Loma Prieta Earthquake
October 17, 1989

PRELIMINARY
RECONNAISSANCE REPORT

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PREFACE

The Earthquake Engineering Research Institute (EERI), with support from the National Research Council (NRC) of the National Academy of Sciences, dispatched teams of scientists and engineers to investigate the effects of the manitude 7.1 Loma Prieta Earthquake of October 17, 1989, shortly after the event. With additional support from the National Science Foundation, team members are studying the effects of the earthquake throughout the Bay Area in an effort to identify lessons that can be learned.

Field studies conducted immediately following major earthquakes help identify areas that need more study and offer an opportunity to recommend measures that can be taken to reduce damage in future earthquakes.

This preliminary report summarizes information gathered by team members during early stages of the investigation and has been prepared in response to widespread interest in the earthquake. Field investigations and cooperative studies with other organization are still in progress. Thus, more definitive conclusions regarding the effects of the earthquake will be developed in the weeks ahead. The final Earthquake Reconnaissance Report will be published in February of 1990.

Recognizing that many Bay Area members would have pressing community and client obligations immediately after the earthquake, EERI staff followed the organization's Response Plan directives and selected subject coordinators from outside the affected area in most instances. The group coordinators are being assisted by local information coordinators in each of the following subjects: geosciences, geotechnical engineering, highway structures, buildings, lifelines, industrial facilities, architecture, urban planning, and social science and emergency response.

The contributions of the coordinators and their teams are acknowledged with gratitude.

EERI is a national, nonprofit, technical society of engineers, geoscientists, architects, planners, and social scientists. Since its inception in 1949, it has conducted more than 200 postearthquake investigations to improve the science and practice of earthquake engineering and the reduction of future earthquake losses by documenting the full range of impacts in a scientific and systematic way. These investigations are conducted on a volunteer basis in cooperation with the university community and governmental agencies.

The NRC and EERI have been working together in postearthquake disaster investigations since 1977.

It must be emphasized that this is a preliminary report that has not undergone the official review process of the National Academy of Sciences. Any opinion, finding, conclusion, or recommendation expressed in this report is that of the authors and does not reflect the views of the National Research Council, the Earthquake Engineering Research Institute, the National Science Foundation, or the organizations of the authors.

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Finally, the contributions of those who reviewed a preliminary version of this report—Lee Benuska, Roger Borcherdt, and Susan Tubbesing—are greatfully acknowledged.

1 SOCIAL SCIENCE AND EMERGENCY RESPONSE

OVERVIEW

The Loma Prieta earthquake of October 17, 1989, had a significant regional impact and will provide some insight into the effects of a great earthquake in an urban setting. Unlike other very damaging California earthquakes, such as the San Fernando, Coalinga, and Whittier events, this earthquake distributed damage widely throughout many counties. For example, light damage was reported as far north as the Sonoma County area and in downtown Sacramento. It is from this perspective that the following preliminary observations are offered.

As of October 27, 1989, the California Governor's Office of Emergency Services reported that ten counties and three cities in other counties had declared local emergencies. The governor proclaimed a State of Emergency on October 17, and the President declared the earthquake as a major disaster on October 18. Total fatalities numbered 67, injuries amounted to 2,435, and total estimated damage was $5.6 billion. As of October 30, some 76,000 requests had been received for various forms of disaster assistance. This earthquake is the most expensive in United States history.

Local emergency response resources generally were adequate, but in several cases were stretched to the limit of their capacity. Some mutual aid was activated, and the state and federal governments supplemented local resources in specific instances. For the first time, the state's plan for mobilizing engineers to inspect buildings was formally implemented. Emergency communications and the gathering and disseminating of disaster intelligence generally were a problem, as they have been historically, especially between levels of government. There were no significant losses to emergency response resources. It appears also that recent planning and preparedness efforts contributed to the effective response efforts. Except at Oakland's collapsed Cypress overpass, immediate lifesaving activities were over in a few hours.

The number of people made homeless by the earthquake exceeded 10,000. Responding to this need is especially difficult in the smaller rural communities, such as Watsonville and larger cities such as Oakland that suffered damage to several old, high-occupancy residential hotels. The ability of victims to deal with this problem seems directly related to their physical mobility and economic capabilities. Some dislocated upper-income Marina District residents relocated to places such as Marin County using their own resources while many dislocated lower-income people remain in emergency shelters and are looking to government for housing assistance.

Damage to small businesses located in older downtown-area buildings appears to be overwhelming, just as after other recent earthquakes, such as Coalinga and Whittier (see Figure 1.1). Occurring just before the Thanksgiving-Christmas holiday period,

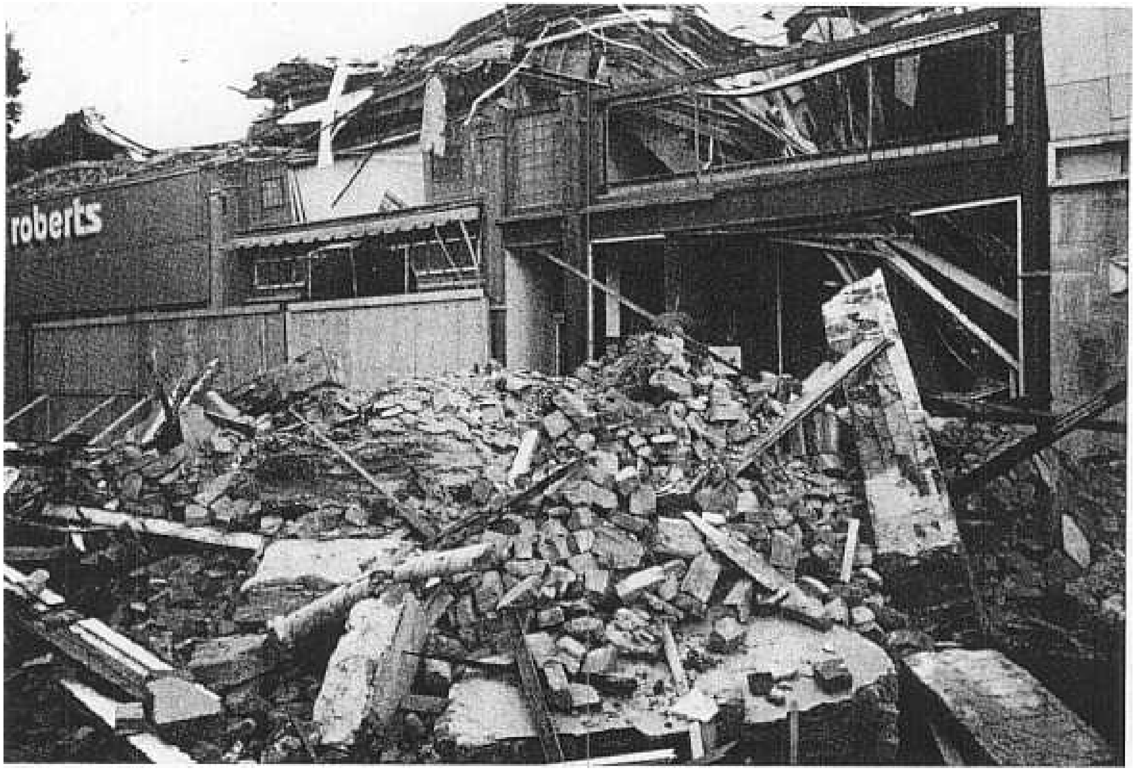


Figure 1.1 The Pacific Garden Mall in Santa Cruz. Many merchants in older downtown areas throughout the affected region may have difficulty recovering because the earthquake took place so close to the important holiday shopping period.

this earthquake may deal a fatal blow to many such businesses. Business owners have coped in various ways: owners who were planning to retire did, inventories were moved to owners' homes or to storage facilities, many incoming shipments were simply rendered "undeliverable," clerks and sales staff have been laid off, some businesses relocated to vacant space in other parts of the community, and many simply did not know what to do, even several weeks after the earthquake—there is widespread concern about cash flow and the owners' own survival. Demolition processes in some areas were moving so quickly that not all affected businesses were able to remove their stock and furnishings. The ability of small businesses to recover will be major problem.

From a media perspective, there were two epicenters: the geologic one and the one between San Francisco's Marina District and Oakland's Cypress Avenue overpass. Because of the World Series, there was a high concentration of media representatives in the Bay Area, which is also a headquarters for the major networks. Their communications generally remained intact, and in the early hours media attention focused on visible and readily available targets. These included Candlestick Park, the Marina fire, and the overpass collapse in Oakland. Largely because of damaged communications, loss of power, access, and small media staffs, little was heard from the worst hit communities in the epicentral area: Santa Cruz, Watsonville, Hollister, Los Gatos, and others. Only after several hours had passed was concern voiced about areas that had not been heard from. The concentrated coverage in the north contributed to misunderstandings about the full effect of the earthquake.

Widespread damage to the region's highways and bridges is having a major impact on commuters and the movement of goods. The biggest problems are the closure of the Bay Bridge, loss of I-880 in Oakland, closure of the Embarcadero freeway and connectors in the San Francisco area, slides and damage to Highway 17 between San Jose and Santa Cruz, and damage to Highway 1 in the Watsonville area. Although traffic levels were lower than normal in the first week or so after the earthquake, they are now returning to normal. This is resulting in major congestion, but commuters are using alternative means of transportation. The Bay Area Rapid Transit District (BART) is carrying tens of thousands more passengers per day and temporary ferry service has been initiated between several East Bay points and San Francisco.

After allocating about $222 million from the state's reserve to meet emergency needs, a special session of the California legislature approved a temporary ¼-cent increase in the sales tax for 13 months, effective December 1, 1989, to provide quickly needed money to help finance early recovery. This is expected to raise about $800 million, most of which appears destined for repairing or replacing state and local government public facilities. Approximately 100 other earthquake-related bills have been introduced as well. It seems clear that when the legislature reconvenes in January, issues related to longer term recovery and financing will be high on the agenda.

FIRES FOLLOWING THE EARTHQUAKE

San Francisco

San Francisco had 27 structural fires and more than 500 reported incidents of fire during the seven hours from the time the earthquake struck until midnight. During this period, some 300 off-duty fire fighters responded to a general recall, approximately doubling the available fire-fighting personnel. Major incidents included:

- Two reported fires and a large fuel spill at the San Francisco airport, resulted in the dispatch of three engines, two trucks, and a battalion chief to the airport from Battalion 10, thus reducing this battalion's strength.
- A structural fire on Bixby Street resulted in the loss of two homes.
- A structural fire at a lumberyard, was reported and was caused by breaks in piping connected to a propane-fueled emergency generator. When the generator was activated, the discharging propane, and consequently the building, ignited. Two engines, one truck, and a battalion chief responded to the fire.
- Structural fires at Divisadero and Jefferson, Cole Street, Larkin and Fulton, and Gough and Sacramento were reported.

These fires were generally reported via telephone and street fire-alarm boxes. Of the 27 fires, three normally would have been second alarms, requiring six engines and two trucks each.

The most serious incident occurred at the intersection of Divisadero and Jefferson streets, in the Marina District. The Marina District is a densely built area of 1920s-vintage, wood-frame, single-family homes and two- and five-story apartment buildings over garages.

Engine 41 had been dispatched to Cervantes and Fillmore to investigate a collapsed building. From that location fire fighters saw smoke and a burning building in the distance. The burning building, a three-story apartment structure typical of the area, was at the northwest corner of Divisadero and Jefferson streets. The fire in this building threatened adjacent structures on the block, as well as collapsed and partially collapsed buildings across Divisadero and Jefferson streets.

Engine 41 responded to the fire and connected to an Auxiliary Water Supply System (AWSS) hydrant in front of the burning building, which had already partially collapsed. Shortly afterward, an explosion occurred inside the building, which collapsed onto the hydrant. In order to save the engine, the fire fighters drove it away immediately, ripping its hose off the hydrant coupling. Engine 41 was then stationed across the street and was assisted by Engine 16 and Trucks 16 and 9.

About this time, water supply problems occurred due to breaks in the Municipal Water Supply System as well as in the high pressure AWSS. Water was then drafted from the Palace of Fine Arts lagoon, about four blocks away, and relayed to the site. Several more explosions occurred and the exposed buildings collapsed onto the fire fighters' hose, causing Engine 41 to run out of hose.

At approximately 6:00 P.M., the fireboat *Phoenix* arrived in the Marina lagoon (two blocks away) and the department's Portable Water Supply System's (PWSS) Hose Tender 25 arrived on the scene with 5,000 feet of five-inch large-diameter hose. The fireboat was able to supply Hose Tender 25, as well as Hose Tender 8, which arrived at about 6:40 P.M. At this time, flames were approximately 75 ft high and visible from several miles away. The entire neighborhood was threatened with conflagration. Via the PWSS, the *Phoenix* then supplied Engine 41, hoses being used on aerial ladders from Truck 2 on Jefferson Street and Truck 10 on Beach Street, and monitors on both sides of the burning building. With this ample water supply, the fire was brought under control at about 8:00 P.M.

Beyond San Francisco

- Berkeley had one major fire, in a one-story auto service building. The fire was probably due to ignition of solvents, and required the response of the entire Berkeley fire department. A wood, three-story building to the west was badly scorched, but otherwise no spreading occurred.
- Oakland did not experience any structural fires in the immediate aftermath of the earthquake.
- Santa Cruz County reported about two dozen buildings destroyed by fire. In the city of Santa Cruz, one structural fire—a single family residence—occurred at 138 Myrtle Avenue, destroying the entire building.
- The Felton fire department building experienced partial collapse. However, fire fighters continued to occupy the structure and provide emergency response.

2 GEOSCIENCES

The major earthquake, which occurred on October 17, 1989 at 5:04 P.M. Pacific Daylight Time (October 18, 1989 00 0415 UTC), was located in the southern Santa Cruz Mountains near the summit of Loma Prieta mountain. The epicenter was about 16 km northeast of Santa Cruz and about 30 km south of San Jose (37° 2.19'N; 121° 52.98'W). The earthquake was assigned an average surface-wave magnitude of $M_s = 7.1$ from teleseismic data provided by the National Earthquake Information Center, a moment magnitude of $M_w = 6.9$ using broad band data (H. Kawakatsu, personal communication) and a Richter magnitude of $M_L = 7.0$ from a Wood Anderson seismograph at the University of California, Berkeley. The earthquake caused levels of ground shaking sufficient to induce structural damage and ground failure at distances near 100 km.

The earthquake occurred on a section of the San Andreas fault system previously identified as a segment with a relatively high probability—30 percent within 30 years (Working Group on California Earthquake Probabilities, 1988)—for an event of magnitude 6.5 or larger. This earthquake reruptured the southernmost 45 km of the 1906 fault break. Historically, this segment of the San Andreas also may have been associated with previous damaging earthquakes on October 8, 1865, and April 24, 1890. The 1865 earthquake reportedly also caused damage in San Francisco to weakly constructed buildings on landfill and to water and gas mains in places of shifting ground.

SEISMOLOGIC ASPECTS

The earthquake occurred along a segment of the San Andreas fault monitored by a central California seismic network operated by the U.S. Geological Survey (Figure 2.1) and by a regional network operated by the University of California at Berkeley. The extent of the rupture zone as defined by the aftershocks extends along a 45-km segment of the fault (Figure 2.2). The hypocenter for the main shock occurs near the center and lower portion of the zone at a depth of 18.5 km. In cross section, the aftershock hypocenters define a rupture plane dipping to the southwest at about 70° with respect to the horizontal (Figure 2.2). Most of the more than 2,300 aftershocks located to date are centered on the San Andreas fault; however a cluster of aftershocks triggered by a M_L 5.0 earthquake 33 hours after the main shock are located southwest of the principal plane in the vicinity of the Zayante fault (Figure 2.2). The largest of these aftershocks ($M_L = 5.0$) has a fault-plane solution similar to that of the main shock but a strike of N10°W.

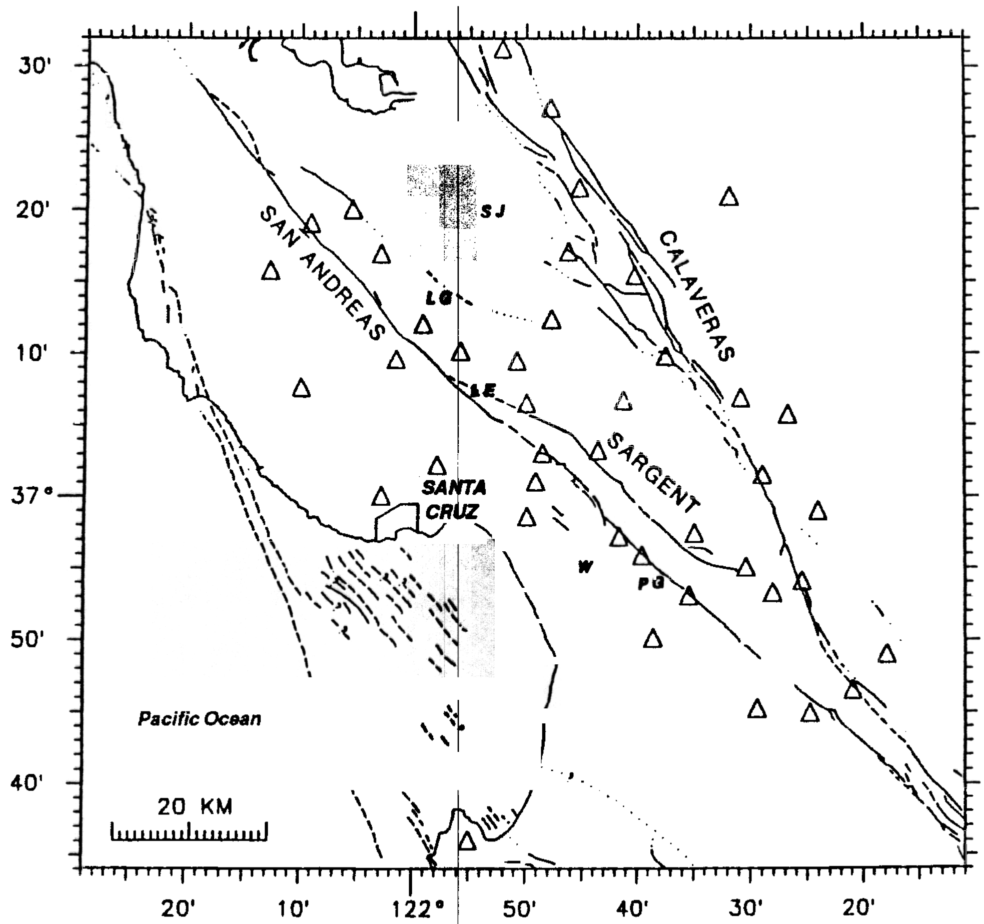


Figure 2.1 Map showing Quaternary faults and seismic stations in the central California network used for earthquake location. Quaternary faults are identified as: SJ (San Jose), LG (Los Gatos), LE (Lake Elsman), W (Watsonville), PG (Pajaro Gap) *(Contributed by D. Eberhart–Phillips, A. Michael, L. Dietz, W. Ellsworth, and colleagues)*

The focal mechanism solution for the main shock (Figure 2.3), derived from first motions recorded on the central California network, indicates right-lateral strike-slip and reverse faulting on a northwest-striking plane. The solution indicates that during the main shock, movement occurred at midcrustal depths of the Pacific plate in a northwestern and upward direction with respect to the North American plate. Parameters for the *P*-wave first-motion solution are strike N130° ±8°E, down-dip direction 220° ±8°E of N, dip 70° ±10° and rake 130° ±15°. Centroid-moment inversions using broad-band teleseismic data yield similar results and a moment estimate of 2.2 $\times 10^{26}$ dyne-cm (H. Kawakatsu, Geological Survey of Japan, personal communication). Seismicity asociated with the main shock and its aftershocks fills a spatial gap along the San Andreas fault as defined by seismicity of the previous 20 years (Figure 2.4). The limited seismicity previously occurring in this segment appears to outline the lower boundary of the current aftershock distribution.

GEOLOGIC ASPECTS

The October 17, 1989, Loma Prieta earthquake (M_s 7.1) was unusual for an earthquake of that magnitude on the San Andreas fault in that deep tectonic slip did not propagate to the surface and form a coherent right-lateral surface trace several kilometers or more in length. The great depth of the earthquake (~18 km) probably contributed to

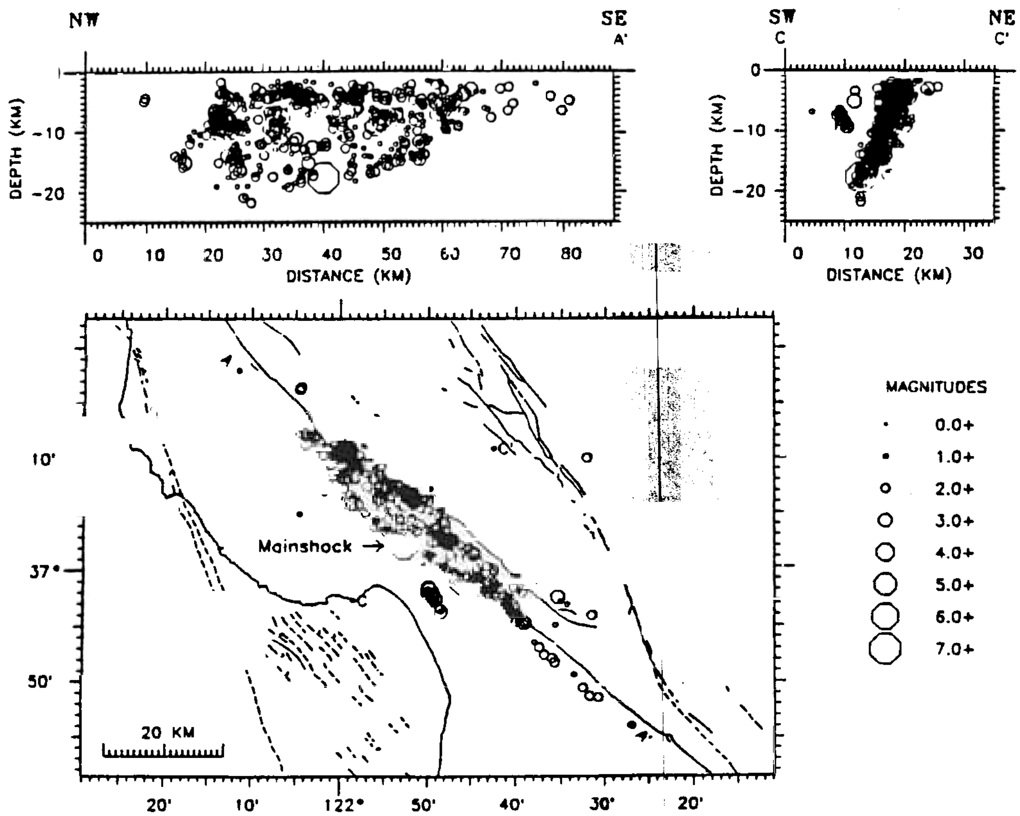
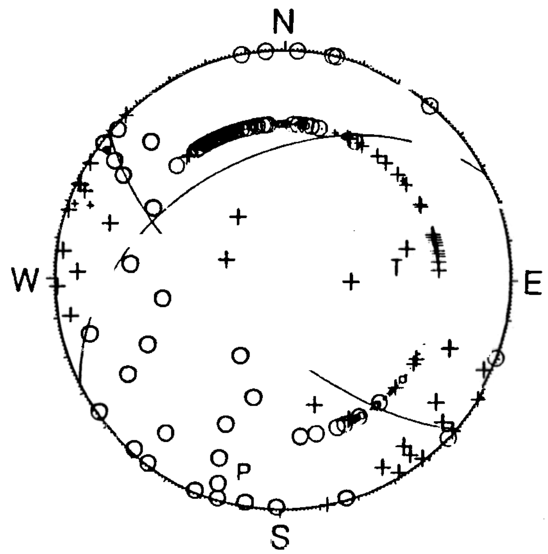


Figure 2.2 Well-located aftershocks in the first three days of the earthquake sequence. *Bottom:* Map view with coastline and Quaternary faults. *Top left:* Longitudinal cross section. *Top right:* Transverse cross section *(Contributed by L. Dietz and colleagues)*

the lack of surface rupture. The earthquake, however, did produce a zone of northwest-trending, extensional fractures with a component of left slip separation along a section of Summit Road approximately 12 km northwest of the epicenter. These fractures commonly follow an existing ridge-crest characterized by northwest-trending linear ridges and intervening swales or depressions. Movement on some of the fractures during the earthquake enhanced the relief of these features suggesting that the features may be the result of paleoseismic events. Previously, Sarna-Wojicicki, Pampeyan, and Hall (1975) interpreted many of these ridges and swales as being fault-bounded. A prominent, discontinuous left-lateral surface break that disrupted Morrell Road in 1906 was reactivated during the Loma Prieta earthquake. Recent activity of this rupture in historic time indicates that paleoseismic investigations might yield useful geologic recurrence information for the Loma Prieta reach of the San Andreas fault.

The Loma Prieta fractures do not have a straightforward and simple tectonic origin as manifested by earlier events on the San Andreas fault in the Carizzo Plain in 1857, in Marin County in 1906, or in the Parkfield area in 1966. The Summit Road fractures occur in an unusual structural and topographic setting where the San Andreas fault crosses beneath a ridge separating the Soquel Creek and Los Gatos Creek drainage basins. The fractures are present along this high divide immediately southwest of a 7° restraining bend in the fault and lie within the upthrown block of this earthquake. Several working hypotheses about the origin of these fractures are: (1) ridgecrest wrenching due to tectonic slip at depth; (2) ridgecrest spreading due to focusing of seismic energy; and (3) ridgecrest cracking associated with arching of the elevated block.



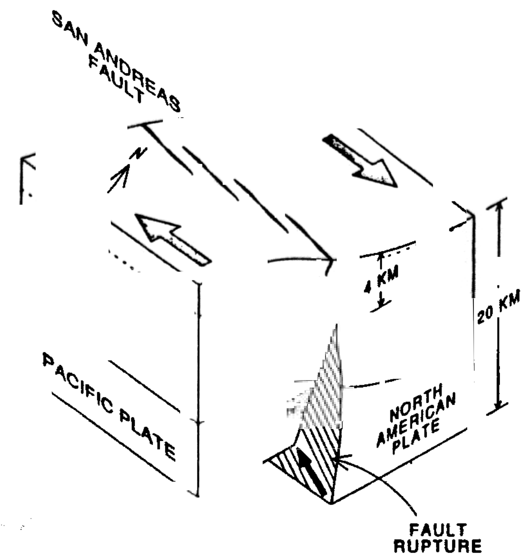


Figure 2.3 *Left:* Lower hemisphere plot of fault-plane solution for the Loma Prieta main shock, based on 267 reports from stations. Circles and pluses indicate dilatational and compressional initial motion, respectively. *Right:* Schematic block model of the inferred slip, showing combinations of vertical and horizontal slip on a buried fault *(Contributed by D. Eberhart-Phillips, A. Michael, M. Rymer, L. Dietz, and colleagues)*

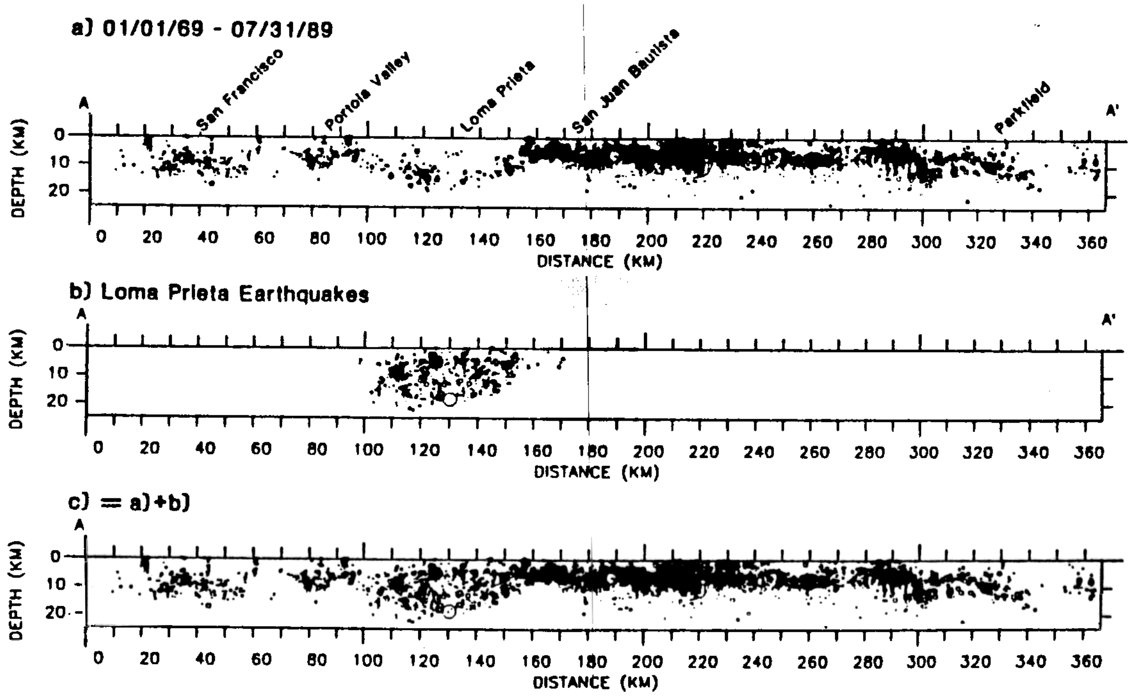


Figure 2.4 Loma Prieta earthquake sequence relative to long-term San Andreas fault seismicity. (a) 360-km-long cross section of seismicity along the fault from the USGS catalog for the preceeding 20 years; (b) Loma Prieta earthquakes; (c) Combination of (a) and (b) shows how the Loma Prieta sequence filled a spatial gap *(Contributed by J. Olsen and colleagues)*

STRONG-MOTION DATA

The earthquake generated an extensive set of strong-motion data. Copies of these data are available from the California Strong-Motion Instrumentation Program and the U.S. Geological Survey. Records were obtained from a total of 131 sites ranging in distance from the fault zone to 175 km. Exceptional features of these data sets include: records

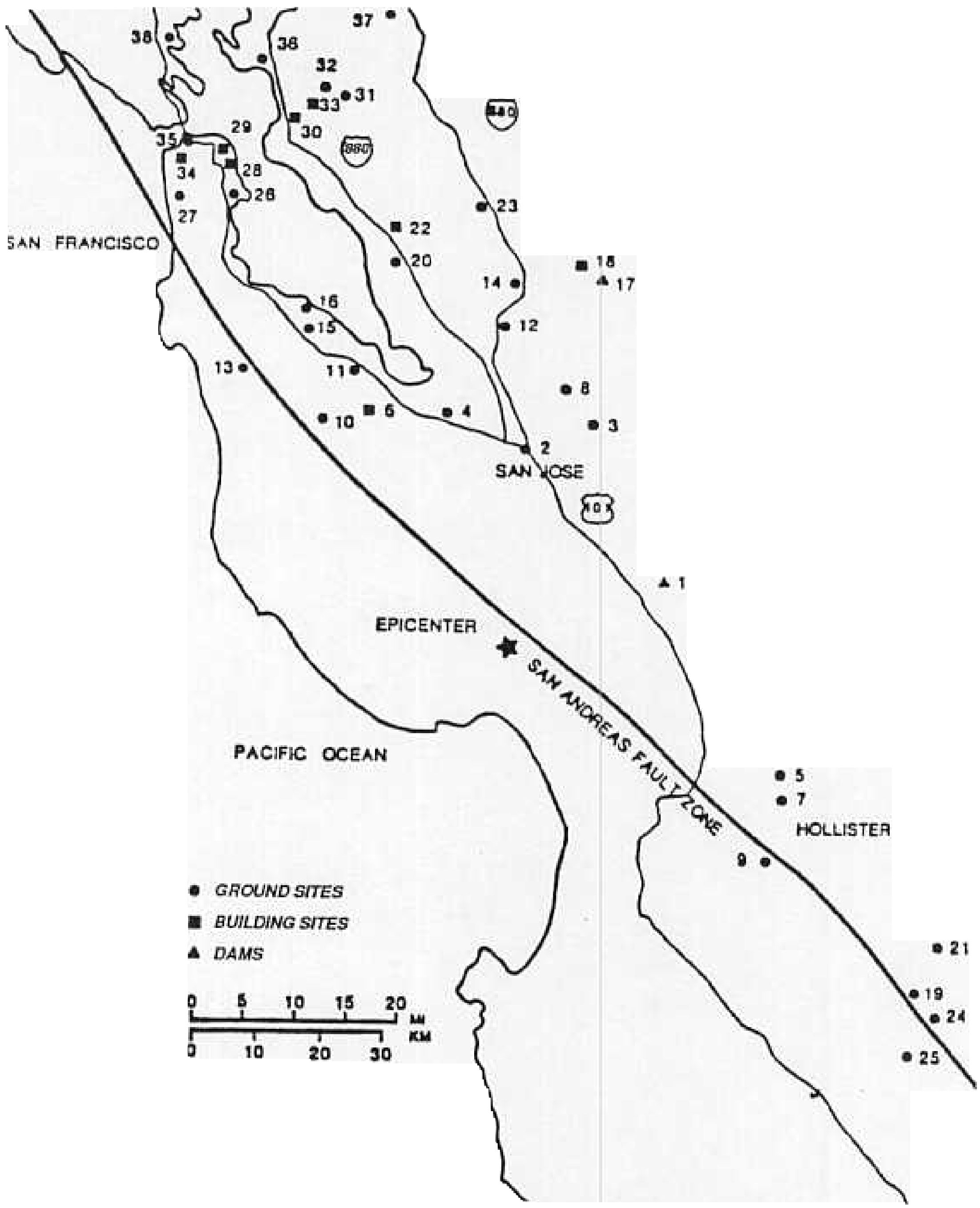


Figure 2.5 Map showing locations of strong-motion stations that were triggered during the main shock. The stations are operated in a cooperative program by the U.S. Geological Survey *(From Maley et al., 1989)*

from well-instrumented structures both of typical and atypical designs, records from well-instrumented dams and freeway overpass structures, records of ground acceleration near the epicenter and in the vicinity of the collapsed I-880 freeway structure, and a unique set of records obtained at sites located on artificial fill and bay mud.

Data Recovered by the U.S. Geological Survey

Records were recovered from 38 stations maintained in a cooperative program by the U.S. Geological Survey (Figure 2.5). Twenty-one of these are ground stations, each

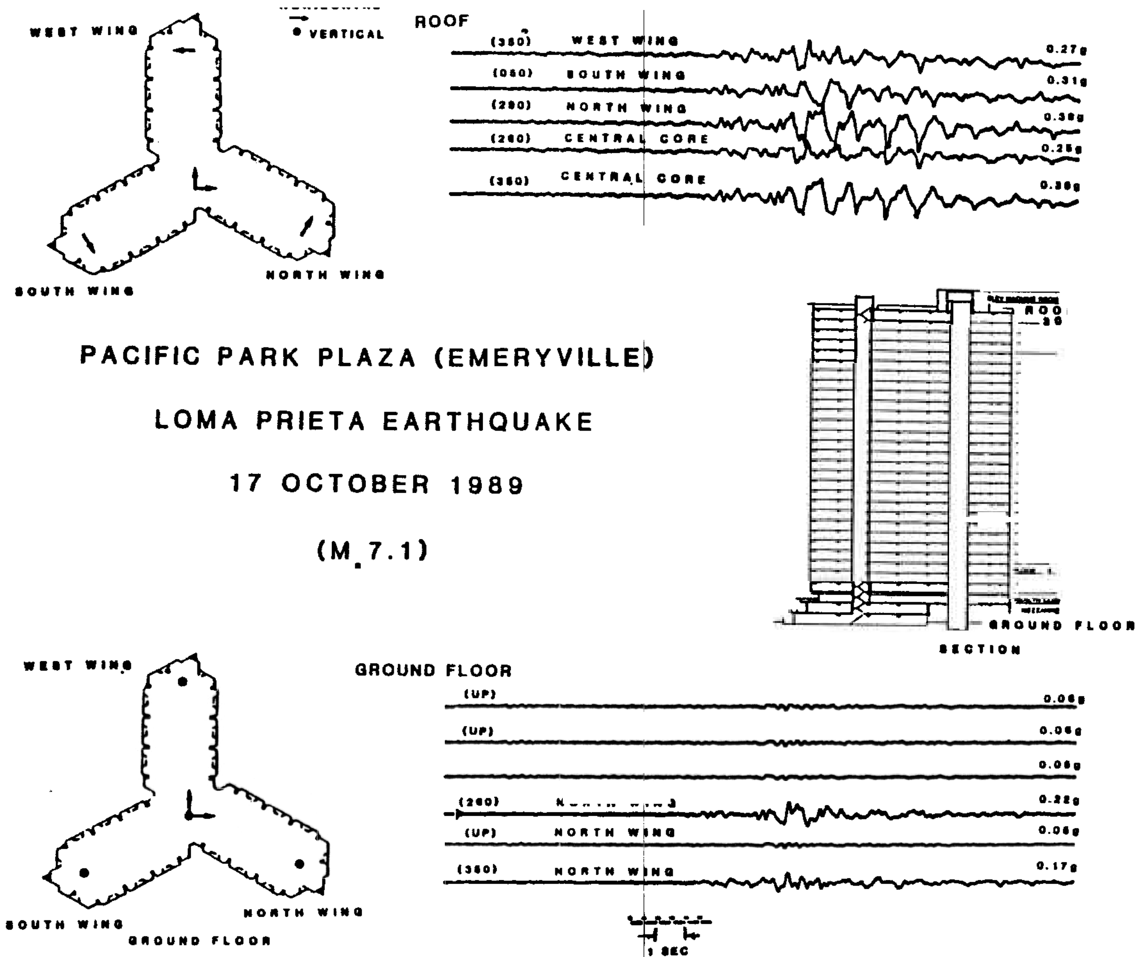


Figure 2.6 Locations of instruments on the ground floor and roof of the Pacific Park Plaza building in Emeryville, California, together with corresponding acceleration time histories recorded during the main shock *(Contributed by M. Çelebi)*

with three-channel accelerographs; the other stations are at 13 buildings (including 5 hospitals), 2 dams, and 2 bridges. Peak horizontal accelerations from USGS and CSMIP are summarized in Table 2.1. A complete tabulation is provided by Maley et al., 1989.

The records obtained from the well-instrumented Anderson dam and the records from five well instrumented structures in the San Francisco Bay area are of special interest. These data are tabulated in Table 2.2. As an example of the data, 11 channels of the 27 recorded in the Pacific Park Plaza building in Emeryville are shown in Figure 2.6. The closest USGS station to the epicenter was Anderson dam at an epicentral distance of 27 km. The peak acceleration values were 26% g on alluvium downstream, 8% g on the rock abutment, and 43% g at the center of the crest.

Six stations recorded the motions in San Francisco and six in the East Bay region. Of particular interest are the records obtained in Emeryville as this site is about 1.8 km from the collapsed I-880 freeway structure. Peak horizontal ground accelerations of 26% g were observed at one of the ground sites at this location. The three recordings obtained on bay mud in Emeryville, Foster City, and at Redwood Shores are also of special interest. These records are discussed in greater detail in the section on engineering seismology in this chapter.

Table 2.1 Station locations, peak values, and epicentral distances; preliminary listing of records obtained by CDMG and USGS (structural maximums shown in parentheses where available)

Station name	Peak Values			Distance
	H1	V	H2	
	g	g	g	km
Corralitos	0.64	0.47	0.50	5
Watsonville, Telephone building (1.24)	0.39	0.66	0.28	11
Capitola	0.54	0.60	0.54	14
Anderson Dam (downstrean) (0.43)	0.25	0.17	0.26	17
Gilroy, Gavilan College	0.37	0.20	0.33	21
Gilroy #1	0.50	0.22	0.43	21
Gilroy Old Firehouse	0.28	0.15	0.25	21
Gilroy #2	0.37	0.31	0.33	22
Santa Cruz	0.47	0.40	0.44	23
Gilroy #3	0.55	0.38	0.37	24
San Juan Bautista, 101 (0.94)	0.15	0.10	0.14	25
Gilroy #4	0.42	0.17	0.32	25
Lexington Dam (0.45)	0.45	0.15	0.41	26
Coyote Lake Dam, downstream	0.19	0.10	0.17	26
Coyote Lake Dam, SW abutment	0.49	0.08	0.15	26
Gilroy #6	0.17	0.10	0.13	28
Gilroy #7, Mantelli Ranch	0.33	0.12	0.23	33
San Jose fwy. (101/280/680 interchange)	0.18	0.08	0.13	34
Saratoga	0.53	0.41	0.34	35
Saratoga W.V. College (0.87)	0.33	0.27	0.26	35
San Jose, G.W. Savings (0.38)	0.11	0.09	0.09	38
San Jose, Town Park Towers (0.37)	0.13	0.09	0.10	38
Halls Valley	0.13	0.06	0.11	38
Salinas	0.12	0.11	0.09	39
San Jose Santa Clara Co. bldg. (0.36)	0.11	0.10	0.09	40
Hollister Warehouse, FF	0.38	0.20	0.18	40
Calaveras Array (cherry flat)	0.09	0.06	0.07	42
Sunnyvale	0.22	0.10	0.19	43
Sago South, tunnel	0.07	0.06	0.07	45
Hollister Airport	0.29	0.16	0.27	45
Monterey, City Hall	0.07	0.03	0.07	46
Agnews - St. Hospital	0.17	0.10	0.16	46
Palo Alto, VA hospital (1.09)	0.34	0.20	0.38	47
Hollister City Hall	0.23	0.22	0.25	47
Calaveras Array (reservoir)	0.13	0.07	0.08	47
Milpitas, 2-story bldg. (0.58)	0.14	0.08	0.10	49
Hollister, SAGO vault	0.06	0.05	0.04	49
Stanford University, SLAC	0.29	0.10	0.19	51
Menlo Park, VA hospital	0.12	0.11	0.27	54
Fremont	0.15	0.07	0.20	56
Palo Alto, 2-story bldg. (0.55)	0.21	0.09	0.20	57
Fremont, Mission San Jose	0.13	0.09	0.11	60
APEEL Array #9, Crystal St.	0.11	0.06	0.12	62
Calaveras Array, Sunol F. S.	0.07	0.03	0.10	63
APEEL Array #2, Redwood City	0.23	0.08	0.28	63

(continued)

Table 2.1 *(continued)*

	Peak Values			Distance
	H1	V	H2	
	g	g	g	km
Woodside	0.08	0.05	0.08	63
Redwood City, Canada campus (0.19)	0.09	0.04	0.05	65
Del Valle Dam (toe)	0.06	0.03	0.04	66
Foster City	0.12	0.09	0.11	66
Livermore , VA hospital (0.15)	0.06	0.03	0.05	67
Foster City, Redwood Shores	0.29	0.11	0.26	70
Upper Crystal Springs Res.	0.16	0.06	0.09	70
Bear Valley #2	0.17	0.10	0.16	70
Upper Crystal Springs	0.10	0.04	0.09	71
APEEL Array #2E Hayward	0.13	0.06	0.16	72
Bear Valley #5	0.07	0.04	0.07	73
Belmont, 2-story office bldg. (0.20)	0.11	0.04	0.10	73
Hayward City Hall, FF	0.09	0.03	0.10	74
Hayward City Hall (bsmt) (0.13)	0.05	0.03	0.06	74
Calaveras Array, Dublin F.S.	0.08	0.03	0.09	75
Hayward CSUH, science bldg. (0.18)	0.05	0.03	0.04	76
Hayward CSUH admin. bldg. (0.24)	0.09	0.05	0.08	76
Lower Crystal Springs Dam (0.10)	0.09	0.03	0.06	77
Hayward Muir School	0.18	0.10	0.14	77
Hayward CSUH, FF	0.08	0.05	0.08	77
Hayward BART, elevated sect. (0.60)	0.15	0.05	0.15	79
Hayward BART, FF	0.16	0.08	0.16	79
Livermore, Fagundes	0.04	0.02	0.04	84
Bear Valley #10	0.10	0.05	0.13	86
S.F. Airport	0.33	0.05	0.24	87
Bear Valley #7	0.04	0.03	0.06	88
Los Banos	0.05	0.01	0.05	88
San Bruno, 6-story office bldg. (0.09)	0.03	0.02	0.12	89
S.F., 1295 Shafter St.	0.11	0.05	0.07	89
So. S.F. Sierra Pt. overpass (0.42)	0.09	0.03	0.05	91
Tracy, sewage plt.	0.06	0.02	0.06	91
So. S.F., 4-story hospital (0.68)	0.15	0.08	0.14	93
S.F.S.U., Thornton Hall	0.14	0.04	0.11	93
S.F., 575 Market (bsmt) (0.23)	0.08	0.06	0.11	96
Oakland, 24-story bldg. (0.38)	0.18	0.04	0.14	97
Emeryville, FF south (0.39)	0.22	0.06	0.26	97
Emeryville, FF north	0.20	0.09	0.22	97
S.F., 600 Montogmery (bsmt) (0.31)	0.12	0.05	0.11	97
Berkeley, U.C. Strawberry	0.04	0.02	0.08	98
Piedmont, 3-story school (0.18)	0.10	0.04	0.07	99
S.F., Diamond Heights	0.12	0.05	0.10	99
Oakland, 2-story Bldg. (0.66)	0.26	0.16	0.21	99
Berkeley, 2168 Shattuck (0.23)	0.09	0.02	0.11	99
Berkeley, U.C. Haviland Hall	0.03	0.02	0.06	99
S.F., Golden Gate Bridge	0.12	0.06	0.24	100
S.F., VA hospital (bsmt) (0.34)	0.08	0.05	0.16	100
Richmond, 2501 Rydin Road	0.08	0.04	0.11	101

(continued)

Table 2.1 *(continued)*

	Peak Values			Distance
	H1	V	H2	
	g	g	g	km
Oakland, Outer Harbor Wharf (0.45)	0.29	0.07	0.27	101
S.F., Rincon Hill	0.09	0.03	0.08	102
Yerba Buena Island	0.06	0.03	0.03	102
S.F., 6-story Bldg. (0.28)	0.09	0.04	0.07	103
Berkeley, 2-story Hospital (0.13)	0.12	0.04	0.11	103
S.F., Telegraph Hill	0.08	0.03	0.06	104
S.F., Pacific Heights	0.06	0.03	0.05	104
S.F., Presidio	0.21	0.06	0.10	105
Treasure Island	0.16	0.02	0.11	105
S.F., Cliff House	0.11	0.06	0.08	107
Martinez, VA hospital	0.07	0.03	0.05	109
Larkspur Ferry Terminal	0.10	0.06	0.14	115

Table 2.2 Summary of recorded strong motion

Epicentral distance	Building	Description	Number of channels	Peak accel., horizontal
96	Pacific Park Plaza 633 Christie Ave. Emeryville	30-story, symmetrical three-winged reinforced concrete (on bay mud)	24 + 3 free-field	FF (0.26g) Ground (0.22g) Roof wing (0.39g)
74	Hayward City Hall	11-story, reinforced concrete framed structure (on consolidated alluvium)	12 + 6 free-field	FF (0.10g) Ground (0.07g) 12th floor g)
99	Great Western Bldg. 2168 Shattuck Ave. Berkeley	Reinforced concrete core, truss structure at roof supports the suspended floors (on stiff soil)	18	Basement (0.11g) 13th floor (0.23g)
97	Transamerica Bldg.	48-story + 204 ft tower steel framed on 9 ft basemat (on stiff soil)	22	Basement (0.12g) 49th floor (0.31g)
96	Chevron Bldg. 575 Market St. San Francisco	41-story, moment-resisting steel framed structure on precast piles	14	Basement (0.11g) 25th floor (0.23g)
27	Anderson Dam	East of Morgan Hill earth/dam with clay core	21	Abutment (0.08g) Downstream (0.26g) Crest (0.42g)

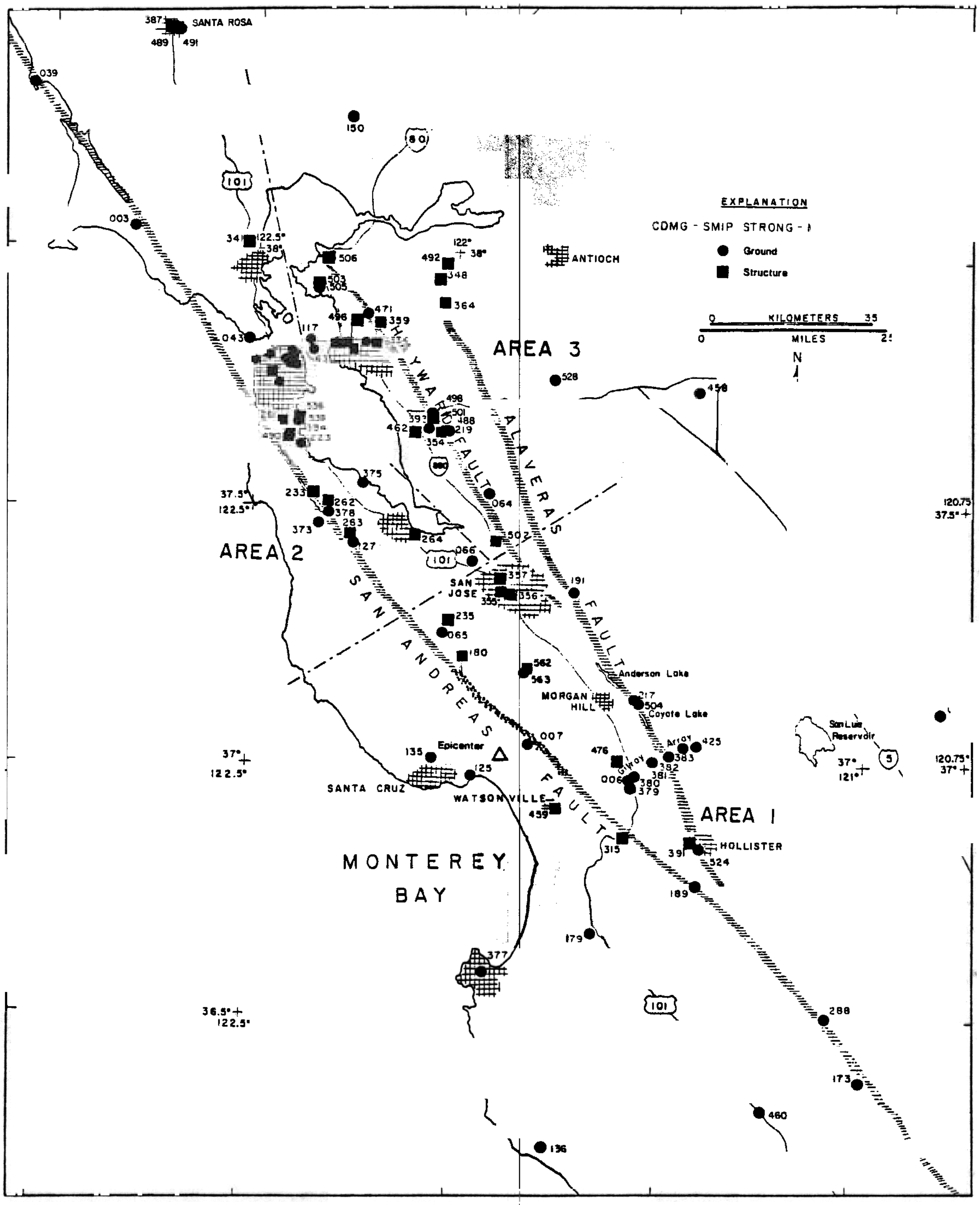


Figure 2.7 Locations of strong-motion stations that were triggered during the main shock. The stations are operated by the California Strong-Motion Instrumentation Program *(Contributed by A. Shakal and staff)*

Data Recovered by the California Strong-Motion Instrumentation Program

Records were recovered from 93 stations of the California Strong-Motion Instrumentation Program (CSMIP). The most distant stations were approximately 175 km from the earthquake (Santa Rosa and Bodega Bay); 25 records were obtained within 40 km of the epicenter (Figure 2.7). A total of 125 records were recovered. A partial summary of the data completed to date is provided in Table 2.1.

The closest CSMIP station to the epicenter is in Corralitos, very close to the San Andreas fault, which recorded 65% g. Three other close-in stations recorded the shaking in the heavily damaged coastal zone from Santa Cruz and Capitola to Watsonville. Peak horizontal accelerations ranged from 40% g at Watsonville to 54% g at Capitola. All four of these stations recorded high vertical accelerations, ranging from 40% g at Santa Cruz to 60% g at Capitola. The recordings also showed long duration, with shaking lasting as much as 10 sec.

Ten CSMIP stations recorded the motion in the city of San Francisco. They recorded peak horizontal accelerations ranging from 9% g at Rincon Hill in eastern San Francisco to 21% g at the Presidio (about 1.5 miles southwest of the heavily damaged Marina District). A station at the airport recorded 33% g. East of San Francisco, stations at Yerba Buena Island and Treasure Island form a rock/soil station pair. These stations, which recorded 6% g and 16% g, respectively, also indicate the level of ground shaking that occurred at the west end of the damaged (eastern) half of the Bay Bridge. Observations of liquefaction on Treasure Island, not far from the instrument site, also make these data important for study.

In Oakland, two stations recorded the motion at locations approximately 2 km (1.5 mi) east and west of the collapsed section of the I-880 freeway. The two stations, an office building in the Lake Merritt district and the Oakland wharf, recorded peak accelerations at base sensors of 26% g and 29% g, respectively, suggesting a similar level of shaking at the freeway. The geologic conditions at the three sites are similar except very near the surface. The wharf record is also important because the wharf is the closest station to the east end of the damaged Bay Bridge (approximately 1 km or 0.6 mi), and the 29% g recorded there should approximate the level of shaking at the bridge.

Records were obtained at a total of 40 extensively-instrumented structures. Important stations include the Sierra Point Overpass on Highway 101 near Candlestick Park. The bridge deck was seismically isolated by Caltrans as part of an upgrade. The motion at the base of the columns was 9% g; at the top of the columns, the peak motion below the isolators was 42% g; the peak motion on the bridge deck, above the isolators, was 32% g, with a reduction in high-frequency components. Other important structures include a 47-story building in the San Francisco financial district, an earth dam in the epicentral area, an overpass at San Juan Bautista, and a strongly shaken 4-story building in Watsonville (1.24 g at the roof).

CSMIP data reduction is still underway. Two early reports are available in the interim. The results given here and in the table are preliminary and subject to revision.

ENGINEERING SEISMOLOGY ASPECTS

Main-Shock Data

The strong-motion records recovered from the Loma Prieta earthquake provide an important data base to investigate the event and its effects. Although a thorough analysis of the records must await digitization of the records, some preliminary conclusions are instructive, especially in the context of possible future studies.

Considering the relatively large distances at whichfor the event, a significant question concerns attenuation of the ground motions with distance. Reported peak accelerations at a selected set of ground sites are shown plotted together with a standard attenuation curve for an event of moment magnitude 6.9 in Figure 2.8. The mean residual for the rock sites is higher than that predicted by the standard curve but not high enough to be considered statistically significant. The statistical model of Joyner and Boore (1988) predicts that the mean residual for 16 out of 100 earthquakes

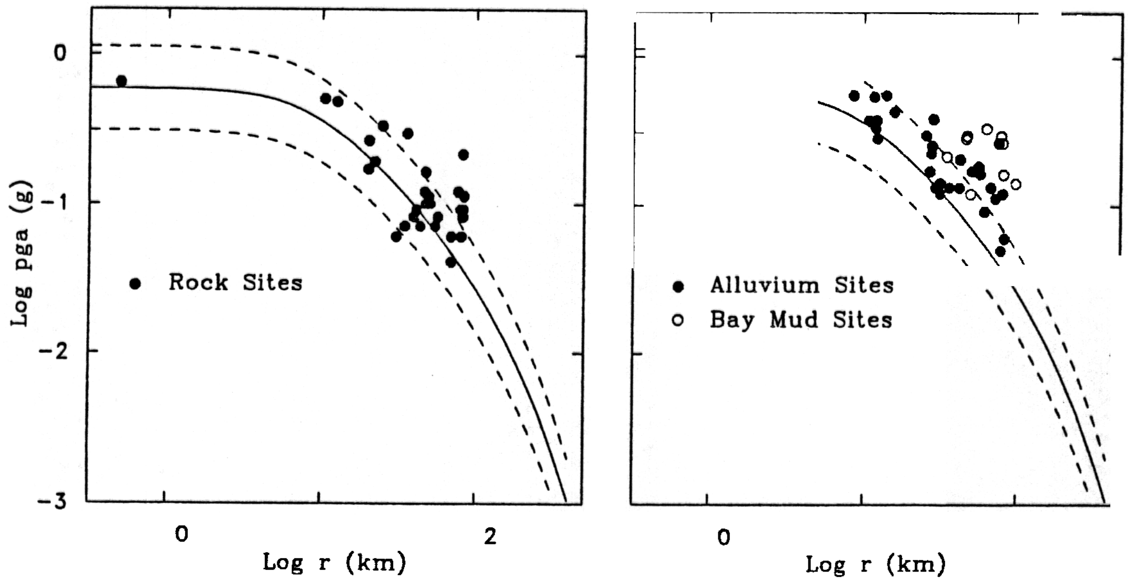


Figure 2.8 Peak accelerations as a function of distance. The peak values are those from the larger of the two horizontal components. Data have been excluded from buildings three stories or greater in height, from dams, and from the bases of freeway overpass support columns. This is in accord with the selection criteria used by Joyner and Boore (1988) to minimize the effects of the enclosing structure. A moment magnitude of 6.9 was used in the equations, and the distance to each recording site was measured from the closest point of the surface projection of the rupture surface, as estimated by the distribution of aftershocks. The recording sites have been classified according to the geologic materials underlying each site. The soil category has been subdivided into alluvium and bay mud. *(Contributed by D. Boore and W. Joyner)*

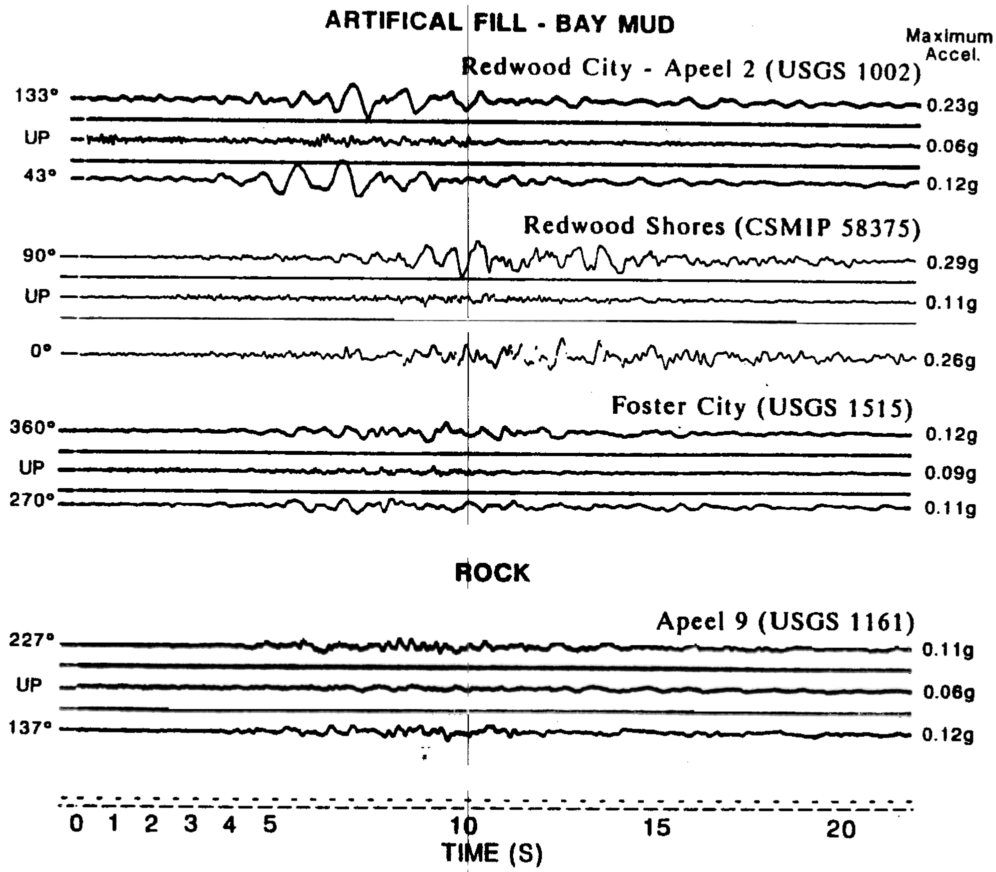


Figure 2.9 Strong-motion records of the main shock from ground sites classified as artificial fill–bay mud and a rock site *(Reproduced from Maley et al., 1989, and A. Shakal et al., 1989)*

would exceed the mean residual observed for this earthquake. The mean residual for alluvium is slightly higher than that for rock. The mean residual for bay mud is considered significantly higher.

The strong-motion recordings obtained on deposits of bay mud are valuable, in that the only previous significant record obtained on these deposits in the region was that obtained at the site of the Southern Pacific building during the earthquake of March 22, 1957 (M_L = 5.3). Strong-motion records obtained at sites underlain by artificial fill and on bay mud in Redwood City, Foster City, San Francisco International Airport, and Emeryville are shown in Figures 2.9 and 2.10. In general, the recordings of horizontal ground acceleration when compared with those obtained at comparable distances on rock show evidence of increased levels and duration of shaking especially for longer periods of shaking near 1 Hz. The recorded vertical accelerations, in general, show less modification.

Maximum vertical and horizontal accelerations for a selected set of sites on artificial fill, bay mud, alluvium and rock are given in Table 2.3. Corresponding ratios of peak acceleration were computed (Table 2.3) using the mean values computed from rock sites at roughly comparable distances. In general, the largest ratios, ranging up to 3.7 are apparent for horizontal accelerations recorded on sites underlain by artificial fill and bay mud. The mean ratios computed for vertical and horizontal accelerations are, respectively, 1.8 and 2.6 for sites on artificial fill and bay mud and 1.9 and 1.8 for sites on alluvium.

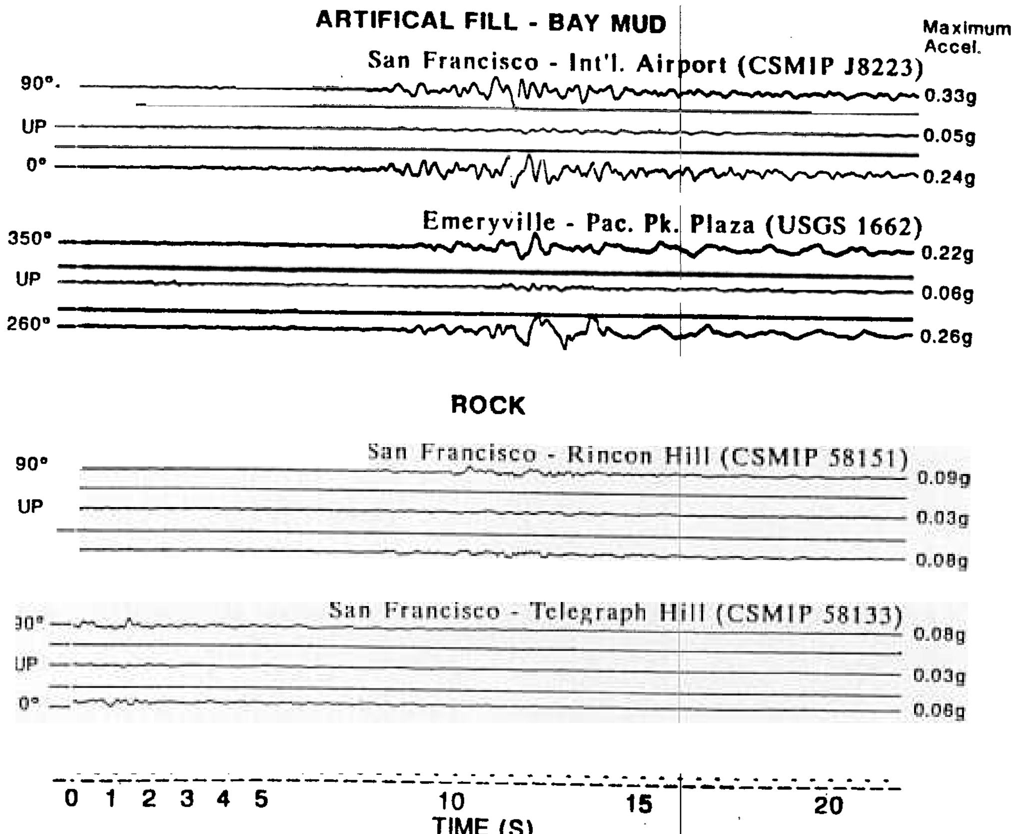


Figure 2.10 Strong-motion records of the main shock from ground sites classified as artifical fill–bay mud and two rock sites *(Reproduced from Maley et al., 1989, and A. Shakal et al., 1989)*

Table 2.3 Maximum and normalized accelerations for selected sites on artificial fill and bay mud, alluvium, and rock in the San Francisco Bay region (Z, vertical; H, horizontal)

Station		Distance	Max.	Accel. (g)	Ratio	
Name	Number	(km)	Z (g)	H (g)	Z	H
Artificial fill; Bay mud						
Redwood City	1002	64	0.06	0.23	1.2	2.3
Foster City	1515	67	0.09	0.12	1.8	1.2
Foster City	58375	70	0.11	0.29	2.2	2.9
Mean			0.09	0.21		
SF Int'l Airport	58223	78	0.05	0.33	1.7	3.7
Emeryville	1162	98	0.06	0.26	2.0	2.9
Mean			0.07	0.25	1.8	2.6
Alluvium						
Sunnyvale	1695	43	0.10	0.22		
Agnews	57066	46	0.10	0.17		
Milpitas	57052	49	0.08	0.14		
Mean						
Fremont	57064	60	0.09	0.13	1.8	1.3
Hayward	58393	77	0.10	0.18	2.0	2.3
Mean						
SF Presidio	58222	105	0.06	0.21	2.0	2.3
					1.9	1.8
Rock						
Apeel 9	1161	63	0.06	0.12	1.2	1.2
Woodside	58127	63	0.04	0.08	0.8	0.8
Mean			0.05	0.10		
Berkeley S.C.	1005	98	0.02	0.08	0.7	0.9
Berkeley M.S.	1006	99	0.02	0.06	0.7	0.7
SF Dia. Heights	58130	99	0.05	0.12	1.7	1.3
SF Rincon Hill	58151	102	0.03	0.09	1.0	1.0
SF Pac. Heights	58131	104	0.03	0.06	1.0	0.7
SF Tele. Hill	58133	104	0.03	0.08	1.0	0.9
SF Cliff House	58132	107	0.06	0.11	2.0	1.2
Mean			0.03	0.09	1.1	1.0

Aftershock Data

Aftershock investigations using portable digital instrumentation are being conducted by a number of institutions, including the U.S. Geological Survey, the Incorporated Research Institutions for Seismology (IRIS), and the Universities of California at Berkeley and Santa Cruz. More than 65 portable digital recorders have been deployed in the epicentral region and in the San Francisco Bay region. As a large number of sites have been occupied for varying lengths of time, a compilation was not feasible as of this writing. However, special studies of note conducted to date include ground response studies in the damaged area of Santa Cruz (K. King, E. Cranswick, USGS, Golden, Colorado), the Cypress structure in Oakland (S. Hough, D. Simpson, Lamont-Doherty Geological Observatory), and sites throughout San Francisco, at the San Francisco International Airport, Foster City, and Redwood Shores (USGS, Menlo Park, California).

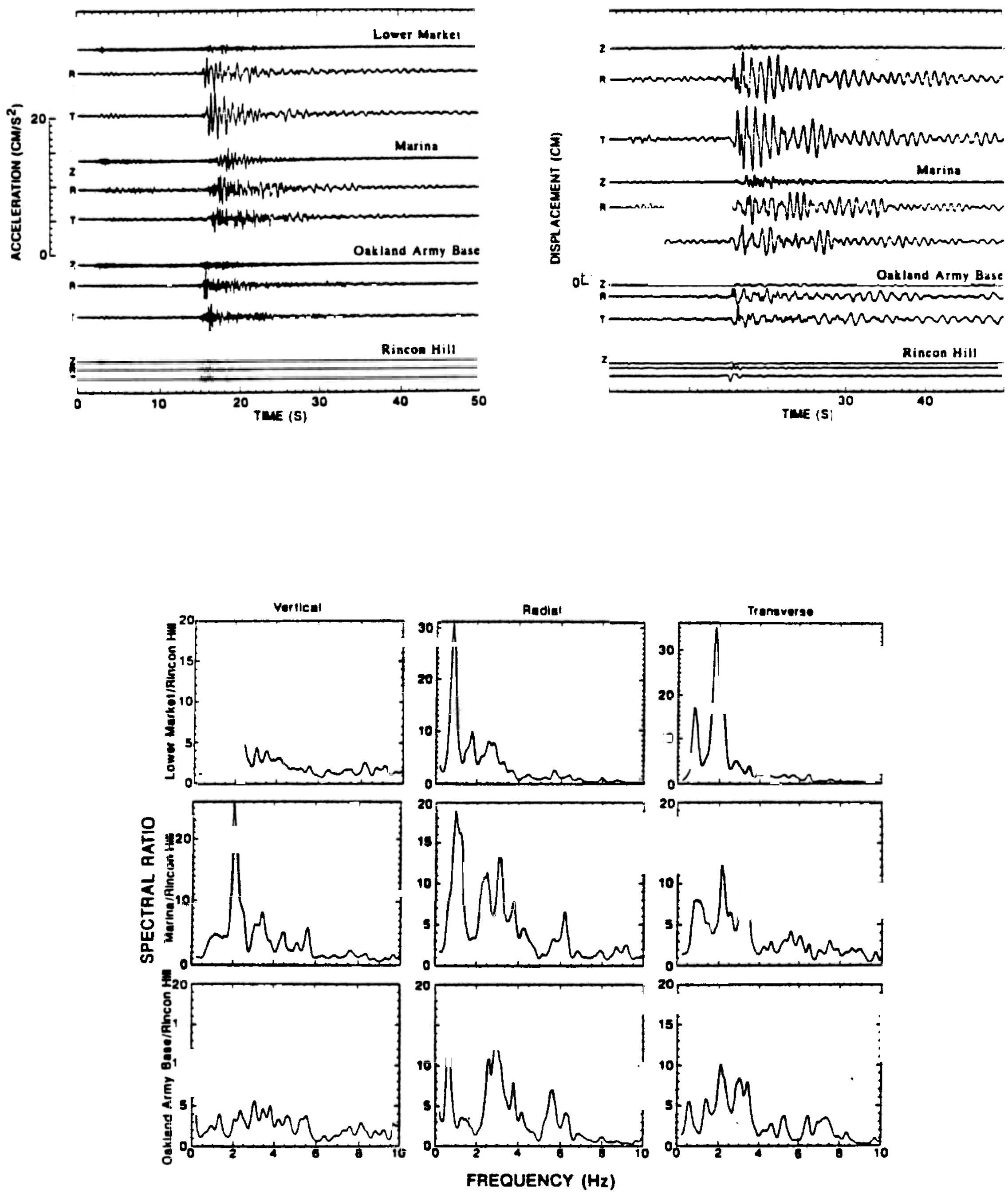


Figure 2.11 Acceleration and displacement time histories inferred from GEOS recordings of a magnitude 5.0 aftershock in the Ferry Building on lower Market Street, in the San Francisco Marina District near North Point and Divisidero streets, on the Oakland Army Base near the toll plaza of the Oakland Bay Bridge, and beneath the Unocal Building on Rincon Hill. Spectral ratios for each component of motion are computed with respect to those recorded on Rincon Hill.

An example of the data recorded from an M_L = 5.0 aftershock as recorded on GEOS (Borcherdt et al., 1985) is shown in Figure 2.11. Three of the recordings were obtained at sites underlain by bay mud and the fourth at a rock site. Time histories are shown for both inferred ground acceleration and ground displacement. The spectral ratios for three components of motion for sites underlain by bay mud (Figure 2.11) were computed with respect to the corresponding component recorded at Rincon Hill.

The spectral ratios appear to reaffirm the existence of predominant periods of shaking for the bay mud sites (Borcherdt and Gibbs, 1976) with levels of shaking at these periods several times higher than on rock.

Working under the auspices of the National Center for Earthquake Engineering Research (NCEER) and the Incorporated Research Institutions for Seismology (IRIS), S. Hough and colleagues from Lamont-Doherty Geological Observatory deployed a total of six stations (PASSCAL, digital recorders) in the vicinity of the Cypress structure to study ground-motion variations caused by variability in surficial geologic conditions (Figure 2.12). A sixth instrument was placed on the uncollapsed section of the freeway for a period of 15 hours. About a dozen aftershocks with magnitudes between 2.3 and 4.6 were recorded at the ground sites. Figure 2.12 shows a comparison of seismograms for a magnitude 4.3 aftershock recorded at sites S1 (on mud), S3 (on alluvium), and S4 (on Franciscan rock in the Oakland hills). Relative to the alluvium site (200–300 meters from the uncollapsed section), recordings on the mud site (approximately 600 meters from the collapsed section) show consistent amplification of weak ground motion, with amplification factors of 5–15 between 3 and 5 Hz.

ACKNOWLEDGMENTS

This chapter represents the combined and cooperative efforts of a large number of contributors from several different institutions. Although the description of the results was the responsibility of the team coordinators, the results could not have been assembled without many individual written contributions. Written contributions for the seismological aspects were received from B. A. Bolt, University of California at Berkeley, and numerous colleagues at the U.S. Geological Survey with principal authors being D. Eberhart-Phillips, A. J. Michael, D. Oppenheimer, and P. Reasenberg. T. Hall (Geomatrix Consultants) provided a summary of geologic observations. R. V. Sharp, M. Clark, K. Lajoie, and colleagues (USGS) also provided written material on geologic aspects of the report. M. Çelebi and A. Shakal provided the CSMIP strong-motion data. Contributions to the engineering seismology aspects section were provided by D. Boore, W. Joyner (Figure 2.8), G. Glassmoyer (Figure 2.11), and other colleagues at the USGS. S. E. Hough and colleagues at Lamont-Doherty Geological Observatory contributed written material and figures on ground-response studies near I-880.

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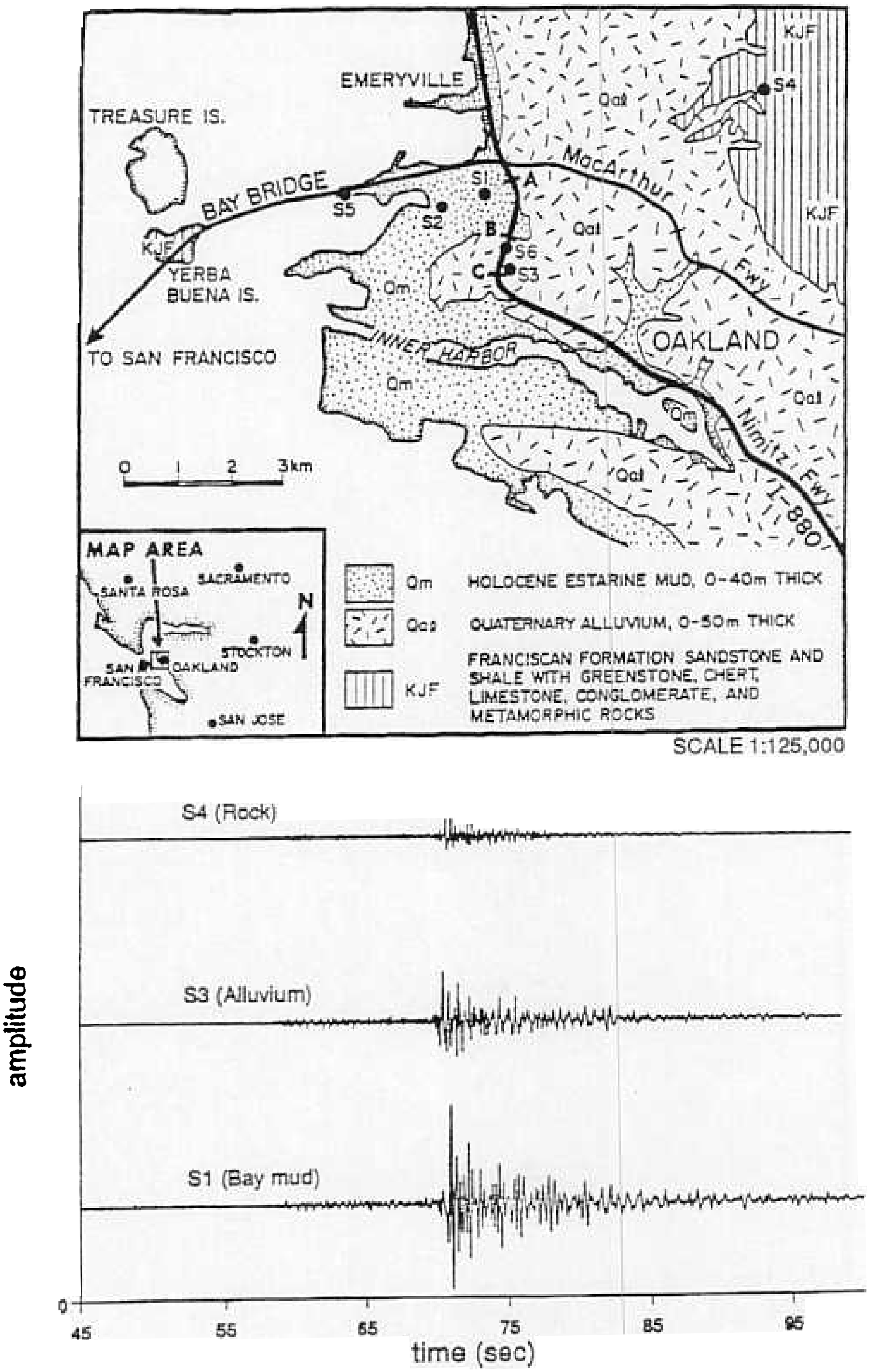

Figure 2.12 Map showing aftershock recording locations, near-surface geology (from Borcherdt et al., 1976), damaged (BC) and collapsed portions of I-880 (BA), and seismograms displayed at equal scale recorded at sites on rock (S4), alluvium (S3), and bay mud (S1) *(Contributed by S. Hough and colleagues)*

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3 GEOTECHNICAL ASPECTS

OVERVIEW

Observations to date indicate that geotechnical effects of the earthquake were significant and subsurface soil conditions contributed greatly to the severity and distribution of earthquake damage. The major geotechnical effects are related primarily to liquefaction, landslides, and amplified ground motions.

Liquefaction, as evidenced by sand boils, lateral spreading, settlement, and slumping to varying degrees at distances as great as 70 miles from the earthquake epicenter, caused great damage in the Marina District of San Francisco, as well as along the coastal areas of Oakland and Alameda in the East Bay area. Liquefaction also occurred along the Pacific Ocean coastline from the southern Marin peninsula in the north to Monterey Bay in the south. The Santa Cruz and Monterey Bay areas experienced significant damage due to liquefaction.

More than 500 landslides and rockfalls were observed in the Santa Cruz Mountains near the epicentral area, and to a lesser extent along the Pacific Coast. These landslides and rockfalls may become more severe and additional failures may become more apparent with the onset of the rainy season.

Subsurface soil conditions exerted a significant effect on levels of strong ground motion as the deep cohesive soil deposits (including bay mud) surrounding the San Francisco Bay amplified the ground accelerations. The amplified motions may have contributed to the extensive liquefaction, especially at greater distances from the epicenter.

OBSERVATIONS

The general area affected by the earthquake and the main locations of liquefaction effects and landslides are shown on Figure 3.1. Figure 3.2 shows four areas within San Francisco for which there is historical evidence of soil liquefaction and large ground deformations during the 1906 earthquake. Photographs of typical liquefaction effects from this earthquake are shown in Figures 3.3 and 3.4. The observed geotechnical effects and their general locations are summarized by county in Table 3.1 (see page 27).

There were no reports of distress or unusual deflections of temporary shored or soil-nailed excavations at construction sites within the affected area. There were also no reports of any problems with permanently soil-nailed walls in the area.

Minor damage to a number of dams was reported, including Lexington Dam, Guadalupe Dam, Newell Dam, Chesbro Dam, Anderson Dam, Soda Lake Dam, and Vasona Dam. The minor damage typically consisted of longitudinal cracks along the crests and/or upper portions of the dam faces, and, in some cases, minor crest

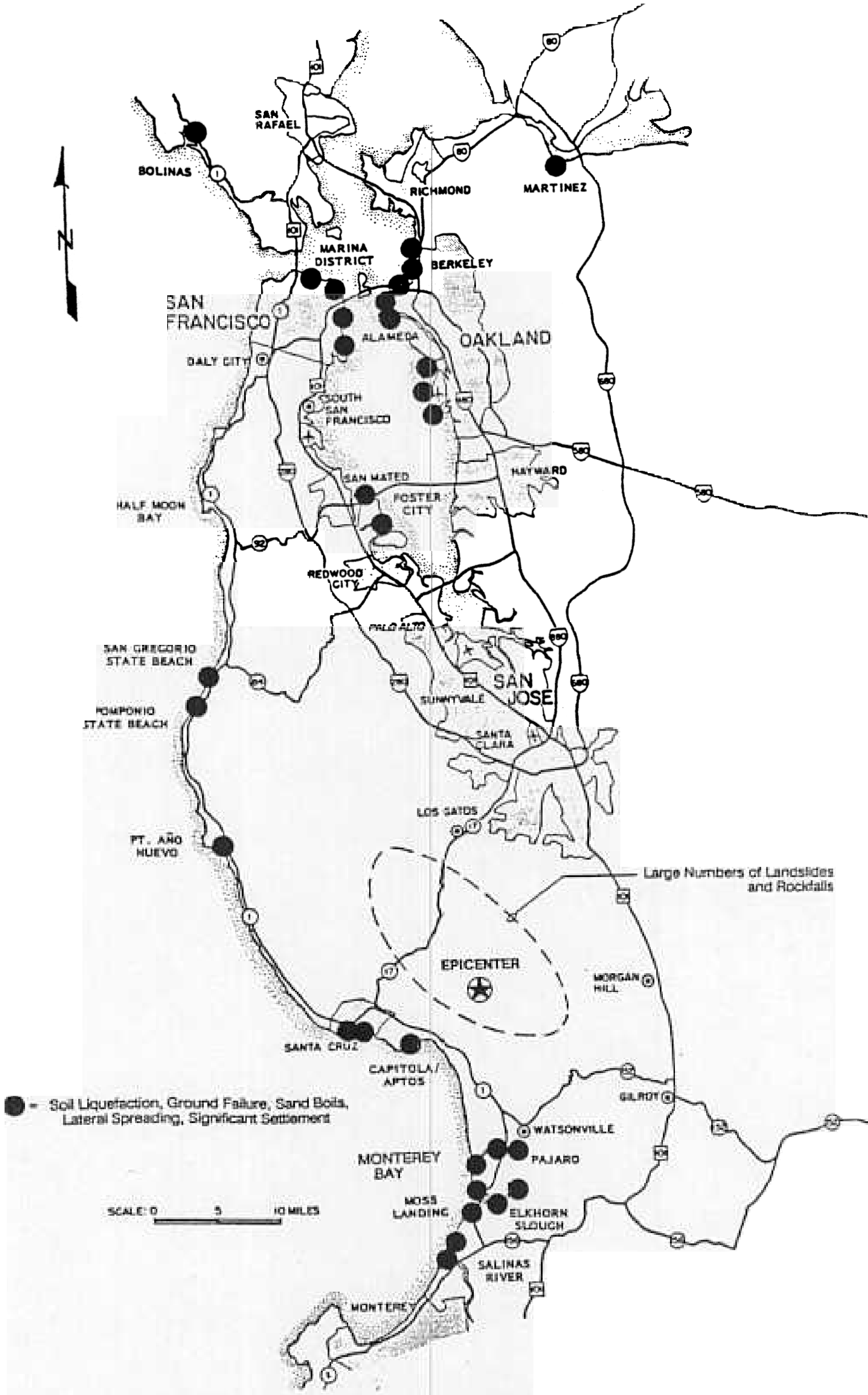

Figure 3.1 Map of affected region *(Courtesy R. B. Seed)*

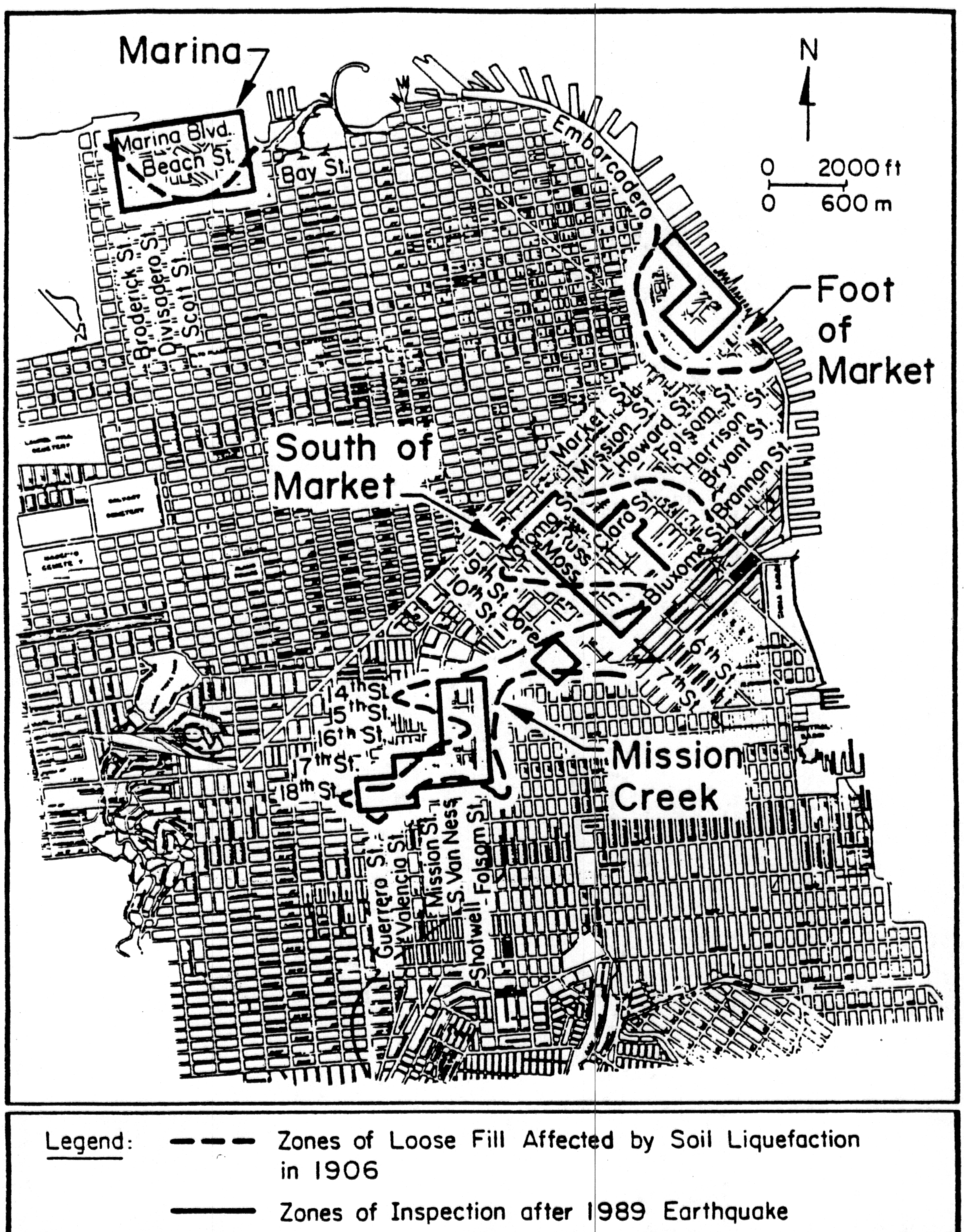

Figure 3.2 Plan view of San Francisco showing zones of 1906 soil liquefaction and inspection after the 1989 earthquake

subsidence. More substantial damage occurred at Austrian Dam, where longitudinal cracking occurred along the crest as well as in the upstream and downstream faces. A transverse rupture or fissure passes through the right abutment of the dam; this fissure

Figure 3.3 Settlement and tilting of buildings in the Marina District of San Francisco

Figure 3.4 Lateral spreading and slumping of the levee along the San Lorenzo River in Santa Cruz

is in close proximity to the mapped segment of the San Andreas Fault, and it is not conclusive at this time that this is a faulting feature.

COMMENTS

Based on lessons learned from past earthquakes and the corresponding advances made in geotechnical engineering, many of the observed geotechnical effects were predictable. However, more can be learned through follow-up research studies. Suggested research studies include the following:

- Effect of deep cohesive soil deposits (bay mud) on severity of shaking and occurrence of liquefaction.
- Occurrence of liquefaction at distances from the epicenter greater than those of reported liquefaction during prior earthquakes of comparable magnitude.
- Case histories of mitigation measures utilized in engineered landfills that behaved well.
- Behavior of battered piles subjected to lateral spreading.

Table 2.1 Observations of geotechnical effects

Location	Liquefaction Effects: Sand Boils	Liquefaction Effects: Lateral Spreads	Liquefaction Effects: Other	Ground Settlement	Landslides	Comments
MARIN COUNTY:						
Bolinas at lagoon on Marin Peninsula	0	0				series of boils
CONTRA COSA COUNTY:						
Martinez (Suisun Bay)	0					adjacent to pile supporting pier
CITY & COUNTY OF SAN FRANCISCO:						
Marina District (see Figure 2)	0		0	0		1 to 2 ft. of erupted sand in garages; also foundation bearing failures, building settlement, buckled pavement and sidewalks, structural distress, broken water and gas lines. Fissures parallel to sea wall in Marina Green and St. Francis Yacht Club area.
Shoreline from San Francisco-Oakland Bay Bridge to Fisherman's Wharf	0			0		cracking, subsidence and sand boils at Pier 45; lateral spread at Pier 39; sand boil at Davis and Vallejo Sts.; pavement, utility and structural damage; subsidence from Filbert Street to south of Ferry Building
Foot of Market St. (see Figure 2)	0		0	0		settlement of area adjacent to concrete piers of double deck Embarcadero Freeway (I-480); sand boils along Embarcadero betweem Ferry Bldg. and Pier 1.
Market St. (Downtown)				0		pavement, utility and structural damage
South of Market St. (see Figure 2)	0		0	0		sand boils along curbs and building lines; buckled pavement, sewerline heaving, cracking, utility line rupture, and foundation displacement
Mission Creek: (see Figure 2)	0			0		liquefaction occurred east of Mission and Capp Streets in same location as in 1906; damage due to differential settlement, rocking and tilting of houses.
China Basin Area						pavement, utility and structural damage
Civic Center						
Financial District						building damage
Hunter's Point						
reasure Island						

Table 2.1 *(continued)*

Location	Liquefaction Effects: Sand Boils	Liquefaction Effects: Lateral Spreads	Liquefaction Effects: Other	Ground Settlement	Landslides	Comments
ALAMEDA COUNTY:						
Bay Bridge approach and Toll Plaza area	0	0		0		roadway cracks
Emeryville	0	0				I-80 roadway damage
Berkeley I-80 frontage road	0	0				roadway damage
Port of Oakland						pavement damage
Howard Terminal	0		0	0		differential settlement between crane rails; damage to to battered piles supporting wharf
7th Street Terminal	0			0		
Small levee failure in close proximity to part where buried tube of BART enters the Bay						no apparent damage to BART
Alameda Naval Air Station	0	0	0			runway damage
Bay Farm Island	0	0				
Oakland International Airport	0	0				runway and levee damage
SAN MATEO COUNTY						
Foster City	no evidence of ground failure in engineered fill					
North of Foster City at perimeter of sanitary landfill	0	0				
South of Foster City along beach	0					
Brewer Island/San Mateo Bridge, San Carlos,	0					
Beaches at Half Moon Bay, San Gregorio Creek, Pomponio Creek and Pt. Año Nuevo		0				

Table 2.1 *(continued)*

	Liquefaction Effects					
Location	Sand Boils	Lateral Spreads	Other	Ground Settlement	Landslides	Comments
<u>SANTA CRUZ COUNTY</u>:						
<u>Santa Cruz</u>:						
Boardwalk	0	0				building damage
Municipal wharf		0				
Harbor	0	0				broken water line
Levee along San Lorenzo River	0	0	0	0		extensive levee damage
Schwan Lake		0				sewer outfall damage and retaining wall movement
Area about 1 km wide, extending 1½ km inland at mouth of San Lorenzo River	0	0		0		pavement buckling, structural damage, including shopping mall
Santa Cruz Mtns near fault rupture region; along Hwy 17 south of Summit Rd.					0	500 to 1,000 slides and rockfalls documented; most 10 to 20 feet deep; damage to houses; roadway closures
<u>CAPITOLA</u>:						
Arana Gulch		0	0			roadway slump
~~Soquel Creek~~		~~0~~				~~bridge and building~~ damage
<u>APTOS</u>:						
Moosehead Drive			0			retaining wall movement
Rio Del Mar Boulevard			0			roadway slump
<u>WATSONVILLE AREA</u>:						
Along Pajaro River and Watsonville Slough	0	0				considerable levee damage along channels
Highway 1 bridge across Struve Slough				0		Both two-lane spans collapsed; concrete bents settled and moved laterally.
Bridge over Pajaro River	0	0	0			7-span bridge closed; sand boils in riverbed near central piers; scarps along east bank; numerous cracks at eastern bridge approach, with sand ejections.

Table 2.1 *(continued)*

Location	Liquefaction Effects: Sand Boils	Liquefaction Effects: Lateral Spreads	Liquefaction Effects: Other	Ground Settlement	Landslides	Comments
MONTEREY COUNTY:						
Moss Landing:						
Along coast	0	0				
State Park entrance	0	0				roadway damage; culvert displacements up to 20 feet
Island and marina	0	0	0	0		pavement damage, Marine Laboratories damaged; buried tanks uplifted; bearing capacity failures
Along east berm of Hwy 1 west of PG&E Power Plant	0					
Monterey Dunes Colony and Molero Roads	0					
Elkhorn Slough and Salinas River	0					
Monterey Bay shoreline					0	extensive slumping

4 BUILDINGS

UNREINFORCED MASONRY BUILDINGS

Much of the spectacular building damage that resulted from the Loma Prieta earthquake was suffered by precode structures, principally of the unreinforced masonry type. The inspection of unreinforced masonry buildings in the five-county area most severely impacted by the earthquake was not complete at the time of this writing. In San Francisco, there are about 2,100 such buildings and 1,517 of these had been inspected at the time this report was compiled. Twenty-nine of the inspected buildings were severely damaged and considered unsafe. Most of these severely damaged buildings were located in the area south of Market Street, where soil conditions had a significant impact on the extent of the damage (see Figures 4.1 and 4.2). Another 490 of the inspected buildings showed some level of damage but were not considered unsafe for use at the time.

Figure 4.1 Unreinforced masonry building on 6th Street in the South of Market District of San Francisco that suffered major damage during the earthquake

Figure 4.2 A portion of the unreinforced masonry wall that fell from a building on 6th Street in the South of Market District of San Francisco

In Oakland, there are about 2,000 unreinforced masonry buildings and the inspection is continuing there, as well. The data on the inspected units are also yet to be compiled.

In previously unreinforced masonry buildings that had been retrofitted, a somewhat inconsistent pattern of success was achieved. Conclusions from the 1987 Whittier earthquake about the need for improved reliability of retrofit procedures seem to have been confirmed in this earthquake.

ENGINEERED BUILDINGS

In assessing the lessons to be learned from the behavior of engineered buildings it is important to underscore the nature of the October 17th main shock, namely ten to fifteen seconds of strong shaking with peak horizontal ground accelerations ranging from 0.67g near the epicenter to around 0.25g in Oakland and other northern cities. In light of this, satisfaction with the relatively good response of most engineered buildings should be tempered with an appreciation that a significantly longer duration of strong ground motion, most likely, would have resulted in a great deal more damage than was caused by this event.

Overall, the objective of preventing collapse and consequent loss of life was achieved even close to the epicenter. A severely shaken four-story reinforced concrete shear-wall building at Watsonville suffered essentially nonstructural cracking despite experiencing a peak acceleration of 0.6g at ground level and 1.2g at the roof.

Although isolated cases of major damage to tilt-up concrete industrial buildings have been reported, collapse of this form of structure was not widespread as was the case in the 1971 Sylmar earthquake. Some instances of damage to steel industrial structures were reported. Most of these were relatively minor, however, such as the stretching of cross braces.

Some patterns of damage to groups of older engineered buildings are apparent. Steel-framed, brick-clad structures in Oakland and other cities characteristically lost

Figure 4.3 Buildings that failed in the San Francisco Marina District typically had structural vulnerabilities and were also built on soft-soil deposits.

portions of the brickwork consistent with the relatively flexible frame loading of the infill panels. Pounding of adjacent buildings in downtown San Francisco and elsewhere resulted in veneers spalling and the debris being deposited in the streets below.

The well established vulnerability of structures under construction was confirmed by several cases in this earthquake. In Hollister a school gymnasium was badly damaged and in Oakland an uncompleted upper high rise steel frame lost several partially connected columns from the top.

A consistent pattern of internal ceiling panels dropping, including many in the international terminal of the San Francisco airport, reinforces the need to secure suspended ceilings. Similarly, several cases of lost precast-concrete panels from high-rise structures should remind designers of the importance of connection details.

Some of the more interesting aspects of engineered building damage occurred in the area south of the San Francisco airport. A penthouse and water tank fell from the top of the Amfac Hotel, causing considerable damage to the elevator shaft. Across the road, the Hyatt Regency hotel suffered shear cracks in the basement wall system and severe vertical spalling of concrete floor slabs in several elevations adjacent to one of the elevator shafts.

Whereas newer structures, and those on firm ground in particular, appear to have suffered little, building damage occurred most often to structures with recognized vulnerabilities and to those built on soft-soil deposits (see Figure 4.3).

ACUTE HOSPITALS AND SKILLED NURSING FACILITIES

Engineered hospital buildings throughout the area performed well in the earthquake and although many did suffer minor system damage, temporary elevator stoppage, and cosmetic damage, there were no operational interruptions. All state licensed acute hospitals and skilled nursing facilities in the counties of San Francisco, Santa Cruz, Santa Clara, San Benito, and Alameda have had on-site structural evaluations by engineers. All facilities continued services throughout the emergency. Those acute hospital buildings constructed under the provisions of the Hospital Act, passed in the 1972 legislative session, performed very well with essentially no damage of any kind. Some acute hospital buildings constructed prior to the Hospital Act experienced a limited amount of structural damage that will require corrective measures.

Some of the damage reported includes the seven-story tower building constructed in 1927 at Peralta Hospital in Oakland, which suffered serious damage and was closed. This building originally was part of the acute hospital but was later changed to an out-patient clinic. The adjacent four-story wing was also closed because of its proximity to the damaged tower. Two stories of the Santa Clara Valley Medical Center were evacuated due to structural damage. Watsonville Community Hospital suffered moderate structural damage, the fourth floor was evacuated due to loss of elevators and exterior windows, and an administration building suffered major damage and was evacuated. Damage to Palo Alto Veterans Administration facilities has been estimated at $30 million, and two of its six buildings were evacuated indefinitely. The entire Stanford Medical Center suffered approximately $4 million of damage.

Skilled nursing facilities, in general, performed fairly well. Typical damage consisted of cracked or spalled plaster and concrete, displaced equipment, occasional broken windows, ceiling damage, etc.

Emergency power generation at all acute hospitals performed properly. Several emergency power systems in skilled nursing facilities did not fare so well.

The Hospital Act is administered by the Office of Statewide Health Planning and Development. Structural plan review and construction supervision for acute hospitals and certain skilled nursing facilities is performed by the Structural Safety Section in the Office of the State Architect.

PUBLIC SCHOOL BUILDINGS

There was only minor structural damage to a few public school buildings from near-field effects of the Loma Prieta earthquake. A preliminary survey of 1,544 public schools in the earthquake-impacted region reveals an estimated $81 million in damage. Only three schools—in San Francisco, Watsonville, and Los Gatos—sustained severe damage. California public school buildings are regulated under the state building code and the Field Act, which establishes procedures for design and construction of public school buildings. The Field Act was passed by the state legislature following the Long Beach earthquake in 1933 and is enforced by the Structural Safety Section in the Office of the State Architect. Many public school buildings have been used as evacuation shelters for the victims of the Loma Prieta earthquake.

Public school buildings located in the stricken area of the Loma Prieta earthquake are being evaluated by structural engineers from the Structural Safety Section office and from the Disaster Emergency Services Committee of the Structural Engineers Association of California at the request of the Office of Emergency Services.

The Loma Prieta school buildings in Los Gatos were constructed in the 1950s and 1960s over hidden branches of the San Adreas fault system. At that time there was no legislative mandate for geologic hazards investigations of school sites. Several years ago it became apparent that these buildings were situated over potentially active fault traces and since then the school system and the state have made efforts to purchase a new fault-free site for this school. In this earthquake, one classroom wing heaved upward and the other wing suffered large cracks in the walls and sidewalks.

Early estimates set San Francisco's district-wide losses at more than $45 million, a third of them at the district's Van Ness Avenue offices. These administration buildings are not subject to the same standards as school buildings. The only San Francisco school that suffered severe structural damage in the earthquake was John O'Connell High School, which, officials say, may cost the district as much as $10 million to restore. The district bought O'Connell, originally a warehouse, in the 1950s and later converted it into a high school. Three additional schools reported substantial damaged buildings: the gym at Benjamin Franklin Middle School, the auditorium at Galileo High School, and many loose bricks at John Swett Elementary.

Oakland's 92 schools fared better, with about $1.5 million in damage.

An example of the effectiveness of the state school strengthening program introduced in 1968 is San Francisco's Winfield Scott School, in the heart of the Marina District, very close to the apartment building that burned to the ground after the quake. The school suffered only minor cracks in the plaster and some damage to the playground. It was built in 1930 and made earthquake-resistant in the 1970s. Its losses were estimated at less than $100,000.

Other typical school building damage in the affected area consisted of loosened clay roof tiles, displaced ceiling panels and plaster, and cracks in chimneys, walls, and concrete slab. Some appliances and equipment were displaced and suffered damage.

Some school buildings still require further investigation and additional data are being collected from school districts.

STATE FACILITIES

Many state facilities have been inspected and determined to have only finish and concrete cracks of a superficial nature. But further study will be required at several sites. As a result of the earthquake, there may be an asbestos hazard in several buildings and appropriate tests are being conducted.

As of this writing, several state buildings have been closed pending further investigation: the Old State building on McAllister in San Francisco, the Industrial Relations building on Golden Gate Avenue in San Francisco, and the State building in Oakland.

A leased state building in San Jose and one in Watsonville have also been closed pending further investigation.

In summary, the response of engineered buildings designed and constructed to recently developed standards was essentially predictable. Clearly, the overall stock of existing buildings in the greater Bay Area includes many that are susceptible to severe earthquake damage and there is much more to glean from our "learning from earthquakes" activities.

5 LIFELINES

Significant damage to lifelines (transportation, water, sewage, power, gas, and communications systems) and the impact of disrupted services on the affected communities has been one of the major characteristics of the Loma Prieta earthquake. Lifeline personnel have been busy restoring service to their communities and it has not yet been possible to gather detailed information about the system, its damage, and response to the damage. Much of the data in this report must be verified and more complete and detailed information collected.

TRANSPORTATION SYSTEMS

Many of the transportation systems in the five-county (Alameda, San Benito, San Francisco, Santa Clara, Santa Cruz) area most severely impacted by the earthquake have been significantly affected, with the highway system suffering the worst damage. The collapse of more than a mile of elevated roadway on I-880 (Cypress Street Viaduct) was the largest contributor to the earthquake death toll (see Figure 5.1). The loss of a 50-ft span of the upper deck of the Bay Bridge (San Francisco–Oakland Bridge) and subsequent damage to the lower deck has caused major transportation problems. There were many additional highway and bridge problems. Of the 1,500 highway bridges in the area, 3 had one or more spans collapse, 10 have been closed due to structural damage, 10 have required shoring so that they can be safely used, and 73 have had less severe damage. Throughout the region, subsidence of bridge approaches next to abutments on scores of bridges have been filled with asphalt to reduce large bumps in the road surface.

Twenty-two bridges from Santa Cruz to north of San Francisco have been inspected and the following general observations can be made.

- The seismic design of highway bridges was significantly revised after the 1971 San Fernando earthquake, where several bridges collapsed. Some bridges built prior to this are therefore known to be vulnerable to major damage, and the Caltrans bridge retrofit program was established to address this problem. The performance of both new and old bridges in this earthquake is therefore of particular interest.
- The greatest damage occurred to older structures on poor ground. The Cypress Street Viaduct and the Bay Bridge are examples of this.
- Bridges of a design and form similar to the Cypress Street Viaduct would very likely have been very severely damaged if the shaking had been of longer duration. In San Francisco, severe damage has been sustained by the Embarcadero structure near Market Street, the I-280 elevated freeway near China Basin, and portions of Highway 101 near Gough and Franklin streets.

Figure 5.1 The greatest damage from the earthquake occurred to older structures on poor ground, such as the I-880 Cypress Street Viaduct.

- Damage to the bent supporting connector between I-880 and the new I-980 freeway (in Oakland) appears to be due to inadequate shear strength on the beam-column joint. Because this structure is new, this result has implications for both new and existing bridges.

The most severe damage was the collapse of the Cypress Street Viaduct. Factors affecting the performance of this viaduct include unconfined shear keys; unconfined column steel; a flexible structure constructed on a flexible soil; variable soil conditions along its length; variable lateral stiffness due to some bents having flexural pins, some being skewed, and some having three columns at the lower level.

The secondary losses associated with the closing of the Bay Bridge will far exceed the direct loss associated with the damage. The failure of Interstate 880, that parallels the Bay south of the Bay Bridge, will cause disruption during its reconstruction, which is estimated to take two to three years. To reduce the impact on surface traffic and access to the port of Oakland, a surface road is planned for completion by the spring of 1990. The temporary closing of several elevated roadways, including the Embarcadero, which distributes traffic into several downtown areas in San Francisco, has caused disruptions to a system that was overloaded much of the time prior to the earthquake. These roadways will be temporarily strengthened, but their long term disposition has not yet been determined.

A large landslide in the Santa Cruz Mountains has disrupted State Route 17, the only direct high-capacity route between Santa Cruz and the San Jose area.

Damage to the control tower at San Francisco International Airport caused the closing of the airport for 13 hours and liquefaction and settling closed a portion of one of the runways at Oakland International Airport. Liquefaction at pier 7 in the Port of Oakland has limited the use of three large cranes. Damage to the Caltrain trackbed, which runs along the San Francisco peninsula, temporarily disrupted service between San Jose and San Francisco. The BART system performed well, including the cross-bay tube, with only temporary disruptions of service to thoroughly check the system.

WATER AND SEWAGE SYSTEMS

Water and sewer systems were damaged in many communities from the epicentral region to San Francisco. Most disruptions to water supplies could be attributed to one of the causes described below. The assessment of damage to sewage collection systems is more difficult and the extent of damage has not yet been assessed. Typically, sewage systems are more seismically vulnerable than water systems.

Extensive damage to water lines from ground deformation. In San Francisco, there were 72 significant pipe failures in the Marina District and 25 breaks outside of this area with 10 of these concentrated in the area south of Market Street. The 12-in. high pressure auxiliary (fire fighting) and regular water lines did not break in the Marina. A break in a 12-in. high pressure line south of Market, where there was significant liquefaction, quickly depleted a 750,000 gal tank used for fire fighting. The drop in pressure in the regular water system in the Marina required that the city bring in a fire boat to supply water to the fire fighting. More than 100 water mains broke in Hollister, and more than 60 broke in Santa Cruz. The failure of a bridge near Santa Cruz also took out water and sewage lines. In Santa Clara County, one of two 66-in. raw water lines failed where it crossed the San Andreas Fault. In Los Gatos, the Monte Verde water treatment plant lost its raw water supply when a 30-in. line inside of the reservoir failed. The East Bay Municipal Utilities District (EBMUD) lost a 60-in. modified concrete pipe when the weld on a spiral steel sheath failed. This was repaired three days after the earthquake. In addition, there were more than 140 broken mains throughout the EBMUD area, and in Sacramento, roof guides of a digester were damaged.

Interruption of pumps and water treatment due to the loss of power. Many communities lost power so that stored water supplies could not be replenished or ground water could not be pumped. Although most areas were without power for only a few hours, sections of Watsonville were without power for four to five days. With the loss of power, several communities had to bypass sewage treatment facilities and dump raw sewage into San Francisco Bay or Monterey Bay.

Damage to water treatment and storage facilities. In Santa Clara County, three or four 100-ft diameter flocculators at the water treatment plant were severely damaged, preventing the mixing of chemicals. Direct sand filtering was used instead, but the normal treatment capacity of 80 million gallons per day was reduced to 27 million gallons per day. In Los Altos Hills, a full one-million-gallon post-tensioned concrete tank split from top to bottom. The failure of four lines ranging from 8 in. to 12 in. caused a total loss of more than two million gallons of water.

Contamination of potable water supplies due to damaged lines. Damage to water and sewage lines created the potential for contamination of the water supply. In remote areas without power and gas, home treatment has not been an option, and residents have had to use bottled water.

Service from many smaller utilities and mutual water companies, serving from 50 to 200 customers in rural areas near the epicenter, was severely disrupted due to many of the above causes. Water tanks were damaged or destroyed, long pipe runs from springs or supplies from larger cities were damaged by landslides and shifting ground, and loss of power prevented pumping. Utility officials anticipate that some of these systems may be out of service until Christmas.

Several communities reported that there was a loss of pressure for fighting fires. Fortunately, there was little wind to spread the fires that started.

One encouraging observation from the earthquake was that computer-based System Control and Data Acquisition (SCADA) systems appeared to perform well, reducing concern about the seismic reliability of these systems.

POWER SYSTEMS

Initial power outages as a result of the earthquake affected about 1.4 million customers. Within 48 hours, service to all but 26,000 customers was restored. The most severe damage occurred at substations, primarily to ceramic members of circuit breakers and transformer oil leaks. Major damage to two key substations in San Jose and San Mateo contributed to the interruption of service to San Francisco and areas of south San Jose. Damage to the 500-kV switchyard at the Metcalf substation limited the ability to serve points up the Peninsula. The 500-kV switchyard at Moss Landing was also severely damaged, interrupting service in Santa Cruz and Watsonville. Transformers of at least one distribution station in the epicentral area also suffered damage. A key element in restoring electrical service after such an event is replacing damaged equipment. In this case, new equipment was flown in from the east coast with the help of the U.S. Air Force, and some equipment from utilities in southern California was provided through mutual aide agreements between utility companies.

Moss Landing Power Plant, located about 30 miles south of the epicenter, has seven units with a total generating capacity of about 2,000 megawats (MW). Only unit 6 (750 MW) was operating at the time of the earthquake and was damaged. Unit 7 (750 MW) had been removed from service before the earthquake for routine maintenance. Its generating units sustained only minor damage but damage to the switchyard prevented them from operating. In San Francisco, the 217-MW unit at Potrero and one of the two 106 MW units at Hunter's Point tripped off line. The third unit came off-line as load dropped within an hour after the quake. Hunters Point was back on line by the October 19. The Potrero unit was damaged but came back on line with the help of steam needed for the feedwater heater generated by the frigate USS Lang. Many small cogenerating plants in the area were undamaged and continued to provide power.

The Diablo Canyon Nuclear Power Generating Plant, located about 140 miles south of the epicenter, experienced very small ground motions and was not affected by the earthquake. One unit was down for refueling and the second unit continued to operate.

GAS SYSTEMS

There has been little damage to gas transmission and large distribution lines, with only three failures reported. There were leaks in a 20-in. semi–high-pressure welded steel distribution line in Oakland, a 12-in. line in Hollister, and an 8-in. line in Santa Cruz. In the Marina District, about ten miles of gas lines will have to be replaced at an estimated cost of $20 million. This operation is expected to take about two months. Outside the Marina District, damage was distributed throughout the city with more than 400 breaks in mains, service, and meter locations. Other cities that reported damage to either mains or services include Los Gatos, Watsonville, Hollister, Richmond, Santa Cruz, San Jose, Oakland, and Alameda.

About 153,000 customers shut off gas service connections to their homes or businesses. Although most public service announcements cautioned that gas should be shut off only if a leak is suspected, several announcements by reporters in the field simply recommended that the gas be shut off. Because gas company personnel typically turn on the gas and relight all pilot lights, the service load was tremendous. In Santa Cruz, for example, about 22,400 out of 48,000 customers shut off their own gas. In the Marina District, after a large fire started and low water pressure was encountered, the fire department requested that gas mains servicing 5,100 customers in the area be shut off. Gas was also shut off in some parts of Watsonville and Santa Cruz.

Four days after the earthquake, gas service was essentially back to normal throughout the system except for San Francisco's Marina District and hard hit areas in the Santa Cruz-Watsonville-Los Gatos area. Two weeks after the quake, the heavy damage to the gas system in downtown Los Gatos was repaired.

COMMUNICATION SYSTEMS

In most earthquakes, the increase in telephone traffic in the hours immediately after the event overloads the system so that there can be a long delay in getting a dial tone on nonpriority lines. All telephone systems are designed to accommodate reasonable peak loads, thus, overloads after an earthquake can be expected. Although the overloading did occur after the Loma Prieta earthquake, in general, calls could be made within most area codes. Service announcements on the radio immediately after the earthquake requested that only emergency calls be made. This probably contributed to the overall good performance of the telephone system.

Damage to Pacific Bell facilities—Pacific Bell is the primary provider of local service in the area—was minor and did not affect service. Some cable trays did show signs of distress. Cable tray hardware is unique to the communications industry. Friction clips that are used to join cable tray segments can slip allowing the trays to sag but this would probably not impact the function of the cables. Friction clips are also used at the supports of the trays, and their slipping may cause the tray to drop. Most West-coast companies use improved hardware that has pins that provide a positive connection. In other parts of the country, however, companies use the less reliable hardware. Overloaded cable trays can aggravate these problems.

The loss of commercial power did cause some communication problems. Telephone systems are designed to run on batteries for several hours. Central offices usually have engine-generators to recharge the batteries so that phone service can be maintained for extended periods without commercial power. There were some problems with engine-generators and in one case service at an office had to be reduced until additional backup power could be obtained.

A more common cause of telephone service disruption was the lack of emergency power for private branch exchanges (PBXs). PBXs are the privately owned phone systems used by companies and large organizations for telephone service within a facility that connect to outside lines provided by the local telephone company. When commercial power is lost, many of these systems have limited or no emergency power capabilities. As a result, all or most of the phones in a given office or an entire building will not operate. In such cases, many people are unaware that the problem is with the

PBX and instead assume that the commercial carrier system is not working. It is important for individuals to know that emergency calls can be made from pay phones or adjacent offices that are not run by the same PBX. Some damage to PBX systems in this quake has been reported.

Normal operation of the long distance network under overload conditions did cause some problems for certain facilities in this earthquake. The earthquake area is serviced by two area codes, 415 north of Mountain View and 408 from Mountain View south. As a means of increasing the availability of service within a local area, long distance load control can lock out incoming calls from other area codes. In this case, callers in adjacent areas with different area codes may find it difficult to phone each other. This was a problem for a hospital located near the area code boundary where callers in the adjacent area code could not get through to the hospital.

6 URBAN PLANNING AND ARCHITECTURE

OVERALL PATTERNS

Preliminary estimates indicate that less than 1% of developed property in the impacted area suffered damage. This is based on estimates of $3.3 billion to residential and commercial property, and $2.3 billion damage to public property.

Although damage was spread throughout a six-county area, from Monterey and San Benito Counties in the south to San Francisco and Alameda Counties in the north, severe damage in the region varied widely from area to area and seemed primarily concentrated in several distinct pockets. These were districts with a heavy concentration of vulnerable building types or ground conditions, or both (San Francisco: Marina District and South of Market; Oakland: downtown and Cypress Street I-880 overpass area; Los Gatos, Santa Cruz, Watsonville, and Hollister).

The number of totally collapsed structures was very small. In fact, the Cypress Street freeway structure was the only total collapse of an engineered structure that resembled the earthquake collapses that caused heavy causalties in Mexico City (1985) and Armenia (1988). This reinforces the opinion that, in earthquakes, heavily occupied nonductile reinforced-concrete frame structures also represent the greatest threat to life in this country.

Although the number of collapses was very low, the total damage figure is very high. For example, even though there was no spectacular damage at the Stanford University Campus, the total damage estimate is approximately $160 million. Of the eight academic buildings closed, all were constructed before seismic codes were adopted. Of the five buildings damaged to the extent that access is limited, four were built before seismic codes came into effect. Serious damage was caused to seven "row houses"—wood-frame communal dwellings for about 160 students. However, no one on the campus was seriously injured.

Severe damage to rehabilitated unreinforced masonry buildings in Los Gatos, Watsonville, and Santa Cruz emphasizes the danger of architectural and interior rehabilitation that does not include seismic strengthening. In Santa Cruz, particularly, many structures on Pacific Garden Mall had been attractively and expensively rehabilitated without appreciable strengthening (see Figure 6.1). Approximately 20 buildings will be demolished, and total losses in Santa Cruz are approaching $170 million.

Figure 6.1 Although many of the structures on the Pacific Garden Mall in Santa Cruz were attractively and expensively rehabilitated, the improvements did not include appreciable strengthening and many were lost.

CASUALTIES

Compared to the property loss, casualties were light. Documenting the characteristics, damage patterns, and impacted areas of this earthquake will provide an opportunity to review, update, and improve on previous Earthquake Vulnerability Analysis Studies developed for preparedness planning that predicted much higher casualty levels for an earthquake of comparable magnitude to this one.

The estimates of 11,000 deaths and 44,000 injuries suggested in a 1980 federal report for an 8.3 magnitude earthquake on the Northern San Andreas Fault need careful review.

DAMAGE TO NONSTRUCTURAL COMPONENTS AND CONTENTS

Once again, the importance of damage control relative to nonstructural building elements was shown to be an important architectural consideration. Some large

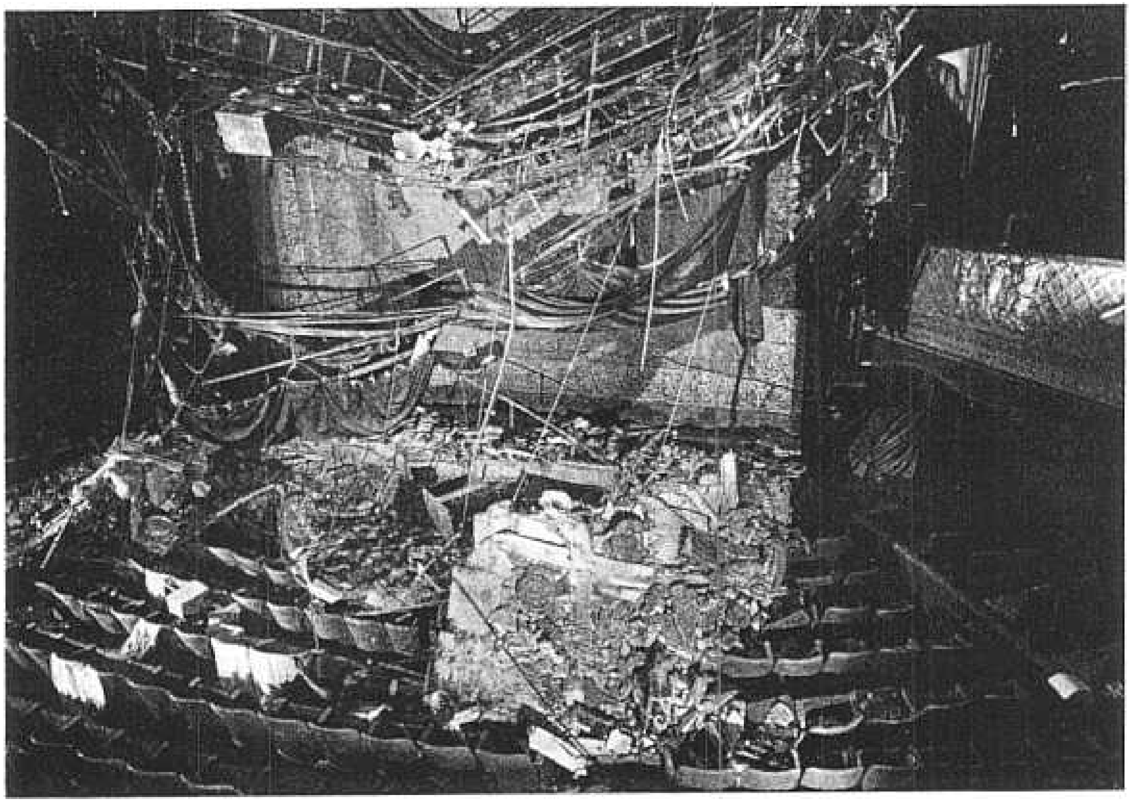

Figure 6.2 The Geary Theater in San Francisco *(Courtesy Frederic Larson/San Francisco Chronicle)*

corporations are reporting up to $45 million or $50 million property damage (among them, Pacific Bell and Pacific Gas & Electric Company).

There appears to be a large amount of damage to gypsum board partitions, glazing, air conditioning units, etc., that, when taken together, represents relatively minor damage for each building, but overall adds up to a large sum for area-wide damage.

Threats of widespread and lethal glazing and cladding damage proved to be unfounded for this magnitude earthquake. Based on preliminary observations, however, this magnitude earthquake appears to be the threshold at which such damage might occur. Although glazing and cladding of new structures performed well, signs of incipient distress are visible in many new buildings in areas such as Foster City, Redwood Shores, and downtown San Francisco.

Overall, nonstructural damage is difficult to assess because it is largely internal and invisible from the outside. There is an urgent need to separate the reporting and tallying of damage levels into specific categories: nonstructural, equipment, architectural, finishes, and contents, and so on. In addition, it would be very useful to know the extent to which nonstructural damage is related to structural damage and deformation. Preliminary observations indicate that most nonstructural (as distinct from contents and equipment) damage is the consequence of structural failure.

Some damage to exterior glazing was seen throughout the San Francisco Bay and South Bay areas. In older buildings, there was considerable damage to storefront-type windows. In downtown San Francisco, the most visible instance of severe glazing damage to a large building was at a retail building on Union Square that, although

Figure 6.3 Characteristic "soft story" vertical-configuration effect on building performance in the Marina District

new in appearance, in fact, was constructed in 1946 as one of the first hermetically sealed buildings in the city.

In downtown Oakland, the exterior cladding (principally glass and brick veneer) and interior elements of one medium-rise building incurred major damage and probably reached the critical loss level of 65% of its replacement cost.

There are several significant cases of interior nonstructural damage:

- At the Geary Theater in San Francisco, only the basic structural-steel supporting system remains of the proscenium arch ceiling (see Figure 6.2). The rest of the nonstructural elements rest in a pile of rubble below, along with the fallen ceiling lighting grid and mounds of ceiling plaster that cover the first six rows of seats in the auditorium. Fortunately the theater, which holds 1,350 spectators, was not in use at the time of the earthquake.
- A personal-computer software maker in Scotts Valley, about five miles from the epicenter, incurred damage when the water piping system in all its buildings ruptured forcing employees out into the parking lot.
- Sales floor contents in retail establishments throughout the area were overturned or thrown off of shelves, but generally, operations resumed very quickly. For example, a large hardware store in Watsonville, near the epicenter, lost almost all of its suspended ceiling and suffered extensive upsets, but all was cleared up and ready for normal operations the day following the earthquake.

- Extensive damage to ceilings and sprinkler systems closed the north terminal of the San Francisco airport for several hours.

HISTORIC BUILDINGS

Several historic buildings (churches and cathedrals, department stores, office buildings, and theaters) in Oakland, San Francisco, Santa Cruz, Los Gatos, and Watsonville incurred moderate to severe damage in the earthquake. These include the Paramount Theater in Oakland and the Geary Theater in San Francisco. Architectural finishes in the San Francisco City Hall were damaged, and more serious damage occurred in Oakland City Hall. A number of churches suffered damage, including severe damage to the Stanford University Chapel and St. Patrick's Church in Watsonville. The Orthodox Cathedral in San Francisco, Sacred Heart Church in Hollister, and a seminary in Menlo Park, where one person was killed, also sustained damage. The historic downtown Emporium-Capwell store in Oakland suffered severe damage, and was closed for repairs.

Damage to all historic buildings needs immediate attention, documentation, and detailed follow-up investigation, and the question of demolition needs to be carefully evaluated.

BUILDING LAYOUT AND CONFIGURATION

Irregularities of plan and elevation, together with irregular location of structural or stiff nonstructural elements contribute to many building failures. This aspect of architectural design played a crucial part in the collapses that occurred in the Marina District of San Francisco. The first-story collapse of several four-story, wood-frame, corner apartment or condominium buildings featured ground floors pierced by garage doors along two sides (see Figure 6.3) and represent characteristic cases of the "soft story" vertical-configuration effect on building performance.

Another aspect of this damage was related to the deterioration of wood sheathing under exterior plaster, brick veneer, and wood siding due to decay and moisture introduced into the wall cavities over the years. Many of the housing units were built before plywood was developed so that wood sheathing consisted of 1 x 6 wood members laid horizontally.

URBAN PLANNING

Urban planners and emergency planners throughout the quake-affected region have been busy coordinating and restoring services, and detailed information on the response of urban systems, from a planner's point of view, has not yet been collated. The urban planning reconnaissance team has established the following priority areas for further study.

- Examine damage to buildings of historic interest (e.g., Los Gatos central area) and the response by local authorities to the conflict between building safety and preservation.
- Identify sources of information for mapping damage to buildings and structures in the region in order to describe the spatial distribution of damage.
- Monitor local agency decision making on the perpetuation of existing land use and construction in heavily damaged areas where liquefaction is likely due to soil conditions (e.g., the Marina district).
- Seek information from the Association of Bay Area Governments and from other jurisdictions that suffered serious disruptions to determine how well their preparedness plans

operated under actual emergency conditions. Examine the effectiveness of preparedness plans after the first 72 hours, the second week, the second month, and forward.

- Identify patterns of adaptation in such areas as rehousing and transportation. Determine what informal solutions—flexible work hours, working at home, citizen policing of private property, public transit patronage, living with friends or family, ad hoc shelters—were used by the population and evaluate their effectiveness. Also, identify adaptive behavior that might be applied to public policy areas and social problems other than disasters, e.g., traffic mitigation and homelessness.
- Plot the short-range economic impact of the earthquake as measured by retail sales, bank receipts, mortgage and consumer lending, worker productivity, and other indicators of economic activity. Attempt to determine the "bounce-back period" in such economic sectors as retailing, tourism, and manufacturing.

7 INDUSTRIAL FACILITIES

PERFORMANCE OF POWER GENERATING PLANTS

Power generation facilities in areas of strong shaking in the Loma Prieta earthquake generally suffered light or no damage.

Pacific Gas and Electric Company's Moss Landing Power Plant was the closest large generation facility to the epicenter. The closest strong-motion instruments—Watsonville about 10 km to the north—recorded peak horizontal ground accelerations of 0.54g. The plant includes seven units, constructed between 1950 and 1968, with a total generating capacity of 2,086 MW. One of the newer 750-MW units was in operation at the time of the earthquake. Damage at the site's 500-kV switchyard caused the plant to trip off-line. The normal supply of AC power from the PG&E grid was then lost and most operating equipment shut down. The plant's internal supply of DC power continued to serve critical systems. Adjacent to the power plant, a 300,000-gallon raw water tank ruptured along the welded seam of the tank wall and base plate. Corrosion damage to the bottom plate may have been a contributing factor in the tank rupture. Additional effects included minor yielding of bracing for the steel frame boiler structures and dents in steelwork due to impact from adjacent piping.

A 120-MW private cogeneration plant near Gilroy also experienced around 0.40g based on nearby strong-motion records. The plant was constructed in the mid-1980s to stringent seismic design standards. The plant supplies power to the PG&E grid at 115-kV. Switchyard equipment at the plant site escaped damage due to its lower voltage and smaller ceramic components. It was restarted a few hours after the main shock following a thorough inspection that revealed no significant damage. More distant from the epicenter, the Hunter's Point Power Plant experienced only superficial damage and stayed on line. The Potrero Power Plant went off-line, reportedly due to relay chatter, and sustained some buckling of seismic restraints on the boiler.

INDUSTRIAL FACILITIES

Industrial facilities in the area near the epicenter are primarily those classified as light industry, such as food processing and computer-related research and production. The heavy industrial facilities include cement and brick manufacturing plants. These facilities experienced moderate to light damage such as isolated instances of brace buckling or stretching. There were no cases of major damage or collapse but production was suspended due to loss of electric power. Mechanical and electrical equipment performed satisfactorily and production resumed within a week. There was no seismic recording instrumentation near the facilities, however, horizontal accelerations are estimated at 0.3 to 0.4g based on nearest records.

Major light industries in the epicentral area are food packing and processing near Watsonville and Gilroy. Because of the proximity to the epicenter, the age of the plants, and installation details of some of the equipment, the facilities experienced significant damage and in most cases suspended production.

Due to the large number of affected facilities only a few have been investigated in detail to date. Damage to the hardest hit food-processing plants included loss of inventory, ammonia (refrigerant) leaks, equipment failure due to undersized anchorage details, piping failures due to connection details or structural damage, and electrical equipment failure caused by power transients—short power surges. Causes for failure of medium-voltage electrical equipment included motor burnout caused by transients in the power supply and lack of relays to protect against such power disturbances.

During these preliminary investigations, certain types of equipment damage have been identified that have not been observed in past earthquakes, such as medium-voltage motor failure. The failures most likely would not have occurred if additional protective relays were included in the switchgear. The Watsonville and Gilroy areas experienced ground accelerations of approximately 0.4g horizontal and in some locations unusually high vertical accelerations greater than 0.5g.

WATER TREATMENT FACILITIES

The reconnaissance team briefly visited and inspected two water treatment plants in the epicentral area: the Santa Cruz Water Treatment Plant in Santa Cruz and the Rinconada Water Treatment Plant in Santa Clara. In general, both plants performed well and suffered little damage. In particular, the Santa Cruz plant suffered no earthquake effects except the loss of off-site power. The plant is equipped with an emergency diesel generator that was activated immediately after the event and was capable of providing sufficient emergency power to the entire facility. The Rinconada Plant apparently also performed well with only some damage to flocculation equipment. Nearly all steel and concrete water-storage tanks throughout the epicentral region performed without damage; however, there have been reported instances of damage to redwood storage tanks.

For more information on water treatment facilities, see Chapter 5 on lifelines.

PETROCHEMICAL FACILITIES

Two petrochemical facilities that sustained damage have been investigated to date. These are the Unocal Terminal and the Texaco Terminal. Both facilities are located in Richmond, California, approximately 60 mi from the earthquake epicenter. Both facilities are constructed on fill adjacent to the bay.

At the Unocal facility all the damage was associated with unanchored, flat-bottom storage tanks. The Unocal facility was constructed in the 1950s on uncontrolled fill. Therefore, all the tank foundations were pads on piles. A total of six tanks experienced damage. All of the tanks had a capacity of between 400,000 and 1,000,000 gallons. Details regarding the tanks are in the process of being obtained from Unocal. All of the tanks that were damaged were essentially full. Other similar tanks that were undamaged were either partially full or empty. Five of the tanks had floating roofs and one had a cone roof. The liquid height was approximately 0.8 times the diameter. All the damage was associated with uplift and overturning of tank walls. Uplift was measured at between 6 in. and 8 in. One tank was cracked vertically at the bottom plate. One tank ruptured when a lateral pipe support, attached to the tank side wall and to a restrained foam line, tore a hole in the sidewall when the tank wall moved up. One tank had a classic elephant-foot buckle near the bottom and ruptured at the side wall–bottom plate connection. Only three of the six tanks that uplifted 6 in. to 8 in. had elephant-foot buckles. All product (gasoline and lube oil) spilled was safely contained within containment dikes on the site and there were no fires.

At the Texaco facility, an 800,000-gal flat-bottom storage tank experienced leakage at the bottom plate. This storage tank was unanchored and supported on a concrete-ring wall. The damage was associated with uplift and overturning. The bottom pipe outlet was allowed 2-1/2 in. of uplift before it was constrained. Because the uplift was greater than 2-1/2 in., the outlet yanked on the bottom causing a leak. The leak was contained safely with a berm.

One overall problem did surface at this plant; most control alarms were triggered by the earthquake. The Texaco facility was built in the 1950s on controlled fill. The damaged tank was the only one that was filled. Partially filled tanks were not damaged except ladders, which were supported by the floating roofs, that derailed.

It has been reported that, at the Chevron Richmond Refinery facility, anchorages of tall vessels were stretched. Damage to piping and equipment low to the ground was negligible. This refinery will be the subject of further investigation.

There are also reports of petrochemical tankage facilities closer to the earthquake epicenter. Those will be investigated to determine if damage has occurred.