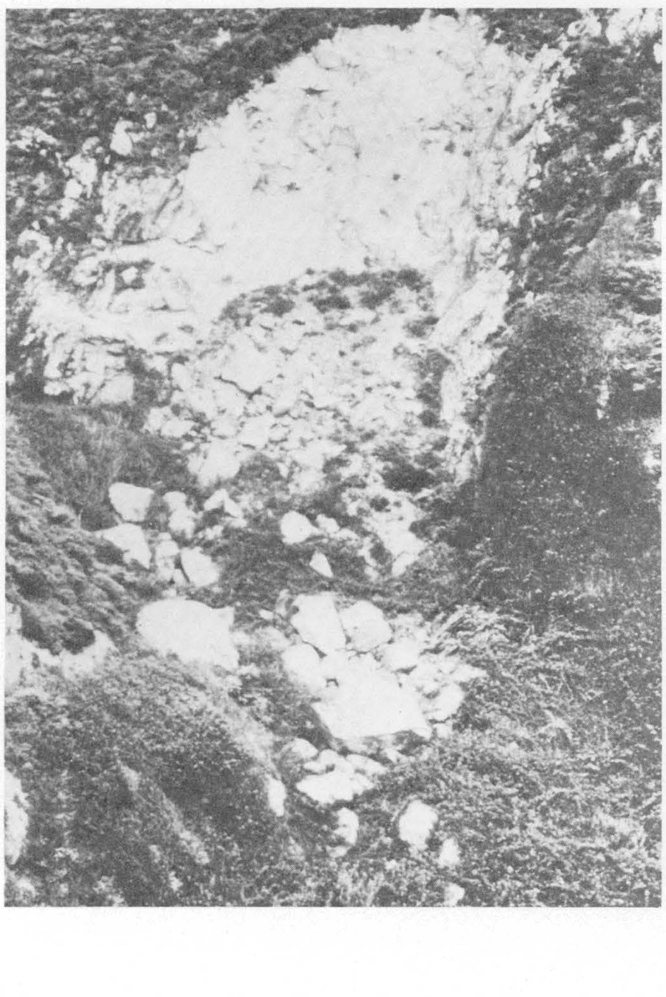


FIGURE 22.—Slide—incoherent or broken masses of rock and (or) other material that have moved downslope by sliding on a surface that underlies the deposit.



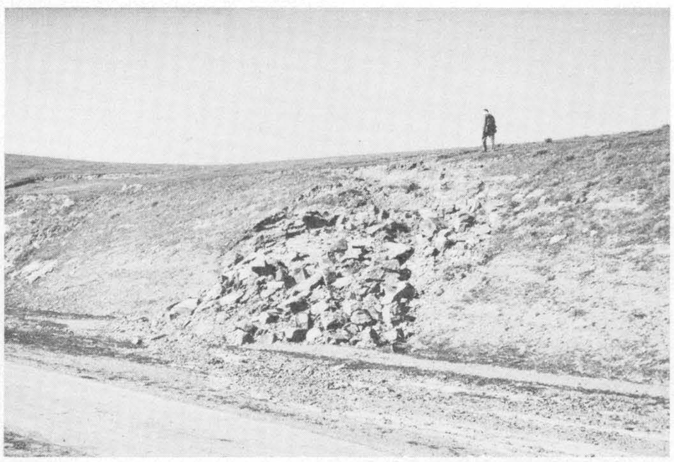


FIGURE 23.—A small rock slide west of Pleasanton, 1971. Note that sliding has taken place along the bedding planes of the sandstone.

◀FIGURE 21.—A small rockfall in the northern part of the bay region. Photograph by Carl M. Wentworth, U.S. Geological Survey.

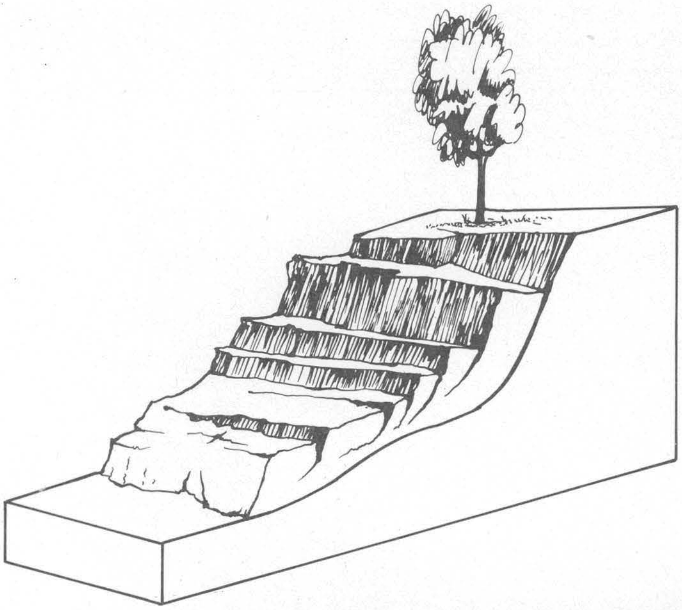


FIGURE 24.—Slump—coherent or intact masses or rock and (or) other material that have moved downslope by rotational slip on surfaces that underlie as well as penetrate the landslide deposit.

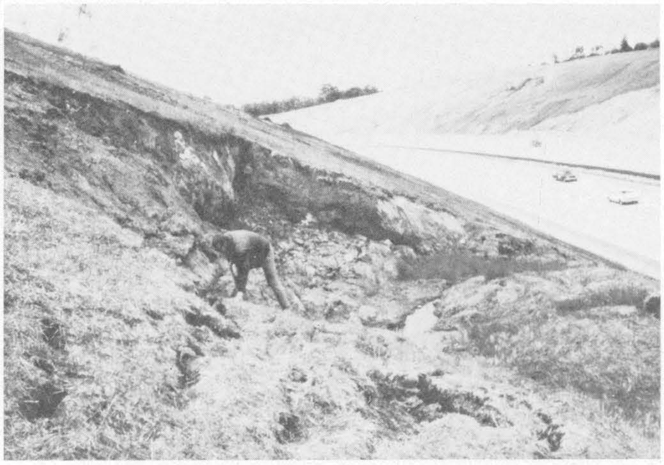


FIGURE 26.—Slump along U.S. Interstate Highway 280 in Woodside. Photograph by Carl M. Wentworth, Geological Survey, 1973. Note ponded water behind slump block in lower right.

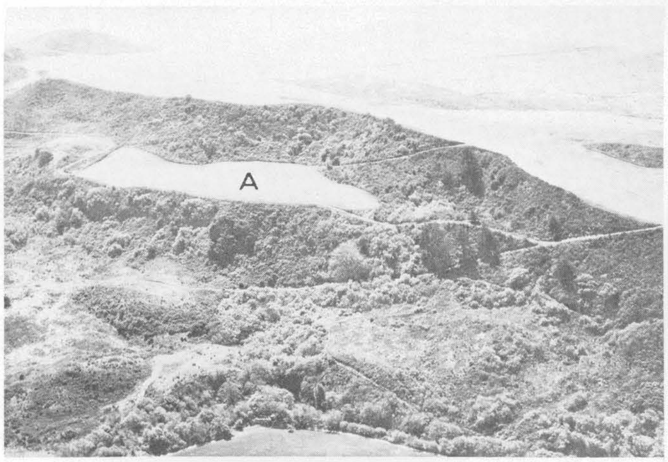


FIGURE 25.—A large slump block (0.8 km) east of San Gregorio. Photograph by Earl E. Brabb, U.S. Geological Survey, 1971. "A" indicates top of dropped block; the scarp is directly behind.

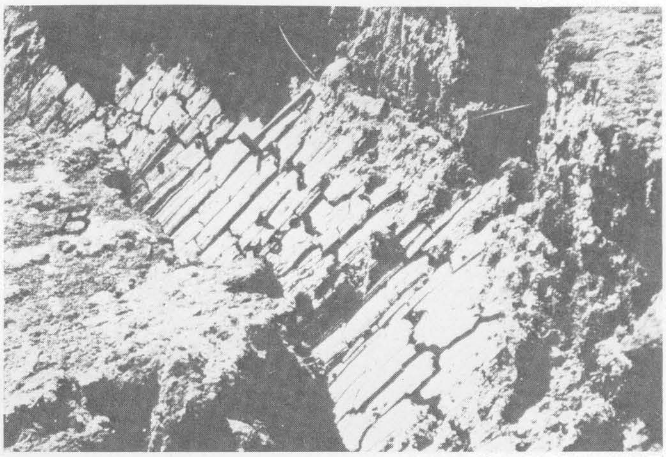


FIGURE 27.—Slump resulting from lateral spreading at a very low slope angle in bay mud on Brewer Island. Note hammer on shear surface; "B" is the top of the dropped block.

lateral spreading. We have incorporated these bay mud areas (Nichols and Wright, 1971) into our relative slope stability categories; however, unlike other categories, which are related in progressive sequence to slope, bedrock geology, and previous landslide history, this type of failure usually takes place in flat areas wholly within the surficial bay mud deposits. Ongoing sedimentation in the tidal margins generally covers the evidence of previous landsliding in a relatively short period of time. Thus, these areas represent a special type of landslide hazard, which will be treated as a separate category but will not be discussed in detail.

FLOWS

Flows (figs. 28–32) are common in the bay region and have caused considerable damage. The movement resembles that of a viscous fluid, and slip surfaces are almost nonexistent. Flow can take place as one or more lobes that move at different rates depending upon the viscosity of the material and the local slope angle. Water is not necessary for flows to take place, but most flows occur during or after periods of heavy rainfall, when the cohesiveness of soil and the bonding of soil by clay minerals breaks down, permitting downslope flow even on fairly gentle slopes. These landslides can move very rapidly and cover distances of several miles along available drainage paths (Sharp and Nobles, 1953) (fig. 30). They commonly are trig-

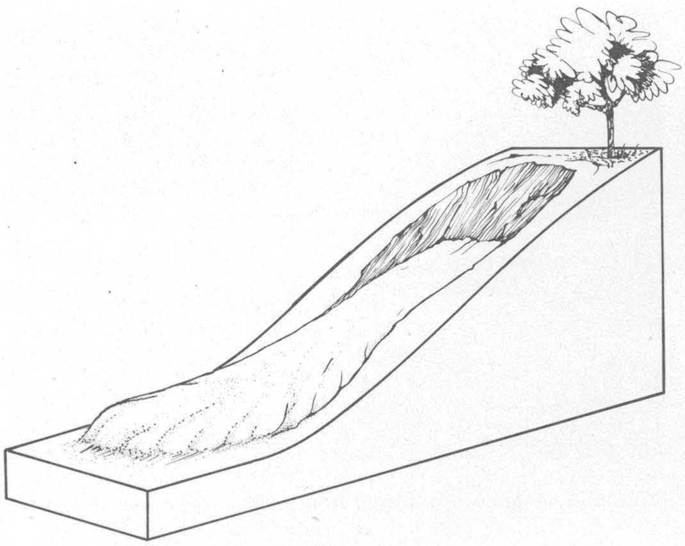


FIGURE 28.—Flow—masses of soil and other colluvial material that have moved downslope in a manner similar to the movement of a viscous fluid.

FIGURE 29.—Debris flow near Dublin, 1971. Note scarp behind tree and toe in foreground.

gered by earthquakes that occur during periods of heavy seasonal rainfall; many were noted during the 1906 San Francisco earthquake (Anderson, 1908; Lawson, 1908). They are generally very dense, containing perhaps 60–70 percent solid material by weight, and have great erosive power.

Because their movement can be rapid, flows can be very dangerous (Cleveland, 1972, 1975). However, generally they are shallow and involve only surficial materials (soils, colluvium, alluvial sediments) and not much, if any, of the underlying unweathered bedrock (figs. 28 and 29). Mudflows are often termed "mudslides" in nontechnical damage reports and newspaper accounts. Some flows also take place within unconsoli-

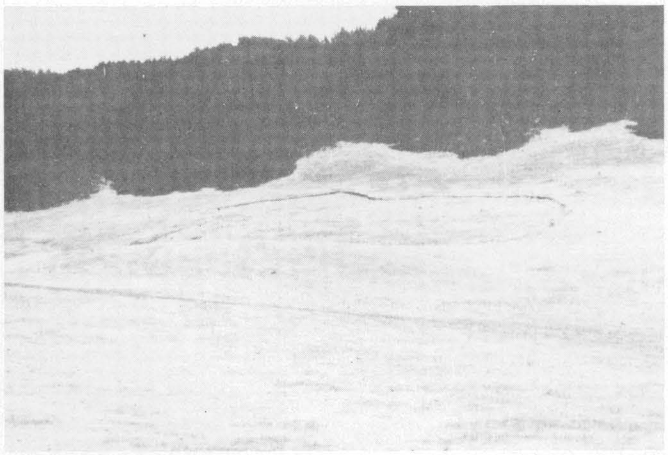


FIGURE 30.—Thin soil flow near Healdsburg, Sonoma County. Photograph by Carl M. Wentworth, U.S. Geological Survey.

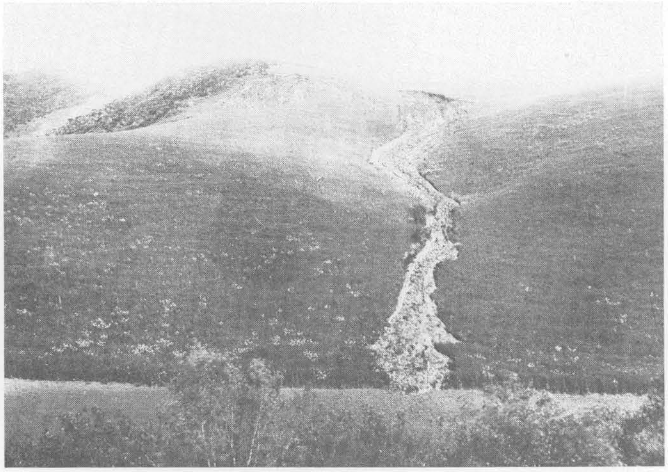


FIGURE 31.—Soil flow located 4 miles(6.4 km) east of Half Moon Bay after the 1906 earthquake. Photograph by Robert Anderson (in Lawson, 1908, pl. 133b).

FIGURE 32.—Large flow south of Gilroy. Photograph by Fred A. Taylor, U.S. Geological Survey. Note the irregular hummocky topography of most of this slope; it indicates the presence of many older landslide deposits.

dated deposits of sand, such as the extensive windblown sand deposits of San Francisco and eastern Contra Costa County.

Debris flows, activated during heavy rainstorms, occur frequently in southern California and cause more deaths, injuries, and damage than all other types of landslides combined (Campbell, 1975). A symposium on mudflows and their classification and origin gives further details of these features (Quart. Jour. Eng. Geology, 1974). Large debris flows caused widespread destruction in the Big Sur area near Monterey in 1972 after brush fires had denuded the hillsides of protective vegetation and heavy rain fell on the exposed slope (Cleveland, 1972) (fig. 33). In rugged country, debris avalanches can cause great damage (Shreve, 1968; Swanston, 1969, 1970; Plafker and others, 1971; Williams and Gray, 1971).

SOIL SLIPS

Small soil slips, many of which measure tens of cubic feet in volume and several feet in depth, are a common type of landslide in the bay region. They occur within the soil layers, may move very rapidly, and generally leave small scars or patches bare of vegetation; they rarely leave recognizable landslide deposits. Because of their ephemeral nature, Kesseli (1943) called these small landslides "disintegrating soil slips". They may be difficult or impossible to map by photointerpretive processes inasmuch as deposits are not formed, and subsequent erosion or revegetation may remove their traces. Consequently, these features, because of their small size even when fresh, have not generally been mapped by photointerpretation. They are therefore not generally noted on the relative slope stability maps presented here. In coastal California, storm-related soil slips can carry debris farther downstream and can contribute substantially to slope erosion (Bailey and Rice, 1969; Scott, 1971; Rice and Foggin, 1971; Campbell, 1974, 1975).

COMPLEX LANDSLIDES

Flows, slides, and slumps form a continuum from very fluid mudflows to slow slumps involving large intact blocks. Where a given landslide lies within this continuum depends on the materials, fluid content, and manner of movement. When naming a type of landslide, the substance that has moved is added as a prefix to the type of movement, producing a descriptive term. Many landslides exhibit features characteristic of several types so precise classification may be impossible. Figure 34 shows a typical example of such a complex landslide with slumping at the top and flowing at the toe.

FIGURE 33.—Damage resulting from a debris flow near Monterey in 1972.

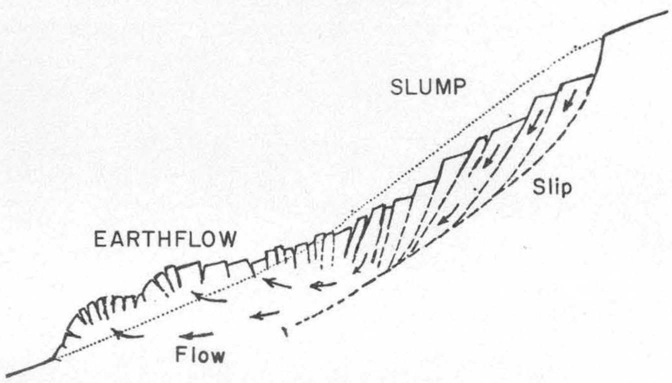
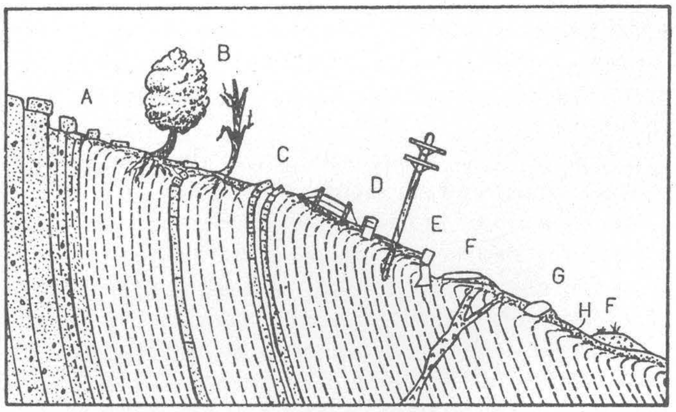


FIGURE 34.—Cross section of a complex landslide showing movement by slumping at the top and flowing at the bottom (from Sharpe, 1938, fig. 8).

CREEP

In most hilly parts of the world, the soil and underlying bedrock normally move slowly downslope under the influence of gravity at rates of millimeters to centimeters per year. This slow but generally steady bending and movement of the hillsides is known as creep; it may involve the upper part of the bedrock as well as the overlying soils and colluvium. The effects of creep and some of the types of damage that it can cause are shown in figures 35 and 36. Caution is necessary, however, in attributing the downslope tilting and upward curvature of trees to soil creep, as suggested by Sharpe (1938, p. 24) and Small (1970, p. 31). Recent work has suggested that the tilting and curvature may be a growth response of the trees to geotrophic and phototrophic conditions unrelated to soil creep (Parizek and Woodruff, 1957; Carson and Kirkby, 1972; Phipps, 1974).



◀FIGURE 35.—Diagram showing creep and its effects (Sharpe, 1938, fig.2). (A) Moved joint blocks; (B) trees with curved trunks concave upslope (a criterion to be used with caution); (C) downslope bending and drag of bedded rock or weathered veins, also present beneath soil elsewhere on the slope; (D) displaced posts, poles, and monuments; (E) broken or displaced retaining walls and foundations; (F) roads and railroads moved out of alinement; (G) turf rolled downslope from creeping boulders; (H) stone-line at approximate base of creeping soil. A and C represent rock-creep; all other features shown are due to soil-creep. Similar effects may be produced by some types of landslides.

FIGURE 36.—Fence posts toppled by creep along Highland Road in Contra Costa County. Photograph by Fred A. Taylor, U.S. Geological Survey.

Because of the steep slopes, thick soil, colluvium, and weak, generally poorly consolidated bedrock in the bay region, creep is taking place on virtually every hillside in the region (Kojan, 1968; Fleming and Johnson, 1975). Creep can cause extensive damage to buildings that may sometimes be mistaken for normal settlement; locally it can be a greater problem than landslides. In some areas, creep can lead to active landsliding, especially in grazing areas where creep may be accelerated as a result of the movements of domestic animals which cut small trails into the hillsides.

SUMMARY

The foregoing discussion of landslides was necessarily brief and simplified because the emphasis of this paper is on regional slope stability for regional planning purposes. There are many other varieties of landslides present in the bay region, and future work should improve our understanding of the history and type of movement of the landslides and perhaps eventually result in a classification scheme that will be more precise and useful for slope-stability studies. The general reader is referred to the following studies for more comprehensive discussions of the nature, type, composition, style of movement, engineering aspects, and classification of landslides: Sharpe (1938), Terzaghi (1950), Krynine and Judd (1957), Eckel (1958), Legget (1962), Leighton (1966), Morton and Streitz (1967), Zaruba and Mencl (1969), Cleveland (1971), Nemcok, Pasek, and Rybár (1972), and Carson and Kirkby (1972).

Landslides are a common natural phenomenon in the San Francisco Bay region and they continue to be a major, if not the most important, erosional process on many slopes. Uplift of many parts of the region along and between active faults accelerates the downcutting by streams and rivers and increases the instability of slopes. Landslides and creep constantly tend to produce topographically lower, more gently sloping areas; in contrast, tectonic uplift and stream erosion tend to produce topographically higher and more steeply sloping areas.

FACTORS CAUSING LANDSLIDES

Many complex interrelated factors contribute to the generation of landslides. Engineering geologists may spend months preparing analyses of soil and rock strength parameters (Early and Skempton, 1972), location of preexisting faults and fractures (Warn, 1966), precipitation records (Prior and Stephens, 1972), slope geometry, the orientation of the bedding planes in relation to slopes (Radbruch and Weiler, 1963; Briggs, 1974), and other factors to determine the causes of individual landslides. Many of the factors and processes that lead to landsliding are summarized in table 4.

The four most important factors that cause slope failures, and to which many other factors are related either directly or indirectly, are (1) the nature of the underlying bedrock or unconsolidated deposits, (2) the angle of slope, (3) rainfall, and (4) the presence of older landslide deposits, which can commonly become reactivated or continue to move intermittently over long periods of time. The San Francisco Bay region includes a wide variety of landforms that are underlain by many different types of bedrock (Schlocker, 1968, 1970; Brabb, 1970; Blake and others, 1971; Brabb and others, 1971; Brabb and Pampeyan, 1972a; Cotton, 1972; Dibblee, 1966, 1972a, b, c and d, 1973a, b, c and d; Sims and others, 1973; Fox and others, 1973; Blake and others, 1974) and unconsolidated deposits (Radbruch, 1957; Nichols and Wright, 1971; Helley and Brabb, 1971; Helley and others, 1972; Lajoie and others, 1974; Lajoie and Helley, 1975). The region includes very flat to very steep slopes (U.S. Geol. Survey, 1972), has a broad range in annual rainfall (Rantz, 1971a, b, c), and contains many thousands of ancient landslide deposits (Wright and Nilsen, 1974). Earthquakes along the numerous active faults of the region are common and cause shaking of the ground, thus contributing to landsliding (Radbruch, 1967, 1968; Radbruch-Hall, 1974; Brown, 1970, 1972; McLaughlin, 1971; Brown and Lee, 1971; Burke and Helley, 1973; Sharpe, 1973; Sorg and McLaughlin, 1975; Sarna-Wojcicki and others, 1975; Wesson and others, 1975; Frizzell and Brown, 1976; Herd and Helley, 1976; Helley and Herd, 1977; Youd and Hoose, 1978). The effects of bedrock geology, slope, and ancient landslides on landsliding are discussed in more detail in a later section in connection with the slope-stability map.

Rainfall is the major seasonal factor in generating landslides and causing continued movement of landslides, because it saturates the ground, thereby adding weight, decreasing friction, and raising the internal pore pressure (Forbes, 1947; Kachadoorian, 1956, 1959; Cleveland, 1971; Prior and Stephens, 1972; Easton, 1973; Erskine, 1973; Nilsen and Turner, 1975; Cleveland, 1975; Campbell, 1975). The effects of rainfall and moisture on clay minerals in soils, sediments, and rocks are particularly complex and have been studied in great detail by many geologists. The reader is referred to works by Gillott (1968), Zaruba and Mencl (1969), Millot (1970), Kerr, Stroud and Drew (1971), Kerr and Drew (1972), Kennedy and Kopp (1972), Einsele, Overbeck, Schwarz, and Unsöld

(1974), and Tourtelot (1974) for discussions of the physical and chemical reactions of the various clay minerals to hydration. Many clay minerals rapidly alter to an incohesive state and tend to form flows or other types of landslides.

The general influence of rainfall on landsliding in the bay region is complex and has not yet been studied in great detail. Nilsen, Taylor, and Dean (1976) based their conclusions on an analysis of landslides that damaged structures throughout the bay region during the rainy seasons of 1968–69 and 1972–73. They found that landsliding generally starts abruptly during heavy winter storms after a previous autumn rainfall accumulation of 10–15 inches (25–38 cm). It seems that the initial slow buildup of rain in the autumn months is most important in providing favorable subsurface conditions for landsliding. Nilsen and Turner (1975) studied landsliding and rainfall in Contra Costa County from 1950 to 1971 and concluded that evapotranspiration between storm periods also was an important factor, larger storms being required to trigger numerous landslides when evapotranspiration was great. In addition, they showed that storms that triggered landslides were smaller in the spring than in the fall, apparently because more moisture is present in the ground in the spring.

Some other conditions that affect landsliding are: (1) the duration and intensity of seismic shaking (Lawson, 1908, p. 384–401; Forbes, 1947; Hadley, 1964; Barosh, 1969; Plafker and others, 1971; Morton, 1971; Youd, 1971; Rogers, 1972; Easton, 1973; Nilsen and Brabb, 1975; Youd and Hoose, 1978); (2) the strength, thickness, and other characteristics of soils (Swanston, 1970; Bailey, 1971; Cleveland, 1971; Frame, 1974; Anderson, 1974); (3) human activities, ranging from the cutting and filling of slopes to excessive watering and devegetation of slopes (Leighton, 1966, 1972; Fisher and others, 1968; Long and Stinnett, 1969; Hicks and Collins, 1970; Briggs and others, 1975); (4) logging activities, particularly clear-cutting (Bishop and Stevens, 1964; Hicks and Collins, 1970; Gray, 1970; Collins and Hicks, 1971; Swanson and Dyrness, 1975); (5) vegetation on slopes, wherein trees with deep tap roots like oaks bind the soil to the bedrock, probably diminishing the likelihood of certain types of landsliding (Corbett and Rice, 1966; Swanston, 1969, 1970; Rice and Foggin, 1971; Bailey, 1971; Frame, 1974); (6) fires, which commonly enhance the probability of certain types of landslides during the following rainy season because the vegetative cover that protects the soil mantle has been burned off (Cleveland, 1972); (7) stream and wave erosion along rivers, creeks, and coastal areas, resulting in undercut slopes, removal of material from the bases of slopes, and local instability (Jones and others, 1961; Leighton, 1972; Easton, 1973; Bedrossian, 1974); (8) effects of strong tidal fluctuations in coastal areas (Easton, 1973; Williamson, 1975); (9) creep of soil and rock—the slow day-to-day downslope movement of slope-forming materials under the influence of gravity—which under certain conditions can convert to more rapidly moving landslides, particularly earthflows, as shown by Sharpe and Dosch (1942) for the Appalachian Plateau region; (10) unusual mineralogy of bedrock units, such as the presence of glauconite in sands, which is thought to contribute to landsliding in some areas such as northern New Jersey (Minard, 1974); (11) changes in ground-water level and major movements of ground water (Erskine, 1973); (12) unusual chemical weathering and degradation of shale, such as has been pointed out by Fisher, Fanaff and Picking (1968) for southeastern Ohio; (13) natural springs, which by supplying moisture continually to surrounding earth materials may induce instability (Williamson, 1975); (14) volcanic activity, wherein the movement of magma and changing eruptive activity may generate rockfalls, crater avalanches, and other slope movements (Tilling, 1974; Tilling and others, 1975); and (15) glacial processes, which typically produce oversteepened slopes particularly susceptible to landsliding (for example, Early and Skempton, 1972).

Some human activities that can cause landslides are shown in figures 37 and 38. Among specific examples in the bay region are the following: (1) Landslides on the flanks of Lone Mountain in the city of San Francisco were caused by a series of civic projects, including the removal of material from the bases of slopes and regrading of slopes (Cogen, 1936); (2) numerous landslides in San Francisco and other parts of the bay region started as a result of construction (Forbes, 1947); and (3) near Sears Point in Sonoma County, landslides initiated by construction at the base of a hill, the location of the landslides being controlled by the geologic structure (Woods, 1958). Steepening the angle, increasing the height, adding water, and placing extra loads on slopes increase the probability of landsliding.

Nilsen, Taylor and Dean (1976), Nilsen, Taylor and Brabb (1976), and Nilsen and Turner (1975) have shown that recent landslides in the bay area are common and cause great damage in or adjacent to urbanized upland areas. Nilsen, Taylor, and Dean (1976) demonstrated that much landslide damage in 1968–69 and 1972–73 occurred in urban areas on slopes steeper than 15 percent grade (8.5°). Nilsen, Taylor and Brabb (1976) and Nilsen and Turner (1975) showed similar relationships in Alameda and Contra Costa Counties.

TABLE 4—*Processes leading to landslides*

[From Terzaghi, 1950, table 1]

Agent	Process That Triggers Agent	Mode of Action of Agent	Slope Materials Most Sensitive to Action	Physical Nature of Action of Agent	Effects on Slope
Transport	Construction operations or erosion	Increase of height or rise of slope	Every material	Changes state of stress in slope-forming material	Increases shearing stresses.
			Stiff fissured clay, shale	Changes state of stress and causes opening of joints	Increases shearing stresses and reduces capillary pressure.
Tectonic stresses	Tectonic movements	Large-scale deformations of earth crust	Every material	Increases slope angle	Increases shearing stresses.
Tectonic stresses or explosives	Earthquakes or blasting	High-frequency vibrations	do.	Produces transitory change of stress	Do.
			Loess, slightly cemented sand, and gravel	Damages intergranular bonds	Decreases cohesion and increases shearing stresses.
			Medium or fine loose sand in saturated state	Initiates rearrangement of grains	Spontaneous liquefaction.
Height of slopeforming materials	Process that created the slope	Creep on slope	Stiff, fissured clay, shale, remnants of old slides	Opens up closed joints and produces new ones	Reduces cohesion and capillary pressure.
		Creep in weak stratum below foot of slope	Rigid materials resting on plastic ones	do.	Do.
Water	Rains or melting snow	Displacement of air in voids	Moist sand	Increases pore-water pressure	Decreases frictional resistance.
		Displacement of air in open joints	Jointed rock, shale	do.	Do
		Reduction of capillary pressure associated with swelling	Stiff, fissured clay and some shales	Causes swelling	Decreases cohesion.
		Chemical weathering	Rock	Weakens intergranular bonds	Do.
	Frost	Expansion of water due to freezing	Jointed rock	Widens existing joints;produces new ones	Do.
		Formation and subsequent melting of ice layers	Silt and silty sand	Increases water content of soil in frozen top layer	Decreases frictional resistance.
	Dry spell	Shrinkage	Clay	Produces shrinkage cracks	Decreases cohesion.
	Rapid drawdown	Produces seepage towards foot of slope	Fine sand silt, previously drained	Produces excess porewater pressure	Decreases frictional resistance.
	Rapid change of elevation of water table	Initiates rearrangement of grains	Medium or fine loose sand in saturated state	Spontaneous increase in porewater pressure	Spontaneous liquefaction.
	Rise of water table in distant aquifer	Causes a rise in piezometric surface in slope-forming material	Silt or sand layers between or below clay layers	Increases porewater pressures	Decreases frictional resistance.

TABLE 4—*Processes Leading to Landslides*—Continued

Agent	Process That Triggers Agent	Mode of Action of Agent	Slope Materials Most Sensitive to Action	Physical Nature of Action of Agent	Effects on Slope
Water	Seepage from artificial source of water (reservoir or canal)	Seepage towards slope	Saturated silt	Increases porewater pressure	Increases frictional resistance.
		Displaces air in the voids	Moist, fine sand	Eliminates surface tension	Decreases cohesion.
		Removes soluble binder	Loess	Destroys intergranular bond	Do.
		Subsurface erosion	Fine sand or silt	Undermines the slope	Increases shearing stress.

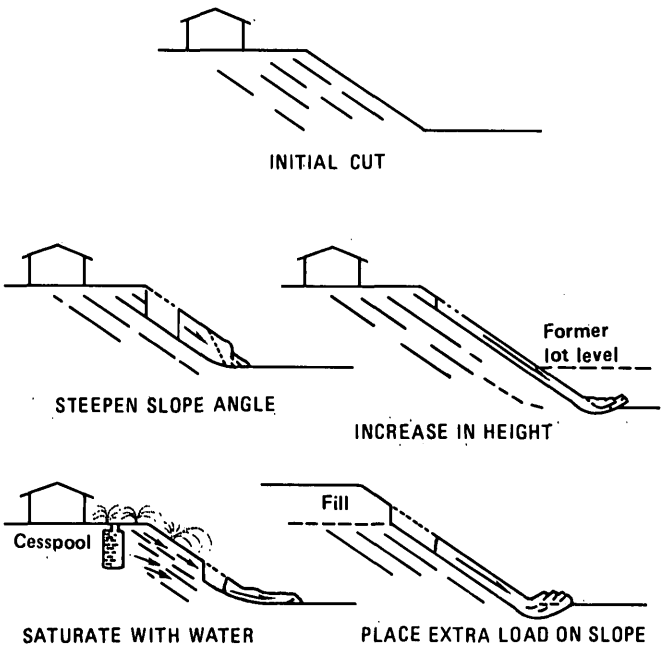


FIGURE 37. Four ways to make a stable cut slope unstable (from Leighton, 1966, fig. 10).

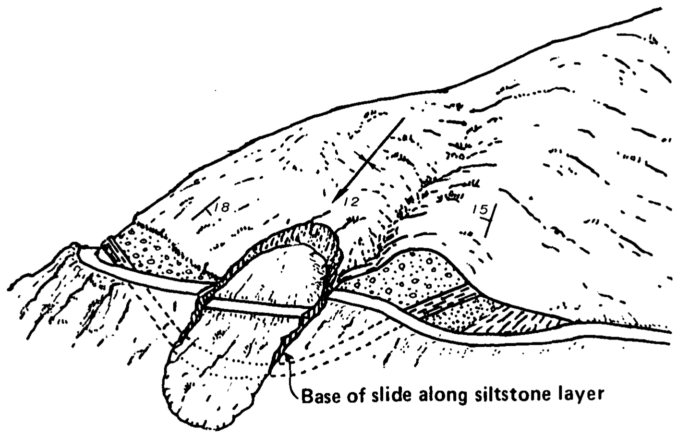


FIGURE 38.—Landslide developed in a syncline (from Leighton, 1966, fig. 9). The rock layers shown were deformed during uplift of the hills into a troughlike fold. This fold is tilted in the direction of the major arrow and is called a plunging syncline. This unstable geologic structure went undetected because of favorable inclinations (as shown in the roadcuts on either side). Porous and permeable conglomerate (shown by small circles) conducted underground water to the dark layer of impermeable siltstone, thereby creating a triggering device for the slide.

Thus, it is clear that many factors, both natural and man-induced, contribute to the generation of landslides. Most of the factors are interrelated in very complex ways. For regional slope-stability analysis, it is impossible to evaluate all these factors, because their influences have not yet been determined throughout the region. Other factors not listed or discussed above may also contribute locally to landsliding.

PHOTOINTERPRETIVE MAPPING OF LANDSLIDES

Landslide deposits, because of their characteristic shapes and features, can generally be recognized in the field and from aerial photographs. In the San Francisco Bay region, landslides continually modify the configurations of slopes (Nilsen and Wentworth, 1971; Nilsen, 1972e; Nilsen and Brabb, 1973; Frame, 1974). The techniques of photointerpretation for mapping landslides have been widely used by many workers (see, for example, Liang and Belcher, 1958; Ritchie, 1958; Ray, 1960; Watson, 1971; Kojan and others, 1972). Photointerpretive mapping is commonly a necessary preliminary to more detailed and specific studies of landslides. It is particularly useful for regional reconnaissance studies and permits a rapid determination of the relative distribution of current landsliding and ancient landslide deposits. Black-and-white photographs at scales of 1:20,000–1:30,000 are generally suitable for most regional mapping purposes. However, color photographs may be more suitable for some purposes and be more helpful in recognizing landslides in some areas. Infrared or other more sophisticated types of film may be useful locally in distinguishing variations in ground moisture, age and state of vegetation, and manmade modifications.

Landslide deposits may be characterized by (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) many flat areas that might appear suitable for construction sites. 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 tall vegetation, such as some redwood forest areas in the western part of the San Francisco Bay region, where the ground surface cannot be seen on the photographs.

Maps showing the distribution of landslide deposits can be prepared on the basis of field examinations, interpretations of aerial photographs, or both. Maps based primarily on photointerpretation have been prepared for much of the San Francisco Bay region (see, for example Nilsen, 1971, 1975) and form one of the basic data sources for the slope-stability maps (pl. 1, 2, and 3). The type of landslide cannot always be distinguised on aerial photographs, particularly older landslide deposits, whose upper surfaces have been subjected to long periods of weathering and erosion. However, in general, these photointerpretive maps indicate areas that have undergone extensive landsliding in the past.

Wright and Nilsen (1974), using a technique similar to one developed by Campbell (1973), produced an isopleth map based on maps prepared by photointerpretation of landslide deposits in the southern part of the bay region. The isopleth map depicts the relative numbers of landslide deposits over a broad area through the use of contour lines (Wright and others, 1974), thus permitting a rapid quantitative comparison of landslide distribution in different parts of the area. The isopleth maps have proved useful for some land-use planning studies and for computer-based studies of slope stability.

SLOPE-STABILITY MAPS

Relative slope-stability maps can be prepared in many ways and from diverse types of information. No formula or technique has yet been developed that covers all situations and all areas. Different techniques have been used to prepare relative slope stability maps for different areas, at different scales, for different purposes, and from different types of information. Many interesting examples of the widely divergent form and style of relative slope stability and landslide susceptibility maps have been published in recent years. These include maps of parts of California by Blanc and Cleveland (1968); Johnson and Ellen (1968); Johnson and Lobo Guerrero (1968); Rogers (1971); Radbruch and Wentworth (1971); Brabb, Pampeyan, and Bonilla (1972); Rice and Strand (1972); Huffman (1971, 1972, 1973); Burnett (1972); Radbruch and Crowther (1973); McGill (1973); Rice (1973); Williams (1973); Saul (1973); Morton, Miller, and Fife (1973); Bishop and Knox (1973); Rogers and Armstrong (1973); Frame (1974); Bedrossian (1974); and Anderson (1974). For other parts of the United States, maps have been prepared by Bailey (1971), Van Horn (1972), Williams (1972), Scott (1972), Maberry (1972), Miller (1973), Simpson (1973a, b), Dobrovolny and Schmoll (1974), and Pomeroy and Davies (1975), among others.

To cover an area as large as the San Francisco Bay region, detailed analyses of individual areas could not be made because of lack of time, personnel, and available data. The three parameters that we used to make our maps—the nature of the underlying bedrock material, the angle of slope of the land surface, and the presence or absence of earlier landslide deposits in the area—were chosen because (1) they were among the important factors that control slope stability, (2) information on them was available throughout the map area, and (3) they could be effectively incorporated into a regional slope-stability analysis. These factors, as well as others, can also be incorporated in computer-based analyses of slope stability, as shown by Newman and others (1978).

It has long been known in the bay region and elsewhere that certain bedrock units are more susceptible to landsliding than others, because of their physical and chemical characteristics, as well as the type and thickness of soil that tend to develop over them. Thus, two adjacent areas that appear to be similar may differ greatly in landslide susceptibility because of the type of underlying bedrock (Kachadoorian, 1956, 1959; Radbruch and Weiler, 1963; Radbruch and Case, 1967; Brabb and others, 1971; Frame, 1974; Anderson, 1974). We have discussed the characteristics of various bedrock units with geologists at the U.S. Geological Survey who have mapped the bedrock geology in the area during the past five years. The bedrock units considered by them to be susceptible to landsliding have been used in determining relative slope stability category 4 (table 5).

TABLE 5.—*Geologic units susceptible to landsliding*

[Many of the stratigraphic names listed below are from unpublished or open-file reports which have not been reviewed for conformity with nomenclature adopted by the U.S. Geological Survey]

Sheet 1 of figure 40 and plate 1 (in pocket)

Northwestern region

Area 1 (Blake and others, 1971):
Franciscan assemblage (KJfm—metamorphic rocks and KJfs—melange; Great Valley sequence (KJvs—unit with more siltstone than sandstone); Petaluma (?) Formation (Tp).

Area 2 (Fox and others, 1973):
Franciscan assemblage (KJfm—metamorphic rocks and KJfs—melange); Petaluma Formation (Tp—*only* at following localities: north of Santa Rosa, southwest slope of Taylor Mountain, southeast part of a Bennett Valley, and east and southeast of Penngrove).

Area 3 (Blake and others, 1974):
Franciscan assemblage (KJfm—metamorphic rocks and KJfs—melange); Tertiary siltstone and silty mudstone with some sandstone near Drake's Bay (Tdbc).

Sheet 2 of figure 40 and plate 2 (in pocket)

Northeastern region

Area 2 (Fox and others, 1973):
Franciscan assemblage (KJfm—metagraywacke, and KJfs—shale and sandstone); Great Valley sequence (KJgvs—sandstone, and KJgvm—mudstone and siltstone); Vacaville Shale of Merriam and Turner (1937) (Tv); Sonoma Volcanics (Tss—sedimentary rocks, only along Howell Mountain Road); Petaluma Formation (Tp—undivided, *only* southeast of Bennett Valley and northeast of Petaluma); and Huichica and Glen Ellen Formations (QThg—*only* southeast of Sonoma).

Area 3 (Blake and others, 1974):
Franciscan assemblage (KJfm—metamorphic rocks, and KJfs—melange); Great Valley sequence (KJgv—sandstone and claystone, *only* near Burdell Mountain); Petaluma Formation (Tpc—claystone, and Tps—claystone, siltstone, and mudstone).

Area 4 (Sims and others, 1973):
Franciscan assemblage (KJfs—shale-graywacke, and KJfm—

TABLE 5.—*Geologic units susceptible to landsliding* —Continued

Area 4—Continued
graywacke and metagraywacke); unnamed formation (KJgvm); unnamed formation (KJgvs or KJvs); Funks Formation of Kirby (1942) (Kf—shale and siltstone); Forbes Formation of Kirby (1942) (Kfo—shale and siltstone); unnamed formation (Ku); unnamed formation (Kgvd—sandstone, siltstone and shale); Martinez Formation (Tpmu—upper mudstone and shale member); unnamed formation (Tpu—shale and sandstone); Capay Formation (Tec—shale and mudstone); Nortonville Shale Member of the Kreyenhagen Formation (Tenl—lower shale unit, Tenu—upper shale unit, and Ten—undivided); Markley Sandstone (Tems—upper sandstone, and Tem—undivided); Orinda Formation (Tpo); Petaluma Formation (Tpc—claystone, and Tps—claystone, siltstone, and mudstone); Huichica and Glen Ellen Formations (Qthg).

Area 5 (Brabb, E.E., unpub. map compilation):
Unnamed shale (Kus); unnamed shale (Ku); Martinez Formation (Tmzu—upper siltstone and shale); Nortonville Formation (Tnv—mudstone and claystone); Markley Formation (Tes—Sidney Siltstone Member); Contra Costa Group (Tcu—undivided); Mulholland Formation (Tml—undivided).

Area 6 (Wagner J. R., and Brabb, E. E., unpub. map compilation):
Franciscan assemblage (KJf—undivided); unnamed shale (Ks); unnamed shale and sandstone (Ksu); unnamed shale (Ksuh); Martinez Formation (Tmzu—upper siltstone and shale); Meganos Formation (Tmgc—shale of Meganos C unit); Nortonville Formation (Tnv—mudstone and claystone); Markley Formation (Tmks—siltstone and shale, and Tmk—sandstone); Orinda Formation (To, Tor—undivided); Moraga Formation (Tmcl—clastic rocks); Siesta Formation (Tst); Contra Costa Group (Tcu—undivided); Mulholland Formation of Ham (1952) (Tmll—lower siltstone, and Tmlu—upper sandstone).

Area 7 (Brabb and others, 1971):
Franciscan assemblage (KJf—undivided); unnamed shale (Ks); unnamed sandstone and shale (Kush—upper shale, and Ku—undivided, *only* along Little Pine Creek southeast of Walnut Creek); Marlife Shale (Kmu—upper shale and siltstone); Joaquin Ridge Sandstone (Kjs—interbedded shale); Moreno Formation (Kmgl—lower shale, and Kmgu—upper siltstone); Martinez Formation (Tmzu—upper siltstone); Meganos Formation (Tmc—shale of Meganos C unit, and Tme—mudstone of Meganos E unit); Nortonville Shale (Tnv); Markley Formation (Tll—lower siltstone, Tlu—upper siltstone, Tml—lower sandstone member, Tsl—lower Sidney Flat Shale Member, Tsu—upper Sidney Flat Shale Member, Tmu—upper sandstone member, and Tmk—undivided).

Sheet 3 of figure 40 and plate 3 (in pocket)

Southern region

Area 3 (Blake and others, 1974):
Franciscan assemblage (KJfs—melange).

Area 6 (Wagner, J.R. and Brabb, E.E., unpub. map compilation):
Jurassic and Lower Cretaceous mudstone and siltstone (JK); Franciscan assemblage (KJf—undivided); unnamed Upper Cretaceous shale and sandstone (Ku, Ksu); Shephard Creek Formation (Ks); Redwood Canyon Formation (Kr); Markley Formation (Tmk); Orinda Formation (To, Tor—undivided except area north-northeast of Alamo); Moraga Formation (Tmcl—clastics); Siesta Formation (Tst); Contra Costa Group

TABLE 5.—*Geologic units susceptible to landsliding*—Continued

Area 6—Continued
(Tcu—undivided); Mullholland Formation of Ham (1952) (Tmll—lower part and Tmlu—upper part);

Area 7 (Brabb and others, 1971):
Franciscan assemblage (KJf—undifferentiated); unnamed Upper Cretaceous sandstone and shale (Ku—along Little Pine Creek only, east and south of Walnut Creek); unnamed Upper Cretaceous shale (Ks); unnamed Upper Cretaceous shale with minor sandstone (Kush); Marlife Shale (Kml—lower shale and siltstone member and Kmu—upper shale and siltstone member); Joaquin Ridge Sandstone (Kjs—shale interbeds); Moreno Formation (Kmgl—shale and claystone and Kmgu—siltstone); Meganos Formation (Tme—Division E); Nortonville Shale (Tnv); Wolfskill Formation (Tw); Oro Loma Formation (Tol).

Area 8 (Brabb and Pampeyan, 1972a):
Franciscan Formation (fs—mostly sandstone and Fsr—sheared); Twobar Shale Member of San Lorenzo Formation (Tst); San Lorenzo Formation and Lambert Shale, undivided (Tls); Santa Margarita Sandstone (Tsm); Purisima Formation (Tpsg—San Gregorio Sandstone Member of Cummings and others, 1962, Tptu—Tunitas Sandstone Member of Cummings and others, 1962, Tpt—Tahana Member of Cummings and others, 1962, Tpp—Pomponio Member of Cummings and others, 1962, and Tpl—Lobitos Mudstone Member of Cummings and others, 1962).

Area 9a (Brabb, E.E., unpub. map compilation):
Franciscan assemblage (KJf—undivided); Knoxville Formation (JK—divided and JKu—upper shale unit); unnamed Upper Cretaceous sedimentary unit (Kush—shale); unnamed Cretaceous Shale Unit (Keh and Khh); Upper Cretaceous unnamed shale (Kfzh, equivalent to the upper shale unit of the Marlife Formation); Shephard Creek Formation (Ks); Redwood Canyon Formation (Kr); unnamed Upper Cretaceous sedimentary unit (Ksu); Orinda Formation (To); Contra Costa Group (1cu); Oro Loma Formation (Tol);

Area 9b (Brabb, E.E. unpub. map compilation):
Franciscan assemblage (fh—predominantly shale with minor sandstone, fsr—sheared, and fs—predominantly sandstone).

Area 9c (Brabb, E.E., unpub. map compilation):
Franciscan Formation (fs—predominantly sandstone and fsr—sheared); unnamed Cretaceous sandstone and shale (Kss); Lower Cretaceous and Upper Jurassic mudstone (KJs); Upper Cretaceous undifferentiated sedimentary rocks, mostly shale and mudstone (TKu); unnamed clay shale (TKs); unnamed Oligocene and Miocene shale and sandstone (Tss); unnamed sedimentary rocks (Tms—mostly mudstone); Purisima Formation (Tp—undivided).

Area 10 (Brabb, 1970):
Franciscan Formation (fh—predominantly shale, minor sandstone; fs—predominantly sandstone, and fsr—sheared); Tos—Lambert and San Lorenzo Formations, undivided (Tos).

Area 11 (Dibblee, 1972a, Milpitas quadrangle):
Unnamed Cretaceous sedimentary rocks (Ksh—shale); Orinda Formation (Tor).

Area 12 (Dibblee, 1972d, Calaveras Reservoir quadrangle):
Franciscan assemblage (fs—undifferentiated and f-mixed rocks, sheared); unnamed Cretaceous sedimentary rocks (Ksh—shale); Orinda Formation (Tor).

Area 13 (Dibblee, 1972b, San Jose East quadrangle):
Franciscan Formation (f—mixed, fs—sandstone, and fsr—sheared); unnamed Cretaceous sedimentary rocks (Kshl—Knoxville Shale of Crittenden, 1951); unnamed Cretaceous sedimentary rocks (Kshu—Berryessa Formation of Crittenden, 1951); unnamed Cretaceous sedimentary rocks (Ksh—shale, undivided); Orinda Formation (Tor).

Area 14 (Dibblee, 1972c, Lick Observatory quadrangle):
Franciscan Formation (f—mixed rocks, fsr—sheared, and fs—predominantly sandstone); unnamed Cretaceous shale (Kshl—Knoxville Formation of Crittenden, 1951); unnamed Cretaceous sedimentary rocks (Kshu—shale, Berryessa Formation of Crittenden, 1951); unnamed Cretaceous sedimentary rocks (Ksh—shale).

Area 15 (Cotton, 1972):
Franciscan assemblage (KJfs—sheared).

Area 16 (McLaughlin and others, 1971):
Franciscan Formation (fsr—sheared, and fs—predominantly sandstone); Upper Jurassic and Lower Cretaceous mudstone (KJs); Upper Cretaceous, undifferentiated shale, mudstone, and sandstone (TKu); Paleocene and Eocene mudstone (Tms); Oligocene and Miocene shale and sandstone (Tss).

Area 17 (Dibblee, 1973a, Morgan Hill quadrangle):
Franciscan Formation (fsr—sheared, and fs—predominantly sandstone); unnamed Cretaceous shale (Kshl—Knoxville Formation of Crittenden, 1950); unnamed shale (Ksh—Berryessa Formation of Crittenden, 1951).

Area 18 (Dibblee, 1973b, Mt. Sizer quadrangle):
Franciscan Formation (fsr—sheared, and fs—predominantly sandstone); Cretaceous shale (Ksh—Berryessa Formation of Crittenden, 1951).

Area 19 (Dibblee, 1973c, Mt. Madonna quadrangle):
Franciscan Formation (fsr—sheared, and fs—predominantly sandstone); unnamed Cretaceous shale (Ksh); unnamed clay shale (TKs); unnamed clay shale and minor sandstone (Tuc).

Area 20 (Dibblee, 1973d, Gilroy quadrangle):
Franciscan Formation (fs—predominantly sandstone); unnamed Cretaceous shale (Kshl); unnamed Cretaceous shale (Ksh—Berryessa Formation of Crittenden, 1951).

Area 21 (Dibblee, 1973e, Gilroy Hot Springs quadrangle):
Franciscan Formation (fsr—sheared, and fs—predominantly sandstone); unnamed Cretaceous, shale (Ksh—Berryessa Formation of Crittenden, 1951).

Other studies have shown that in the bay region most landslides occur on slopes greater than 15 percent (8.5°), very few on slopes of 5–15 percent (3–8.5°), and virtually none on slopes of 0–5 percent (0–3°) (Kachadoorian, 1956, 1959; Bonilla, 1960; Brabb and others, 1972; Frame, 1974; Nilsen and others, 1975; Nilsen, Taylor and Brabb, 1976). Similar relations have been noted in some other areas (Briggs, 1974; Morton, 1976). Accordingly, we have incorporated these slope intervals in the relative slope stability categories.

Numerous studies in the bay region and elsewhere have shown that most landslides in any particular year occur in areas of previous landsliding (Kachadoorian, 1956, 1959; McGill, 1973; Frame, 1974; Nilsen and Turner, 1975; Nilsen, Taylor and Brabb, 1976;

Bailey, 1971; Kojan and others, 1972; Nilsen, Taylor and Dean, 1976). Commonly the new landsliding consists simply of renewed movements of old landslides as a result of natural causes, such as earthquakes and unusually intense rainfall, or modifications of slopes by the activities of man. Some types of landslides, however, particularly storm-generated soil slips, may not be related to areas of previous landsliding; Morton (1976) shows this for a part of southern California. Our analysis incorporates and generalizes the distribution of landslide deposits and possible landslide deposits shown in published and unpublished maps.

We have used five categories and one subcategory of relative slope stability because we felt that fewer categories would inadequately express the range in stability, and that more categories would be somewhat confusing and introduce boundaries between categories that are unsupported by the type of data available to us. Detailed work in individual areas, of course, may permit division into more categories or subcategories based on criteria other than the ones we selected.

PREPARATION OF SLOPE-STABILITY MAPS OF THE SAN FRANCISCO BAY REGION

The relative slope-stability maps were prepared by a procedure that involved combining available information about slopes, bedrock and surficial geologic units, and landslide deposits. Maps at a scale of 1:125,000 were prepared for each of these features and were then superimposed in various combinations to produce derivative maps. The final derivative maps were the relative slope stability maps (pl. 1, 2, and 3). The sources of data for landslide maps, bedrock and surficial geologic maps, and other previously completed relative slope stability maps of the San Francisco Bay region are shown in figures 39, 40, and 41, respectively.

To show how the slope-stability maps were derived, we present a series of smaller maps of the same part of northern Contra Costa and southern Solano counties (fig. 42) that illustrate the type and quality of available data and the sequence of overlaying and combining of data. We began with the slope data, then incorporated the information about landslide deposits, and finally incorporated the bedrock and surficial geologic data.

SLOPE MAPS

Slope maps of the San Francisco Bay region were prepared by the U.S. Geological Survey (1972) at a scale of 1:125,000 (fig. 43). These maps divide the region into areas of 0–5 percent (0–3°), 5–15 percent (3–8.5°), 15–30 percent (8.5–17°), 30–50 percent (17–26.5°), 50–70 percent (26.5–35°), and steeper than 70 percent (35°) slope. They were prepared by a photomechanical process from standard U.S. Geological Survey topographic quadrangle maps of the area (fig. 6). These slope maps are extremely detailed and show thousands of very small discontinuous areas of a particular slope. Because of the large amount of detail, the small size of many of the areas, and the inclusion of slope intervals steeper than 15 percent, it was necessary for us to prepare generalized or simplified slope maps from the published maps that showed broader areas of approximately the same slope and showed only the 0–5 percent, 5–15 percent, and greater than 15 percent slope intervals. The generalized slope maps were prepared manually from original plates that showed areas of less than 5 percent slope and greater than 15 percent slope. Areas smaller than about 300 m in longest dimension were eliminated from our derivative maps because we were primarily interested in the regional patterns and trends of slope intervals, not the details. A part of one of our generalized slope maps is shown in figure 44.

MAPS OF LANDSLIDE DEPOSITS

Published and unpublished maps showing the distribution of landslide deposits in the San Francisco Bay region were available from a number of sources (fig. 39). The maps were generally at scales of 1:24,000 or 1:62,5000, and had been prepared by a variety of mapping techniques. Some were based completely on photointerpretation, others on field mapping, and some on combinations of the two. Locally, detailed engineering geologic studies that included drilling, geophysical, soils, and geochemical investigations provided additional data.

The available maps also differed in the types of landslide deposits that had been mapped; some geologists are very conservative and map only those deposits that show evidence of recent movement and have clearly recognizable features of landslide deposits (fig. 18). Other geologists are less conservative and map older deposits that may have only a few features characteristic of landslide deposits; these older deposits are sometimes mapped with separate symbols to indicate the lower degree of confidence that the geologist had in recognizing the deposit as a landslide. Other geologists may indicate, with queries, areas seen on aerial photographs that may possibly be landslide deposits, incipient landslides, or very ancient features that have been so modified by subsequent erosion and uplift that they are extremely difficult to identify. Thus, the maps of landslide deposits available to us varied (1) in amount of detail shown, (2) in the relative numbers of landslide deposits mapped, (3) in the types of landslides mapped, and (4) in the technique of mapping used.

From the available maps at different scales showing the distribution of landslide deposits, we prepared 1:125,000-scale maps of landslide deposits for the San Francisco Bay region. Figure 45 is an example of part

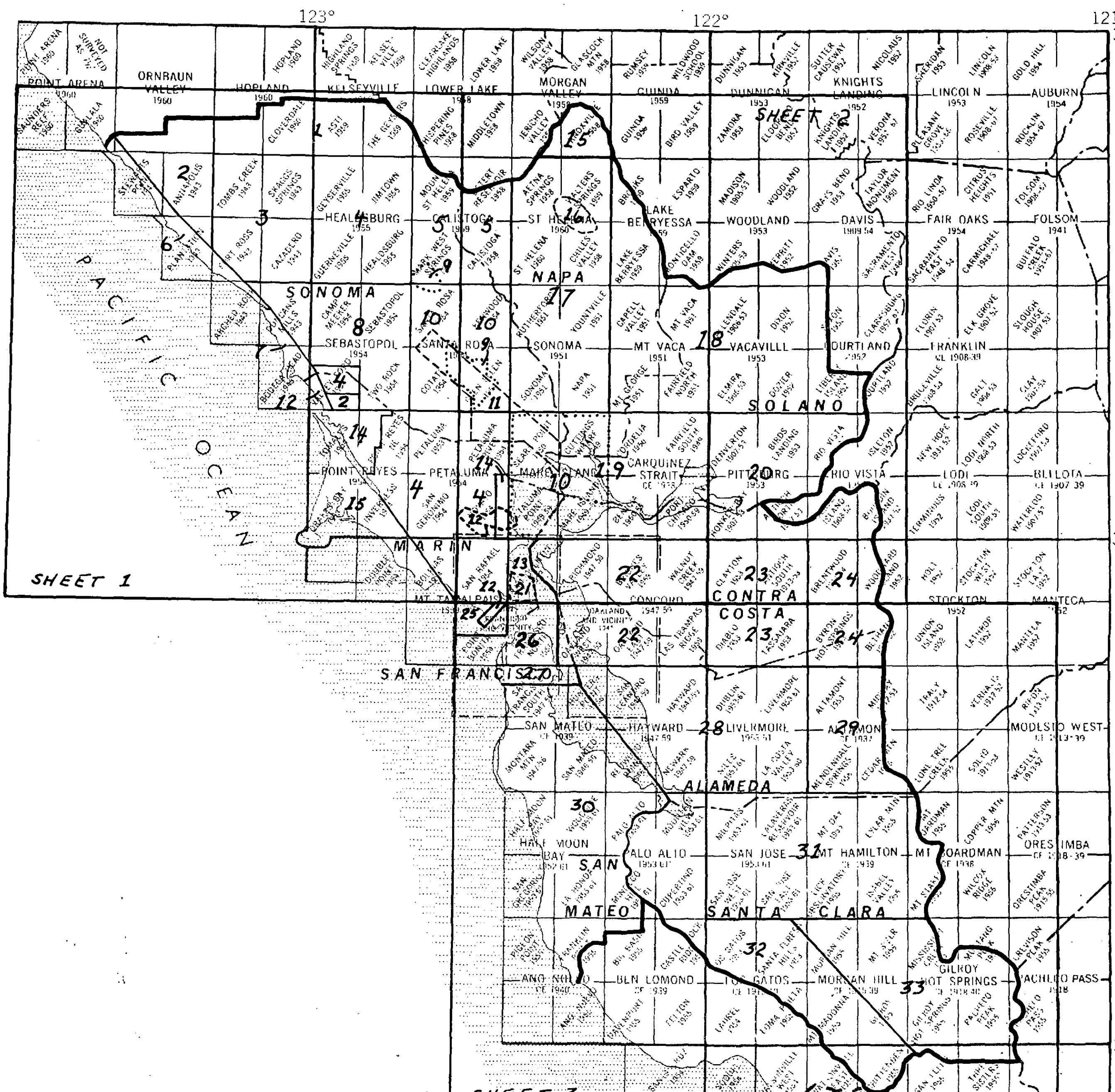


FIGURE 39.—Sources of landslide mapping.

1. Frizzell (1974)
2. Blake and others (1971)
3. Edgar H. Bailey, unpublished data, 1:62,500
4. Carl M. Wentworth, unpublished data, 1:24,000
5. Fox and others (1973)
6. Huffman (1972)
7. Huffman (1973)
8. Douglas M. Morton, unpublished data, 1:24,000
9. Huffman (1971)
10. John A. Bartow, unpublished data, 1:24,000
11. Gladys Louke, unpublished data, 1:24,000
12. Rice and Strand (1972)
13. Virgil A. Frizzell, Jr., unpublished data, 1:24,000
14. Blake and others (1974)
15. Wright and Reid (1975)
16. Dave Wagner, unpublished data, 1:12,000
17. Kenneth F. Fox, Jr., unpublished data, 1:24,000
18. Sims and others (1973)
19. Frizzell and others (1974)
20. Sims and Nilsen (1972)
21. John T. Alfors, unpublished data, 1:24,000
22. Nilsen (1973b)
23. Nilsen (1971)
24. Nilsen (1972b)
25. Julius Schlocker, unpublished data, 1:24,000
26. Schlocker and others (1958)
    Schlocker (1974)
27. Bonilla (1971)
28. Nilsen (1973a)
29. Nilsen (1972c)
30. Brabb and Pampeyan (1972b)
31. Nilsen (1972a)
32. Earl E. Brabb, unpublished data, 1:62,500
    Rogers (1971)
    Rogers and Armstrong (1973)
33. Nilsen (1972d)

FIGURE 39.—Continued.

of one of these maps. Many small landslides that are shown as enclosed areas on the original larger scale maps were reduced to dots at the smaller scale. From the source maps, we incorporated all the landslide deposits shown, including those mapped with queries or other degrees of uncertainty. As a result, the maximum possible number of landslide deposits shown by the authors was incorporated in our maps.

The maps of landslide deposits were generally far too detailed and complex for us to use easily in the slope-stability analysis. Consequently, as was done for the slope maps, we prepared generalized or simplified maps of the landslide deposits. These generalized maps were made primarily by grouping large and small landslide deposits that were located close to one another as larger areas underlain by many closely spaced landslide deposits. Figure 46 is an example of a generalized map of landslide deposits.

These generalized maps were prepared manually by enclosing areas within which the mapped landslide deposits were spaced less than 1,000–1,500 feet (300–460 m) apart. Thus, areas with numerous closely spaced, small landslide deposits or with closely spaced small, medium, and large landslide deposits are enclosed as zones, belts, strips, and irregularly shaped areas. All areas more than about 1,000–1,500 feet (300–460 m) wide that do not contain landslide deposits but may be surrounded by closely spaced landslide deposits are delineated on the maps. The generalizing process results in the inclusion of many areas less than 1,000–1,500 feet (300–460 m) wide that are not covered by landslide deposits within the enclosed areas of landslide deposits. Thus, as a result of the generalizing process, narrow areas unaffected by landslide processes are included within the areas affected by landslide processes. Solitary medium and large landslide deposits are delineated separately and not grouped with other landslide deposits more than 1,000–1,500 feet (300–460 m) away. Solitary small landslide deposits are shown separately.

The general topography and direction of slope were also used to delineate the landslide deposits. Landslides on the same continuous slope, creek bank, ridge top, or cliff have been grouped together because they are presumably generically related.

SURFICIAL AND BEDROCK GEOLOGY MAPS

Geologic maps of the San Francisco Bay region were prepared at a scale of 1:125,000 from the published and unpublished sources shown in figure 40 (index map). These maps show the distribution of the geologic units that underlie the region; the units are divided according to their age and rock type (fig. 47).

From discussions with geologists of the U.S. Geological Survey in Menlo Park, Calif., who have done mapping of or research on the physical properties of hillside materials, and from our own working experience in the bay region, we outlined on the maps those geologic units generally considered to be especially susceptible to slope failures (fig. 48). Each of these units has had a history of extensive landsliding and generally forms relatively unstable slopes. The names of the bedrock units judged to be susceptible to slope failure are listed in table 5 according to their age and the areas where they occur.

The muds along the margins of San Francisco Bay

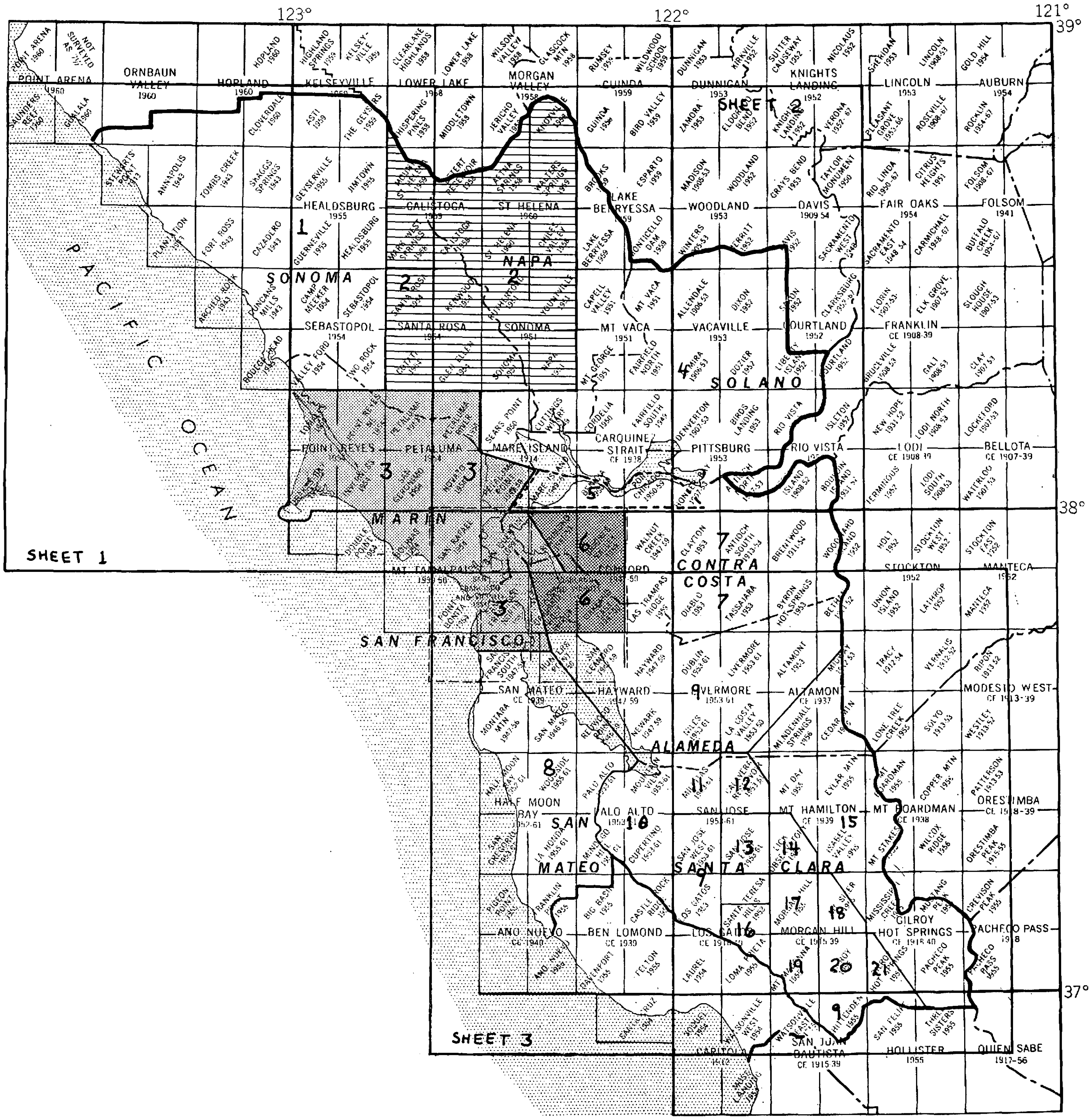


FIGURE 40.—Sources of bedrock mapping.

and the San Joaquin-Sacramento River delta, which generally form tidal marshes, swamps, and lagoons, are also susceptible to failure, even when nearly flat lying. These wet, unconsolidated, soft muds tend to flow laterally into cuts and are particularly susceptible to movement during earthquakes. These deposits had to be mapped separately for slope-stability purposes because of their unique properties and were outlined as a separate category on the geologic map using the previous mapping of Nichols and Wright (1971) (fig. 48).

DERIVATION OF THE SLOPE-STABILITY MAPS

After completing the steps described above, we combined each generalized slope map with the corresponding generalized landslide deposits map and geologic map. These three maps, all at the scale of 1:125,000, were combined in two stages to produce the completed slope-stability maps of plates, 1, 2, and 3.

The first stage of this procedure was the combination of the generalized slope maps (fig. 44) and the generalized maps of landslide deposits (fig. 46). This stage was accomplished by overlaying the slope maps on the maps of landslide deposits and transcribing the generalized areas of landslide deposits onto the slope maps (fig. 49). By this procedure, preliminary relative slope stability maps were produced that had four categories: (1) areas of 0–5 percent (0–3°) slope, (2) areas of 5–15 percent (3–8.5°) slope, (3) areas greater than 15 percent (8.5°) slope, and (4) areas underlain by landslide deposits.

In the final stage, the preliminary relative slope stabilty maps (fig. 49) were combined with the modified geologic maps showing the distribution of bedrock and surficial deposits considered to be especially susceptible to slope failures (fig. 48). This stage was accomplished by superimposing the preliminary slope-stability maps on the modified geologic maps and transferring to the slope-stability maps the boundaries of all geologic units considered to be especially susceptible to slope failure (fig. 50). The bedrock units were transferred only in areas underlain by slopes greater than 15 percent (8.5°); where gentler slopes were present, the units were not transferred. However, the moist, unconsolidated muds surrounding the bay were placed in a separate category because they are exclusively in areas of 0–5 percent (0–3°) slope.

Thus, the final relative slope stability maps show the San Francisco Bay region divided into five categories and one subcategory of slope stability: (1) 0–5 percent (0–3°) slope, (1A) 0–5 percent (0–3°) slope underlain by moist unconsolidated bay muds, (2) 5–15 percent (3–8.5°) slope, (3) greater than 15 percent (8.5°) slope, (4) greater than 15 percent slope underlain by bedrock geologic units considered to be especially susceptible to slope failure, and (5) areas underlain by individual or closely spaced landslide deposits. These five categories and one subcategory effectively divide the map into areas ranging from relatively stable to relatively unstable.

EXPLANATION OF SLOPE-STABILITY CATEGORIES

Each of the areas shown on the relative slope stability maps (pl. 1, 2, and 3) is underlain by a different combination of slope angle, type of bedrock unit, type of surficial unit, or number of landslide deposits; the areas are thus separable into distinctive categories in terms of relative slope stability. However, because of the scale used and the extent of generalization used to prepare the working maps, there may be many small areas within each mapped category with higher or lower slope-stability characteristics. These areas are too small to show at the scale used.

1. Blake and others (1971)
2. Fox and others (1973)
3. Blake and others (1974)
4. Sims and others (1973)
5. Earl E. Brabb, R. Wagner, and H. S. Sonneman, unpublished data 1:24,000
6. R. Wagner and Earl E. Brabb, unpublished data, 1:24,000
7. Brabb and others (1971)
8. Brabb and Pampeyan (1972a)
9. Earl E. Brabb, unpublished data, 1:24,000
10. Brabb (1970)
11. Dibblee (1972a, Milpitas quadrangle)
12. Dibblee (1972d, Calaveras Reservoir quadrangle)
13. Dibblee (1972b, San Jose East quadrangle)
14. Dibblee (1972c, Lick Observatory quadrangle)
15. Cotton (1972)
16. McLaughlin and others (1971)
17. Dibblee (1973a, Morgan Hill quadrangle)
18. Dibblee (1973b, Mt. Sizer quadrangle)
19. Dibblee (1973c, Mt. Madonna quadrangle)
20. Dibblee (1973d, Gilroy quadrangle)
21. Dibblee (1973e, Gilroy Hot Springs quadrangle)

FIGURE 40.—Continued.

CATEGORY 1

Category 1 consists of areas of 0–5 percent (0–3°) slope that are not underlain by landslide deposits or other surficial deposits that are highly susceptible to slope failures. They may be underlain by bedrock units that are susceptible to slope failures on steeper slopes but are generally stable at these low slopes. The areas within category 1 are generally underlain by floodplain alluvium, alluvial terrace deposits, marine terrace deposits, and gently sloping alluvial fan deposits; but they may also form the flat, gently sloping summit areas of some ridge crests and mountains. They may locally be susceptible to flooding and to deposition of debris flows derived from surrounding uplands during periods of heavy rainfall. However,

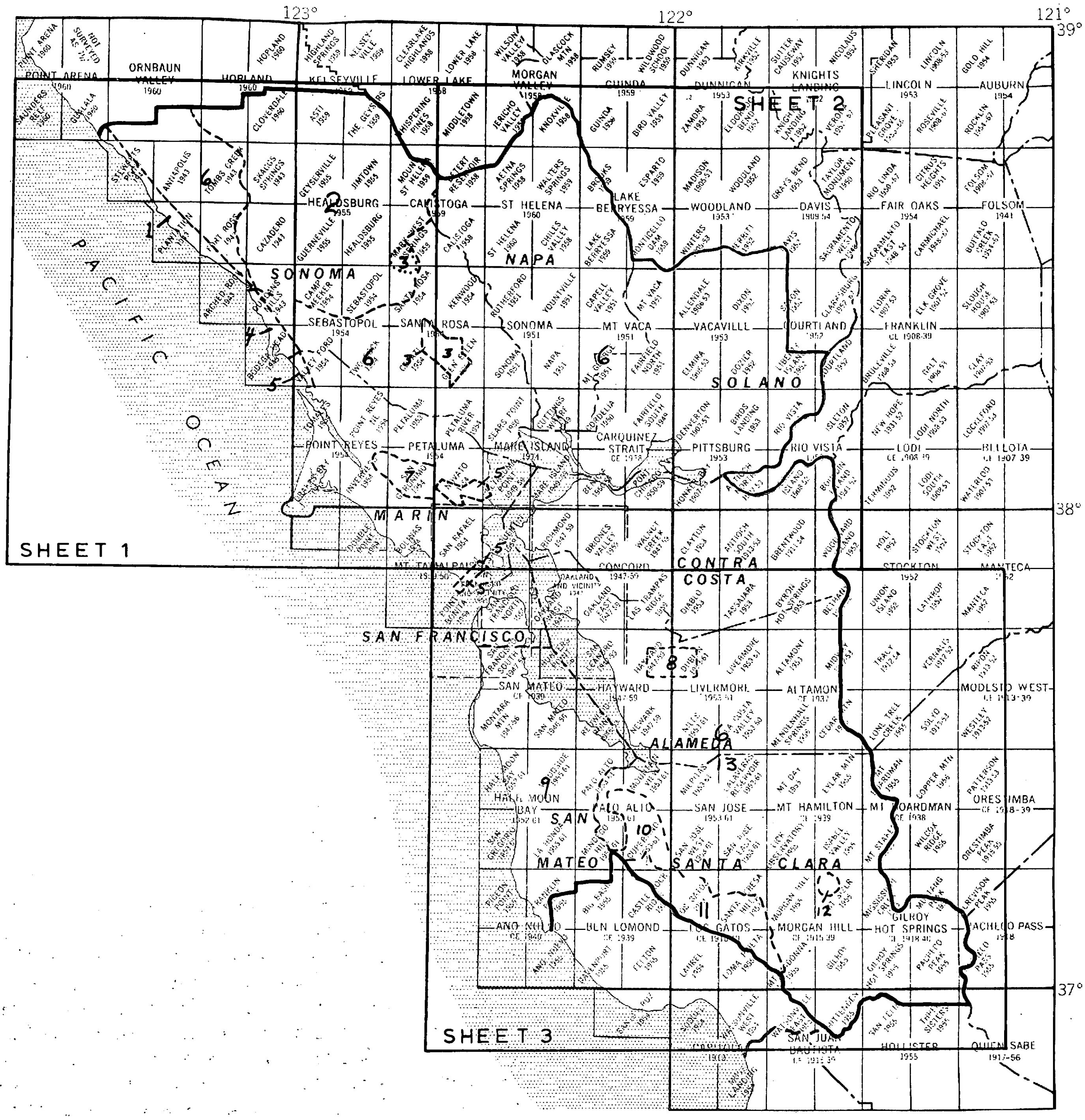


FIGURE 41.—Areas of previous slope stability studies.

within the category 1 areas the slopes are generally stable.

Exceptions may include some small areas of steeper slopes adjacent to roads, creeks, rivers, and coastal margins. These areas may include riverbanks, coastal cliffs, and edges of terraces; they are generally too small or narrow to be shown at this scale and commonly have low relief. Riverbanks may be particularly hazardous during periods of flooding and the coastal areas particularly hazardous during severe storms. In addition to these exceptions, the areas in category 1 may be underlain by bedrock types that are locally unstable at slopes of 0–5 percent (0–3°) and therefore susceptible to landsliding.

CATEGORY 1A

Category 1A consists of areas of 0–5 percent (0–3°) slope that are underlain by moist unconsolidated sediments surrounding San Francisco, San Pablo, Suisun, and Grizzly Bays and in the confluent Sacramento and San Joaquin delta. These areas are generally tidal flats, marshes or swamps, unless modified by artificial fill, so they are susceptible to flowage, lateral movement and liquefaction at slopes of less than 1° (Nichols and Wright, 1971; Youd, 1973; Youd and others, 1975). During earthquakes, they are particularly susceptible to ground failure, and structures built on artificial fill placed over the muds may be damaged. The margins of tidal channels are especially subject to failure when undercut, excavated, or subjected to differential loading.

1. Huffman (1972)
2. U. S. Army Corps of Engineers (1967)
3. Huffman (1971)
4. Huffman (1973)
5. Rice and Strand (1972)
6. Radbruch and Wentworth (1971)
7. Twiss and others (1970)
8. Burnett (1972)
9. Brabb, Pampeyan, and Bonilla (1972)
10. Rogers (1971)
11. Rogers and Armstrong (1973)
12. Frame (1974)
13. Wright and Nilsen (1974)

FIGURE 41.—Continued.

CATEGORY 2

Category 2 consists of areas of 5–15 percent (3–8.5°) slope that are not underlain by landslide deposits or other deposits that are highly susceptible to slope failures. They may be underlain by bedrock units that are susceptible to slope failures at steeper slopes but are generally stable at slopes of 5–15 percent (3–8.5°). The areas within category 2 are generally underlain by colluvial deposits, alluvial fans, tilted alluvial flood plains, and marine and alluvial terraces that commonly form gently sloping areas at the bases of upland areas.

These areas are generally relatively stable but may include locally steeper slopes along roads, creeks, rivers, or the coast that may be more susceptible to landsliding but are too small or narrow to be shown at this scale. In addition, some areas within category 2 may be underlain by bedrock types that are locally unstable at slopes of 5–15 percent (3–8.5°) and therefore susceptible to landsliding.

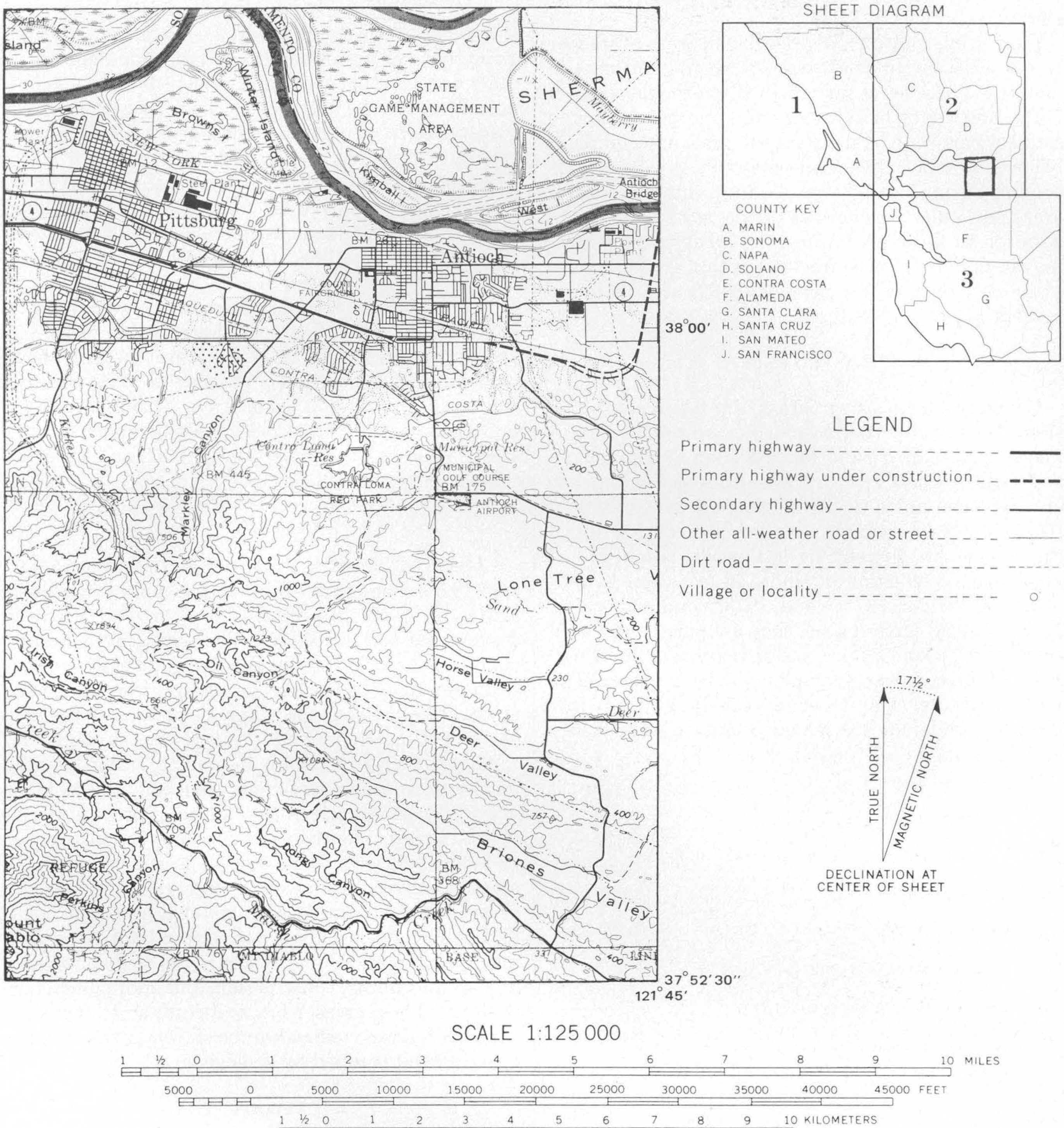
CATEGORY 3

Category 3 consists of areas of greater than 15 percent (8.5°) slope that are underlain neither by landslide deposits nor by bedrock units that are susceptible to landsliding. This category generally comprises hillside and upland areas that are commonly underlain by bedrock rather than surficial deposits, although colluvial deposits may be present on the lower parts of the slopes and in ravines or canyons.

These areas are generally reasonably stable but may include some small areas that are locally unstable for various reasons, such as the failure of areas above or below that are underlain by bedrock types susceptible to landsliding or by landslide deposits; proximity to areas of active erosion along creeks, rivers and coastal areas; slopes saturated with water adjacent to lakes and reservoirs; proximity to active landslides that may be enlarging; and man's activities such as logging, cutting and filling, construction, and adding moisture to slopes. These areas may also include small landslide deposits not large enough to be shown at this scale or to have been mapped by geologists.

CATEGORY 4

Category 4 consists of areas of greater than 15 percent (8.5°) slope that are underlain by bedrock units that are highly susceptible to landsliding but are not underlain by landslide deposits. This category comprises hillside and upland areas that are commonly underlain by bedrock rather than surficial deposits, although colluvial deposits may be present on the lower parts of the slopes or in canyons and ravines.



CONTOUR INTERVAL 200 FEET
DOTTED LINES REPRESENT 40-FOOT CONTOURS
DATUM IS MEAN SEA LEVEL
DEPTH CURVES AND SOUNDINGS IN FEET—DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS APPROXIMATELY 2 TO 5 FEET

FIGURE 42.—Topographic map of part of northern Contra Costa and southern Solano Counties, Calif. (from U.S. Geol. Survey, 1970, Sheet 2).

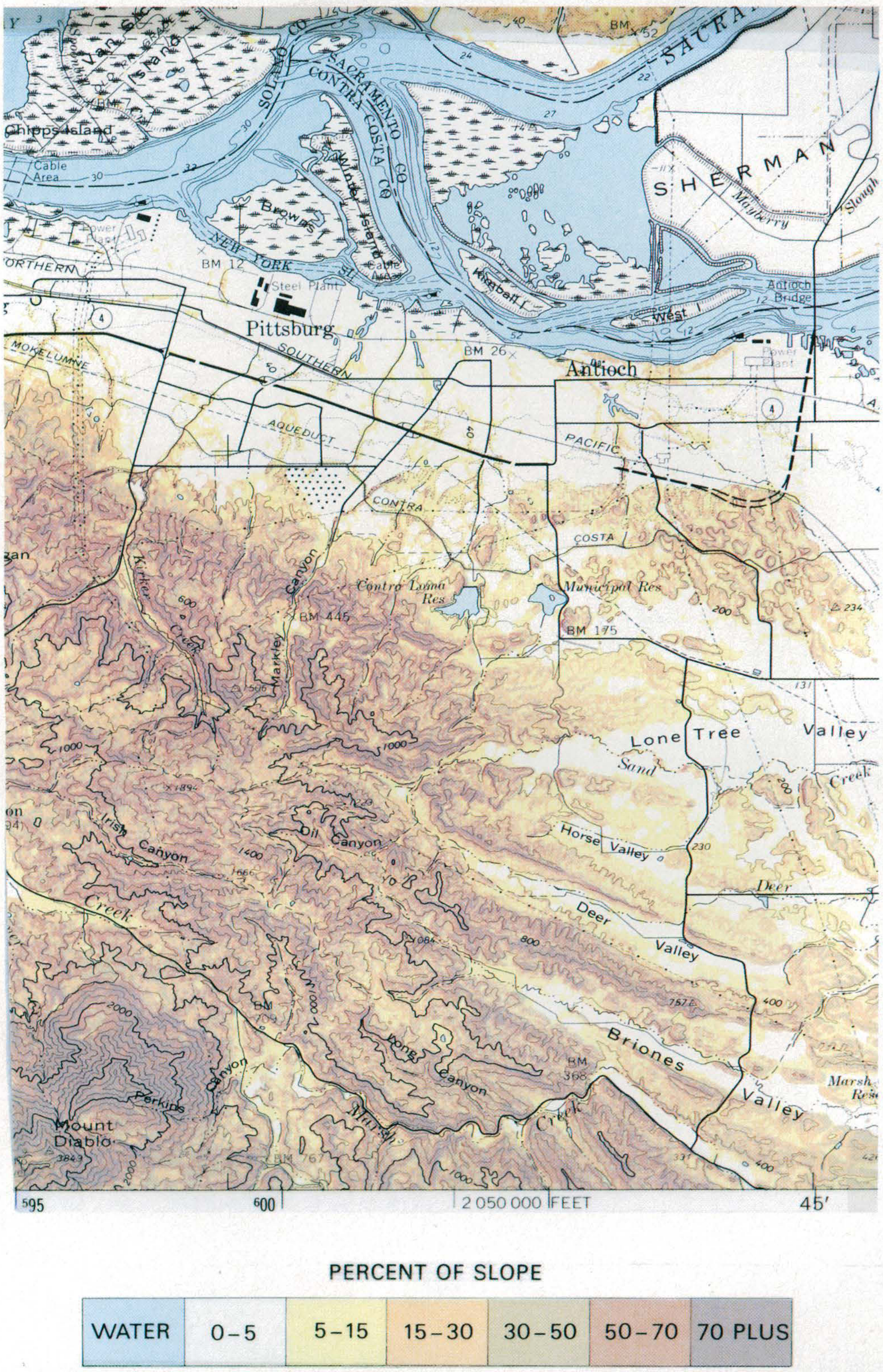


FIGURE 43.— Slope map of part of northern Contra Costa and southern Solano Counties, Calif. (from U.S. Geol. Survey, 1972, Sheet 2).

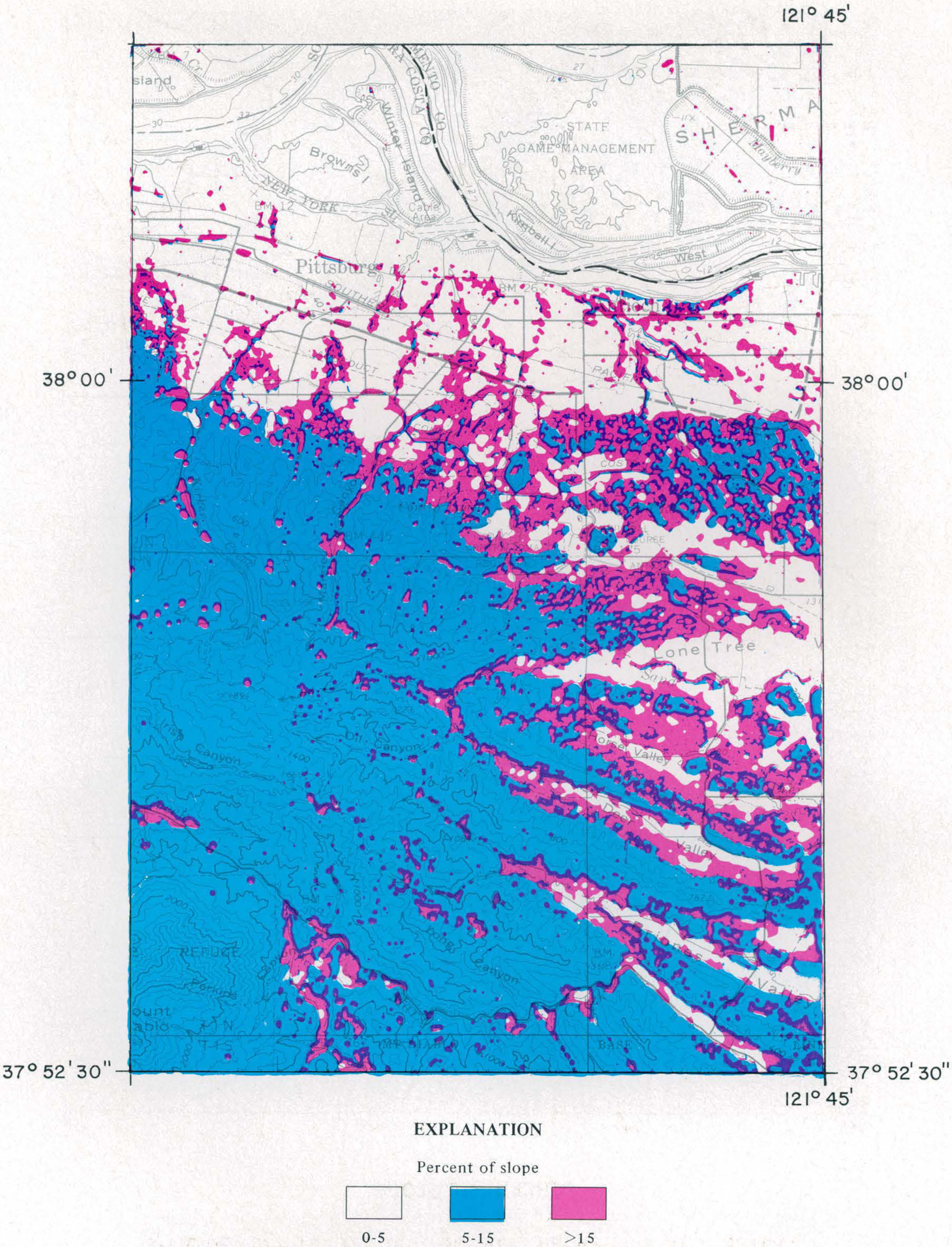
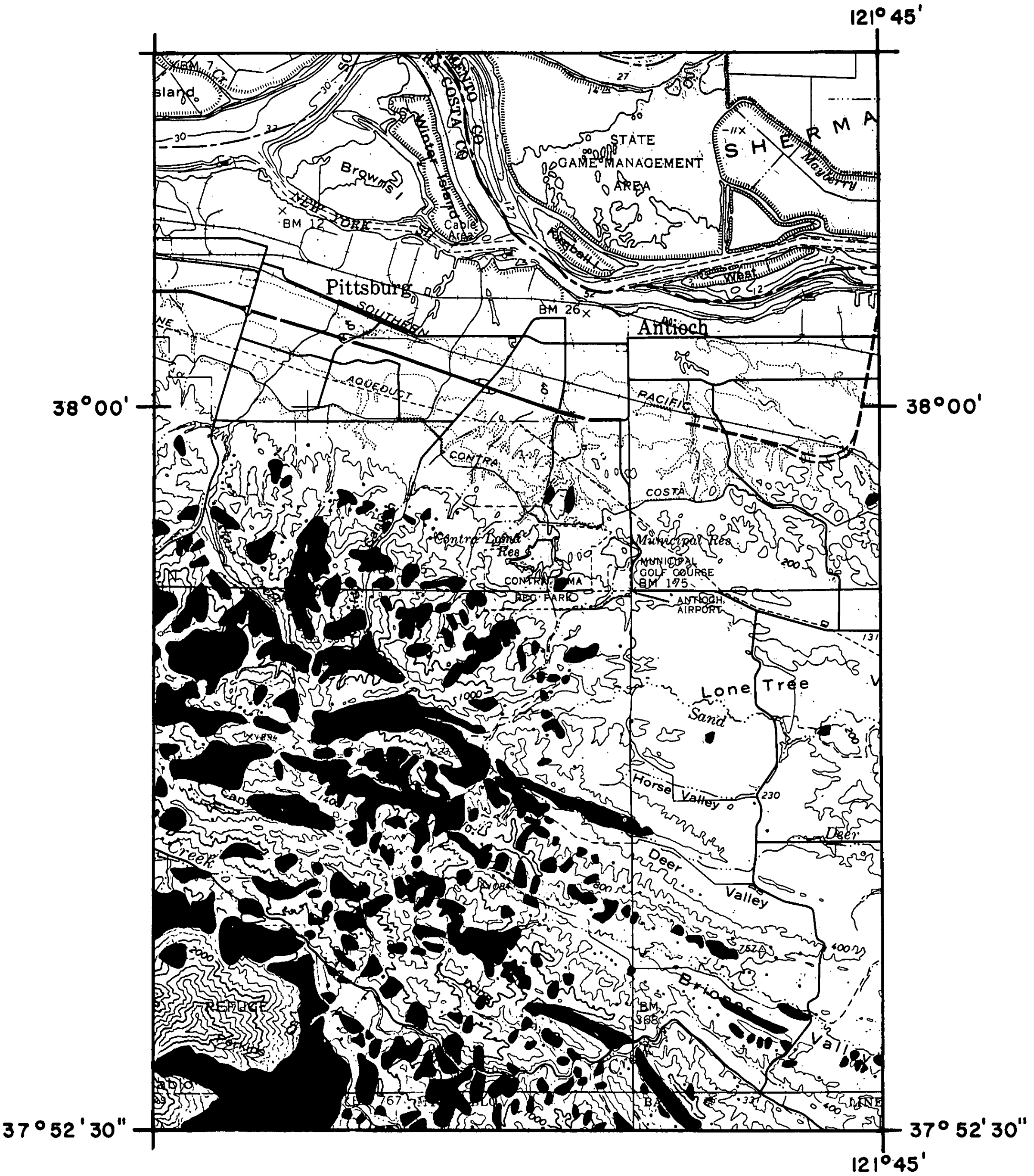


FIGURE 44.— Generalized slope map of part of northern Contra Costa and southern Solano Counties, Calif.

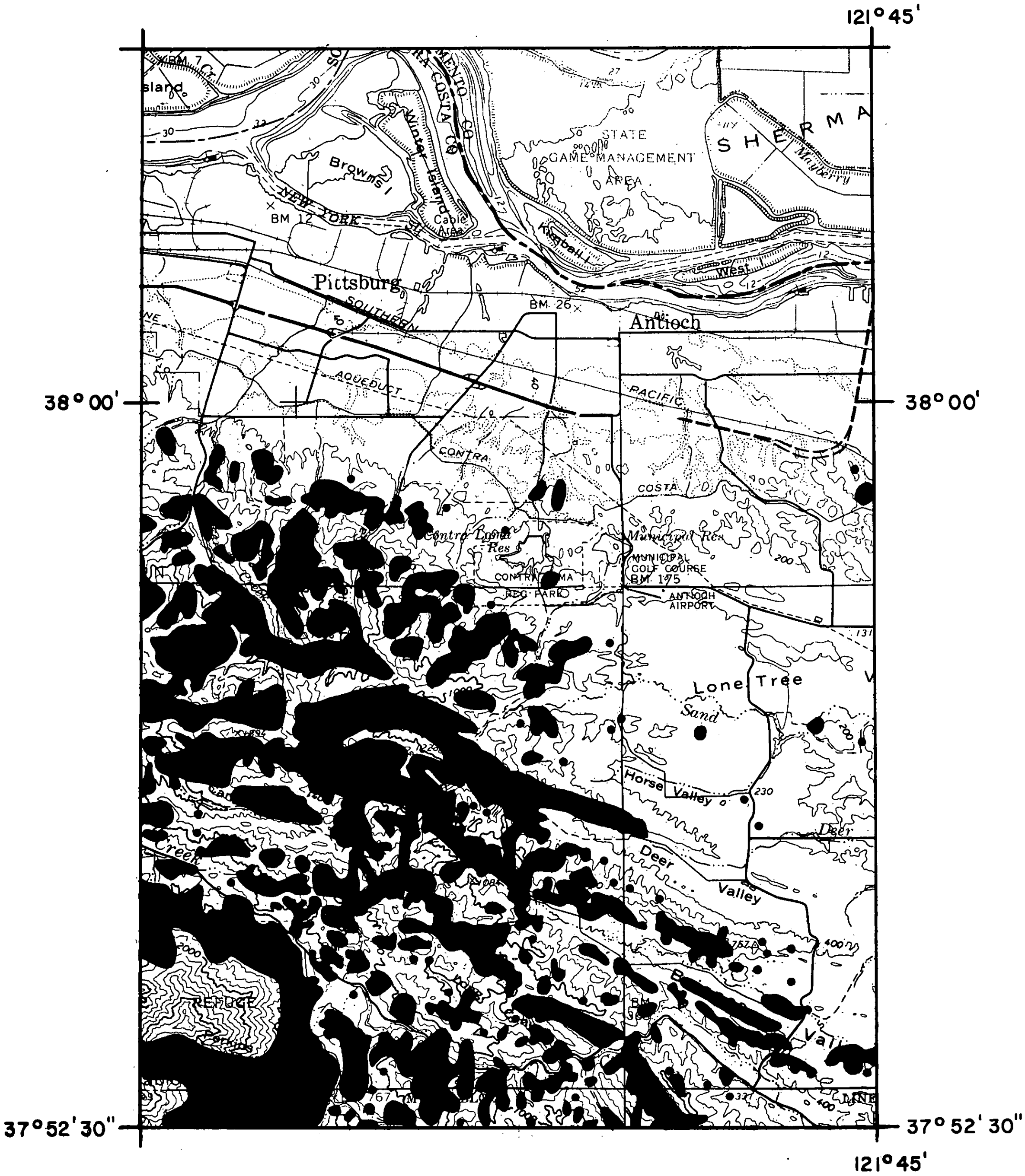


EXPLANATION

Large landslide deposit larger than 500 feet in longest dimension

Small landslide deposit approximately 200-500 feet in longest dimension

FIGURE 45.—Photointerpretive map of landslide deposits in part of northern Contra Costa and southern Solano Counties, Calif. (modified from Nilsen, 1971 and Sims and Nilsen, 1972).



EXPLANATION

Areas underlain by single landslide deposit or group of closely spaced large and small landslide deposits

Single isolated small landslide deposit

FIGURE 46.— Generalized photointerpretive map of landslide deposits in part of northern Contra Costa and southern Solano Counties, Calif.

These areas are susceptible to future landsliding even though landsliding has not occurred there in the past. The underlying bedrock units possess physical characteristics, such as extensive shearing or jointing, poor consolidation, and structurally weak components that make them susceptible to slope failures and have caused slope failures in adjacent areas. The exact conditions required for future landsliding in these areas are not known, but under the effects of high rainfall, seismic activity, the influence of man, and other fac-

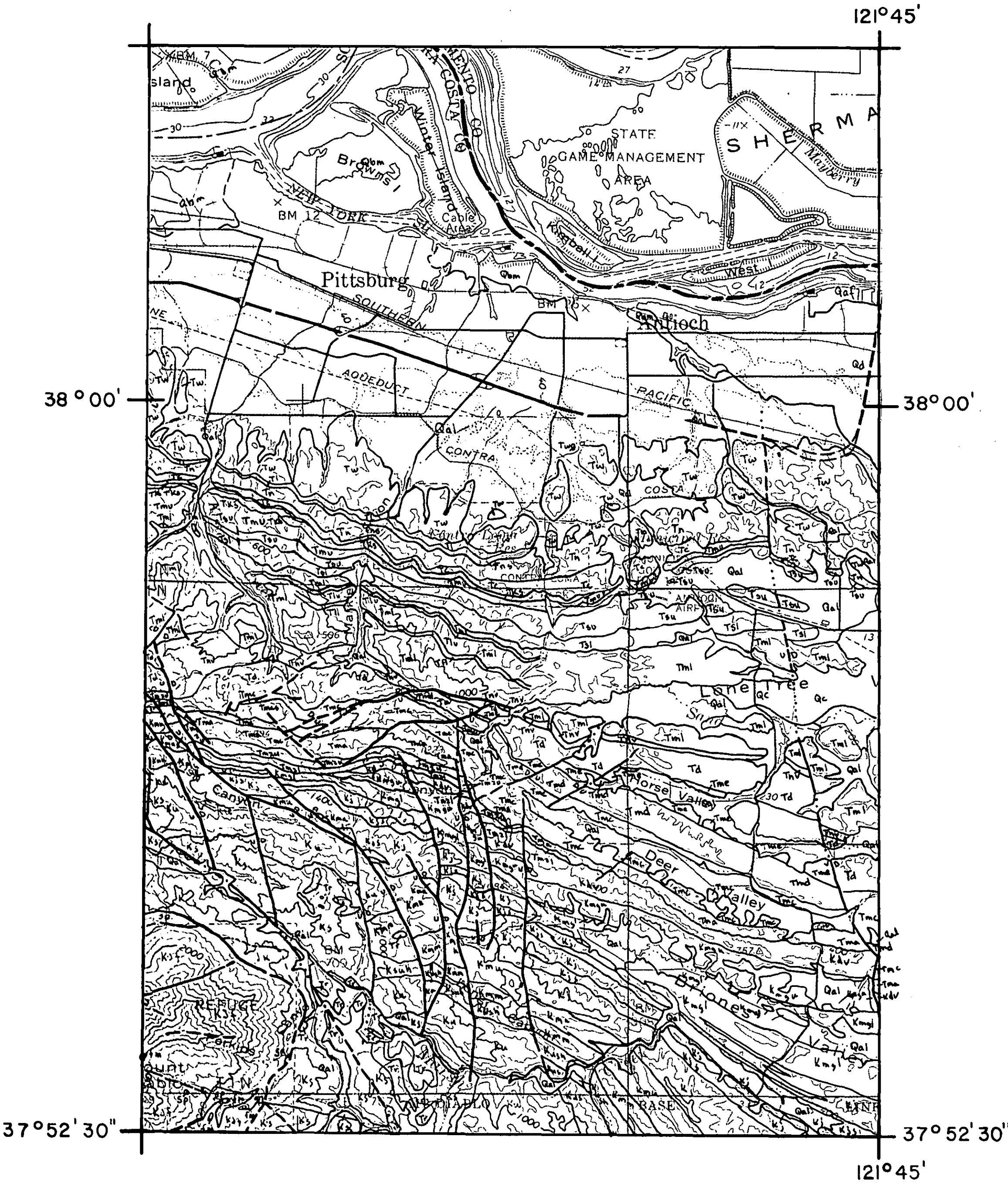


FIGURE 47.— Geologic map of part of northern Contra Costa and southern Solano Counties (from Brabb and others, 1971 and Sims and others, 1973).

tors mentioned previously, these areas are likely to be unstable. Category 4 may include some small areas within it that are locally more unstable for the reasons mentioned under category 3. Conversely, local areas within category 4 may be more stable than the average because of variations in the local character of the bed-

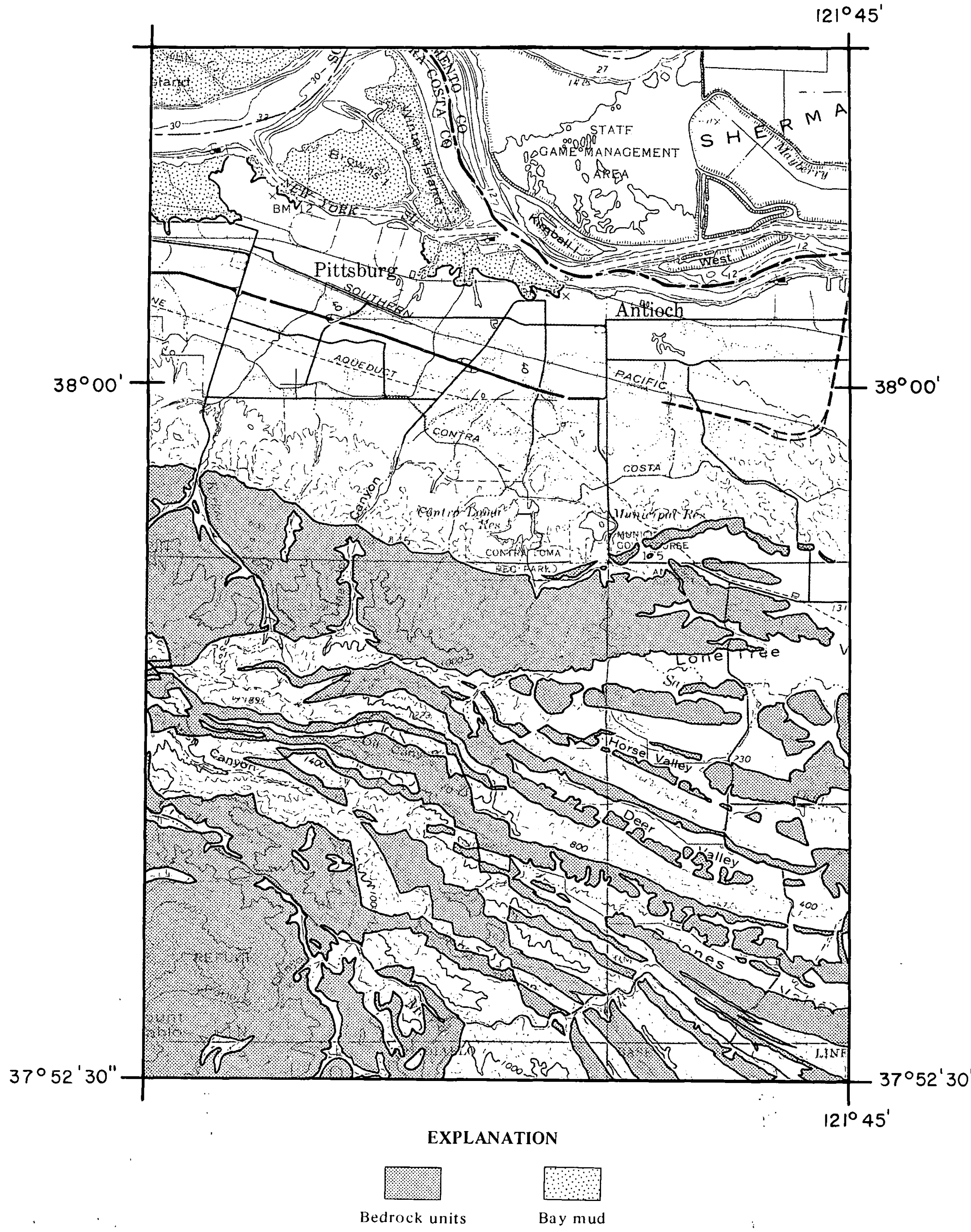
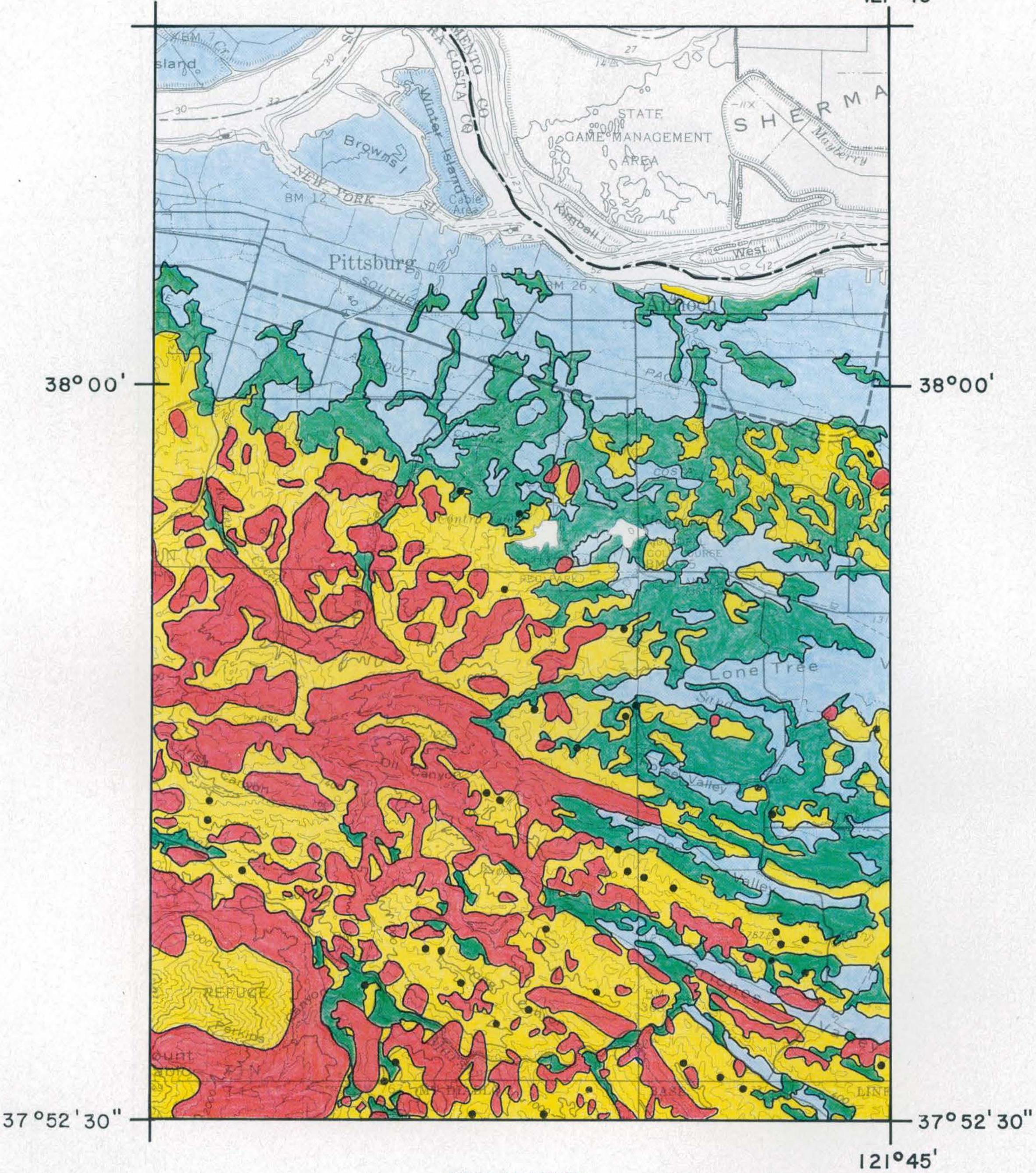


FIGURE 48.— Distribution of bedrock and surficial geologic units considered to be especially susceptible to slope failures in part of northern Contra Costa and southern Solano Counties (modified from Brabb and others, 1971, Nichols and Wright, 1971, and Sims and others, 1973).



EXPLANATION

Areas of less than 5 percent slope and no landslide deposits

Areas of 5-15 percent slope and no landslide deposits

Areas of greater than 15 percent slope and no landslide deposits

Areas underlain by single landslide deposit or group of closely spaced large and small landslide deposits

• Single isolated small landslide deposits

FIGURE 49.—Preliminary relative slope stability map of part of northern Contra Costa and southern Solano Counties derived by combining the generalized slope map (fig. 44) and generalized map of landslide deposits (fig. 46).

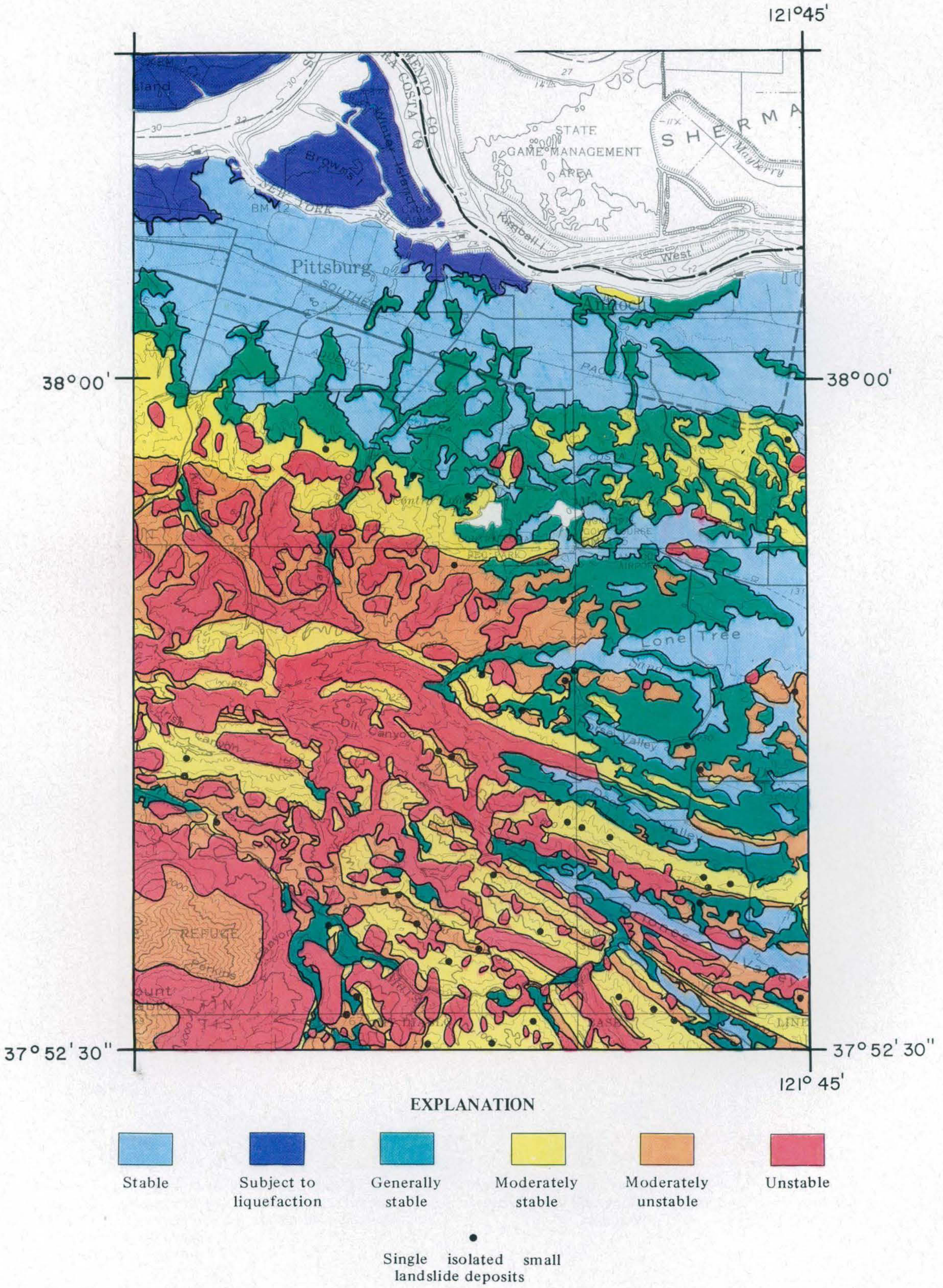


FIGURE 50.—Relative slope stability map of part of northern Contra Costa and southern Solano Counties derived by combining the preliminary relative slope stability map (fig. 49) and map of bedrock and surficial geologic units considered to be especially susceptible to slope failures (fig. 48).

rock units, which may include small areas where the rocks are different from those shown on the geologic maps we used.

CATEGORY 5

Category 5 consists of areas underlain by or immediately adjacent to landslide deposits. They range in slope from 0 to 90° and may be underlain by any bedrock type but they are underlain most commonly by bedrock or surficial deposits that are highly susceptible to landsliding. This category comprises a wide variety of topographic situations, commonly hillsides steeper than 15 percent (8.5°) and steep slopes adjacent to coastal areas and river banks. They are commonly underlain by bedrock units, but substantial areas are underlain by surficial deposits such as alluvial, marine terrace, and colluvial deposits. Many areas are in places where the slopes have been modified by construction, logging or cutting and filling of the ground.

The areas of category 5 have undergone landsliding in the past and are generally very susceptible to future landsliding, especially if the slopes are cut and filled. They do, however, include many small or narrow areas less than 1,000–5,000 feet (300–1500 m) across that are not underlain by either landslide deposits or bedrock units highly susceptible to landsliding; however, they are too small or too narrow to be shown at this scale and at the level of generalization that we used.

USES AND LIMITATIONS OF MAPS

These maps provide a generalized regional representation of the relative stability of slopes in the San Francisco Bay region. They are based on more data and are at a larger scale (1:125,000) than an earlier map at a scale of 1:500,000 showing the estimated relative abundance of landslides in the San Francisco Bay region (Radbruch and Wentworth, 1971). However, the slope stability maps are of smaller scale and are not based on as much information as previously published, more detailed relative slope stability maps that cover smaller areas, such as that by Brabb, Pampeyan, and Bonilla (1972) at a scale of 1:62,500 for San Mateo County, Frame (1974) for the Mount Sizer area in Santa Clara County at a scale of 1:12,000, Rogers (1971) and Rogers and Armstrong (1973) for part of the Santa Cruz Mountains in Santa Clara County at a scale of 1:12,000, Rice and Strand (1972) and Huffman (1971) at a scale of 1:24,000 for parts of the San Francisco Bay region, and others shown on the slope stability index map (fig. 41). The scale of the present maps is suitable for a variety of regionally oriented purposes, especially those that require a uniform and consistent evaluation of slope stability and one that is independent of jurisdictional boundaries.

At the present time, many land-use and regional planning decisions in the San Francisco Bay region are being made without the necessary background of earth-science information. Except for the detailed maps of small areas and the San Mateo County map (Brabb and others, 1972), general maps of relative slope stability that cover large areas have not been available for regional land-use and planning studies in the bay area. Preliminary evaluations by Kockelman (1975, 1976) indicate widespread use of almost all recent U.S. Geological Survey publications related to landsliding and slope stability. Several maps have formed the basis for land-use planning decisions.

The present maps have a variety of potential uses for long-range regional land-use planning for such purposes as: transportation and communication networks; nuclear reactor sites or other large power plants; major research facilities that require large areas with stable foundations; national defense establishments; urban development and growth; pumping plants and pipeline locations for the movement of water, natural gas, or petroleum; large industrial sites; open spaces such as regional park systems, wildlife areas, and golf courses; and development and utilization of coastal areas and flood basins where landsliding may be an important constraint. The maps may also serve as a guide for planning future slope stability studies within the bay region by indicating those areas where severe problems may be expected and by showing the extent of our present knowledge throughout the region. The regional trends in relative slope stability may be used in a variety of studies of the physical environment by demonstrating relationships between slope stability and other natural or manmade phenomena such as, for example, seismic activity (Borcherdt and others, 1975). The maps may aid in the preparation of general plans for various communities, especially as part of the seismic safety and open-space elements.

The maps have been greatly generalized and simplified in order to present a broad picture of the variations in slope stability. The original landslide mapping, bedrock mapping, and slope mapping have all been generalized and simplified. Because of this generalizing, the maps should not be used to interpret the stability of specific or local areas—such use is unwarranted and unintended.

The maps have shortcomings that limit some of their uses, and these must be clearly pointed out to the user. As has already been stated, the maps are based on an analysis of only three factors that affect slope stability—previous landslide activity, general nature of the underlying bedrock, and angle of slope of the land surface. The maps are thus primarily oriented toward the study of natural slope stability. The stability of cut slopes, as for excavations, is a separate area of study involving more detailed analyses of the engineering characteristics of bedrock units. Many other factors that influence slope stability, some of which were mentioned in the introduction, have not been used in this analysis but may be of importance locally. Computer analysis of the factors contributing to landsliding, which might be feasible for this region (Adams, 1975), has not been utilized.

The maps rely on the landslide and bedrock mapping done by a variety of workers, who mapped with differing techniques, skills, and philosophies, yielding maps that vary considerably in character. We have adopted their mapping and used it in our analysis without attempting to weigh its accuracy, quality, or veracity. The mapping of landslide deposits, done largely by photointerpretation, has produced particularly variable interpretations of what constitutes a mappable landslide deposit. Where we have had overlapping coverage, we have shown all of the landslide deposits mapped by all of the workers, so as to maximize the size of the areas underlain by landslide deposits. In addition, we have shown as unquestioned those landslide deposits mapped as questionable or possible in those areas that the worker was not certain whether the topographic feature seen in the aerial photographs was a true landslide or not. The map user is encouraged to go back to the original source map if more detail is needed.

The authors have conducted limited field studies in the map areas and have no detailed information regarding the chemical, physical, and engineering characteristics of the bedrock materials, although some of this information is presently being collated. Most importantly, few data were available regarding the history of movement of the mapped landslide deposits or their nature—whether they are flows, slides, falls, or slumps, and whether they are thin surficial landslide deposits or thick deposits extending deep into the underlying bedrock. Confident statements regarding slope stability are difficult to make without such data.

The maps are largely based on the presence of landslide deposits, but the deposits of some types of landslides are not preserved. These types include many soil slips, mudflows, and debris flows that form during periods of heavy rainfall; the moving material generally is transported rapidly downslope along short, steep drainage channels that are tributary to larger streams (Campbell, 1975). Debris is commonly deposited downstream on alluvial fans or possibly alluvial plains and is not recognizable as a landslide deposit on aerial photographs. These types of slope failure are commonly the most dangerous in terms of hazards to life, because they move rapidly and occur very suddenly. Areas where large alluvial fans have developed at the base of steep slopes should be regarded as potentially very hazardous; because of the procedures used to make this map, these areas are generally not included within unstable areas.

Some other types of landslide deposits may be modified very quickly by natural or man-made processes, so they are not easily recognized. Many such areas have been mapped (see Wright and Reid, 1975, for example) as being underlain by anomalous topographic configurations the origin of which may be from landsliding but which could also be due to other reasons. These areas are also not necessarily included within unstable areas on the slope-stability maps.

No detailed analysis was done on the stability characteristics of the bay muds of category 1A. For more information pertaining to their hazard potential, see Youd (1973), Nichols and Wright (1971), and the references cited in these papers.

Specific problems regarding slope stability, as portrayed on our maps, may be present in certain small areas. For example, a specific problem exists in the western part of plate 2 (northeastern bay region), where resistant volcanic rocks of the Sonoma Volcanics are in contact with less resistant sedimentary rocks of the Petaluma, Huichica and Glen Ellen Formations (Fox and others, 1973). Commonly the resistant volcanic rocks underlie relatively steep slopes above gentler lower slopes that are typically more unstable than the higher slopes because of the difference in underlying rock types (K. F. Fox, Jr., written commun., 14 May 1974); thus in some parts of the map area, because of the geologic situation and the method used to prepare the map, the relative stability of lower and higher slopes may be reversed. The role the geologist plays in urban development, major construction, regional planning, site investigations, and other activities, will increase in the future, particularly as the geologist obtains better information and prepares more useful maps (Price, 1972; Taylor, 1972; Rawlings, 1972).

Our maps should be regarded as an initial attempt to predict regional slope stability, to be superseded in future years as better data and techniques become available.

SUGGESTIONS FOR FUTURE RESEARCH

In order to prepare more detailed slope-stability maps in the San Francisco Bay region, research and data collection must be expanded. Future work should be oriented toward obtaining standardized data covering the entire map area. In this section we mention some of the types of studies that seem important to us for future slope-stability studies.

Mapping of landsliding deposits should be more uniform and clearly defined with regard to purpose, objective, and minimum size of deposits. A group of well-trained photogeologists with reasonably similar skills will be required to obtain uniform and compatible maps. Many comparisons should be made between photointerpretation and ground observations to improve the uniformity of mapping. As the present maps clearly indicate, nonuniform mapping poses serious problems in the preparation of regional maps.

Mapping of bedrock and surficial geology should also be more uniform. Changes in stratigraphic names across quadrangle boundaries and complex stratigraphic facies changes must be clearly indicated. However, for slope-stability analyses, a standard geologic map is not the most suitable tool. An engineering geologic map that groups different mapped units in terms of similar engineering and physical characteristics rather than age would be more suitable for slope-stability analyses. Surficial deposits should also be mapped in this manner, to provide uniform coverage of the entire area.

Much research and mapping of other factors that contribute to landsliding should be undertaken. Mapping of soil types and soil characteristics such as strength, thickness, and physical and chemical changes under the influence of water will be required in order to incorporate soils data into slope-stability mapping. Another important factor about which little is known is the effect of rainfall on slope stability: how much rainfall and what sequence of storms are required to generate landslides in different areas? is there any correlation between mean annual rainfall and landslide frequency? Some information about these relationships is available, but further studies are required.

The effect of geologic structure on landslides has been examined in a few local areas in the bay region, but no generally applicable and regionally useful studies have been completed. The relations between vegetation and slope stability are poorly known—locally, grass-covered slopes seem to be more prone to landsliding, although in other areas tree-covered slopes are more susceptible. Areas covered with chaparral appear to be unusually stable in many parts of the region. However, the effect of vegetation on soils and hillsides in terms of slope stability is poorly understood. Despite having reasonably good maps of vegetation cover in the map area, we were unsure about how these maps should be used and whether the influence of vegetation was comparable in any way with the influence of bedrock, slope, and previous history of landsliding on slope stability.

Another important factor that was not treated in our study is the effect of seismic shaking on slope stability. We know, of course, that seismic shaking contributes to slope instability in general, and that landslides are commonly generated in the bay region during or after major earthquakes (Nilsen and Brabb, 1975). However, we have little information about the effects of seismic waves passing through landslide deposits, or marginally stable slopes, and thus are not able to make predictions about the specific effects of certain types and magnitudes of earthquakes in the bay region.

Finally, more data are required concerning the effects of development on natural slopes. Many studies have clearly shown that cutting and loading of slopes have contributed to landsliding in specific areas, but the regional effects of major development over broad areas have not been studied and are not well known. What types of development and how extensive must it be in different areas to contribute to extensive landsliding?

In summary, we have just begun to study natural slope stability in the San Francisco Bay region, and much work must be done before more detailed and more useful regional and local slope-stability maps can be prepared. This assessment is also applicable to the United States as a whole, as pointed out by Sorenson, Ericksen, and Mileti (1975).

USE OF SLOPE-STABILITY INFORMATION IN LAND-USE PLANNING

By T. C. VLASIC and W. E. SPANGLE

RELEVANCE OF THE BAY REGION SLOPE-STABILITY INFORMATION TO LAND-USE PLANNING

The preceding section identifies the range of slope-stability conditions that need to be considered for land use and development in the San Francisco Bay region. Within limits, earth-science information can be applied in land-use planning to help define constraints on land use. The relative slope stability map, although unsuitable for individual site studies, can be applied to regional analysis of policy for areawide land use, inventory of potential open space (in response to State-mandated open-space planning), and initial evaluation of regionally significant projects. In addition, this information is useful to planning agencies throughout the bay region for evaluating the impact of land-use proposals and determining the need for detailed studies.

The real relevance of the slope-stability information will, of course, hinge on its actual use by regional, county, and city planning agencies. To assist these agencies, the interpretive tables in this section have been prepared. The tables describe the range of land-use conclusions that earth scientists agree can reasonably be drawn from the 1:125,000-scale relative slope-stability map.

RESPONSIBILITY OF THE USER

Almost every jurisdiction in the bay region has some hillside areas with slopes of questionable stability. Slope stability, therefore, is important in land-use planning by the local jurisdictions, as well as by the ABAG (Association of Bay Area Governments) and other regional agencies with land-use management responsibilty. Planners and decisionmakers at local and regional levels must assume the responsibility of seeing that slope stability is given consideration. In fact, State planning requirements make it mandatory that local planners and decisionmakers assume this responsibility.

The land-use planning process described in the introduction of this report stated that issues need to be identified, objectives set, and critical data collected and interpreted. The relative slope-stability map of the bay region can provide an important input for regional, county, and city agencies. It is the responsibility of each planning agency to determine what information is available and how it relates to their planning program.

If the relative slope stability map of the region indicates the possibility of a significant landslide hazard within a local jurisdiction (particularly for lands that are developed or in the immediate path of development), the planning agency will need to take steps to determine how it may limit the land use. More detailed mapping may be needed. If the hazards are significant, the jurisdiction should take measures to reduce risk to an acceptable level. Some jurisdictions have already established procedures whereby detailed slope-stability information prepared by a professional engineering geologist is incorporated into their land-use planning and decisionmaking. Examples of such procedures are described later in this report.

INTERPRETATION OF SLOPE STABILITY CATEGORIES

Tables 6 and 7 were prepared to show the range of potential risk to life and property represented by the relative slope stability categories shown on the map and described on pages 41 through 53.

Table 6 summarizes the characteristics of the stability categories, including slope and general qualities of stability. In addition, the table provides a rating of the categories in terms of relative risk to life and property from *low* to *moderate* to *high* risk. The ratings are stated in general terms in keeping with the scale of the relative slope-stability map. The risk ratings are based on evaluation of the factors contributing to slope stability used in deriving the map categories. Level of risk is an important factor in evaluating capability of lands to accommodate urban development.

The risk ratings are based on a rational and consistent analysis of the factors used to develop the relative slope-stability information for land-use planning purposes.

In using this risk information, the earth scientists advise that:

> the relative slope-stability map of the San Francisco Bay region be regarded by the map user as an initial attempt to predict regional slope stability, to be superseded in future years as more and better data and techniques become available. Because of the method of map preparation and resulting generalization of basic information, the map is not appropriate nor intended to be used to interpret the stability of specific local areas. It is simply a generalized regional representation of the relative stability of slopes in the San Francisco Bay region and should be considered as a framework for more detailed studies of smaller areas, where more specific geologic and engineering data and information are required.

With this qualification, then, the risk to life and property that may be encountered in any particular mapped area can be found by referring to table 7.

RELEVANCE TO LAND-USE PLANNING

Perhaps the most important function of the map is that it establishes a consistent regionwide description of relative slope stability. It can be used to determine the relative risk from slope failure in any jurisdiction and to label areas where particular attention must be paid to landslide hazards. It also provides a framework for more detailed slope-stability studies. The map shows that in many areas such studies will be necessary both for formulating and implementing local plans and for reviewing regional projects. Furthermore, regional slope-stability information will help define the future refinements needed to evaluate slope-stability conditions for land-use planning.

The discussion of the actual relevance of the relative slope stability map of the San Francisco Bay region to bay area planning agencies has been divided

TABLE 6.—*Characteristics of relative slope stability categories and relative level of risk to life and property*

Category	Slope (percent)	Stability	Risk to Life and property	Comments
1	0–5	Generally stable (slopes are not underlain by landslide deposits or other surficial deposits that are highly susceptible to slope failure).	Low	1. Locally bedrock may be unstable and therefore susceptible to landsliding. 2. Limited areas along creeks, rivers, coastal cliffs, and edges of terraces have steeper slopes than those generally found in this category. They are generally too small or narrow to be shown at this scale and commonly have low relief. Riverbanks may be particularly hazardous during periods of flooding and the coastal areas during periods of storms. 3. Some deposits (alluvial terrace, marine terrace, alluvial fan) may be locally susceptible to flooding and debris flows from surrounding uplands during periods of intense rainfall.
2*	5–15*	do*	Low*	1. Some areas may be underlain by bedrock types that are locally unstable and therefore susceptible to landsliding. 2. Limited areas along creeks, rivers, or coastal margins have steeper slopes and may be susceptible to landsliding but are too small or narrow to be shown at this scale.
3*	>15 (some hillsides as steep as 90°)	Reasonably stable (slopes are not underlain by either landslides deposits or bedrock units that are susceptible to landsliding).	Moderate*	1. Small areas are locally unstable owing to various reasons including: a. Failure of areas above or below that are underlain by bedrock types susceptible to landsliding or by landslide deposits; b. Proximity to areas of active erosion along creeks, rivers, and coastal areas; c. Saturated slopes adjacent to lakes and reservoirs; d. Proximity to active landslides that may be enlarging; e. Activities such as logging, cutting, and filling, construction and adding moisture to slopes. 2. This category may include small landslide deposits not large enough to be shown at this scale or to have been mapped.
4*	>15 (some hillsides as steep as 90°)	Susceptible to future landsliding (slopes are underlain by bedrock units that are highly susceptible to landsliding but are not underlain by landslide deposits).	*Moderate-high*	1. Local areas may be more stable than the average. 2. The bedrock units with high susceptibility to slope failure may include some small areas within them that are locally more unstable for the same reasons as mentioned for category 3. 3. Exact conditions required for future landsliding are not known, but under the effects of high rainfall, seismic activity, human activity, and other factors, the bedrock units within this category that are highly susceptible to slope failure may become unstable.
5*	0–100*	Highly susceptible to landsliding (slopes underlain by bedrock or surficial deposits that have slid and are highly susceptible to future landsliding).	*High*	1. Many areas are not underlain by either landslide deposits or bedrock units highly susceptible to landsliding but are too small or too narrow to show at this scale and level of generalization. 2. Areas that have undergone landsliding in the past and are generally very susceptible to future landsliding, especially if the slopes are cut and filled.

TABLE 6.—*Characteristics of relative slope stability categories and relative level of risk to life and property*—Continued

Category	Slope (percent)	Stability	Risk to Life and property	Comments
1A[1]	0–5*	Highly unstable (slopes underlain by moist unconsolidated muds).	*High*	1. Areas susceptible to flowage, lateral movement, and liquefaction at slopes less than 1°. 2. During earthquakes, these areas are particularly susceptible to ground failure and may cause damage to structures built on artificial fill placed over the muds. 3. Such areas may be particularly susceptible to failure along the margins of tidal channels and when cut into, excavated, or subjected to differential loading.

[1]Special category of instability. For specific description of differences between category 1A and other categories, see pages 41 through 53.

into two parts—its relevance to regional agencies and its relevance to city and county agencies.

REGIONAL AGENCIES

As at any level of planning, the relative slope stability map is only one item of basic data to be incorporated into regional planning and decisionmaking. The map will be of greatest use in assessing the nature and general extent of slope stability conditions. This assessment could lead to appropriate general policy for use of lands in the several risk categories. The data can also be used in formulating policies for avoiding or mitigating identified hazards. More specifically, the map and interpretive information should be useful in land-capability studies.

ABAG (Association of Bay Area Governments) will find the map useful in identifying critical areas and developing regional policies, standards, and criteria for project review. The map was used in the agency's evaluation of the general capabilities of land to accommodate urban growth and development (Laird and others, 1978). Those areas of greatest relative instability can be identified from the map. The planner can also readily identify those areas with the fewest limitations to land use. The areas of greatest relative stability can then be considered as the location for more intensive future urban development. Other limitations to development in areas identified as relatively stable (for instance, flood-prone areas and areas with seismic hazards and other geologic problems) can be assessed in region-wide land-capability studies. The map could also be used by ABAG in selecting projects in moderate-to high-risk areas for more detailed slope-stability evaluation.

The MTC (Metropolitan Transportation Commission) should find the map useful in developing an environmental impact analysis of the regional transportation plan, specific transportation projects, and changes within a transportation corridor. The map can be effectively used by MTC to identify those areas where additional study will be necessary before locating, designing, and constructing specific facilities. This information can be incorporated into regional policies, objectives, and proposals as well as project-review criteria.

The BCDC (Bay Conservation and Development Commission) will probably find little use for the map. Instead, BCDC will refer to the map on bay muds (Nichols and Wright, 1971), or the extensive information that was prepared specifically for the BCDC San Francisco Bay Plan adopted by the State legislature in 1969.

The CCC (California Coastal Commission) could find the map useful as background for identifying issues. However, the Central and North Central Regional Commissions would be likely to refer to more detailed slope and landslide maps for their own areas.

CITY AND COUNTY AGENCIES

City and county agencies may use the map as a basis for identifying issues. For local land-capability analysis, for designating specific local comprehensive land-use plans, and for developing land-use strategies and regulations, the map would not be adequate. Far more detailed data on slope stability for the agencies' area of responsibility would be necessary for preparing and implementing a plan. The exact nature of the detailed data necessary should be determined in conjunction with the more detailed maps from which this map was prepared and with a professional geologist serving the jurisdiction (either a staff geologist or a consultant).

The relative slope-stability map does indicate how extensive slope-stability problems will probably be and the most effective approaches that can be taken in

TABLE 7.—*Slope-stability categories for land-use planning*

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.

planning and land-use regulation program. It also helps a local jurisdiction put its slope-stability conditions into context with the region as a whole.

In summary, while the bay region slope-stability map is a benchmark in regional mapping, the planner and any other map user must be continually aware of the limitations of the data. In addition, it is important for local agencies who think they may have significant slope-stabilty problems to consult with professional geologists to define the magnitude of the problems they need to address in their land-use planning and decisionmaking. The next section will deal specifically with how regional and local agencies can apply slope-stability information in land-use planning, and it will include guidelines on how to acquire more detailed slope-stability information.

APPLICATION TO LAND-USE PLANNING

Planning for slope stability has already been briefly described, and the planning activities of Federal, State, regional, and local agencies introduced. This earlier discussion indicated very generally the responsibilities, data needs, and land-use responses for effective slope-stability planning. The discussion that follows elaborates on these descriptions, detailing the current methods of applying slope-stability information in land-use planning.

Landslides are a local phenomenon; consequently, local agencies (city and county) have the key responsibility for reducing risk from landslide hazards. Local planning, however, should be responsive to Federal, State, and regional objectives, standards, and decision criteria relevant to slope stability. The discussion in this section, therefore, describes the Federal, State, and regional requirements and decision criteria that affect local land-use planning and then provides examples of plans, focusing on city and county needs, and details of how agencies have acquired the necessary slope-stability data.

In considering slope-stability information in land-use planning, some very broad basic guidelines became apparent. These guidelines are provided below. The section concludes with a discussion of the roles and responsibilities of the various professionals involved in the process of planning for slope stability.

For those wishing to acquire only a general understanding of how slope-stability information can be applied in land-use planning, it is suggested that the basic guidelines and examples of actual planning efforts be reviewed, and then go back to the discussion of the objectives, standards, and decisions of Federal, State, and regional agencies if more information is desired.

BASIC GUIDELINES

Slope instability, in conjunction with other geologic hazards, can be a major factor in determining how land is used. Because of the local nature of the landslide problem, city and county agencies have the greatest responsibility for ensuring that detailed slope-stability analyses are completed where necessary. To assist planners and decisionmakers in dealing with slope-stability concerns, the following basic guidelines are offered:

1. When slope-stabilty hazards have been identified, make such information available to all who might be interested in or potentially affected by the hazard.
2. Pay special attention to landslide hazards when preparing comprehensive land-use policy, plans, and implementation strategies.
3. When potential slope-stability hazards have been identified in an already developing area, make and implement appropriate plans for mitigating the hazards. Where necessary, such measures as relocation of residents where damage is imminent, slope stabilization, removal of structures in the highest risk area, and disaster-preparedness plans (particularly in seismically active areas) should be taken.
4. Evaluate potential slope-stability hazards by using maps of adequate scale and detail before any contemplated development or structure reaches the site selection or design stage.
5. Develop and adopt standards of design and construction to obtain acceptable levels of safety.
6. See that all proposals for development on slopes of questionable stability are thoroughly reviewed by competent professionals.
7. Require adequate independent inspection during construction to enforce the safety measures called for in the approved plans.

APPLICATION IN PLAN FORMULATION

How slope-stability information is used in formulating land-use plans varies depending upon such factors as level of government, nature of agency responsibility, professional and financial capabilities, and the physical conditions contributing to slope instability. Described below are the key Federal, State, and regional agencies that have shown concern about landslide hazards in the San Francisco Bay region through adopting objectives, standards, and decision criteria that specify local uses of land. Although they are discussed here in connection with plan formulation, these higher agencies affect implementation as well. In the development of city and county general plans in the bay region, planning agencies have not only been responsive to the standards and requirements of higher levels of government but, as is shown below, have in many cases gone further than mandated.

In recent years, land-capability studies have become effective tools for evalutating the physical capability of lands to accommodate a range of uses. A general description of a land capability analysis is provided later in this section to show how slope-stability information might be applied.

FEDERAL LEVEL

Federal agencies that fund, permit, or review land-disturbing human activities often have very special responsibilities, and some have exhibited only peripheral concern for slope stability. HUD (Department of Housing and Urban Development) has assumed the most direct responsibility for ensuring that slope-stability problems are addressed in the process of urban development. The following HUD programs and requirements are important because they establish guidelines for planning activities at State, regional, and local levels.

REQUIRED LAND-USE ELEMENT OF THE COMPREHENSIVE PLANNING ASSISTANCE PROGRAM

The Comprehensive Planning Assistance Program administered by HUD provides grants for planning to municipalities, counties, and metropolitan, regional, and State agencies (U.S. Dept. Housing and Urban Development, 1954). Any planning agency or jurisdiction, including those in the bay region, wishing to receive a grant under this program must have developed or are expected to complete a land-use element and a housing element pursuant to Section 600.72 of the HUD–701 program requirements. The required land-use element must contain integrated policies to guide governmental decisionmaking "on all matters relating to the use of land." The element must identify land-use needs, land-resource development, and the impact of policies on areas of critical concern. In addition, the element must identify where growth should and should not take place and consider the environmental protection required in determining future growth patterns. The land-use element must take potential slope-stability hazards into account in the land-use plans of agencies receiving grants if factors contributing to slope instability are present within their jurisdictions.

The importance of such HUD requirements is underscored by the fact that under the Housing and Community Development Act of 1974, HUD has been directed to consult with those Federal agencies charged with implementing the nation's environmental protection policies to insure that comprehensive planning is in accord with national environmental protection policies. Thus an Interagency Agreement between HUD and EPA (Environmental Protection Agency) provides that the results of planning and management efforts completed under EPA 208 program requirements (areawide waste-treatment management planning assistance) may fulfill HUD–701 requirements in areas where the two programs overlap. EPA-208 program requirements are permitted to dominate because their planning provisions match up with the HUD–701 program and because their implementation provisions have no counterpart in the HUD program. The agreement helps to rationalize planning assistance and to ensure that land-use planning for water quality is developed within the broader framework of comprehensive planning (U.S. Environmental Protection Agency, 1975).

HUD HOUSING PRODUCTION AND MORTGAGE CREDIT/MINIMUM PROPERTY STANDARDS

HUD standards define the minimum level of acceptability of design and construction for Federally assisted housing and housing eligible for Federally insured mortgages. The Minimum Property Standards consist of four volumes (U.S. Dept. of Housing and Urban Development, 1973), Volume I, One- and Two-Family Dwellings; Volume II, Multi-family housing; Volume III, Care Type Housing; and Volume IV, a Manual of Acceptable Practices. The fourth volume contains backup and illustrative material for the three volumes of mandatory standards.

These standards require that land-development proposals take note of natural hazards such as landsliding. Project design and review must insure that potential hazards from slope instability be addressed. Thus, information on slope stability in both project design and review stages is required.

FEDERAL DISASTER ASSISTANCE PROGRAM

The Federal Disaster-Assistance Administration (FDAA) directs, manages, and coordinates the Federal disaster-assistance program (U.S. Dept. Housing and Urban Development, 1975). Under this program, governed by the Federal Disaster-Relief Act of 1974, landsliding may constitute a "major disaster" if, in the opinion of the President, it causes damage of sufficient severity and magnitude to warrant major-disaster assistance. Such a "major disaster" might result from seismically induced landslides affecting a large area or landslides caused by unusual rains in an urban area.

The FDAA encourages the development of comprehensive disaster-preparedness plans by the states and local governments, and, to reduce losses from disasters, encourages adoption of hazard-mitigation measures including land-use and construction regulations. In addition, the Disaster Relief Act of 1974 requires, in part, that any state or local government that receives a loan or grant under the Act agrees to study the hazard and act to mitigate it in the disaster area. Where landslides are possible, slope-stability information is essential for effective disaster-preparedness plans and hazard-mitigation programs.

STATE LEVEL

OFFICE OF PLANNING AND RESEARCH

The OPR (Office of Planning and Research), responsible to the Governor, prepares long-range State goals and policies for land use and environmental quality. The OPR, however, has no direct control over land use. Concern for slope stability was set forth in the office's report on environmental goals and policy (California Office of Planning and Research, 1973). In part, these goals and policies include the geologic-hazard information developed during preparation of the State's Urban Geology Master Plan (Alfors and others, 1973).

The following goals and policies contained in OPR's 1973 report regarding "environmental resources and hazards" have particular significance in regard to planning for slope stability:

It is the Goal of the State to identify and protect the significant and critical environmental resources and hazards of the State for the benefit and enjoyment of present and future generations.

To accomplish this Goal, it is the Policy of the State:

1. to identify through its departments and political subdivisions all potentially significant and critical environmental resources and hazards throughout California, and after thorough evaluation, adopt and define those geographic areas of the State which do contain environmental resources and hazards of Statewide importance as being areas of Statewide Interest or of Critical Concern;
2. to evaluate, through its departments and political subdivisions, all activities, as they may significantly affect the environmental resources and hazards of the State which are areas of Statewide interest or Critical Concern; undertake measures to minimize those activities which will have a detrimental effect on such resources, and encourage the development of programs which will enhance the quality of these resources for future generations. During the interim period before the Critical Concern areas are adopted, this Policy shall apply to all of the areas listed in this Report as areas of Statewide Interest or potential areas of Critical Concern;
3. to encourage local units of government to consider the areas listed in this Report as areas of Statewide Interest or potential areas of Critical Concern in the preparation of their individual General Plans, including but not limited to open space, conservation, scenic highways and seismic safety elements; and
4. to consider those areas of Critical Concern as high priority in any Statewide acquisition, lease, or enforcement programs.

The report describes those geologic hazards that threaten "life and property" that need to be carefully evaluated before decisions are made to change land use. To deal with these hazards, the report includes an "Environmental Resources Protection Plan" with 11 basic recommendations for land-use legislation, of which the following relate to slope stability:

that areas of critical environmental or hazardous concern to the entire state be designated;

that guidelines be formulated to encourage orderly development and protection from natural calamities while minimizing adverse impact upon people or resources which have been designated of critical environmental or hazardous concern;

that the resolution of conflicts and the performance of regulatory functions occur at the level of government closest and most responsive to the people affected;

that innovative and creative programs affecting land uses or affecting these areas of critical concern be encouraged through the efforts of the private sector and government entities.

The CIR (Council on Intergovernmental Relations) (now part of OPR) advised and assisted cities, counties, districts, and regional planning agencies. As part of this responsibility, the CIR adopted guidelines for the preparation of local general plans (California Council on Intergovernmental Relations, 1973) that assisted local governments in preparing State-mandated general-plan elements and discussed the use of slope-stability information in formulating the elements. By action of the State Legislature, the CIR was abolished, its functions transferred to OPR, and a Local Government Advisory Council created (Assembly Bill No. 551, Sept. 1975).

CALIFORNIA RESOURCES AGENCY

The California Resources Agency includes a number of departments, boards, and commissions that affect the use and development of land through planning and regulation, grants to local government, and their own construction projects and operations. Some functions of key bodies within the agency that are relevant to use of slope stability information are summarized below.

The Department of Conservation includes the CDMG (California Division of Mines and Geology). The CDMG prepared the Urban Geology Master Plan for California (Alfors and others, 1973), which evaluates the nature, magnitude, and costs of geologic hazards in the State and recommends actions for their mitigation. The CDMG also provides technical information on landsliding and the relative stability of slopes. In several instances, usually under special contract with a jurisdiction, the CDMG has developed technical information and interpreted it for local planning purposes.

The Department of Parks and Recreation has the responsibility for acquiring, developing, and maintaining State parks. The department ensures that park use and park development projects consider the slope-stability conditions of the area. It also administers State grants to local agencies for acquiring and developing parks.

STATE LANDS COMMISSION

The State Lands Commission has the responsibility for administering the sale and leasing of State-owned public lands. It has power to affect the manner in which lands under its jurisdiction are used, and it can require that slope stability be adequately studied as part of its project-review functions.

BUSINESS AND TRANSPORTATION AGENCIES

The Department of Transportation, the Department of Housing and Community Development, and the California Housing Finance Agency seem to have significant concern for slope stability.

Caltrans (The Department of Transportation) is responsible for planning and building State transportation facilities. Because knowledge of slope stability is important in the location and design of such facilities, Caltrans makes extensive use of geology in planning and construction. The agency has developed special techniques for measuring slope stability, using for example subaudible rock noise (Means and Hoover, 1973), and has conducted extensive research into the design of stable cut slopes.

The HCD (Department of Housing and Community Development) is broadly responsible for housing and community development activities. The functions of the Department are (Sedway and Cooke, 1975):

> to 'assist' local governments and private enterprise on community development and housing matters; to establish, administer and enforce minimum housing standards and regulations pursuant to various housing related laws; to maintain a statistics and research service; to 'make recommendations' to the Governor for changes in state and federal housing laws; and to 'encourage' planning and other activities intended to increase housing supply and quality. It was required to develop the California Statewide Housing Element and is 'responsible for coordinating federal-state relationships in housing' and for 'encouraging full utilization' of federal programs which assist 'the residents of this state, the private housing industry and local government, in satisfying California's needs.'

HCD is also empowered to prepare a statewide housing plan (an extension of the State Housing Element) in cooperation with government and industry. Among other things, the plan is to include an analysis of local building codes. Although the analysis is to focus on flexibility in the uses of new materials and methods of construction and building code enforcement, there is also the opportunity to evaluate the adequacy of code requirements with regard to geologic hazards. The overall State goal is to provide enhanced living environments, particularly for people of low or moderate income.

Another responsibility of HCD is to develop and propose regulations to guide certain activities of the California Housing Finance Agency. Thus, HCD could recommend hazard-risk criteria for the Finance Agency to use in lending money for new housing.

The CHFA (California Housing Finance Agency), in existence since September 1975, is empowered to sell bonds to raise money for lending at below market interest rates to qualified housing sponsors or to approved commercial lenders in order to increase the housing supply for Californians of moderate, low, and very low incomes. In lending money, CHFA is to ensure that the planning of such developments emphasizes "superior design." Thus, CHFA has the opportunity to ensure that developers will provide for identification and mitigation of geologic hazards such as unstable slopes.

REGIONAL LEVEL

ASSOCIATION OF BAY AREA GOVERNMENTS

ABAG (The Association of Bay Area Governments), in carrying out its areawide comprehensive planning responsibilities, has prepared and approved a regional plan that provides a policy framework for considering future growth of the bay region. The regional plan is composed of the entire body of goals, objectives, and policies that have been adopted by ABAG (Tranter, 1972) and provides strategies for implementing them. Significant attention has been paid to geologic hazards, including potential for slope failure, primarily through goals, objectives, and policies for public safety and open-space preservation.

ABAG's Regional Plan: 1970–90 (Assoc. Bay Area Govts., 1970) outlines broad strategies for guiding urban development in a manner that would preserve urban communities, discourage urban sprawl, protect open land, and minimize disturbance to natural processes. Open–Space Plan Phase II (Assoc. Bay Area Govts., 1972) provided for identification of the characteristics of the region's remaining open land and established a framework for preserving open space serving the following functions: managed resource production and preservation; protection of health, welfare, and well-being; public safety; outdoor recreation; and guiding urban growth. Areas with landslide hazards (identified in a report by Radbruch and Wentworth, 1971) were included under "open space for public safety" of the Phase II plan.

Since completion of the 1972 open-space program, ABAG has instituted the Urbanization and Development Program to create a conscious strategy for guiding urban growth in the bay region. This program is designed to carry out the city-centered policies of the regional plan by directing growth into existing developed areas while preserving open land. The concerns for open space, particularly "open space for guiding urban growth" contained in the Phase II plan have been incorporated in the Urbanization and Development Program.

Evolving from ABAG's earlier planning efforts are policy guidelines for land having regionally significant environmental characteristics. These guidelines are being developed to supplement the "environmental framework" presented earlier in the regional plan and the Phase II plan. A report, (Areas of Critical Environmental Concern, Assoc. Bay Area Govts., 1975, p. 9) includes these recommendations:

Review Criteria—Specific regional interests in various land areas throughout the nine counties are identified and criteria presented for use in reviewing the consistency of local plans and projects with regional objectives. This review procedure is a vital function in a regional planning process which endeavors to retain maximum planning flexibility at the local government level.

Recommendations to local governments.—Recommendations are made to local governments and regional, State, and Federal agencies on their roles and responsibilities in implementing regional objectives in critical areas.

Urbanization policy.—The report continues support of an urban development policy that channels future growth into existing communities and removes development pressure from nonurbanized lands.

The following specific recommendations in the critical areas report regarding slope stability (Assoc. of Bay Area Govts., 1975, p. 45, 46) reflect the local nature of slope problems:

Local agency actions. Administering a program of subdivision, hillside, and grading ordinances that require preparation of a geologic and soils engineering report prior to development of areas subject to landsliding, erosion, or bearing material problems.

New recommendations. Support state or federal legislation requiring local agencies to administer a program requiring the preparation of a geologic and soils engineering report prior to development of an area subject to possible slope stability, erosion, or bearing material problems.

To complement and reinforce the public safety policies contained in the critical areas report, ABAG has prepared a second policy guideline, Regional Earthquake Safety Issues and Objectives (ABAG, 1976). This policy guideline was based on two earlier projects: a land capability study and a hazards evaluation study.

The land-capability study was a project sponsored by U.S.G.S. as part of the San Francisco Bay Region Study. The project developed a method to define the ability of land to accommodate a particular land use on the basis of geologic and hydrologic costs. The purpose of this study was to show how earth-science information could be made more useful to local decisionmakers (Laird and others, 1979).

The hazards evaluation study was prepared as part of a project sponsored by the Federal Defense Civil Preparedness Agency. The DCPA program had the following objectives (ABAG, Apr. 1975, memo to members of the Civil Preparedness Tech. Advisory Comm.):

To prepare a source file of information on disasters and disaster mitigation.
To prepare a risk evaluation methodology.
To develop a civil preparedness plan of action for ABAG.

The Civil Preparedness Technical Advisory Committee was formed to draw up a plan of action for ABAG. The committee concluded that ABAG should have no operational role in disaster response. ABAG should, however, advocate governmental and citizen support for disaster preparedness and promote regional and local efforts in hazard reduction and planning of disaster response and postdisaster recovery. This philosophy later became a part of the policy guideline on earthquake safety. As part of the DCPA-funded project, ABAG prepared a booklet, *Hazards Evaluation for Disaster Preparedness Planning* as a guide to local governments in establishing priorities for disaster preparedness (Assoc. Bay Area Govts., 1976). The report presents a systematic procedure for describing, analyzing, and evaluating hazards (including landslides), and suggests ways a local jurisdiction can reach decisions on what hazards are important, what measures can effectively reduce them, and what priorities for action should be set.

The evolution of ABAG's comprehensive planning activities from adoption of the regional plan to preparation of the critical environmental areas plan, land capability study, hazards evaluation booklet, and earthquake safety policy guideline reflects the stated position "that the Association must and will develop and adopt the type of guidelines, based on a thorough recognition of the intricacies of the regional setting, which will enable attainment of a desired future by providing guidance without needlessly limiting options" (Tranter, 1972). ABAG is updating its regional plan in 1977 and 1978 to incorporate this extensive hazards work.

METROPOLITAN TRANSPORTATION COMMISSION

MTC (The Metropolitan Transportation Commission), in coordinating development of regional transportation facilities, has prepared and adopted a regional transportation plan and has developed an environmental impact assessment process for use in plan evaluation and project review. Both the plan and the impact assessment recognize the importance of geologic processes, such as landsliding, to location, design, and construction of transportation facilities, and require a geologic evaluation in hazardous areas before a proposal or specific project is approved. The RTP (Regional Transportation Plan) was adopted in 1973 and has been updated and revised annually. The plan contains policies to avoid or minimize adverse impacts on the physical environment. Two policies in the RTP establish the basis for considering geologic hazards (Metr. Trans. Comm., 1974b, p. 14):

MTC shall, in conjunction with regulatory agencies such as the State Public Utilities Commission, employ standards of safety and high quality in the regional transportation system.

Earthquake and seismic technology shall be used in the planning, location and construction of new transportation facilities.

The RTP also describes the regional transportation system and its needs and problems and establishes guidelines for the development and revision of the system consistent with adopted policy and as "***part of a continuing, comprehensive evaluation of transportation from a regional perspective" (Metr. Trans. Comm., 1974b, p. 50). "Factors" to be assessed in the ongoing review of proposals include "Health/Safety/Amenity." Under this heading, one question that must be addressed is (Metr. Trans. Comm., 1974b, p. 51–52):

Will the proposal significantly***change the potential for the occurrence of or damage from natural hazards such as earthquakes, slides, floods, subsidence, tsunamis?

The RTP policies, system description, and review standards establish the framework for MTC review of regionally significant transportation projects. MTC cooperates with ABAG in the review process, providing comments related to transportation. MTC approval is required for certain projects including transbay bridges, public multicounty transit systems on exclusive rights of way, all applications from local governments or districts for State or Federal funds related to transportation, and construction of the State Highway System. MTC also reviews required Federal and State environmental documents on projects in the bay region for compatibility with the RTP.

To assist MTC in making decisions on regional transportation issues that are consistent with the RTP, a process to assess environmental impact has been developed. This process involves preparing an information base covering all aspects of the regional environment. An important part of the imformation base is a study of the present environment that has been completed for MTC by the consulting firm of Wallace, McHarg, Roberts, and Todd. The study includes an inventory of the environment, technical evaluation of data, environmental assessment procedures, and 77 unique maps ranging in scope from regional urbanization patterns to habitats of wildlife species (Metr. Trans. Comm., 1975, p. 3). The maps and technical evaluations focus on five "impact areas." One impact area is the "Natural Process Inventory," which includes mapping and technical evaluation of topography, geology, and hydrology. The data used for this impact area include the landslide information from Brabb, Pampeyan, and Bonilla (1972), Radbruch and Wentworth (1971), and Wright and Nilsen (1974).

Data from the Wallace, McHarg study, along with other data contained in the environmental-impact assessment, provide a framework for analysis of the environmental impacts of transportation plan elements, specific transportation projects, and changes within a transportation corridor.

As the MTC Regional Transportation Plan continues to evolve, it will be coordinated with the regional land-use planning activities of ABAG. MTC has concluded an agreement with ABAG by which ABAG's regional land-use plan will serve as a guide for MTC transportation plans. The RTP, therefore, will be guided by the ABAG plan for critical environmental areas and other ABAG planning standards for use of lands with potential geologic hazards. Under the agreement, ABAG will review the RTP to determine regional impact and will recommend amendments to its own plan as necessary to meet the goals of both agencies.

SAN FRANCISCO BAY CONSERVATION AND DEVELOPMENT COMMISSION

The BCDC (San Francisco Bay Conservation and Development Commission) was created by the State Legislature to prepare a comprehensive plan for San Francisco Bay and its shores and to control development within its area of jurisdiction. This area includes San Francisco Bay, a strip 100 feet (30 m) landward along the bay shore, as well as salt ponds, managed wetlands, and certain waterways. In 1969, the State Legislature adopted the bay plan and empowered BCDC to issue or deny permits for projects that would fill, extract materials, or substantially change a water, land, or structural use within its jurisdiction. Local governments retain basic land-use controls but, in effect, BCDC holds veto power over any project in conflict with the San Francisco Bay Plan.

The following findings and policies were developed by BCDC, based on extensive studies of stability of bay muds (Goldman, 1967) and the safety of fills (Steinbrugge and others, 1968); they establish the basis for current BCDC regulation of filled lands and other unstable soils within its jurisdiction:

Findings

a. To reduce risk of life and damage to property, special consideration must be given to construction on filled lands in San Francisco Bay. (Similar hazards exist on other poor soils throughout the Bay Area, including soft natural soils, steep slopes, earthquake fault zones, and extensively graded areas.)

b. Virtually all fills in San Francisco Bay are placed on top of Bay mud. Under most of the Bay there is a deep, packed layer of old Bay mud. More recent deposits, called younger Bay mud, lie on top of the older muds. The top layer of young mud presents many engineering problems. The construction of a sound fill depends in part on the stability of the base upon which it is placed.

c. Safety of a fill also depends on the manner in which the filling is done, and the materials used for the fill. Similarly, safety of a structure on fill depends on the manner in which it is built and the materials used in its construction. Construction of a fill or building that will be safe enough for the intended use requires (1) recognition and investigation of all potential hazards—including (a) settling of a fill or a building over a long period of time, and (b) ground failure caused by the manner of constructing the fill or by shaking during a major earthquake—and (2) construction of the fill or building in a manner specifically designed to minimize these hazards. While the construction of buildings on fills overlying Bay deposits involves a greater number of potential hazards than construction on rock or on dense hard soil deposits, adequate design measures can be taken to reduce the hazards to acceptable levels.

d. There are no minimum construction codes regulating construction of fills on Bay mud because of the absence of sufficient data upon which to base such a code. Hazards vary with different geologic and foundation conditions, use of the fill, and the type of structures to be constructed on new fill areas. Therefore, the highest order of skilled judgment, utilizing the available knowledge of all affected disciplines, is required to (1) recognize and investigate all potential hazards of constructing a fill, and (2) design the fill and any construction thereon to minimize these hazards.

e. In the absence of adequate fill construction standards or codes, the BCDC appointed a Board of Consultants consisting of geologists, civil engineers specializing in soils engineering, structural engineers, and other specialists, to review, on the basis of available knowledge, all new fills that might be permitted in the Bay Plan, so that no fills would be included upon which construction might be unsafe. No specific fills are included in the Plan, but the Board of Consultants has completed an initial set of criteria (published separately as "Carrying Out the Bay Plan: The Safety of Fills") as a guide to future consideration of specific fill proposals.

Policies

1. The Bay agency should appoint a Fill Review Board consisting of geologists, civil engineers specializing in soils engineering, structural engineers, and architects competent to and adequately empowered to (a) establish and revise safety criteria for Bay fills and structures thereon, (b) review all except minor projects for the adequacy of their specific safety provisions, and make recommendations concerning these provisions, (c) prescribe an inspection system to assure placement of fill according to approved designs, and (d) gather, and make available, performance data developed from specific projects. These activities would complement the functions of local building departments and local planning departments, none of which are presently staffed to provide soils inspections.

2. Even if the Bay plan indicates that a fill may be permissible, no fill or building should be constructed if hazards cannot be overcome adequately for the intended use in accordance with the criteria prescribed by the Fill Review Board.

3. To provide vitally needed information on the effects of earthquakes on all kinds of soils, installation of strong-motion seismographs should be required on all future major land fills. In addition, the Bay agency should encourage installation of strong-motion seismographs in other developments on problem soils, and in other areas recommended by the U. S. Coast and Geodetic Survey, for purposes of data comparison and evaluation.

The BCDC Engineering Criteria Review Board, established as recommended in Policy 1, has proved to be effective in implementing safety policies. The Board's example and influence have extended far beyond the limits of BCDC's jurisdiction (San Francisco Bay Conservation and Development Comm., 1974).

It should be noted that unstable bay muds within the jurisdiction of BCDC have been included as Category 1A on the relative slope stability map of the bay region contained herein.

CALIFORNIA COASTAL ZONE CONSERVATION COMMISSION

The CCZCC (California Coastal Zone Conservation Commission) was established by initiative of the State's voters in 1972. Working with six regional commissions, the CCZCC was charged with preparing a plan for the future of the California coastal zone. While the California Coastal Plan was being prepared, the commissions controlled all development, through a permit process, to insure consistency with the objectives of the legislation and the polices of the emerging plan. Coastal areas of the bay region are represented by two regional commissions: Central (San Mateo County) and North Central (San Francisco, Marin, and Sonoma Counties).

The plan (Calif. Coastal Zone Cons. Comm., 1975) was presented to the Governor and State Legislature in December 1975 for adoption and implementation. Under the terms of the initiative, the CCZCC and the six regional commissions were to expire on January 1, 1977, unless legislation was enacted to create successors to them.

In September 1976 the California Coastal Act of 1976 was enacted establishing the California Coastal Commission and six regional coastal commissions as successors to the commissions created by the 1972 initiative. Under the terms of the Act, the six regional commissions will expire 30 days after the last required local coastal program has been certified, but no later than January 1, 1981.

The California Coastal Plan is a policy document with findings and recommendations for conservation and development of the coastal environment. It is significant to note the importance assigned in the plan to geologic hazards, including slope stability and the potential land-use impacts.

The Coastal Plan describes landslides and mudflows as two major geologic hazards in the California coastal zone with substantial risks to life and property (CCZCC, 1975, p. 84). Mapping and regulation to reduce slope-stability hazards are recommended (CCZCC, 1975, p. 86):

> Slope Stability Hazards Can be Minimized by Mapping and Regulation. Slope-stability mapping is a primary tool for assessing potential landslide hazard, while regulation of land use and site preparation is the chief means of minimizing slope stability hazards. At present, both mapping and regulation are incomplete within the coastal counties. Mapping has often been undertaken only when intensive development is contemplated and landslide hazard is suspected; however, the Division of Mines and Geology has or is preparing maps for Sonoma, Marin, Santa Cruz, Ventura, Los Angeles, Orange, and San Diego Counties. Regulation is normally adopted only after damaging landslides occur. Slope-stability maps must be supplemented by specific analysis of individual sites if construction is proposed in areas indicated to be hazardous.

Policies based on these findings were approved by the CCZCC recommending that: (1) the State role in geologic programs be strengthened through increased authority for State agencies in identifying and regulating land use in hazardous areas; (2) the State adopt legislation requiring more specific response to local geologic hazards, including specific planning guidelines and land-use regulations that local agencies would have to adopt (for example, Chapter 70 of the Uniform Building Code dealing with grading requirements and specific geologic studies). Also included are recommendations for development or reconstruction in hazardous areas and preventing public subsidy for hazardous developments.

Local land-use decisions within the coastal zone will require detailed evaluation of potential geologic hazards. The plan recommendations were based on a balancing of public and private costs and represent the belief that a resource as unique as the coastal zone must be preserved for the enjoyment of future Californians.

CITY AND COUNTY GENERAL PLANS

California law requires that each city and county prepare and adopt a comprehensive long-term general plan for physical development. The law further stipulates that the plan include nine mandatory elements, of which the following directly or indirectly involve slope-stability information (Calif. Council on Intergovernmental Relations, 1973):

The land-use element designates the general distribution, location, and extent of land used for various purposes and is based on analyses including such factors as topography and geology. Further, the land-use element makes polices regarding natural and manmade hazards, such as slope stability, identified in other mandatory elements, particularly the seismic safety and safety elements.

The conservation element is a plan for the preservation, management, and wise utilization of natural resources including water, forests, soils, wildlife, minerals, and other natural resources. In part, the conservation element provides the data and policy necessary to evaluate the environmental impact of specific proposals. Conservation policy should address the need for slope-stabilization information.

The open-space element is a plan for the preservation and conservation of open space. Open space retained for reasons of public health and safety includes areas which require regulation because of hazardous or special conditions such as earthquake fault zones, landslide areas, and other hazards.

The seismic-safety element identifies and appraises seismic hazards. Mudslides, landslides, and slope stability must be considered in addition to other hazards. The seismic-safety element provides primary policy inputs to planning for land use, housing, open space, circulation, and safety.

The safety element, in part, locates known geologic hazards and provides standards and general criteria for land use relating to such hazards. The element defines the general nature of the regulations and programs needed to correct or mitigate the hazards of their effects.

These mandatory elements have been added to state law one by one in a piecemeal manner; consequently, there is considerable overlap. In addition, the element by element format of the State requirements is not necessarily conducive to the preparation of planning documents that are internally consistent and easily used by decisionmakers. Nevertheless, it is clear the State Legislature intends that geologic hazards such as slope instability be adequately considered in local planning, location of critical facilities, evaluation of environmental impacts of land-use proposals, and conservation and preservation of open space.

State general-plan requirements have considerably affected the gathering and use of earth-science information in many communities, particularly where potential landsliding, earthquakes, or flooding were either already known or readily identified. Consequently, jurisdictions have acquired earth-science information, including slope-stability maps of appropriate scale and level of detail to insure that potential hazards will be adequately recognized in general plans. Many jurisdictions have consulted with engineering geologists (or have their own staff geologists) to determine the information necessary to prepare safety elements.

PORTOLA VALLEY GENERAL PLAN

The experience of the town of Portola Valley in the application of earth-science information, including slope-stability information, is unique and noteworthy. This experience is primarily the result of the town's physical setting, low-density development at the time of incorporation, a local group of geologists dedicated to bringing extreme geologic hazards to the town's attention, and a political climate receptive to the use of earth-science information in making planning decisions.

Portola Valley is situated about 30 miles (50 km) south of San Francisco, on the bay side of the Santa Cruz Mountains. Most of the town's 10 square miles (26 km) lies in a rift valley formed by the active San Andreas fault. West of the fault, the Santa Cruz Mountains are formed of Tertiary marine sedimentary rocks with some interbedded basalt and diabase. Numerous landslide deposits, some of large proportions, exist on the steep slopes of this area. East of the San Andreas fault are Tertiary marine sediments together with rocks of the older Franciscan Formation. This area has no serious landslide problems.

The town was incorporated in 1964 for the purpose of preserving the natural qualities of the environment. Several geologists who were residents of the community brought geology to the attention of the Town Council shortly after incorporation. This group persuaded the town to include geologic considerations in plans and regulations. The town has accomplished much in mitigating geologic hazards and is recognized for its pioneering efforts in seismic-hazard planning. The discussion that follows, however, focuses primarily on its activities in planning for slope stability.

The general plan for the town was drawn up in 1963–64, before the development of a significant earth-science data base for the community and before State adoption of requirements for open space, conservation, seismic safety, or safety elements. The plan did, however, propose a basic pattern of development for the western hillside areas that would concentrate development on the ridges and leave the steep and unstable canyons as open space. Subsequently, with additonal earth-science information in the vicinity of the San Andreas fault, the general plan was amended to replace previously proposed public institutional uses with open-space proposals.

Since adoption of the general plan, Portola Valley has pursued a successful program that makes extensive use of geologic information in land-use planning. A key ingredient in this program has been the availability of volunteer professional geologists who have helped formulate the town's program. The Geologic Hazards Committee, appointed in mid-1967, was composed of professional geologists, an attorney experienced in landslide litigation, and a local building inspector. This committee was to "recommend ways in which geologic factors should be taken into account in order to minimize losses by homeowners and developers in the towns of Portola Valley and Woodside." The committee made three major recommendations:

(1) The town should retain a town geologist to consult on ordinance administration and amendments as well as to develop basic geologic data.

(2) The town should review all ordinances to make certain geologic hazards are taken into consideration.

(3) The town should compile a "Geologic Hazards Map."

The town has followed these recommendations by retaining a town geologist, reviewing and revising regulations, and mapping geologic hazards. The geologic hazards map has been of great help in developing specific land-use regulations and preparing the recently adopted "Seismic/Safety Element." In addition, the map is being used in a current study of the adequacy of existing proposals for general-plan land use.

The Portola Valley geologic study consists of two detailed maps: a "Geologic Map" and a "Movement Potential of Undisturbed Ground Map" (Geologic Hazards Map), which have been adopted by resolution to guide land-use decisions (Town of Portola Valley, 1974). The mapping program included extensive field investigations and took approximately four years to complete. The maps were prepared at a scale of 1:6,000 by graduate students from a nearby university under the direction of the Town Geologist. The basic geologic information was put on a base map of the town that shows topographic features, property lines, and other cultural features.

The geologic map includes landslide features and identifies "active," "dormant," "recent," "old," and "Quaternary" landslides. More than half of the hillsides in the western part of the town's planning area are mapped as subject to landslide activity.

The geologic hazards map separates all land within the town into four categories of relative geologic stability (table 8). [The categories are defined in table 8.] Slope stability was the important consideration in preparing the map.

The following policies, based on the two maps concerning landslide hazards were included in the Seismic Safety Element adopted by the Town Council on August 13, 1975:

1. Review all proposed developments with respect to the Geologic Map and Movement Potential of Undisturbed Ground map *** of the Town. Require geologic and soil reports for all significant development of all areas shown as landslides. Reports should be responsive to the information indicated on these maps.

2. Locate structures for human habitation and most public utilities as not to risk other than minimum disturbances from potential landslides. Give due consideration to mitigating measures, based on geologic and other reports acceptable to the Town, which can be taken to reduce the risk from seismic and non-seismic hazards to an acceptable level****

TABLE 8.—*Description of categories shown on "movement potential of undisturbed ground map," Portola Valley, Calif.*

Relatively stable ground	
Sbr	Level ground to moderately steep slopes underlain by bedrock within approximately 3 feet (1 meter) of ground surface or less; relatively thin soil mantle may be subject to shallow landsliding, settlement, and soil creep.
Sun	Unconsolidated granular material (alluvium, slope wash, and thick soil) on level ground and gentle slopes; subject to settlement and soil creep; liquefaction possible at valley floor sites during strong earthquakes.
Sls	Naturally stabilized ancient landslide debris on gentle to moderate slopes; subject to settlement and soil creep.
Sex	Generally highly expansive, clay-rich soils and bedrock. Subject to seasonal shrink-swell, rapid soil creep, and settlement. May include areas of nonexpansive material. Expansive soils may also occur within other map units.
Areas with significant potential for downslope movement of ground	
Pmw	Steep to very steep slopes generally underlain by weathered and fractured bedrock; subject to mass wasting by rockfall, slumping, and raveling.
Ps	Unstable, unconsolidated material, commonly less than 10 feet (3 m) thick, on gentle to moderately steep slopes subject to shallow landsliding, slumping, settlement, and soil creep.
Pd	Unstable, unconsolidated material, commonly more than 10 feet (3 m) thick, on moderate to steep slopes; subject to deep landsliding.
Areas with potential for surface rupturing and related ground displacements associated with active faulting	
Pf	Zone of potential permanent ground displacement within 100 feet (30 m) of active fault trace.
Unstable ground characterized by seasonally active downslope movement	
Ms	Moving shallow landslides, commonly less than 10 feet (3 m) thick.
Md	Moving deep landslides, commonly more than 10 feet (3 m) thick.

3. Where roads or utility lines are proposed to cross landslide areas, for reasons of convenience or necessity, they should be permitted only if special design and construction techniques can be employed to assure that acceptable risk levels will be met.

4. Adopt implementing policies and (or) regulations which are consistent with policies 1–3 above and which will help assure that any failures of ground due to landslides will not endanger public or private property beyond levels of acceptable risk defined in this statement.

How these policies are being implemented and how slope-stability information is used by Portola Valley in land-use regulation and project review is described in the section on "Application in Plan Implementation."

HAYWARD GENERAL PLAN

With limited resources, the city of Hayward is attempting to integrate earth-science concerns into all phases of its planning program. The city is located in Alameda County on the east side of San Francisco Bay and south of Oakland. Hayward has grown rapidly in recent years to a current population of approximately 94,000 and continues to be under strong development pressures. Natural features of Hayward include a sizeable stretch of marshlands and shorelines along the bay, a large undeveloped hillside area to the east of the urbanized plain, and the Hayward fault. Major planning studies have been completed or are underway for all three areas. The discussion that follows focuses on the planning related to the 14,000 acre (5,700 hectare) Hayward hillside.

The Hayward Hill Area Study was completed as background for the preparation of a general plan for the Hayward hillside (Hayward Planning Dept., 1971). Basically a land-capability study, the report describes in detail the geology, soils, vegetation, climate, and hydrology of the hill area. Assistance was given by the Cordilleran Section of the Geological Society of America, which held a symposium in 1970 to discuss the area's environment and the effects of urbanization on the hills. The study defines unstable or potentially unstable lands; lands with soil limitations for development; and potential hazards from fire, flood, and siltation. Suggestions included the use of cluster development, preservation of wooded and geologically unstable areas, and a variety of engineering and construction practices to minimize potential hazards. In addition, the city staff has suggested that an "environmental-hazards" zoning district similar to flood-plain zoning be established for parts of the hill area.

For the hill area study, Hayward obtained basic geologic information through a special contract with the (CDMG) California State Division of Mines and Geology. Maps of bedrock geology, seismic and nonseismic movement, and slope stability were produced, based on fieldwork and photogeology. Aerial photographs taken in 1967 at a scale of 1:12,000 and in 1950 at a scale of 1:24,000 were used to determine the incidence of sliding during the 15-year period and to locate debris flows requiring field checks.

In addition to the basic geologic information, other earth-science work was included in the hill study. Soils information was obtained from the Soil Conservation Service, and hydrologic data were obtained from a paper presented to the Geological Society of America symposium by Dr. Thomas A. Pagenhart and from Robert E. Ellis of the Alameda County Flood Control and Water Conservation District.

The information contained in the hill study was used for the proposed plan for the Hayward hillside, and the geologic data from the study has been incorporated in the Hayward Earthquake Study (City of Hayward Planning Comm. Subcommittee on Land Use and Development Regulations, 1972). The proposed plan for the Hayward hillside takes into consideration the slope-stability problems identified by CDMG. Although this plan has not been acted upon by the City Council, the plan findings and recommendations, and the basic data these findings and recommendations are based upon, have been important to the Council's evaluation of urban expansion, future city boundaries, and interaction with the Alameda County Local Agency Formation Commission[3] (Hayward Planning Dept., 1975).

The Hayward Earthquake Study, which has been adopted by the City Council as part of the city's Seismic Safety Element, contains findings and recommendations related to potential hazards associated with slopes susceptible to landsliding during an earthquake. Based on the hill study's identification of slopes susceptible to landsliding, the earthquake study makes the following findings:

> The hill area east of the city contains sedimentary rocks which have been broken by faulting and bent into folds. Slope deposits are composed of sand, silt, and clays which cover nearly all the bedrock formations. The slope deposits contain expansive clay minerals which cause the entire mass to shrink and swell in periods of dry and wet weather. Debris flows are common on the valley walls when the slope is between 25 and 40 percent. There is a strong possibility of landsliding in this area during an earthquake.
>
> Ground rupture and cracking are not the only high seismic risks associated with an earthquake. Ground shaking, landslides, and liquefaction can also cause substantial damage to life and property during an earthquake. Therefore it is important that the proper precautions be taken outside of the fault corridor to further protect the safety of the citizens of Hayward.

The following measures were recommended to insure that future development would consider such problems as slope instability:

(1) Detailed soils and geologic reports and grading plans should be submitted with construction plans for any new subdivision within the city of Hayward.

(2) A grading permit from the City Engineer should be required before any grading within the city, except for grading meeting very specific criteria.

(3) The definition of "Quarry" should be expanded, and the operation of quarries should be more strictly regulated so that grading will be compatible with natural site conditions.

The recommendations for grading and quarrying regulations conclude "***the damage to the environment as a result of these operations can only be effectively prevented by the rigid application of these regulations, and this will require adequate personnel to carry out close inspection of all grading operations."

The city planning staff is attempting to bring together the environmental data and recommendations into an innovative response to State general plan requirements that will better serve the land use planning needs of the community. This effort is to include four "elements" covering the subject required in the General Plan.

The first, a "Conservation Environmental Protection Element", provides guidelines for current development. The "Hayward Conservation and Environmental Protection Study" (Hayward Planning Dept., 1975) has been completed as the background document to this element. Included in the background study is a map of the significant environmental conditions of the city and a composite "Significant Factors Map" accompanied by a matrix describing the probable environmental impacts of various development activities (fig. 51). Geologic data from the earlier studies, including the "Hills Area Study," have been used to define the "Geological Conditions" on the map.

According to the city planning staff (Martin Storm, written comm., Dec. 1975, and recent telephone con-

[3] In 1963, Local Agency Formation Commissions (LAFCO's) were created by the State Legislature (Gov. C., Title 5, Div. 2, Part 1, Chap. 6.5 and 6.6, 1963). There is a LAFCO in each county to oversee the formation and alteration of boundaries of all local government agencies. The District Reorganization Act of 1965 (Gov. C., Title 6, Div. 1) provides uniform procedures for changes in district organization (such as annexations, detachments, consolidations, dissolutions, mergers, and complete reorganization) and for review by LAFCO's of proposals for such changes.

versation), proposed development could be reviewed against the Significant Factors Map and environmental impact matrix. If the proposed development is found to affect the environment adversely, either the developer would have to mitigate the adverse effects, or, if public safety is involved and the adverse effects cannot be acceptably mitigated, the development would be denied.

Although this innovative effort is still, for the most part, in the conceptual stage, it does indicate a well-organized approach for the use of earth-science information in planning.

SONOMA COUNTY GENERAL PLAN

Because of problems from landsliding, Sonoma County has, over the past several years, made increasing use of slope-stability data in its land-use planning. The dimensions of the landslide problem in the county are indicated by the fact that during the winter of 1968–69, the countywide public and private cost resulting from landsliding was more than $6 million, the highest of any of the nine bay-area counties (Taylor and Brabb, 1972). To deal with these hazards, the county obtained geologic and hydrologic data from the U.S. Geological Survey and contracted with the California Division of Mines and Geology for geologic-hazard mapping to be applied specifically in land-use planning.

Sonoma County is located north of San Francisco and consists of approximately 1,010,500 acres (409,000 hectares) of land (fig. 52). The county is bounded by the Pacific Ocean on the west and northwest and by San Francisco Bay on the southeast. Fairly rugged mountains rise from the coast to an elevation of 3,500–4,000 feet (1,000–1,300 m) in the northern half of the county. A large valley, which contains the county seat and urban center, the city of Santa Rosa, occupies the south-central area of the county. The southwestern port of the county is generally low, rolling grassy hills ranging in elevation from 500–600 feet (150–180 m). The cities of Petaluma and Sonomá are located in narrow valleys in the southwestern and southeastern parts of the county, respectively. At the lower ends of Sonoma and Petaluma valleys are tidal flats reclaimed from San Pablo Bay.

Because of the physiographic diversity of the county, land-use planners must deal with a variety of earth-science problems, not the least of which is slope stability. As part of the county's 1973 Open Space Element Phase II program, a computer-aided environmental data system was developed to help collect, store, and evaluate basic earth-science data. The system utilized 250 acre (100-hectare) grid cells (1,000 m square) for organizing and recording information; computers for storing, manipulating, and displaying information; and a value-setting procedure called the "Delphi system" for identifying and incorporating citizen value judgments. The purpose was to plan for open space in response to California open-space element requirements.

Development of the Phase II Open-Space Element was based on maps showing the environmental characteristics of the county. Initially, ten "environmental source" maps were prepared at the scale of 1:62,500 (1 inch equals approximately 1 mile) making use of existing data on a variety of subjects including geologic hazards, slope, soils, hydrology, and climate. The data were recorded by grid cell and stored in the computer. The stored data were manipulated by computer to produce eight more maps showing slope instability, soil erosion, soil shrink/swell, and soil pressure limitations.

To establish priorities for open-space planning, the environmental source maps were used in a capability analysis to generate three "environmental sensitivity maps" showing "hazardous areas," "sensitive areas," and "unique areas." Weights, or "importance ratios," were assigned to the various environmental factors through combining planners' values and citizen committee members' values and using the Delphi process mentioned earlier (Sonoma County Planning Dept., 1973).

Two of the three environmental sensitivity maps were based in part on slope-stability information. The hazardous areas map showed those areas liable to environmental problems including landslides. The sensitive areas map indicated areas where man's activities might have sufficient impact on the environment to lead to deterioration or destruction of the natural equilibrium. Sensitive areas mapped included areas with steep slopes. As described in the Phase II Open Space Element, "In Hazardous Areas, natural forces threaten man; in Sensitive Areas man endangers the natural ecobalance."

The studies on slope instability that were used to prepare the "Environmental Sensitivity Maps" were:

1. *Preliminary Geologic Map of Western Sonoma County and Northernmost Marin County, California* (Blake and others, 1971). This map was prepared at the scale of 1:62,500 and is based on data compiled and modified from a variety of sources.
2. *Geology for Planning in the Sonoma Mountain and Mark West Road Areas, Sonoma County, California* (Huffman and Armstrong, 1974).

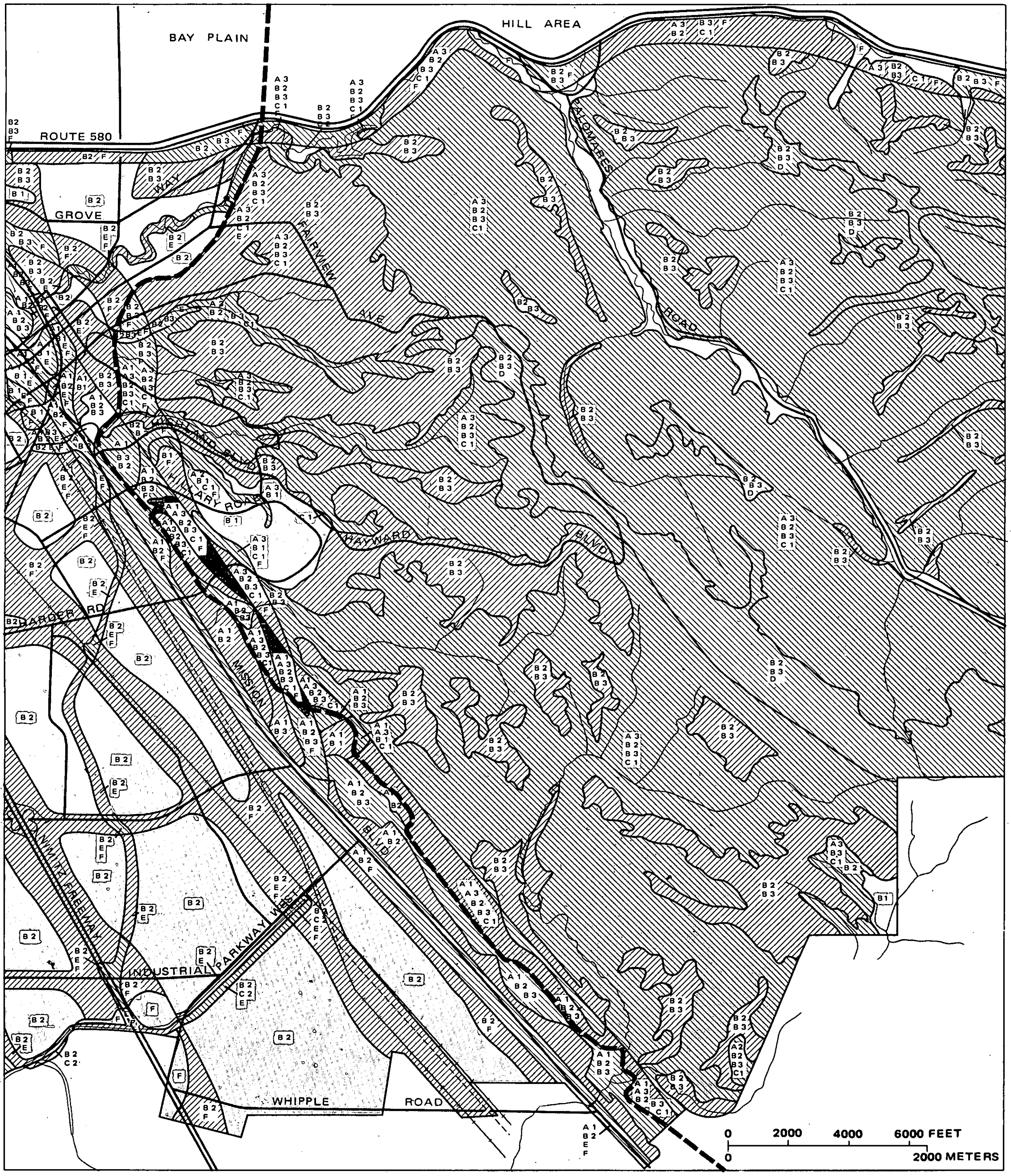


FIGURE 51.—Map of significant factors and probable environmental impacts, Hayward, Calif.

PROBABLE ENVIRONMENTAL IMPACTS

ENVIRONMENTAL CONDITIONS		DEVELOPMENT ACTIVITIES							
	Designation	Structures	Roads	Utility pipes and cables	Landfills excavations and grading	Landscaping with native species	Exotic landscaping needing water supplements	Irrigation	Disposal or application of toxic materials
GEOLOGICAL									
HAYWARD FAULT CORRIDOR	A-1	▲–	▲?	▲–	▲?			▲?	
LIQUIFIABLE GRANULAR DEPOSITS	A-2	▲–	▲–	▲–	?◀ ▲–				
UNSTABLE HILL AREAS	A-3	?◀▲–	?◀ ▲–	▲–	?◀ ▲–	+◀ ▲–	?◀ ▲–	–◀	
UNCONSOLIDATED SEDIMENTS ('YOUNG MUD')	A-4	?◀▲–	?◀ ▲–	▲–	?◀ ▲–				
SOILS									
DISTURBED AREAS	B-1					+◀	?◀		
SEPTIC TANK LIMITATIONS	B-2	▲–						▲–	
EROSION HAZARDS	B-3	?◀▲?	?◀	▲–	?◀	+◀	?◀	–◀ ▲–	
VEGETATION									
SLOPE STABILIZERS	C-1	–◀	–◀		–◀	+◀	–◀	–◀	–◀
FRESHWATER HABITATS	C-2	–◀	–◀		–◀	+◀	–◀	?◀	–◀
SALT MARSH (EXISTING AND PROPOSED)	C-3	–◀	–◀		–◀	+◀	–◀	?◀	–◀
SALT WATER EVAPORATION PONDS	C-4	–◀	–◀		?◀	+◀	–◀		–◀
VEGETATION WITH SPECIAL ESTHETIC SIGNIFICANCE	✱	–◀	–◀		–◀	?◀	?◀	?◀	?◀
CLIMATE AND AIR QUALITY									
HIGH WIND SPEED AND CHILL	D	?◀▲–	?◀ ▲–		?◀	+◀ ▲–	+◀▲–	▲–	–◀ ▲–
HYDROLOGY									
FLOOD HAZARD AREAS	E	?◀▲–	?◀ ▲–	▲–	?◀	+◀ ▲–	?◀		
NOISE POLLUTION									
POTENTIAL NOISE IMPACT	F	+◀▲–	–◀		?◀	+◀	+◀		

◀ Probable development impact on environmental conditions

▲ Probable environmental impact on development activities

+ Favorable impacts

– Adverse impacts

? Varying impacts depending on specific sites and activities involved

NUMBER OF ENVIRONMENTAL CONDITIONS NOTED

0 1 2 3 4 5 6

SIGNIFICANT FACTORS MAP

FIGURE 51.—Continued

This map, completed by M. E. Huffman under CDMG contract to the county, was prepared at the scale of 1:24,000 and is based on field observation and analysis of aerial photographs.

3. *Geologic Hazards Study—North Sonoma Coast.* Two studies covering the coastal area between the Gualala and Estro Americana Rivers were also completed by Huffman, under CDMG contract with the county, and included mapping of the study area at the scale of 1:24,000. The data were gathered by field observation and analysis of aerial photographs.

Michael Huffman of CDMG, who prepared several maps in conjunction with the County Advanced Planning Staff, interpreted the data for three critical geologic formations for application in the county environmental data system, particularly in connection with the hazards and slope stability maps.

The result of the data gathering and analysis of the Open-Space Element Phase II program (Sonoma County Planning Dept., 1973) was the mapping of the hazardous, sensitive, and unique areas. It was recommended that the open-space character of these lands be protected by an interim open-space zoning

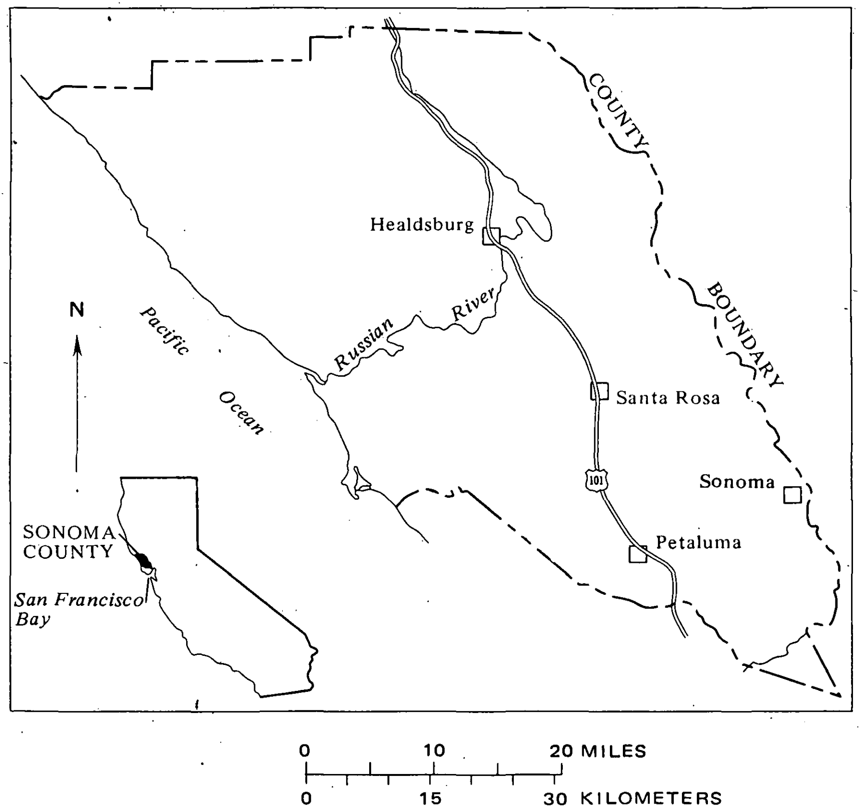


FIGURE 52.—Sonoma County, Calif. The valley floors and adjacent low hills produce wine grapes, prunes, pears, apples, row crops, and oats for hay. The hills in the southwestern part of the county are used for grazing dairy cattle and sheep. Areas east of the hills are mainly range, pasture, and mixed woodland. Sheep and beef cattle are raised in these areas. Douglas fir and redwood are logged in the northern half of the county.

ordinance and permit process until the final open-space element was completed and integrated with the general plan. Although the Phase II Open-Space Element and an interim open-space zoning ordinance have been adopted by the County Board of Supervisors, the computerized environmental-data system has been set aside because of its complexity.

The Sonoma County Planning Department has prepared an ERME (Environmental Resources Management Element), which incorporates the final open-space element and the conservation, seismic safety, and safety elements required by the State (Sonoma County Planning Dept., 1975). Important to the development of geologic-hazard policy and recommendations in the ERME was the report, *Geology for Planning in Sonoma County*, prepared for the county by the California Division of Mines and Geology (Huffman and Armstrong, 1974). This report identifies those areas subject to geologic hazards, such as seismically induced ground motion, fault rupture, tsunamis, and slope instability.

The ERME recommends that the areas identified as having geologic hazards be regulated by an open-space combining district (Sonoma County Planning Dept., 1975, p. 42). The intent is that before development can occur in the areas regulated by the combining district, performance standards will have to be met for resource management and public safety. An important recommendation is that a County staff geologist administer an engineering geologic study of all hazardous areas (Sonoma County Planning Dept., 1975, p. 57). Other recommendations include strict enforcement of grading provisions and the planning of future geologic studies to assist the county in implementing its general plan.

The slope-stability information contained in the Huffman and Armstrong (1974) report identifies four stability categories for the county. The report recommends that in three of the four categories engineering-geology reports be required before tentative tract approval for land development. Such a recommendation from the earth scientist has had an important effect on the development of the Sonoma County ERME.

The county planning staff believes that the significant role assigned to evaluating geologic hazards in the general plan will result in more rational land use and less impact on the natural geologic processes. This goal will, of course, be dependent on the adoption by political decisionmakers of measures to implement the ERME and other general-plan elements.

LAND-CAPABILITY STUDIES

Land-capability studies have emerged in recent years as effective tools for evaluating the physical capability of lands to accommodate land uses. The basic task of land-capability analysis is to focus on the physical landscape, identify its elements and their characteristics, and determine the capacity of the land to support the land uses under consideration.

For example, a capability study might address the problem of determining which lands in a planning area can most easily accommodate residential development. Land characteristics, or factors, are selected that represent the natural qualities most unsuitable to residential use. Such factors might include hazards such as unstable slopes, flooding, active faults, erosion, expansive soils, steep slopes, or thin soils. Positive qualities in the natural landscape such as types of vegetation or sand and gravel reserves are also often included.

The capability study is structured to judge the effect of all the selected factors, both individually and collectively, on the land-use option being considered and to express the impact of all factors by a single total score for any designated portion of the planning area. It thus provides a method for comparing the relative capability of land based on an explicit set of assigned values.

Capability studies may vary, but they generally fit the description given above. To illustrate the manner in which earth-science information can be used in such studies, seven distinct steps are listed below:

1. Select the land-use option to be considered.
2. Select the natural physical factors to be included in the evaluation.
3. Define the land units to be used in recording information for each factor.
4. Obtain or prepare maps with information on the factors selected in Step 2.
5. Assign rating values to the factors.
6. Assign weights to each of the factors.
7. Determine weighted capability and total score of each land unit.

The use of these steps is illustrated in a simplified hypothetical example of a land capability study considering a residential land use. Our example shows a step-by-step application of the method, using only three earth-science factors to simplify the illustration. The example is intended to be purely illustrative and should not be construed as recommending specific numerical values. Obviously, it is impossible to provide a universally applicable description of a capability study. Also, the terms used to describe the study components vary considerably. Therefore, the following description is purposely general and intended only to serve as an example of the use of earth-science information in land-capability studies.

Step 1. *Select the land-use option to be considered.* The land use option is selected from various possible land uses for planning area, such as residential, industrial, agricultural, or transportation. In our example we will consider residential use.

Step 2. *Select the natural physical factors to be included in the evaluation.* These factors might include geologic hazards, soils, steepness of slopes, vegetation, susceptibility to flooding, and other natural factors known to be important in relation to the land-use options. In our example, we will consider only slope stability, erosion potential, and vegetation (table 9, first column).

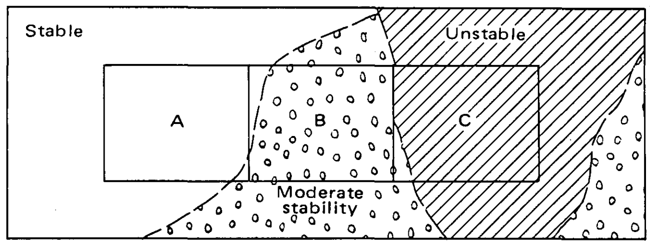
Step 3. *Define the land units to be used in recording information for each factor.* The shape, size, and number of land units needed are dependent on the size of the planning area and the nature of the planning problem. Scale, detail, and accuracy of available data, and time, money, and manpower constraints often affect decisions regarding the size of land units and the level of detail that can be handled. A grid-cell system of land units is commonly used and can facilitate computerization. The land units are delineated on a map of the planning area at a scale appropriate to the problem. For our example, we will use three grid cells (see fig. 53).

TABLE 9.—*Weighted capability factors*

Factor	Factor conditions	Rating values	Factor weight	Weighted capability
Slope Stability	Stable	10	10	100
	Moderately stable	5	10	50
	Unstable	0	10	0
Erosion potential	Insignificant	10	2	20
	Moderate	5	2	10
	High	0	2	0
Vegetation	Conifer forest	7	3	21
	Oak-grassland	10	3	30
	Grassland	3	3	9

SLOPE STABILITY FACTOR

Overlay grid cells on slope-stability map to determine factor conditions in grid cells

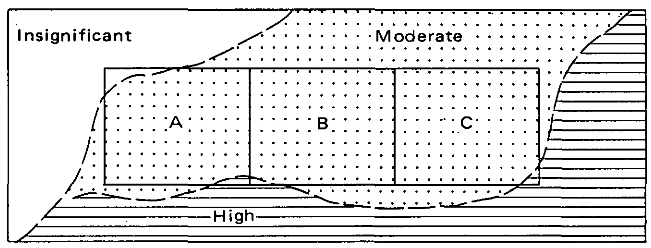


Weighted capability of factor conditions; determined from capability table (table 9)

Cell A	Cell B	Cell C
100	50	0

EROSION POTENTIAL FACTOR

Overlay grid cells on erosion-potential map to determine factor conditions in grid cells

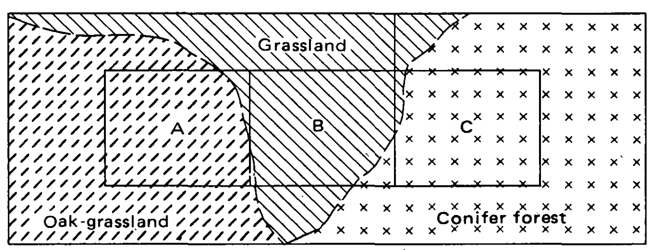


Weighted capability of factor conditions; determined from capability table (table 9)

Cell A	Cell B	Cell C
10	10	10

VEGETATION FACTOR

Overlay grid cells on vegetation map to determine factor conditions in grid cells



Weighted capability of factor conditions; determined from capability table (table 9)

Cell A	Cell B	Cell C
30	9	21

TOTAL CELL SCORES

Weighted capability, slope stability
+
Weighted capability, erosion potential
+
Weighted capability, vegetation

total cell score

Cell A	Cell B	Cell C
100	50	0
10	10	10
30	9	21
140	69	31

Step 4. *Obtain or prepare maps with information on the factors selected in step 2.* A set of maps with information describing the factors selected is needed—all with a common scale and level of detail. Typically, each factor is represented by one map in the set. To be of maximum usefulness to the analysis, each map would present information on the selected factor by showing conditions (table 11) significant to the land-use options being considered. The number of conditions identified will vary depending on the planning problem being addressed and the level of detail and accuracy of the data.

For some studies data will be available as interpretive maps, that is, maps which define areas in relation to advantages or limitations for land uses, or relative risk from natural hazards. Most capability studies will depend, at least in part, on data that have not been collected or interpreted specifically for the analysis. Any interpretation of these data or assignment of values for use in the capability analysis should be done by or under the supervision of a qualified professional who understands both the limits of reliability of the data and the requirements of the planner. In our example we will use interpretive maps showing the conditions for the three factors (conditions listed in table 9; maps shown in fig. 53).

Step 5. *Assign rating values to factor conditions.* A rating scale is chosen to express the relative conditions identified for each factor in step 4. From the scale a number, or rating value, is assigned to each factor condition. For example, assume that conditions of slope stability range from stable to unstable. The conditions might be assigned values from a rating scale of 0–10, with stable slopes receiving a value of 10 and unstable slopes receiving a value of 0. Intermediate conditions would be assigned values between 0 and 10 (table 9).

Step 6. *Assign weights to each of the factors.* A suitable weighting scale is selected from which a number, or weight, is assigned to each factor to represent that factor's relative importance to, or impact on, the particular land use being considered. For example, slope stability might be extremely important to the land-use option, whereas erosion potential is less important. Therefore, on a weighting scale of 0–10, slope stability might be assigned a weight of 10 and erosion potential a weight of 2 (table 9).

Step 7. *Determine weighted capability and total score of each land unit.* The weighted capability is determined for each factor condition identified in step 4. The weighted capability is calculated by multiplying the rating value (step 5) by the factor weight (step 6). For example, assume the stable slope condition has been assigned a rating value of 10 and the slope stability factor has been assigned a rating value of 10. The weighted capability of the stable slope condition would be 100 (cell A in fig. 53).

The weighted capability is thus calculated for each condition of all the factors (last column of table 9).

After the weighted capability has been calculated for each factor condition, each land unit can be assigned a score to determine its relative ability to accommodate the land-use option. This is accomplished by overlaying the map of land units with the appropriate factor map. Each factor condition for each land unit can be identified and the weighted capability recorded. The total score for each land unit is obtained by adding together the weighted capabilities of all the factor conditions recorded for the land unit (fig. 53).

From this general description, it is apparent that the assignment of rating values and factor weights re-

◀FIGURE 53.—Hypothetical example of a land-capability study considering a residential land-use option—grid-cell scoring and interpretation. Total scores for grid cells indicate relative capability of cells to accommodate residential land use. Grid cell A is stable, with moderate erosion potential and oak-grassland cover. Grid cell B is moderately stable, has moderate erosion potential, and grass cover. Grid cell C is unstable, has moderate erosion potential, and a conifer forest cover. On the basis of these three capability factors, grid cell A is by far the best for residential use. Grid cell C is unfit for residential use because of unstable slopes.

quires informed judgment. In some studies, quantitative data may be available to assist in assigning values and weights; in other studies, it is necessary to rely on experience. In any event, the judgments made can be questioned and modified as necessary. Obviously, many other factors relating to land characteristics need not be considered in actual practice. An advantage of the capability analysis is the ability to expand the number of factors considered.

The example illustrates the use of the land-capability analysis in scoring several land units for the same land-use option.

A further application of the land-capability study that has not been illustrated would be a comparison of the capability of the same grid cell for alternate land uses to determine the best use of the grid cell. This comparison would be accomplished through capability analyses for all land-use options being considered in a planning program, using the same data and land units. Some changes of numbers would probably be required to compare alternative land uses.

A somewhat different approach to land-capability analysis has been taken by ABAG in a recent study (Laird and others, 1979). ABAG, as a participant in the San Francisco Bay Region Study, developed a method for expressing land capability in terms of the dollar costs associated with hazard-mitigation measures, potential property damage from natural hazards, and loss of natural resources. The method was tested in a pilot land-capability analysis of a portion of the Santa Clara Valley.

The pilot study was focused on geologic and hydrologic hazards and resources and made use of many products of the Bay Region Study. Natural factors considered included earthquakes, flooding, bearing strength, slope stability, erosion and sedimentation, septic tank limitations, and natural resources. The land uses included agricultural or rural, semi-rural residential, single-family residential, multi-family residential, regional commercial, downtown commercial, industrial manufacturing, and freeways.

The total expected cost associated with each natural constraint and resource for each land use was calculated. For landsliding, expected costs were based on the relative slope stability map by Nilsen and Wright included in this report (pls. 1, 2, and 3).

The costs for each land use by slope stability category[4] are listed in table 10 (Laird and others, 1979, p. 53).

Cost information for each 24.9-acre (10-hectare) grid cell in the pilot study area was aggregated for each land use. The resulting number indicates for each cell "the dollar cost per acre expected to be incurred by developing that cell with that land use." (Laird and others, 1979, p. 59). The range of total costs was divided into six capability levels and a land-capability map for each use was printed by computer. The study shows that the expected costs in landslide areas are quite high for most uses.

TABLE 10.—*Costs associated with landslide potential*

[From Laird and others, 1979]

Land use	Slope stability category 5	4	3	2	1
	Cost per acre (0.4 hectare)				
Rural or agricultural	$ 40	$ 30	$ 20	$ 10	0
Semirural residential	1,000	700	200	100	0
Single-family residential	40,000	20,000	8,000	2,000	0
Multi-family residential	200,000	100,000	50,000	9,000	0
Regional shopping centers	100,000	80,000	30,000	8,000	0
Downtown commercial	200,000	100,000	50,000	20,000	0
Industrial	100,000	70,000	30,000	10,000	0
Freeways	20,000	20,000	7,000	4,000	0

Capability analysis is an evolving technique, and the results of each study must be evaluated. The reliability of the results in any such analysis is affected by (1) the quality of the basic data, (2) the factors included in the analysis, (3) the judgments made in assigning values to the factor conditions, and (4) the weighting of the factors.

Because the assignment of values and weights is rather subjective, it is imperative that the capability scores be carefully evaluated. Where the results appear to be unreasonable, changes may be needed in the assigned values; any adjustments made should be documented. The results should be carefully qualified to insure that the numbers do not imply a greater precision than is warranted. If the precision appears overstated, the scores may need to be put in more general terms.

Although any capability analysis will be limited and require qualification, the technique appears to be a reasonable and effective tool for evaluating the relative physical capability of lands to accommodate land uses. And, with more knowledge and experience and better information, the reliability of the results will improve.

Although a land-capability study can provide an analysis of the physical capability of land units to accommodate a variety of land-use options, it is only one input into the process of determining land-use policy and a land-use plan. Land-use policy and allocation of land uses in a plan would be determined from an overall suitability evaluation. Land-suitability studies take into consideration the full range of cultural, social, and economic factors, and existing land-use and

[4] Category numbers do not necessarily match numbers used elsewhere in this paper. Refer to the ABAG study for further explanation.

development patterns, in addition to physical land capability factors. Suitability studies differ from capability studies, then, in that they consider all factors affecting land-use decisions rather than just the physical characteristics of the land. A capability study is one part of a suitability study.

APPLICATION IN PLAN IMPLEMENTATION

Many approaches and techniques are available for insuring that land use is consistent with the goals and policies set forth in comprehensive plans. To minimize damage from landsliding, approaches and techniques range from strict regulation of land use and development to preservation of the most hazardous areas as permanent open space. Given the variety of physical conditions and land uses in any area, it is usually necessary to implement a comprehensive program for landslide hazard mitigation.

A number of factors influence successful plan implementation. As noted earlier, success depends on the regulatory power of the jurisdiction that has prepared and adopted the plan. Another critical factor is the effectiveness of the various professionals and political decisionmakers. Of particular importance is the understanding by decisionmakers of the impact of their decisions on public and private costs and risks. They should understand the basis for the plan and the techniques being used to implement it. Also, they should be willing to obtain and consider professional advice from such specialists as soils engineers, engineering geologists, civil engineers, and planners. The careful definition of the roles of these professionals and good relations between them are also important.

Some techniques of and approaches to plan implementation are described below, including examples of actual applications. It is important for each jurisdiction to choose the techniques best suited to the slope-stability problems of its planning area. The choice should be based on an accurate evaluation of local conditions and should be within the legal framework established by State-enabling legislation and case law for land-use planning and regulations. The techniques described below are not evaluated in terms of their relative merit. Rather, each type has evolved to deal with specific problems and situations and, as a result, should be considered independently. Also, the methods described can rarely be applied in exactly the same manner in different locations.

EARLY WARNING SYSTEM

The early warning system[5] is a tool for locating areas where conflicts between potential development and natural hazards are most likely. Planners can then focus on those areas having the most immediate potential for such conflict. The system not only incorporates information on the natural physical and biological condition of the land but also considers these conditions in relation to the "needs" of potential development. The needs include those physical and nonphysical conditions (proximity to roads, utilities and services, land values, taxes, and so on) necessary to support the types of land use that can be expected in the planning area.

First, the conditions necessary to support development are identified by analysis of the land-use type and by interviews with developers (such as home builders, logging companies, and industrial developers). After the conditions necessary to accommodate the various land-use types are identified, the landscape of the planning area is evaluated in terms of how to accommodate the land uses effectively. The resultant relative potential for development is indicated on base maps of the planning area. Second, these maps are evaluated against maps of the significant physical and biological conditions of the planning area, including but not limited to such elements as landslide hazards, erosion, sedimentation, flooding, and habitat of rare or endangered species.

Where areas with great relative potential for development are hazardous or have significant biological value, the agency has an early warning of where problems can be expected. Planning efforts should be focused on such areas to minimize potential conflict between development and the natural environment.

REGULATIONS

The range of local regulations available to carry out a general plan is given in figure 54. This figure also shows the relation of ordinances to the general plan and illustrates the typical degree of detail required for geologic data at each stage of the planning-regulation-development process. In the sequence depicted, each succeeding regulation requires more detailed information than the preceding regulation. The use of the various regulations to implement land-use plans is described below.

ZONING ORDINANCE

The zoning ordinance sets up the basic provisions governing land use, its intensity, and certain development requirements. The zoning ordinance generally provides that intensity of land use decrease in areas identified as unstable and that development be located in areas of greatest stability in hillside areas. The following zoning approaches have been used where slope-stability problems exist.

[5]This description is a summary of discussion in the report by Patri, Streatfield, and Ingmire (1970).

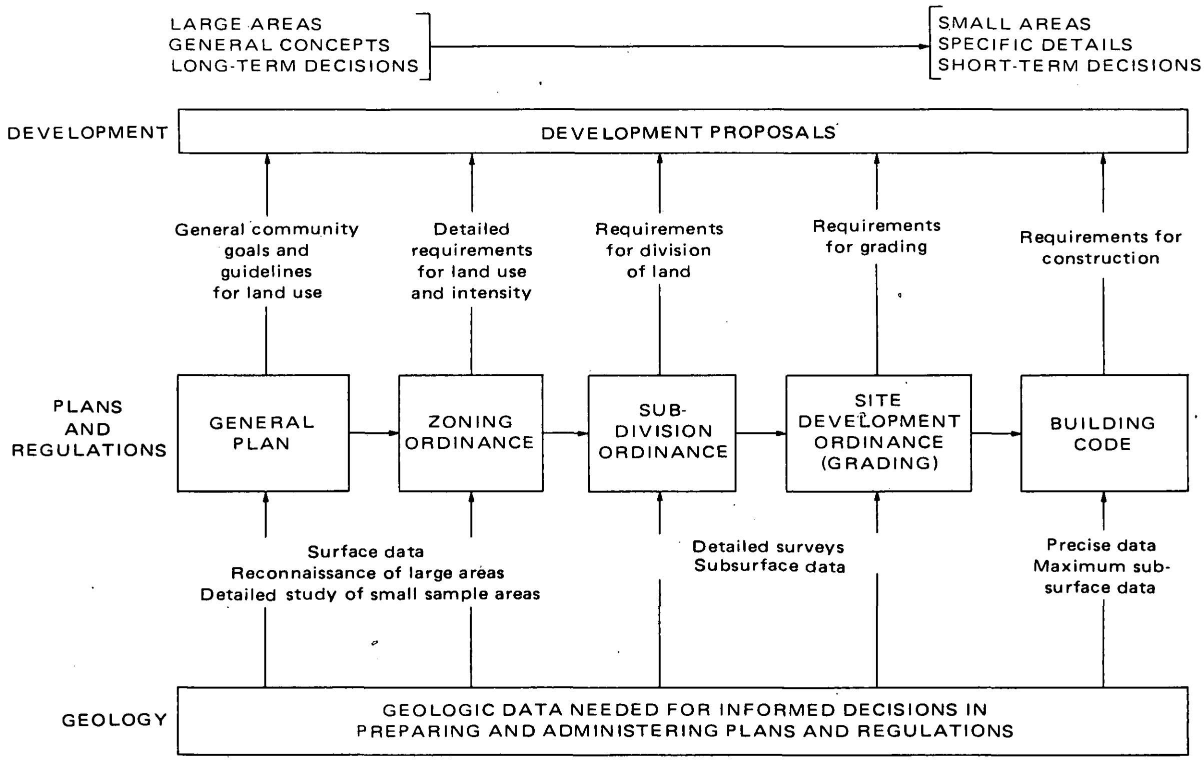


FIGURE 54.—The planning-regulation-development process. Geologic data are useful at every step in the process; more specific detail is needed as one progresses from general plans to actual building construction (Mader and Crowder, 1971.)

SLOPE-DENSITY PROVISIONS

Slope-density provisions establish maximum permissible densities of development for terrain with various degrees of steepness. As the steepness of the terrain increases, allowable density decreases, thus decreasing the amount of development permitted.

The reason for such regulation is that as slope increases, the potential for damage to the environment or the development increases. Of particular significance is the increased potential for slope failure, erosion and sedimentation, accelerated runoff, and scarring from site grading. Although some of these problems, such as slope failure, do not always increase with steepness of slope, they frequently do. Obviously, the nature of the underlying material will also greatly affect the potential for slope failure and erosion.

In addition to a required decrease in density with increase in slope, some regulations require that the steepest parts of the land be maintained in a natural state. Thus, development on all slopes steeper than a certain percent is prohibited. For example, the city of Pacifica in San Mateo County allows no development on slopes exceeding 35 percent (that is, where actual, not average, slope is greater than 35 percent).

Variations of the slope-density regulations have been utilized by communities in the San Francisco Bay region. For example, according to the municipal code, Los Altos Hills requires a minimum parcel area of one acre (0.4 hectare) with a required increase in the size of the parcel with increases in average slope as follows:

Average slope (percent)	*Net acres per parcel*
10	1.000
15	1.120
20	1.273
25	1.474
30	1.750
35	2.154
40	2.800
45	4.002

Where the average slope is more than 45 percent, the Los Altos Hills zoning ordinance provides that development of the parcel, including number of lots and net lot area, shall be based on demonstration by the applicant (including detailed soils and geologic studies) of how the parcel can be developed to minimize degradation of the natural environment and risk from natural hazards.

The slope-density provisions of the Town of Portola Valley require an increase in both gross area per dwelling unit and minimum parcel area with an increase in slope as follows:

Average slope (percent)	Gross area acres per dwelling unit	Required minimum parcel area (acres)
1 and under	1.13	1.02
10	1.36	1.22
15	1.52	1.36
20	1.73	1.55
25	2.00	1.79
30	2.37	2.13
35	2.91	2.63
40	3.76	3.42
45	5.32	4.91
50 and over	9.09	8.70

The Portola Valley ordinance also provides:

Where any lands in any parcel are in excess of 50%, such lands may be treated separately and the number of dwelling units permissible on the 50% and over lands may be added to the number permissible on the balance of the parcel to obtain the total permissible (density) on the entire parcel (Town of Portola Valley, 1967).

The slope-density provisions of the Hillside Preservation District of Pacifica specify the percentage of the parcel to be retained in a natural or undisturbed state as follows (Pacifica, Calif., 1973):

Average slope (percent)	Percent of site of remain in natural state
10	32
15	36
20	45
25	57
30	72
35	90
40	100

All Development within the Hillside Preservation District is to be accomplished under planned development ordinance provisions, which include standards for area, coverage, density, yards, parking, and so on, based on evaluation of the individual site in accord with guidelines set forth within the ordinance.

In addition to the slope-density regulations, each jurisdiction described above requires that development of slope-density regulated land also be based on detailed analyses of the soils and geologic conditions of the individual site. Site development must be based on the findings of these analyses and the densities reduced, if necessary, to provide safety and prevent environmental degradation. For a more complete analysis of the use of slope-density regulations throughout the United States, the reader is referred to the American Society of Planning Officials publication by Thurow, Toner, and Erley (1975).

Resource Management Zoning

The County of San Mateo has developed and adopted a RM (Resource Management) Zoning District regulating density of use and intensity of development to ensure that "***development is consistent with the level of services which reasonably can be provided, will conserve natural features and scenic values, and that areas hazardous to development or life are left open or limited in use" (San Mateo County, 1973). Under RM provisions, maximum density is determined by evaluation of a parcel against a "list of criteria" such as natural hazard areas, scenic areas, and proximity to services and facilities. For example, under RM regulations, those parts of a parcel identified as the least stable (categories V, VI, and L on the map by Brabb and others, 1972) are limited to one dwelling unit per 40 acres (16 hectares).

The RM district provisions also include special review procedures for any proposed development within the district. As part of these procedures, an applicant is required to submit an Environmental Setting Survey early in the design and review process, describing the environmental resources of the property and analyzing, in general terms, the constraints that they place on land development. As part of the survey, the applicant must have completed detailed topographic, geologic, and soils analyses of the site.

RM district regulations also contain the following "slope instability area criteria" that establish how development is affected by identified landslide hazards (Brabb and others, 1972):

The following criteria shall apply within all areas defined as highly unstable on the Landslide Susceptibility Areas Map:

(a) The following uses shall be prohibited: structures designed or intended for relatively dense human occupancy, including but not limited to multiple residential uses, schools and hospitals, critical public services and high-risk facilities, including but not limited to fire and police stations, emergency relief storage facilities, water storage tanks, dams, and power plants.

(b) This area may contain areas suitable for low-density residential uses, such as single-family detached residential dwellings. However, such developments shall not be permitted unless the applicant demonstrates that no other locations less susceptible to such hazards are reasonably available on the site for development, and through detailed geologic site investigations and adequate engineering design, that proposed locations are suitable for the uses proposed, and that direct damage to such uses or indirect threat to public health and safety would be unlikely.

(c) The applicant shall demonstrate that the development will not contribute to the instability of the land and that all structural proposals including excavation, access roads, and other pavement have adequately compensated for soils and other subsurface conditions.

Any "criteria" map upon which RM district provisions are based can be challenged more when a more detailed study has been completed; the allowable density is then based on the more accurate information.

CLUSTER ZONING

Cluster zoning is a technique by which lot size may be reduced below the minimum otherwise required in a zoning district if the developer agrees to preserve land as permanent open space for the benefit of the community. By use of this technique, open space may be maintained without impairing the development potential of a large parcel. Development is clustered on the lands with the fewest limitations. Lands identified as geologically unstable are left as permanent open space.

Commonly the concentration of development that is permitted under cluster zoning is controlled by provisions of the planned unit development. Such provisions allow greater design flexibility within guidelines that require that the development fit the natural characteristics of the land. Potential advantages include: improved site design with less disturbance of the natural landscape; lower street and utility costs, both initially and for long-term maintenance, made possible by reduced lot frontages; avoidance of the need for structures or facilities to cross areas of natural hazards; greater flexibility in the mixing of residential building types; and greater freedom in design without loss of essential amenities or needed housing and services. In addition, planned unit development can reduce housing costs and, therefore, provide a mechanism for addressing both natural hazards and economic problems.

Clustering techniques are often required in hillside areas in combination with special density provisions, such as were noted earlier for the city of Pacifica.

SUBDIVISION ORDINANCE

The subdivision ordinance governs the way in which land is divided and roads and utilities are installed. The ordinance, to regulate division of land effectively, should define existing and potential natural hazards, including problems of slope instability and necessary solutions, such as any special engineering measures that have to be taken. Subdivision ordinances in California are defined by State legislation in the Subdivision Map Act. This act contains requirements for subdivision of land that must be incorporated into local subdivision ordinances, including standards for land division, specific problems that must be addressed, the procedures under which subdivision is to occur, and the form of the final official subdivision map. One of the most important parts of the State Subdivision Map Act is Sec. 66474, which requires that the legislative body of a city or county deny a subdivision if any of the following conditions exist:

> That the design or improvement of the proposed subdivision is not consistent with applicable general and specific plans.
>
> That the site is not physically suitable for the type of development.
>
> That the site is not physically suitable for the proposed density of development.
>
> That the design of the subdivision or the proposed improvements are likely to cause substantial environmental damage or substantially and avoidably injure fish or wildlife or their habitat.
>
> That the design of the subdivision or the type of improvements is likely to cause serious public health problems.

The State General Plan and the Subdivision Map Act make it clear that city and county subdivision ordinances must ensure that problems such as slope stability be resolved before subdivision may proceed. To this end, subdivision ordinances may include provisions similar to the following:

(1) All subdivisions shall result in the creation of lots that are capable of being developed or built upon while retaining the basic natural qualities of the site. No subdivision shall create lots that are impractical for improvement or use owing to steepness of terrain, location of water courses, flooding, earth movement, size, shape, or other physical conditions.

(2) To ensure that problems of slope instability are identified, initial subdivision maps submitted for public approval shall be accompanied by, and designed in response to, the following types of investigations:

- (a) A preliminary soils study describing the nature of the subsurface soils and any soil conditions that would affect the geometry of the proposed development. The evaluation report shall state whether the proposed development is feasible and shall provide general solutions for all identified hazardous problems. It shall include the locations and logs of any test borings and percolation test results if on-site sewage disposal is proposed.
- (b) An engineering geology evaluation defining conditions on the site may be required. It shall state whether the proposed plan is feasible and shall provide general solutions for all identified problems. The evaluation shall include the location and logs of any test borings and shall evaluate the effect of the geology on the proposed development and on adjacent properties. The report shall point out specific areas where development may create hazardous conditions. A

set of recommended guidelines for preparing engineering geologic reports has been prepared by the Calif. Div. Mines and Geology, (1975).

(3) Areas identified as high risk shall be reserved by means of protective easement or dedicated as permanent open space.

(4) All measures necessary to ensure stability of building sites shall be taken in areas of potential risk from natural hazards. All conditions necessary to ensure mitigation of such risks shall be attached to the subdivision approval.

(5) All streets and utilities shall be so located as to avoid hazardous areas and minimize adverse impact of human activity on the natural landscape.

(6) Subdivision maps that are to become the officially certified record of approved land division shall indicate all identified geologic hazards. In addition, a note shall be placed on the face of the map indicating the author of the geologic study and the date it was prepared.

(7) All grading for subdivision improvement shall conform with the grading regulations of the jurisdiction.

SITE DEVELOPMENT ORDINANCE

To avoid landslide problems effectively, this ordinance must regulate site development so that the natural equilibrium of slopes will not be upset or will be improved. In general, such ordinances should require that grading for land development disturb the natural terrain as little as possible, unless extensive grading is needed to correct specific conditions.

Chapter 70 of the Uniform Building Code (Internat. Conf. Building Officials, 1973) contains minimum grading requirements. If these requirements are administered properly, the code can be effective in minimizing environmental degradation. Chapter 70, in part, requires that engineering methods be applied to control landsliding and settlement and provides standards for fill compaction and foundation design intended to minimize damage from settlement. The building official may also require an engineering geology report that will include data and recommendations to be incorporated in the grading plan. He may require a final geologic grading report that describes the site and certifies its adequacy for the intended use.

The specific provisions of any grading code will be effective only if adequately trained personnel are available to administer the code. Professional personnel involved in code enforcement may include architects, landscape architects, engineering geologists, soils engineers, and civil engineers.

BUILDING CODES

Although the content and scope of building codes vary from jurisdiction to jurisdiction, all codes generally prescribe minimum standards for construction methods and materials. While some codes contain detailed specifications, others prescribe standards that define the performance objectives and allow flexibility in choice of materials and designs. The performance-standard approach can be extremely useful in mitigating hazards, provided that the standards are reviewed and administered by qualified professionals.

Potential problems from unstable slopes can be mitigated when building codes include adequate performance specifications. Engineering geologic studies of a building site are required by some jurisdictions where a hazard has been identified in the comprehensive plan or through subdivision review. To be effective, the codes must require that the design be responsive to site conditions. For example, the foundation design of a building or structure should take into account soil creep and other slope-stability problems that have been found in detailed soils and geologic studies of a building site.

Standards and specifications in building codes must also contain clear guides to the administrators who issue or deny building permits. If it is determined from detailed studies of a specific site that engineering solutions to slope instability presently available cannot insure that construction will not damage public property or adjacent private property during the normal economic life of such property, the building permit should be denied.

PUBLIC POLICIES AND PROGRAMS

Slope-stability information can be incorporated into public policies and programs in a variety of ways. A policy can be adopted that requires geologic information of specified detail and accuracy to serve as the basis for determining appropriate land use when slope-stability problems have been recognized. On the other hand, a policy might specify allowable land uses based on conditions of geologic stability.

Slope-stability information can also be important in the development of policies for matters such as urban growth, community facility planning, cost estimating, and rational land valuation. The following policies might be adopted:

a. Refuse utility extensions to undeveloped areas identified as having extensive geologic hazards.

b. Specify the level of geologic stability necessary for an acceptable site in relation to the proposed community facility.

c. Determine the cost of reducing landslide hazards to levels acceptable to the community. For example, an existing school threatened by geologic hazards might either be modified through reconstruction to withstand the hazard or be relocated in a safe area. Such costs could be incorporated into the jurisdiction's capital-improvements programs.

d. Establish policy guidelines for determining property values for both land appraisal and assessment so that land cost estimates and assessment for tax purposes will more accurately reflect actual land use and development potential, taking into account limitations inherent in the natural land conditions.

e. In capital-improvement programming, consider such hazards as slope instability in estimating project timing and costs. For example, it may be determined that identified hazards pose an imminent threat to public buildings or facilities, and immediate expenditures of public funds are necessary to mitigate the hazard; or hazardous areas may be acquired, over a period of years, for permanent public open space.

A unique example of how slope-stability information can be incorporated in local land-use policy is provided by the experience of Portola Valley, Calif. On pages 68 through 69 of this report, it was shown that geologic processes have been considered in the development of the comprehensive plan for the town, and the current general plan takes note of geologic information contained on two detailed maps depicting the geology and geologic hazards that affect the town's planning area. Policy that has been adopted by the town to guide land-use decisions is also based on these two maps.

The "Geologic map" and "Movement potential of undisturbed ground map" were adopted as the official geologic maps of the town on May 8, 1974, (Town of Portola Valley Res. No. 500–1974, 1974). The background statement contained in the resolution adopting the maps describes the essential provisions regarding map use as follows:

> The Town Council of Portola Valley realizes the extreme importance of geologic data in many decisions which face the town. It also realizes that geologically hazardous conditions exist in extensive portions of the town. While results of highly detailed geologic studies might justify detailed restrictions on the use of some lands, such studies are not now available for most of the town. The geologic maps which have been prepared by the town, however, are based on the study of aerial photographs, field investigations, and other available geologic studies and portray geologic conditions with considerable accuracy. Given this level of data, the Town Council finds it appropriate to adopt these maps as policy, to have them serve as guidelines for administering the affairs of the town, and to modify them from time to time as better information becomes available. It is the Town Council's intention that these maps and related land-use policies shall be employed as guides in all decisions to which they are relevant and shall be adhered to unless modifications or deviations are permitted as provided for herein.

The resolution also contains a table (reproduced here as table 11) that describes permissible uses for each land-stability category shown on the "Movement potential map" (the nature of these categories is described on p. 69). The resolution states that the land-use policies shown on the table shall be adhered to, and that "these policies have been established on the premise that, in future action, the Town wants to avoid any major failures of ground due to landsliding which would endanger public or private property." The resolution requires that the maps and land-use policies "***shall be used in all decisions of the Town Staff, Committees, Commissions, and Town Council where geologic considerations are relevant. It shall, in particular, be employed in applications under the following regulations: (1) Zoning Ordinance; (2) Subdivi-

TABLE 11.—*Criteria for permissible land use in Portola Valley*

[From Mader, 1974; Y—Yes (construction permitted); [Y]—Normally permitted, given favorable geologic data and(or) engineering solutions; N—No (construction *not* permitted); [N]—Normally *not* permitted, unless geologic data and(or) engineering solutions favorable]

	LAND STABILITY SYMBOL[1]	ROADS		HOUSES			UTILITIES	WATER TANKS
		PUBLIC	PRIVATE	¼-Ac	1-Ac	3-Ac		
MOST	Sbr	Y	Y	Y	Y	Y	Y	Y
	Sun	Y	Y	Y	Y	Y	Y	Y
STABLE	Sex	[Y]	Y	[Y]	Y	Y	Y	[Y]
	Sls	[Y]	[Y]	[N]	[Y]	[Y]	[Y]	[N]
	Ps	[Y]	[Y]	[N]	[Y]	[Y]	[Y]	[N]
	Pmw	[N]	[N]	[N]	[N]	[N]	[N]	[N]
	Ms	[N]	[N]	N	N	N	N	N
	Pd	N	[N]	N	N	N	N	N
	Pse	N	N	N	N	N	N	N
	Md	N	N	N	N	N	N	N
LEAST STABLE	Pf	[Y]	[Y]	(Covered by zoning ordinance)			[N]	[N]

[1]S - Stable
P - Potential movement
M - Moving
br - bedrock within 3 feet (1 m) of surface
d - deep landsliding
ex - expansive shale interbedded with sandstone
f - permanent ground displacement within 100 feet (30 m) of active fault zone
ls - ancient landslide debris
mw - mass wasting on steep slopes, rockfalls, and slumping
s - shallow landsliding or slumping
se - movement along scarps of bedrock landslides
un - unconsolidated material on gentle slope

sion Ordinance; (3) Site Development Ordinance; (4) Building Code."

PROJECT REVIEW

Planning agencies regularly review public and private projects that fall directly within their area of jurisdiction, or that originate from other governmental units and affect the agencies' planning area. Some aspects of project review have already been discussed, but city and county planning agencies also normally review variances, conditional use permits, and rezoning applications.

In addition to local projects, planning agencies review projects being undertaken by other governmental agencies because of concern that the project will have impact on the local planning area. In recent years, through both Federal and State requirements for environmental-impact assessment, project review has become increasingly formalized.

In all project-review functions, and specifically A–95 review (see below) and environmental-impact assessment, the relevant basic earth-science data area are critical. In an area like the San Francisco Bay region, evaluation of slope stability is essential.

LOCAL PROJECT REVIEW

Local project review procedures can provide a consistent method to determine if proposed projects are affected by problems of slope stability and what measures are available to reduce these problems to levels the community is willing to live with. Project review with regard to slope stability problems might proceed as follows:

Initial review.—The first step would be a review of the best available slope-stability information. Ideally, this review should be done under the direction of a certified engineering geologist serving the jurisdiction.

Detailed study.—If the review uncovers the potential for slope failure as a result of proceeding with the proposed project, the engineering geologist serving the jurisdiction should conduct further studies and recommend measures to mitigate the hazard. Some measures might include modifying the proposed project on the basis of a more detailed study. The guidelines for the detailed study should have been set by an independent engineering geologist serving the jurisdiction. The study should be completed by professionals who can recommend ways of mitigating the hazards.

Acceptance of detailed study and project approval.—The detailed study, including recommendations for mitigating the hazard, should be reviewed by the engineering geologist and, if appropriate, the civil engineer serving the jurisdiction. The final recommendations of the study accepted by the engineering geologist and civil engineer should be attached as conditions of project approval when final action is taken by the approving agency.

A-95 REVIEW

A–95 review, so called because it was described in U.S. Government Office of Management and Budget Circular A–95, is a procedure designed to coordinate federally funded projects with State, regional, and local plans and programs.

Under this procedure, notification of application for Federal funds for a wide variety of projects must be submitted to designated State and regional clearinghouse agencies for review for consistency with State, regional, and local plans, policies, standards, and other criteria. The clearinghouse agency forwards the notification to other agencies potentially affected by the project for their review and comment. The appropriate public agencies are thus assured of the opportunity to comment on the consistency of proposed projects with their plans and policies and on the possible environmental impacts (including slope instability) of the proposal, as well as social, economic, civil rights, or other aspects of the project.

A–95 review is purely advisory; comments are submitted to the funding agency. In a revision of A–95 review procedures that became effective in January of 1974, however, the funding agency must state the reasons for funding a specific project receiving an unfavorable review. This requirement presumably gives more weight to the review process.

ENVIRONMENTAL IMPACT ASSESSMENT

The NEPA (National Environmental Policy Act) of 1969 requires that an "Environmental Impact Statement" be prepared for many Federal projects. The statement must include:

1. the environmental impact of the proposed action,
2. any adverse environmental effects that cannot be avoided should the proposal be implemented,
3. alternatives to the proposed action,
4. the relation between local short-term uses of the environment and the maintenance and enhancement of long-term productivity, and
5. any irreversible or irretrievable commitments of resources that would be involved in the proposed action should it be implemented.

Since the adoption of NEPA, many states have adopted similar legislation requiring impact evaluation for state-funded projects and state and local planning efforts. In California, for example, the California Environmental Quality Act of 1970, as amended, requires that an EIR (Environmental Impact Report) be prepared for any discretionary project or activity to be carried out or approved by a public agency that may have substantial adverse impact on the environment. Under the guidelines implementing this law, an EIR is usually required for plans, plan amendments, zoning ordinance changes, related public actions, and development proposals that may have substantial adverse effect on the environment. (For a more complete discussion on Federal and State requirements, see Burchell and Listokin, 1975.)

The requirement for environmental impact assessment, whether Federal or State, is, in effect, superimposed on the normal review process of the jurisdiction. Projects subject to environmental impact assessment are still reviewed for conformity with regulations of the appropriate jurisdiction. Local regulations may require environmental information over and above that required by Federal or State law.

Under Federal environmental impact assessment requirements and State requirements similar to those in California, the potential problems from slope instability (among other things) must be determined and measured to mitigate the problems described. Local agencies with responsibility for carrying out or approving a project should require that the project be reviewed against available slope-stability information. If it is determined that the project site is potentially unstable, more detailed geologic investigations can be required as part of the environmental-impact assessment before the local agency acts on the project. From such studies, the agency will be better able to make decisions that will maintain acceptable levels of risk.

ROLES OF PROFESSIONALS

LAND-USE PLANNER

It is the planner's basic responsibility to work with other professionals to incorporate earth-science information effectively into the land-use planning process. The planner is in the key coordinating position and must be able to communicate society's needs to the earth scientist and, at the same time, explain to decisionmakers how earth-science information may affect the consequences of different decisions. Most importantly, the planner needs to see that land-use regulations provide for input by geologists and engineers or other professionals to ensure that development will maintain acceptable levels of risk.

To assume this responsibility, a planner should have a general understanding of earth-science information and how the information can be acquired and applied in land-use planning. The planner should have had some college course work or other formal experience in environmental geology that has provided familiarity with earth-science reports and maps, basic earth-science terminology, and sources of earth-science data useful for planning.

CIVIL ENGINEER

The civil engineer, in California as in other states, is a professional certified by the State who is intimately involved with the process of land development. Structural engineers have specialized in the structural design of buildings, structures, and facilities. Soils engineers have specialized in soil mechanics and foundation engineering.

The public-sector civil engineer or structural engineer needs to have a general appreciation of the planning and land-development processes and of the roles and activities of the other engineering professionals. In addition, the engineer is often asked to help develop land-use plans, land-use regulations, and standards that will insure that problems of soils and slope stability will be addressed in the planning, regulation, and development of land.

Under land-development regulations, the certified civil engineer should be assigned responsibilty for preparing and approving grading and drainage plans for certification of completed grading including surface drainage facilities. As part of this responsibility, the civil engineer should be required to ensure that grading plans, as appropriate, take into consideration the findings from soils and geologic studies of the site. The civil engineer should also be responsible for coordination of the activities of the soils engineer and engineering geologist in their studies.

A soils engineer is a certified civil engineer specializing in soil mechanics and foundation engineering. These disciplines apply the principles of soil mechanics to the study of the engineering properties of earth materials.

The soils engineer's specific responsibilities include studying existing soil conditions and advising the civil engineer of soils problems that affect grading for land development. In addition, the soils engineer is frequently on site during grading to inspect and, as necessary, test soils moved, exposed, or disturbed. The soils engineer determines building-foundation requirements and designs subsurface drainage, erosion control, buttresses, and other soil-related features. Under land-development regulations, the soils engineer should be required to certify plans and specifications for grading and foundations as well as completed grading and construction.

ENGINEERING GEOLOGIST

An engineering geologist in California is a geologist registered by the State who, because of his specific professional knowledge is certified to apply the geological sciences to engineering practice for the purpose of seeing that the geologic factors are recognized and adequately provided for.

The engineering geologist should have a general understanding of land-use planning, to be able to contribute to the development of land-use plans and to help implement regulations that will maintain acceptable risk levels. The engineering geologist should also be able to present geological information in a form that can be easily incorporated into the land-use planning process.

The certified engineering geologist should be responsible for studying, mapping, and reporting on the geology of a project site and advising the civil engineer and soils engineer on conditions that might affect grading and site development. The engineering geologist should review geological conditions during construction to determine if modifications are necessary to grading plans. Land-development regulations should require that the engineering geologist certify plans and specifications and final grading and construction to insure that design and development has been completed in accordance with the recommendations.

INTERRELATIONS

Professionals working together can provide the data needed by decisionmakers in defining and maintaining acceptable levels of risk from geologic hazards. Fortunately, the San Francisco Bay Region Study and similar studies and projects are helping to improve the working relations of the professionals and the usefulness of earth-science data. Also, decisionmakers and the general public are learning the importance of earth-science data to land-use decisions and are becoming aware of the professional knowledge necessary for data gathering and interpretation. Through improved working relations and greater understanding of the importance of earth-science data to decisionmaking, it seems likely that engineering and geologic professionals will play an increasingly important role in land-use decisions.

SUMMARY AND CONCLUSIONS

By T. H. NILSEN, T. C. VLASIC, and W. E. SPANGLE

MAPPING OF RELATIVE SLOPE STABILITY

The stability of natural slopes can be studied in many ways, and a number of techniques can be used to produce a relative slope-stability map, depending upon (1) the purpose of the map, (2) the types of information and data available, and (3) the relative importance of different factors causing landslides in a particular area.

The relative slope-stability maps of the bay region were prepared through analysis of angle of slope, distribution of landslide deposits, the characteristics of bedrock and surficial geologic units. These factors were chosen because previous studies in the bay region indicated that most landsliding occurs on slopes steeper than 15 percent, in areas where landsliding has previously taken place, and on slopes underlain by particular geologic units or sequences of geologic units.

The relative slope-stability maps for the San Francisco Bay region are somewhat limited because they do not take into account other natural factors that are also important. As a result, the maps should be modified in the future as more data become available on such factors as rainfall, soil strength and thickness, vegetation, response to seismic events, and the effects of geologic structure on slope stability. In addition, as more data become available about the type, age, and distribution of landslide deposits and the physical and engineering characteristics and distribution of bedrock units, the maps can be improved. In the interim, the maps can be used in conjunction with other data as they become available.

In using the relative slope-stability maps of the bay region, or any earth-science product, the user must keep in mind the factors that were not considered in map preparation and limitations in map use specified by the earth scientists. Most importantly, maps made at the scale, detail, and accuracy of these maps should not be used to reach final decisions on the relative slope stability of small areas, which should be examined in detail by engineering geologists and soils engineers.

The slope-stability data presented herein are an initial attempt to assess regional slope stability, to be superseded in future years when better data and techniques become available. The study should be considered as a framework on which to build future techniques and methods of mapping slope stability.

APPLICATION OF SLOPE-STABILITY INFORMATION TO LAND-USE PLANNING

As slope-stability problems will vary greatly from area to area, local planning must consider the scale, detail, and accuracy of the basic earth-science information available. The magnitude of the slope-stability problem must be evaluated in relation to other physical, social, economic, and political factors.

Ordinarily, more detailed and accurate slope-stability information is needed for the application of land-use regulations, project review, and environmental impact assessment than is necessary for general planning purposes.

After slope-stability problems have been identified, a risk analysis can be made to determine the level of risk the community is willing to accept and to serve as a basis for planning policy.

No specific rule can be provided that, when followed, will insure that all slope-stability problems in a jurisdiction are addressed. Rather, it is important that the planning agency be aware of the natural conditions of the area and the possibility that problems may arise from slope instability. At that point, a program can be developed that utilizes a combination of policies, regulations, and decision criteria to ensure that potential hazards are recognized and mitigated to acceptable levels of risk.

Planning staffs need to have earth-science and engineering specialists available as working partners if earth-science problems are to be understood, communicated to decisionmakers, and considered in the land-use planning process. The relative slope-stability maps of the San Francisco Bay region indicate that:

(1) Large areas of the San Francisco Bay region are relatively unstable and susceptible to natural slope failure.
(2) Urban development of these areas could be very hazardous because of the propensity of the terrain for slope failure.
(3) Safe development of the unstable hillsides, where possible, may require extensive modifications of the slopes by cutting and filling, thereby destroying the natural beauty of these areas.
(4) Lands in moderate to high categories or subcategories of slope instability should not be committed to development without detailed study by engineering geologists, soils engineers, and civil engineers to determine whether they are suitable for development and to estimate the level of risk involved.
(5) In many cases, it may prove less costly and safer to leave these areas in open space or low-density development.

RECOMMENDATIONS FOR IMPROVING THE PROCESS OF PLANNING FOR SLOPE STABILITY

SLOPE-STABILITY INFORMATION

Relative slope stability mapping should be based on standardized data covering the entire study area. Mapping and analysis of more of the many factors that contribute to natural slope stability will improve the accuracy of derived slope-stability maps. These factors include (1) angle of slope; (2) type, age, and distribution of landslide deposits; (3) character and distribution of bedrock geologic units; (4) rainfall; (5) soil strength and thickness; (6) vegetation; and (7) response to seismic events.

Relative slope-stability analysis will be improved by better understanding of the effects of human activities on slope stability, including the cutting, loading, and addition of water to slopes. In particular, research on the regional effects of major development over broad areas is needed to answer such questions as, "What type and how extensive must development be in different areas before it contributes to extensive landsliding?"

PLANNING FOR SLOPE STABILITY

The improvement of working relations between planners and the professionals involved in analyzing natural land conditions should continue through projects such as the San Francisco Bay Region Study. These efforts should focus on (1) alerting the planner to new earth-science data and data-gathering techniques that might significantly affect land-use decisions; (2) alerting the earth scientist to the changing data needs of planners as new techniques for guiding land use evolve; and (3) describing earth-science concerns in a manner understandable to decisionmakers and others with responsibility for setting land-use policy.

More research is needed on the interpretation of landslide and other geologic hazard information as it applies to risk analysis. This research should focus on developing a consistent method of calculating the public and private costs involved with development of potentially hazardous areas. Costs should be clearly defined so that decisionmakers can readily determine the risk to life and property associated with any proposed land development or use.

More comprehensive policies and specific guidelines are needed at the Federal and State level to identify critical hazard areas and to establish acceptable risk levels. Such policies and guidelines would provide a better framework within which local jurisdictions can determine acceptable risk levels and establish urban growth and development policies to avoid encroachment into hazardous areas. Guidelines for property taxation are needed so that the actual limitations to development imposed by natural hazards are recognized in the tax structure.

CONCLUSIONS

Much has been said in the preceding pages regarding hazards associated with unstable slopes and the need for careful planning to minimize risk to life and property. The planning guidelines and examples that have been cited emphasize, appropriately for this study, planning to achieve safety from a geologic hazard. This emphasis, however, may at times tend to oversimplify the complex planning-decisionmaking process.

Each day in any jurisdiction, a number of planning decisions are made that require the balancing of many social and physical concerns. The people making these decisions, whether technical staffs or public bodies, are often confronted with volumes of information intended to describe the social, economic, political, and environmental consequences of alternative actions. Weighing and balancing this information to reach decisions that best meet community needs is a formidable task, often further complicated by disagreement between equally qualified professionals as to the consequences of any single action.

It cannot be overemphasized that to consider and balance all social, historical, and physical concerns in order to address successfully the variety of planning issues facing conscientious decisionmakers today is a tremendous undertaking. For example, it may be found that to best meet the needs of a community, sites with potentially significant physical limitations may have to be developed and in fact can be safely developed if careful planning and proper management techniques are employed. We hope that the information in this report and in other San Francisco Bay Region Study reports will help decisionmakers ensure safe land use, and that planners, engineers, earth scientists, decisionmakers, and the general public will be better prepared to work together to respond to the full range of needs facing their community, be it a city, county, region, state, or nation.

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