Earthquakes and the Urban Environment

Volume III

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Graydon Lennis Berlin
Flagstaff, Arizona
November 1978

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Graydon Lennis Berlin was born in St. Petersburg, Pennsylvania, on May 21, 1943, and educated in the public schools there. He received a B.S. degree in 1965 from Clarion State College (Earth-Space Science), an M.A. degree in 1967 from Arizona State University (Geography), and a Ph.D. degree in 1970 from the University of Tennessee (Geography). He began his educational career in 1968 as an Assistant Professor of Geography and Research Associate at Florida Atlantic University. He joined the faculty at Northern Arizona University in 1969, attaining the rank of Associate Professor of Geography in 1975. Between 1969 and 1978, Dr. Berlin was also a Research Geographer on a part time basis with the U.S. Geological Survey. At the present time he is the Director of the Advanced Training of Foreign Participants in Remote Sensing Program, a joint venture of Northern Arizona University and the U.S. Geological Survey.

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PLANNING FOR SEISMIC HAZARDS

I. LAND USE PLANNING

Land use planning has been used only recently as a method to mitigate losses due to earthquake hazards. In California and Alaska, for example, urban growth in recent decades has moved ahead with little regard to seismic hazards (Figure 3 in Volume I, Chapter 1). According to Mader,[1117] urban planners in the past have "generally not been sufficiently aware of seismic problems and therefore have too often simply ignored them." In addition, elected government officials "are often unaware of seismic problems or, if aware, find it difficult to deal with vague events such as earthquakes in the day-to-day realism of political decisions."[1117] Unlike the situation in existing urban areas where development patterns are already established, proper land use plans and decisions can reduce risks from seismic hazards in regions currently experiencing the urbanization process. Mader[1118] notes that although "experience is lacking, there are a number of promising approaches to dealing with seismic problems in land use planning."

A. Land Use Plans: A Sampling from California

In California, especially as a result of the February 9, 1971 San Fernando earthquake, several key pieces of legislation have been enacted to achieve seismic hazard reduction via land use planning. The California Legislature enacted *Senate Bill (SB) 351* in 1971 requiring all cities and counties to prepare and adopt a *seismic safety element* in their long-range *general plans* (Government Code Section 65302).* The element must consist of an identification and appraisal of seismic hazards including surface faulting, ground vibrations, ground failures, tsunamis, and seiches. In addition, an appraisal of mudslides, landslides, and other processes related to slope stability must be considered simultaneously with seismic hazards. The Governor's Earthquake Council has stated that the intent of the law is to require cities and counties to consider *all* seismic hazards in planning programs to reduce deaths, injuries, property damage, and economic and social dislocations resulting from future seismic events.[1119] With the passage of this legislation, seismic safety became a state concern with the burden placed on local and county governments to deal with seismic problems when making planning decisions.[1117]

The first seismic safety element study was prepared for the tri-cities of El Cerrito, Richmond, and San Pablo in western Contra Costa County.[1120] It was designated a model study by the Governor's Office of Intergovernmental Management and the California Council on Intergovernmental Regulations; the latter organization distributed the study to all cities in California. The essential parts of the tri-city study are (1) detailed findings of potential earthquake hazards, existing land uses, and disaster implications, (2) policies to regulate existing development and guide future development, and (3) specific recommendations for action by the three cities to reduce the impact of minor and major earthquakes.[1120]

In 1973, the California Division of Mines and Geology (CDMG) published and dis-

* California law also requires a general plan to include a land use element, a circulation element, a housing element, a conservation element, an open-space element, a noise element, a scenic highways element, and a safety element. The law further requires that zoning and subdivision of the land be consistent with the general plan.[1118]

tributed a detailed set of guidelines to serve as an additional aid for the preparation of seismic safety elements. The publication, entitled *Guidelines to Geologic/Seismic Reports*, was prepared by the Southern California Section of the Association of Engineering Geologists.[1121]

In early 1977, a committee of the California Safety Commission conducted a statewide survey and found that approximately 80% of all cities and counties had adopted seismic safety elements.[1118] Most of the elements contain background material prepared by geologists and planners and a policy statement to be included as a part of the general plan.[1118] According to Mader,[1117,1118] (1) the elements are of varying quality, ranging from those that brush the topic to those that treat the subject in great depth, (2) a variety of approaches have been used to deal with seismic safety,* and (3) the modifications to land use plans in response to the seismic data have varied. Mader[1118] summarizes the impact of Senate Bill 351 to date.

> . . . It is clear, however, that effects of the legislation have been felt state-wide and have led to local identification of seismic problems and formulation of policy, and are leading toward significant impacts on land use decisions. The newly adopted elements have not, however, been in effect for sufficient time to judge their real impact. The State has by means of this legislation told local government to take seismic safety into consideration in general plans. The State has not yet said it will judge the adequacy of the local response.

California has taken a far-reaching approach in directing local government to cope with one particular seismic hazard — fault rupturing.[1117] The *Alquist-Priolo Special Studies Zones Act* of 1972** (amended in 1974 and 1975) requires the State Geologist (Chief, California Division of Mines and Geology) and the State Mining and Geology Board to assist "cities, counties, and state agencies in the exercise of their responsibility to provide for the public safety in hazardous fault zones."[1122] The act is designed to provide a means for reducing personal and property damage resulting from movement along an active fault. The legislation applies to new real estate developments and structures designed for human occupancy, with the exception of single-family wood-frame dwellings, in designated hazardous zones.[1123] Basically, a habitable structure must be sited so as to avoid "undue hazards" that could be created either by surface faulting or by fault creep, and geologic studies are required along specified fault traces as a prerequisite to construction projects.[1117,1123] The following is a summary of the official responsibilities and functions required by the act.

The State Geologist has the continuing responsibility to delineate *Special Studies Zones* that encompass limited areas centered on potentially hazardous faults. A zone boundary defines an area that the State Geologist believes warrants detailed geologic investigations to determine the presence or absence of hazardous faults.[1124] The State Geologist must revise existing zones and delineate new zones as additional geologic and seismic data become available; the zones are delineated on 7.5 minute (1:24,000) topographic maps. *Preliminary Review Maps* of new and revised zones are issued 1 July each year, and *Official Maps* are released 1 January of the following year. Once Preliminary Review Maps are released, cities, counties, and state agencies affected by Special Studies Zones have 90 days in which to review the maps and to submit comments to the State Mining and Geology Board.[1121]

Under Phase I of the CDMG program, Special Studies Zones were compiled for the San Andreas, Calaveras, Hayward, and San Jacinto faults. Phase I zoning was completed in 1974. Phase II of the program has been extended to the following faults: Antioch, Buena Vista, Elsinore-Chino, Fort Sage, Garlock, Kern Front, Manix, Mal-

* Mader[1118] discusses the different approaches used in the seismic safety elements of Santa Barbara County, Santa Clara County, San Jose, and San Francisco.

** Formerly known as the *Alquist-Priolo Geologic Hazards Zones Act.*

ibu Coast-Raymond, Newport-Inglewood, Owens Valley, Rogers Creek-Healdsburg, San Gregorio, Sierra Madre-Santa Susana-Cucamonga (includes San Fernando), Whittier, and White Wolf.[1121] As of January 1, 1978, a total of 261 Official Maps had been issued by the State Geologist.[1125]

The State Mining and Geology Board has the responsibility of formulating policies and criteria to guide affected cities and counties, serving as an Appeal Board for disputes that cannot be handled at the local level, and advising the State Geologist. The following is a summary of policies and specific criteria adopted by the board.[1123]

Policies

1. Specifies that the Act is not retroactive.
2. Suggests methods relating to review of Preliminary Maps prior to issuance of Official Maps.
3. Policies and criteria apply only to areas within Special Studies Zones.
4. Defines *active fault* (equals potential hazard) as a fault that has had surface displacement during Holocene time (last 11,000 years).

Specific Criteria

1. No structures for human occupancy are permitted on the trace of an active fault. (Unless proven otherwise, the area within 50 feet (15.2 m) of an active fault is presumed to be underlain by an active fault.)
2. Requires geologic reports directed at the problem of potential surface faulting for all real estate developments and structures for human occupancy.
3. Requires that geologic reports be placed on open file by the State Geologist.
4. Requires cities and counties to review adequacy of geologic reports submitted with requests for development permits.
5. Permits cities and counties to establish standards more restrictive than the policies and criteria.
6. Sets fees for building permits at 0.1 percent of estimated assessed valuation of proposed structure
7. Defines a) structure for human occupancy, b) technically qualified geologist, and c) new real estate development.

Affected cities and counties (1) are responsible for the local implementation of the act, (2) approve or disapprove sites for every new real estate development or structure designed for human occupancy within Special Studies Zones, and (3) collect fees for building and development permits to cover administrative costs. State agencies have the responsibility for siting state structures safely within Special Studies Zones.[1123] As noted by Hart,[1123] in many cases where the existence of a fault hazard is unclear, a local jurisdiction must decide whether or not a proposed development or habitable structure is an acceptable risk based upon the site investigation made by a geologist licensed in California.

A special agency, the *San Francisco Bay Conservation and Development Commission (BCDC)*, was created by the California Legislature with authorization to prepare and enforce a comprehensive plan for controlling development along the shoreline of San Francisco Bay. BCDC shares jurisdiction with cities and counties over land use decisions and, with minor exceptions, a permit from BCDC is required for all projects within its area of jurisdiction.[1118] As noted by Mader,[1118] the commission "in effect, holds veto power over any project proposed in conflict with the San Francisco Bay Plan."

California also has adopted legislation for the siting of new public school and hospital buildings to insure that the proper foundation and geologic conditions are assessed for seismic safety (also discussed in Volume 2, Chapter 3). For example, under the *Hospital Safety Act* (Senate Bill 519), the California Division of Mines and Geology is assigned the responsibility of determining the adequacy of geologic/seismic reports for new hospital sites prepared by certified engineering geologists and submitted to the Office of Architecture and Construction[952] (Figure 1). CDMG uses *Guidelines to Geologic/Sesmic Reports,*[1121] *Recommended Guidelines for Determining the Maximum Credible and the Maximum Probable Earthquakes,*[1124] and *Checklists for the*

FIGURE 1. The Fairmont Hospital in San Leandro, California is one of many hospitals located within the active Hayward fault zone. A major earthquake along this fault would very likely put all of these hospitals out of commission. In 1973, the California Legislature enacted the *Hospital Safety Act* to prevent the construction of new hospitals within fault zones. (Courtesy of James L. Ruhle and Associates, Fullerton, Calif.)

Review of Geologic/Seismic Reports[1127] in the review process for determining if the appropriate foundation and earthquake conditions were considered and properly evaluated in the analysis of seismic safety."[951]

As noted by Mader,[1117] *environmental impact reports (EIR)* can be effective in defining potential seismic hazards, and because they are required for a wide variety of projects, they can cover developments "not otherwise subject to adequate governmental review."[1117] However, Mader[1117] further observes that because environmental impact reports "are for information purposes, they do not insure that problems which are uncovered will be treated properly in development plans." In California, the *Environmental Quality Act* of 1970, with amendments, requires all state and local agencies to prepare, or to have prepared by contract, an environmental impact report on any project that could have a significant effect on the environment.[1128, 1129] The geologic problems that must be considered in the preparation and review of an EIR are (1) earthquake hazards, (2) loss of mineral resources, (3) waste disposal, (4) slope and/or foundation instability, (5) erosion, sedimentation, flooding, (6) land subsidence, and (7) volcanic hazards. Earthquake hazards include (1) fault movement, (2) liquefaction, (3) landslides, (4) differential compaction/seismic settlement, (5) ground rupture, (6) ground shaking, (7) tsunamis, (8) seiches, and (9) flooding from the failure of dams and levees.[1130] The California Division of Mines and Geology is responsible for the review of geologic analyses in the reports to determine if the appropriate geologic factors have been adequately considered.[1129–1131] To assist in the review process and to provide guidance to public agencies, EIRs are evaluated on the basis of checklists and guidelines contained in the CDMG publication *Guidelines for Geologic/Seismic Considerations in Environmental Impact Reports*,[1130] which identifies the geologic conditions present in the report area and a list of elements that should be included in the report.[1129]

Zoning ordinaces can be used effectively for dealing with seismic hazards at the local level. The Town of Portola Valley* has adopted several innovative procedures for reducing the impact of seismic hazards. For example, the town's *subdivision ordinance* requires a geologic report to be submitted with the application for a subdivision to

* Portola Valley occupies a site within the San Andreas fault zone southeast of San Francisco.

insure that the proposed site is physically suitable for the residential development. The report must be approved by the Town Geologist prior to development.[1117,1118] In addition, a *fault setback ordinance* was enacted because the San Andreas and other active faults pass through the community. One requirement of the ordinance is that no structure designed for human occupancy can be located closer than 15.2 or 30.4 m to a fault trace with a known or inferred location, respectively.[971] Additional requirements of this ordinance are described in Volume II, Chapter 3.

B. Possible Land Use Plans and Building Policies for Mitigating Earthquake Hazards

Nichols and Buchannan-Banks[1132] describe various types of land use plans and building policies that can be implemented for developing and developed areas, respectively, to mitigate losses arising from surface faulting, ground shaking, ground failure, and tsunami and seiche effects.

1. Surface Faulting

1. Land uses that would be compatible with ground displacement should be recommended for future development. Compatible uses include undeveloped open-space, recreational areas such as golf courses, parking lots, and drive-in theaters. Only those uses essential to public welfare, such as utility and transportation facilities, should be considered in areas of extremely high risk.
2. Establishment of a fault hazard easement, requiring varying setbacks from active faults, can reduce the risk. The more critical the structure, the greater the setback. This type of approach is being used in Portola Valley, California.
3. For any development to be within or immediately adjacent to an active fault, detailed geologic studies should be required to demonstrate "that the construction would conform to standards of community safety and that an undue hazard to life and property would not ensue." This procedure is addressed by the Alquist-Priolo Special Studies Zones Act in California.
4. Where urban development already exists within active fault zones, jurisdictions can adopt policies leading to the removal of critical-engineered structures on the most accurately located active fault traces. Nonconforming building ordinances could be considered that would require "the eventual removal of structures in the greatest danger, starting with those that endanger the greatest number of lives — schools, hospitals, auditoriums, office buildings, and apartment houses, followed by commercial buildings, and perhaps eventually by single family residences."

2. Ground Shaking

1. In areas expected to be severely shaken in future earthquakes, low-density land uses might be appropriate for future development.
2. Building code criteria appropriate to ground vibrations can be adopted. For example, the most stringent regulations might be applied to thick, water-saturated areas having long fundamental periods of vibration that would closely match the natural periods of high-rise buildings.
3. Ordinances could require detailed geologic, soil, and engineering analyses for structures having high occupancies in areas suspected to have the greatest motion. A procedure similar to this is now required for public school and hospital construction in California.
4. Hazardous building and parapet abatement programs can be initiated. The former program was first implemented in Long Beach, California, and the latter in Los Angeles.

3. Ground Failure

1. In areas where instability can be expected, open-space or other nonoccupancy uses could be implemented.
2. Analyses could be required to demonstrate that a hazardous condition has been eliminated by site preparation work or special engineering design before occupancy unit plans are approved.
3. In developed areas where a severe instability problem exists, consideration should be given to the implementation of a hazardous building ordinance or to the initiation of nonconforming use procedures.

4. Tsunami and Seiche Effects

1. Stringent controls should be applied to all land uses within areas that could be subject to tsunami and seiche runup or potential areas of inundation downstream from water-retaining structures that are sited within active fault zones and landslide-prone areas.
2. Controls could include the following: (1) allow only those land uses that are essential (docks, warehouses) in possible inundation areas, and warn owners and occupants of the potential hazards, (2) prohibit new construction in undeveloped inundation zones, (3) initiate warning systems and evacuation plans, and (4) eliminate potentially dangerous dams.

Because neither the location nor the magnitude of *tectonic land changes* can be predicted, very little can be done to minimize the effects before the deformation occurs.[1132]

C. Earth Science Data for Identifying and Assessing Seismic Hazards

It is essential to have a broad-based earth science information inventory if land use policies and regulations are to be used effectively to minimize earthquake hazards. However, Linville[1133] observes that in most seismic areas "hazards have not been identified on a scale that can be significant for planning." In other instances, earth science data may be available, but they "must be translated from scientific and technical language into a form that can be used effectively in the decision making process."[1134] Nichols and Buchannan-Banks[1132] have compiled a list of earth science data types and sources that are likely to yield the most useful data for identifying and assessing the potential seismic hazards of a given area.

1. Bibliographic research of geological and geophysical data, seismicity, historic earthquake records, including accounts of damage from shaking, faulting, and tsunamis.
2. Interpretation of remote sensing data, including conventional aerial photographs. Both the earliest and most recent photography at different scales should be examined.
3. Regional geologic maps, generally at a scale of 1:62,500 or larger. These commonly will have been prepared by the U.S. Geological Survey or state surveys.
4. Special-purpose detailed geologic maps of fault traces and zones, landslides, unconsolidated deposits subject to liquefaction, settlement, and subsidence . . . These may have been prepared only by private consultants for individual sites although the federal and state surveys have been preparing such maps for large areas in recent years.
5. Repeated geodetic measurements over long periods (decades) to detail possible horizontal and vertical land or sea changes. These are normally conducted by public agencies to establish mapping control and design of facilities.
6. Geophysical surveying to determine such things as depth to bedrock, seismic velocities, earth structures, magnetic properties of rocks, or shear wave properties. Surveying may have been conducted for research or design of specific facilities.
7. Measurements of fault creep and earth strain. Normally undertaken for research.
8. Seismometer arrays to determine seismic activity, fault location, type and attitude, and likely hypocenters; conducted for research.
9. Strong-motion instrumentation data from different geologic environs and representative buildings; collected for design and research.

10. Trenches across critical faults to determine location and type of displacement and to secure samples that permit age dating of past movement to determine frequency of fault displacement. Trenches dug and examined both for research and site exploration.
11. Subsurface exploration to locate water levels and barriers and to obtain samples for determination of soil properties needed in computing ground response characteristics. Such data are largely collected by consultants as part of site exploration studies.
12. Detailed topographic maps and submarine profiles are needed to estimate slope stability, prepare possible inundation maps, and evaluate tsunami runup potential. Where available, these normally have been prepared by federal agencies but are being made increasingly for design of large coastal installations.
13. Empirical or theoretical modeling of ground response in typical geologic/soil environments. Such work has been done in universities, by consultants, and by government researchers in the United States and some other countries.
14. Preparation of relative risk maps. These have largely been prepared for specific, large land development projects.

The types and amount of data will vary with the area in question, depending upon the geologic complexity, earthquake history, the type and distribution of land use (existing, planned), the level of planning development, and the amount of funding available.[1131]

1. The San Francisco Bay Region Environment and Resources Planning Study

Because of the recognized need for incorporating earth science data in planning efforts, the U.S. Geological Survey and the Office of Policy Development and Research of the Department of Housing and Urban Development initiated a pilot program in 1970 to develop an essential earth science information base that could be used to relate geologic hazards with land use planning and decision-making efforts. The experimental program centered on the nine-county San Francisco Bay region.[1135,1136] The philosophy and intent of the *San Francisco Bay Region Environment and Resources Planning Study* has been summarized by Borcherdt.[1134]

> Although the study focuses on the nine-county . . . San Francisco Bay region, it bears on a different issue that is of national concern — how best to accommodate orderly development and growth while conserving our national resource base, insuring public health and safety and minimizing degradation of our natural and manmade environment. The complexity, however, 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 insure 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 decision-making 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 the 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.

The study encompasses four program elements: (1) topographic, (2) geologic and geophysical, (3) hydrologic, and (4) planning. The basic products of the study are maps and three types of reports: (1) basic data contributions, (2) technical reports derived from the basic data for a technical audience, and (3) interpretive reports which represent final derivations for a nontechnical audience, such as elected officials.[1137] The investigations and products for the geologic and geophysical elements (active faults, slope stability and engineering behavior of bedrock areas, physical properties of unconsolidated deposits, seismicity and ground motions) are presented in Appendix G.

Cooperative funding for the San Francisco Bay study was continued through 1975 by the two federal agencies. The U.S. Geological Survey ended the study as a separate, formal project on June 30, 1976. By early 1977, more than 100 maps and reports covering a wide range of topics had been published, and many of the methods devised and tested in this study have been adapted and used elsewhere.[1136]

2. Seismic Zonation — San Francisco Bay Region

The geologic environment influences the severity of a seismic event by determining "(1) the potential location and size of damaging earthquakes, (2) the potential for rupture of the ground surface by faulting, both slow creep and sudden movement, (3) the potential for damaging levels of ground shaking on different geologic units at various distances from the source of the earthquake, (4) the potential for flooding from dam failures, tsunamis, seiches, and tectonic changes of land level, and (5) the potential for shaking-induced ground failures such as landslides and those related to liquefaction."[1138] A recent U.S. Geological Survey study demonstrates that it is feasible to assess the above potential earthquake effects for the purposes of *seismic zonation** for a portion of the San Francisco Bay region using *existing* geologic and geophysical knowledge. Seismic zonation represents the necessary base from which land use plans can be developed to minimize future earthquake losses.[1138]

In the USGS study,[1138] methodologies are described for constructing the basic tools needed for seismic zonation in the San Francisco region: (1) an active fault map,[45] (2) data for estimating bedrock motion at the surface,[513] (3) differentiation of sedimentary deposits and a map showing qualitative estimates of ground motion,[535,1139] (4) a map showing areas of potential inundation by tsunamis,[1140] (5) a map showing liquefaction potential,[1141] and (6) a map showing landslide susceptibility.[552]

Borcherdt et al.[630] then developed a methodology for the "composite application" of the basic tools described in the above paragraph to predict the geologic effects of potential earthquakes. To illustrate the strategy, a demonstration profile was selected perpendicular to the San Andreas fault from Sky Londa to the southern tip of the Coyote Hills, along which a $M_L = 6.5$ earthquake was postulated (Figure 2).

The demonstration profile includes five geologic units on the basis of physical properties.[630]

1. Bay mud; most recently deposited soft clay, silt, and minor sand; contains more than 50 weight percent water;
2. Holocene alluvium; poorly consolidated clayey silt, sand, and gravel; contains less than 40 weight percent water;
3. Late Pleistocene alluvium; primarily same material composition as Holocene alluvium, but contains less water and is more consolidated; in some places overconsolidated (soil-engineering sense);
4. Pliocene and early Pleistocene deposits; primarily continental Santa Clara and marine Merced Formations consisting of semiconsolidated and consolidated sandstone, siltstone, and mudstone; and
5. Pre-Tertiary and Tertiary bedrock; includes Franciscan Formation, consisting mostly of sandstone and shales with lesser amounts of radiolarian chert, greenstone, limestone, and serpentine; marine sandstone and shale of Eocene, Miocene, and Pliocene age; and Page Mill Basalt, consisting of lava flows and pyroclastic rocks of Miocene age.

The stratigraphic relations of the five units are illustrated in Figure 3.

The effects of the postulated earthquake (surface faulting, ground shaking, flooding, liquefaction, and landsliding) are dependent upon the distribution of the geologic units with respect to the San Andreas fault. Generalized predictions for each geologic effect along the profile are described below and shown in Figure 3.[630]

Surface Faulting

On the basis of past observation, the postulated magnitude 6.5 earthquake probably would be associated

* Delineation of geographic areas with varied potentials "for surface faulting, ground shaking, liquefaction, and landsliding during future earthquakes of specific size and location."[1138]

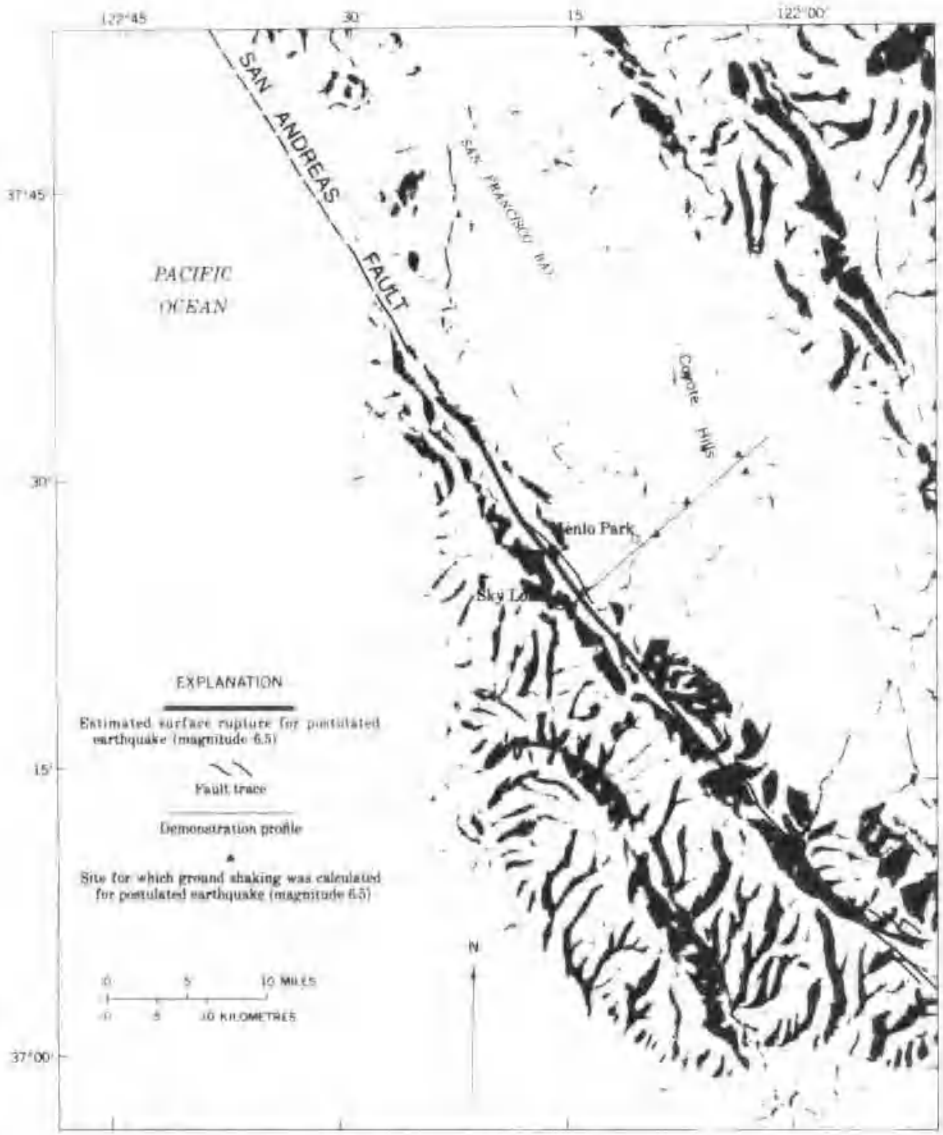

FIGURE 2 Location of demonstration profile and estimated length of rupture associated with a postulated earthquake of local magnitude (M_L) 6.5 on the San Andreas fault, southwestern San Francisco Bay region. (From Borcherdt, R. D., Brabb, E. E., Joyner, W. B., Helley, E. J., Lajoie, K. R., Page, R. A., Wesson, R. L., and Youd, T. L., Studies for Seismic Zonation of the San Francisco Bay Region, Borcherdt, R. D., Ed., U.S. Geological Survey Professional Paper 941-A, U.S. Government Printing Office, Washington, D.C., 1975, 89.)

with right-lateral displacement along the San Andreas fault that may be as great as 1 m . . . The length of estimated surface rupture is 40 km . . . plus or minus about 10 km . . . The main zone of surface rupture will range in width from a few metres . . . to several tens of metres . . ., but small fractures and permanent ground distortion may extend to much greater distances. Locally, branch and subsidiary faults, such as the Black Mountain fault, the Cupertino fault, and the Cañada fault, may also move, but movements on such lesser faults are much more difficult to predict. If sympathetic surface movements do occur along these lesser faults, they are expected to be less than on the main fault rupture.

Ground Shaking

In general, strong shaking (50-125 cm/s) . . . could be expected from the postulated earthquake for all

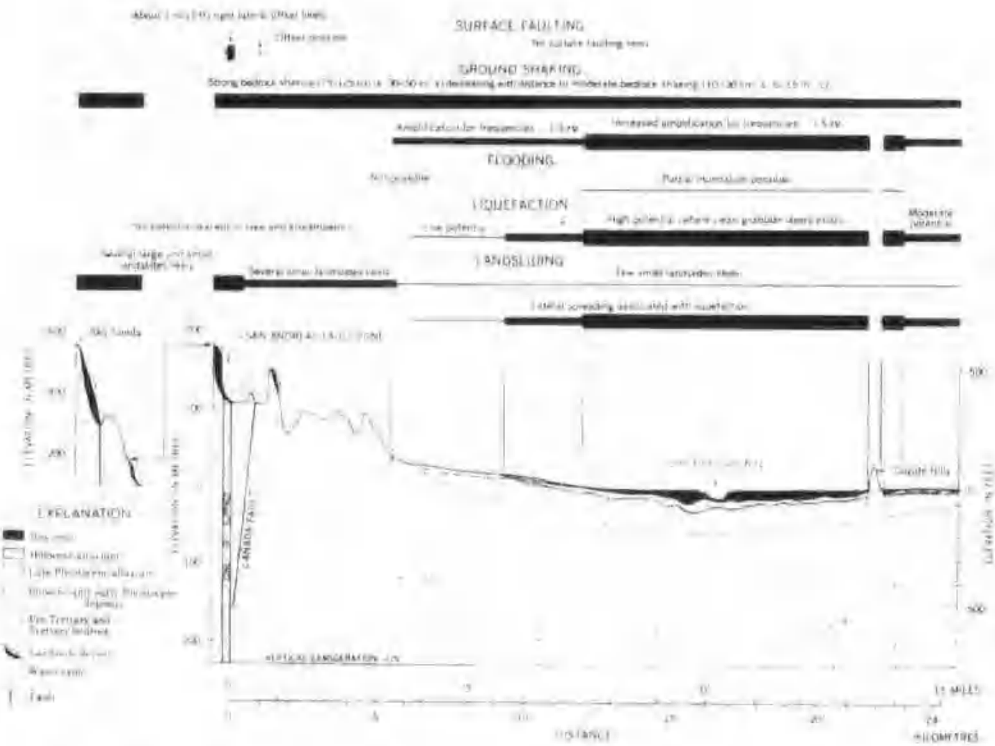

FIGURE 3. Predicted geologic effects of a postulated earthquake (M_L = 6.5) on the San Andreas fault (see Figure 2 for location of demonstration profile and estimated length of surface rupture). The severity of each earthquake effect is indicated qualitatively by thickness of underlining and quantified to the extent permitted by the current state-of-the-art for seismic zonation on a regional scale. The severity of the predicted earthquake effects generally depend on the type of underlying geologic material. Geologic cross section compiled by K. R. Lajoie. (From Borcherdt, R. D., Brabb, E. E., Joyner, W. B., Helley, E. J., Lajoie, K. R., Page, R. A., Wesson, R. L., and Youd, T. L., Studies for Seismic Zonation of the San Francisco Bay Region, Borcherdt, R. D., Ed., U.S. Geological Survey Professional Paper 941-A, U.S. Government Printing Office, Washington, D.C., 1975, 91.)

surface bedrock sites along the profile west of the bay plain . . . The model calculations suggest that a substantial amplification of bedrock shaking in the frequency range below 1.5 hertz could be expected for all parts of the demonstration profile underlain by alluvial deposits, with increased amplifications for the parts underlain by bay mud. The predicted amplifications are large enough to suggest that ground shaking for frequencies below 1.5 hertz may be stronger at the sites underlain by bay mud and alluvium than at sites underlain by bedrock much closer to the fault. Manmade structures with natural periods coinciding with those of the underlying unconsolidated geologic deposits are particularly susceptible to damage.

Flooding

. . . For the postulated earthquake, the most probable cause of inundation by water is the failure of dams or dikes. Flood water from such failures could originate from either San Francisco Bay or upland reservoirs.

For the postulated earthquake, the likelihood of a large vertical offset of the sea floor or large submarine landslide necessary to generate a tsunami seems remote . . .

The postulated earthquake . . . probably is not large enough to generate a seiche in San Francisco Bay. However, seiches could be generated in the Upper and Lower Crystal Springs Reservoirs.

The tectonic setting of the San Francisco Bay region suggests that large tectonic changes of land level (such as occurred during the 1964 Alaska earthquake) are very unlikely to accompany the postulated earthquake. Only minor local changes in vertical elevation of about 0.3 m . . . were produced by the 1906 (San Francisco) earthquake.

Liquefaction

. . . Sediments with the greatest potential for liquefaction are the clay-free granular layers within the bay