PLANNING SCENARIO

FOR A MAJOR EARTHQUAKE ON THE RODGERS CREEK FAULT IN THE NORTHERN SAN FRANCISCO BAY AREA

SPECIAL PUBLICATION 112

1994



DEPARTMENT OF CONSERVATION

Division of Mines and Geology

0 5 Kilometers

0 10 Miles

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PLANNING SCENARIO FOR A MAJOR EARTHQUAKE ON THE RODGERS CREEK FAULT IN THE NORTHERN SAN FRANCISCO BAY AREA

By

CALIFORNIA DEPARTMENT OF CONSERVATION

DIVISION OF MINES AND GEOLOGY

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July 1994

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FOREWORD

- During the last 25 years earthquakes of about magnitude (M) 6 or greater have caused loss of life or property in California: 1968 Borrego Desert, 1971 San Fernando, 1975 Oroville, 1979 Imperial Valley, 1979 Coyote Lake, 1980 Livermore, 1980 Mammoth Lakes, 1980 offshore Humboldt County, 1983 Coalinga, 1984 east of San Jose, 1984 northwest of Bishop, 1986 Palm Springs, 1986 Chalfant (Mono County), 1987 Whittier Narrows, 1987 Superstition Hills (Imperial County), 1989 Loma Prieta, 1992 Petrolia (Humboldt County), 1992 Landers and Big Bear, and 1994 Northridge. Assessments and conclusions presented in this planning scenario were completed before the January 1994 Northridge earthquake occurred. The experience gained from the Northridge earthquake probably would not significantly change the general nature of the assessments made in the present scenario.

- During the 110 years preceding 1968, California had been struck by seven major earthquakes of about M7 or greater: 1857 Fort Tejon, 1868 Hayward, 1872 Owens Valley, 1906 San Francisco, 1923 offshore Humboldt County, 1940 Imperial Valley, and 1952 Kern County. Most of these occurred while California was still sparsely populated, or occurred away from population centers.

- The 1989 Loma Prieta earthquake (M7) in the Santa Cruz mountains killed 63 persons and caused over $5.9 billion in damage.

- The Rodgers Creek fault was possibly the source of the 1898 earthquake of M6.7, which severely damaged the Mare Island Naval Yard as well as the towns of Sonoma and Petaluma.

- Significant damage occurred in Santa Rosa on October 1, 1969 from two earthquakes of M5.6 and M5.7 originating near the juncture of the Rodgers Creek and Healdsburg faults.

- The Working Group on California Earthquake Probabilities (WGCEP) estimates a 30 year probability of 22 percent for a M7 event on the Rodgers Creek fault.

- This planning scenario gives estimates of how the various lifelines can be affected following the scenario earthquake. These estimates assume that equipment, repair materials, access, and response personnel are available. If they are not available for each lifeline, then priorities must be set, and certain lifeline elements will be out of service for longer periods. The scenario mainly addresses the initial 3 day response period.

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EXECUTIVE SUMMARY

The Rodgers Creek Fault

The Rodgers Creek fault (RCF) is an active, steeply eastward dipping, right-lateral strike slip fault mapped from San Pablo Bay on the south to the city of Santa Rosa on the north. The Working Group on California Earthquake Probabilities (WGCEP, 1990) has calculated for the Rodgers Creek fault a slip rate of 9 ± 2 mm/yr, a recurrence interval for major earthquakes of 222 ± 74 years, and a 30 year probability of 22 percent for a M7 earthquake.

Characteristics of the Scenario Earthquake

Faulting extending the 27 miles (43 km) length of the RCF is postulated. A maximum surface displacement of 6 feet (2 m) and an *average* displacement of about 3 feet (1 m) is predicted. The displacement is assumed to be horizontal right-lateral strike slip. Minor dip slip or vertical components of faulting will occur locally.

A large area in the North Bay within zones of Modified Mercalli Intensity (MMI) VIII or greater is highly susceptible to liquefaction. This area is drained by the Petaluma River, Sonoma Creek, and the Napa River and underlain with intertidal deposits. Some areas of bay mud and some younger fluvial deposits in the East Bay area, and San Francisco and Marin counties are susceptible to liquefaction.

Comparison to the 1906 San Francisco and 1989 Loma Prieta Earthquakes

In the Sonoma County area the Rodgers Creek scenario earthquake (M7) will generate MMI up to VIII and IX as occurred in the 1906 San Francisco earthquake of $M \sim 8$.

The central Bay Area, including San Francisco and Oakland, will experience much the same kind of damage as it experienced in the 1989 Loma Prieta earthquake. Because ground motion intensities in areas to the north will be higher for the Rodgers Creek earthquake, there will be even greater damage in these areas.

Buildings

The most common types of potentially hazardous buildings found in the Napa and Sonoma county areas, and affected parts of Solano and Marin counties, include:

1. **Unreinforced Masonry Buildings**

   The seismic strengthening of unreinforced masonry (URM) buildings is a risk reduction measure. Retrofitted buildings have greatly improved resistance to collapse of walls and parapets, but the seismic resistance of these structures is less than that of new construction built to the latest seismic codes. After the scenario event, many retrofitted URM's will be economically unrepairable and some may collapse.

2. **Pre-1940 Wood Frame Houses**

   Wood frame dwellings built before 1940 or even 1950 have often shifted or fallen from their foundations in earthquakes. This has been due to lack of foundation anchorage or to weak cripple walls connecting the first floor to the foundation.

3. **Pre-1973 Tilt-up Concrete Buildings**

   Probably the most common cause of severe damage to pre-1973 tilt-up construction has been separation between the concrete tilt-up wall panels and the roof, resulting from inadequate ties. This can allow the wall panels to fall outward, leading to collapse of the roof and floors. These buildings are common as warehouses or office buildings in industrial parks.

4. **Non-ductile Concrete Frame Buildings**

   These are typically pre-1971 lightly reinforced concrete frame structures without adequate detailing of reinforcement in columns, beams, and joints.

5. **Mobile Homes**

   Mobile homes installed without seismic foundation restraints are often damaged in earthquakes. In 27 mobile home parks in San Benito, Santa Clara, and Santa Cruz counties, 24 percent of the homes (592 out of 2,434) moved or fell off their foundations during the Loma Prieta earthquake.

Public Schools

All public school buildings in the planning area have been designed to meet earthquake resistant design provisions, which have continued to improve since the 1933 Field Act. State universities, while not technically subject to the Field Act, have built their new buildings in conformance to its seismic provisions.

Schools shaken at high intensity within 5 miles (8 km) of the fault are subject to damage. We assume that underground utility service lines such as water, natural gas, and sewage, which cross the Rodgers Creek fault will be damaged. As a result, some schools in critical areas will be unusable for emergency shelter even if their structures remain undamaged by the postulated earthquake.

Hospitals

Hospitals close to surface fault rupture can be seriously affected by disruption of utilities, and by access problems. For response planning purposes, we anticipate that out of 2,004 beds in the 16 hospitals in the North Bay, 463 (23 percent) will be unavailable for treatment of earthquake related casualties. As seen in the 1989 Loma Prieta earthquake and others, severe non-structural building damage to hospital facilities also will lead to loss of bed capacity.

Up to 35 percent of the beds will be unavailable near the fault, where ground shaking intensities of MMI IX are postulated. Percentages of bed capacity loss will diminish to 30, 25, and 10 percent at sites with ground shaking intensities of VIII+, VIII-, and VII, respectively.

Highways

Damage to the highway system will be widely scattered throughout the Bay Area. There will be major closures in Santa Rosa, Petaluma, Napa, and along the north shore of San Pablo Bay. More distant effects will lead to freeway closures immediately south of the Benicia-Martinez Bridge, east of the Bay Bridge, and west of the Richmond-San Rafael Bridge. In general, the MMI VIII and IX areas where the highways are most vulnerable are north of Richmond and north of the most densely populated part of the Bay Area. Highway 37 across the tidal marsh north of San Pablo Bay will be damaged and unavailable for more than 3 days. Highways in the planning area that have not been seismically improved will have damage similar to that in the Loma Prieta earthquake.

Airports

Sonoma County Airport and Napa County Airport are crucial for immediate airlift into the most populated areas. Napa County Airport, which will be damaged and of limited use for 1 or 2 days, cannot take C-130 aircraft and will be restricted to small aircraft. Sonoma County Airport, which will be damaged but will remain open, can take C-130 aircraft, but not the larger C-141 aircraft.

Land transportation from three major regional airports (Alameda NAS, Oakland International, and San Francisco International) may be disrupted by potential bridge damage that could sever major highway links. In addition, liquefaction of soils under runways and taxiways is possible at these three major airports. Travis AFB, which is 25 miles (40 km) from the RCF rupture, has superb airlift facilities and is outside the damage area. It will be a major post-earthquake asset.

Marine Facilities

Most of the docks in the greater San Francisco Bay Area are supported on piles. These will be mostly unaffected as in the 1906 San Francisco and 1989 Loma Prieta earthquakes. However, tarmacs, aprons, access roads, and other paved surfaces placed over fill areas will fail due to settlement and spreading of soils owing to liquefaction.

Port facilities will remain 90 percent operational after the postulated earthquake once power is restored. If power outages are extremely heavy and service is not restored within 24 hours, operational effectiveness of the terminals will be reduced to 75 percent of normal capacity. Usable docks in the heavily damaged areas will require emergency power and special off-loading capabilities.

Military shipyard and terminal installations clustered in Oakland, Alameda, and Vallejo typically are on Bay mud and artificial fill. Substantial soil displacements in these areas will limit operations.

Railroads

The rail lines along Suisun Bay, San Pablo Bay, and the Carquinez Strait will be interrupted critically for the initial 3 day post-earthquake period. Low capacity rail lines along the north shore of San Pablo Bay will be displaced by liquefaction and closed for repairs up to 7 days as will be the lines at Black Point, Sears Point, and the Napa Slough areas.

All movable span bridges in MMI VIII+ and IX zones are subject to misalignment due to heavy ground shaking. Repairs will require up to a week. Because of electric power outages lasting up to 48 hours, the Benicia-Martinez lift span over the Carquinez Strait and the two pivot ridges over the Petaluma River will be inoperable. All three could be transfixed or jammed in either an open or closed position, blocking the railroad lines if open, or delta marine transport if closed.

Electric Power

During the first 3 days after the earthquake, virtually all portions of the planning area will experience some loss of power. The cities of Santa Rosa, Petaluma, and Sonoma will be strongly shaken areas (MMI VIII+ and IX) and will experience the longest power outages. Service to most areas of Santa Rosa will be restored in 24 hours, but some areas of the city may experience outages lasting as long as 5 days.

The earthquake will not shut down any significant power plant or interrupt other sources of supply, such as the 500 kV Pacific Intertie. Damage to PG&E facilities will be confined primarily to substations and distribution facilities. The Lakeville Substation, a critical link in providing service to the planning area, will be damaged and closed for up to 2 days. To continue service while repairs are being made, electric power will be distributed over alternate lines.

Damage to the distribution system (less than 60 kV network) will be significant in Sonoma and Napa counties, with up to 30 percent of service connections being without power for the first 36 hours.

Natural Gas

Principal sources of natural gas for the planning area are well outside the strongly shaken areas, and will not be damaged by the scenario earthquake. However, transmission and distribution lines will be damaged where they cross landslides, ground subject to liquefaction, and fault breaks. Areas served by these facilities could be without gas for as long as several weeks.

Damage to gas lines and facilities serving the central Bay Area, including San Francisco and the cities of the East Bay, should be minimal and repairs should be accomplished rapidly. Only in limited areas, such as the Marina District of San Francisco, will poor ground conditions result in substantial damage to distribution

systems and prolonged interruption of service. After the 1989 Loma Prieta earthquake, many distribution lines were repaired and upgraded for improved seismic performance. However, we expect that gas service will be disrupted again.

Fires will break out in the downtown areas of Santa Rosa, Napa, and Petaluma where older wood frame buildings are clustered in areas of potential liquefaction. Local fires fed by gas line breaks will occur in other communities, particularly those with MMI VIII or greater (e.g. Sonoma, Novato, and Vallejo). The damage to water supply services will make firefighting difficult, with complete fire control taking 2 days.

Water Supply

The water supply from the Sonoma County Water Agency intake structures along the Russian River near Forestville will be reduced due to a power outage and to aqueduct breaks caused by ground failure. Distribution and transmission lines traversing the Rodgers Creek fault will be damaged, with restoration taking at least 4 days. The cities of Napa, Petaluma, Vallejo, and Rohnert Park will have pipelines near rivers damaged by ground deformation caused by soil liquefaction, with restoration taking up to 2 weeks. The city of Santa Rosa will have lines damaged by fault displacement, with restoration taking up to 2 weeks. That portion of Santa Rosa west of the fault will be unable to get water from the many storage reservoirs to the east of the fault until repairs are made. Vallejo will have breaks due to ground deformations caused by liquefaction of soils on the east side of the Napa River, along the Mare Island Strait, and at the Benicia State Recreation Area.

Waste Water

Waste water lines that cross the Rodgers Creek fault will be damaged and open trenches may be needed to carry raw sewage for short distances. Facilities in the

city of Santa Rosa will be impacted by fault rupture and liquefaction. That portion of the collection system east of the fault will be cut off from the Laguna Treatment Plant. Major trunk lines such as the 36-inch crosstown trunk line will be severed.

The flow capacity of the collection system in areas of potential liquefaction will be reduced by 50 percent. Main effluent lines of the Napa, Novato, and Santa Rosa city systems will be interrupted with breaks where they cross areas of potential liquefaction.

Immediately after the earthquake, treatment plants without emergency power will shut down, discharging emergency treated raw sewage into holding ponds, creeks, rivers, and the Bay for up to 1 week.

Communications

The "off-hook" condition produced by intense shaking, coupled with intense call saturation will disable general telephone service for 6 hours or more. Within 20 miles (32 km) of the fault, essential services telephone lines will be 50 percent usable in the first day, and 75 percent usable at the end of the second day. Depending on the availability of power, the amateur radio service should remain more than 50 percent effective because of pre-disaster arrangements for use of bands reserved for emergencies. Remote satellite terminals relying on telephone or microwave circuits will be 40 to 50 percent effective. Antennas and related structures will remain 70 percent effective.

Petroleum

The several major petroleum pipelines in the planning area cross extensive areas of structurally poor ground near the bay margins. Ground failures resulting from liquefaction will cause differential ground movements that can damage pipes. Pipe connections at terminal facilities are similarly vulnerable due to the differing

response between buried pipe and rigid structures. Direct damage to refineries, most of which are of rugged construction, will be relatively modest in view of the large number of structures, tanks, and pipes involved.

For planning purposes, we assume that 10 percent of the flat bottom tanks at refineries and tank terminals in the planning area will buckle, and 5 percent will rupture and leak. We also assume that some post-earthquake refinery fires will occur. These will be suppressed within 4 days by plant personnel with on-site fire suppression systems that use water from the bay. Another related hazard is the release of toxic emissions from petrochemical processing or storage facilities.

PREVIOUS WORK

There are several pertinent publications that either concern the effects of nearby earthquakes in the planning area or help in assessing the hazard posed by the Rodgers Creek fault. Planning scenarios similar to this one are available for a M8.3 earthquake on the San Andreas fault (Davis and others, 1982) and for a M7.5 earthquake on the Hayward fault (Steinbrugge and others, 1987).

According to Toppozada and others (1992a), the southern end of the Rodgers Creek fault may have ruptured in 1898, producing a M6.7 earthquake that was destructive from Mare Island to Petaluma.

Except for the moderate locally destructive earthquakes of October 1969 (M5.6 and M5.7) (Steinbrugge and others, 1970; Cloud and others, 1970), it has been nearly a century since the last large event.

Schwartz and others (1992) have initiated paleoseismic work northwest of the probable 1898 rupture zone. Their preliminary results indicate that the slip rate was between 6 and 10 mm/yr during the last 750 years and that the recurrence interval at the midpoint of the fault is between 130 and 370 years. The most recent event at the midpoint occurred before 1808 and produced about 2 m (6 feet) of offset, which is indicative of a M7 earthquake. WGCEP (1990) calculated a probability of 22 percent for a M7 event occurring on the fault between 1990 and 2020.

The hazard produced by a particular event is heavily influenced by the geologic setting in which it occurs. The geology, including the outlines of some of the main landslides in the planning area, was summarized on the Santa Rosa 1:250,000 scale map of Wagner and Bortugno (1982). Similarly, liquefaction potential within the planning area was summarized by Sowers and others (1992).

A detailed map of the Rodgers Creek fault was released recently by Hart (1992), and an update on recent research concerning the fault was included in Borchardt and others (1992).

INTRODUCTION

This report assesses the vulnerability of lifelines to a major earthquake on the Rodgers Creek fault (RCF) in the North San Francisco Bay area. The first section provides the geology and seismology input for the study. Later sections assess the geologic and engineering damage to transportation and utility lifelines.

The Planning Area

The planning area, approximately centered on the Rodgers Creek fault, is 30 miles (50 km) wide and 80 miles (130 km) long (Figure S-1). The base map area includes San Francisco and Oakland, and the North Bay area including Napa, Sonoma, Petaluma, and Cotati Valleys. The map area covers portions of Marin, Sonoma, Napa, Lake, Solano, Contra Costa, Alameda, San Mateo, and San Francisco counties.

Approximately 4 million people reside in the planning area, with the greater concentration of population being in the Bay area south of the Rodgers Creek fault. The area encompasses most of the population of Marin, Sonoma, Napa, and parts of other counties. It encompasses virtually all the urbanized area likely to experience Modified Mercalli Intensities (MMI, refer to Appendix A) of VIII or greater resulting from this scenario earthquake. These are the areas within which significant damage will occur.

Earthquake Planning Scenario Maps

Maps are included in this report showing the locations of major transportation and utility lifelines and principal medical care, school, and fire station facilities. One map (Map S) summarizes the regional geologic and seismological basis for development of the scenario damage assessments. This basic geotechnical

information includes the location of the Rodgers Creek fault (RCF), the predicted shaking intensity distribution, the areas with potential for liquefaction, and areas subject to fault rupture and seismically induced landslides. This information enables the reader to visualize the extent to which particular facilities are exposed to the predicted shaking intensities and to ground failure hazards.

The ground surface will be deformed in areas of fault rupture and warping along the RCF, by liquefaction in the valleys and deltas, and by landslides in the mountains. Structures built on compressible deposits where the water table is high are subjected not only to the effects of relatively low frequency, high amplitude vibrations, but also to disruption caused by differential settlement or lateral spreading due to liquefaction. These considerations are reflected in the damage assessments.

Damage Assessments

Damage assessments have been hypothesized for various facilities, in order to plan for a worst case scenario. These damage assessments are based largely on the predicted intensity distribution and areas of potential ground breakage as shown on the Earthquake Planning Scenario maps. The assessments are based on the effects of past earthquakes, appraisals by engineers and public agency officials knowledgeable in earthquake damage effects, and professional judgment by the authors. Users of these data must recognize that assessments of the performance of individual facilities are hypothetical and are not the result of site-specific evaluations. They are intended to portray, for planning purposes, a representative range of the types of earthquake effects that will occur, thereby providing emergency planners and other users with a reasonable perspective on the impact of this scenario earthquake. The scenario assessments address mainly the first 3 days following the earthquake.

Use and Limitations of Scenario Maps and Damage Assessments

The general approach in formulating damage assessments was first to evaluate the regional pattern of ground shaking and ground deformation, second to visit representative sites in the field, and third to interpret the resulting earthquake performance of various major facilities. The effects of the scenario earthquake on individual bridges, power plants, or other lifeline elements, are based mainly on the authors' professional judgments and the experience from previous earthquakes. It is, therefore, improper to use the earthquake scenario for any purpose other than emergency response and preparedness planning. For example, decisions on whether to replace or retrofit lifeline elements must be based on detailed investigations of the elements and their specific geologic settings. This scenario does however, identify high risk areas where such detailed evaluations should be considered.

The damage assessments illustrate a regional damage pattern that is likely to result from an earthquake of M7 on the Rodgers Creek fault from Santa Rosa to San Pablo Bay. An earthquake of different magnitude or location on this fault, or an event on any one of many other faults in the planning area, would result in different intensity and damage patterns.

The predicted seismic intensity distribution from which the damage is assessed, is based on a particular model. There is no general agreement as to the most realistic model to be used for predicting intensity distribution, and a different model would yield a different intensity pattern. In addition, the quality of available information on which the seismic intensity distribution map is based varies throughout the planning area. Only general geologic information is available for most of the area. Modeling of ground shaking on a regional basis by using this generalized geologic information can produce plausible damage conclusions appropriate only for emergency planning. Conclusions regarding

specific structures, such as the desirability of upgrading seismic resistance, require detailed engineering analysis and site-specific geologic information.

While no scenario is accurate in detail, it provides planners with a regional pattern of the degree and a representation of the types of problems that will confront emergency response personnel.

We hope this planning scenario contributes to the efforts of the following users:

- Local, state, and federal officials with emergency planning responsibilities.
- Elected officials who need to visualize the threat to commit themselves to the leadership roles needed.
- Private sector managers and planners who must understand the scope of the hazard to prepare for it.
- Educators, journalists, and others who must communicate to the public the character of the threat, and the importance of preparedness in mitigating its effects.
- The general public who need to support public mitigation efforts and develop personal strategies to minimize the effects of the earthquake on themselves and their families.

SECTION 1

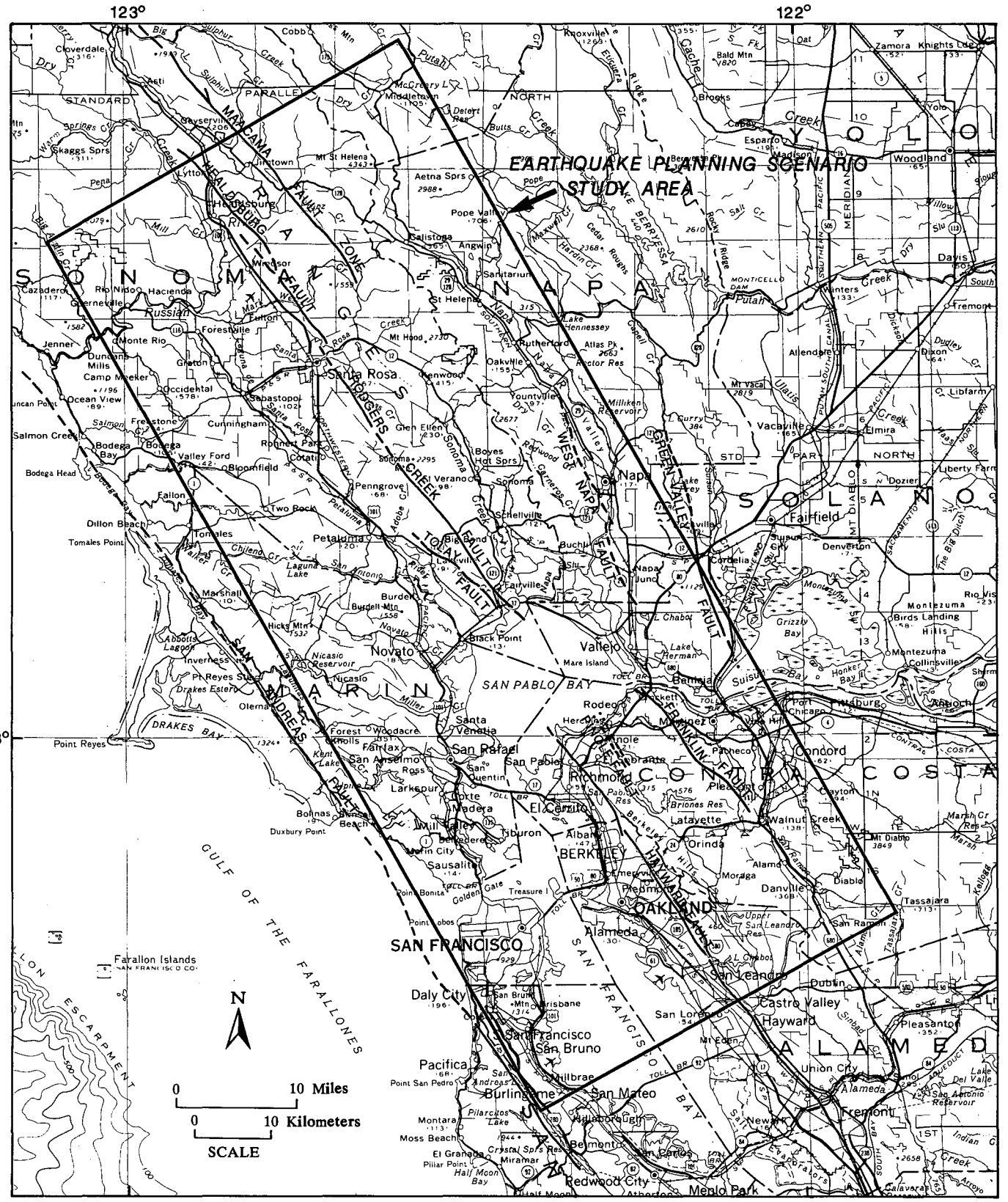
GEOLOGY AND SEISMOLOGY

THE RODGERS CREEK FAULT

Recent studies describe the Rodgers Creek fault as a major northwest trending extension of the Hayward fault (WGCEP, 1990; Budding and others, 1991; Schwartz and others, 1992). The zone comprising the Rodgers Creek fault also includes the Healdsburg fault, which extends from Healdsburg to Santa Rosa where it joins the Rodgers Creek fault, which reaches San Pablo Bay near Sears Point (Figure S-1). Evidence is accumulating that the Rodgers Creek fault continues across San Pablo Bay (Wright and Smith, 1992; Anima and others, 1992; Toppozada and others, 1992) possibly joining the Pinole fault on the south shore, where it takes a 6-km step to the Hayward fault. This scenario hypothesizes an earthquake of magnitude (M) 7 on the segment known as the Rodgers Creek fault.

The Rodgers Creek fault is an active, steeply eastward dipping, right-lateral strike slip fault (Wong, 1991) mapped from San Pablo Bay on the south to the city of Santa Rosa on the north. The total length of the Rodgers Creek fault for the purposes of this scenario is 26.5 miles (43 km). Most of the length of the Rodgers Creek fault lies within andesitic and basaltic flows of the Tertiary Sonoma Volcanics in the Sonoma Mountains. The fault is topographically expressed by scarps, linear valleys and troughs, sags, sag ponds, and right laterally offset streams along much of its trace. Large portions are obscured by massive landslides in the Sonoma Mountains.

The Working Group on California Earthquake Probabilities (WGCEP, 1990) has calculated for the Rodgers Creek fault a slip rate of 9 ± 2 mm/yr, a recurrence interval for major earthquakes of 222 ± 74 years, and a 30 year probability of 22 percent for a M7 earthquake.


123°
122°
38°
EARTHQUAKE PLANNING SCENARIO STUDY AREA
MAACAMA FAULT ZONE
HEALDSBURG-RODGERS CREEK FAULT
RODGERS CREEK FAULT
HAYWARD FAULT
WEST NAPA FAULT
GREEN VALLEY FAULT
HUNTER FAULT
TOLAY FAULT
SAN ANDREAS FAULT
FAULT
GULF OF THE FARALLONES
SAN FRANCISCO BAY
SAN PABLO BAY
SONOMA
NAPA
SOLANO
CONTRA COSTA
ALAMEDA
SAN FRANCISCO
OAKLAND
BERKELEY
Santa Rosa
Petaluma
Novato
Vallejo
Napa
Fairfield
Richmond
San Rafael
Daly City
Hayward
Fremont
Pleasanton
Livermore
Concord
Walnut Creek
Redwood City
Menlo Park
San Mateo
Burlingame
Pacifica
Farallon Islands
Point Reyes
Bodega Bay
Tomales Point
Dillon Beach
Bodega Head
Sonoma
Glen Ellen
Kenwood
Oakville
Rutherford
St Helena
Calistoga
Santa Rosa
Windsor
Healdsburg
Cloverdale
Geyserville
Mt St Helena
Mt Hood
Atlas Pk
Lake Hennessey
Milliken Reservoir
Lake Berryessa
Putah Creek
Cache Creek
Winters
Davis
Woodland
Dixon
Vacaville
Elmira
Suisun City
Fairfield
Benicia
Martinez
Pittsburg
Antioch
Concord
Pleasant Hill
Walnut Creek
Lafayette
Orinda
Moraga
Danville
San Ramon
Dublin
Pleasanton
Livermore
Castro Valley
San Leandro
Alameda
Oakland
Berkeley
Richmond
San Pablo
El Cerrito
Albany
Emeryville
Piedmont
Sausalito
Tiburon
Belvedere
Mill Valley
Corte Madera
Larkspur
San Anselmo
Fairfax
Ross
San Quentin
Point Bonita
Golden Gate
Treasure I
Point Lobos
Daly City
San Bruno
South San Francisco
Millbrae
Burlingame
San Mateo
Foster City
Hillsborough
Belmont
San Carlos
Redwood City
Menlo Park
Atherton
Palo Alto
Los Altos
Mountain View
Sunnyvale
Cupertino
Los Gatos
Saratoga
Milpitas
Fremont
Newark
Union City
Hayward
San Lorenzo
Alameda
Tracy
Mt Diablo
Mt Eden
Mt Vaca
Mt Tamalpais
Bolinas
Stinson Beach
Duxbury Point
Point Reyes
Inverness
Olema
Nicasio
Petaluma
Cotati
Rohnert Park
Cotati
Penngrove
Two Rock
Valley Ford
Bloomfield
Freestone
Occidental
Guerneville
Monte Rio
Jenner
Cazadero
Forestville
Sebastopol
Graton
Cunningham
Salmon Creek
Ocean View
Duncans Mills
Camp Meeker
Russian
Fulton
Mark West
Laguna de Santa Rosa
Petaluma
Adobe Creek
Sonoma Creek
Napa River
Napa Creek
Napa Valley
Napa Sonoma
Carneros
Yountville
Oakville
Rutherford
St Helena
Calistoga
Aetna Springs
Pope Valley
Howell Mtn
Angwin
Sanitarium
Deer Park
Bale Mtn
Knoxville
Middletown
Lower Lake
Clear Lake
Cobb Mtn
Big Sulphur Creek
Sulphur Creek
Putah Creek
Cache Creek
Capay
Esparto
Madison
Brooks
Zamora
Knights Landing
Yolo
Solano
Napa
Sonoma
Marin
Contra Costa
Alameda
Point Reyes Station
Drakes Estero
Abbotts Lagoon
Limantour
Drakes Bay
Tomales Bay
Bodega Bay
Bodega Head
Salmon Creek
Estero Americano
Estero de San Antonio
Laguna de Santa Rosa
Petaluma River
Petaluma Marsh
Sonoma Creek
Napa River
Napa Marsh
Suisun Bay
Grizzly Bay
Honker Bay
Montezuma Hills
Birds Landing
Collinsville
Suisun Marsh
Carquinez Strait
Mare Island
Vallejo
Benicia
Martinez
Pittsburg
Antioch
Port Chicago
Concord Naval Weapons Station
Lake Chabot
San Leandro Reservoir
Briones Reservoir
Pinole Point
Point Pinole
Point Richmond
Berkeley Hills
Oakland Hills
San Ramon Valley
Diablo Range
Mt Diablo
Tassajara
Alamo
Sycamore Valley
Livermore Valley
Altamont Pass
Tracy
Delta-Mendota Canal
California Aqueduct
Pacific Gas & Electric Co.
Southern Pacific
Northwestern Pacific
Sacramento Northern
Monticello Dam
Putah South Canyon
Lake Curry
Lake Sonoma
Lake Mendocino
Lake Pillsbury
Lake Berryessa
Lake Hennessey
Milliken Reservoir
Atlas Peak Reservoir
Rector Reservoir
Lake Herman

The Alquist-Priolo Earthquake Fault Zoning Act

The Alquist-Priolo Act was enacted in 1972 to mitigate the hazard of surface fault rupture along active faults in California. The purpose of this Act is to avoid locating structures for human occupancy across traces of active faults. Responsibilities for carrying out the provisions of the law are shared by State and local government. Specifically, the State Geologist (Department of Conservation, Division of Mines and Geology) is required to establish regulatory zones -- known as Earthquake Fault Zones (EFZ), formerly known as Special Studies Zones -- for those faults considered to be "sufficiently active and well defined as to constitute a potential hazard to structures from surface faulting or fault creep." Cities and counties must regulate most building projects within the EFZ's by requiring geologic investigations before issuing development permits.

The Division of Mines and Geology (DMG) has designated EFZ's for both the Rodgers Creek and Healdsburg faults. These faults are considered to have been active during Holocene time, and have a high potential for surface rupture in future major earthquakes. Copies of the seven EFZ maps involved in the scenario are appended to this report. Where more than one strand of the Rodgers Creek fault exists we chose the better defined, collinear segments to define a generalized fault trace for ground rupture during the scenario earthquake (Map S).

The effectiveness of the Alquist-Priolo Act varies from place to place, depending largely on how well the fault is defined. Even so, the law only applies to new real estate development and structures for human occupancy. Many older structures may sit astride active traces of the Rodgers Creek fault. The extent of damage produced by this scenario event will depend on the amount of displacement that occurs locally on the fault and on measures taken to mitigate the hazard.

EARTHQUAKE HISTORY

Earthquakes that have (or could have) caused damage in the area between Santa Rosa and San Pablo Bay are described briefly below.

1808

From 21 June to 17 July, 18 earthquakes were felt in the Presidio of San Francisco and caused some damage there. Little else is known about these events because the Sonoma Mission and Pueblo were not established until 1823. These events could have originated on neighboring faults such as the San Andreas, Hayward, or Rodgers Creek.

1836 June 10

Following the destructive Hayward fault earthquake of 1868, the local press reported that old time residents recalled a similar event in 1836 "the effects of which were felt along the foothills from San Pablo Bay to Mission San Jose. There were large fissures in the earth, and the shocks must have been much heavier than those we have lately experienced." Louderback (1947) interpreted this to indicate a source on the Hayward fault. On this basis, Toppozada and others (1981) assigned M~7 from the presumed extent of faulting. Consequently the shaking intensities between Santa Rosa and San Pablo Bay would have been comparable to the Modified Mercalli Intensity (MMI) VII to VIII (refer to Appendix A) effects observed in that area during the 1868 earthquake.

1855 August 27

This event was mildly damaging from San Francisco to southern Sonoma County. Toppozada and others (1981) estimated M~5 and a location on the northern shore of San Pablo Bay.

1868 October 21

The Hayward fault was the source of the destructive 1868 earthquake. Comparisons of the size of the isoseismals of the 1868 event to those of the 1984 Morgan Hill and 1989 Loma Prieta events give estimates averaging about M7.2 for the 1868 event (Toppozada and others, 1992b). In Napa, Santa Rosa, and Petaluma, the 1868 earthquake cracked walls and threw down chimneys. The recurrence on the Hayward fault of an earthquake of that size would be destructive to the present-day infrastructure throughout the metropolitan Bay area (Steinbrugge and others, 1987).

1892 April 19 and 21

These M~6.5 earthquakes were destructive between Vacaville and Winters (Toppozada and others, 1981; Toppozada, 1987). In Napa, Petaluma, and Santa Rosa windows were broken and plaster was knocked down. Several chimneys also fell at Santa Rosa.

1893 August 9

This event of estimated M~5 was located in southern Sonoma County (Toppozada, 1981), where it shook some plaster and chimneys down in Santa Rosa.

1898 March 30

This earthquake had an estimated M6.7 and probably occurred on the southern end of the Rodgers Creek fault (Toppozada and others, 1992a). The isoseismal map of this destructive earthquake is shown in Figure S-2. At the Mare Island Naval yard on landfill several buildings collapsed. Similar destruction occurred at Schellville and also on Tubbs Island, although the distribution of structures was sparse. At Vallejo hundreds of chimneys fell. At Petaluma 260 chimneys had to be rebuilt. At Sonoma scores of chimneys were cracked and twisted.

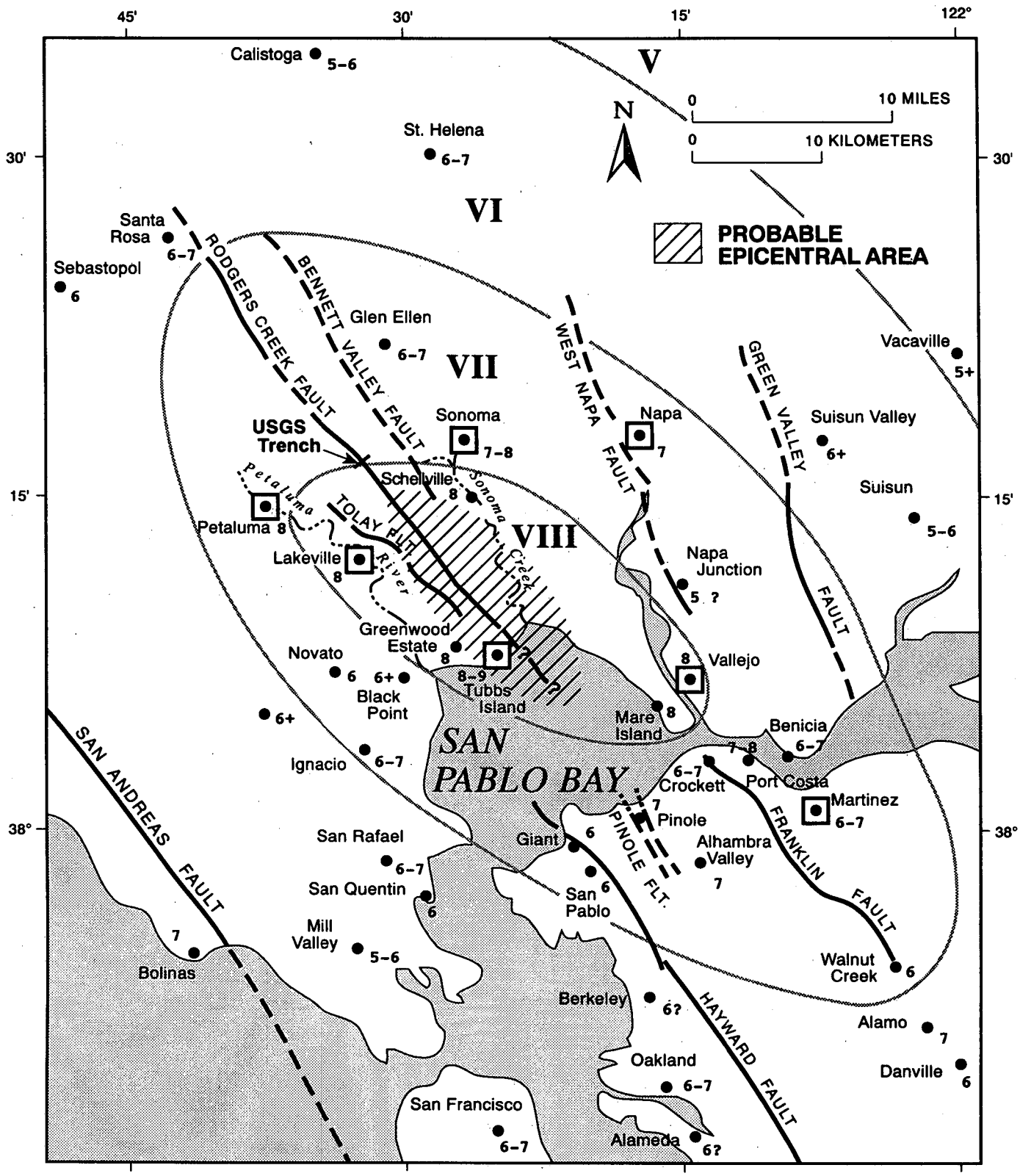


Figure S-2. Isoseismal map for the 1898 Mare Island earthquake (M6.7) showing the local faults and probable epicentral area. *From Toppozada and others (1992a).*

1906 April 18

This great earthquake (M~8) is popularly named for San Francisco, where much of the destruction occurred. The San Andreas fault ruptured for about 250 miles (400 km) between the counties of San Benito and Humboldt. Between these counties, MMI VII or greater effects extended from the coast to about 50 miles (80 km) inland (Lawson, 1908; Toppozada and Parke, 1982). At Santa Rosa seven to eight business blocks were destroyed by the earthquake and ensuing fire; 61 people died and at least a dozen were "missing". At Sonoma and Petaluma nearly all the chimneys fell.

1969 October 1

Two earthquakes of M5.6 and M5.7 separated by 83 minutes occurred in northern Santa Rosa near the juncture of the Healdsburg and Rodgers Creek faults. Serious damage was confined to Santa Rosa where hundreds of chimneys fell, brick walls cracked conspicuously, and some wood frame houses fell off their foundations or were otherwise seriously damaged (Steinbrugge and others, 1970).

THE SCENARIO EARTHQUAKE

Rationale for Selecting the Earthquake

The rationale for selecting the scenario earthquake on the Rodgers Creek fault zone is as follows:

- The RCF has been active during the Holocene epoch, which is the last 11,000 years (Hart, 1982).

- The WGCEP (1990) estimates a 30 year probability of 22 percent for an event of M~7 on the RCF.

- The RCF is part of an associated fracture zone consisting of the Hayward, Rodgers Creek, Healdsburg, and Maacama faults. This fault system extends 175 miles (280 km) from near San Jose to Mendocino County (Slemmons and Chung, 1982).

- Recently excavated trenches had evidence for several major pre-historic earthquakes on the RCF (Budding and others, 1991). These observations have led to the estimate of a minimum slip rate on the fault of 2.1 to 5.8 mm/yr for the last 1,300 years. The rate has been revised upward to
9 ± 2 mm/yr by WGCEP (1990), and to 6.4 to 10.4 mm/yr for the past 750 years by Schwartz and others (1992).

- The major pre-historic events noted above, and a lack of micro-earthquake activity along the RCF from the Sonoma Mountain to San Pablo Bay suggest that this segment of the fault is locked and accumulating stress. This conclusion is further supported by the lack of observable surface creep along the RCF, even though active creep occurs on the Maacama fault to the north and on the Hayward fault to the south (Lienkaemper and others, 1991; Lienkaemper and Borchardt, 1992).

- The 1898 Mare Island earthquake (M6.7), occurred near the southeastern end of the RCF and caused widespread destruction in and around Mare Island, Sonoma, and Petaluma (Toppozada and others, 1992a).

- The 1969 Santa Rosa earthquakes (M5.6 and M5.7) occurred near the northwestern end of the RCF and caused significant damage at Santa Rosa.

- The RCF is closely surrounded by the urbanizing valleys of Napa, Sonoma, and Petaluma, and traverses the city of Santa Rosa.

Characteristics of the Scenario Earthquake

Subsurface faulting extending 26.5 miles (43 km) on the RCF is postulated. The northern end is at Santa Rosa; the southern end is at San Pablo Bay. Surface faulting will be discontinuous, and occur mainly on the Holocene active traces shown on
Map S.

A 43-km fault rupture would produce a M7.2 (Bonilla and others, 1984), M6.8 (Wyss, 1979), or M6.9 event (Slemmons, 1982). M7 is assumed for planning purposes.

A maximum surface displacement of 6 feet (2 m) is predicted using Slemmons' relations. The more prevalent *average* displacement is usually half the maximum value, or about 3 feet (1 m). The displacement is assumed to be horizontal right-lateral strike slip. Minor dip slip or vertical components of faulting will occur locally.

Potentially damaging ground shaking continues for about 25 seconds within 25 miles (40 km) of the fault. Potentially damaging aftershocks occur for weeks following the main shock, with a few earthquakes in the M5 to 6 range.

Predicted Seismic Intensity Distribution

Introduction

To develop an earthquake planning scenario, it is necessary to estimate the regional patterns of ground shaking and permanent ground deformation. This

procedure is aided by assuming that the effects of the scenario earthquake can be deduced from previous earthquakes about which there is some knowledge.

Seismic ***intensity*** at a particular place is a measure of the felt and damaging effects of an earthquake. A numerical value at a given place conveys the various effects on buildings, furnishings, etc. Several intensity scales have appeared during the last century (Barosh, 1969). The Modified Mercalli Intensity (MMI) scale, used in the scenario, is reproduced and related to the Rossi-Forel scale in Appendix A.

Earthquake ***magnitude*** (M) is an instrumental measure of earthquake size, regardless of intensity effects or location. Earthquakes of similar magnitudes can have different reported maximum intensities depending on population distributions. For example the 1969 Santa Rosa earthquake (M5.7) had a maximum reported MMI of VII, while the larger 1980 Mono County earthquake (M5.8) had a maximum reported MMI of only VI.

The degree of ground shaking resulting from the scenario earthquake will depend on several factors. Among the most important is the distance from the Rodgers Creek fault. Generally, the amplitude of vibratory motion diminishes away from the source of excitation. The vibrations associated with earthquakes are complex. Characterizing their anticipated effects at specific locations is further complicated by variations in the geologic materials through which they pass. Consolidated bedrock transmits most seismic frequencies while unconsolidated alluvium preferentially amplifies low frequencies which could be damaging to multistory structures.

Development of Seismic Shaking Intensity Map

To prepare a regional intensity map for assessing lifeline damage, Reichle and Kahle (1986) developed an algorithm based on the Evernden model (Evernden and

others, 1973, 1981; Evernden, 1975; and Evernden and Thomson, 1985). This computer model calculates the MMI on a grid of reference points throughout a region by employing empirical equations that account for attenuation with distance from the fault source. These values are then adjusted for the influence of surface geology.

Reichle and Kahle's model is used in this scenario, and differs from that of Evernden and others (1981) in that it assumes that shaking intensity does not depend on depth to water table. Also, it predicts intensities for bedrock sites within 3 miles (5 km) of the fault and at distances greater than 25 miles (40 km) on unsaturated alluvium that are approximately 1 unit higher than Evernden's. The model was guided by the areal extent of MMI VII and VIII shaking for earthquakes of M~7 on other California faults, notably the 1868 Hayward (M~7) and the 1952 Kern County earthquakes (M7.7), and the 1989 Loma Prieta earthquake (M~7).

Development of the seismic intensity distribution Map S began with attenuation versus distance calculations plotted as ellipses centered on the Rodgers Creek fault. With distance from the fault, each successive ellipse is a tenth intensity unit less than the previous one. On well consolidated bedrock within a distance of 5 miles (8 km) of the fault the ellipses denote MMI VII; within 19 miles (30 km) they are MMI VI or greater. In areas of less consolidated ground, seismic intensities due to shaking can be up to 2 units higher. Therefore, for areas within 5 miles (8 km) of the fault, MMI IX will occur on the softest ground, while MMI VII will occur on the densest bedrock.

The geologic base data needed to adjust the calculated intensity values have been generalized from the San Francisco - San Jose 1:250,000 scale geology map of Wagner and others (1991) for the map area south of 38° latitude. For the area north of 38° latitude the geologic data were obtained from the Santa Rosa

1:250,000 scale geology map of Wagner and Bortugno (1982). Table S-1 lists the geologic units in the map area and the intensity adjustment factor assigned to each unit. The seismic intensity for consolidated bedrock is increased by this factor to include the effect of geology. Table S-1 is similar to Evernden and others (1981), but the factors are positive instead of negative, because the algorithm gives intensity for consolidated bedrock instead of for alluvium. Evernden and others (1981) have a range of 3 for the intensity adjustment factor. Our Table S-1 has a range of only 2 for the intensity adjustment factor, because we consider that shaking intensity on saturated Holocene deposits is only 2 units higher than on consolidated bedrock. Also, our classifications for some geological units differ slightly from Evernden and others (1981). For instance, shear wave velocities are higher in Plio-Pleistocene deposits than in Holocene deposits (Fumal and Tinsley, 1985). Thus we consider Plio-Pleistocene sedimentary deposits to be more consolidated and to have slightly less intensity amplification (+1.8) than Holocene sedimentary deposits (+2.0).

Intensities higher than MMI IX are not shown because MMI X through XII are generally attributed to the secondary effects of ground breakage. MMI X through XII may occur in the areas of potential ground breakage (faulting, liquefaction, landslides) identified on Map S.

Characteristics of the Seismic Intensity Distribution Map

Shaking

Intensities generally are highest at the fault and decrease with distance from the fault. This concentric pattern is modified by the areal distribution of geologic materials that respond differently to shaking. This accounts for the MMI being VII nearest the fault in the rocky area of the Sonoma Mountains, and for MMI IX occurring up to 5 miles (8 km) away from the fault in unconsolidated alluvium in Sonoma and Petaluma valleys.

TABLE S-1

GEOLOGIC UNITS AND SHAKING INTENSITY ADJUSTMENT FACTORS

GEOLOGIC MAP UNITS	INTENSITY FACTOR
Volcanic Rocks Santa Rosa quadrangle[1]: QTcv, PsV, Mbm, Mpt San Francisco-San Jose quadrangle[2]: Mpt, Mv^{b}, Mzv, Jv	+0.3
Jurassic and Cretaceous rocks Santa Rosa quadrangle: KJf, Jgd San Francisco quadrangle: KJf, Jgd, K1	+0.8
Jurassic through Eocene sedimentary rocks Santa Rosa quadrangle: Emk, Ec, Eum, Ed, En, Pmz, Ku, KJu, K1 San Francisco quadrangle: Emk, Ek, Ed, Em, En, Pmz, Ku, KJu, Kp	+1.2
Tertiary sedimentary rocks Santa Rosa quadrangle: Pwg, Pp, Msp, Mmy, San Francisco-San Jose quadrangle: Msp, Mmy, Mcc, Tu, TKu	+1.5
Plio-Pleistocene sedimentary rocks Santa Rosa quadrangle: QT San Francisco-San Jose quadrangle: QTm	+1.8
Quaternary sedimentary deposits Santa Rosa quadrangle: Q, Qls, Qi, Qo, Qt San Francisco-San Jose quadrangle: Q, af, Qi, Qs, Qls, Qc, Qo	+2.0

[1] Wagner and Bortugno (1982).
[2] Wagner and others (1991).

After applying the geological intensity factors listed in Table S-1, the corrected intensities were rounded to integer values. Half integers are shown only for the MMI VIII range: VIII- indicates 8.0 to 8.4, and VIII+ indicates 8.5 to 8.9. The half integers help to differentiate between Miocene deposits having a geological factor of 1.5 and Quaternary deposits having geological factors of 1.8 (Plio-Pleistocene) to 2.0 (Holocene), which will shake more strongly.

The map includes all urban areas affected by MMI VIII or greater, which extend throughout Napa, Sonoma, and Petaluma valleys, and to Vallejo, Richmond, and San Rafael.

Within the planning area, there are local zones where ground breakage could produce intensities greater than MMI IX, and these include:

a) Portions of the RCF where surface rupture occurs.

b) Areas where liquefaction occurs (e.g., Petaluma, Cotati, Mare Island, Napa, and San Rafael).

c) Areas where landslides occur in the hilly country north of the bay, and parts of the coastal Marin and Sonoma counties up to 25 miles (40 km) from the RCF (Figure S-1).

For example, MMI IX is indicated on the map in Rohnert Park, but the liquefaction potential is high there, and if liquefaction occurs, the intensity would be greater than IX.

Fault Rupture

The scenario earthquake postulates rupture of 26.5 miles (43 km) of the RCF (Map S), which is basically the segment defined by the WGCEP (1990). The seismic intensities at sites straddling the fault rupture could be higher than those indicated on Map S due to fault displacement.

Liquefaction

Areas with high potential for ground failure due primarily to liquefaction for the scenario earthquake were identified and plotted on Map S. Three factors must be present for liquefaction to occur within a particular foundation material:

1. A high water table.
2. Layers of loose sand.
3. Earthquake shaking of intensity greater than MMI VI.

A large area in the North Bay within zones of MMI VIII or greater is highly susceptible to liquefaction. This area is drained by the Petaluma River, Sonoma Creek, and Napa River and overlain with intertidal deposits (Qi). Other susceptible areas in the North Bay include narrow zones along the Napa and Petaluma rivers, and Sonoma Creek. The Laguna de Santa Rosa near Sebastopol is especially susceptible to liquefaction. Some areas of bay mud and some younger fluvial deposits in the East Bay, San Francisco, and Marin County are susceptible to liquefaction.

The areas delineated on Map S as having high potential for ground failure include all bay mud deposits (Nichols and Wright, 1971), all areas considered of high liquefaction potential by numerous authors, and most areas in which ground failure was noted in the 1906 San Francisco earthquake (M~8) (Youd and Hoose, 1978; Nason, 1980a, 1980b, 1982). For the area north of 38° latitude, the map was prepared from the recent compilation of Sowers and others (1992). The liquefaction potential has not been evaluated north of 38° 30′ latitude. Other basic data sources used in the map compilation are described by county below:

Alameda County: The data of Helley and others (1972) was the prime reference, with additional data from Legg and others (1982).

Contra Costa County: The Richmond area is generalized, with Zones I, II, and IV of Bishop and others (1973) considered susceptible to ground failure. To the east of Richmond we used unit III of the Contra Costa County Planning Department (1974), as modified north of Rodeo by using the data of Helley and others (1979).

San Francisco County: We used the data of Jacobs (1974), but excluded some dune sand at high elevations southwest of Lake Merced.

San Mateo County: In addition to the areas delineated "moderate to locally high" in liquefaction potential by Woolfe and others (1975), the younger basin (Qb) and beach deposits (Qs) of Lajoie and others (1974) were included. The alluvial fan deposits (Qy and Qyo) in the northeastern corner of the county are unlikely to fail (Lajoie and others, 1974) and were not considered susceptible to liquefaction in this scenario.

Seismically Induced Landslides

Areas subject to seismically induced landsliding (SIL) are shown on Map S. Not all the areas shown as susceptible to landslides will fail in this way, and small slides could occur in areas not shown as being susceptible. Also, as a result of the scenario earthquake, scattered landslides or rock falls may occur in susceptible areas outside of the planning area. In particular, a heavy rainy season could contribute to seismically induced landsliding west of the planning area along coastal California, and also east of the planning area along the Coast Ranges (Figure S-1).

The earliest DMG earthquake planning scenarios (Davis and others, 1982a; 1982b) mentioned the potential for SIL but did not show it on the map. The northern San Andreas scenario (Davis and others, 1982a) simply stated that routes through the Santa Cruz Mountains would be closed by landslides like those

produced in the 1906 San Francisco earthquake (M~8). The Hayward scenario (Steinbrugge and others, 1987) delineated areas subject to SIL. It used existing landslide maps and, where such maps were not available, simply delineated slopes greater than 30 percent as susceptible. Since the preparation of that scenario, specific techniques for analyzing SIL potential have been developed and used to produce a large scale map for San Mateo County (Wieczorek and others, 1986). These techniques can be applied on a site by site basis when the character of the bedrock is known (Wilson and Keefer, 1985), but for our regional analysis we used a more general approach. Lifelines are affected by two SIL effects: disrupted slides and falls, and coherent slides. Disrupted slides and falls include rock falls, soil falls, disrupted soil slides, and rock slides, and generally impact lifelines from above. Coherent slides include rock slumps, soil slumps, rock block slides and slow earth flows, and generally affect lifelines from below. We assume that falls can occur on slopes of greater than 70 percent throughout the planning area, and that slides can occur on slopes of greater than 30 percent in the MMI VIII and IX zones. Three steps were taken to prepare the SIL overlay:

1. Previously mapped landslides in the planning area, within 25 miles (40 km) of the fault, were included regardless of the shaking intensity. Data south of the 38th parallel are from Wagner and others (1991). Data north of the 38th parallel are primarily from Wagner and Bortugno (1982). Supplemental landslide data were obtained from Bortugno (1987), Manson (1988), Smith (1986), and Huffman and Armstrong (1980).

2. Slopes steeper than 70 percent have high potential for disrupted slides and falls. Loose materials at the angle of repose (typically between 33° and 37°, or 65 percent to 75 percent slope) require only a slight horizontal acceleration to cause them to tumble down slope. Disrupted slides and falls are common in MMI zones as low as VI (Keefer, 1984). There are many areas of 70 percent or greater slopes within the Rodgers Creek earthquake scenario planning area, but they are generally too small to show at our map scale.

Nevertheless, we expect some of the steeper areas to have disrupted slides and falls. These small areas include the steeper parts of some canyons in the Sonoma and Mayacamas mountains as well as other areas of the North Coast Ranges, the steeper flanks of some mountain peaks, steep rock escarpments, steep swales below ridge crests, landslide headscarps, and road cuts. Beneath each steep slope lies a "runout" zone wherein disrupted slides and falls may impact. Some of these slopes could be affected by coherent slides as well. These small, steep zones are not near populated areas, and should have only localized effects on lifelines.

3. Slopes of greater than 30 percent and less than 70 percent have a high potential for coherent slides if the MMI is greater than VII (Map S). The potential for SIL usually increases with slope, but even the most unstable materials seldom experience SIL unless the slope is over 30 percent (Keefer, 1984). If the earthquake occurs in conjunction with unusually high moisture levels associated with the end of the rainy season or with improper drainage, even normally stable materials may fail. In the 1989 Loma Prieta earthquake (M7), coherent slides mostly occurred in areas of MMI greater than VII (Spittler and others, 1990; Manson and others, 1991). Consequently in this scenario, we assume that coherent slides will occur only on slopes steeper than 30 percent in areas of MMI greater than VII. Coherent slides have been observed at MMI VII or less (Keefer, 1984), but in these zones we assign relatively high potential for SIL only to areas of previously known landslides and to disrupted slides and falls on slopes of greater than 70 percent.

Comparison to the 1906 San Francisco and 1989 Loma Prieta Earthquakes

In the Sonoma County area the Rodgers Creek scenario earthquake (M7) will generate MMI up to VIII and IX as occurred in the 1906 San Francisco earthquake

of M~8. This can be seen by comparing the 1906 intensities within about 30 km of Santa Rosa from Figure S-3 with the scenario Map S.

The Bay Area, including San Francisco and Oakland, will experience much the same kind of damage as in the 1989 Loma Prieta earthquake. Because ground motion intensities in areas to the north will be higher for the Rodgers Creek earthquake, there will be even greater damage in these areas. For example, in Richmond the Loma Prieta earthquake produced MMI VI, whereas the Rodgers Creek earthquake will produce MMI VII (Figure S-4).

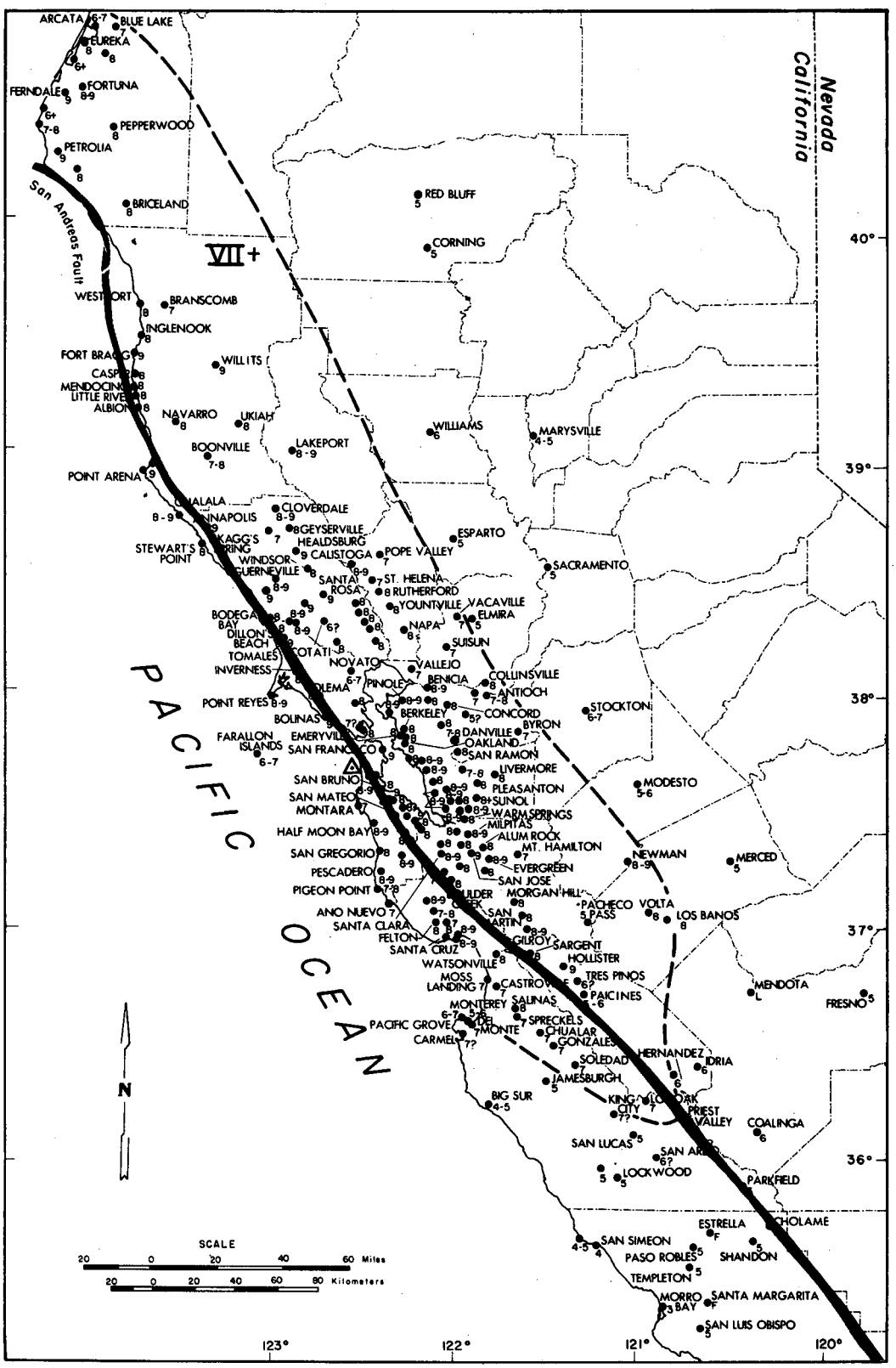


Figure S-3. Felt intensities for the 1906 earthquake of M~8. ***From Toppozada and Parke (1982).***

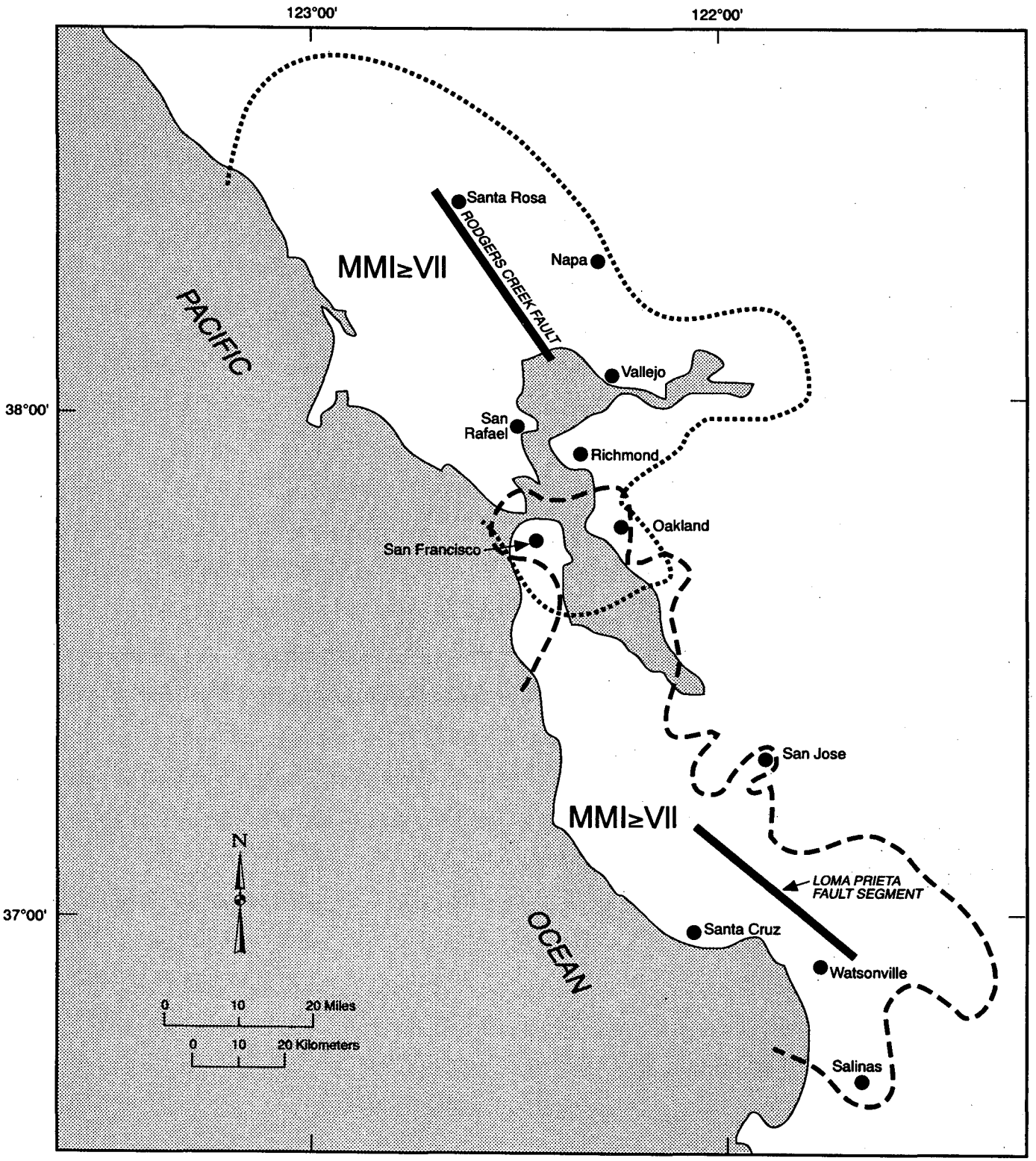


Figure S-4. Comparison of the areas shaken at MMI VII or greater by the Rodgers Creek scenario earthquake (dotted contour) and the 1989 Loma Prieta earthquake (dashed contour). The distance of San Francisco and Oakland from the Rodgers Creek fault is half that from the Loma Prieta fault segment.

SECTION 2

BUILDINGS AND STRUCTURES

BUILDINGS

Introduction

Most buildings along coastal California will be subjected to a major damaging earthquake at one time or another. Current seismic provisions in California building codes are intended to protect life and reduce property damage. By establishing the year 1933 (Long Beach earthquake) as an applicable baseline in the development of earthquake-resistant design, it has become possible to develop a general relative scale of the vulnerability of representative building classes to earthquakes. The development of seismic building codes and improved earthquake-resistant design since 1933 provides us with relationships between building classes, construction types, and their seismic performance that allows for the damage assessment of classes of structures on a collective, technical, and probabilistic basis.

Earthquake scenarios describing damage patterns can never predict precisely what will occur, but they can give emergency planners an idea of the general nature of the disaster. A truly scientific statement that a building, facility, or lifeline system will survive, remain operable, or be severely damaged, can be given only in probabilistic terms.

> "In a parallel situation, one cannot predict that a person who is driving under the influence of alcohol will certainly have an accident, but one can state that the probabilities are significantly higher than if he were not. Knowing building construction types and past earthquake performance of structures with given characteristics, realistic scenarios of probable damage can be developed for use in disaster response planning. ...The numerical values associated with each response planning topic represent reasonable maximum expected conditions. In other words, these values are credible; they have past data or experienced judgment behind them. The quality of the numbers vary depending upon the extrapolation of past data, the reliability of the assumptions supporting the calculations, and the quality of judgment behind the decisions" (Steinbrugge and others, 1987).

The effect that earthquakes have on buildings and facilities depends on many variables, including:

1. Magnitude of the earthquake.
2. Geological characteristics of the site.
3. The earthquake's focal depth.
4. Severity and duration of ground shaking.
5. Character of ground response according to soil types.
6. Code provisions in force at the time of the building's design.
7. Building construction type, configuration, and size.
8. Quality of construction.
9. Proper building maintenance.

One of the most important variables used to assess a building's seismic performance is its date of construction, because this determines the performance standards that governed the original design and construction. Because building code provisions normally are not retroactive, most existing buildings have not had the benefit of recently developed performance standards.

Seismic Considerations

Building Damage and Ground Motions

The success with which a building responds to the dynamic loads induced by earthquake ground motion determines the level of its seismic performance. As intended by the code governing earthquake-resistant design, seismic performance standards for buildings currently lean toward the protection of life and are only partially directed toward damage control. The exceptions include the 1972 California Hospital Act, enacted after the 1971 San Fernando earthquake (M6.4), and the Field Act for public school safety, enacted after the 1933 Long Beach earthquake (M6.3). Both will be discussed later.

The current building code, to be updated in 1994, maintains that seismic design will "resist major earthquakes of the intensity or severity of the strongest experienced in California without collapse, but with some structural as well as

nonstructural damage." In addition, the code states that "In most structures, it is expected that structural damage, even in major earthquakes, could be limited to repairable damage." Design for damage control usually encompasses life safety, but design for life safety does not necessarily include damage control. As an understanding of this philosophy is important, the following description of earthquake ground motions and building response is abstracted from Steinbrugge and others (1987):

> "The seismic motions at the source of destructive earthquakes are generally rapid and irregular oscillatory motions having large amplitudes. Of considerable significance is the fact that earthquake waves change in character as they travel away from their energy sources. Human observations as well as seismographic records show that the very rapid and violent ground oscillations (short period motions) in the epicentral regions are quickly damped and dispersed, leaving principally slower long-period motion at the greater distances from the earthquake source. The greater the distance, the slower the observed predominant oscillations. The predominant oscillations at large distances from the earthquake can be so gentle that they may not be felt by all persons, and yet be strong enough to cause water in reservoirs to oscillate with some destructive effects."
>
> "Buildings respond differently to different kinds of ground motion. Each building has its own specific vibrational characteristics based on its stiffness. Each building will therefore respond to the particular ground motion at the site in a specific manner. One of these vibrational characteristics is termed the structure's natural period of vibration. In general, the taller the building, the longer is its natural period of vibration. If the building's natural period of vibration roughly coincides with a few cycles of the principal motions of the earthquake, quasi-resonance or a condition similar to near-resonance will occur. As a result of this quasi-resonance, the vibratory motions of the building may dramatically increase, along with damage. Damage from quasi-resonance is generally observed in taller buildings from distant earthquakes."
>
> "Based on the changes in ground motions as a function of increasing distance, observed damage patterns tend to reverse with distance. Damage to low, rigid (short-period) buildings predominates over high-rise (long-period) damage in the epicentral and energy-source regions nearer the fault. At a distance over 100 miles, for example, high-rise building damage may predominate over that of even poorly built one-story structures. This was dramatically evidenced in Mexico City during the September 1985 earthquake."

"The historical damage patterns are associated with short-period motions (i.e., rapid back-and-forth motions). Isoseismal maps are based on short-period effects."

"In general, light mass structures perform much better than do heavier mass structures. Conceptually, this is due to the fact that the ground moves away from the structure during an earthquake, and the structure must follow these movements. The heavier the mass of the structure, the greater will be the inertial (resisting motion) force on the structure. Therefore, a "heavy substantial" building which is not designed to be earthquake resistant is more likely to fail than a "flimsy" wood frame structure. Countless examples of this exist throughout the historic record."

"Long-period motion principally affects high-rise buildings. An excellent example of long-period is demonstrated by the 1952 Kern County, California, earthquake. This earthquake resulted in numerous instances of non-structural damage to multi-story steel or concrete frame buildings in Los Angeles and Long Beach, but essentially no damage to one-and two-story buildings of any kind in the same area. These cities are located 70 to 90 miles from the epicenter. Generally, the affected buildings were 10 to 12 stories high and had a measured natural period of vibration of 1 to 2 seconds, but buildings as low as 6 stories were also damaged. (The many modern high-rise structures of over 20 stories did not exist then.")

Historically, building codes have been one of the principal means for reducing the destructiveness of earthquakes. Earthquake-resistant designs have been highly effective, with the seismic performance of structures improving with each improvement in the code. Exceptions have occurred when:

a) The design is an ill-advised interpretation of minimum design standards.

b) The building is not built according to the architect's or engineer's drawings and specifications (e.g., poor inspection).

c) The building owner unwittingly weakens critical structural components of the building during remodeling.

Special Earthquake Hazard Mitigation Legislation In California

The Field Act

After the 1933 Long Beach earthquake, California developed the first set of seismic provisions to be placed in the building code. At the same time, the California Field Act for the safety of public schools was enacted into law by the state legislature and assigned to the Office of the State Architect regulatory powers over public school design and construction. As evidenced by the 1952 Kern County, 1983 Coalinga, and 1987 Whittier-Narrows earthquakes, these new construction standards proved to be successful. In the 1989 Loma Prieta earthquake the Marina Middle School served as a shelter for the homeless and as an emergency services command post in the severely damaged Marina District of San Francisco.

As originally enacted, the Field Act applied only to new public schools (private schools were not included in the mandate). Because the act was not retroactive, all remaining older public schools throughout California continued to be used. However, in 1969, the Garrison Act addressed the difficult task of abating the hazard posed by the older public schools. It required the abatement of hazardous older schools by 1977 (later extended to 1978 to accommodate a few local public school districts). Non-Field Act public schools are now essentially gone, although older private schools still exist as an earthquake hazard.

Hospital Act and Unreinforced Masonry Building Act

Three other earthquake laws were enacted in 1972, 1986, and 1993, which focused on specific building types:

1. The Hospital Act which was adopted after the 1971 San Fernando earthquake.

2. The Unreinforced Masonry Building (URM) Act (also known as SB 547 and later as Section 88-75) enacted in 1986.

3. An earthquake hazard disclosure requirement for residential dwellings was adopted as part of the Provisions in the Business and Professional Code (originally proposed as AB 200) in January 1993.

Potentially Hazardous Buildings

Earthquake experience has shown that certain types of buildings have had a much greater incidence of severe damage than others. These are often designated as potentially hazardous buildings. The most common types of potentially hazardous buildings found in the Napa and Sonoma county areas, and affected parts of Solano and Marin counties, include:

1. Unreinforced masonry buildings.
2. Pre-1940 wood frame houses.
3. Pre-1973 tilt-up concrete buildings.
4. Non-ductile concrete buildings.
5. Mobile homes.

Each of these is discussed below. Planners must be aware of the hazards that these buildings present, along with the consequences for the local community when they fail.

Unreinforced Masonry Buildings

These are old brick buildings (Figure B-1) built in the 1930's or before. Most are historic structures. Unreinforced masonry (URM) structures, particularly bearing-wall structures, are classified as one of the more hazardous forms of construction found in the United States. After a strong earthquake, URM structures still standing near the epicenter usually are so heavily damaged that demolition is required.

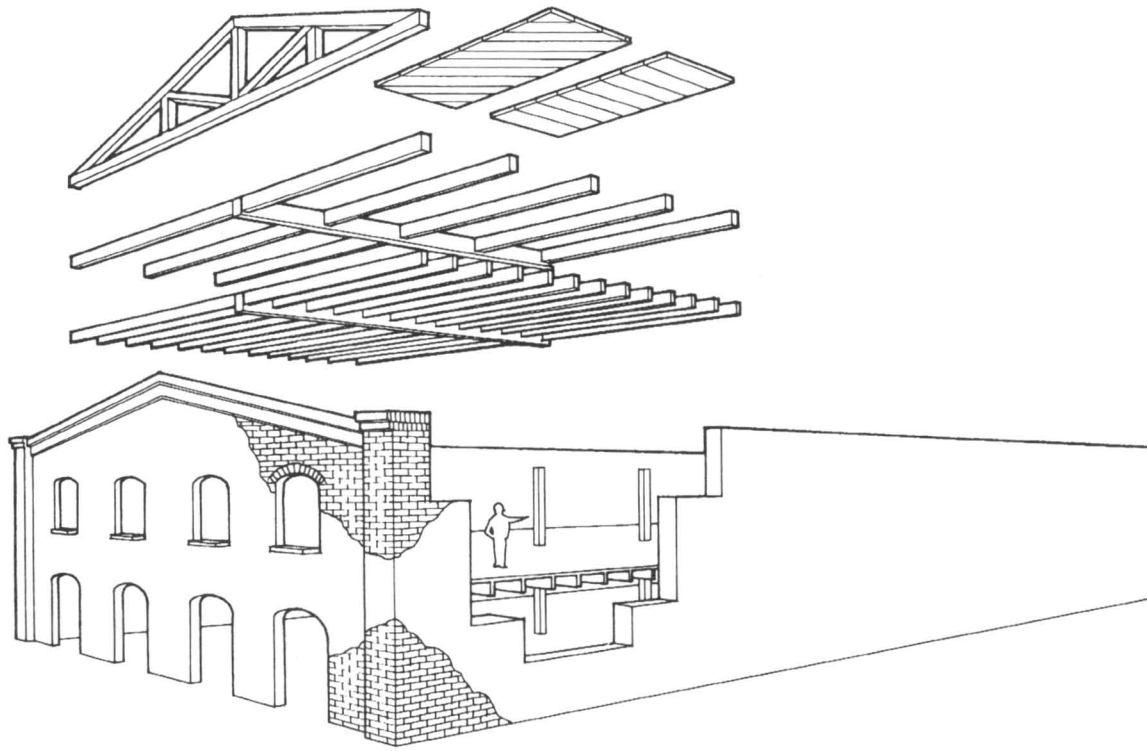


Figure B-1 Typical unreinforced masonry bearing wall building (URM). *From Lagorio and others (1986).*

URM buildings have several typical characteristics. First, they do not have steel reinforcing in the walls, hence the name "unreinforced masonry." Second, they are often built with weak mortar, or mortar that as deteriorated with age. Some of these buildings lack metal ties connecting the walls with floor or roof structural members. It is this latter characteristic, in particular, that makes these structures a hazard. During an earthquake, exterior walls often fall outward, creating a serious life-safety risk to pedestrians or people running from the building (Photo B-1).

Cities located in Seismic Zone 4 in California have been required by the State, under SB 547, to identify URM buildings in their jurisdiction and notify the owners, and to begin a program of hazard mitigation.

The seismic strengthening of URM buildings is a risk reduction measure. Retrofitted buildings have greatly improved resistance to collapse of walls and



Photo B-1 Unreinforced brick buildings frequently lose parts of walls in earthquakes. Falling brick is a major life-safety concern. This structure was damaged in the 1987 Whittier earthquake. *Photo by Ronald Gallagher.*

parapets, but the seismic resistance of these structures is less than that of new construction built to the latest seismic codes. After the scenario event, many retrofitted URM's will be economically unrepairable, and some may collapse.

URM Buildings in North Bay Counties of the Planning Area

As in other jurisdictions of the San Francisco Bay Area, principal cities in the planning area, in the four North Bay counties of Marin, Napa, Sonoma, and Solano, have an inventory of these old URM buildings. Typical occupancy of this building class tends to be related to industrial, commercial/mercantile (retail stores, offices, etc.), multi-residential (apartments), and hotel uses.

URM buildings in Santa Rosa were seriously affected by the small earthquakes of October 1, 1969 (M5.6 and M5.7). According to Steinbrugge and others (1970):

"The earthquakes were not strong enough to cause building collapse, although one major brick wall partially fell, other brick walls were cracked or partially failed, hundreds of brick chimneys toppled, and a number of older wood frame dwellings fell off their foundations or were otherwise seriously damaged."

... "Damage to approximately $5,000,000 worth of commercial buildings in the central business district occurred. In this area, according to available reports, it appears that:

1. Twenty-one buildings were damaged beyond repair and must be demolished.
2. Thirty-five were damaged but are capable of being repaired to meet vertical load requirements, but not lateral load requirements.
3. Eighteen were damaged but can be repaired to meet vertical and lateral load requirements."

"The principal damage to non-dwelling construction was in the older commercial areas located in the heart of the city. This district is approximately bounded by South "A," Montgomery Drive, and Seventh Street. The damaged structures were usually old brick bearing wall buildings with sand-lime mortar. None of the damaged brickwork was reinforced, and none was even remotely earthquake resistive by today's standards."

"There was little new in the damage patterns to heavy-mass non-earthquake-resistive structures. However, the damage did seriously affect the downtown mercantile area, and had the potential of causing serious disruptions in the commercial life of the city" (Steinbrugge and others, 1970).

After the Santa Rosa earthquake series of 1969, the City of Santa Rosa implemented an urban renewal program in the damaged downtown area. The program required special bracing for salvaged URM buildings.

Table B-1 lists URM building inventories of nine principal cities having the SB 547 program in place in the four North Bay counties located closest to the RCF. We visited all nine cities and inspected them with reference to the size, density, and location of their URM buildings. As seen in Napa, Petaluma, and Santa Rosa (Figures B-2, B-3, and B-4) the URM buildings typically are clustered in and

around the central business district. They range from one to three or four stories in height. In Petaluma and Santa Rosa, a total of 62 URM buildings have been upgraded.

TABLE B-1
UNREINFORCED MASONRY BUILDINGS IN THE PLANNING AREA

City	County	Total No. of URM Bldgs.	Number Upgraded	Number Demolished	MMI* in Scenario
Novato	Marin	13	3	N/A	VIII+
San Rafael	Marin	42	N/A	N/A	VIII-
Napa	Napa	52	N/A	N/A	VIII-
Vallejo	Solano	46	19	0	VII, VIII-
Healdsburg	Sonoma	16	N/A	N/A	VII
Petaluma	Sonoma	98	30	0	VIII+
Santa Rosa	Sonoma	66	32	6	IX
Sebastopol	Sonoma	56	N/A	N/A	VIII-, VIII+
Sonoma	Sonoma	17	7	N/A	VIII+, IX

* Refer to Map S

Most of the URM buildings listed in Table B-1 are in areas in which the scenario event will produce shaking intensities of MMI VIII or MMI IX. In the past, such intensities have produced severe and extensive damage to URM buildings. For planning purposes, we assume that severe damage or collapse will occur to URM buildings in Santa Rosa, Sonoma, Petaluma, Novato, and Sebastopol. Major damage will occur to URM buildings in San Rafael, Napa, Vallejo, and Healdsburg.

Loma Prieta data on the seismic performance of URM buildings (e.g., Table B-2), lifelines, and other facilities in the rest of the planning area are available through the *National Clearing House for Loma Prieta Earthquake Information Catalog, October 1992*, The National Information Service for Earthquake Engineering (NISEE), Earthquake Engineering Research Center (EERC), University of California at Berkeley, and the Earthquake Engineering Library, California Institute of Technology (CALTECH), Pasadena, California.

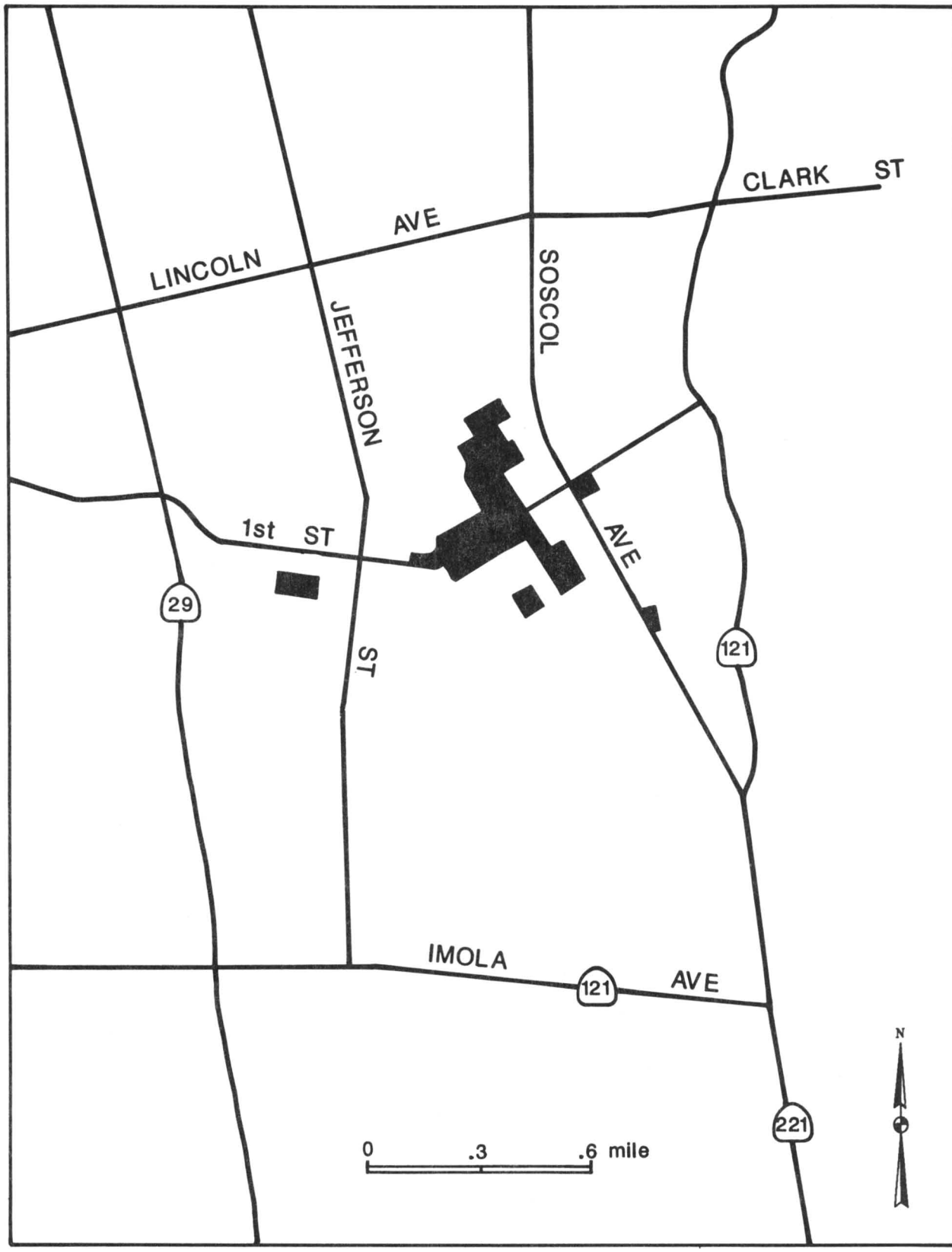


Figure B-2 Generalized location map of URM buildings in Napa.

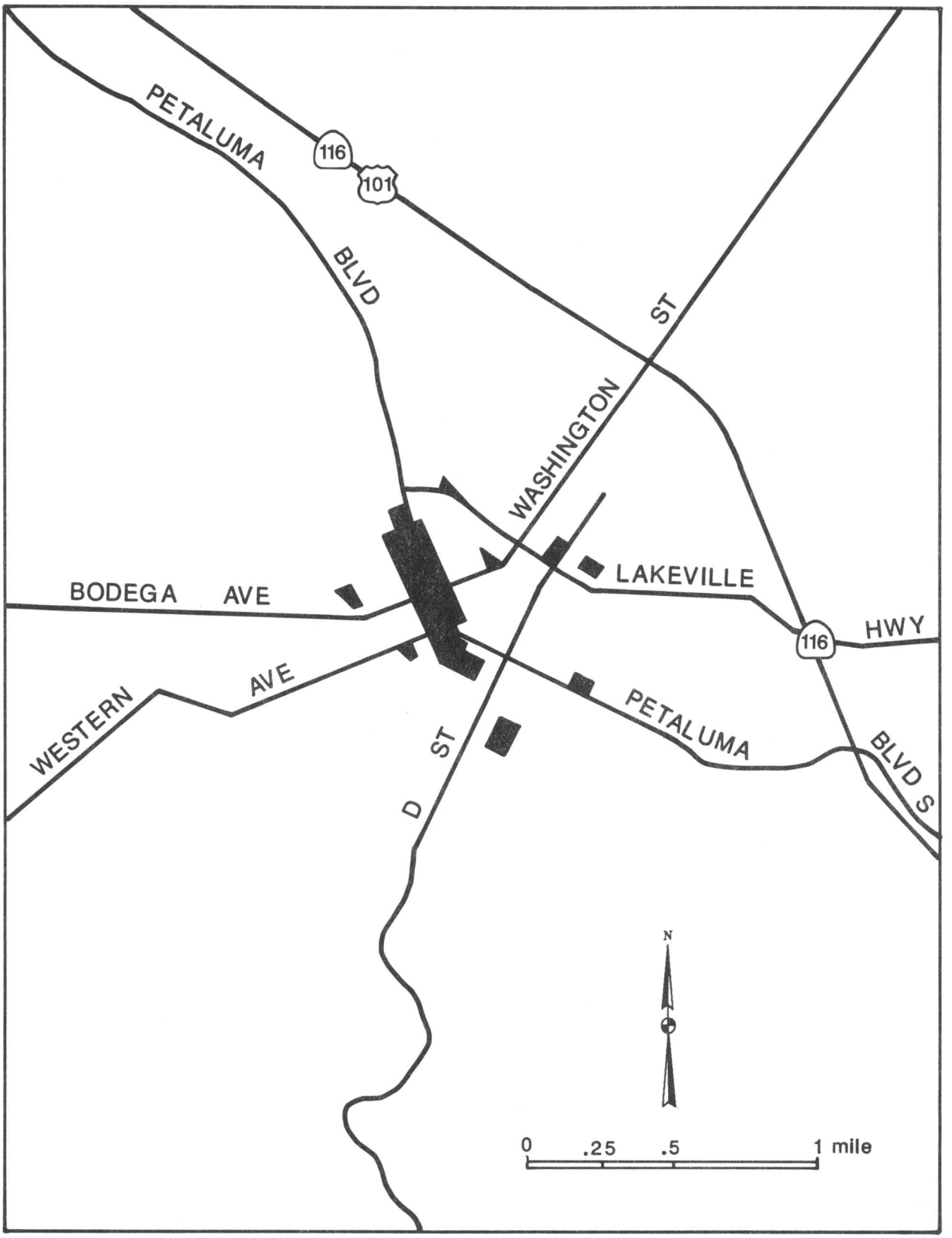


Figure B-3 Generalized location map of URM buildings in Petaluma.

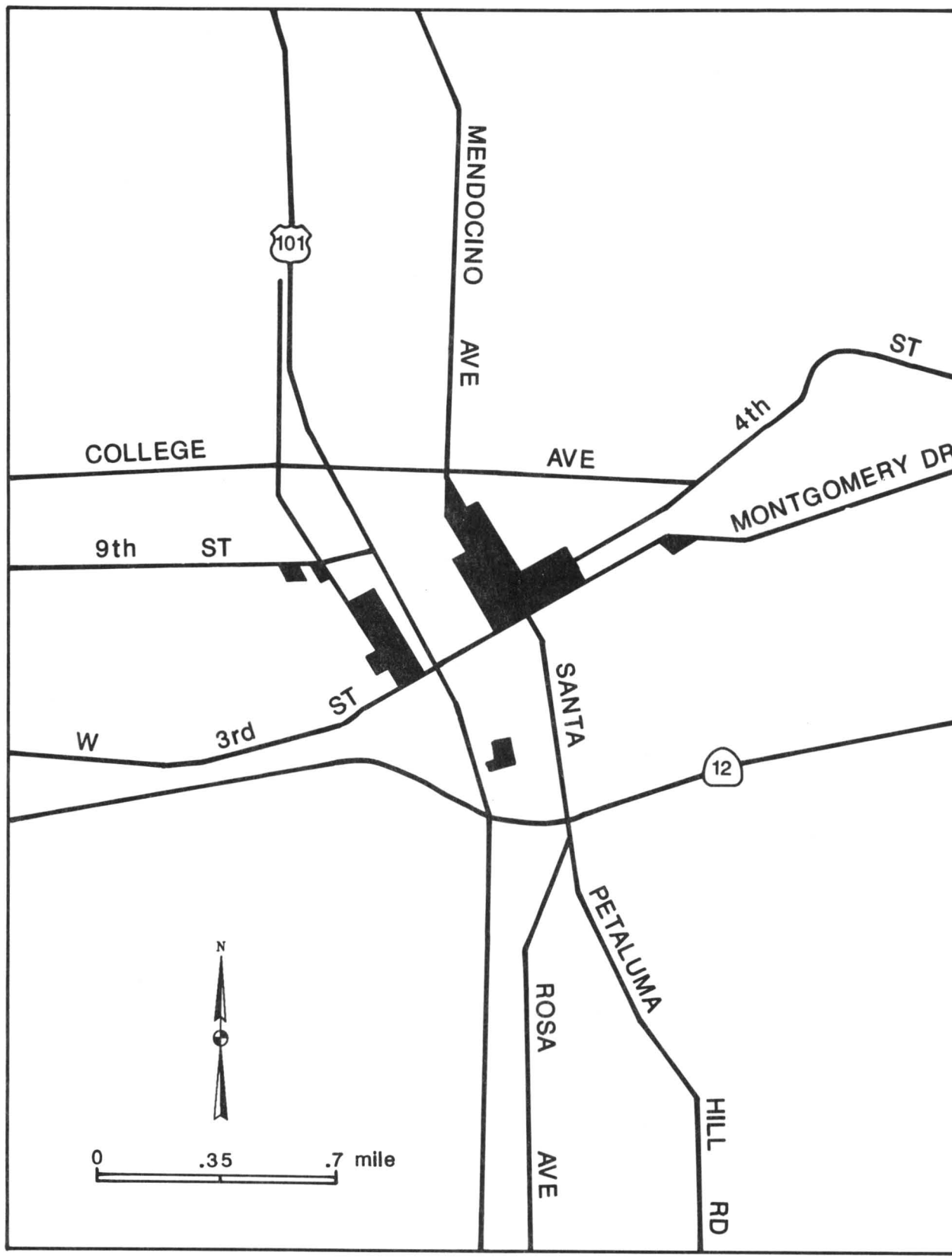


Figure B-4 Generalized location map of URM buildings in Santa Rosa.

TABLE B-2
TYPES OF DAMAGE TO UNREINFORCED MASONRY BUILDINGS IN THE CITY OF SAN FRANCISCO DURING THE 1989 LOMA PRIETA EARTHQUAKE

TYPES OF DAMAGE	NUMBER OF BUILDINGS
Falling individual units or trim	103
Veneer damage or delamination	100
Falling of portion of the wall	61
Falling of entire wall	36
"X" cracks in spandrels	125
Vertical cracking at edge of spandrel	176
Piers or walls ("X" or stepped cracking)	198
Horizontal cracks at top/bottom of pier	201
Damage from debris from adjacent buildings	7
Roof or floor failure due to movement of exterior wall	13

From EERI, 1990.

"Much of the spectacular building damage that resulted from the Loma Prieta earthquake was suffered to pre-code structures, principally the unreinforced masonry type (URM). Such buildings, constructed of wood-frame roof and floor systems supported by thick unreinforced brick walls, were commonly constructed throughout California before the adoptions of building codes with provisions to make buildings seismic-resistant. ...Unreinforced masonry buildings failed in areas close to the earthquake epicenter and as far away as San Francisco and Monterey. ...The major shaking in and around Santa Cruz contributed to heavy damage to the unreinforced masonry buildings, particularly in the Pacific Garden Mall. Because unreinforced masonry buildings are non-ductile, brittle structures whose lateral systems are incapable of dissipating energy in an inelastic manner, the strength of these short-period buildings must exceed the product of their reactive weight and the peak ground acceleration in order to survive seismic shaking. Many of the buildings failed. The observed modes of failure were similar to those that occurred in other earthquakes: out-of-plane brickwork failure, diaphragm flexibility/failure, in-plane brickwork failure, and pounding" (EERI, 1990).

Pre-1940 Wood Frame Houses

Wood frame construction (Figure B-5 and Photo B-2) is probably the most common in California. Most wood frame structures are single-family dwellings with wood stud walls. Well-designed wood frame structures have had a good earthquake performance record, but, as indicated below, an important class of wood frame dwelling has had major problems.

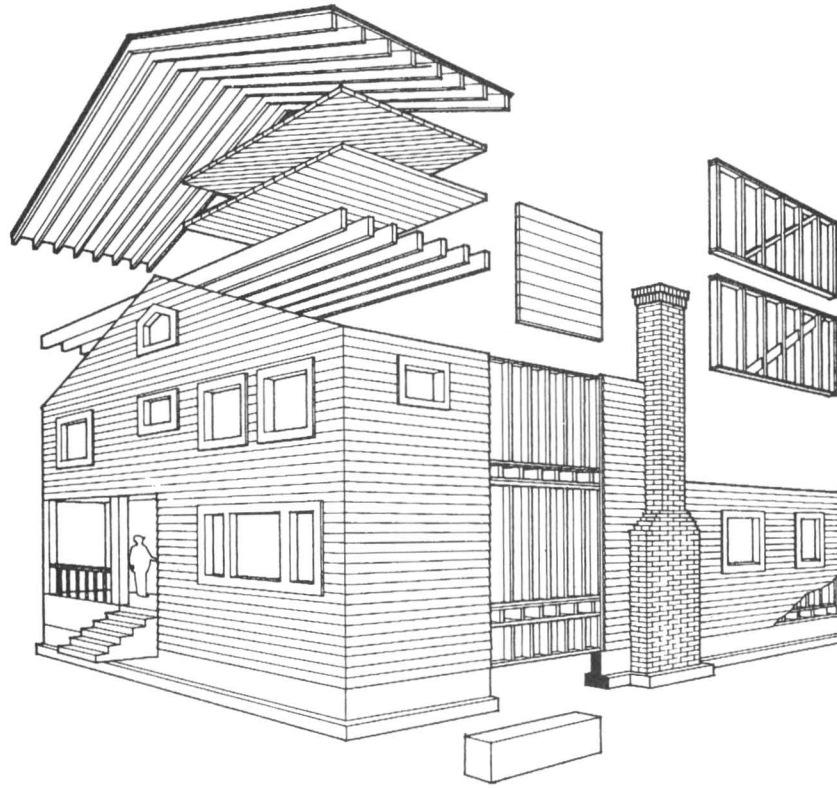


Figure B-5 Typical pre-1940 wood frame. *Lagorio and others, 1986.*



Photo B-2 This two-story pre-1950 wood frame house shifted off its foundation in the 1989 Loma Prieta earthquake. While damage is often repairable, occupants must find other shelter during reconstruction. *Photo by Ronald Gallagher.*

Wood frame dwellings built before 1950 have often shifted on or fallen from their foundations in earthquakes. This has been due to lack of foundation anchorage, or to weak cripple walls between the foundation and the first floor. While the risk to life is small, repairs can be expensive, and the occupants must find new shelter during the reconstruction.

During the 1989 Loma Prieta earthquake, damage to pre-1940 houses was widespread in the strongly shaken areas. Dozens of pre-1950 Watsonville houses shifted off their foundations (Photo B-2). While much of this damage was repairable, it imposed an added burden on the community of finding shelter for the inhabitants of these dwellings at a time when community resources were already severely taxed.

The State of California recently enacted, under AB 200, a requirement for earthquake hazard disclosure for residential dwellings. After January 1, 1993 (as required under provisions of the Business and Professional Code), all transfers of 1- to 4- unit dwellings of conventional wood frame construction must deliver to the purchaser a copy of the *Homeowners Guide to Earthquake Preparedness*. The transferor is required to complete the earthquake hazards disclosure part of the Guide. This legislation is intended to identify such hazards as unanchored (i.e., unbolted) foundation plates, unbraced cripple walls, and inadequately anchored water heaters.

In the 1969 Santa Rosa earthquakes, the dollar losses to dwellings were placed at $4 million. At the time, dwellings in Santa Rosa were generally one-story and two-story single family detached wood frame structures. According to Steinbrugge and others (1970):

> "Earthquake damage to these wood frame dwellings in Santa Rosa was greater than that experienced in recent California earthquakes of similar Richter magnitude. It is thus necessary to refer back to the 1933 Long Beach, California earthquake for substantially greater damage. The

magnitude of the Long Beach earthquake was 6.3, and therefore was a larger earthquake on the magnitude scale than those which occurred in Santa Rosa (M5.6, and M5.7). ...Table 1 [below] is a breakdown of the wood frame dwellings by age and degree of damage.

TABLE 1. of Steinbrugge and others, 1970

Significantly damaged wood frame dwellings (in The Santa Rosa Earthquake of 1969)
Based on Santa Rosa Building Department records as of December 4, 1969.
Final figures may vary somewhat.

STATUS	AGE GROUP		
	PRE-1920	1920-1940	1940-1969
Demolished or probably will be demolished...	18	8	0
Repairable or demolition questions at this time.	11	1	0
TOTAL	29	9	0

It is clear from Table 1 that older dwellings suffered heaviest damage. This follows historical patterns and is readily explainable by rot, general deterioration in the foundation area, and inadequate bracing by today's standard. Damage was almost equally divided between one-story and two-story buildings."

Dramatically increased homelessness will be a major problem in areas having pre-1940 wood frame dwellings.

"In the 1989 Loma Prieta earthquake, there were over 13,000 displaced persons (with some later estimates reaching as high as 20,000) and over 8,000 damaged or destroyed dwelling units (including single family homes, apartment buildings, and mobile homes). In the Watsonville area alone, approximately 2,000 residences were lost. Over 1,000 dwelling units were destroyed in Oakland. At the time, in San Francisco it was estimated that it would take roughly two years to replace and rebuild the estimated 5,000 housing units lost at a cost of about $191 million. ...Public school buildings, county fair grounds, and national guard armories, all of which performed well during the Loma Prieta earthquake, served as emergency housing shelters. About 200 families from the Watsonville area were housed in exhibition halls on the county fair grounds. Many of the temporary shelters were operated by the Red Cross" (Lagorio, 1990, p. 291).

During the April 1992 Cape Mendocino earthquake:

"Most of the buildings that suffered damage in this earthquake were wood frame houses and 1 and 2 story wood frame commercial buildings. Homes slid off foundations. Chimneys collapsed." (EERI, 1992).

Pre-1973 Tilt-Up Concrete Buildings

Earthquake problems associated with pre-1973 tilt-up construction (Figure B-6) can be significant. Probably the most common cause of severe damage has been separation between the concrete tilt-up wall panels and the roof, resulting from inadequate ties. This can allow the wall panels to fall outward, leading to collapse of the roof and floors (Photo B-3). These buildings are common in industrial parks, as warehouses or office buildings. One or two wall failures can shut down an entire building. In the 1971 San Fernando earthquake 22 tilt-up buildings partially collapsed, and 51 others were moderately to severely damaged.

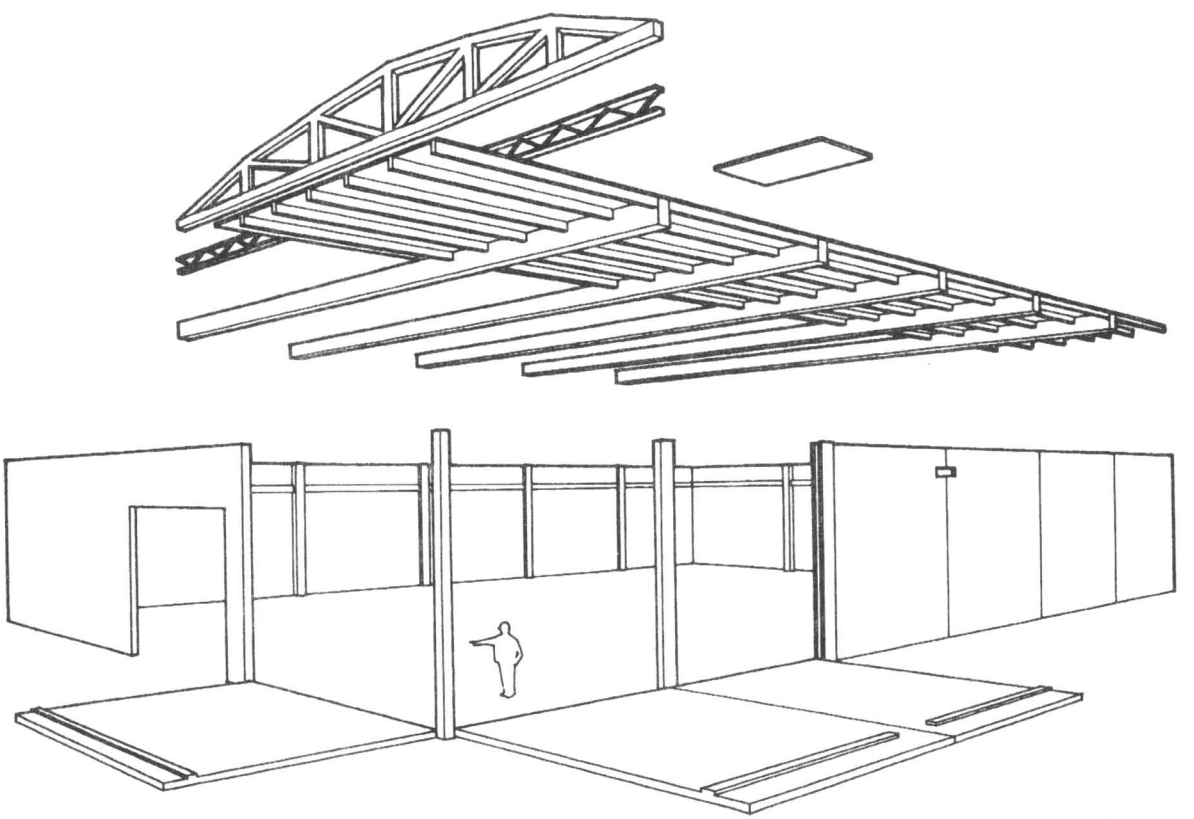


Figure B-6 Typical pre-1973 tilt-up construction. *From Lagorio and others, 1986.*



Photo B-3 Tilt-up construction heavily damaged by the 1971 San Fernando earthquake. Note that some exterior walls have fallen outward causing the roof to collapse.

Non-Ductile Concrete Frame Buildings

These are typically old lightly reinforced concrete frame structures built before 1971 without adequate detailing of reinforcement in columns, beams, and joints (Figure B-7). These brittle structures cannot withstand repeated cycles of earthquake shaking, leading to serious damage or collapse (Photos B-4 and B-5).

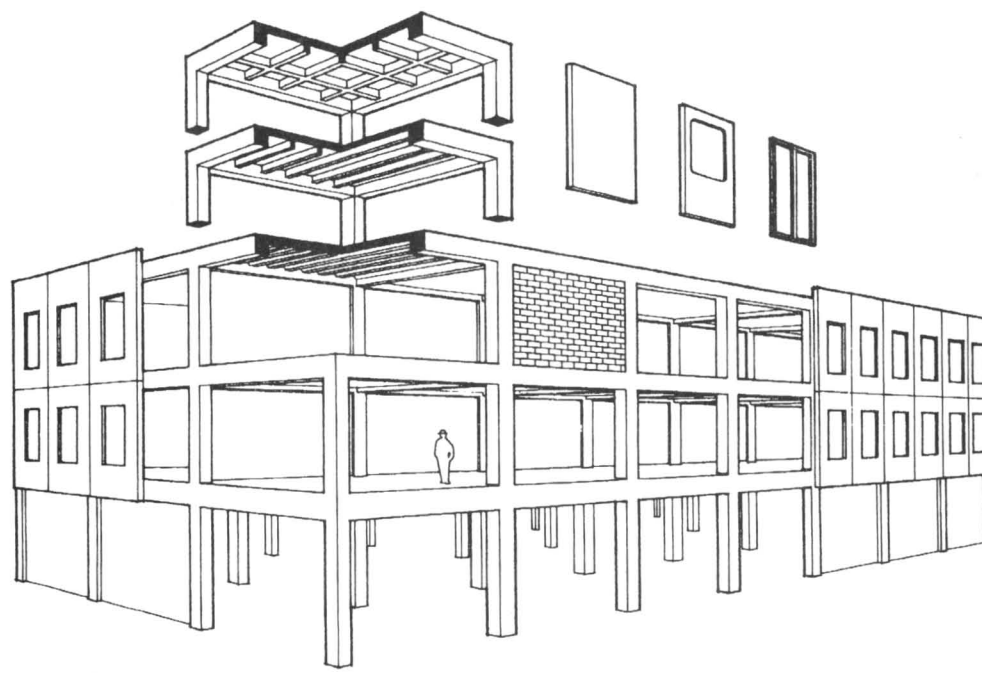


Figure B-7 Typical non-ductile concrete frame. *From Lagorio and others, 1986.*



Photo B-4 This non-ductile concrete parking structure suffered severe damage and partially collapsed in the 1987 Whittier earthquake. This type of construction is a collapse hazard under strong shaking. *Photo by Ronald Gallagher.*



Photo B-5 Close-up of the parking structure showing structural failure of the non-ductile concrete columns. *Photo by Ronald Gallagher.*

Mobile Homes

Mobile homes installed without seismic foundation restraints are often seriously damaged in earthquakes. In 27 mobile home parks in San Benito, Santa Clara and Santa Cruz counties, 24 percent of the homes (592 out of 2,434) moved or fell off their foundation supports during the Loma Prieta earthquake. In the most strongly shaken parts of Santa Cruz County, many parks had over 50 percent of their homes fall off foundations. There were no failures in State regulated parks when the homes had properly installed State approved seismic restraints.

Planning Considerations

Response planners should verify and be knowledgeable of the locations of the hazardous buildings in their jurisdictions. Contingency plans for post-earthquake recovery should focus on these areas. In particular, planners might review the performance of URM buildings during the 1989 Loma Prieta earthquake (M7) in Santa Cruz, Watsonville, and San Francisco's South of Market District.

Without seismic retrofitting, most of the pre-World War II wood frame dwellings in MMI IX areas and many in the MMI VIII will be uninhabitable after the scenario earthquake. Contingency plans for emergency shelters for those rendered homeless by the earthquake should be developed. A review of the emergency housing needs required by homeowners and renters after the 1989 Loma Prieta and 1992 Cape Mendocino earthquakes will offer valuable insights for planners.

PUBLIC HIGH SCHOOLS

General Characteristics

In California, public schools normally are found in a safe condition after an earthquake. As a result, they can serve as a critical resource for mass shelter and feeding in areas where homes are destroyed or rendered uninhabitable. They are especially good because they have large sites, ample parking spaces, cafeterias, gymnasiums, and other amenities.

Earthquake-resistant design has focused on public school buildings in California since the 1933 Long Beach earthquake (M6.3). A wealth of information exists on the seismic performance of public school facilities (California State Department of Education, 1992; Chakos and Nathe, 1992; Meehan, 1990; Office of the State Architect, 1990; Jephcott and Hudson, 1974; California State Department of Education, 1971; and EERI, 1992).

This extensive technical knowledge and professional experience in the design of California public schools accounts for their improved seismic performance over the years. We therefore found it unnecessary to conduct further field inspections of public school buildings in the planning area except for general site location reviews of selected schools.

Map H-S shows the location of public high schools near the Rodgers Creek fault and in areas of expected high intensities of ground shaking in Marin, Napa, Sonoma, and Solano counties. Public elementary schools, middle schools, other special school facilities, and institutions of higher education are too numerous to plot on maps of this scale, and accordingly, are not shown. While this section of the report is directed toward public high schools, the remarks are applicable to all public schools, and those private schools constructed to Field Act standards.

Seismic Characteristics

As mentioned, public schools in California received special legislative attention with respect to seismic safety following the 1933 Long Beach earthquake. Over the years, the Field Act has been successfully implemented through strictly enforced design and construction practices by the Office of the State Architect in Sacramento.

Since the Field Act was passed, however, the seismic design provisions of building codes have undergone continued improvement. With respect to the Hayward fault, just to the south of the Rodgers Creek fault, Steinbrugge and others (1987) state:

> "Looking back in time, it is fair to say that some of the Field Act Schools of 50 years ago would not comply with today's Field Act requirements, and indeed could not be built today without including significant improvements. While the overall performance of public schools will continue to be excellent, it is unreal to expect perfection, particularly in view of the large number of public schools in the near vicinity of the Hayward fault."
>
> "The performance of public schools has been far better than that for other buildings using similar construction materials, but this performance has not been perfect. For example, structural damage occurred to buildings at Arvin High School in the 1952 Kern County earthquake (M7.7). Structural damage also occurred in the West Hills Community College in Coalinga as a result of the 1983 Coalinga earthquake (M6.5) (Meehan, 1983). In no case was there a major life hazard, and costs of repair were a small fraction of the buildings' value. Experience shows that damage can occur to Field Act schools, and these buildings will not be useable until repairs are completed."

Reports issued on the seismic performance of public schools during the 1989 Loma Prieta earthquake (M7) showed once again that school facilities designed under the Field Act perform well (Meehan, 1990; Office of the State Architect, 1990). Damage inspection after the earthquake revealed that:

"There was only minor structural damage to most public school buildings from the nearfield effects of the Loma Prieta earthquake. A preliminary survey of 1,544 public schools in the earthquake-affected region reveals an estimated $81 million in damage. Only five schools sustained severe damage."

"Fortunately, the Loma Prieta earthquake occurred after normal school hours. Hazards from unbraced and unanchored nonstructural items were evident in many school buildings. The following significant hazards continue to constitute a danger to classroom occupants during an earthquake: pendant-mounted light fixtures without safety cables; suspended acoustical ceiling systems installed without bracing or perimeter wires along with their unattached air-conditioning grilles; light lenses, and light fixtures; unanchored four-drawer file cabinets, unanchored shelving, and their contents."

"Many public school buildings have been used as evacuation shelters for the victims of the Loma Prieta earthquake" (EERI, 1990).

"There was a displacement in the roof line of a classroom wing at the Loma Prieta Elementary School. The classroom wing was constructed in 1960 in compliance with Field Act standards. The displacement is the result of a ground surface heaving under the classroom wing. The floor slabs and foundations are also racked at this location."

"A covered passage roof beam separated from the building corner," and an "exterior plywood joint separated at the C.T. English Middle School which is located about one-fourth mile from the Loma Prieta Elementary School."

"Several school buildings in the area affected by the earthquake were constructed prior to the enactment of the Field Act. These buildings had been subsequently strengthened or retrofitted to meet building regulations which were less stringent than current building standards. The three-story Branciforte Elementary School in Santa Cruz was built about 75 years ago, well before the Field Act. This building was retrofitted in 1956. The structural system performed very well but plaster fell in several locations where the plaster was supported by wood lath backing. Wood lath is no longer permitted in new construction and must be removed when public school rehabilitation projects are undertaken. Soquel Elementary School is about 50 years old and was constructed during the early years of the Field Act. This building also had plaster fall from old wood lath back. A heating radiator also fell off the wall."

"Watsonville High School's main building was constructed in 1917, prior to the Field Act; and some rehabilitation work was done in 1935. This building experienced extensive plaster damage where plaster was installed over wood lath. This building suffered damage to the heavy Spanish roof tile and large window glass areas. While the building was being surveyed to determine the extent of earthquake damage, it was learned that there were other structural deficiencies which will require correction or may lead to eventual abandonment of the building."

After the earthquake, "Eighty-nine school buildings were investigated and found acceptable for operation as emergency shelters for people who had been displaced from their earthquake damaged homes. Many of these school buildings were used as shelters for several weeks after the earthquake" (Meehan, 1990).

As observed after the 1989 Loma Prieta earthquake, "public school damage from this earthquake reinforces once more the conclusion that pre-Field Act buildings that were retrofitted in the period from 1933 into the 1960s remain the most likely buildings to suffer structural damage in severe earthquakes. The seismic-resistant upgrade of these buildings was done to structural standards that were different and often less stringent than current requirements" (EERI, 1990).

"Building codes have undergone significant changes based on recorded evidence from earthquakes in the last 20 years. Also, the construction industry has seen many changes in the use of the building materials since 1933. It would be prudent to examine all school buildings constructed or retrofitted during the early days of the Field Act. These buildings need to be examined to determine if they possess the necessary design and materials strength and stiffness to perform adequately in future earthquakes or if the lack of proper maintenance or deterioration has reduced their strength" (Meehan, 1990).

"The two classes of buildings that could present problems are the concrete non-ductile frame structures built before 1973 and the concrete and unreinforced masonry pre-Field Act buildings that were retrofitted in the years before 1955. Both of these classes of buildings should be reviewed by structural engineers for compliance with today's requirements for ductility... Requirements for these two classes of buildings were upgraded considerably in the early 1970's.

The other area of concern for school buildings constructed prior to 1970 is in the performance of non-structural elements such as "T-bar" ceilings, pendant hung light fixtures, unbraced suspended plaster ceilings, large panels of window glass and all types of cabinets and shelving. If these

items are damaged in an earthquake of course they can be cleaned up and the building can be put back in use. However, they can be of considerable hazard to the occupants at the time of the earthquake. As an example the Landers Elementary School, located 0.4 of a mile from the initial ground faulting of the Landers-Big Bear Earthquake, suffered some damage to the "T-bar" ceiling system located in the Multi-Purpose Room as well as losing its water supply due to failures in the local water system. However, it served as the evacuation shelter for the local community for some weeks after the event. The fallen items from the "T-bar" ceiling were cleaned up and water was provided by tank truck from the nearby U.S. Marine base and canned water was supplied by one of the Southern California breweries. The basic building performed very well in spite of what must have been a high level of ground shaking" (Jephcott, 1993).

Planning Considerations

As explained in the Buildings chapter, the only remaining non-Field Act schools are private schools that still are an earthquake hazard. All public school buildings in the planning area have been designed to meet earthquake-resistant design provisions required under the Field Act at the time of construction.

State institutions of higher education, which technically are not subject to the Field Act, nevertheless have built their new buildings in conformance to its seismic provisions. Unfortunately, some of the old buildings are still being used for classrooms. For example, as recently as 1978, 18 percent of the footage at the University of California campuses was rated as seismically poor or very poor (Degenkolb and Wylie, 1978).

Table PS-1 shows the distribution of public high schools by district in the North Bay county areas according to expected intensity of shaking and distance from the Rodgers Creek fault. Note that four of the high schools listed are outside the immediate boundaries of the planning area and are not shown on Map H-S.

TABLE PS-1
PUBLIC HIGH SCHOOLS IN THE PLANNING AREA*

Schools	School District/County	Distance From Fault - km	MM Intensity +
North Marin High	Novato/Marin	14	VIII +
Novato High	Novato/Marin	14	VIII +
San Marin High	Novato/Marin	14	VIII +
San Rafael High[1]	San Rafael/Marin	22	VIII-
Terra Linda High	San Rafael/Marin	19	VIII-
Mewah Mountain High	Tamalpais Union/Marin	26	VII-
Redwood High	Tamalpais Union/Marin	25	VII-
San Andreas High	Tamalpais Union/Marin	25	VII
Sir Francis Drake High	Tamalpais Union/Marin	23	VIII-
Tamalpais High	Tamalpais Union/Marin	29	VII
Calistoga High	Calistoga/Napa	17	VIII-
Napa High	Napa/Napa	19	VIII-
Vintage High	Napa/Napa	20	VIII-
St. Helena High	St. Helena/Napa	20	VIII-
Cloverdale High[2]	Cloverdale/Shasta	N/A	N/A
Johanna Echols-Hansen[2]	Cloverdale/Shasta	N/A	N/A
Benicia High	Benicia/Solano	23	VII
Hogan High	Vallejo/Solano	14	VIII-
Vallejo High	Vallejo/Solano	15	VIII-
El Molino High	Forestville/Sonoma	17	VII
Geyserville Educational Park[2]	Geyserville/Sonoma	N/A	N/A
Healdsburg High	Healdsburg/Sonoma	24	VII
Mountainview High	Healdsburg/Sonoma	24	VII
Casa Grande High	Petaluma/Sonoma	6	IX
Petaluma High	Petaluma/Sonoma	9	VII
San Antonio High[3]	Petaluma/Sonoma	7	IX
El Camino High[3]	Rohnert Park/Sonoma	8	VIII +
Rancho Cotate High	Rohnert Park/Sonoma	6	IX
Ridgeway High	Santa Rosa/Sonoma	2	VIII +
Montgomery High	Santa Rosa/Sonoma	2	IX
Santa Rosa High	Santa Rosa/Sonoma	2	VIII +
Piner High	Santa Rosa/Sonoma	4	VIII +
Analy High	Sebastopol/Sonoma	13	VIII-
Laguna High	Sebastopol/Sonoma	13	VIII-
Agua Caliente High	Sonoma/Sonoma	8	VII
Sonoma Valley High	Sonoma/Sonoma	6	IX

* Refer to Map H-S
\+ Refer to Appendix A
1 Madrone High School located on same site
2 Not in planning area
3 Continuation High School

High schools having high intensity ground shaking within 3 miles (5 km) of the fault are subject to damage (Table PS-2). We assume that underground utility service lines, such as water, natural gas, and sewage, crossing the Rodgers Creek fault will be damaged. As a result, schools in critical areas will be unusable for emergency shelter even if their structures remain undamaged by the postulated earthquake.

TABLE PS-2

SUMMARY OF PUBLIC HIGH SCHOOL SITES

Number of Schools	Distance from Fault - km	MM Intensity +
3	2	IX - VIII +
1	4	VIII +
6	5 - 8	VII - IX
3	9 - 13	VIII-
20	14 - 32	VII - VIII
TOTAL 33		

\+ Refer to Appendix A

Planning Scenario

Because of their size, location, and on-site service facilities, public schools, and in particular high school buildings, will be available as evacuation shelters for victims of the earthquake. The most critical schools are where damage to the existing housing stock will be the most severe.

We expect the majority of wood frame public schools to survive the scenario event without significant structural damage. These are commonly one story elementary schools and those high schools with one story "open planning and

exterior courtyards" (also referred to as the "open wing configuration") surrounding the classrooms and other facilities. Although the buildings will be safe for emergency use, there will be some functional restrictions, owing to disrupted utility services, broken windows, fallen ceiling tiles, and jammed doors. Such nonstructural effects will occur to 10 percent of the classrooms within 10 miles (16 km) of the Rodgers Creek fault. Nonstructural damage typically impairs school functions for 1 or more days.

Planners should identify the location and construction type of: 1) any remaining pre-Field Act school buildings, and 2) school buildings constructed in the early days of the Field Act that were retrofitted between 1933 and the early 1960s. These facilities will require damage assessments by professional engineers and architects immediately after the earthquake. Following the experience of the Loma Prieta earthquake, we assume that 25 percent of these retrofitted school buildings will be damaged. This professional assessment activity will be of considerable assistance in recovery efforts related to public schools. Any structural damage or significant cracking requires a long delay in re-occupancy.

Public school structures that are two or more stories high often are designed with reinforced concrete or other unit masonry wall materials. Shortly after the event, these also will need inspection by professional engineers and architects before occupancy is allowed on any long-term basis. If any significant cracking is found, occupancy will be delayed for repairs. Inspection takes from 2 to 3 days, with repairs taking an additional 1 to 5 weeks depending on the severity of damage.

Immediately after the earthquake, road closures, particularly at elevated viaducts and interchanges such as Route 101 and Highway 12 at Santa Rosa, Route 101 and Highway 116 at Petaluma, Route 101 and I-580 at San Rafael, and Highways

12 and 29 in the Napa area, will retard access to school sites. Alternative routes to schools with potential access problems should be identified and established before the earthquake.

Two of the 10 high schools in areas of anticipated heavy ground shaking (MMI VIII and IX) and within 5 miles (8 km) of the Rodgers Creek fault will have extensive non-structural damage, utility service disruption, and some structural damage. In the 1971 San Fernando earthquake, 10 percent of the schools in the VIII zone and 25 percent of the schools in the IX zone had moderate losses (2 to 20 percent damage ratio) (Mualchin, 1993). The rest had little or no loss (<2 percent damage ratio). Thus, for planning purposes, we postulate that these particular schools will be closed for inspection and repairs for 5 weeks or more.

HOSPITALS

General Characteristics

The fundamental focus of the seismic issues and concerns emphasized in this planning scenario relate to the earthquake vulnerability of major transportation and utility lifeline systems in the planning area. However, when setting priorities among the many public demands, the disaster response planner must give highest attention to saving lives. Hospital buildings, facilities, and services are obviously vital in this regard. Staff personnel and medical resources, including medical supplies and equipment both on site and in warehouses and/or distribution centers, blood banks, ambulance services, clinical laboratories at hospitals, and other critical assistance provisions must be ready and available.

A general acute care hospital is defined as a medical facility providing specific medical services, including an emergency room with facilities for intensive care and surgery, and having a patient capacity of 99 beds or more. Because of the demographic characteristics of the planning area, however, there are numerous small hospitals that could assume a critical emergency role in responding to the disaster. The problems faced by these small hospitals are similar to those of the large facilities. Accordingly, all hospitals shown on Map H-S were reviewed for seismic vulnerability and inspected in the field regardless of their bed capacity (Table Ho-1).

The principal and critical hazard areas in the Rodgers Creek earthquake scenario are in the North Bay counties of Marin, Napa, Sonoma, and part of Solano (City of Vallejo). This chapter is restricted to the 16 major hospitals with a total of 2,004 beds listed in Table Ho-1 and shown on Map H-S.

TABLE Ho-1

HOSPITALS IN NAPA, SONOMA, MARIN AND PART OF SOLANO* COUNTIES[x]

Name - Location	County	MM Intensity**	No. of Beds	Distance From Fault - km
Healdsburg General Hospital	Sonoma	VII	49	23.0
Kaiser Foundation-Santa Rosa	Sonoma	VIII+	110	3.4
Santa Rosa Community Hospital	Sonoma	VIII-	145	2.2
Santa Rosa Memorial Hospital	Sonoma	IX	225	0.5
North Coast Rehabilitation Center	Sonoma	IX	61	0.5
Warrack Medical Center	Sonoma	IX	79	2.5
Palm Drive Hospital	Sonoma	VIII-	46	12.5
Petaluma Valley Hospital	Sonoma	IX	99	7.0
Sonoma Valley Hospital	Sonoma	IX	87	6.5
Sutter Solano Medical Center	Solano	VII	108	18.5
Kaiser Foundation-Vallejo	Solano	VIII-	229	18.0
Novato Community Hospital	Marin	VIII+	63	14.0
Kaiser Foundation-San Rafael	Marin	VII	120	19.0
Marin General Hospital	Marin	VII	235	24.0
St. Helena Hospital and Health Center	Napa	<VII	160	22.5
Queen of the Valley Hospital	Napa	VIII-	188	21.5

[x] Refer to Map H-S
* City of Vallejo only
** Refer to Appendix A

For a complete inventory of all types of medical facilities located in the planning area and throughout California, refer to the *Health Facilities Directory, July 1991*, issued by the Licensing and Certification Division, California Department of Health Services.

A large percentage of the new hospitals constructed in the State under the performance standards established by the Hospital Act of 1972 incorporate various types of structural steel design, and many are composed of building configurations limited to four or five stories. These general building characteristics also are common among the new hospitals found in the planning

area. The implications of the planning and construction of medical facilities designed under the 1972 Hospital Act are described below.

Seismic Characteristics

Medical facilities are critically dependent on utility lifeline support systems (e.g., water supply, electric power, and waste water removal). In addition, hospital buildings are vulnerable to:

1. Structural damage.
2. Non-structural damage.
3. Internal failure of utility support systems.
4. Damage to critical supplies, contents and equipment.
5. Accessibility of ambulances and emergency service vehicles.
6. Fire following earthquake.

These are some of the problems faced by one hospital after the Santa Rosa earthquakes of October 1, 1969:

> "The 10:32 p.m. emergency at the Memorial Hospital was a result of containers of chemicals and flammable liquids in the laboratory store room being disturbed and falling on the floor. With the situation complicated by electrical power failure, an engine company and the fire marshall continue to stand by. Upon losing normal electric power after the first shock, the hospital emergency generator started automatically and provided power for about 45 minutes before it had to be shut down. The hospital was without power for approximately 75 minutes before normal electric power was restored. There were no portable emergency power (battery operated) units available in the hospital."
>
> "The fire marshall called for an additional engine company at 11:35 p.m., following a fire ignited by chemical reaction. Although confined to a small laboratory and storage area, the fire was of some intensity and did considerable localized damage. ...Fire control with water was difficult due to the nature of the flammable liquids. Dry powder was used to knock the fire down, and then small amounts of water for overhaul. Smoke damage occurred in the surgery, on the floor above, due to a reported non-conforming access hole which had been cut out of the first floor ceiling of the laboratory storage room. The surgery could not be used for 24 hours" (Steinbrugge and others, 1970).

In 1971 the San Fernando earthquake severely damaged four major modern hospitals. This shocked a great many people and led the State of California to adopt the Hospital Seismic Safety Act of 1972. The Act requires the establishment of rigorous seismic design regulations for hospital buildings and requires that new hospitals, and additions to existing hospitals, have the capacity, as far as practical, to remain functional after a major earthquake. Some damage could occur, but all necessary services must be available in the disaster aftermath.

According to Jephcott (1993), "the most critical element is the water supply system," as recognized by the Veteran's Administration which includes an emergency water tank holding about 700 gallons per bed in its hospitals.

For electrical backup, all post-1973 hospitals are required to have emergency generators designed to remain functional after an earthquake, but there is no regulation requiring them for pre-1973 hospitals. "As an example, at the Watsonville Hospital in the 1989 Loma Prieta earthquake a pre-1973 emergency generator unit was shaken off of its vibration isolator mounting and did not continue to function. Adjacent to it was a post-1973 emergency generator unit of comparable size that stayed in place..." (Jephcott, 1993).

During the 1989 Loma Prieta earthquake:

> "Those acute hospital buildings constructed under provisions of the Hospital Act, passed in the 1972 legislative session, performed very well with essentially no damage of any kind [But they were only in the MMI VI and VII zones]. Some acute hospital buildings constructed prior to the Hospital Act experienced a limited amount of structural damage that will require corrective measures."
>
> "The seven-story tower building, constructed in 1927 at Peralta Hospital in Oakland suffered serious damage and had to be closed. This building originally was part of an acute hospital, but is 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, an administrative building suffered major damage and was evacuated, and the legs of a 3,000 gallon LOX [liquid oxygen] tank broke loose from the baseplates. The tank would have fallen over if a temporary guide wire had not been fixed to the top and tied back to an existing structure. 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 in damage."
>
> "Elevators in hospital facilities posed a separate problem. The hospitals in five affected counties (Alameda, San Francisco, San Mateo, Santa Clara, and Santa Cruz) for which damage reports were taken, reported on a total of 428 elevators. Of those, 282 (65.9 percent) were tripped by motion detectors and out of service for 10 minutes to 7 hours. ...Of these 282 elevators, 50 (17.7 percent) sustained damage that took them out of service for an additional 4 hours to 3 weeks" (EERI, 1990).

We expect hospitals built to the standards of the 1972 Act to perform well in a strong earthquake, particularly in comparison with ordinary buildings. Hospitals in California built after 1950 were generally required to have a seismic design, but these are not expected to possess the same amount of seismic resistance, and did not have the damage control features, as those constructed under the 1972 Act. The Act also required seismic design of equipment and architectural elements. Before 1972 there were few or no such requirements. Items such as emergency generators, battery racks, and large medical apparatus must be secured against sliding or overturning. This greatly increases the likelihood of their post-earthquake availability.

After the 1989 Loma Prieta event, an earthquake damage assessment of hospitals in East Bay and South Bay counties was issued by the California Office of the State Architect (OSA). Out of a total of 17 hospital buildings inspected, five had no building damage, five had non-structural damage, six had minor structural damage, and one had structural damage to an old tower built in 1927

"considered serious enough to compromise its capability to withstand another earthquake." The nonstructural damage patterns were generally limited to damaged elevators, equipment anchorage and pipe support damage, spalling and buckling of tile at seismic joints, failure of vertical fan anchorage at roof level, and minor cracks at ceilings and walls (OSA, 1989).

Non-structural damage and the performance of elevators also posed special problems for acute general hospitals in the MMI VI zone of the Landers and Big Bear earthquakes of June 28, 1992:

> "There was no structural damage reported in any hospital as of July 7, except for some displacement of a pre-cast concrete balcony facade at the Eisenhower Medical Center in Rancho Mirage. Nonstructural damage included a broken water line in the kitchen at the JFK Hospital in Indio. An elevator at Desert Hospital in Palm Springs shut down due to damage in the shaft. Counterweights at five out of eight elevators came out of their tracks at Loma Linda University Medical center and seismic expansion joints were damaged. Two elevators were disabled due to counterweights at St. Bernardine Medical Center. Superficial cracking of interior drywall was widely reported" (EERI, 1992).

Another seismic requirement enacted in 1972 that affected new hospitals and other structures was the Alquist-Priolo Earthquake Fault Zoning Act. The purpose of this act is to delineate zones encompassing the traces of active faults. The zones are defined by the State Geologist for faults considered to be active and a potential hazard to structures. Structures that straddle faults are subject to ground movements from surface rupture that can cause severe structural damage.

The Act applies only to new structures, and many older buildings in Santa Rosa, including the Community Hospital, lie within the Alquist-Priolo Earthquake Fault zones.

Planning Considerations

Hospitals close to surface fault rupture can be seriously affected by earthquake strong shaking, by disruption of utilities, and by access problems. Hospitals not constructed to the standards of the 1972 Hospital Seismic Safety Act can be seriously damaged, even at some distance from the fault. In addition, those hospitals with unanchored emergency equipment such as generators and battery racks, medical apparatus, and other laboratory equipment can suffer serious impairment of operations.

In studying the post-earthquake operational capabilities of hospital facilities, planners should review the following five items:

1. Physical damage to buildings.
2. Loss of life and injuries to personnel and patients.
3. Loss of medical supplies and equipment.
4. Loss of hospital function from disrupted utility services or access problems.
5. Evacuation of hospitals adjacent to major surface faulting.

Given the closeness of the expected damage areas to the San Francisco Bay Area (Santa Rosa is about 50 air miles from San Francisco), overflow casualties can be taken by helicopter to hospitals in San Francisco, Oakland, and other Bay Area cities (Table Ho-2). There are more than 20,000 beds in the greater Bay Area, and even more beds are available in Sacramento and Travis AFB. Aside from initial emergency medical treatment, most of the problems associated with the scenario earthquake will involve transporting the injured to the appropriate hospitals.

Because of the rural and suburban nature of Sonoma and Napa counties, getting the injured to hospitals may be difficult. If a local hospital is closed by earthquake damage, travel to the next closest hospital may involve distances of over 20 miles (32 km) on congested roads.

TABLE Ho-2

HOSPITAL BED CAPACITY IN OTHER BAY AREA COUNTIES

County	Total Bed Capacity
Alameda	4,279
Contra Costa	2,385
San Francisco	6,873
San Mateo	2,403
Santa Clara	4,838
Solano	307*
TOTAL	21,085

* Excluding Vallejo.

Planning Scenario

Under the scenario event, surface fault rupture and strong ground shaking are expected along the length of the fault. Santa Rosa, at the northwestern end of the fault, is the closest large city to the fault. For planning purposes, we assume that ground rupture in Santa Rosa will be sufficient to damage structures in the fault zone. Surface and subsurface utilities crossing the fault will be severed and out of service until repaired. Roads traversing the special studies zone also will be damaged, and travel on them may be difficult or blocked for several hours.

Although hospital structures in and near the fault zone will be seriously damaged, ample experience shows that some of these structures can survive quite well. Nevertheless, emergency planners should make appropriate site studies and mitigate hazards as was done at a medical facility in Alameda County (Steinbrugge and others, 1987). Such site mitigation activities should include methods to maintain utility services and provide alternate access routes.

Hospitals several miles or more from the fault will have outages of water and power for 24 hours. The four hospitals within 3 miles (5 km) of the fault (Table Ho-1) could have water outages for 3 days and power outages for 2 days.

For planning purposes, we assume that at least one medical facility constructed before enactment of the 1972 legislation and located in an Alquist-Priolo Earthquake Fault zone will be disabled. Hospital facilities constructed since the Hospital Act of 1972 will remain functional, although they may lose electric power, water supply, or natural gas.

One way of examining the potential loss of facilities is to estimate hospital bed loss rather than building damage. A slightly damaged building evacuated for psychological or liability reasons will result in a critical loss of hospital beds, just as would severe structural damage. Table Ho-3, summarizes the total loss of bed capacity anticipated in the planning area according to projected ground shaking intensities at hospital facility sites. For response planning purposes, we anticipate that out of 2,004 beds in the 16 hospitals in the North Bay, 463 (23 percent) will be unavailable for treatment of earthquake related casualties. As seen in the 1989 Loma Prieta earthquake and others, severe non-structural building damage to hospital facilities also will lead to loss of bed capacity.

Up to 35 percent of the beds will be unavailable near the fault where ground shaking intensities of MMI IX are postulated (Table Ho-3). Percentages of bed capacity loss will diminish at sites with lower ground shaking intensities to 30 percent in VIII+ areas, 25 percent in VIII- areas, and 10 percent in VII areas.

TABLE Ho-3

SUMMARY OF ESTIMATED HOSPITAL BED LOSSES

Number of Hospitals	Total Beds	Estimated % Loss*	Estimated Bed Loss	MM Intensity**
5	551	35	193	IX
3	219	30	66	VIII +
3	534	25	134	VIII-
5	700	10	70	VII

* Loss of bed capacity by category. (Most of the beds in the IX zone are in new buildings.)
** Refer to Appendix A.

As mentioned, emergency response planners should note the locations of large acute health care facilities elsewhere in the greater San Francisco Bay Area (Table Ho-2). Planners also must confirm the availability of overland routes or else provide helicopters or other means to move overflow casualties. Immediately after the earthquake the following bridges are expected to be closed or have restricted access: Petaluma River Bridge on Route 37; Napa River Bridge on Route 12/29; Benicia Bridge on Highway 680; Richmond-San Rafael Bridge; Oakland-San Francisco Bridge (refer to Highways chapter below and Map Hi).

SECTION 3

TRANSPORTATION LIFELINES

HIGHWAYS

General Characteristics

The California Department of Transportation (Caltrans) was created in 1972, and is one of the leading organizations in the area of seismic design and research of highway bridges. Caltrans, which contributed most of this chapter, is based in Sacramento and operates out of 12 district offices and has over 300 maintenance stations throughout the state.

The Rodgers Creek earthquake planning scenario considers the portion of the state highway system located in Districts 4 and 10. The Caltrans District 4 office is in San Francisco and serves most of the planning area. The District 10 office is in Stockton and serves the Solano County portion of the planning area. There are 25 interstate and state highway corridors in the planning area. Over 400 miles (644 km) of the highway network and some 1,110 structures were studied in formulating the scenario for the highway system.

Seismic Characteristics

In the scenario event, Routes 12, 37, 116, and 121 straddle the fault break and will experience shaking of up to MMI IX. A Federal Highway Administration study (U.S. Department of Transportation, 1982) considers that areas having MMI greater than VII can have significant highway damage. However, long structures on soft soils in the MMI VII zone of the Loma Prieta earthquake collapsed. The Cypress Structure was destroyed and a 50-foot section of the Bay Bridge fell.

As a result of the 1971 San Fernando earthquake (M6.4), Caltrans implemented design criteria and details for bridges that improved seismic resistance. The most significant future damage will occur in structures designed between 1946 and

1971 that have not yet been retrofitted. However, a legislative mandate following the 1989 Loma Prieta earthquake (M7), required that all seismically deficient state structures be under contract for retrofit by December 1993.

The initial Caltrans retrofit program (1971-1985) involved the application of hinge restrainers to unrestrained superstructure expansion joints. The subsequent single column retrofit program concentrated on increasing the seismic resistance of single column substructures to current standards. By July 1992, all but 25 of the 271 single column bridges statewide had been advertised for retrofit. The detailed review of as-built plans for all state bridges is completed. The current retrofit program is to increase the seismic resistance of deficient bridge structures. Although retrofitting is no guarantee against collapse under the most intense shaking, it does improve the chances that a structure will survive with repairable damage. Examples of repairable damage include the tipping of short rocker bearings, minor cracking of piers and columns, and vertical displacements where asphalt can be filled in. Retrofitted structures may be significantly damaged and require road closure for repair, but they generally will not collapse. Important structures, such as the San Francisco Bay toll crossings, are to be retrofit so that they will be repairable without closure. However, until retrofit is complete, outage times will remain uncertain.

The scenario event, having an average surface displacement of 3 feet, will damage roadways crossing the fault. Likewise, areas of potential liquefaction and seismically induced landslides will impact the highway system. The amount of movement due to liquefaction and landslides is erratic and difficult to predict. Most failures to the highway system involve blockage by rockfalls, settlement of fills, and slumping of soils near streams and other water bodies.

We reviewed the general characteristics of the structures in light of their historic failure mechanisms. In particular, the damage patterns witnessed during the Loma Prieta earthquake were used for many of the predictions in this scenario. In weak structures, damage can occur in MMI VII zones far from the epicenter when soil conditions and structure period match, leading to resonant amplification. Collapse of the Cypress Structure during the Loma Prieta earthquake is the classic example (Photo Hi-1).



Photo Hi-1 Collapsed steel rebar and concrete column of the Cypress I-880 freeway structure, Oakland, California. A 1-mile length of this double-decked reinforced-concrete viaduct collapsed onto commuter traffic killing 42 and injuring many others during the Loma Prieta earthquake. The failed column in the foreground supported the top deck. Built in the 1950's, the columns had vertical steel reinforcing rods but lacked the spiral reinforcing rods used in modern construction. *Photo by Michael Rymer, courtesy of the U.S. Geological Survey.*

Planning Considerations

Planners need to identify major emergency corridors that will have the least amount of damage in the earthquake. The best emergency routes are wide, at grade or on stable ground, and should avoid adjacent tall buildings and power lines that could be damaged. Utility companies and local government agencies need to identify installations and facilities they will need to inspect, repair, operate, or access in the emergency. Emergency planners then need to examine available routes to critical facilities, assess the potential for damage, and identify the most probable access route. Critical facilities include communication centers, hospitals, airports, heliports, staging areas, fuel storage sites, and other locations essential to emergency response operations. Highway emergency response plans need to be coordinated with those developed for air and rail. Access to and travel through stricken areas will be difficult and will be limited to the highest emergency priorities.

Planning Scenario

1. The MMI VIII and IX areas where the highways are most vulnerable are north of Richmond, and north of the most densely populated region.

2. Highways across tidal marshes in the North Bay area will be damaged and unavailable for more than 3 days.

3. Highways in the San Francisco and Oakland areas will have damage similar to that in the Loma Prieta earthquake.

Damage Assessments

Damage assessments have been postulated for certain major highway facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site.

Locations of damage assessments are shown on Map Hi. Routes not discussed may be assumed to be open with delays due to heavy traffic and obstructions. The outage times listed below for the Bay Area bridges will remain uncertain until they have been seismically retrofitted. The scheduled retrofits are indicated below under assessments 28, 31, 34, 40, and 43.

MAP NO.	HIGHWAYS
1	**Route 101 (north from Route 12)** Restricted (MMI VII to IX). Moderate to low liquefaction potential. Minor repairable damage will occur. Route will remain open with slowed traffic flow for 8 hours.
2	**Route 128 (northwest from Route 29)** Restricted (MMI VIII-). Potential for coherent slides. Minor roadway damage will occur near landslide locations. Traffic will be restricted to one lane with interrupted flow and minor delays for 8 hours.
3	**Route 12 (Sebastopol)** Restricted for 12 hours (MMI VIII+). High liquefaction potential.

Minor liquefaction damage to the bridge crossing of Laguna de Santa Rosa. Traffic will be limited to emergency travel only for 12 hours.

4 **Route 101/12 Interchange (in Santa Rosa)**
Restricted for 3 days (MMI IX).
Moderate to low liquefaction potential.
Moderate damage will occur at the Route 12/101 Separation Interchange. Traffic will be limited to one lane with interrupted flow for 3 days to permit repair work.

5 **Route 12 (in Santa Rosa at Rodgers Creek fault crossing)**
Closed for 24 hours (MMI IX).
Moderate to low liquefaction potential.
Fault rupture.
Road closed due to moderate damage near fault break. Detours will be necessary for 8 hours. Moderate damage to the structure near Brigham Avenue will restrict traffic to emergency vehicles for 24 hours. The structure crossing Santa Rosa Creek will experience settlement of the embankments and approaches but will remain open with slowed traffic flow for 12 hours.

6 **Route 101 (between Route 116 and Route 12)**
Restricted for 8 hours (MMI IX).
High liquefaction potential.
Only minor damage will occur from shaking. Fill settlement will occur due to liquefaction at bridges in Rohnert Park.

7 **Route 101/116 Interchange (in Rohnert Park)**

Restricted for 8 hours (MMI VIII+).

Minor repairable damage will result from movement at the Route 101/116 Interchange Separation. Between the north and south junctions with Route 116, only minor movement with minor to no damage will occur. Route 116 will be open north to Guerneville and south to Petaluma.

8 **Route 12 (through the Sonoma Valley)**

Restricted for 10 hours (MMI VII to IX).

Moderate liquefaction potential in places.

Minor traffic disruptions will occur in Sonoma Valley due to pavement cracking and fill settlements. Repair time is negligible.

Minor structure damage is possible at Hooker Creek and Agua Caliente Creek. The structures will remain open with slowed traffic flow for 10 hours.

9 **Route 128 (Napa River crossing in Rutherford)**

Open (MMI VIII-).

High liquefaction potential.

No damage is expected to the Napa River Bridge. Route 128 will be open from Calistoga south. Route 29 will be open as far south as Napa.

10 **Route 101/116 Interchange and Petaluma River Crossing (in Petaluma)**

Closed for 2 days (MMI IX).

High liquefaction potential.

Minor road surface disruptions and moderate overpass damage will

occur due to MMI shaking of IX. Traffic on the Route 101/116 structures will be restricted to one lane with interrupted flow and moderate delays for 36 hours. Moderate structure damage and fill settlement is expected across the Petaluma River. The Petaluma River remains unpassable for up to 2 days.

11 **Route 116 (Rodgers Creek fault crossing)**

Closed for 8 hours (MMI VII to IX).

Moderate to low liquefaction potential.

Fault rupture.

Heavy damage will occur to the road surface near the fault break. Road closed for 8 hours until damage is temporarily repaired with fill material.

12 **Route 12/121 (from Route 29 to Route 116)**

Restricted to one lane for 24 hours (MMI VIII+ to IX).

Moderate to low liquefaction potential.

Road open but subject to temporary delays and single lane traffic for 24 hours as a result of a few small landslides and liquefaction settlement of the roadway. The bridge across Sonoma Creek will show definite signs of movement and repairable damage due to liquefaction in the MMI IX zone.

13 **Napa River Crossing (in Napa)**

Restricted to one lane for 24 hours (MMI VIII-).

High liquefaction potential.

This is not on the state highway system. Minor liquefaction damage will occur. Traffic will be restricted to one lane with interrupted flow for 24 hours.

14 **Route 121 (Napa River crossing in Napa)**

Restricted to one lane for 24 hours (MMI VIII-).

High liquefaction potential.

Minor liquefaction damage to the road and bridge crossing the Napa River. Traffic will be restricted to one lane with interrupted flow and delays for 24 hours.

15 **Route 12/29 (Napa River crossing)**

Closed for 24 hours (MMI VIII-).

High liquefaction and landslide potential.

Moderate liquefaction damage will occur at the bridge crossing the Napa River. It will be closed during the first 24 hours for damage assessment and repairs. A landslide will block two of the north-bound lanes north of the 12/29 interchange for 12 hours. The Route 29/221 interchange will be closed for 24 hours due to liquefaction.

16 **Route 101 (Marin County)**

Restricted to one lane for 36 hours (MMI VII to VIII+).

High liquefaction and landslide potential.

Some lanes of Route 101 will be disrupted by landslides. Traffic will be restricted to one lane for 36 hours.

17 **Route 121 (Rodgers Creek fault crossing)**

Closed for 8 hours (MMI IX).

Moderate to low liquefaction potential.

Fault rupture.

Heavy to moderate damage caused by the fault break and liquefaction. Roadway closed for 8 hours until temporary repairs can be made.

18 **Route 37 (from Route 101 to Route 121)**

Closed for 3 days (MMI VIII+ to IX).

High liquefaction potential.

Except for a small stretch near Petaluma Point, the roadway will undergo extensive liquefaction and settlement.

The structure across the Petaluma River will suffer moderate structural and liquefaction damage. The approaches will likely settle and repairs will necessitate closure.

19 **Route 37 (near Sears Point at Rodgers Creek fault crossing)**

Closed for 3 days (MMI IX).

High liquefaction potential.

Fault rupture.

Moderate to heavy damage to the roadway and structures from liquefaction and the fault break.

20 **Route 37 (Sonoma Creek to Napa River)**

Closed for 2 days (MMI IX).

High liquefaction potential.

Liquefaction and fill settlement will disrupt the roadway.

Moderate structural and liquefaction damage will affect the bridge crossing Sonoma Creek.

21 **Route 37/101 Interchange**

Restricted for 36 hours (MMI VIII+).

High liquefaction potential.

Minor damage to the Route 37/101 interchange structure. Repairs will restrict traffic to one lane interrupted flow for 36 hours.

22 **Route 12 (Jameson Canyon)**

Restricted for 36 hours (MMI VIII-).

High liquefaction and landslide potential.

Liquefaction will disrupt the pavement and several small landslides will reduce this route to a one lane highway.

23 **Route 37 (Bridge crossing the Napa River at Mare Island)**

Restricted for 36 hours (MMI VIII-).

High liquefaction potential.

The bridge crossing the Napa River adjacent to Mare Island will suffer moderate damage as a result of liquefaction and strong shaking. Traffic will be restricted to emergency vehicles for 36 hours.

24 **Route 29 (near Vallejo)**

Restricted for 24 hours (MMI VIII-).

High liquefaction potential.

Route 29, between the junction with Interstate 80 and the junction with Route 37, will suffer minor liquefaction damage to the roadway, but will remain open with slowed traffic flow. Repairs can be made within 24 hours. The Route 29/80 Separation structure will experience minor damage, but will remain open.

25 **Route 37/80 Interchange**

Restricted for 24 hours (MMI VII to VIII-).

High liquefaction and landslide potential.

As a result of landslides, the structures at the Route 37/80 interchange will suffer minor damage. A landslide will occur on I-80

immediately north of the interchange. It will block two east-bound lanes. Delays will occur for 24 hours as traffic will be restricted to one lane.

26 **Interstate 80 (Solano County)**

Restricted for 12 hours (MMI VIII-).

High liquefaction and landslide potential.

Road open, but subject to temporary delays for 12 hours as a result of small landslides partially blocking two west-bound lanes. Several structures may also be affected by these landslides but detours and earthwork repairs will permit near-normal traffic flow.

27 **Route 101 (San Rafael area, Marin County)**

Restricted for 24 hours (MMI VII to VIII-).

High liquefaction and landslide potential.

Single lane traffic for 24 hours in the area partially blocked by small landslides. Minor structure damage and liquefaction damage will also restrict traffic to one lane.

28 **Interstate 80 (Carquinez Bridge)**

Restricted for 24 hours (MMI VII).

High liquefaction potential on south end of bridge.

Any damage to the Carquinez Bridge is expected to be minor and will not affect traffic flow. According to Gates (1993), the Carquinez Bridge is being analyzed for retrofit and a new parallel crossing is being discussed. The retrofit will permit essentially elastic performance and closure time will be limited to inspection. This bridge is scheduled to be retrofitted by the end of 1997.

29 **Interstate 780 (Solano County)**

Restricted for 24 hours (MMI VII to VIII-).

High liquefaction potential.

Road generally open and passable. Possible small delays for 24 hours through areas of minor roadbed disruption due to liquefaction. No structures damaged.

30 **Interstate 680 (Solano County)**

Restricted for 36 hours (MMI VII).

High liquefaction and landslide potential.

Bridge abutments and fills will settle. Minor delays due to rerouting and confinement to single lane traffic for 36 hours. The viaduct in Benicia just north of the Interstate 680/780 interchange will suffer moderate structural and liquefaction damage. Repairs will take 24 to 36 hours during which traffic will be restricted to one lane in each direction.

31 **Interstate 580 (Richmond-San Rafael Bridge)**

Closed for 36 hours (MMI VII).

High liquefaction potential near the western approach.

According to Gates (1993), "the Richmond-San Rafael Bridge will remain open during this scenario earthquake. No collapse is expected and damage can be repaired without closure. The approaches will suffer liquefaction damage and require closure for 36 hours. Despite the fact that this structure is well inside the MMI VII zone for the Rodgers Creek event, retrofit measures will allow the structure to perform elastically under even more intense shaking. Possible out-of-service time is negligible. Retrofit plans are underway and will hopefully be implemented by 1999."

32 **Interstate 80 (Contra Costa County)**

Restricted for 36 hours (MMI VII) with isolated closures.

Potential for minor landslides.

Traffic will be restricted to one lane for 24 to 36 hours by pavement buckling and small landslides. Several small bridges from El Cerrito to Pinole will be damaged and traffic will be restricted to emergency vehicles for 24 hours. Structures over Solano Avenue and McBryde Avenue in Richmond will incur moderate structural damage and will be closed to traffic. Detours can be made available via interchange ramps and surface streets.

33 **Route 4 (Contra Costa County)**

Restricted for 12 hours (MMI VII).

High liquefaction potential.

Damage to Alhambra Avenue undercrossing will allow only single lane traffic through the area for the first 12 hours.

34 **Interstate 680 (Benicia-Martinez Bridge)**

Restricted for 24 hours (MMI VII).

High liquefaction potential.

Any damage experienced by the Benicia-Martinez Bridge will be minor. Liquefaction will produce damage at both approaches and traffic will be restricted to emergency vehicles for 24 hours during the inspection period. According to Gates (1993), "the Benicia-Martinez Bridge was seismically upgraded during the recent completed widening." This bridge is scheduled for additional retrofitting by the end of 1999. Smoke from local refinery fires and toxic releases will temporarily close the Benicia-Martinez Bridge (Petroleum chapter, assessment P7).

35 **Route 101/1 Interchange (Marin County)**

Restricted for 36 hours (MMI VII).

High liquefaction potential.

The structures near the Route 101/1 interchange at Richardson Bay will experience moderate damage. Traffic will be restricted to emergency vehicles for 36 hours.

36 **Interstate 580 (Richmond, Contra Costa County)**

Open (MMI VII).

High liquefaction potential.

Although this highway crosses a zone with high potential for liquefaction, the roadway and all its structures were recently completed to the latest seismic standards.

37 **Interstate 680 (Contra Costa County)**

Closed for 12 hours (MMI VII).

High liquefaction potential.

Closed immediately south of the Benicia-Martinez Bridge due to severe pavement settlement and distortions from liquefaction. The route is only passable to high clearance four-wheel drive vehicles. Single lane light emergency traffic can be established in the area within 8 hours. Emergency repairs to the roadway can be made within 12 hours. Bridge approaches along the rest of Interstate 680 may settle but no traffic restrictions are expected.

38 **Interstate 580/80 Interchange**

Restricted for 24 hours (MMI VII).

High liquefaction potential.

Minor structural damage due to liquefaction is expected at the Interstate 580/80 interchange in Albany. Traffic will be restricted to one lane with interrupted flow with delays for 24 hours.

39 **Route 123 (Berkeley)**

Open (MMI VII).

Potential for landslides.

40 **Route 101 (Golden Gate Bridge)**

Open (MMI VII).

High liquefaction potential at south end.

As in 1989, the Golden Gate Bridge will perform well during this earthquake. It should suffer little damage and remain open to traffic. According to Singh and Tabatabaie (1991), the north and south towers of the Golden Gate Bridge could have a maximum relative longitudinal displacement of up to 20 inches during a great earthquake on the nearby San Andreas fault. According to Gates (1993), the Golden Gate Bridge has already been partially retrofitted "and can be expected to perform quite well during this scenario earthquake. Added retrofit is under design and will be out to contract within the year..." This bridge is scheduled to be retrofitted by the end of 1996.

41 **Route 1 (San Francisco County)**

Restricted for 24 hours (MMI VII).

High liquefaction potential.

The approach structures to the Golden Gate Bridge will likely be damaged and traffic limited to one lane through this area. Improved traffic capacity can be established in about 24 hours.

42 **Interstate 80 (San Francisco County)**

Open (MMI VII).

The western end of the Bay Bridge is anchored in Franciscan sandstone on Rincon Hill. Access to Yerba Buena Island will be uninterrupted. Liquefaction potential in the area does not involve the bridge or its approaches.

43 **San Francisco-Oakland Bay Bridge, east of Yerba Buena Island**

Closed 2 days for inspection (MMI VII).

High liquefaction potential at Toll Plaza.

Shaking at this site will be as strong or stronger than it was during the Loma Prieta earthquake in 1989. During that earthquake, the eastern side of the bridge moved 7 inches to the east, with the 50-foot section at Pier E9 dropping off its 6 inch seat support (Thiel, 1990). The damage was repaired and the seat support was increased to 8 inches. According to Thiel (1990, p. 149), "a secondary support system is planned that will prevent the deck systems from dropping should the stringers move eastward more than 8 inches relative to their seat supports." At Pier E23 rivets sheared off according to Thiel (1990, p. 147), and "only 1/4 inch of longitudinal bearing distance remained on the seat support following the earthquake. Thus, a deck collapse, similar to the one that occurred at Pier E9, nearly took place at Pier E23." The repair at E23 involved an increase in the length of the bearing seats.

According to Gates (1993), "the San Francisco-Oakland Bay Bridge should remain open during this scenario earthquake. No collapse is expected and damage can be repaired without closure. The secondary support system mentioned in the Governor's report has already been implemented where necessary. Currently, additional

retrofit measures are being installed and advanced analysis techniques are being used to study other potential deficiencies to improve the service level performance of this structure. Important structures such as this one will be retrofit to perform elastically with no collapse for events with a return period of 400 years. The prudent out-of-service time outlined in this scenario event remains negligible. All retrofit measures are targeted to be completed by 1997."

44 **Interstate 80 (eastern approach to San Francisco-Oakland Bay Bridge)**

Closed for 2 days (MMI VII).

High liquefaction potential.

Road closed for 2 days due to extensive liquefaction damage near the toll plaza area. Damage pattern will be similar to the liquefaction damage experienced at the east end of the San Francisco-Oakland Bay Bridge during the Loma Prieta earthquake of October 17, 1989. "This damage alone would probably have caused closure of the bridge for several days had the fallen span not already caused the bridge to be closed" (McNutt, 1990, p. 133).

45 **Route 242/680 Interchange (Contra Costa County)**

Open (MMI VII).

This structure will have minor damage but should remain open.

46 **Interstate 80 (Alameda County)**

Closed for 36 hours (MMI VII).

High liquefaction potential.

Generally impassable from the San Francisco-Oakland Bay Bridge to Albany due to soil failures and subsequent bridge damage.

Rerouting over surface streets will cause major delays. Limited light emergency traffic with some detours may be restored in 24 to 36 hours. The structures east of the Bay Bridge toll plaza will suffer moderate damage as a result of liquefaction effects, with traffic being restricted to a single lane for 48 hours.

47 **Interstate 980/580 Interchange (Alameda County)**
Restricted for 24 hours (MMI VII).
The Interstate 980/580 interchange and surrounding viaducts will be damaged. Traffic will be restricted to emergency vehicles for 24 hours until repairs can be made.

48 **Route 24 (Contra Costa County)**
Open (MMI < VII).
The Caldecott tunnels will be open in both directions.

49 **Interstate 280 (San Francisco)**
Restricted for 3 days (MMI VII).
High liquefaction potential.
Small portions of Interstate 280 in San Francisco will be closed due to minor damage of those bridges in areas susceptible to liquefaction. Traffic will be rerouted to surface streets until repairs are made. Anticipated repair time is 60 hours.

50 **Interstate 880/980 Interchange (Oakland)**
Restricted for 36 hours (MMI VII).
High liquefaction potential.
The structures near the Interstate 880/980 interchange will suffer liquefaction damage and result in traffic being restricted to one lane with interrupted flow for 24 to 36 hours.

51 **Route 61/980 Interchange (Oakland)**

Restricted for 12 hours (MMI VII).

High liquefaction potential.

Liquefaction damage will occur to the Route 61/980 interchange and surrounding structures. Traffic will be restricted to emergency vehicles for 12 hours.

52 **Route 101/280 Interchange (San Francisco)**

Closed for 18 hours (MMI VII).

The Route 101/280 interchange will experience moderate damage and will be closed. A single lane of traffic can be restored through the interchange area within 18 hours. Surface street detours with significant delays will be available through this area.

53 **Route 61 (Inner Harbor, Alameda)**

Restricted for 36 hours (MMI VII).

High liquefaction potential.

The Posey and Webster Street tunnels will suffer liquefaction damage and pavement cracking. Traffic will be limited to one lane with delays for 36 hours.

54 **Route 61 (San Leandro Bay)**

Restricted for 36 hours (MMI VII).

High liquefaction potential.

The bascule bridge across San Leandro Bay will suffer minor damage due to liquefaction and settlement. Travel will likely be restricted to one lane interrupted flow with delays for 24 to 36 hours.

55 **Interstate 880 (Alameda County)**

Restricted for 24 hours (MMI VII).

High liquefaction potential.

Traffic will be limited to emergency vehicles for 12 to 24 hours due to minor bridge damage and considerable pavement damage throughout the liquefaction zones.

56 **Route 101 (San Mateo County)**

Restricted for 36 hours (MMI VII).

High liquefaction potential.

Fill settlements and liquefaction damage to the roadbed will occur. Traffic will be restricted to a single lane with some detours to surface streets for 36 hours. No closures will be necessary.

57 **Route 101 (Oyster Point to Interstate 380)**

Restricted for 24 hours (MMI VII).

High liquefaction potential.

Minor liquefaction induced damage to the structures south of Oyster Point along Route 101. Traffic will be restricted to one lane interrupted flow with delays for 24 hours. The Route 101/380 interchange will remain open and undamaged.

58 **Interstate 380 and Route 82 (San Mateo County)**

Open (MMI VII).

Interstate 380 and Route 82 will suffer no damage and remain open.

59 **Route 101 (Millbrae)**

Restricted for 8 hours (MMI < VII).

High liquefaction potential.

Restricted for 8 hours due to minor pavement settlement from liquefaction near the San Francisco Airport. Access to the airport is possible via Route 82 (El Camino Real).

AIRPORTS

General Characteristics

Airports in the vicinity are listed below. All except for Travis Air Force Base (AFB) are shown on Map A-M. Numbers A1 to A11 refer to the map and to the damage assessments at the end of this chapter. The airports in Napa and Sonoma counties were visited and reviewed for potential earthquake damage.

Hamilton AFB in Marin County was decommissioned several years ago and is no longer in operation. The former air base is now slated for high density development as a housing and office building complex, but still could be available in an emergency.

County and Small Commercial Airports:

- A2 Sonoma County (C-130)
- A4 Napa County
- A7 Buchanan Field, Concord (C-130)
- A11 Former Sonoma Air Center (C-130 and C-141) [Seldom used]

Secondary Airports:

- A1 Healdsburg
- A3 Sonoma Sky Park
- A5 Marin County (Gnoss Field)

Major Commercial Airports:

- A9 Oakland International (C-130 and C-141)
- A10 San Francisco International (C-130 and C-141)

Military Airfields:

- A6 Travis Air Force Base (AFB), near Fairfield in Solano County (C-130 and C-141)
- A8 Alameda Naval Air Station (NAS) (C-130 and C-141)

Airports with runways capable of supporting C-130 aircraft (requiring at least 5,000 feet of runway and pavement strength to withstand 130,000 pounds wheel weight, dual tandem) are indicated as (C-130). Those capable of supporting C-141 aircraft (at least 5,000 feet of runway and sufficient pavement strength to withstand 250,000 pounds wheel weight, dual tandem) are indicated as (C-141).

Two major commercial airports and one military airport (Oakland International, San Francisco International, and Alameda NAS) are south of the MMI VIII area. Surface transportation to and from them, however, requires crossing one or more of the major bridges in the San Francisco Bay Area (Golden Gate, Richmond-San Rafael, San Francisco-Oakland, Carquinez, or Benicia-Martinez bridges). Another major military airfield, Travis AFB, is in the city of Fairfield, Solano County, about 15 miles (24 km) east of Napa.

Seismic Characteristics

Earthquake concerns for airports can be classified in one of the following categories:

1. Ground access and egress.
2. Damage to runways and taxiways.
3. Damage to buildings, including control towers.

The minimum requirements for emergency operations are ground access (and egress) to the airport and usable runways and taxiways, and power for major airports. Damage to or collapse of buildings, including the control tower, can generally be temporarily handled for the emergency period, particularly for military airlift operations.

Ground access and egress implies that vehicles can come and go between the airport and the affected communities. This may be required for the evacuation of

injured and importation of food and other emergency material. Access problems can be created by collapse of adjacent freeway structures, road blockage by nearby landslides, and settlement due to soil liquefaction. Access considerations also must include the operation of utilities such as power, telephone, and water.

Runway damage can render an airport unusable for emergency flights. The most serious threat to runways is damage from liquefaction of the underlying soils. Liquefaction can result in breaks in the pavement with differential settlements and lateral spreading of adjacent parts of runways. Federal Aviation Administration (FAA) regulations require the closing of a runway when there is a break (i.e., crack) in the pavement 3 or more inches wide. Damage to pavements from liquefaction can easily cause this much separation.

The 1964 Alaskan earthquake provided an excellent example of airport operations after a M9.2 event. Of 64 airports inspected after the earthquake, 13 were found to have had runway or taxiway damage. Nevertheless, virtually all airports were operational within hours after the event despite runway damage and building damage. Some resourcefulness, however, was required. For example, the collapse of the control tower at Anchorage International Airport required use of radios in a grounded plane for air traffic control.

During the 1989 Loma Prieta earthquake (M7), major runway damage occurred at both Oakland International Airport and Alameda NAS. In both instances, damage was caused by liquefaction. Alameda NAS was closed for over 2 months, and Oakland International lost 3,000 feet of runway. San Francisco International was closed for about 13 hours. The control tower there suffered minor damage, a cargo building suffered major damage, and some passenger terminals experienced extensive nonstructural damage, including water damage from fire sprinkler heads impacted by swinging suspended ceilings (EERI, 1990).

Planning Considerations

Air transport will play an important role in the Rodgers Creek earthquake scenario, but not to the same extent as it would for a large event on the Hayward or San Andreas faults. Because the major population centers in the central planning area are the cities of Santa Rosa, Vallejo, and Napa, use of the Sonoma County Airport and Napa County Airport is crucial for immediate airlift into the most populated areas. Napa County Airport cannot take C-130 aircraft and will be restricted to small aircraft. Sonoma County Airport can take C-130 aircraft, but not the larger C-141 aircraft.

Land transportation from three of the four major regional airports (Alameda NAS, Oakland International, and San Francisco International) may be disrupted by potential bridge damage which could sever major highway links. In addition, liquefaction of soils under runways and taxiways is possible at these three major airports. Travis AFB, which is 25 miles (40 km) from the RCF rupture, has superb airlift facilities and is outside the damage area. It will be a major post-earthquake asset.

The use of helicopters to transport people and material for search and rescue, and general damage assessment should be given a high priority in planning. Helicopter staging areas are relatively easy to set up. At airports (even decommissioned ones) they can be coordinated with incoming aircraft, some of which do not even have to make a complete landing to unload material (Becker, 1993).

None of the county, secondary, and small commercial airports in Marin, Napa and Sonoma counties, with the exception of Marin County Airport (Gnoss Field), will have local access problems.

Planning Scenario

Emergency air transport to and from the disaster area is vital to response activities, particularly during the first 72 hours. Initial response will be through Sonoma County Airport and the secondary airports. Napa County Airport will be functional after an initial inspection. Travis AFB is the most reliable site for large scale movement of material into the stricken area.

Travis AFB can handle a large scale airlift, should this be needed. Its runways can handle C-130, C-141, and the mammoth C-5A transport aircraft. Vehicular movement of personnel and material to Sonoma and Napa counties and to the city of Vallejo can be made without crossing any major bridges. However, the eastern end of the Jameson Canyon Road may be impaired by a localized landslide that would restrict traffic for 36 hours.

Damage Assessments

Damage assessments have been postulated for certain airport facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of airports (except Travis AFB) are shown on Map A-M.

MAP NO.	AIRPORTS
A1	**Healdsburg Airport** Open (MMI VII).
A2	**Sonoma County Airport** Open (MMI VIII-). There will be some damage to buildings and structures. This will hinder, but not prevent, airport use for emergency purposes. In good weather this facility can land planes in daylight without problems. Their uninterruptable power supply backup for instrument landings is only good for 2 to 3 hours. They are otherwise dependent on local electrical power. They have asphalt runways which can only take C-130 aircraft with less than 130,000 pound wheel weights.
A3	**Sonoma Sky Park Airport** Open (MMI IX).
A4	**Napa County Airport** Limited use for 24 to 48 hours (MMI VIII+). North-south runway borders zone of potential liquefaction. There will be some damage to buildings and structures. This will hinder, but not prevent, airport use for emergency operations.
A5	**Marin County Airport (Gnoss Field)** Closed (MMI VIII+). High liquefaction potential. Access road and runway will be damaged by soil liquefaction between Highway 101 and the Petaluma River.

A6 **Travis Air Force Base, near Fairfield**

Open (MMI < VII).

Travis AFB will survive the earthquake with little damage. This facility is not built on soils with high liquefaction potential (Perkins and others, 1981). Because of its location and the likelihood that roads from the base to the damaged areas will be in service, Travis AFB will be the most reliable source for airlift operations that cannot be handled by either Sonoma or Napa County airports. Traffic through Highway 12 in Jameson Canyon will be restricted for 36 hours (refer to assessment 22 in Highways chapter).

A7 **Buchanan Field, Concord**

Closed for up to 36 hours (MMI VII).

High liquefaction potential.

Runway damage from soil liquefaction.

A8 **Alameda Naval Air Station**

Closed for up to 2 months, except for helicopter operations,

High liquefaction potential.

(MMI VII).

Both runways were closed for 2 months due to liquefaction damage (McNutt, 1990) after the 1989 Loma Prieta earthquake. A repeat of this damage is expected.

A9 **Oakland International Airport**

Limited use for up to 2 weeks (MMI VII).

High liquefaction potential.

The airport is built entirely on fill, and the water table is within 5 feet of the surface (Steinbrugge and others, 1987). We expect a repeat of the liquefaction damage to runways that occurred during

1989 Loma Prieta earthquake (M7). After the 1989 Loma Prieta earthquake, OAK had "Sand boils up to 18 inches high..." (Dames and Moore, 1989). "Several breaks in the pavement were as large as 20 inches in width...on land that was reclaimed...in the 1960s through placement of 10 to 15 feet of uncompacted hydraulically dredged sand fill. The 3,000-foot extension that suffered the earthquake damage had previously experienced settlement problems." Somewhat higher ground motion is predicted for the Rodgers Creek earthquake (MMI VII) than that experienced during Loma Prieta earthquake. Some 3,000 feet of the 10,000 foot main runway will be severely damaged by liquefaction. The 6,200 foot general aviation runway will be used until the main runway is reopened. According to Becker (1993), the old north field survived the 1989 Loma Prieta event just fine and could be used in an emergency. It is seldom used by large aircraft now because of complaints from residents in the new development at Bay Farm Island.

A10 **San Francisco International Airport**

Closed for 12 hours with limited use for 3 days (MMI VII).
High liquefaction potential.

Normal operations will resume after 3 days. The Rodgers Creek earthquake will cause the same intensity of ground shaking as that caused by the 1989 Loma Prieta earthquake (M7). Runways were not damaged by the Loma Prieta event, but the control tower and some terminals experienced substantial nonstructural damage. This caused the airport to close for about 13 hours. There was a power failure and flooding (EQE Engineering, 1989; McNutt, 1990). Initial flight operations were at a 50 percent level, and it took several days to resume normal operations.

A11 **Former Sonoma Air Center**

Open (MMI VIII+).

Moderate liquefaction potential.

According to Becker (1993), the 10 inch thick, 7,000 foot long concrete runways at this old airport are suitable for landing C-141 aircraft. The fact that the associated facilities are not currently operating is not of overwhelming importance for emergency use. Another advantage of this airport is its proximity to the epicentral region. Being only 2 miles west of the Route 12/101 interchange in Santa Rosa, it is the only airport besides the former Hamilton Field capable of supporting the huge C-141 aircraft. Until this airport finally undergoes redevelopment, it will remain a valuable resource for possible emergency use.

MARINE FACILITIES

General Characteristics

There are many marine facilities of major importance located along San Francisco Bay, San Pablo Bay, and Suisun Bay in the planning area. The docks, cranes, and other components and services which comprise commercial port facilities in the greater San Francisco Bay Area are extensive and distributed throughout the planning area. Terminals in San Francisco, Oakland, Richmond, and the Carquinez region, were reviewed for potential earthquake damage, surveyed, and/or inspected in the field.

Representative types of marine facilities in the area include military and commercial facilities. Also distributed around the coast lines of the planning area are numerous small scale harbors for yacht clubs and pleasure craft, such as the Berkeley Marina, the San Francisco Marina Small Craft Harbor, San Leandro Marina, Port Sonoma/Marin near Petaluma Point, the Richardson Bay/Sausalito area, and others, which are not included in this report.

The major military facilities are Hunter's Point Naval Shipyard in San Francisco, Treasure Island Naval Station in San Francisco Bay, U.S. Naval Supply Center in Oakland, Point Molate U.S. Naval Fuel Depot in Richmond, Mare Island Naval Shipyard in Vallejo, and the U.S. Naval Magazine in Port Chicago. The U.S. Coast Guard maintains a small facility on Coast Guard Island in the estuary between Oakland and Alameda.

The Port of Oakland, consisting of a large cluster of commercial shipping terminals, is the largest container port on the Pacific Coast, and the second largest in the United States. Its marine facilities consist of four large terminal areas: the Outer Terminal, the Seventh Street Complex, the Middle Harbor, and the Inner Harbor. On an annual basis, the Port receives and ships over 14 million

metric revenue tons of cargo. Its container terminal facilities and support services cover 475 acres along 19 miles (31 km) of waterfront property on the east side of San Francisco Bay. These include 28 berths, 17 of which serve container, combination container/breakbulk, and roll-on/roll-off ships. There are 26 container cranes, and an additional 75 acres for cargo uses. All the terminals are served by rail spurs and heavy flat-bed and truck-trailer rigs.

The Port of San Francisco covers an area of about 7 miles (11 km) in length and reaches from the San Francisco Maritime National Historic Park to India Basin north of Hunters Point. Three million metric revenue tons of general cargo pass through this port on a yearly basis.

The Port of Richmond is the primary San Francisco Bay Area seaport for petroleum fuels and other liquid bulk products. Container handling facilities are also available in the Richmond Inner Harbor area. As a conglomerate set of primary shipping facilities, it handles 18 million short tons of cargo per year overall. Many of the terminals in the area are privately owned, such as the Chevron (Standard Oil) Pier, while other port properties are leased to respective shipping tenants.

Seismic Characteristics

As a principal basis for deriving probable damage patterns to port facilities in the planning area, experiences and data from the 1989 Loma Prieta (M7), 1964 Alaska (M8.4), and 1906 San Francisco (M~8) earthquakes are pertinent. Information on the seismic performance of rail mounted cranes, quay walls, equipment, and support structures can be extrapolated for planning purposes and applied to estimate damage resulting from the Rodgers Creek scenario earthquake.

A review of the 1906 San Francisco, 1964 Alaska, and other earthquakes indicates:

> "Extensive port facilities existed in San Francisco at the time of the 1906 earthquake. The earthquake performance of the pile supported docks along San Francisco's waterfront was excellent, although the soil in some fills nearby settled in terms of feet. Pile supported docks have generally performed well in earthquakes; the major exceptions in the 1964 Alaskan earthquake were due to submarine landslides and similar conditions which do not exist in the port facilities of the study area."
>
> "On the other hand, quay wall facilities have not performed comparatively well. (Quay wall facilities are docks which consist of waterfront walls with earthen fills behind them.) One quay wall failed in the Puget Sound earthquake of April 29, 1965 [M6.5], large walls failed in Puerto Montt (Chile) in 1960 [M8.5], in Tokyo in 1923 [M8.2], in Niigata in 1964 [M7.5], and in many other shocks. These failures have generally been attributed to the liquefaction of the soils behind the quay walls, forcing the walls outward due to the liquefied soil pressures" (Algermissen and others, 1972).

After the 1989 Loma Prieta earthquake (M7), a post-earthquake reconnaissance investigation and damage survey was completed for the Port of Oakland, the Port of San Francisco, and the Port of Richmond. In addition to interviewing maintenance and operations engineers of the seaports, investigators inspected actual damage to the facilities.

Relative to the performance of the Port of San Francisco:

> "The primary cause of damage was liquefaction of the fill material, which resulted in settlement of the piers supported by fill relative to the portions of the piers supported by piles. Settlement continued for several weeks after the earthquake. ...Because of significant structural damage at different locations along the waterfront, some buildings were condemned. Structural damage included cracked concrete walls and displaced asphalt decks in warehouses on Piers 45 and 48, caused by settlement of underlying fill; cracking and collapse of unreinforced clay tile walls in an office building on Pier 70; and the buckling of columns at the clock tower above the Ferry Building (the offices for the Port of San Francisco are located in the Ferry Building)."

"The Agriculture Building adjacent to the Ferry Building was closed because of differential settlement. Other damage at the port included many broken water mains, many broken batter piles, cracked concrete decks above piers, and damage to five container cranes. ...Two damaged container cranes were jacked back onto their rails and the damaged steel plates on the cranes' legs were replaced by a contractor. While this was being done, standby cranes were brought into service and ships were being unloaded by Thursday, October 19. (Author's note: The earthquake occurred at 5:04 p.m. on Tuesday, October 17) ...Water and gas lines were repaired within 1 week after the earthquake. ...Power had been turned off by PG&E because of concern that gas leaks might cause fires. Electric power was restored by 2:00 p.m. on October 19" (EERI, 1990).

Relative to the San Francisco Embarcadero and the Port of San Francisco:

"Extensive damage to the Embarcadero Freeway Viaduct (I-480) after the 1989 Loma Prieta earthquake (M7) has resulted in its demolition. The area immediately in front of the Ferry Building and the northern Piers 1-7 is now clear. The corresponding threat of a collapsed Embarcadero Freeway structure blocking access/egress to the piers has disappeared. Access to the waterfront area, however, may still be impaired by debris and damage along other approach thoroughfares" (EERI, 1990).

Relative to the performance of the Port of Oakland:

"Initial estimates set the Port of Oakland damage repair at $75 million. Damage occurred primarily at the Seventh Street Complex and the Middle Harbor; the Inner Harbor and Outer Harbor were relatively undamaged. As with the Port of San Francisco, the primary cause of damage was liquefaction of fill and the resulting settlement and spreading of areas on fill relative to areas supported by piles. The many broken water and fire lines washed the fine material from the soil, causing both settlement and uplift of the asphalt pavement at numerous locations throughout the port. Concrete batter piles were broken at the Seventh Street Complex terminals and the Matson Terminal. ...Wood piles with concrete followers were broken at the Middle Harbor, resulting in condemnation of a building that was supported on these piles. The piles broke at the wood-concrete interface. Throughout the port, damage to piles and settlement of fill occurred up to 3 weeks after the earthquake. A container crane derailed at the Middle Harbor and the 100 foot gauge distance between the rails increased up to 4 inches. Twenty-three container cranes sustained damage estimated at $500,000. At the Seventh Street terminals the crane rails that were on fill settled as much as 12 to 15 inches relative to the rail on piles, rendering the cranes inoperable. The rail spur serving Terminal 40

is currently out of service because of horizontal and vertical displacement of the rails on fill relative to a portion of the spur supported by piles. Significant settlement and separation of the truck access road to Terminals 35-38 at the Seventh Street Complex occurred as a result of liquefaction."

"The Seventh Street Complex was shut down. Half of this complex was temporarily repaired and back in service by March 1990. ...Except for the crane at the Middle Harbor that was derailed, all other container cranes remained operable. The derailed crane was repaired and operable within a day after the earthquake despite the increased gauge length of the rails."

"Water lines for which the port was responsible were repaired within 2 weeks. Water lines maintained by the City of Oakland were repaired within a week after the earthquake" (EERI, 1990).

Relative to the Port of Richmond:

"The primary damage sustained at this port was a ruptured gasoline storage tank at the UNOCAL Terminal... Fuel from this tank was contained by the surrounding berm. There was some liquefaction at the undeveloped areas of fill south of Terminal No. 3. There were sand boils at Terminal No. 3 and broken water lines at the Ford Plant located on fill east of Terminal No. 3."

"Unloading of cargo was delayed for 24 hours because of the gasoline leak. The fire department shut off power to the terminals, because they feared that sparks might ignite the fumes from the spilled gas. Also, a ship that had arrived to unload automobiles was sent to deep anchorage until the gasoline was cleaned up. ...Within 48 hours after the earthquake the entire port facility was functioning normally" (EERI, 1990).

During an earlier historic earthquake in the planning area, the 1898 Mare Island earthquake (M6.5), severe damage occurred to facilities on the Mare Island Naval Shipyard in an area now identified as having liquefaction potential. Visible evidence of ground failure, including "crevices" were noted over a large area (Toppozada, and others, 1992). The Rodgers Creek scenario earthquake will cause similar ground failures and consequent damage to facilities at the shipyard due to liquefaction and shaking.

Planning Considerations

Most of the docks in the greater San Francisco Bay Area are supported on piles. These will be mostly unaffected as in the 1906 San Francisco and 1989 Loma Prieta earthquakes. However, tarmacs, aprons, access roads, and other paved surfaces placed over fill areas will fail due to settlement and spreading of soils owing to liquefaction.

Pipelines from storage tanks to terminals will rupture where they cross areas of structurally poor ground near the docks. Restricted egress and access to terminals and docks from damaged freeways, viaducts, and nearby surface streets will be more common than damage to pile supported docks. Water supply lines will be disrupted where they cross poor ground near the docks.

Cranes often are damaged and thrown off their rails during a major earthquake, but they do not turnover readily unless the supporting dock fails. Loading and unloading at container terminals will be curtailed.

Planning Scenario

Port facilities will remain 90 percent operational after the postulated earthquake once power is restored. If power outages are extensive and service is not restored within 24 hours, operational effectiveness of the terminals will be reduced. Usable docks in the heavily damaged areas still will require emergency power and special off-loading capabilities.

Damage is anticipated to the refineries and their storage tanks (refer to *Petroleum Products* chapter). Some flat-bottom gas and oil storage tanks will rupture. For purposes of disaster planning, oil leakage as described above under *Seismic Characteristics* is to be expected. Along the margins of San Pablo Bay and the

Carquinez Strait, the MMI generated by the postulated Rodgers Creek earthquake will be in the VII to VIII range, in contrast to MMI VI or less generated in the same locations by the 1989 Loma Prieta earthquake (Figure S-4).

Marine shipping to and from Sacramento, Stockton, Port Chicago, and Pittsburg will be restricted if the Benicia Southern Pacific railroad bridge over the Carquinez Strait is jammed in the closed position. Barges may transport heavy equipment and supplies to San Francisco, Marin County, and other Bay Area destinations. However, there may be problems if long distance shipments are involved. Truck traffic to and from the ports may have to be rerouted to more southern parts of the Bay Area via undamaged access routes. Appropriate coordination efforts with other ground transport services will be required for efficient transfers.

Military shipyard and terminal installations clustered in Oakland, Alameda, and Vallejo typically are on Bay mud and artificial fill. Substantial soil displacements in these areas will diminish operational capacities. The postulated Rodgers Creek earthquake will not impair port facilities by more than 15 percent overall.

The appropriate roles that marine transport can assume in emergency response efforts should be determined. Locations with suitable land access and loading capabilities, that are most likely to be available for post-earthquake access to marine terminals and transport, should be identified. Port facilities outside the heavily affected areas should be considered along with ground transport for selecting the most effective means of providing needed equipment and supplies.

Damage Assessments

Damage assessments have been postulated for certain marine facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be

construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of marine facilities are shown on Map A-M.

MAP NO.	MARINE FACILITIES
M1	**Mare Island Naval Reservation, Solano County** Closed for 12 hours (MMI VIII-). High liquefaction potential. Ground failure will occur over a large area with substantial damage to shipyard facilities and terminals caused by liquefaction and shaking. The southern half of the island, which has a coast guard station, will have little or no liquefaction and will suffer less damage than the northern half.
M2	**Port Facilities Rodeo-Crockett, Contra Costa County** Closed for 4 days (MMI VIII-). High liquefaction potential. Moderate damage to local, privately owned shipping facilities of oil refineries and chemical plants in a narrow zone of liquefaction along this area at the southeast edge of San Pablo Bay.
M3	**Benicia, Solano County** Closed for 3 days (MMI VII). High liquefaction potential. There will be minor damage to marine facilities and petroleum fuel pipelines, with extensive damage along a narrow band of soft ground where liquefaction will cause subsidence.

M4 **Port of Richmond, Contra Costa County**

Closed for 3 days (MMI VII).

High liquefaction potential.

Rupture of 10 percent of storage tanks and threat of fire at terminals will cause port area to be closed for 3 days with corresponding delays in unloading cargo.

M5 **Port of San Francisco, San Francisco County**

Port facilities will remain 90 percent functional (MMI VII).

High liquefaction potential.

Most damage will be caused by liquefaction of fill material, resulting in settlement wherever piers are supported by fill. Substantial damage to office buildings and warehouses will be caused by settlement of fills. Two container cranes will be thrown off their rails with standby cranes being brought into service. Damage to water and gas lines will be repaired within 1 week. Port facilities will remain 90 percent functional, and truck access routes will be 90 percent accessible. Some facilities will be closed for inspection and repair for up to 3 weeks. As a result of the 1989 Loma Prieta earthquake, "slight ground subsidence and cracking was observed at Pier 80" (McNutt, 1990).

M6 **Port of Oakland, Alameda County**

Harbor areas disrupted for 1 week (MMI VII).

High liquefaction potential.

Facilities at two specific harbor areas operating at 50 percent capacity for up to 4 months. Severe damage caused by failure and settlement of uncompacted hydraulic fill will occur at two of the four harbor areas, resulting in a 30 percent loss of terminal operation during the initial 72 hour post-earthquake period.

Functional problems will arise with a loss of 10 to 15 percent of the 26 container cranes owing to direct damage or derailment due to soil failures. Operational capacity will be disrupted by failure of electric power (up to 24 hours) and water supply (up to 2 weeks). Surface access routes and rail lines damaged by liquefaction and settlement of soils will decrease capacity by 10 percent for up to a year.

As a result of the 1989 Loma Prieta earthquake, the parking lot settled and the curb shifted bayward at Port View Park (Borchardt, 1991a). "Differential settlements on the order of 4 to 12 inches [occurred] ...between a pile-supported wharf and fill at the Port of Oakland" (Dames & Moore, 1989). "One terminal constructed entirely on fill suffered extensive damage as well as subsidence. Thirty percent of this terminal area became unusable" (EQE Engineering, 1989).

RAILROADS

General Characteristics

Selected railroad bridges and facilities were reviewed and inspected for seismic resistance and potential for earthquake damage. Railroad access to the planning area will be severely impacted by the scenario earthquake. In this light, the importance of railroad access for hauling emergency freight, including replacement of heavy equipment and critical supplies, should be carefully considered. Alternatives should be developed where outages are expected.

Over the past 22 years, the management of railroad systems has changed although routes, bridges, and rail lines are mostly as they were constructed in the 1860's through the 1920's. Of the major railroad networks shown on Map R, the most heavily used for hauling freight (and by AMTRAK passenger trains) are the Southern Pacific (SP), Atchison Topeka and Santa Fe (AT&SF), and Union Pacific (UP) lines.

The Western Pacific Railroad (WP) merged with UP in 1981. The Alameda Belt Line (ABL), serving the Island of Alameda, is now jointly owned by AT&SF and UP railroads. In September 1986, SP sold the line north of Rocktram (north of Napa Junction) to the Napa Valley Railroad Company, which now runs north to St. Helena as a tourist attraction. On July 1992, The Joint Powers Board (JPB) of San Francisco, San Mateo, and Santa Clara counties assumed ownership of the SP line from San Francisco to San Jose.

The Northwestern Pacific Railroad (NWP) is a wholly-owned Southern Pacific subsidiary that serves the counties of Marin, Sonoma, and Mendocino. Compared to company-operated main lines, existing traffic levels on the NWP are extremely small. In 1990, NWP sold the line south of Ignacio to the Golden Gate Bridge, Highway and Transportation District (GGBH&TD). The line has been closed,

pending a decision on its future use. GGBH&TD also has the option to buy the remainder of the NWP lines, and the SP line from Schellville in Sonoma County, to Lombard in Napa County. The only railroad line that crosses the Rodgers Creek fault is NWP in southern Sonoma County. BART (Bay Area Rapid Transit) is south of the area of greatest shaking in this scenario.

Seismic Characteristics

Several of the railroad lines in the planning area cross areas of potential liquefaction. Such poor ground conditions become even more critical during the wet season. Under dynamic loading, fills placed over poor ground will settle, crack or spread at roadbeds and bridge approaches (Borchardt, 1991a, 1991b), (Photo R-1). For an excellent reference on seismic damage to railroads, refer to McCulloch and Bonilla (1970).

Even though the roadbeds in the planning area have been compacted by many years of use, they still face problems in areas having high liquefaction potential as experienced during the 1906 San Francisco earthquake:

> "Embankments across marshes, or with soft strata underlying them, settled more or less. In some cases, the settlement was vertical; in other cases, there was considerable horizontal with vertical movement. At one point on the marsh between Benicia and Suisun, on the Southern Pacific, the settlement was 11 feet; at another point, 5 feet. These were all vertical" (Lawson, 1908).

This area along the Suisun-Benicia shoreline has had a long history of problems dealing with roadbed settlement, dating to the original construction of the railroad:

> "The laying of the railroad between 1877-1879 presented an unexpected and unique problem to the Central Pacific Company...the "marsh sink." Since the roadbed skirted the Suisun Benicia shoreline, marsh or tule land was part of the terrain. Anything of weight placed in the area would sink out of sight...ties, rails, railcars,

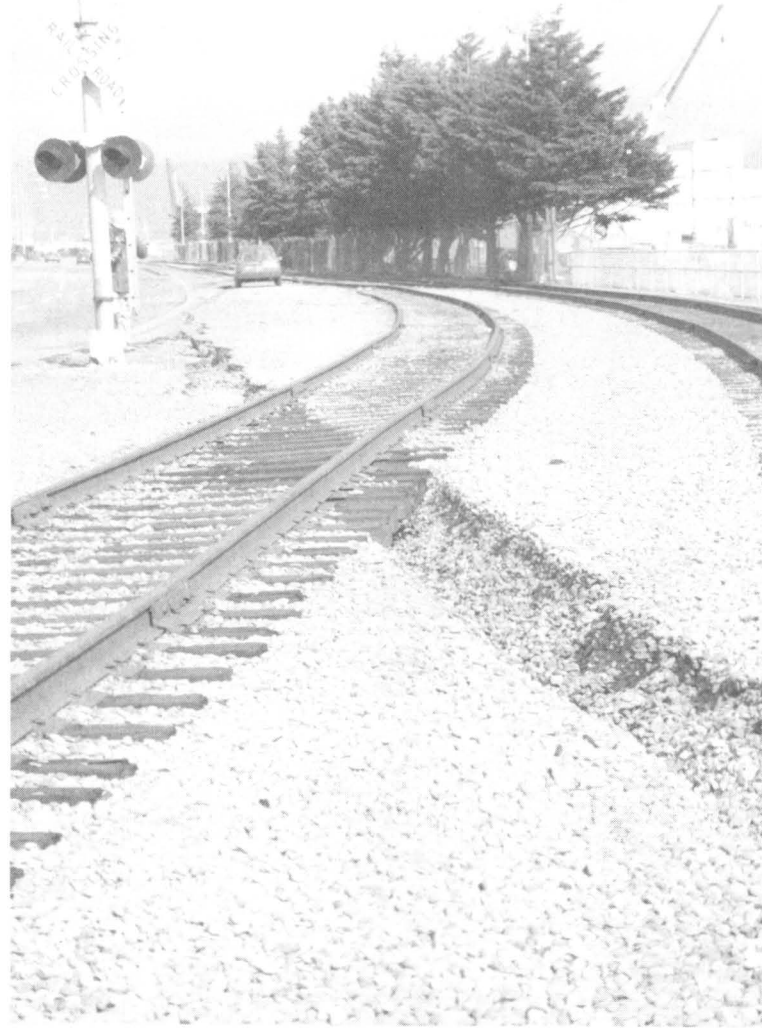


Photo R-1 Liquefaction damage to railroad tracks due to lateral spreading at the Port of Oakland as a result of the 1989 Loma Prieta earthquake. *From Borchardt, 1991a.*

equipment, etc. To overcome the problem, the company dumped millions of tons of granite stone from the Sierras into the ravenous marsh. Finally a stable roadbed was established" (Benicia Arsenal, Benicia Camel Barn Museum, Benicia Railroad Bridge Construction Exhibition, 1992).

Another account of the "Suisun Sinks" after the 1906 earthquake relates that "During this time there were between 300 and 400 men employed continuously on the sinks, which were very troublesome until August 1905 at which time the

heavy sinks were controlled so that there was no interruption of traffic for some time; but the fill continued to settle more or less during the balance of the year and up until the morning of the big earthquake April 18, 1906, when the fill settled 12 feet." From 1913 to 1915, SP embarked on a massive rehabilitation program for the entire Suisun sink area. This led to the observation that "the sink territory for the first time in many years was being maintained by regular gangs only, in addition to day and night watchmen at intervals" (Southern Pacific, 1916).

One characteristic of railroads is that switching and signaling systems depend on electric power. These systems have backup battery power supplies which will operate main line power switches, lights, bells, and gates for 2 to 3 days before battery depletion. Without commercial, generator, or battery power, the trains will operate at restricted speed (not over 20 mph) and grade crossing warning systems will not function.

Railroad drawbridges also depend on electric power for normal operation. If an emergency back-up power source does not exist, the drawbridge, if open at the time of the scenario earthquake, will remain open, blocking traffic in both directions.

According to (NOAA, 1973), railway bridges seldom experience major damage except in areas subject to surface fault rupture and/or ground failure. However, when bridge damage does occur, repairs usually involve more than the 3 day scenario period.

Movable bridges are especially vulnerable to earthquakes. For example:

> "In the 1949 earthquake (M7), the piers of a bascule railroad bridge in Seattle shifted from 4 to 7 inches (10 to 18 cm). Although realignment of the tracks was the only required correction, the bridge was not open to traffic for several days" (Olsen, 1975).

Rail facilities also are subject to closure by major damage to freeway overpasses, bridges, and interchanges. As indicated by the seismic performance of the Cypress Street Viaduct, the San Francisco Embarcadero Freeway, and Struve Slough Bridges during the 1989 Loma Prieta earthquake (M7), overpasses and bridges are vulnerable to significant damage and collapse in areas of strong ground shaking and/or soil liquefaction.

Planning Considerations

Because of their repair capabilities, including extensive use of outside contractors, the railroads will solve most of their reconstruction problems with little attention from emergency service organizations responsible for disaster response. Nevertheless, damage and the loss of electric power will have a serious impact on railroad facilities. Complete restoration of rail service to critical facilities throughout the area will take 1 to 2 weeks. The interrelationships between railroads, other systems of transport, and utility lifelines should be scrutinized to resolve jurisdictional problems and set work priorities before the scenario earthquake occurs.

In general, the major railroad freight lines, terminals, and facilities in the planning area are in areas having high liquefaction potential where failures are expected. This is particularly true for southern Sonoma, Solano, and Napa counties, northern and western Contra Costa County, and western Alameda County. These rail facilities and services are of vital importance in moving heavy freight to, within, and from major port terminals, industrial plants, military installations, and heavy manufacturing establishments. Contingency plans probably should include the establishment of temporary transport terminals outside areas where severe damage to major railroad lines is expected. At Carquinez Strait, Benicia, Vallejo, and Martinez, planners should consider transporting critical heavy equipment by barge and/or air.

Planning Scenario

The rail lines along Suisun Bay, San Pablo Bay, and the Carquinez Strait will be interrupted critically for the initial 3 day post-earthquake period. Low capacity rail lines along the north shore of San Pablo Bay will be displaced by liquefaction and closed for repairs up to 7 days as will be the lines at Black Point, Sears Point, and the Napa Slough areas.

All movable span bridges in MMI VIII+ to IX zones are subject to misalignment due to heavy ground shaking. Repairs will require up to a week. The movable bridges over the Carquinez Strait and Petaluma River will be closed for up to 8 days.

Because of electric power outages lasting up to 48 hours, the Benicia-Martinez lift span over the Carquinez Strait and the two pivot bridges over the Petaluma River will be inoperable. All three could be transfixed or jammed in either an open or closed position, blocking the railroad lines if open, or delta marine transport if closed.

Damage Assessments

Damage assessments have been postulated for certain railroad facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of railroads are shown on Map R.

MAP NO.	RAILROAD LOCATIONS
R1	**Northwestern Pacific (NWP), Rohnert Park** High liquefaction potential. Closed for over 1 week (MMI IX). The southern access to the Bay Area from this low capacity rail line will be disrupted at this point.
R2	**Napa Valley Railroad Company (NV), Rutherford [Tourist Attraction]** High liquefaction potential. Closed for 2 months (MMI VIII-). This tourist route will be disrupted by ground failure wherever it crosses areas having high liquefaction potential. The system will remain closed as all available personnel work on high priority lines.
R3	**Northwestern Pacific (NWP) at Petaluma River, Sonoma County** High liquefaction potential. Closed for at least 1 week (MMI VIII+). Embankments will be damaged. The drawbridge over the Petaluma River will be misaligned and will be closed to traffic from 2 to 8 days. There were sand boils northwest of Petaluma in a MMI IX area in 1906 (Youd and Hoose, 1978, location 287; Davis and others, 1982b).
R4	**NWP at San Antonio Creek/Petaluma River Marshlands** High liquefaction potential. Closed for 3 to 7 days (MMI IX). Liquefaction of marshland areas along San Antonio Creek will disrupt and deform tracks.

R5 **NWP at Black John Slough/Rush Creek**

High liquefaction potential.

Closed for 2 to 7 days (MMI VIII+).

Disruption of lines by liquefaction of poor soils.

R6 **NWP at Tidal Marshes near Novato Creek**

High liquefaction potential.

Closed for 2 to 7 days (MMI VIII+).

Liquefaction in marsh areas near creek causes misalignment of tracks.

R7 **GGBH&TD [Abandoned line]**

High liquefaction potential.

Tracks and tunnels have been closed until the Bridge District decides on the future use of this right-of-way. As seen from Map S, this right-of-way crosses areas having high liquefaction potential at over a half dozen places. Its future use for a transportation route will require extensive geotechnical study and mitigation.

R8 **NWP from Novato, Marin County, to Schellville, Sonoma County**

High liquefaction potential.

Closed for 3 to 7 days (MMI VIII+, IX).

The rail line disruption and deformation will be due to liquefaction in marshland areas around Novato Creek, Petaluma River, Tolay Creek, and Sonoma Creek. There was lateral spreading at the Petaluma River crossing, an area of MMI IX shaking, in 1906 (Youd and Hoose, 1978, location 260; Davis and others, 1982b).

R9 **NWP at Rodgers Creek Fault Zone**

Closed for up to 3 days (MMI VIII+).

Fault rupture.

Fault displacement will disrupt tracks, requiring realignment and repairs. Because the tracks are nearly perpendicular to the fault, and because this crossing is near the end of the fault, the disruption will be minimal.

R10 **Southern Pacific from Schellville to Napa Junction**

High liquefaction potential.

Closed for 8 days (MMI VIII+, IX).

Rail lines disrupted and deformed due to liquefaction around Napa River and Napa Slough. Bridge damage and settlement of approaches as a result of liquefaction at the crossing will close the bridge over the Napa River.

R11 **SP Branch to Rocktram (Napa vicinity)**

High liquefaction potential.

Closed for 3 to 7 days (MMI VIII-).

The tracks from Suscol Creek to downtown Napa Station will be unusable due to liquefaction ground failure.

(the SP rail line stops about 3/4 mile north of this point).

R12 **SP to Vallejo via Jameson Canyon, Napa/Solano Counties**

Landslide and liquefaction potential.

Closed for up to 2 days (MMI VIII-).

Localized landslides and rock falls cause disruption to the rail line, and liquefaction causes settlement in the west part of the canyon.

R13 **Mare Island Strait Terminal, Solano County**

High liquefaction potential.

Closed for up to 2 days.

Liquefaction ground failures disrupt railroad bed.

R14 **SP Line along South Shore San Pablo Bay, Contra Costa County**

High liquefaction potential.

Closed for up to 2 days.

Railroad bed disrupted in shoreline areas due to ground failure caused by localized liquefaction.

R15 **SP Railroad along Suisun Bay North Shore, Solano County**

High liquefaction potential.

Closed for 3 to 5 days (MMI VIII).

Closed due to soil failures and disruption of railroad bed along Suisun sink territories. Refer to the quotes above (under *Seismic Characteristics*) concerning Suisun marsh and description of settlement during the 1906 event at location No. 254 in Youd and Hoose (1978).

R16 **SP Crossing at Benicia-Martinez Bridge, Solano/Contra Costa County**

Closed for 5 days.

Lift-bridge portion jammed due to ground shaking. Misalignment of bridge and repairs of minor damage require closure of the bridge for up to 5 days. Loss of electric power for more than 24 hours would curtail operation of the lift section.

R17 **SP and AT&SF East of Martinez, Contra Costa County**

High liquefaction potential.

Closed for up to 2 days (MMI VIII).

Ground failure due to liquefaction in Hastings Slough and Seal Creek areas will disrupt rail lines. Lateral spreading occurred near the SP tracks at three different places in 1906 (Youd and Hoose, 1978, location 252; Davis and others, 1982b).

R18 **SP Spur to Richmond Inner Harbor**

High liquefaction potential.

Closed for up to 2 days (MMI VII).

Spur to Richmond harbor area disrupted by lateral spread due to liquefaction similar to that experienced in the 1989 Loma Prieta earthquake.

R19 **SP Rail Line along the East Bay shore near Berkeley, Alameda County**

High liquefaction potential.

Closed for 3 to 4 days (MMI VII).

Inspection of rail lines and localized repairs to roadbed disrupted by ground failure.

R20 **JPB Caltrain Commuter Station, San Francisco City and County**

High liquefaction potential.

Closed for up to 12 hours (MMI VII).

Closed for inspection.

R21 **UP Spur to Port of Oakland**

High liquefaction potential.

Closed for 3 to 5 days (MMI VII).

Spur to harbor area disrupted by lateral spread resulting from liquefaction of soils similar to the 1989 Loma Prieta experience (Photo R-1).

R22 **JPB Caltrain Commuter Line, San Francisco/San Mateo County**

High liquefaction potential.

Closed for 12 hours (MMI VII).

As a result of the 1989 Loma Prieta earthquake, ground failure of Caltrain occurred between San Francisco and San Jose (McNutt, 1990). Minor damage caused by localized ground failure will result in disruption of service during the immediate post-earthquake period and for safety inspection of rail lines.

R23 **ABL, Island of Alameda**

High liquefaction potential.

Closed for up to 2 days (MMI VII).

Damage caused by localized ground failure will disrupt rail service along Alameda estuary as it did in 1989 (McNutt, 1990).

R24 **BART**

Closed for 12 hours (MMI VII).

There is high liquefaction potential in a few places, but judging from the 1989 experience, this will have no effect on BART. After an initial inspection, BART will perform satisfactorily, as it did after the Loma Prieta earthquake. As in 1989, some stations will be without power for illumination and ticket machines, but the third rail will remain electrified. There is some battery backup power for illumination. According to EERI (1990, p. 270-272), there was minor damage at "the transition structure between the transbay tubes and the West Oakland Station, and at several stations in the East Bay. The transbay tubes suffered minor water seepage but no structural damage." In San Francisco, the power outage prevented

removal of normal underground seepage between the Powell Street and Civic Center stations. Water rose to within 2 inches of the top of the rails before generators could be obtained to operate the sump pumps.

SECTION 4

UTILITY LIFELINES

ELECTRIC POWER

General Characteristics

Electric power is supplied to the planning area by the Pacific Gas & Electric Company (PG&E). Routes of transmission lines and locations of major generating facilities and substations that serve the area are shown on Map E, (refer to Table E-1). We visited one major plant in the planning area, and completed field surveys of six others.

Within a complete electric power service system there are many critical elements, including five primary components:

1. Power generating plants.
2. High voltage transmission lines.
3. Transmission and distribution substations.
4. Distribution lines.
5. Control and communication centers.

Seismic Characteristics

Earthquakes have frequently disrupted electric power service. In simple terms, sources of disruption may come from one or more of the following four elements:

1. Temporary imbalance in the system due to simultaneous loss of many customers' power use.
2. Disruption of the source of supply.
3. Damage to transmission facilities.
4. Damage to the distribution system.

According to Savage and Matsuda (1993):

> "Immediately following a major earthquake, electric power service within the region affected by the earthquake will be temporarily disrupted due to the imbalance created between the amount of electric power provided by the utility and the customer demand. This imbalance, if sufficiently large, will cause the power service to disconnect. The earthquake can also cause distribution lines to slap together, causing shorting and relaying of local distribution circuits. These types of disruptions do not necessarily involve

damage to the utility system, but often involve delays in reconnecting customers while the nature of the outage is being investigated and safety precautions are being taken before energizing circuits. ...customers should expect power to be disrupted at least briefly (for a few minutes) when a strong earthquake occurs."

TABLE E-1

ELECTRIC POWER GENERATING PLANTS

Facility	County	Type[1]	Generating Capacity MW
Hunters Point	San Francisco	CT/ST	429
Potrero	San Francisco	CT/ST	363
Oakland	Alameda	CT	165
Oleum	Contra Costa	COG	87
Martinez	Contra Costa	COG	46
Avon	Contra Costa	COG	46
Contra Costa[2]	Contra Costa	ST	1260
Pittsburg[2]	Contra Costa	ST	2002
The Geysers[2]	Solano	GEO	909

[1] CT Combustion Turbine
ST Steam Turbine
COG Cogeneration
GEO Geothermal
[2] Located outside immediate planning area

Sources of electric power supply include generating plants, such as fossil, hydro and nuclear power plants, and power supplied from transmission inter-ties with power grids with many diverse power sources. Generating facilities are typically rugged. For instance, the Moss Landing Plant (2,000 MW) on Monterey Bay was shaken at MMI VII by the Loma Prieta earthquake but damage to the seven generating units there was relatively minor (EERI, 1990).

Transmission facilities consist of high-voltage transmission lines and substations. Generally, transmission towers and lines are resistant to damage from ground shaking, but they can be damaged by ground movements caused by surface fault

rupture, liquefaction, or landsliding. The effects of ground movements, however, are much more local than are ground shaking effects.

The 1992 Landers earthquake in San Bernardino County provides excellent evidence of the performance of high-voltage transmission towers during a M7.5 seismic event:

> "Significant damage was limited to severe deformation of a high-voltage transmission tower located astride the north end of the Camp Rock-Emerson surface fault rupture. The fault passed directly between the legs of the bolted steel frame 220 kV tower, moving two of the legs approximately 9 feet (3 m). This resulted in substantial deformation of the steel tower and failure of several braces. No damage was sustained by the lines or the ceramic insulators, and the tower continued to provide adequate support. The lines were later disconnected from the electrical grid as a precaution during repairs" (EERI, 1992).

Transmission facilities are vulnerable mainly at high-voltage substations. During the Loma Prieta earthquake, three such substations (Moss Landing, Metcalf, and San Mateo) suffered major damage. Within the Moss Landing substation (MMI VII, about 18 miles (29 km) from the epicenter) four live tank circuit breakers were severely damaged as well as 10 of 12 current transformers (EERI, 1990). The type of damage experienced at Moss Landing, and the other two substations, is not without precedent. In fact, high-voltage substations generally are considered the least seismically resistant element in electric power supply systems. A week-long substation outage is rare, except for extremely high voltage equipment (Borchardt and Manson, 1986).

According to Savage and Matsuda (1993):

> "For high-voltage substations affected by very strong shaking (such as is recorded within 5 or 10 kilometers of a large fault rupture), it is likely that there will be some damage such that one or more lines through the substation will go out of service either directly because of the damage or due to automatic protection relaying of circuits. In the event of damage, especially extensive damage to circuit breakers and switches, the emergency response used is to restore some level of service by

> bypassing the damaged components. Such bypassing can usually be accomplished within hours (less than a day). Transformer damage can be longer to bypass, because spare parts or even mobile transformers may need to be carried by helicopter into the site. However, basic functional restoration is not expected, in general, to take longer than several days. This restoration does not, of course, mean that all damage is completely repaired. It does mean, however, that the customers served by the substation can be supplied."

Low voltage systems contain shorter and less massive porcelain insulators, have much greater redundancy, and resist damage more than transmission systems. There was relatively little damage to distribution systems after the Loma Prieta earthquake, with the damage described as being equivalent to that produced by a severe winter storm that may occur once a year (EERI, 1990).

The overall effect of the Loma Prieta earthquake on the electrical power system has been summarized as follows:

> "Approximately 1.4 million consumers suffered interruption of their electrical service as a result of the earthquake. Within 48 hours, service had been restored to all but 26,000 customers. Parts of Watsonville, however, were without electricity for 4 to 5 days" (McNutt, 1990).

Planning Considerations

There are no major power plants in the strongly shaken areas (MMI VIII and IX). Sources of power to the planning area, particularly Sonoma and Napa counties, come from outside the area and will be unaffected by the Rodgers Creek earthquake. Disruption of power service to institutions, businesses, and residences will come from initial post-earthquake destabilization of the system, and damage to substations and local distribution systems. Portions of the planning area, especially Sonoma, northern Marin and Napa counties, and Vallejo will be without power for a day or more after the earthquake.

Vital facilities and other lifelines discussed in the report, especially water supply, waste water treatment, and communications, will be affected by interruptions in electrical power. Emergency planning for such facilities must recognize that power in certain areas can be out for extended periods. It is crucial that hospitals, emergency operations centers, water and waste water systems, and other vital facilities have their own emergency power sources. Those without emergency power sources must be identified, and the appropriate emergency procedures should be developed to compensate for this.

Planning Scenario

During the first 3 days after the earthquake virtually all portions of the planning area will experience some loss of power, at least temporarily. The cities of Santa Rosa, Petaluma, and Sonoma are in strongly shaken areas (MMI VIII+ and IX) and will experience the longest power outages. Service to most areas of Santa Rosa will be restored in 24 hours, but some areas of the city may experience outages lasting as long as 5 days.

The Rodgers Creek earthquake will not shut down any significant power plant or interrupt other sources of supply, such as the 500 kV Pacific Intertie. Damage to PG&E facilities will be confined primarily to substations and distribution facilities. For instance, the Lakeville Substation, a critical link in providing service to the planning area, will be damaged and closed for up to 2 days. To continue service while repairs are being made, electric power will be distributed over alternate lines. The towers of a set of parallel high voltage transmission lines crossing a large area of liquefaction along the marshlands of San Pablo Bay will be damaged by settlement and subsidence.

There will be damage to parts of the distribution system (less than 60 kV network), particularly in Sonoma and Napa counties. We assume that 25 to 30

percent of the service connections in Sonoma and Napa counties will be without power for the first 36 hours.

The central Bay Area, including San Francisco and the East Bay cities, will have relatively brief power outages. We expect minor damage to substations and transmission lines, resulting in widespread power outages of 4 hours or more. Physical damage to facilities in the central Bay Area will be at about the same level as that which occurred in the 1989 Loma Prieta earthquake. Because much of the equipment is new, the damage to underground conduits and vaults in the Marina District of San Francisco will be less severe than it was in 1989. Nevertheless, power there will be out for up to 3 days.

Electric power service facilities are vulnerable to major seismic events, particularly in areas of severe ground shaking (MMI VIII or IX), liquefaction, surface faulting, or landslides.

Critical facilities in the planning area, such as hospitals, fire and police stations, emergency communications and operations center, water supply pumping stations, and water treatment plants will require standby generating equipment and adequate emergency fuel.

Damage Assessments

Damage assessments have been postulated for certain electrical power facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of electric power transmission lines and major power generation and substation facilities (except the Geysers and Pittsburg power plants) are shown on Map E.

MAP NO.	ELECTRIC POWER FACILITIES

E1 **The Geysers-Sonoma County**

Open (MMI VII).

Facilities at the Geysers geothermal power plant will be moderately shaken. There will be only minor damage due to shaking and landsliding.

E2 **Fulton Substation-Sonoma County**

Closed for up to 2 days (MMI VIII+).

This facility is located in a zone of strong shaking and damage to electrical equipment will cause the facility to close.

E3 **Transmission Lines Crossing the Sonoma Mountains, Sonoma County**

Shut down for up to 3 days (MMI VII).

Landsliding in the Sonoma Mountains will damage several consecutive towers along these transmission lines, resulting in a shutdown.

E4 **Lakeville Substation**

Closed for up to 2 days (MMI VIII+).

This facility is located 3.3 miles (5.3 km) from the Rodgers Creek fault in a zone of very strong shaking. It is on alluvium about 90 feet above sea level and is 0.3 mile (0.5 km) from the nearest creek.

E5 **Transmission Lines Crossing the Sonoma Mountains, Sonoma County**

Shut down for up to 3 days (MMI VII).

Shaking will produce liquefaction along the Napa River, causing these lines to be disconnected from the power grid.

E6 **Tulucay Substation, Napa County**

Open (MMI < VII).

This facility is built on a minor cut and fill in bedrock between 30 and 70 feet above sea level. During the Loma Prieta earthquake, the Newark Substation, also in a MMI VI zone, had only a few gasket leaks (EERI, 1990, p. 336).

E7 **Ignacio Substation, Marin County**

Closed for 1 day (MMI VII to VIII+).

Moderate liquefaction potential.

This substation handles all power routed south into Marin County. The eastern half of the substation is founded on bedrock, while the western half is on shallow Bay mud. The hill to the east would prevent lateral spreading in that direction. The nearest free face is a shallow canal 600 feet to the northwest. Although minor settlement will occur, this will not affect operations significantly. Bay mud in the surrounding region will have an MMI of VIII+, but the thin mud layer at this site will result in an MMI of VII, similar to that of nearby bedrock.

E8 **Transmission Lines**

Sonoma County

Closed for up to 4 days (MMI VIII- to IX).

Ground failure due to landslides and liquefaction will disrupt these two lines.

E9 **Transmission Lines-North San Pablo Bay, Sonoma/Solano Counties**

Damaged but operable (MMI VII).

Ground failure due to liquefaction will damage many towers, but the transmission lines will remain operable. Nevertheless, the lines will be disconnected from the electrical power grid while repairs are made.

E10 **Transmission Lines, Solano County**

Closed for up to 5 days (MMI VII).

Several towers will be damaged by landsliding caused by the earthquake, but alternate transmission lines can be used. Repairs to towers will first require removal of landslide debris for accessibility.

E11 **Richmond/Antioch Fuel Line**

Inspection and repairs completed in 3 days (MMI VIII-).

High liquefaction potential.

This fuel line between refinery and power plants crosses areas of high liquefaction potential along the bay margin. The San Andreas and Hayward scenarios hypothesized damage along this pipe line under predicted MMI VIII to IX shaking (Davis and others, 1982a; Steinbrugge and others, 1987).

E12 **Oleum Power Plant**

Closed 24 hours (MMI VIII-).

High liquefaction potential.

This plant had no damage under the MMI VI shaking of the Loma Prieta event. The scenario earthquake, however, will generate stronger shaking here (MMI VIII-) than at any other power plant. For a review of the type of damage to be expected, refer to the summary concerning the Moss Landing Power Plant, which was in

the MMI VII zone of the Loma Prieta event (EERI, 1990, pp. 208-214). Six inches of soil subsidence at Moss Landing produced only a few minor leaks in some gas pipes.

E13 **Pittsburg Power Plant**

Closed 6 hours (MMI VII).

High liquefaction potential.

This plant will suffer only minor damage, but it will require about 6 hours for inspection.

E14 **Richmond Substations**

Closed 2 days (MMI VII).

High liquefaction potential.

These two substations will have moderate damage to high voltage transformers.

E15 **Oakland Power Plant**

Closed 6 hours (MMI VII).

High liquefaction potential.

This plant will suffer only minor damage, but it will require about 6 hours for inspection.

E16 **Power Plants and Substations, San Francisco**

Closed for 6 hours (MMI VII).

High liquefaction potential.

The Embarcadero and Martin stations will remain open as they did after the Loma Prieta event. According to EQE Engineering (1989), in the 1989 Loma Prieta earthquake "Hunter's Point...stayed on-line and had only superficial damage. The Potrero Power Plant went

off-line due to relay chatter..." Photos and details concerning the minor damage produced under 0.1g peak horizontal acceleration are given in EERI (1990, p. 214-216). A modern cogeneration plant at Gilroy also was in the MMI VII zone. It suffered no damage and, after inspection, was restarted within 7 hours of the Loma Prieta earthquake.

NATURAL GAS

General Characteristics

Natural gas is supplied to the planning area by the Pacific Gas & Electric (PG&E). The major facilities and routes of the major gas transmission pipelines serving the area are shown on Map G. Selected locations and facilities were reviewed for seismic vulnerability and surveyed in the field.

The bulk of the gas supply to the area is provided through large-diameter transmission lines that enter California at the Oregon and Arizona borders.

Seismic Characteristics

The typical gas supply system has three major elements:

1. Transmission system.
2. Underground storage facilities.
3. Distribution system.

While gas supply systems are typically rugged and have performed well in past earthquakes, some damage has occurred, particularly to transmission and distribution systems.

The transmission system carries gas from gas production or storage fields in high pressure lines. This system may include terminals, compressor stations, and pressure limiting stations. Transmission pipelines can survive strong shaking, but are vulnerable to large permanent ground deformation. For example, during the February 9, 1971 San Fernando earthquake (M6.4), several gas transmission lines suffered numerous breaks in an area that experienced surface fault rupture and resulting permanent ground deformation. The lines ranged from 12 to 26 inches in diameter and were of welded steel construction. One 6 mile length of pipeline had 52 separate breaks (NOAA, 1973).

However, according to Savage and Matsuda (1993):

> "Large-diameter, high-pressure gas transmission lines are inherently highly resistant to damage in earthquakes due to either shaking or permanent ground displacements. Even when damaged, such gas lines are still able to safely contain the gas flow. ...operation of a damaged line would likely continue, and the repairs could be made several weeks later....All efforts are made to keep the gas system pressurized even though damaged, providing there are no significant safety issues involved. If parts of the system must be depressurized, then it will likely take days to purge the shut-in portion of the system and re-light the affected customer connections."

Modern underground storage facilities, which are depleted gas and oil fields, are practically invulnerable to earthquake damage. The planning area no longer has above-ground gas holders.

The typical gas distribution system consists of a vast network of relatively small diameter (2 to 8 inch) underground lines and related above ground control facilities. Major earthquake vulnerabilities of distribution systems include permanent ground deformation and strong shaking of non-ductile distribution lines that may have deteriorated with age or corrosion. New arc-welded steel lines and plastic lines are more ductile than the old lines and are expected to perform better. If permanent ground deformations occur, such as those caused by liquefaction, landsliding, or surface fault rupture, the old lines generally are much more vulnerable than the new lines, but both can be damaged. During the 1971 San Fernando earthquake (M6.4), the distribution system serving 17,000 customers in a 12 square mile area was severely damaged by deformation caused by surface fault rupture:

> "The distribution system in the hard hit area consists principally of 2, 3, and 4 inch welded steel mains and 3/4 inch welded steel services. The violent earth movement pulled, compressed, and twisted the piping system resulting in broken mains, valves, and service risers. There were approximately 181 breaks in mains, mostly at welds, but some occurred in the pipe and others in valves or fittings. There were 137 breaks in service and 62 breaks at service-to-main connections..."

"In the Sylmar-San Fernando area, all supply to the damaged distribution system was closed down. Each customer's meter was closed (or removed if the structure it served was damaged severely). The area was then subdivided into 12 segments or subisolation areas to facilitate the location and repair of leaks. Then subsection by subsection the area was repressured and service restored to individual customers."

"In preparing to restore service, some 22,000 feet of new supply line in sizes 6, 8, and 10 inches was installed and tested to provide a supply to the distribution regulator stations from the Pacific Lighting Service Company 26 inch Line 85. Also, it was found necessary to replace about 11,600 feet of badly damaged distribution main. One hundred and seventeen services were altered or replaced. One hundred and thirty nine services were disconnected or abandoned at the main."

"The 12 subisolation areas varied in number of customers from 140 to 3,375. The first three had service restored to customers by Sunday, February 14, and the last was back in service on Saturday, February 20. By Monday, February 22, 15,644 meters were returned to service. About 342 others were restorable, but customers were not ready and 343 meters had to be removed because the structures they served were severely damaged or demolished."

"In the period February 9 [the day of the earthquake] through 21, there were about 200 men working two 12 hour shifts around the clock to repair mains and services. In addition, there were, from time to time, between 160 to 360 customer service men working on customers' premises to turn off meters and to restore service after repairs were made."

"In the 4 mile section of Glenoaks Boulevard between Foothill Boulevard and Huntington Street, there were two or three fires within the streets at broken gaslines. Throughout the area there were a number of instances reported where water heaters overturned and broke loose. It is believed, however, that damage to buildings by fires associated with gas was nil or relatively minor" (NOAA, 1973).

During the 1989 Loma Prieta earthquake (M7):

"The gas transmission lines and large diameter distribution mains experienced only three leaks due to the earthquake. Unstable soil in the Marina District of San Francisco caused damage that resulted in the

replacement of approximately 10 miles of cast iron and steel distribution mains with polyethylene plastic pipe. Also in the Marina, 1,500 services to 5,400 individual meters were replaced in less than 5 weeks. Three miles of distribution mains were replaced in Los Gatos and Watsonville. Other damage was scattered and minor."

"PG&E restored service to over 150,000 customers whose gas service had been turned off. A total of 1,100 service personnel participated in the relighting process, including 400 from other utilities in the west. Within a week, service was restored to all customers with undamaged piping" (EERI, 1990).

Gas lines can be damaged where they enter buildings or connect to water heaters. This sometimes causes localized outbreaks of fire as in the Marina District of San Francisco in 1989 after the Loma Prieta earthquake (refer to the *Water Supply* chapter).

During the June 1992 Landers earthquake (M7.5):

"Two residential fires occurred in Landers following the 4:58 tremor. Both structures burned down completely. The fires were probably caused by gas leaks from overturned water heaters and/or electrical arcing. In Yucca Valley, two mobile homes fell off their supports and caught fire. One unit burned down completely" (EERI, 1992).

Planning Considerations

Principal sources of natural gas for the planning area are located well outside the strongly shaken areas, and these will not be damaged or impaired by the scenario earthquake.

Transmission lines will be damaged where they cross landslides, ground subject to liquefaction, and fault rupture. The extent of damage is difficult to predict because high pressure transmission lines are typically stronger and more rugged than distribution lines, but for planning purposes, the possibility of breaks and

leaks at these locations must be considered. Because there are fewer lines involved in transmission than in distribution, repairs to transmission facilities generally can be accomplished rapidly.

Numerous breaks and leaks will occur in the distribution system throughout the strongly shaken area, especially wherever ground failure occurs as a result of liquefaction, landslides, or surface fault rupture. These areas include parts of Santa Rosa, Napa, Petaluma, and Vallejo.

While gas will be available to most of the planning area, distribution systems in areas near surface fault rupture and areas susceptible to liquefaction could be without gas for as long as several weeks. Restoration within the distribution system is a gradual process as described in the following:

> "Unlike electricity, which can usually be turned off and on at will, the restoration of gas service is an expensive and time consuming task. If a pipeline is broken, or part of a distribution network loses all pressure, every customer being supplied from that network must individually shut down before repressuring can begin. To prevent explosions, the entire system of mains, feeders, and service lines in the affected area must be purged before pilot lights can be relighted and service restored. In addition, extensive gas leak detection surveys may be needed, using flame ionization equipment throughout the affected area" (LNG Task Force, 1980).

Damage to gas lines and facilities serving the central Bay Area, including San Francisco and the cities of the East Bay, should be minimal and necessary repairs should be accomplished rapidly. Only in limited areas, such as the Marina District of San Francisco, will poor ground conditions result in substantial damage to distribution systems and prolonged interruption of service. After the 1989 Loma Prieta earthquake, many distribution lines were repaired and upgraded for improved seismic performance.

Planning Scenario

In many parts of the strongly shaken areas (MMI VIII+ and IX), gas service will be disrupted by the earthquake. For those so affected, or for those who mistakenly shut their gas off, it could be days rather than hours before service will be restored. In Santa Rosa, which is subject to surface fault rupture, and in Napa, Petaluma, and Vallejo, which are subject to ground movements caused by liquefaction, outages may last up to 2 weeks. In areas not subject to ground failure outages may last up to 5 days.

As indicated in the *Water Supply* chapter, we expect fires to break out in the downtown areas of Santa Rosa, Napa, and Petaluma, particularly where older wood frame buildings are clustered in areas of potential liquefaction. Local fires fed by gas line breaks will occur in other communities, particularly those with MMI VIII or greater (e.g. Sonoma, Novato, and Vallejo). The damage to water supply services will make firefighting difficult in these areas. Unless emergency water supply is immediately available, fire control will take from 2 to 3 days.

Natural gas transmission lines from northern Contra Costa County cross the Carquinez Strait into Solano County for further distribution to Napa, Sonoma, and Marin counties over the newer of the two Carquinez bridges. The seismic response of the bridge will affect the performance of gas transmission. While only minor damage to the bridge was reported after the 1989 Loma Prieta earthquake, the intensities for the scenario earthquake will be 1 unit higher (MMI VII). We expect the bridge to be closed to traffic for up to 12 hours while safety inspections of the bridge and natural gas transmission lines are completed.

Damage Assessments

Damage assessments have been postulated for certain natural gas facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of natural gas facilities are shown on Map G.

MAP NO.	NATURAL GAS FACILITIES
G1	**Distribution Lines, Santa Rosa** Some parts of the system will be closed for over 3 days (MMI IX). Moderate liquefaction and fault rupture potential. Strong shaking will cause random breaks in gas lines in this community with the most breaks in the oldest lines. Some breaks will occur along the fault rupture. There will be some isolated post-earthquake fires due to service line breaks and overturned water heaters.
G2	**Transmission Line, Santa Rosa** Open (MMI VIII+). High liquefaction potential. Liquefaction at Santa Rosa Creek will have little effect on this transmission line.
G3	**Distribution Lines, Rohnert Park** Closed for 3 days (MMI IX). High liquefaction potential. Strong shaking will cause only a few breaks in gas lines in this relatively new community, with the most breaks in the oldest lines.

There will be some isolated post-earthquake fires due to service line breaks and overturned water heaters.

G4 **Transmission Line, Petaluma**

Closed for up to 3 days (MMI VIII+).
High liquefaction potential.
Liquefaction along Petaluma Creek will produce distortion in the pipeline. This will require excavation, inspection, and evaluation of the hazard.

G5 **Distribution Lines, Petaluma**

Some parts of the system will be closed for 3 days (MMI VIII+).
High liquefaction potential.
Strong shaking and liquefaction will cause some breaks in gas lines in this community with the most breaks in the oldest lines. There will be some isolated post-earthquake fires due to service line breaks and overturned water heaters.

G6 **Distribution Lines, Sonoma**

Some parts of the system will be closed for 2 days (MMI VIII+).
Moderate to low liquefaction potential.
Strong shaking will cause service breaks in gas lines in this community with the most breaks in the oldest lines. There will be some isolated post-earthquake fires due to service line breaks and overturned water heaters.

G7 **Distribution Lines, Napa**

Some parts of the system will be closed for 2 days (MMI VIII-).
High liquefaction potential.

Strong shaking and liquefaction will cause some breaks in gas lines in this community with the most breaks in the oldest lines. There will be some isolated post-earthquake fires due to service line breaks and overturned water heaters. May be closed for 3 days due to unavailability of gas through G12 and G11.

G8 **Transmission Lines, South of Petaluma**

Closed for up to 3 days (MMI IX).

High liquefaction potential.

These lines will be damaged due to ground failure caused by liquefaction near the Petaluma River.

G9 **Transmission Lines, Crossing Fault, Sonoma Mountains**

One line closed and one line open (MMI VII).

Fault rupture hazard.

The oldest of these transmission lines will be ruptured by surface fault displacement, where it crosses the RCFZ in the Sonoma Mountains. However, Line 21 completed in 1988, is a 24 inch diameter ductile steel pipe laid in a specially constructed trench for 100 feet on either side of each of three traces of the Rodgers Creek fault (Burcham and Von Houten, 1992). Line 21 may survive a meter of offset on the fault.

G10 **Transmission Line, Sonoma Valley**

One line closed and one line open (MMI IX).

High liquefaction potential.

The oldest of these two transmission lines will be damaged by ground failure caused by liquefaction, but the new line will survive (refer to G9).

G11 **Transmission Line, South of Napa**

Closed for up to 3 days (MMI VIII-).

High liquefaction potential.

Liquefaction along the Napa River will damage this pipeline.

G12 **Transmission Line, Crossing Napa River**

Closed for up to 2 days (MMI VIII-).

High liquefaction potential.

Liquefaction along the Napa River will damage this pipeline.

G13 **Transmission Line, North of Novato**

Closed for up to 3 days (MMI VIII+).

High liquefaction potential.

Some settlement will occur here.

G14 **Distribution Lines, Novato**

Some parts of the system will be closed for 2 days (MMI VIII+).

High liquefaction potential.

Strong shaking and liquefaction will cause breaks in gas lines in this community with the most breaks in the oldest lines. There will be some post-earthquake fires due to service line breaks and overturned water heaters. May be closed for 3 days due to unavailability of fuel through G11 and G12.

G15 **Transmission Line, Crossing Carquinez Strait**

Open (MMI VII).

A short closure for inspection of the bridge and transmission line will be necessary. The gas line is on the newest of the two bridges and will suffer no significant damage.

G16 **Transmission Line, Greater San Rafael Area**

Closed for up to 2 days (MMI VIII-).

High liquefaction potential.

Damage to transmission line along this route due to liquefaction-induced ground failure. May be closed for 3 days due to unavailability of fuel through G11 and G12.

G17 **Transmission Line, San Rafael, Marin County**

Closed for 12 hours (MMI VIII-).

Moderate landslide potential.

Closed for inspection of minor movement caused by a seismically induced landslide. May be closed for 3 days due to unavailability of fuel through G11 and G12.

G18 **Transmission Line, Contra Costa County**

Open (MMI VII).

High liquefaction potential.

This line crosses the zone of high liquefaction potential for only a short distance.

G19 **Transmission Line, Richmond Area**

Closed for up to 2 days (MMI VIII-).

High liquefaction potential.

Moderate damage to transmission line due to liquefaction-induced ground failures.

G20 **Transmission Line, Vicinity of Corte Madera, Marin County**

Closed for up to 2 days (MMI VIII-).

High liquefaction potential.

Moderate damage to transmission line from ground failure caused by liquefaction. May be closed for 3 days due to unavailability of fuel through G11 and G12.

G21 **Transmission Line, Richmond Harbor Area**

Closed for up to 2 days (MMI VII).

High liquefaction potential.

Moderate damage to transmission line due to ground failure caused by liquefaction in the Richmond harbor area.

G22 **Distribution Lines, Marina District, San Francisco**

Closed for 3 days (MMI VII).

Known area of high liquefaction potential.

Distribution lines will be damaged and local fires will break out. A broken gas line was partly responsible for the dramatic fire that broke out in the Marina area shortly after the 1989 Loma Prieta earthquake. "Gas and water service was disrupted for weeks... Virtually the entire underground gas system was replaced" (Baldwin 1991). The Marina had 5,100 customers without service for up to 2 months and the damage to the gas transmission system cost $20 million to repair (McNutt, 1990). Half the lines were repaired with medium density polyethylene placed in existing steel and cast iron pipes, while the rest of the lines were replaced with new plastic pipes (O'Rourke and others, 1991b). Figure S-4 in the Geology and Seismology section showed that the shaking intensity from the scenario earthquake will be slightly greater than it was in the 1989 Loma Prieta earthquake.

G23 **Distribution Lines South of Market Street, San Francisco**

Open (MMI VII).

High liquefaction potential.

The shaking intensity from the scenario earthquake will be slightly greater than it was in the 1989 Loma Prieta earthquake. Nevertheless the distribution lines here will survive the minor liquefaction that will occur in the area.

G24 **Transmission Line, Oakland**

Open (MMI VII).

High liquefaction potential.

"Three isolated failures in the distribution system of the East Bay...caused by local soil failures..." (EQE Engineering, 1989). Pipes over the top of an underground walkway were offset 15 inches and repaired in 1 day. Others broke where they were attached to bridges that failed.

The shaking intensity from the scenario earthquake will be slightly greater than it was in the 1989 Loma Prieta earthquake. Nevertheless, this transmission line will survive the minor liquefaction that will occur in the area. A M7.5 earthquake on the nearby Hayward fault would damage this line (Steinbrugge and others, 1987).

G25 **Transmission Line, South San Francisco**

Open (MMI VII).

High liquefaction potential.

The shaking intensity from the scenario earthquake will be the same or slightly greater than it was in the 1989 Loma Prieta earthquake. This transmission line will survive the minor liquefaction that will occur in the area. A M8.3 earthquake on the San Andreas fault would damage this line (Davis and others, 1982b).

WATER SUPPLY

PART I: WATER SUPPLY SYSTEMS

General Characteristics

The main water supply aqueducts and primary sources for the conveyance of water to local communities throughout the planning area are shown on Map W. The principal water supply service agencies and their sources of water in the planning area are listed in Table W-1. Five of the largest agencies in Napa, Sonoma, and Marin counties were visited, and all major dams and reservoirs, and a representative selection of storage tanks were inspected.

The Hetch Hetchy System (San Francisco Water Department) serves 2.2 million people in San Francisco, San Mateo, and parts of Santa Clara and Alameda counties; East Bay Municipal Utility District (EBMUD) serves 1.1 million people in Alameda and Contra Costa counties; Sonoma County Water Agency serves 300,000 people in Sonoma County and northern Marin County, which is supplied through the Petaluma and North Marin aqueducts; Marin Municipal Water District serves 167,000 people in central and southern Marin; Vallejo Department of Water and Dams serves 110,000 people in Vallejo and other smaller cities in southwestern Solano County; and the City of Napa Municipal Water System serves 75,000 people. The two systems most critical for supplying water to the populated areas closest to the Rodgers Creek fault zone (RCFZ), are the Sonoma County Water Agency and the North Bay Aqueduct (serving Napa) systems.

All water supply systems in the planning area include typical water storage tanks. For example, the Sonoma County Water Agency and the City of Santa Rosa have an extensive system of welded steel water storage tanks as an integral part of their water supply facilities. Sonoma County facilities consist of 13 storage tanks, reaching from Forestville in the north to Sonoma and Petaluma in the

TABLE W-1

WATER SERVICE AGENCIES AND SOURCES OF SUPPLY

District	Major Water Sources
Sonoma County Water Agency (SCWA)	Lake Mendocino/Russian River Lake Sonoma/Dry Creek
City of Napa, Public Works Department, Municipal Water System	Lake Hennesey Reservoir Milliken Reservoir North Bay Aqueduct
City of Vallejo Department of Water and Dams	Lake Berryessa [Bureau of Reclamation] North Bay Aqueduct Sacramento-San Joaquin Delta
North Marin Water District	SCWA-Petaluma Aqueduct Stafford Lake
Marin Municipal Water District	Soulajule Reservoir Nicasio Reservoir Alpine Lake Bon Tempe Lake Lake Lagunitas Kent Lake Phoenix Lake SCWA-Petaluma Aqueduct
East Bay Municipal Utility District (EBMUD)	San Pablo Reservoir Briones Reservoir Upper San Leandro Reservoir Lake Chabot Storage Reservoir Mokelumne River Aqueduct
City and County of San Francisco, Bureau of Environmental Regulations and Management, Water Department	San Andreas Lake Reservoir Tuolumne River via O'Shaughnessy Dam in Yosemite National Park and the Hetch Hetchy Aqueduct
City of Healdsburg, Water Department	Russian River and local wells

south. The largest complex of County storage tanks is in Spring Lake Regional Park. It consists of four steel tanks holding a total of 36 million gallons (Mg) of water. New steel storage tanks under construction are being added to the system. When completed in 1995, the entire system (16 tanks) will have a total capacity of 110 Mg.

Sixteen storage tanks are used to supplement the local water supply under the jurisdiction of the City of Santa Rosa Utilities Department. All of these tanks are on the east side of the RCFZ. Communities on the west side rely on water from the county aqueduct system. All storage is in flat bottom welded steel tanks except for one which is an elevated type holding 0.3 Mg and another which is a 2 mg concrete tank with a flat bottom. The largest storage tank is in northern Santa Rosa and has a 4 mg capacity.

Seismic Characteristics

After an earthquake, water becomes especially vital, as it is required for fire-fighting, as well as for drinking and sanitation. Prolonged water outages can have serious economic consequences for a community. Planning for post-earthquake water supply is a critical element in the earthquake disaster plan of every community.

Earthquake concerns for water supply systems can be classified as follows:

1. Damage to sources of supply (e.g., dams, reservoirs, storage tanks, intakes at rivers).

2. Damage to transmission facilities connecting sources of supply to local communities (e.g., aqueducts).

3. Damage to treatment facilities.

4. Damage to the distribution network, including storage tanks and pumping stations.

Damage and disruption of sources of supply can include dam, reservoir, or storage tank failure and damage or power outage at river intake facilities. In the 1971 San Fernando earthquake (M6.4), the upstream face of the embankment of Lower Van Norman Reservoir slumped and almost caused a catastrophic dam failure. A considerable volume of water in this 20,500 acre foot capacity reservoir had to be removed on an emergency basis. Had the dam failed, thousands of homes and tens of thousands of people living in the area below the dam would have been flooded and loss of life would have been high. Refer to *Part II: Dams and Reservoirs* for further discussion.

Transmission facilities, such as aqueducts and conduits and their supports are susceptible to ground failure from landslides and liquefaction. The junction of above and below ground parts of pipelines is particularly important. Aqueducts commonly have open channels, tunnels, and large diameter steel or concrete pipe. In the 1971 San Fernando earthquake, the 76 inch diameter welded steel of the Saugus pipeline in the Second Los Angeles Aqueduct had a compression failure in one section and several tension failures of mechanical couplings in another section. This was caused by a massive landslide (NOAA, 1973).

Treatment facilities also have been damaged by both ground movement and shaking effects. They can be disrupted by power outages. The $45 million Jensen Filtration Plant and inlet tunnel were heavily damaged by the 1971 San Fernando earthquake. Damage resulted from lateral earth movements of 3 feet horizontally and 1 foot vertically. This was due to landslide movement and consolidation of compacted fill (NOAA, 1973). During the 1989 Loma Prieta earthquake, the Rinconada Water Treatment Plant, with 80 million gallons per day (mgd) capacity, suffered damage to three of its four up-flow clarifiers. Wave action and differential movement damaged the interior metal structure. The fourth clarifier was empty at the time. The plant operated at 50 percent capacity until repairs could be made (EERI, 1990).

In major earthquakes, distribution systems generally experience many pipeline breaks and leaks. Brittle pipes and those deteriorated by corrosion are especially vulnerable to ground failure. The vulnerability of underground pipe in areas of ground failure is greatest for asbestos cement pipe, followed closely by cast iron pipes and steel pipe with caulked or gas-welded joints. Steel with arc welded joints has shown superior performance (Eguchi and others, 1983). Acidic soils produce significant corrosion, increasing failure rate for both cast iron and steel piping.

As a result of the October 1, 1969, Santa Rosa earthquakes (M5.6 and 5.7), only "minor damage occurred at a water storage tank site, a pumping station (Sixth and "A" Streets), and a dam...significant damage was confined almost entirely to the water distribution system" (Steinbrugge and others, 1970).

After these two moderate earthquakes, the city of Santa Rosa had:

a) 14 water main breaks in 4 inch or larger lines.
b) 5 water line breaks in 2 inch and 3 inch lines.
c) 21 service connection breaks.

During the southern California, 1992 Landers earthquake (M7.5):

> "Water distribution systems suffered damage to pipelines and storage tanks in the Landers epicentral area, where local groundwater wells and storage tanks supply all the water. Water customers were without water for several hours to two weeks. Hundreds of water line breaks were reported in the Landers area. Much of the pipeline damage occurred in the fault zone, where pipes were not able to survive the large displacements."
>
> "At least six water tanks were damaged, ranging in size from 42,000 gallons to 417,000 gallons. Four damaged tanks were removed from service. Damage included bulging at the base of the tank (elephant's foot), shell and roof damage, shell splitting at access hatches, and severed piping. There was no reported damage to water wells or booster pumping plants other than loss of power supply and ground subsidence adjacent to wells."
>
> "Water pipe breaks reportedly occurred in buildings as far away as Westminster, Santa Ana, and San Diego" (EERI, 1992).

The Loma Prieta earthquake produced about 350 leaks in water mains in the Central Bay Area. Many occurred in unstable ground areas, such as the Marina District of San Francisco, where more than 100 breaks occurred. Many other breaks were due to corrosion of pipe and fittings or occurred in old cast iron pipe with fixed joints. Most breaks were in 4, 6, and 8 inch diameter mains, but at least one 60 inch line suffered a break. Breaks also occurred in many service connections (EERI, 1990).

According to Baldwin (1991), "120 repairs were made to the Municipal Water Supply System's 100 to 200 mm diameter cast iron conduits." In the Marina area, "as much as 10 m of loose, fine sandy fill rests on unconsolidated natural deposits. Ground water is commonly encountered within 2 m of the ground surface." And "Due to the relatively short duration...liquefaction is thought to have just begun... So, if a future earthquake is centered closer, shaking intensity will certainly be higher, and one should expect greater devastation." Unfortunately, "the concept of a neighborhood soil improvement program has been rejected."

The 1989 Loma Prieta earthquake and resulting fires, particularly the fire in the Marina District of San Francisco, illustrate some of the problems related to interactions among lifelines in high density urban areas:

> "San Francisco had 27 structural fires and more than 500 reported incidents of fire during the 7 hours from the time the earthquake struck until midnight. ...Berkeley had one major fire, in a one-story auto service building. A wood three-story building to the west was badly scorched, but otherwise no spreading occurred....Santa Cruz County reported about two dozen buildings destroyed by fire. In the city of Santa Cruz, one structural fire...in a single-family residence...occurred at 136 Myrtle Avenue, destroying the entire building."
>
> "Shortly after the earthquake, commercial power was lost [in the Marina District]. The fire dispatch center has an emergency generator and an uninterruptable power supply for their dispatch computer. The 15-year-old computer soon had more calls than it could handle and went down. As a

result, the timing of events is not as precise as it would normally be. There were 600 calls in the interval between the earthquake and midnight; there would be normally about 100 calls in a 24 hour period. There were problems with the saturation of radio communications. The fire department has three radio frequencies. Because of the large number of units out, the system got saturated, so some messages had to be repeated several times before they got through."

"The Marina fire illustrated some of the interactions among lifelines. The saturated telephone system prevented the fire from being reported, and the saturation of the fire department radio communications system also complicated the response. The losses of power prevented remotely controlled isolation valves on the Auxiliary Water Supply System (AWSS) from operating. Gas leaks in the collapsed structures contributed to the fire. Water for fighting fires could not be obtained from the regular water system or the AWSS due to pipe failures" (EERI, 1990).

It is difficult to determine the extent of leaks and damage to the distribution system until water pressure is restored. For this reason, it may take days or weeks to totally repair damage in the densely populated, heavily impacted areas. In these situations, fresh water for domestic purposes often has to be supplied by tanker trucks or above ground temporary lines.

Firefighting efforts are hampered during the first 24 hours by blocked streets, insufficient work force, and structurally damaged fire stations, in addition to the lack of water or power. Power outages particularly affect water supplies wherever pumping is required for distribution. Gravity flow systems are better able to withstand power outages.

Planning Considerations

We expect all water systems within the planning region to suffer some damage. In areas of intense shaking or ground failure, pipeline breaks will be numerous.

Breaks will be most common where water lines are corroded or otherwise deteriorated with age. Treatment facilities, structures, and equipment with poor seismic design will suffer damage and impairment.

The components of each water supply system--the source, aqueducts and transmission pipelines, local storage reservoirs, pumping stations, treatment facilities, and distribution lines--must be viewed in the context of the entire system and its performance. Impairment of any major element can seriously compromise the performance of the entire system. Effects on other systems, such as electric power and waste water treatment, also must be kept in mind.

It is essential that water agencies examine their transmission and distribution systems in detail to identify areas and facilities most likely to be impaired. Existing maintenance programs should be reviewed and new programs established to progressively upgrade facilities of questionable seismic resistance, particularly in areas of high vulnerability.

Stocks of materials and equipment to make emergency repairs must be readily available at all times. Mutual aid arrangements are extremely important in these cases. The scale of earthquake damage to water lines will be magnitudes greater than non-seismic breaks and leaks normally experienced. Thus, water agencies must maintain an adequate stock of critical repair materials that have long lead times for procurement.

In areas having a significant possibility of water outage, plans need to be developed for providing potable water via ground transportation. Emergency power sources must be provided for those vital elements (e.g., pumping stations) without a backup power supply.

Generally, water supply cannot be restored to an area where sewer lines are still broken or not functioning. Where general damage to the water distribution system occurs, restoration of water mains begins at the lowest topographic point, progressing uphill so that broken sewers in the same areas do not contaminate still broken water lines.

A recent preliminary study *Water Distribution Systems - Seismic Evaluation Program Status Report* by EBMUD explains how a major earthquake on the Hayward fault will disrupt its water supply and distribution system in the East Bay:

> "Preliminary findings showed that a M7.0 quake on the (Hayward) fault would close two of the three tunnels that carry water from reservoirs and treatment plants in Contra Costa County to cities west of the Oakland hills. The capacity of the remaining tunnel would be cut in half."
>
> "In addition, one third of the water system's reservoirs could empty quickly, and three aqueducts that carry water from the Sierra foothills could be seriously damaged."
>
> "The study said damage to pipelines would require up to 3,600 repairs, compared with 160 needed after the 1989 Loma Prieta quake" (Halstuk, 1992).

During the April 25-26, 1992 Cape Mendocino earthquakes (M7.0, M6.2, and M6.4), the "most significant loss of water service occurred in the city of Rio Del when an 8 inch water main broke at the riser at the abutment of the southbound Eel River Bridge. The break caused supply tanks to drain, leaving the city without a water supply. An emergency potable supply was provided by the American Red Cross, National Guard, and Anheuser Busch, Inc. Fire protection was supplied by contractor tank trucks. Water supply to the city was restored four days later..." (EERI, 1992).

Planning Scenario

The water supply from the Sonoma County Water Agency intake structures along the Russian River near Forestville will be reduced due to a power outage and to aqueduct breaks caused by ground failure.

Distribution and transmission lines traversing the Rodgers Creek fault will be damaged. Restoration of services will take at least 4 days. The cities of Napa, Petaluma, Vallejo, and Rohnert Park will have pipelines near rivers damaged by ground deformation caused by soil liquefaction. Restoration of service will take up to 2 weeks. The city of Santa Rosa will have lines damaged by fault displacement. Restoration of service will take up to 2 weeks. That portion of Santa Rosa west of the fault will be unable to get water from the many storage reservoirs to the east of the fault until repairs are made. Vallejo will have breaks due to ground deformation caused by liquefaction of soils on the east side of the Napa River, along the Mare Island Strait, and at the Benicia State Recreation Area.

In areas of intense shaking (e.g., MMI IX) or ground failure, two to four main breaks in every residential block will be common where nonductile cast iron or asbestos cement pipe exists. In these areas, repairs of water supply lines will be delayed because of contamination from broken or severed sewer lines in the vicinity.

In areas of strong shaking (e.g., MMI VIII and greater), 5 to 10 percent of the flat bottom water storage tanks will have failures sufficient to cause a loss of water. According to NAS (1973), "The behavior of large liquid storage tanks during earthquakes has an importance far beyond the mere economic value of the tanks

and contents. If, for instance, a water tank collapses, as it did during the 1933 Long Beach earthquake (M6.3), the loss of public water supply can have serious consequences."

Typical damage patterns for large liquid storage tanks are:

1. Total collapse.
2. Roof buckling.
3. Damage to the connection between the roof and the shell.
4. Shell wall buckling.
5. Separation of shell from bottom plate (with loss of contents).
6. Separation in pipe-to-tank connections (with loss of contents).

The central Bay Area, including San Francisco and the cities of the East Bay, will experience much the same kind of damage as it experienced in the 1989 Loma Prieta earthquake. Because ground motion intensities in some areas will be somewhat higher for the Rodgers Creek earthquake, there will be even greater damage than in 1989. For example, in western Contra Costa County, the Loma Prieta earthquake produced MMI VI, whereas the Rodgers Creek earthquake will produce MMI VII (Figure-S4).

In Napa and other Napa Valley communities, the significance of a water outage will increase dramatically if the scenario earthquake occurs in a dry year. Affected water supply systems are expected to be moderately to severely crippled under this scenario.

The Sonoma Aqueduct in Sonoma Valley will be subject to localized leakages owing to heavy ground shaking (MMI IX) postulated at the southern end near Fetters Hot Springs, Boyes Hot Springs, and El Verano.

Because of failures in local water distribution systems, many communities will be asked to use emergency supplies, boil their water, or take other measures against contamination for up to 1 week.

For disaster response planning, authorities should expect localized fires to break out in the downtown areas of Santa Rosa, Napa, Petaluma, and San Rafael (refer to *Natural Gas* chapter), and in other areas where older wood frame buildings are clustered. Because of damage to water supply and distribution lines, difficulties will be experienced in fighting fires in these areas. Unless emergency water supply is immediately available, complete fire control will take up to 48 hours. Owing to the public's crucial need for water, it is assumed that highest priorities will be given to the restoration of electric power to all major pumping and treatment facilities.

Damage Assessments

Damage assessments have been postulated for certain water supply facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of water supply facilities are shown on Map W.

In Sonoma County aqueducts are buried pipelines.

MAP NO.	WATER SUPPLY FACILITIES
W1	**Wohler and Mirabel Intakes at the Russian River** Water supply reduced to 20 mgd for 2 days (MMI VIII-). High liquefaction potential. The power outage will require emergency generators. One Wohler collector will be shut down by failure of an emergency generator. The Mirabel collectors will continue running on power supplied by two emergency generators.

W2 **Cotati Intertie Aqueduct, Sonoma County**

Closed for up to 3 days (MMI VIII+).

High liquefaction potential.

Aqueduct locally damaged due to ground failure at the crossing of an area susceptible to liquefaction along Laguna de Santa Rosa north of Sebastopol.

W3 **Water Supply in Santa Rosa, Sonoma County**

Closed for up to 3 days (MMI IX).

Fault rupture hazard.

This 36 inch diameter steel pipeline will break where it crosses the Rodgers Creek fault.

W4 **Petaluma Aqueduct, Rohnert Park**

Closed for up to 3 days (MMI IX).

High liquefaction potential.

Pipeline damaged due to liquefaction between Santa Rosa and Rohnert Park.

W5 **Pipeline from Lake Hennessey Reservoir, Napa County**

Closed for up to 3 days (MMI VIII-).

High liquefaction potential.

Disruption to pipeline at crossing of the Napa River due to ground movements from localized liquefaction.

W6 **Pipeline from Rector Reservoir, Napa County**

Closed for up to 3 days (MMI VIII-).

High liquefaction potential.

Pipeline damaged by localized liquefaction at the crossing of the Napa River.

W7 **Water Supply Pipelines in Napa, Napa County**

Closed for up to 3 days (MMI VIII-).

High liquefaction potential.

The major water supply pipelines will be damaged due to ground failure by localized liquefaction along the Napa River.

W8 **Pipeline south of the City of Napa**

Closed for up to 3 days (MMI VIII-).

High liquefaction potential.

Water supply pipeline will be damaged by ground failure due to liquefaction at crossing of the Napa River.

W9 **North Bay Aqueduct, Napa County**

Closed for up to 3 days (MMI VII).

Landslide potential.

Facilities of the North Bay Aqueduct in Jameson Canyon will be damaged due to landslides. The water treatment plant will not be significantly damaged.

W10 **Petaluma Aqueduct, Sonoma County**

Closed for up to 2 days (MMI VIII+).

High liquefaction potential.

Ground deformation causes damage.

W11 **North Marin Aqueduct, Marin County**

Closed for up to 3 days (MMI VIII+).

High liquefaction potential.

This aqueduct is damaged by shaking and ground failure due to liquefaction in the Novato Creek drainage.

W12 **Water Supply Pipeline, Marin County**

Closed for up to 1 day (MMI VIII-).

Landslide potential.

Minor pipeline damage due to landslide.

W13 **San Pablo Pipeline, Contra Costa County**

Closed for up to 2 days (MMI VIII-).

High liquefaction potential.

This major water supply line in the East Bay distribution system will sustain damage due to liquefaction.

W14 **Marina District Distribution System, San Francisco**

Closed for up to 7 days (MMI VII).

High liquefaction potential.

Although the replacement lines here are of better quality than those damaged in the Loma Prieta event, the liquefaction potential remains high, and the intensity from the scenario earthquake will be somewhat greater than in 1989 (Figure S-4). Thus, the damage due to ground deformation caused by liquefaction generally may be similar to that in 1989.

W15 **Lower Market Street Distribution System, San Francisco**

Partially closed for up to 3 days (MMI VII).

High liquefaction potential.

This area was described by O'Rourke and others (1991b) as susceptible to liquefaction and pipeline breaks. Ground deformation due to liquefaction will damage the system.

W16 **Mission Creek Distribution System, San Francisco**

Partially closed for up to 3 days (MMI VII).

High liquefaction potential.

This area was described by O'Rourke and others (1991b) as susceptible to liquefaction and pipeline breaks. After 1906 this area was formally recognized as susceptible to liquefaction by having its auxiliary water system isolated from the rest of the system through a single gate at 6th and Market. Unfortunately, "Because of electric power loss at the time of the [1989] earthquake the valve could not be closed remotely" (O'Rourke and others, 1991b). Ground deformation due to liquefaction will damage the system.

W17 **East Bay Distribution System**

Partially closed for up to 5 days (MMI VII).

High liquefaction potential.

Many breaks occurred in the water distribution system between Richmond and San Leandro during the 1989 Loma Prieta earthquake (Dames and Moore, 1989, also refer to map in EERI, 1990, p. 249). According to McNutt (1990), the East Bay had 200 water main breaks. "Ground failure, particularly liquefaction, played a large role in causing damage to water mains" (McNutt, 1990). The EBMUD system had 120 breaks, with 60 in the raw water pipeline supplying the Sobrante filter plant, and 20 in cast iron pipes near Laney Community College in Oakland (Dames & Moore, 1989).

PART II: DAMS AND RESERVOIRS

General Characteristics

The principal dams and storage reservoirs that serve the major water suppliers in the planning area are shown on Map W. Table W-2 lists the major reservoirs including their storage capacity, location, and the Modified Mercalli Intensity (MMI) postulated for each site. Not included are small distribution reservoirs such as:

a) Kimball Canyon, Bell Canyon, and Rector Reservoir in Napa County
b) Santa Rosa Creek Reservoir and Lake Alpine in Sonoma County
c) Lake Lagunitas in Marin County
d) Lake Chabot in Vallejo (Solano County)

Monticello Dam at Lake Berryessa is in Napa County outside the planning area. Field reconnaissance and site investigations were completed for the dam and reservoir locations listed in Table W-2.

Lake Ralphine, in Santa Rosa, is no longer classified as a reservoir for the storage of water supply. It now functions solely as a recreational lake in Howarth Memorial Park and serves as a source of water for firefighting. Spring Lake, with its three dams, is in the adjacent Spring Lake Regional Park and is used for flood control .

Seismic Considerations

Dams have failed during earthquakes in many parts of the world. In the United States, Sheffield Dam, an earthen dam, failed in the 1925 Santa Barbara earthquake (M6.3). The earthen Hebgen Lake Dam was damaged, but remained serviceable after the 1959 Montana earthquake (M7.1) on a fault that was less than 1,000 feet from the spillway. A massive earthquake-induced landslide

TABLE W-2

MAJOR STORAGE RESERVOIRS IN THE PLANNING AREA

Name	County	Storage Capacity*	MM Intensity**
Lake Chabot	Alameda	10,350	<VII
Upper San Leandro Res.	Alameda	41,440	<VII
Briones Res.	Contra Costa	60,510	VII
San Pablo Res.	Contra Costa	38,600	VII
Apline Lake	Marin	8,900	<VII
Bon Tempe Lake	Marin	4,000	<VII
Kent Lake	Marin	32,900	<VII
Nicasio Res.	Marin	22,400	<VII
Phoenix Lake	Marin	411	<VII
Soulajule Res.	Marin	10,570	VII
Stafford Lake	Marin	4,300	VII
Lake Hennesey	Napa	31,000	<VII

* Acre Feet

** Refer to Maps S and W, and to Appendix A

caused the dam to be overtopped by several waves. The partial failure of the Lower Van Norman Dam in the 1971 San Fernando earthquake (M6.4) required the evacuation of 80,000 inhabitants in the flood plain.

Other dams have performed well during earthquakes. For example, "In 1906, a 7 foot right-lateral offset on the San Andreas Fault went through a knoll which formed an abutment for the two sections of the San Andreas Dam. This 93 foot high earthen puddle core dam was constructed in 1868-1870 and was uninjured. The Lower Crystal Springs Dam is a concrete dam and is located within 100 feet of the 1906 fault breakage; it survived the 1906 earthquake without injury" (Algermissen and others, 1972).

In the 1969 Santa Rosa earthquakes (M5.6 and M5.7), "The Lake Ralphine Dam (earth) experienced minor characteristic, longitudinal surface cracks, not considered to be of serious consequence...The cracks were immediately sealed

after the earthquake to eliminate water penetration. This earth dam, constructed in 1882, has a storage capacity of 418 acre feet" (Steinbrugge and others, 1970).

In the 1989 Loma Prieta earthquake (M7), most reservoirs were at low levels because it was the third year of a drought in California. There was no major damage to any storage reservoirs in the central and south Bay areas. However, "The Austrian Dam, constructed in 1950 with the capacity of 6,200 acre feet had cracks in the embankment and spillway. The embankment cracks have been excavated and recompacted, and the spillway cracks have been filled with epoxy. Lexington Dam, constructed in 1952 with the capacity of 21,200 acre feet, had transverse cracking at the abutments, which has been repaired by recompaction. ...The Newell Creek Dam in the Monterey Bay area, constructed in 1960 with a capacity of 8,700 acre feet, had a longitudinal crack on the upstream face, which has been excavated and recompacted...In Santa Cruz, crews were dispatched within an hour to inspect the reservoirs and Newell Creek Dam, and they began to repair leaks within 2 hours. Crews worked 12 hour shifts with the assistance of three private contractors" (EERI, 1990).

Harder (1991) analyzed the performance of earth dams during the Loma Prieta earthquake and found that of 111 dams within 50 miles of the epicenter, 21 were built before 1906 and had little damage. Four were hydraulic fill and had little damage. Moderate damage was suffered by Austrian Dam, which was 7 miles from the epicenter and had accelerations up to 0.69. It was damaged with longitudinal cracks on both sides of the crest. The top settled 2.5 feet. Soda Lake Dam probably was built partly on liquefiable granitic silt tailings (Wills and Manson, 1990; Borchardt, 1991a) and developed a semicircular crack (Harder, 1991).

The partial failure of the Lower Van Norman Dam during the 1971 San Fernando earthquake stimulated a statewide program of seismic investigations and modification of major dams. Since the 1971 San Fernando earthquake (M6.4), water supply districts throughout the state have undertaken programs to review and improve the safety of the weakest dams in their jurisdictions. For example, by 1981, EBMUD had completed a program in which all of the weakest dams in their system were reevaluated and/or rebuilt to improved seismic standards. In early 1992, EBMUD announced the completion of a second program in which all their dams were reviewed once again with recommendations being made for additional upgrading efforts (Halstuk, 1992; Fagan, 1994). Other water supply agencies and districts in the Rodgers Creek planning area, also have conducted reviews of the dams within their jurisdiction. The Marin Municipal Water District (MMWD) review of Phoenix Lake reservoir, which is used for emergency water supply, found it to be in critical condition. As a consequence, its spillway was lowered.

Planning Considerations

Water supply in the Rodgers Creek fault planning area is provided by several systems, each generally dependent on local storage reservoirs served by aqueducts for efficient and reliable operations. Storage reservoirs, storage tanks, and dams of each system must be reviewed and appraised in the context of the entire system and its performance.

It is important that all water agencies and districts continue to review and examine their storage reservoirs in detail to identify those most likely to be damaged or impaired. Programs should be vigorously maintained to progressively upgrade reservoir facilities and dams in areas of high vulnerability.

Planning Scenario

For purposes of response planning, we assume the dam at Phoenix Lake Reservoir will develop longitudinal cracks on the upstream side and that repairs will be required. The dams at two recreational lakes near Santa Rosa will require inspection. They are Lake Ralphine and Spring Lake.

WASTE WATER

General Characteristics

The major waste water treatment jurisdictions in the planning area are:

1. City of Santa Rosa, Utilities Department
2. Napa Sanitation District
3. Central Marin Sanitation Agency
4. Vallejo Sanitation and Flood Division, City of Vallejo
5. East Bay Municipal Utility District (Alameda and Contra Costa Counties)
6. Bureau of Environmental Regulations and Management, and Water Pollution Control Service (City and County of San Francisco)

Representative agencies were visited, and selected facilities in Santa Rosa, Napa, Marin, and Alameda counties were inspected for potential earthquake damage.

There are numerous minor jurisdictions, and some of these are interrelated. For example, in Marin County alone there are 24 separate entities involved in the collection, transport, treatment, and disposal of sewage. The Central Marin Sanitation Agency, for instance, has a large treatment facility that treats sewage received from five collection districts. The effluent from the Central Marin plant travels through an outfall line extending 8,000 feet into San Francisco Bay.

As can be seen on Map WW, most treatment plants are along the margins of San Francisco Bay, San Pablo Bay, the Carquinez Strait, and other shorelines. One facility is near the Pacific Ocean at the west side of San Francisco. Others are in interior regions of the planning area with outfall lines near rivers, such as the Napa River and marshlands (WW4, WW5, WW6) or the Laguna de Santa Rosa (WW1). Some of these systems involve gravity flow from the service area to the treatment plant with discharge in an outflow line, and others require pumping for all or part of their operation. The so called "Super Sewer" from the Livermore Valley which continues through Fremont and San Leandro (WW20) is an excellent

example of the latter. The Santa Rosa Laguna Water Reclamation Plant is an activated sludge tertiary treatment plant with effluent filtration that treats the waste water from Santa Rosa, Rohnert Park, Sebastopol, and the South Park area. The plant removes organic and suspended material provided by secondary treatment followed by filtration. Waste water effluent is also disinfected before irrigation reuse of discharge to the Laguna de Santa Rosa.

In general, waste water treatment plants have only limited storage capacity either in the form of basins or holding ponds. If the treatment sequence cannot be restored before storage capacity is surpassed, it will be necessary to discharge waste water by using emergency methods of treatment to reduce the risk of pollution. The importance of storage capacity during an earthquake is significant. For example, during the June, 1992 Landers and Big Bear earthquakes (M7.5 and M6.6), considerable damage occurred within a secondary treatment plant of a regional waste water collection agency in the Big Bear Lake area. However, with adequate storage, the biological treatment process was maintained, and there was no operational loss in the system (EERI, 1992).

Damage at critical facilities along the Bay margins, river delta regions, or other areas with a high potential for soil liquefaction, combined with the loss of electric power will necessitate sewage discharge directly into bays, deltas, rivers, or creeks at designated bypass locations. This will be accompanied by some corresponding level of pollution at most waterways, which will pose a public health risk.

In the oldest cities, it is common to find waste water collection lines laid in the same trench as water distribution lines. Damage to both lines may occur in areas of high ground shaking or ground failure, resulting in the contamination of potable water. This occurred in the City of Watsonville during the 1989 Loma Prieta earthquake, where leakage from damaged sewage lines contaminated water

supply distribution lines in the same trench. In general, the water supply cannot be restored in areas where sewer lines remain broken or are not functioning (refer to *Water Supply* chapter).

Seismic Characteristics

The impact of earthquakes on waste water systems can be considered from three standpoints:

1. Damage to the collection system.
2. Damage to treatment plants.
3. Discharge of untreated or poorly treated sewage into holding ponds, rivers, or the Bay.

Waste water collection systems are primarily susceptible to earthquake damage as a result of broken underground pipelines. Lines typically made from relatively brittle clay, asbestos cement, or concrete pipe generally tolerate little movement without fracture. Damage tends to be greatest where permanent ground movements occur due to surface fault rupture, landslides, or liquefaction. The distribution of damage is commonly considered similar to that suffered by other buried conduits, such as those carrying water, natural gas, and petroleum products. Because most sewer lines are not pressurized, broken lines are not readily detected unless a blockage or severely restricted flow is experienced. In areas of damage, television cameras may be used to find cracked and broken lines.

During the 1971 San Fernando earthquake (M6.4), the sewage collection system was damaged in the Sylmar area, particularly in areas of fault rupture and permanent ground movement. In a 15 square mile area that included Sylmar, over 126,000 feet of mainline sewer had to be reconstructed. The damage consisted of crushed and cracked pipe, broken (compression failure) and pulled

(tension failure) joints, and damage to manholes. The latter consisted of shifting of rims as well as some cracking of the manholes themselves (NOAA, 1973).

Treatment facilities have been closed due to equipment failures, and power outages. During the 1989 Loma Prieta earthquake (M7), wave action at the 40 million gallons per day Palo Alto Waste Water Treatment Plant caused fiberglass scum troughs to fall onto the sludge sweeping scraper in the bottom of a clarifier, causing it to jam. Two days were required to repair this clarifier, but fortunately the plant was back in operation in 2 hours because an empty clarifier was available (EERI ,1990).

Regional waste water treatment plants in San Francisco and Oakland lost power but suffered no major structural damage during the Loma Prieta earthquake. There were some short time releases of sewage into San Francisco Bay and the Pacific Ocean. The Oakland plant lost commercial power for 7 hours (EERI, 1990).

Waste water treatment plants are generally located on poor ground that is highly susceptible to earthquake induced ground failure. This seldom results in damage to massive individual structures that are well designed and supported by piling or engineered fills. Instead, differential motion between structures and inlet and outlet lines often causes damage. In general, the contiguous trunk lines and outfalls also are areas prone to ground failure.

Planning Considerations

Damage to collection systems will be similar to that experienced by water supply and distribution systems. Soil liquefaction in the structurally poor ground areas will be a major source of damage (refer to Map WW). To a much lesser extent, landslides, particularly at the end of a prolonged wet season, will cause damage

to the collection systems in hilly areas. In areas of water outage or breaks in sewer lines, temporary facilities, such as the portable sanitary facilities used on construction sites, will have to be provided as they were after the 1971 San Fernando and 1989 Loma Prieta earthquakes.

Buildings and other special structures found at treatment plants are usually earthquake resistive, particularly those built since the mid-1970's. In poor ground areas, large buildings and other major structures are normally on pilings and should survive without any major structural damage. Internal appurtenant piping and equipment are generally earthquake braced and intended for heavy duty. Building entry by pipes or conduits will be likely points of damage. Electric power outages will affect those treatment facilities and pumping or lift stations without emergency generators.

Damage is likely in structures containing rotating equipment or other moving devices, with the damage being due to the wave action of sloshing liquids. Differential settlements will occur between underground piping and the connected buildings. The result of these differential settlements is to crack or break the pipe where it joins the building. This is a particular concern for pressurized lines (e.g., force mains).

The quantity of waste water flowing to treatment plants will diminish immediately after the earthquake due to the closure of industrial plants and the reduction in the supply of potable water.

Treatment plant buildings, tanks, piping, machinery, and equipment are all subject to earthquake damage. If a treatment plant becomes inoperable, untreated sewage must bypass the plant and be dumped into holding ponds, creeks, rivers, or the Bay. The discharge of raw or poorly treated waste water may be necessary, and will cause public concern. This should be reviewed beforehand

with the appropriate environmental agencies. Public announcements should also be readied for distribution immediately after the earthquake. Review of the adequacy of chlorination storage, piping, and machine tie down is of utmost concern. Programs to control chlorine spills are vital for all affected waste water stations.

The time required for assessing damage and making repairs to a damaged collection system depends on the availability of personnel, equipment, and materials. In the relatively small area affected by the 1971 San Fernando earthquake, 90 miles (145 km) of sewer lines were surveyed by pulling television cameras through them. From a practical standpoint, however, until water supply is restored, discharge of sewage into sewer connection lines will be significantly reduced.

Planning Scenario

Waste water lines that cross the Rodgers Creek fault will be damaged, and open trenches may be needed to carry raw sewage for short distances. Alternatively, emergency planners will have to provide either temporary emergency housing arrangements for neighborhoods heavily impacted by the earthquake or temporary sanitary facility units.

Facilities in the City of Santa Rosa will be impacted by fault rupture and liquefaction. That portion of the collection system east of the fault will be cut off from the Laguna Treatment Plant. Major trunk lines such as the 36 inch crosstown trunk line will be severed.

The City of Napa will be cut off from the new Suscol Treatment Plant because a 66 inch diameter line to the plant traverses ground subject to liquefaction.

The flow capacity of the collection system in areas of potential liquefaction will be reduced by 50 percent. The main collectors in these areas will be damaged, but will retain 75 percent of their capacity in those sections where gravity flow is possible. Main effluent lines of the Napa, Novato, and Santa Rosa city systems will be interrupted with breaks where they cross areas of potential liquefaction. Thirty days will be needed to restore service.

The central Bay Area, including San Francisco and the East Bay cities, will experience much the same kind of damage as it experienced in the 1989 Loma Prieta earthquake. Because ground motion intensities in some areas will be higher than they were in 1989, there will be even greater damage than in 1989. For example, western Contra Costa County will have MMI VII under the Rodgers Creek earthquake whereas during the Loma Prieta earthquake intensity did not exceed MMI VI.

Immediately after the earthquake, treatment plants without emergency power will shut down. Santa Rosa's special electric power system, which uses methane gas from its treatment plant, will be unable to support full plant function. Power requirements will diminish as the quantity of arriving waste water diminishes. Restoration of power will be a function of priorities. For instance, initial preference will be given to direct life support operations such as hospitals and water systems. This, in turn, will require emergency treated raw sewage to be discharged into holding ponds, creeks, rivers, and the Bay for up to 1 week.

Damage Assessments

Damage assessments have been postulated for certain waste water facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be

construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of waste water facilities are shown on Map WW.

MAP NO.	WASTE WATER FACILITIES
WW1	**Laguna de Santa Rosa Treatment Plant** Closed for up to 2 days (MMI VIII+). High liquefaction potential. This is an upgraded plant in a strongly shaken area. There will be some structural and nonstructural damage. A diesel-fueled generator can operate the facility for several days if electric power is cut. The main effluent line will be interrupted where it crosses an area of potential liquefaction north of the treatment plant.
WW1a	**Oakmont Plant** Closed for up to 2 days (MMI VIII+) Moderate liquefaction potential This plant is a tertiary treatment plant that is operated during the summer months to provide water to the Oakmont Golf Course. There is a trunk line that connects it to the remaining portion of the Santa Rosa system and delivers the waste water to the Laguna Treatment Plant (WW1) during non-irrigation months, traditionally November through April. The trunk line, known as the Los Alamos Trunk, crosses the Rodgers Creek fault. Should a major earthquake interrupt this trunk line, the plant could be activated and waste water from the east side of the fault could be treated (Carlson, 1993, written communication).

WW2 **Waste Water Treatment Facility, Petaluma**

Closed for up to 3 days (MMI VIII+).

High liquefaction potential.

The Petaluma plant is 5 miles (8 km) from the fault and in an area that will undergo extensive ground failure due to liquefaction. This facility will be damaged, and raw sewage will be discharged into the Petaluma River.

WW3 **Waste Water Treatment Plant, Sonoma**

Closed for 1 day (MMI IX).

Moderate liquefaction potential.

This facility is built near the marsh between 15 and 25 feet above sea level. One of the settling tanks is about 50 feet north of Schell Creek, a tributary of Sonoma Creek. Differential settlement due to liquefaction will make this tank unusable.

WW4 **Imola Treatment Plant, Napa**

Closed for up to 3 days (MMI VIII-).

High liquefaction potential.

This old plant is about 600 feet east of the Napa River at 5 to 10 feet above sea level. Inlet and effluent lines will be damaged by differential settlements and subsidence between buried lines and structures. Nonstructural and structural damage will occur. The concrete line (66 inch diameter) from Imola to Suscol plants will be damaged by ground displacement caused by liquefaction near the Napa River. Sewage will run into the Napa River.

WW5 **Suscol Treatment Plant, Napa**

Capacity restricted for up to 2 days (MMI VIII-).

High liquefaction potential.

This modern plant is built 12 feet above sea level about 500 feet east of the Napa River. Inlet and effluent lines will be damaged by differential settlements between buried lines and structures. Nonstructural and minor structural damage will occur.

WW6 **Waste Water Treatment Plant, Napa County**

Capacity restricted for up to 3 days (MMI VIII-).
High liquefaction potential.
This facility borders marshy ground. The nearest free face is a canal about 2,000 feet to the west.

WW7 **Waste Water Treatment Plant, Vallejo**

Closed for up to 3 days (MMI VIII-).
High liquefaction potential.
This facility is built between 5 and 10 feet above sea level about 500 feet east of Mare Island Strait, the nearest free face.

WW8 **Waste Water Treatment Plant, Novato**

Closed for up to 3 days (MMI VIII+).
High liquefaction potential.
This facility is built at sea level adjacent to a small canal and 800 feet north of Novato Creek.

WW9 **Waste Water Treatment Plant, Novato**

Capacity restricted for up to 1 day (MMI VII to VIII+).
High liquefaction potential.
This facility is built on a former island in the marsh (VIII+) between 4 and 40 feet above sea level. As a consequence of its location on bedrock, the plant will have minimal damage, although the pipeline crossing the bedrock/marsh boundary will develop leaks.

WW10 **Waste Water Treatment Plant, Gallinas, Marin County**

Capacity restricted for up to 1 day (MMI VIII-).

High liquefaction potential.

This facility is built on a former peninsula adjacent to the marsh (VIII+) between 10 and 40 feet above sea level. As a consequence of its location on bedrock, the plant will have minimal damage.

WW11 **Waste Water Treatment Plant, Richmond**

Closed for 3 days (MMI VIII-).

High liquefaction potential.

This facility is built between 0 and 5 feet above sea level about 100 feet south of San Pablo Creek, the nearest free face. Extensive shaking and liquefaction will damage this facility.

WW12 **Waste Water Treatment Plants, Pinole**

Closed for 3 days (MMI VIII-).

High liquefaction potential.

These facilities are built on the modern Pinole Creek alluvial fan between 0 and 5 feet above sea level. They are about 150 feet south of where the creek enters San Pablo Bay, the nearest free face. Extensive shaking and liquefaction will damage these facilities.

WW13 **Waste Water Treatment Plant, Rodeo**

Closed for 3 days (MMI VIII-).

High liquefaction potential.

This facility is built between 0 and 5 feet above sea level about 50 feet south of San Pablo Bay, the nearest free face. Extensive shaking and liquefaction will damage this facility.

WW14 **Waste Water Treatment Plant, Crockett**

Capacity restricted for up to 3 days (MMI VII).

High liquefaction potential.

This facility is built between 0 and 5 feet above sea level south of San Pablo Bay, the nearest free face. There will be moderate damage due to shaking and minor liquefaction at this facility.

WW15 **Waste Water Treatment Plant, Benicia**

Capacity restricted for up to 2 days (MMI VII).

High liquefaction potential.

This facility is built between 10 and 20 feet above sea level about 500 feet north of a channel leading to San Pablo Bay, the nearest free face. There will be moderate damage due to shaking and minor liquefaction at this facility.

WW16 **Waste Water Treatment Plant, Martinez**

Capacity restricted for up to 2 days (MMI VII).

This facility is built between 5 and 20 feet above sea level about 100 feet east of a channel leading to the marsh along Carquinez Strait, the nearest free face. There will be moderate damage due to shaking and minor liquefaction at this facility.

WW17 **Waste Water Treatment Plant, Concord**

Capacity restricted for up to 2 days (MMI VII).

High liquefaction potential.

This facility is built about 25 feet above sea level about 200 feet east of Walnut Creek, the nearest free face. There will be moderate damage due to shaking and minor liquefaction at this facility.

WW18 **Waste Water Treatment Plant, Richmond**

Capacity restricted for up to 2 days (MMI VII).

High liquefaction potential.

This facility is built between 15 and 40 feet above sea level about 1,200 feet west of Santa Fe Channel near Richmond Harbor, the nearest free face. There will be moderate damage due to shaking and minor liquefaction at this facility.

WW19 **Waste Water Treatment Plant, Oakland**

Capacity restricted for up to 1 day (MMI VII).

High liquefaction potential.

This facility is built on fill immediately south of the Bay Bridge approach. It is about 5 feet above sea level and 700 feet from the nearest free face. There will be only minor damage due to shaking at this facility. After the Loma Prieta earthquake, this plant in the MMI VII zone merely "lost commercial power from two feeds for 7 hours" and the "roller guide assembly anchorage failed on most guides..." (EERI, 1990). "Raw sewage overflows caused by power failure occurred...at the East Bay Municipal Utility District water treatment plant in Oakland" (McNutt, 1990).

"The Oakland regional plant lost commercial power from two feeds for seven hours. ...The Oakland sludge gas engine generators are being modified to operate automatically under emergency conditions" (EERI, 1990, p. 260-261).

WW20 **Waste Water Treatment Plant, San Leandro**

Capacity restricted for up to 1 day (MMI VII).

High liquefaction potential.

This facility is built on fill between 0 and 5 feet above sea level and

200 feet from a channel leading to San Francisco Bay, the nearest free face. There will be minor damage due to shaking and liquefaction at this facility.

WW21 **Waste Water Facility, Ocean Beach, San Francisco**
Capacity restricted for up to 1 day (MMI VII).
High liquefaction potential.
This facility is built at sea level, extending into the Pacific Ocean, the nearest free face. There will be only minor damage due to shaking at this facility.

WW22 **Waste Water Facility, North Beach, San Francisco**
Capacity restricted for up to 1 day (MMI VII).
High liquefaction potential.
A power outage will result in the release of some untreated sewage to the Bay.

WW23 **Waste Water Treatment Plant, Bayview, San Francisco**
Capacity restricted for up to 1 day (MMI VII).
High liquefaction potential.
This facility is built about 25 feet above sea level about 2,000 feet south of Islais Creek Channel, the nearest free face. There will be minor damage due to shaking at this facility. A power outage will result in the release of some untreated sewage to the Bay.

WW24 **Waste Water Treatment Plant, South San Francisco**
Capacity restricted for up to 1 day (MMI VII).
High liquefaction potential.
This facility is built at sea level about 50 feet south of a channel

leading to San Francisco Bay, the nearest free face. There will be minor damage due to shaking at this facility.

WW25 **Waste Water Treatment Plant, SFO**

Open (MMI < VII).

High liquefaction potential.

This facility is built at sea level about 300 feet from a channel leading to San Francisco Bay, the nearest free face. There will be only minor damage due to shaking at this facility.

WW26 **Waste Water Treatment Plant, Burlingame**

Open (MMI < VII).

High liquefaction potential.

This facility is built at sea level about 300 feet from a channel leading to San Francisco Bay, the nearest free face. There will be only minor damage due to shaking at this facility.

COMMUNICATIONS

Communication systems discussed in this section include the public telephone system, various emergency communication systems, and commercial radio and television services. The public telephone system in the planning area is mostly operated by Pacific Bell. This system includes the 911 system for emergency calls for police, fire and medical assistance. Map C shows the location of Pacific Bell Central Offices in Napa, Sonoma and Marin counties and the City of Vallejo.

Emergency communication for fire, police, sheriff, city and county public works, and public utilities, uses primarily radio systems. In general, each of these systems, which provides two-way radio communication, is independent of the telephone system, and usually has its own emergency power supply. Commercial radio and television so far provide only one-way communications, but they nevertheless are somewhat effective in disseminating information to the public after a disaster.

Data collected on telephone systems given below was based in part on information obtained from Pacific Bell and the California Department of General Services, Office of Telecommunications. We visited five Pacific Bell central office buildings as part of the data collection for this report.

PART I: TELEPHONE SYSTEMS

General Characteristics and Seismic Considerations

Telephone systems comprise a vast, complex, and interconnected network; yet they are also self-supporting on a local basis. One service provided by the telephone companies is intra-exchange traffic, that is, calls between telephones within the area served by a single central office or "exchange." Another is inter-exchange service whereby calls are switched between two central offices within a region. There is a third service, similar to inter-exchange, whereby calls are routed to a long distance facility. Each of these services can be provided by a variety of system configurations.

During major disasters, telephone communications typically are adversely affected by the overloading that results from too many calls from within and from outside the affected area. This situation can be further complicated by physical damage to telephone buildings and equipment from ground shaking and by disruption caused by loss of electric power and subsequent failure of some auxiliary power sources.

Call saturation occurs whenever the demand for the telephone service exceeds the number of switches and lines available. There are three main causes of call saturation: 1) earthquake shaking, 2) concern calls, and 3) emergency calls.

Earthquake shaking in the MMI, VIII and IX zones may be strong enough to knock telephone handsets from their receivers. Each of these "off-hook" conditions ties up a phone company switch. After a major earthquake, building occupants should check for displaced handsets and rectify.

Concern calls reflect our desire for instant information. Thus, a well-rehearsed Civil Defense radio network could reduce the number of "What was that?" calls to police and fire departments. The broadcasting of accurate, up-to-date damage estimates and seismological details could reduce the number and length of calls attempting to relay that information.

Emergency calls produce their own form of call saturation. Not all emergencies are equal, and some type of triage is necessary to use scarce emergency services efficiently. Call saturation becomes a moot point when all 911 operators are busy or whenever all emergency personnel have received their field assignments.

Call saturation is usually the most disruptive to essential service groups (e.g., police, hospitals) when there is no system to process emergency calls automatically on a previously established priority basis. The experience of the long distance system after the 1989 Loma Prieta earthquake (M7) provides an excellent example of overloading:

> "On the day after the earthquake, 27.8 million calls were attempted to the 415 and 408 area codes that serve the area affected by the earthquake. Only 9.5 million calls were completed, but they represent almost a threefold increase over the normal daily volume of 3.5 million" (EERI, 1990).

The 415 area includes San Francisco and surroundings, and was in the MMI VII zone. The 408 area includes Santa Cruz and San Jose, and was in the MMI VIII and VII zones (Figure S-4).

The local telephone system was similarly affected. Saturation of the system was severe on the day of the earthquake. On the day after the earthquake, a record 80 million calls were made within the nine-county Bay Area compared to the 55 million daily average (EERI, 1990).

Telephone systems are composed of many subsystems, each interconnected and interdependent. The failure of one link in this electronic "chain" can effectively disable a portion of the system, reducing its effectiveness, but not completely destroying it. We also assume that the damaged portions will be repaired to a limited extent. Criteria such as geographical coverage, the number of system elements, and functional integration, were considered in estimating the post-earthquake effectiveness of a particular system. While the maximum capacity of any system is represented as 100 percent, most operate at about 90 percent due to ongoing maintenance.

The effects of the scenario earthquake must be applied to this ratio to determine the degree to which the overall effectiveness is reduced. "Effectiveness" is defined as the ability of a system to perform to its design limits and provide the intended service.

Telephone companies, and Pacific Bell in particular, have special seismic standards that are designed to prevent or minimize earthquake damage to equipment, but the seismic design of their buildings is typically the same as that for ordinary industrial facilities (150 lb/ft^2 floor loading). Pay phones are no longer better than regular phones, because, being privately owned, many of these are no longer installed and maintained to the high standards of Pacific Bell (Jim Cotter, personal communication, 1993).

Telephone systems are surprisingly rugged. Considering the area impacted, damage and disruption of the phone system from the 1989 Loma Prieta earthquake, except for call overloading, was relatively modest.

There were no reports of building damage causing an outage of telephone service after the Loma Prieta earthquake. However, the following description of damage to an Oakland facility is a reminder of this possibility:

> "In Oakland, a major facility that contained Pacific Bell and AT&T equipment had severe structural damage. There was no significant damage to communication equipment. On the roof, a cooling tower used for the air conditioning system was damaged, but the cool weather made it unnecessary. In light of the short duration and small bedrock motion in the area from this earthquake, one can speculate that more severe ground motions could cause the loss of the building. Had this occurred, communications in Northern California would have experienced major long term disruptions" (EERI, 1990).

The Loma Prieta earthquake also caused problems with emergency generators in telephone system central offices:

> "The loss of commercial power did cause some problems in three central offices. All but one of Pacific Bell's 160 central offices worked throughout the disaster without impairment. Central offices contain batteries to operate the telephone system for several hours in case commercial power is lost. In addition, the central offices have engine generators to recharge the batteries, so telephone service can be maintained for extended periods without commercial power. However, there were some problems with engine generators. In one central office in San Francisco, asbestos was being removed from the room that contained the engine generator, which put the regular unit out of service. A rented unit, located outside the building, served as a replacement during the remodeling. This unit failed to start, and workers found and replaced a clogged fuel filter. The generator then started, but it would not carry load and eventually caught fire. A replacement generator was obtained before there was any disruption of service at the central office. In another office, which has diesel and turbine powered generators, the turbine powered generator had a faulty governor that caused fluctuations in speed, so it had to be taken out of service. A cooling system water pump for the diesel engine was shut off, and the diesel engine shut down automatically when it overheated. Service was reduced by shutting down three of the five switches at the office until additional backup power could be obtained. At the Hollister central office, an engine generator could not be started. A replacement generator was obtained before it was discovered that a damper, used to shut off the air intake, was closed" (EERI, 1990).

It is generally difficult to forecast the detailed effects of a major earthquake on telephone systems, but a number of outcomes can be anticipated. These include possible hardware damage such as cable breaks in areas of ground failure,

damage to surface cable carriers, system call saturation during the post-earthquake recovery period, and access problems for repairs. We can learn much from previous events. Most recently, telephone systems were strongly shaken in the June 1992 Landers earthquakes (M7.5) and the Big Bear (M6.6) events in Southern California.

> "Telephone systems performed well, although telephone service was affected by the usual postearthquake high volume congestion. Reported damage included a downed overhead cable and a few tension failures in buried cable. Although there were some temporary disruptions immediately following the event, telephones were generally working throughout the epicentral region within a few hours. Sporadic local outages were reported for about three days following the earthquakes" (EERI, 1992).

This is how the 911 public safety communication system operates:

> "The emergency communication systems, commonly referred to as the 911 system, is the primary means for individuals to obtain services, such as police, fire, and medical assistance. The system consists of public safety answering points (PSAP), which have operator positions (consoles), radio communication ability, a tape system to record all calls, and emergency backup power. Some PSAPs also have computer-aided dispatch that logs dispatches and indicates the disposition of units based on data provided by the PSAP. Typically, each county has a PSAP that receives emergency calls from unincorporated areas within the county and from communities that do not have their own PSAP... In larger county systems, which may have as many as 30 operator positions, an operator will receive a call, identify the appropriate response agency (fire, police, or medical), and transfer the call to a dispatcher for that agency. In smaller centers, such as those for a city, which may have as few as two operator positions, the operator also serves as a dispatcher. In a location where the sheriff's department operates the system, police calls will be dispatched and fire and medical calls transferred" (EERI, 1990).

In areas strongly shaken during the Loma Prieta earthquake, many PSAP's were impaired. The following is a report on the Santa Cruz PSAP, which was located in one of the more strongly shaken areas (MMI VIII):

"Commercial power was lost for about two hours at the Santa Cruz PSAP, and it was sporadic for some time after that. Emergency power worked but ran out of fuel during one of the subsequent power outages. There was no dial tone delay, but calls could not be made to the southern part of the county due to line or circuit busy signals. The 911 system was overloaded, which prevented callers from reaching the PSAP. During one 25 minute interval shortly after the earthquake, radio communications to the ambulances in the southern part of the county were inoperative. During another 25 minute period, about two hours after the earthquake, all power and telephones were dead for an unknown reason. Even after telephone communications improved, there were some areas in Watsonville that could not be telephoned. As a result of a training program, equipment in the PSAP had been secured, so the tape unit and other items did not fall over. Between 5:00 PM and midnight over 300 callers reported gas leaks. The PSAP had an unlisted number for contacting the local PG&E office. There were several structural fires and grass fires, and some mobile homes had fires related to gas leaks. Ambulance resources were exhausted in five minutes, but there were no serious injuries, so individuals were able to provide for their own transportation to the hospital" (EERI, 1990).

Planning Considerations

Some basic assumptions have been made in this analysis:

1. The shaking intensities in this scenario are shown on Map S.

2. Areas experiencing intensities greater than MMI VII will have some hardware damage although it will not have a large regional impact.

3. Some underground cables will be damaged by ground failure or water intrusion, but this will not preclude switching alternatives.

4. Most essential service lines will receive priority restoration wherever possible.

5. Most telephone company back-up power sources will be functional.

6. Access to outgoing long distance lines will be unaffected.

7. Access to incoming long distance lines will be blocked for up to 3 days.

8. Interchange facilities will be difficult to access, but will remain essentially intact.

9. Shortly after the event, numerous relatively simple failures will occur, for example, the "off-hook" condition produced by intense shaking.

Coupled with intense call saturation, these will disable general telephone service for 6 hours or more (refer to Map C for levels of anticipated effectiveness during the initial 3 days post-earthquake recovery period).

Most of the central office buildings were constructed during the 1960s through the 1970s. After the 1989 Loma Prieta earthquake, various central offices (such as the one in downtown Oakland) have undergone seismic rehabilitation to stiffen structures by adding additional shear walls. Nonstructural building and equipment damage will occur at central office buildings in areas of high ground shaking (MMI VIII+, IX) around Santa Rosa, Rohnert Park, Cotati, Petaluma, and Fetzer Hot Springs.

A network of Pacific Bell cables crisscross the planning area. Major parts of this network include cable systems over the San Francisco-Oakland Bay Bridge, in the BART Transbay Tunnel, and a link cable circumscribing the entire greater San Francisco Bay Area. Despite the collapse of a section of the bridge deck at the eastern end of the San Francisco-Oakland Bay Bridge during the 1989 Loma Prieta earthquake, the communications cable over the bridge did not fail. Twenty foot cable loops provided at each end of the bridge were able to take up the slack without rupture. As a standard practice, Pacific Bell provides cable loops (i.e., extra cable lengths) at critical locations where extra tolerance is needed to avoid excessive stress on the cable. Pacific Bell has recently installed underground fiber-optic cables for its high capacity lines between key central offices.

Cellular Telephone System

Cellular communication systems consist of an array of transceivers (radio transmitters and receivers) technically called "cells." These cells communicate to the subscriber's mobile telephone and are connected through leased lines, private lines, and microwave links to a switch operated by a cellular telephone company. The number of calls that a cell can handle simultaneously depends on the cell equipment, but it typically ranges from 15 to 60 simultaneous calls.

Because this system is an extension of a normal telephone network, it has the same operational problems. But because cellular service is not dependent on cable except where it connects with Pac Bell, it is potentially more reliable than basic telephone service.

Shortly after the 1989 Loma Prieta earthquake, there were mixed reports on the usefulness of cellular phones. Some indicated that cellular telephones worked much better than regular telephones. Still others were unable to complete calls.

As with the regular phone system, this was because the cell serving an area may become saturated during emergency periods, degrading the service.

> "One company that has four switches lost power on a cell located on Loma Prieta Mountain. The generator failed to start, but a new circuit card, installed the next morning by a crew flown in by helicopter, corrected the problem. ...In Los Gatos, cellular telephones from one company were out of service for about half an hour and then service became intermittent. Reports indicated that microwave communication antennas were misaligned. An equipment rack for one of the telephone companies on the fourth floor of a major communications building in Oakland pulled expansion anchors from a wall, tipped over, and caused a short circuit, which blew a fuse. A recording head on one of two computer disks mounted in an equipment rack crashed, which damaged a sector of the disk; the disk was reformatted and continued to operate" (EERI, 1990).

Planning Scenario

Emergency response agencies have some of their telephone lines, sometimes as little as 10 percent, predesignated as essential service lines. For planning purposes, it is postulated that after the scenario earthquake, these essential services telephone lines will be 50 percent usable in the first day, and 75 percent usable at the end of the second day. This assessment is for most of the area within 20 miles (32 km) of the fault. Table C-1 provides information regarding the location of the telephone central offices with respect to the fault and expected MMI intensity.

TABLE C-1

TELEPHONE CENTRAL OFFICE LOCATIONS

MM Intensity*	Number of Central Offices
IX	4
VIII+	3
VIII-	9
VII	7
<VII	6
	TOTAL 29

* Refer to Maps S and T, and to Appendix A

Because of call overloading and system saturation the availability of telephone communications for the general public will be significantly lower than for emergency response agencies using essential service lines. As experienced in previous earthquakes, general use telephone service may be out for up to 1 week in some areas. Although specific structural damage to telephone facilities may be moderate, loss of commercial power will cause problems in central office buildings. Emergency power will be required to continue operations.

Map C shows areas that are zoned generally according to the expected level of telephone system effectiveness expected during the first 3 days following the earthquake. Four levels of effectiveness are shown. This map is very general, and was prepared with guidance from James Cotter of the California Department of General Services' Office of Telecommunications.

PART II: EMERGENCY COMMUNICATIONS AND COMMERCIAL RADIO AND TELEVISION

General Characteristics and Seismic Considerations

As indicated in Part I, telephone systems, will not be fully accessible immediately after the scenario earthquake. In certain cases, full general availability of telephone services will not be possible for a week after the event. During this emergency period, accordingly, emergency communication efforts by radio may become a viable alternative.

Radio communication systems, when built and maintained with adequate safeguards, are less susceptible to disruption and damage because of their lesser dependence on wire cable and the relatively smaller size of their components than phone systems. In addition, many advances in radio communication system and component technology, such as remote satellite terminals, high powered transmitters, ultra-high frequency systems, and others, have been made since the late 1960's. This has led to more compact, mobile, lightweight, and highly efficient units than those used in the past. However, many of these high-tech components and facilities are still vulnerable to damage from earthquake forces.

Radio components include control consoles, base stations, electrical cabinets, microwave radio, repeaters, transmission towers, mobile relays, mobile radios, hand held radios, and portable systems. The failure of any specific component may not adversely affect the total system because of the numerous options built into radio design. However, as in the case of telephone communication systems, the availability of electric power is essential to radio operation. Furthermore, tabletop and desk top radio control consoles are vulnerable to earthquake damage if they are not secured.

Damage to radio communication systems and TV facilities may affect the following elements:

Radio communication and TV stations, studio/buildings
Station equipment
Receiving, transmission, repeater towers
Appurtenant structures and facilities

In the planning area, tower stations generally are on poor ground along the Bay shore or on firm ground on mountain tops. During the 1989 Loma Prieta earthquake:

> "For selected narrow frequency bands, recordings of both the main earthquake and aftershocks reveal ground motion amplification at some soft sites was eight to ten times that recorded on rock sites" (Governor's Board of Inquiry on the 1989 Loma Prieta Earthquake, 1990).

Transmitting towers are either atop transmitter buildings, on the ground adjacent to buildings, in the Bay itself, or on an adjacent hilltop sufficiently elevated to avoid obstructions. Towers are from 140 to over 500 feet high. One of the towers on San Bruno Mountain in San Mateo County rises to an elevation over 1,400 feet above sea level, while a tower atop mountains in the San Jose area is 4,000 feet above sea level (Algermissen and others, 1972).

The lessons of the 1989 Loma Prieta earthquake should be memorized by planning experts:

> An individual reported that "he saw the top of a 45 foot tall power pole, which supported the transformer providing power to the transmitters at the site, swing back and forth 15 feet. The transformer, which was bolted to the pole, fell to the ground after tearing the steel mounting tabs away from it. At this site, an abandoned, blast-hardened, reinforced concrete Air Force radar tower was severely damaged. Two 500 gallon propane tanks that rested in cradles, but were otherwise unanchored, moved, broke their piping connections, and disrupted the fuel supply to the engine generator at the site. In this case, it was possible to restore emergency power within half an hour. Commercial power was restored in about 3 days."

"Many sites lost commercial power. At one site, the emergency generator tipped over and was inoperable; at another, the batteries that started the generator were dead; at a third, the batteries tipped over, broke, and spilled acid on equipment. Many sites were without power until commercial service was restored. Many systems have only battery backup power, which means that if commercial power is off for an hour or two, the transmitter goes off the air. High elevation repeaters used by ham operators appeared to be particularly vulnerable, as they lost about 30 of their 35 systems in the earthquake affected area; however, not all of these repeaters are used for emergency communications. On Mount Diablo, a repeater used by hams operating out of OES Region 2 was down for about 2 hours due to the failure (not earthquake related) of a control board."

"Much of the equipment located at hilltop stations was damaged. ...At one site that served about 30 different antennas, each with its own electrical cabinet, all thirty systems were inoperable as a result of the earthquake. Only two of the cabinets were anchored, and most were thrown across the room, breaking antenna and power connections. Backup batteries fell, broke connections, and spilled acid over other equipment that had fallen to the floor. One cabinet, although anchored at its base and top, leaned over at about 45 degrees, which broke its antenna connection. While some systems could be restored, many needed major repair and were out of service for an extended period."

"Some important communication facilities were disrupted. For example, Coast Guard Channel 16, the emergency channel for ship-to-shore radios, and a radio transmitter for the station at Monterey were down until 10:00AM the day following the earthquake. One repeater used for emergency service was lost; it was replaced by a private unit. Two additional units were used for emergency service to expand capabilities" (EERI, 1990).

Office of Emergency Services

Each county in the Rodgers Creek fault planning area has a local Office of Emergency Services (OES) which serves the area through an appointed Emergency Services Coordinator, Manager, or Director (Table C-2).

These county offices serve as command centers for emergency response to damaging earthquakes. Radio communications are used extensively, when telephone systems become saturated during initial emergency response periods.

As in the case of telephone communication systems, the availability of emergency power in OES offices is clearly essential to radio communication. Also, tabletop and desktop radio control consoles and equipment are highly vulnerable to earthquake damage, if they are not secured.

TABLE C-2

LOCATIONS OF COUNTY EMERGENCY SERVICES OFFICES

Office	County	City
Department of Emergency Services	Alameda	San Leandro
Office of Emergency Services	Contra Costa	Martinez
Department of Emergency Services	Marin	San Rafael
Department of Emergency Services	Napa	Napa
Office of Emergency Services	San Francisco	San Francisco
Department of Emergency Services	Solano	Fairfield
Department of Emergency Services	Sonoma	Santa Rosa

In the 1989 Loma Prieta earthquake:

> "The OES lost power for about 2 hours, but emergency power worked without problems. Telephones became saturated during peak hours for about 1 week following the earthquake. One to five ham operators were available around the clock for 4 days; they were primarily used when the telephone system became saturated at peak hours during the day" (EERI, 1990).

At local Emergency Operations Centers after the 1989 Loma Prieta earthquake:

> "Perhaps the most serious problems reported by all jurisdictions centered on inadequate EOCs, poor or disrupted communications between organizations and between field and central headquarters within

> organizations, and lack of interorganizational coordination at the operation level. All reports point to the need for hardened EOCs with adequate space and communication networking capabilities, autonomous power sources, and defined command and control charts that indicate who should be at the EOC and who should not" (EERI, 1990).

Of the seven EOCs listed in Table C-2, only Santa Rosa is in a zone of MMI IX. For purposes of emergency response planning, it is assumed that EOCs located in areas of heavy ground shaking (MMI VIII+ or MMI IX) will incur serious damage to furnishings, equipment, and communication systems. As indicated previously, this will be particularly true for installations where critical equipment is not appropriately secured, anchored, or protected from falling (i.e., including overturned cabinets or bookcases) wall furnishings or objects. This also applies to standby power sources such as emergency power generators and other vital equipment.

Planning Considerations

Several types of voice radio communication systems exist in the planning area. Typically, such systems include a base station that is normally a fixed facility with a high powered transmitter and a fixed antenna. It is possible for mobile units to communicate with the base station and with one another. Ultra-high frequency systems (UHF) in the planning area are used by emergency response agencies, including fire departments, police stations, public safety answering points, and other organizations. These systems are critical to emergency communications and their failure can lead to serious deterioration of emergency response efforts during the immediate post-earthquake recovery period.

In dealing with any radio communication system, it is clear that the reliability of outside power supply connections and on-site emergency power generating systems must be given careful consideration in areas of high seismicity. Unless

design and installation standards give consideration to their performance under earthquake loads, operational capacity can be severely restricted and/or totally disrupted as has been seen in several cases investigated since the 1989 Loma Prieta earthquake.

During the 1989 Loma Prieta earthquake, radio, television, newspapers, and other components of the public media had to rely on emergency plans, if any such plans existed. Following the earthquake, "the key problems for all the media generally involved the loss of commercial power and a lack of emergency generating capacity. To a lesser extent, there was also a transportation problem, which made coverage difficult when power was restored. This contributed to limited coverage in the epicentral area, causing most of the world to believe that San Francisco was the hardest hit area, rather than Santa Cruz and its surroundings. ...Five radio stations in the region used flashlights, emergency generators, and a degree of phone service to keep the Bay Area informed, reassured, and connected during the first dark hours after the earthquake" (EERI, 1990).

The emergency generator failed at one major radio station, however it was able to tap into another emergency generator which gave the station's broadcast studio a few lights and the capacity to stay on the air. During the night, gallons of fuel had to be carried up the 30 flights of stairs to keep the generator going because the elevators, damaged during the earthquake, were inoperable.

Planning Scenario

The performance of radio base stations on roof tops will depend on the condition of the building itself and the availability of emergency electric power. Systems that use control stations normally have backup power. However, the failure of an

emergency power source at a station will disrupt operations until commercial power is restored.

New high-tech, sophisticated consoles are better protected against physical damage and normally have emergency power available. However, some of their components may not be as robust. If a key component of a large console fails, many radio systems will be fragmented, placing a burden of communications on remote stations that also may be vulnerable to earthquake damage. For planning purposes, we assume that self contained tabletop base stations will be 40 percent effective, tabletop control consoles 55 percent effective, and large free standing consoles 50 percent effective. Tabletop and desktop radio consoles and equipment that are not secured will be damaged and unusable after the earthquake.

Repeaters are not dependent on control circuits and are normally provided with backup emergency power. Stations on mountain tops will be subjected to structural, electrical, and other forms of internal, nonstructural and equipment damage. Repeater stations closest to the fault source will experience technical problems. We assume repeaters will be initially 60 percent effective, declining as emergency power supplies are exhausted and technical problems develop, and will become 40 percent effective after 24 hours.

American Radio Emergency Service (ARES), an organization of amateur radio operators, is organized to provide communications assistance in emergencies, and has been effectively used in the past. A similar organization, Radio Amateur Emergency Services (RACES), has also been effective in providing emergency radio communications during disasters. The Governor's Office of Emergency Services (OES) in California has integrated these radio systems into its emergency operating procedures. However, all amateur radio stations are also subject to the same types of hazards described earlier. Nonetheless, there are extensive

vehicular radio and repeater systems available under these amateur radio services. Under the conditions described in the scenario earthquake, much of the first post-disaster intelligence may come from this private sector resource. The amateur radio service should remain more than 50 percent effective because of pre-disaster arrangements for uses of bands reserved for emergency uses and the long distance capabilities of the equipment.

Similar to radio base stations, remote terminals relying on telephone or microwave circuits will be 40 to 50 percent effective. Terminals near stations will have greater likelihood of survival (approximating 75 percent). Recent developments in satellite communication systems have made them one of the most reliable methods of communications from point to point. Because the orbiting satellites are impervious to earthquake damage, they are among the most significant resources for communication systems after the scenario earthquake.

Aircraft and marine communications systems operating on emergency channels will be at least 50 percent effective provided that radio transmitters for their stations, or moored maritime resources, remain operable. While emergency response planners should investigate the potential of either service for providing good quality emergency communications, existing land based systems may remain completely incompatible. Previous studies indicate that the relative importance of such radio services increases as recovery efforts get under way.

As indicated by their performance during the 1989 Loma Prieta earthquake, antennas and related structures should remain 70 percent effective. Although some antennas will be severely damaged, it is unlikely that they will fail on a large scale.

PETROLEUM

General Characteristics

Crude oil arrives at Bay Area refineries by ship and pipeline. After refining, the petroleum products are delivered to customers throughout the Bay Area by pipeline, tanker truck, and ship.

There are six major petroleum refineries and three tank terminals operating in the San Pablo Bay and northern San Francisco Bay areas (Table P-1). They are between 10 and 20 miles (16 to 32 km) from the Rodgers Creek fault, with the largest operated by Chevron USA in Richmond, about 14 miles (23 km) from the southern end of the fault (Map P). All are subject to damage by shaking from the scenario earthquake.

In California, this refinery area (Map P) is second only to Los Angeles as a heavy industrial hub including petrochemical processing, storage facilities, and chemical plants. The Chevron refinery was the first built in the area, with its construction commencing at the turn of the century.

Major oil companies have great financial and human resources. These resources are typically located throughout the United States, and can be called on when needed. While self sufficient in this sense, restoration of functions vital to the public requires liaison and coordination with local disaster response planners.

For example, water, natural gas, and electric power are vital for day to day refinery operations. These are supplied by local utilities and are not under the control of the oil companies, except at the Chevron refinery.

TABLE P-1

MAJOR PETROLEUM FACILITIES

Name - Location	County	No. of Tanks	Capacity Barrels/day
Tosco Refinery, Avon	Contra Costa	N/A	130,000
Pacific Refining Co., Hercules	Contra Costa	50	55,000
Shell Refinery, Martinez	Contra Costa	490	140,000
Unocal Tank Terminal, Richmond	Contra Costa	60	N/A
Arco Tank Terminal, Richmond	Contra Costa	50	N/A
Texaco Tank Terminal, Richmond	Contra Costa	42	N/A
Chevron Refinery, Richmond	Contra Costa	700	250,000
Unocal Refinery, Rodeo	Contra Costa	250	82,000
Exxon Refinery, Benicia	Solano	54	130,000

Modified from EERI, 1990, p. 219.

We inspected one major refinery in Contra Costa County as a representative of petroleum products facilities, and did general field surveys of three others, along with their associated above surface pipeline systems.

Seismic Characteristics

Earthquake damage to petroleum facilities may be classified in three categories:

1. Damage may occur to incoming oil transportation facilities such as pipelines and marine terminals.

2. The refinery may:

   a) suffer direct damage such as broken piping, ruptured storage tanks, and structural damage to process towers;
   b) suffer serious secondary damage from post-earthquake fire;
   c) become nonfunctional due to loss of water, natural gas or electric power.

3. The distribution system may become impaired from damage to storage facilities or pipelines.

Refineries are very complex facilities and are typically conservatively designed and constructed. They consist not only of conventional structures such as buildings, but they have many structures that are unique to refineries. These include process equipment such as very large vertical pressure vessels, heat exchangers, storage tanks, fans, and piping. Over time, a typical refinery may undergo numerous additions and modifications. Each of these may be designed and constructed by several different groups, and the elapsed time may span several decades. Because seismic design standards have changed considerably over the last several decades, the seismic resistance of a given refinery may vary with the age of the construction, with newest structures and process equipment expected to perform best.

The earthquake performance of refineries and other petroleum product plants has been reasonably good from the standpoint of avoiding extensive structural damage, but there have been several instances of major damage caused by post-earthquake fire. In 1952, the Paloma Cycling Plant survived the Kern County earthquake (M7.7) until two large, 2,500 barrel butane spheres collapsed, releasing highly volatile material. The gaseous material spread over the area and ignited, causing a major fire (Steinbrugge, 1982). Following the 1964 Niigata, Japan earthquake (M7.5), a post-earthquake fire at the Showa Oil Company refinery burned continuously for over 2 weeks (Steinbrugge, 1982). There also have been isolated instances of fire at failed storage tanks such as that at petroleum tank farms along the Seward waterfront following the 1964 Alaska earthquake (NAS, 1973).

Even without earthquake shaking, various refineries and chemical plants in the northern Contra Costa County section (Figure P-1) of the planning area have had a series of fires, explosions, and toxic chemical releases during the last 5 years. In 1992 an explosion at one of the major refineries in Martinez shattered windows in the immediate area, causing nearby homes to be evacuated. In June 1992 a

series of fires at a chemical plant resulted in the evacuation of nearby businesses and the closure of Interstate 680:

> "Three sulfuric acid fires at a chemical plant in Martinez critically injured two plant workers and caused evacuation of nearby businesses and the shut-down of a major freeway linking two counties. ...Interstate 680, the major link between Solano and Contra Costa counties, was shut down from about noon to 2:30 p.m., causing lengthy traffic delays. ...the Martinez-Benicia Bridge was closed in both directions because of the dense chemical smoke, which also caused the evacuation of Martinez Auto Dismantlers on Waterfront Road" (Taylor and Delvecchio, 1992).

In 1993, the mishandling of oleum (semi-solid form of sulfuric acid) closed Interstate 80 in Richmond for several hours, and in Avon a defective valve caused a minor oleum release at the Tosco refinery.

During the Loma Prieta earthquake (M7), local refineries and tank terminals had some structural and tank damage. Structural damage at refineries was varied. The bracing on two large reactor service structures buckled, but the reactor vessels showed no damage. Several fan support structures also had structural damage, including buckled bracing, sheared bolts, and torn welds. In some cases, the fan structure damage was so great that the capacity to resist seismic forces was virtually lost (EERI, 1990). Without seismic upgrading, this equipment would be again susceptible to damage in the scenario event.

According to Hsiu (1993):

> "Chevron has performed in-house seismic assessment work, and found most of the refinery facilities possess fairly good seismic performance capacity, despite being built to older codes. A seismic retrofit program is currently underway."

Damage to storage tanks comes from sidewall buckling, bottom plate separation from sidewalls, and from sloshing of liquids. Sloshing often damages or destroys fixed or floating tank tops. Rigidly connected piping also often breaks when the tank rocks because the piping does not possess sufficient flexibility. While

spillage of oil from such damage may be spectacular, it has not been serious when contained within dikes and kept free of ignition sources.

There were many reports of tank damage following the Loma Prieta earthquake. Damage was primarily related to uplift of unanchored tank walls and typically occurred at soft soil sites (e.g., Tuttle and others, 1990). Major leaks occurred in several tanks, but the product was trapped within containment dikes. No fires occurred (EERI, 1990). For additional data on storage tank damage, refer to the *Marine Facilities* chapter.

Pipelines to and from refineries are designed to carry products under high pressure. These are constructed of welded steel and generally are quite rugged. In the absence of ground failure, the earthquake performance of such pipelines generally has been good. In fact, a large diameter line carrying natural gas across the White Wolf fault was not damaged during the 1952 Kern County earthquake (M7.7). Fuel lines were undamaged during the 1979 Imperial Valley earthquake (M6.4). Natural gas transmission lines crossing Turnagain Arm of Cook Inlet at Anchorage experienced no damage in the 1964 Alaska earthquake (M9.2) despite the poor ground. A major water line (Hetch Hetchy Aqueduct) to San Francisco performed without damage in the great 1906 earthquake (M~8), even though it was founded on bay mud. Extensive damage in the form of numerous breaks did occur, however, to natural gas transmission lines during the 1971 San Fernando earthquake (M6.4). The pipeline breaks occurred in areas of surface fault rupture and ground deformation.

Planning Considerations

Bay Area refineries will experience shaking from the Rodgers Creek earthquake that will be stronger than that experienced in the 1989 Loma Prieta event. Predicted intensities for the Rodgers Creek event in northern Contra Costa County

are MMI VII, while this area experienced MMI VI in the Loma Prieta earthquake (Figure S-4). Thus the impact on the refineries will be greater than that of the Loma Prieta earthquake, but less than it would be from a major earthquake on the Hayward fault (MMI VIII, Steinbrugge and others, 1987).

The refineries and tank terminals listed in Table P-1 are near bay margins. Foundation materials vary. Some sites are on rock outcrops, and others are on Bay mud. During the Loma Prieta earthquake, damage to refineries was concentrated at facilities on Bay mud and other loose, compressible and saturated soils; facilities supported on piles performed well. Photos and details concerning the effect of the Loma Prieta earthquake on refineries and petroleum pipelines in the MMI VI zone are in EERI (1990, p. 218-238). In sum, various braces and anchorages were distorted by the shaking. On soft ground numerous nearly full, unanchored tanks with height/width ratios of greater than 0.5 were damaged. Three tanks leaked, but the material was trapped by containment dikes. No fires occurred. Most facilities were back in operation 6 days after the earthquake.

As previously mentioned, refineries are very complex facilities, and detailed analysis and prediction of their behavior during a major earthquake is beyond the scope of this study. Detailed, site-specific engineering studies are required to determine the vulnerability of each facility's refining and storage capability.

Facilities used for the manufacture, processing, and storage of various petrochemicals warrant special attention to reduce the risk of post-earthquake fire and the release of toxic substances.

Unanchored tanks at soft soil sites at refineries and tank terminals are especially susceptible to damage and leaks. Leaks may also result from breaks in rigidly connected piping. Because of the possibility of post-earthquake fire and environmental damage, tanks should be given detailed seismic evaluations.

The low earthen embankments used as retention dikes around fuel and oil storage tanks, evaporation ponds and waste containments did not fail during the Loma Prieta earthquake (Hsiu, 1993).

The several major petroleum pipelines in the planning area cross extensive areas of structurally poor ground near the margins of bays. Ground failures resulting from liquefaction can cause differential ground movements that can damage pipes. Pipe connections at terminal facilities are also similarly vulnerable due to the differing response between buried pipe and rigid structures.

Shut-off valves are installed on many pipelines, and these will function automatically when the line pressure drops below a particular threshold, such as would occur in the case of a pipe rupture. Some of these valves are dependent on electrical power, however, and will not function if power is lost. Should a petroleum pipe rupture during the dry season, a post-earthquake fire could be a serious problem. This threat is also present during the rainy season should escaping fluids be ignited as storm waters wash them into sewers.

All of the petroleum product pipelines that serve the metropolitan area should be examined in detail relative to their vulnerability to ground failure. The adequacy and locations of automatic shut-off valves should also be examined for post-earthquake functioning. Locations for temporary storage of emergency fuel supplies, including those for aviation fuels, should be predetermined and emergency procedures established to ensure that these supplies will be available when needed.

Planning Scenario

Direct damage to refineries may involve ruptured tanks, buckled steel stacks, stretched anchor bolts for processing towers, stretched or buckled bracing in

support structures, broken brick linings in boilers, broken and cracked piping, and piping shifted off its supports. Older steel tanks that are not anchored to their foundations will rock or shift, rupturing some tanks and breaking attached rigid piping. Direct damage to refineries, most of which are of rugged construction, will be relatively modest in view of the large number of structures, tanks, and pipes involved.

For planning purposes, we assume that 10 percent of the flat bottom tanks at refineries and tank terminals in the planning area will buckle, and 5 percent will rupture and leak. We also assume that some post-earthquake refinery fires will occur. These will be suppressed within 4 days by plant personnel with on-site fire suppression systems that use water from the bay. Another related hazard is the release of toxic emissions from petrochemical processing or storage facilities. Because of dense smoke from two localized fires and incidents related to the release of toxic emissions from petrochemical processing and chemical plants in the immediate area, Interstate 680 and the Martinez-Benicia Bridge will be closed to traffic in both directions for 8 hours.

A typical refinery will be shut down for inspections and repairs, but the outage period will be relatively short. Refinery personnel will make necessary repairs, except for fire damage, to restore normal operations. Refineries, and parts of refineries, at rock and stiff soil sites will be less strongly shaken and have lesser amounts of damage than those on soft soil sites. Electric power and water supplies will be interrupted. The restoration of water service will be the more time consuming of the two.

The damage to refineries, tank terminals, and pipelines will be insignificant, and thus there will be no widespread gasoline shortage in the planning area. Any shortages will be local and of short duration.

Damage Assessments

Damage assessments have been postulated for certain petroleum related facilities as set forth below. The statements regarding the performance of facilities are hypothetical and are intended for planning purposes only. They are not to be construed as site-specific engineering evaluations. Outage and repair times assume that materials, equipment, and human resources are available and on site. Locations of petroleum products facilities are shown on Map P.

MAP NO.	PETROLEUM
P1	**Pipeline and Refinery, Exxon Company, Solano County** Operations curtailed for up to 3 days (MMI VII). Minor damage to pipeline facilities in areas susceptible to liquefaction. According to EERI (1990, p. 219), the "Exxon and Shell refineries are on sites cut in stiff materials, which partially explains why they reported no damage" in the Loma Prieta earthquake.
P2	**Pipelines between Richmond and Martinez, Contra Costa County** Inspection and repairs completed in 3 days (MMI VII to VIII-). High liquefaction potential in places. Localized pipeline damage due to ground failures caused by liquefaction.
P3	**Pipeline Terminal Facilities at Richmond, Contra Costa County** One terminal facility closed for up to 4 days (MMI VII). High liquefaction potential. Some flat bottom tanks rupture and leak contents. Ground failure caused by liquefaction will cause minor damage to pipelines and terminal facilities, and some spilling of petroleum products.

P4 **Pipelines in Richmond/San Pablo area, Contra Costa County**

Inspection and repairs completed in 3 days (MMI VIII-).

High liquefaction potential.

Pipelines damaged by ground failures due to liquefaction.

P5 **Chevron Refinery and Tank Terminal**

Partially closed for 24 hours (MMI VII).

Closed for inspection. Most of this facility is built on bedrock, where the MMI will be less than VII. The few facilities in the low area have foundations reaching bedrock. Soil investigations by Dames and Moore indicate no liquefaction potential in the refinery (Hsiu, 1993).

P6 **Bay Crossing Pipelines and Terminals**

Open (MMI VII).

High liquefaction potential.

These survived the 1989 Loma Prieta earthquake (M7) with no problems. The shaking intensity during the scenario event will be similar.

P7 **Interstate 680 and Martinez-Benicia Bridge**

Closed to traffic for 8 hours (MMI VII).

High liquefaction potential.

Closure due to dense smoke from fires and release of toxic emissions from refineries and chemical plants.

GLOSSARY

ALLUVIUM	Surficial sediments consisting of poorly consolidated gravels, sands, silts, and clays deposited by flowing water.
BEDROCK	A general term for coherent, usually solid rock, that underlies soil or other unconsolidated surficial material.
DEFORMATION	A general term for the processes of folding, faulting, shearing, compression, or extension of rocks.
EARTHQUAKE	Vibratory motion propagating within the earth or along its surface caused by the abrupt release of strain from elastically deformed rock by displacement along a fault.
FAULT	A fracture (rupture) or a zone of fractures along which there has been displacement of adjacent earth material.
FAULT LINE	A scarp that has been produced by differential erosion along an old fault line.
GROUND FAILURE	Permanent ground displacement produced by fault rupture, differential settlement, liquefaction, or slope failure.
GROUND RUPTURE	Displacement of the earth's surface as a result of fault movement associated with an earthquake.
ISOSEISMAL AREA	An area composed of points of equal earthquake intensity on the earth's surface.
INTENSITY	A measure of the effects of an earthquake at a particular place. Intensity depends on the earthquake magnitude, distance from epicenter, and on the local geology.

GLOSSARY (cont)

LIFELINES	Facilities such as highways, bridges, tunnels, major airports, electrical power lines, fuel pipelines, communication lines, water supply lines, marine terminals and railroads.
LIQUEFACTION	The transitory transformation of sandy water-saturated alluvium with properties of a solid into a state possessing properties of a liquid as a result of earthquake shaking.
MAGNITUDE	A measure of the size of an earthquake, as determined by measurements from seismographic records.
MODIFIED MERCALLI INTENSITY SCALE	Refer to Appendix A.
REINFORCED MASONRY	Masonry construction with steel reinforcement.
ROSSI-FOREL INTENSITY SCALE	Refer to Appendix A.
WATER TABLE	The upper surface of ground water saturation of pores and fractures in rock or surficial earth materials.

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SECTION 5

APPENDIXES

APPENDIX A

Modified Mercalli Intensity Scale of Wood and Neumann, and its Relation to the Rossi-Forel Scale

The numbers in parentheses in the left margin and the initials R.F. refer to the Rossi-Forel intensity scale.

I — Not felt—or, except rarely under especially favorable circumstances.
Under certain conditions, at and outside the boundary of the area in which a great shock is felt:
[I R.F.] sometimes birds, animals, reported uneasy or disturbed;
sometimes dizziness or nausea experienced;
sometimes trees, structures, liquids, bodies of water may sway–doors may swing very slowly.

II — Felt indoors by few, especially on upper floors or by sensitive or nervous persons.
Also, as in grade 1, but often more noticeably:
[I to II R.F.] sometimes hanging objects may swing especially when delicately suspended;
sometimes trees, structures liquids bodies of water may sway, doors may swing very slowly;
sometimes birds animals reported uneasy or disturbed;
sometimes dizziness or nausea experienced.

III — Felt indoors by several, motion usually rapid vibration.
Sometimes not recognized to be an earthquake at first.
[III R.F.] Duration estimated in some cases.
Vibration like that due to passing of light or lightly loaded trucks or heavy trucks some distance away.
Hanging objects may swing slightly.
Movements may be appreciable on upper levels of tall structures.
Rocked standing motor cars slightly.

IV — Felt indoors by many, outdoors by few.
Awakened few, especially light sleepers.
[IV to V R.F.] Frightened no one unless apprehensive from previous experience.
Vibration like that due to passing of light or lightly loaded trucks.
Sensation like heavy body striking building or falling of heavy objects inside.
Rattling of dishes, windows, doors; glassware, and crockery clink and clash.
Creaking of walls, frame, especially in the upper range of this grade.
Hanging objects swung in numerous instances.
Disturbed liquids in open vessels slightly.
Rocked standing motor cars noticeably.

V — Felt indoors by practically all, outdoors by many or most: outdoors direction estimated.
Awakened many or most.
[V to VI R.F.] Frightened few—slight excitement, a few ran outdoors.
Buildings trembled throughout.
Broke dishes, glassware to some extent.
Cracked windows—in some cases, but not generally.
Overturned vases, small or unstable objects, in many instances with occasional fall.
Hanging objects, doors swing generally or considerably.
Knocked pictures against walls or swung them out of place.
Opened or closed doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well-filled open containers.
Trees, bushes shaken slightly.

APPENDIX A (continued)

VI — Felt by all indoors and outdoors.
Frightened many, excitement general, some alarm, many ran outdoors.

[VI to VII R.F.] — Awakened all.
Persons made to move unsteadily.
Trees, bushes shaken slightly, moderately.
Liquid set in strong motion.
Small bells rang—church, chapel, school, etc.
Damage slight in poorly built buildings.
Fall of plaster in small amount.
Cracked plaster somewhat, especially fine cracks; chimneys in some instances.
Broke dishes, glassware in considerable quantity, also some windows.
Fall of knick-knacks, books, pictures.
Overturned furniture in many instances.
Moved furnishings of moderately heavy kind.

VII — Frightened all—general alarm all ran outdoors.
Some or many found it difficult to stand.

[VIII - R.F.] — Noticed by persons driving motor cars.
Trees and bushes shaken moderately to strongly.
Waves on ponds, lakes, and running water.
Water turbid from mud stirred up.
Incaving to some extent of sand or gravel stream banks.
Rang large church bells, etc.
Suspended objects made to quiver.

Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.
Cracked chimneys to considerable extent walls to some extent.
Fall of plaster in considerable to large amount, also some stucco.
Broke numerous windows, furniture to some extent.
Shook down loosened brickwork and tiles.
Broke weak chimneys at the roof-line (sometimes damaging roofs).
Fall of cornices from towers and high buildings.
Dislodged bricks and stones.
Overturned heavy furniture with damage from breaking.
Damage considerable to concrete irrigation ditches.

VIII — Fright general—alarm approaches panic.
Disturbed persons driving motor cars.

[VIII+ to IX - R.F.] — Trees shaken strongly—branches, trunks broken off, especially palm trees.
Ejected sand and mud in small amounts.
Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.
Damage slight in structures (brick) built especially to withstand earthquakes.
Considerable in ordinary substantial buildings, partial collapse, racked, tumbled down, wooden houses in some cases; threw off panel walls in frame structures, broke off decayed piling.
Fall of walls.
Cracked, broke, solid stone walls seriously.
Wet ground to some extent, also ground on steep slopes.
Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
Moved conspicuously, overturned, very heavy furniture.

APPENDIX A (continued)

IX — Panic general.
Cracked ground conspicuously.

[IX + R.F.] — Damage considerable in (masonry) structures built especially to withstand earthquakes:
threw out of plumb some wood-frame houses built especially to withstand earthquakes;
great in substantial (masonry) buildings, some collapse in large part;
or wholly shifted frame buildings off foundations, racked frames;
serious to reservoirs; underground pipes sometimes broken.

X — Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.

[X R.F.] — Landslides considerable from river banks and sleep coasts.
Shifted sand and mud horizontally on beaches and flat land.
Changed level of water in wells.
Threw water on banks of canals, lakes, rivers, etc.
Damage serious to dams dikes, embankments.
Severe to well-built wooden structures and bridges, some destroyed.
Developed dangerous cracks in excellent brick walls.
Destroyed most masonry and frame structures, also their foundations.
Bent railroad rails slightly.
Tore apart, or crushed endwise, pipe lines buried in earth.
Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI — Disturbances in ground many and widespread, varying with ground material.
Broad fissures, earth slumps, and land slips in soft wet ground.
Ejected water in large amount charged with sand and mud.
Caused sea-waves (tidal waves) of significant magnitude.
Damage severe to wood-frame structures, especially near shock centers.
Great to dams, dikes, embankments, often for long distances.
Few if any (masonry) structures remained standing.
Destroyed large well-built bridges by the wrecking of supporting piers or pillars.
Affected yielding wooden bridges less.
Bent railroad rails greatly, and thrust them endwise.
Put pipe lines buried in earth completely out of service.

XII — Damage total–practically all works of construction damaged or greatly destroyed.
Disturbances in ground great and varied, numerous shearing cracks.
Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.
Wrenched loose, tore off large rock masses.
Fault slips in firm rock with notable horizontal and vertical offset displacements.
Water channels, surface and underground, disturbed and modified greatly.
Dammed lakes, produced waterfalls, deflected rivers, etc.
Waves seen on ground surfaces (actually seen, probably, in some case).
Distorted lines of sight and level.
Threw objects upward into the air.

APPENDIX B

LOMA PRIETA EARTHQUAKE

Impact on Structures and Lifelines

The Division of Mines and Geology Special Publication 104 (McNutt and Sydnor, 1990) summarizes the geological, seismological, damage, and response aspects of the 17 October 1989 Loma Prieta earthquake.

The following summary of effects was abstracted from the ERRI Earthquake Spectra, May 1990, titled "Loma Prieta Earthquake Reconnaissance Report", by Carl Johnson of Johnson & Nielsen Associates.

Buildings

Unreinforced masonry (URM) buildings were damaged in and around Santa Cruz and as far away as San Francisco and Monterey. About 50 percent of the 2,000 URM buildings in the San Francisco area suffered damage which varied from minor architectural damage to major structural failures.

Many older houses suffered collapse of sub-floor structure and numerous two to four story residential structures in the Marina area were severely damaged due to liquefaction and earth shaking.

Most engineered buildings performed well. However, the short duration (10 seconds) of heavy shaking should not be considered a severe test.

Engineered hospital buildings throughout the area performed well and all acute care facilities continued to operate throughout the emergency. Emergency power generation at all acute hospitals performed properly; however, elevators were out of service from 10 minutes to 7 hours in 65 percent of hospital facilities.

There was only minor structural damage to some public school buildings. A preliminary survey of 1,544 public school buildings indicated $81 million in damage. The major damage occurred in the O'Connell High School in San Francisco, a 1920 converted manufacturing building, and the Central District Office Building in San Francisco, also an older building not subject to the same requirements as school buildings. Hazards from unbraced and unanchored non-structural items were evident in many school buildings.

State building facilities constructed under modern building code requirements performed well, but sustained varying degrees of non-structural damage.

Bridge Structures

There are approximately 1,500 bridges in the five counties affected by the Loma Prieta earthquake. More than 80 bridges suffered minor damage, 10 needed temporary supports and 10 were closed due to major structural damage. Three bridges suffered one or more collapsed spans. The cost to restore these structures to their pre-earthquake operational capacity is estimated at $1.8 to 2.0 billion. The greatest damage occurred to older structures on poor ground, such as the Cypress street viaduct in Oakland which collapsed catastrophically. This failure together with the failure of a link span between a pair of trusses on the San Francisco-Oakland Bay Bridge have been extensively described in numerous reports.

LIFELINES

Water Supply

No damage occurred to the aqueduct systems or to storage reservoirs in the eight county area. However, severe damage and failures to several storage tanks occurred in the Los Gatos-San Jose area, including an unanchored 100,000 gallon steel tank, a 700,000 gallon steel tank and a collapsed 10,000 gallon redwood tank. A 1,100,000 gallon post-tensioned concrete tank in the Los Altos Hills failed with a 4 inch wide rupture along a vertical joint. In San Lorenzo Valley, five redwood tanks were lost, ranging in size from 10,000 to 150,000 gallons.

There were approximately 350 water main leaks in the Central Bay area, mainly in cast iron pipe with a rigid bell and spigot joints. Longitudinal and circumferential breaks due to ground shaking and differential settlement were particularly prevalent in areas of liquefaction. Corrosion of pipe and fittings also caused some of these breaks. Numerous breaks in water mains occurred in other areas affected by the earthquake.

There was no reported damage to water treatment plants in the Central Bay area. However, mechanical failures due to water sloshing was reported in treatment plants in other areas.

Loss of water supply occurred in many areas with damaged water mains and where loss of power to pumping plants occurred, leaving some users without water supply for up to 2 weeks.

Waste Water

In the Central Bay area, severe liquefaction caused damage to sewer mains in a six block area of Alameda. Regional waste water treatment plants in San Francisco and Oakland had no major structural damage; however, loss of power

caused some short-time releases of sewage into the Pacific Ocean and San Francisco Bay. The Oakland plant lost power for two feeds for 7 hours. In San Francisco, damage included circumferential cracks in 84 and 96 inch outfall lines and leaks in a 66 inch pressurized concrete pipe. Losses of power demonstrated the need for emergency power supplies for pumping plants.

Several waste water treatment plants in the South Bay area performed well with no serious structural damage. Some miscellaneous damage to mechanical equipment did occur in numerous plants. Most plants had adequate emergency power to operate with the loss of commercial power.

In the Monterey Bay and Santa Cruz areas, treatment plants suffered only minor damage. Many breaks in sewer mains and secondary sewer lines occurred in low lying areas of liquefaction, unstable soils and high water table. In the Santa Cruz area, a joint separation in a 36 inch pipe force main required the installation of a by-pass line which diverted sewage into the Monterey Bay.

At the Santa Cruz regional waste water treatment plant (expanded in 1976 and 1989) 6 inch ductile iron pipe sheared off in several locations where the ground settled away from pile-supported buildings. There was a release of 800,000 gallons of raw sewage in Santa Cruz as a result of loss power from 30 to 35 hours to the pumping station. This area also had miscellaneous breaks in the 6 to 54 inch collection system. The treatment plant operated for 24 hours on an emergency generator.

Highways

State Highway 17 in Santa Cruz and Santa Clara counties sustained substantial damage during the earthquake, resulting in closures and delays for about 1 month while the highway was being repaired. Damage due to landslides, liquefaction,

rockfalls, roadway subsidence, cracked pavements, ground ruptures, retaining wall failures, etc., caused closures and delays for up to 2 days on numerous highways in the affected area.

Airports

At the San Francisco Airport, the control tower suffered considerable damage including falling ceiling panels, loss of one window, falling and sliding of equipment, etc. All navigational equipment was unaffected except for one antenna. Fuel storage tanks and piping systems were undamaged. Normal flight operations were suspended immediately after the earthquake due to disruption in the control tower. No serious damage occurred to the two sets of runways. The airport was officially re-opened on the morning of October 18, the day after the earthquake. In the North Terminal about 80 percent of the lightweight acoustical ceiling panels fell and sprinkler heads released extensive amounts of water in public areas. Commercial power was lost shortly after the earthquake and was restored 2 1/2 hours later. All but one of the 14 diesel generators used to provide emergency power started automatically. All elevators in the terminal shut down due to action of seismic switches. They were restored to service in about 2 hours.

The Oakland Airport has two runways and two FAA certified control towers, one at the commercial airport and the other at the adjacent general aviation airport. The main 10,000 runway is built on hydraulic fill from 5 to 10 feet thick. Three thousand feet at the north end of this main runway and the dike that borders the bay were severely damaged by liquefaction. Sand boils on and adjacent to the runway up to 40 feet in diameter appeared. The control tower for this runway lost three windows but continued to operate. Liquefaction caused damage to the crosswalk structure between terminals and also rupture of a 16 inch diameter water main which caused collapse of a service road. Airport officials shut down airport operations immediately after the earthquake to allow inspection of runway

damage. Flights were then diverted to the adjacent general aviation runway. In 1½ hours, flights were shifted back to the main runway which had been shortened to 7,000 feet. Communication problems occurred at this airport due to inadequate capacity of equipment. Commercial power was not lost.

The San Jose International Airport has three runways. The control tower lost one window and a number of objects fell and overturned. Apart from a few minutes of interruption for inspections of runways, airport operations were not disrupted. Commercial power was lost shortly after the earthquake and was restored after 5½ hours. The emergency generator started and operated as intended.

The Alameda Naval Air Station consists of an airport, port facilities and berthing facilities. There are two runways of 8,000 and 7,200 feet and a terminal building. A squadron of six helicopters is based at this station along with 20 other aircraft. Much of this station is built on fill, so there was substantial liquefaction at the site. Both runways were closed due to severe damage. Part of the terminal building was condemned due to structural damage. Water and gas distribution systems were damaged; however, there was no disruption of power. Helicopter pads remained operational and were used for emergency and relief operations. Four thousand feet of one runway was opened 10 days after the earthquake for emergency purposes using lightly loaded aircraft.

The Watsonville Airport has two lighted 4,000 foot runways, serving general aviation without a control tower. Power was lost shortly after the earthquake. The airport did not have emergency power. The only damage was to hangar doors which fell from their support rails. This airport was used to bring relief and emergency supplies and personnel into the area which was isolated because of the closure of highways and bridges due to earthquake damage

Communication Systems

Telephone equipment performed well in the intense shaking in the epicentral area and the moderate shaking experienced in most other areas. Most equipment problems were with emergency power generators. The saturation of the telephone system was very severe until midnight on the day of the quake. The emergency response community had difficulty using telephones during working hours for several days after the earthquake. In general, the public had difficulty getting a line to call 911 for service. Overall, the emergency communication system performed well. This good performance might be attributed in part to the moderate intensities of shaking experienced in high density areas. The major problem encountered was the saturation of the telephone system. There was a serious lack of emergency power in many areas and in some instances the emergency power was unreliable. Amateur radio emergency communication groups played an important role.

Electric Power Supply

Three major generating stations are the Moss Landing Power Plant (2000 MW) on Monterey Bay, the Potrero Power Plant (210 MW) on San Francisco Bay, and the Hunter's Point Plant (390 MW) also on San Francisco Bay. The Moss Landing Plant, about 18 miles (29 km) south of the earthquake epicenter sustained miscellaneous damage of about $5 million, not including switchyard damage. The other two generating plants suffered only minor damage. Damage to transmission substations had the most significant impact on the power system. Major damage occurred at the Metcalf, Moss Landing and San Mateo substations, while less damage was sustained at the Monte Vista and Newark substations. The types of damage were similar to that sustained in many previous earthquakes including live-tank circuit breakers, current transformers, disconnect switches, transfer buses, porcelain support columns, etc. Many aerial distribution lines were downed and thousands of fuses in distribution feeders were blown. Some pole mounted distribution transformers fell from their poles. Many poles in the

Santa Cruz Mountains were lost due to landslides. In the Marina district, two below ground transformer vaults floated to the surface and conduits were ruptured.

Natural Gas

The gas transmission supply lines and large-diameter distribution mains experienced only three leaks due to the earthquake. Unstable soil in the Marina District of San Francisco caused damage that resulted in replacement of approximately 10 miles (16 km) of cast iron and steel distribution mains with polyethylene plastic pipe. Three miles of distribution mains were replaced in Los Gatos and Watsonville. PG&E restored service to over 150,000 customers whose gas service had been turned off. Within a week, service was restored to all customers with undamaged piping.

Petroleum Refineries and Tank Farms

Most all major oil companies operate refineries north of San Francisco. Foundation materials at the various sites vary from rock outcrops to deep deposits of bay mud along bay shores. In general, damage at facilities was concentrated at locations of deep soils. Equipment located on bedrock performed well. Damage to refinery structural framing was generally due to lack of ductility and poor detailing of steel connections. In some instances it was due to lack of seismic bracing. There were no catastrophic failures in petroleum facilities and no fires were reported. There were many reports of tank damage, most of which was at soft-soil sites. This is not surprising in view of the great number of tanks associated with the various refineries (over 1,700). Damage typically occurred in tanks which were nearly full. Unanchored tanks with height/diameter ratios exceeding 0.5 were vulnerable. Buckles and tears in tank walls and breaks in piping connections caused oil leakage which was held within containment dikes.

Railways

Three rail-based transportation systems serve the area affected by the earthquake: 1) the Bay Area Rapid Transit (BART); 2) the San Francisco Municipal Railway (MUNI); and, 3) Caltrain. There was almost no earthquake damage to any of these rail systems. Some minor damage occurred in the transition structure between BART transbay tubes and the West Oakland Stations and at several stations in the East Bay. The transbay tubes suffered minor water seepage. In San Francisco, the most serious problem resulted from loss of power to stump pumps which remove water which enters the subway from an underground stream between the Powell Street and Civic Center stations. Immediately after the earthquake, power was lost in San Francisco to one of seven PG&E feeds that supply BART with traction power. All of MUNI's electric powered trolleys, cable cars and buses were unable to function because of loss of power. About 60 percent of this service was restored within 1 day. The Caltrain system uses the Southern Pacific tracks to provide commuter service between San Jose and San Francisco. There was no significant damage to this system. All service was restored within 5 hours after the earthquake, after mandatory inspections had been completed.

APPENDIX C

MAPS OF SEISMIC INTENSITY AND LIFELINES

MAP

S	Seismic Intensity Distribution
H-S	Hospitals and Public Schools
Hi	Highways
A-M	Airports and Marine
R	Railroads
E	Electrical Power
G	Natural Gas
W	Water Supply
WW	Waste Water
T	Telephone Communications
P	Petroleum