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NORTHRIDGE EARTHQUAKE: LIFELINE PERFORMANCE AND POST-EARTHQUAKE RESPONSE

Building and Fire Research Laboratory
Gaithersburg, MD 20899

United States Department of Commerce
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Abstract: The Northridge earthquake of January 17, 1994 produced the strongest ground motions ever instrumentally recorded in an urban setting in North America. This monograph describes the earthquake performance, emergency response, and recovery for the following lifeline systems: electric power, water, wastewater, communications, roads and bridges, railroads, ports, airports, gas, and liquid fuels. In addition, the impact of lifeline disruption on emergency response capabilities of hospitals and fire suppression elements of the emergency response community are discussed. For each lifeline damage, emergency response methods used to cope with damage and disruption, and the restoration and recovery processes are described. Implemented and proposed changes in equipment and facility design specifications, operating procedures, and emergency response plans are described. Each section summarize the lessons learned, makes recommendations to improve system earthquake response and identifies needed research.

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Technical Council on
Lifeline Earthquake Engineering,
American Society of Civil Engineers

Edited by Anshel J. Schiff

A report to:

U.S. Department of Commerce
Technology Administration
National Institute of Standards and Technology
Building and Fire Research Laboratory
Gaithersburg, MD 20899

April 1997

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William M. Daley, *Secretary*
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Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
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The work presented in this monograph was prepared by Dr. Anshel J. Schiff of Stanford University, with the inputs from twenty two experts in different lifeline systems, under the auspices of the Technical Council on Lifeline Earthquake Engineering (TCLEE), American Society of Civil Engineers (ASCE). Funding to support this follow-up study of the Northridge earthquake was provided by the National Institute of Standards and Technology.

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ABSTRACT

The Northridge earthquake of January 17, 1994 with estimated direct losses of about $20 billion, caused the greatest financial losses of any natural disaster in the US since 1906. It produced the strongest ground motions ever instrumentally recorded in an urban setting in North America. Casualties included 33 dead, more than 7000 injured, and over 20,000 left homeless. Most lifelines experienced some damage and disruption. The earthquake was especially disruptive to transportation and water systems and cause extensive damage to power systems.

This monograph describes the earthquake performance, emergency response, and recovery for the following lifeline systems: electric power, water, wastewater, communications, roads and bridges, railroads, ports, airports, gas, liquid fuels. In addition, the impact of lifeline disruption on emergency response capabilities of hospitals and fire suppression elements of the emergency response community are discussed. For each lifeline, damage, emergency response methods used to cope with damage and disruption, and the restoration and recovery processes are described. Implemented and proposed changes in equipment and facility design specifications, operating procedures, and emergency response plans are described. Each section summarize the lessons learned, makes recommendations to improve system earthquake response and identifies needed research.

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CONTRIBUTING AUTHORS

For each section the principal author is listed first followed by co-authors or contributing authors. In some cases, a sub-section within a section was authored by a different individual, in which case the subsection and author are indicated.

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Foreword
    Anshel J. Schiff
1. Introduction
    Anshel J. Schiff
2. Geoscience, Geotechnical, and Strong Motion Data
    Anshel J. Schiff
3. Power Systems
    Anshel J. Schiff, Ron Tognazzini, Dennis Ostrom
4. Water Systems
    LeVal Lund
    Tom Cooper (Water Tanks)
5. Wastewater Systems
    LeVal Lund
6. Communications
    Felix Wong, Alex Tang
7. Bridges and Roadways
    Mark Yashinsky
8. Railroads
    Curt Edwards
9. Ports
    Charles Farrar
10. Airports
    Anshel J. Schiff
11. Overview of Transpotation Systems
    Stephen Leung, Albert yee, Larry Wesemann
12. Gas Systems
    Tom D. O'Rourke, Richard W. Gailing, Douglas G. Honegger, Carl Strand
13. Liquid Fuel Systems
    Tom Cooper
14. Applications of New Technologies
    Ronald Eguchi, James D. Goltz, Hope A. Seligson
15. Hospitals with Emphasis on Lifelines
    Mark Pickett
16. Fire Department Emergency Response
    Carl Sepponen
17. Summary and Conclusions
    Anshel J. Schiff

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TABLE OF CONTENTS

1. INTRODUCTION

The Northridge earthquake (M_W 6.7) of January 17, 1994 with estimated direct losses of about $20 million, caused the greatest financial losses of any natural disaster in the US since 1906. It produced the strongest ground motions ever instrumentally recorded in an urban setting in North America (Science, 1994). Casualties included 33 dead as a direct result of the earthquake, more than 7000 injured treated at hospitals, and over 20,000 left homeless (1). The earthquake was very disruptive to transportation and water systems and cause extensive damage to power systems. Most lifelines experienced some damage and disruption.

SCOPE AND FOCUS

This monograph is the first of its kind published by TCLEE. In addition to data on the performance of lifeline equipment and facilities typically gathered immediately after an earthquake, follow up investigations have been conducted about one year after the earthquake to gather additional information about earthquake response and post-earthquake mitigation actions taken by utilities. Because of the timing of the follow-up investigation, information on buried lifelines is more complete, after action reports written by utilities are often available, and information on the post-earthquake response by utilities has been collected and evaluated. In addition, information on methods used to cope with damage and disruption are investigated so that emergency response procedures used to restore service are documented. Changes and proposed changes in facility or equipment design, equipment installation practices, operating practices, and emergency response plans have been investigated and discussed. In general, both the good and poor performance of equipment and installation practices are discussed.

This monograph is directed towards two types of audiences. The first is the general audience who is interested in lifelines and their earthquake performance. To address this audience, technical terms are defined and the impacts of equipment damage on system performance is described. The monograph is also directed to utility personnel. To meet the needs of this group, the description of damage, failure modes, and factors that may have contributed to the damage are discussed in detail so that the monograph will also be useful to the specialist.

ORGANIZATION OF REPORT

Section 2 reviews the seismological, geotechnical and strong motion data associated with the earthquake. Each of Sections 3 through 14 focus on an individual lifeline. In general, each of these sections contains an overall description of the lifeline, a description of facility and equipment damage, a description of the post-earthquake response and methods used to cope with damage and disruption, and the recovery. In addition, changes or proposed changes in equipment or facility design, equipment specifications, operating procedures, and emergency response plans resulting from the earthquake are discussed. Section 14 discusses the use of new technologies in this earthquake. Sections 15 and 16 review the response of hospitals and fire systems with an emphasis of the impact of lifeline disruption on their performance.

REFERENCES

1 "The Magnitude 6.7 Northridge, California Earthquake of 17 January 1994," Science, Vol. 266, 21 October, 1994, pp 389- 397.

2. SEISMOLOGICAL, GEOTECHNICAL, AND STRONG MOTION DATA

The descriptions in this section are drawn primarily from two sources (Science, 1994, and Todd, 1994) and contains excerpts from these documents.

SEISMOLOGICAL SETTING

The Northridge earthquake occurred at 4:30 a.m. local time on January 17, 1994. The epicenter was located at 34°12'N, 118°32'W, about 30 km west-northwest of downtown Los Angeles. The focal depth has been estimated at about 15-20 km. The National Earthquake Information Center has calculated the 20-s surface wave magnitude of the earthquake as 6.7 (M_S) and the USGS assigned it a seismic moment magnitude (M_W) of 6.7 . Strong shaking lasted about 15 seconds in the epicentral area.

The causative fault of the Northridge earthquake is part of a broad system of thrust faults that result from a 160-km left step in the Pacific-North American plate boundary at the Big Bend of the San Andreas fault. Figure 1.1 shows known faults and epicenters of earthquakes larger than M_L 6 between 1932 and 1993 in the region. The complex deformations resulting from the compression associated with movement around the Big Bend has generated many north-dipping and south-dipping subparallel faults, only some of which come to the surface.

The Northridge earthquake occurred at the intersection of several mapped faults. The causative fault does not extend to the surface and was not mapped before the earthquake. The earthquake began at the southeastern corner of its fault plane and ruptured up to the northwest for about 15 km. There is not evidence of the slip above a depth of 8 km. Had the rupture come closer to the earth's surface, the shaking might have been more severe in a limited area.

There were not immediate foreshocks. The aftershock zone averaged 22 events per year from 1981 to 1993 that were above M 1.7, which is typical of the dispersed background seismicity of the area. There were over 3000 aftershocks of $M > 1.5$

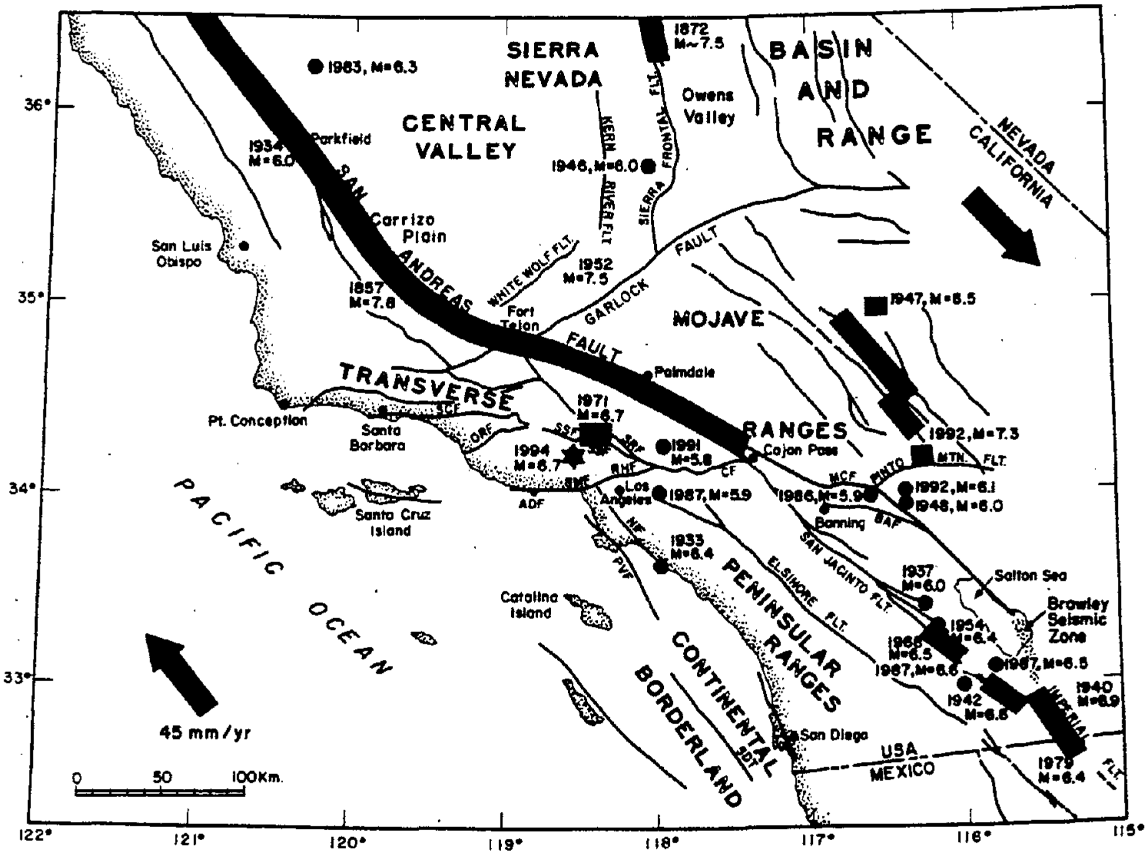

Fig. 1.1 Map of southern California showing major faults and epicenters. (Source: USGS)

recorded in the first three weeks after the earthquake. The largest aftershock (M 5.9) occurred one minute after the mainshock.

Elastic strain released by the earthquake measurably deformed the crust over 5000 km^2 surrounding the epicenter. The region was lifted up as much as 70 cm and displaced horizontally as much as 21 cm.

GEOTECHNICAL SETTING

No surface faulting was observed from the causal fault. This is in contract with the 1971 San Fernando earthquake, which was located near this event, that had 15 km of well defined surface faulting. There were broad zones of secondary surface ruptures observed that are not readily attributed to common modes of shaking-induced ground failure. They may in part be a response to tectonic deformation. These zones were concentrated near the epicenter, in Granada Hills just east of the inferred rupture surface, and along the north flank of the Santa Susana Mountains. Most of the surface displacements observed in natural ground in these areas are extensional and cumulative displacements across the fracture zone rarely exceeded a few tens of centimeters.

Displacements on the secondary ground ruptures are small, but the linear extent of these zones is comparable to what might be expected for a surface-faulting earthquake of similar magnitude. However, they did cause substantial damage in densely developed areas.

Liquefaction produced sand blows and other evidence of permanent ground deformation in alluvial deposits and filled land at several sites within 48 km of the epicenter. This deformation damaged pipelines, water supply channels, and flood control debris basins. However, the Northridge earthquake caused much less ground failure due to liquefaction than the 1971 San Fernando earthquake.

GROUND MOTION

The Northridge earthquake produced strong ground motion across a large part of the Los Angeles metropolitan area. More strong motion records were obtained within 25 km of the source than had been recorded in any other event (Science, 1994). The peak horizontal accelerations recorded were larger for its magnitude than other similar earthquakes. The vertical and horizontal ground accelerations and velocities were large, but the average peak accelerations are no more than one standard deviation above the mean of the data from other earthquakes. Directivity probably increased the ground motions in the area north of the epicenter. In the area estimated to have the largest ground motions for the fault geometry, a peak velocity of 170 cm/s was recorded, the largest ground velocity recorded to date. The time history and response spectra for this record are shown is Fig. 3.50.

Figure 1.2 shows the peak horizontal and vertical ground accelerations recorded at some instruments operated by the USGS's National Strong Motion Program. Table 1.1 show peak horizontal and vertical accelerations at selected sites in the range of 5 km to 38 km from the epicenter. Figure 1.3 shows examples of recorded ground velocities for stations in the area. Figure 1.4 shows a velocity contour map for the area.

REFERENCES

"The Magnitude 6.7 Northridge, California Earthquake of 17 January 1994," Science, Vol. 266, 21 October, 1994, pp 389- 397.

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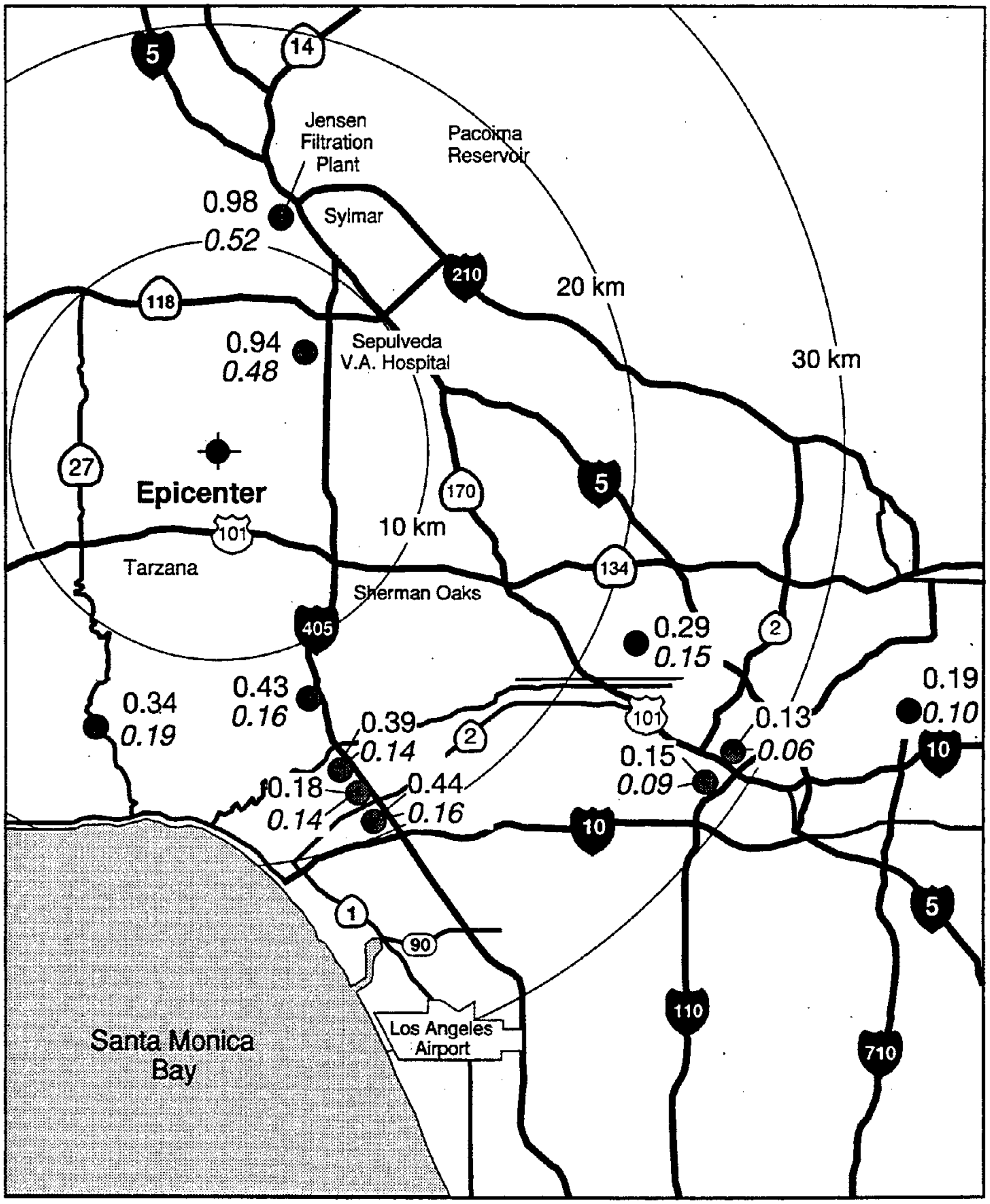


Source: USGS

Legend: ● 0.13 = Horizontal
0.06 = Vertical

Fig. 1.2 Peak horizontal and vertical ground accelerations recorded at selected sites operated by USGS's National Strong Motion Program. (Source: USGS)

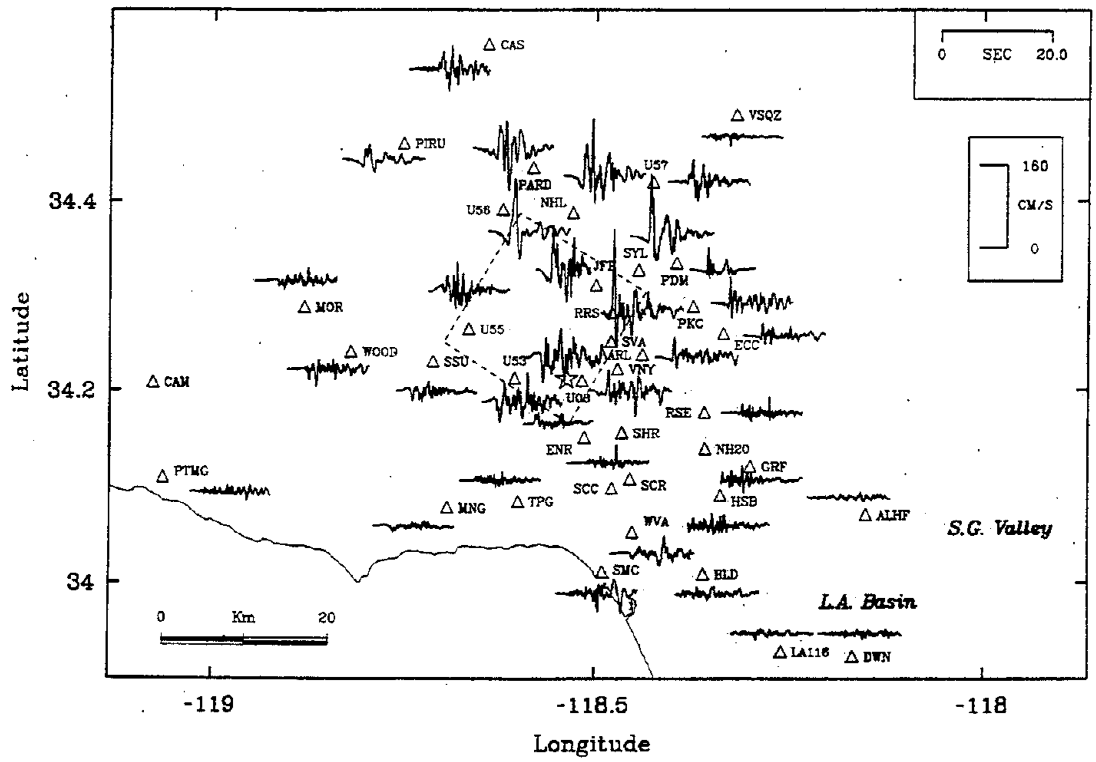

Recorded Ground Velocities

Fig. 1.3 Recorded ground velocities at selected sites. (Source: USGS)

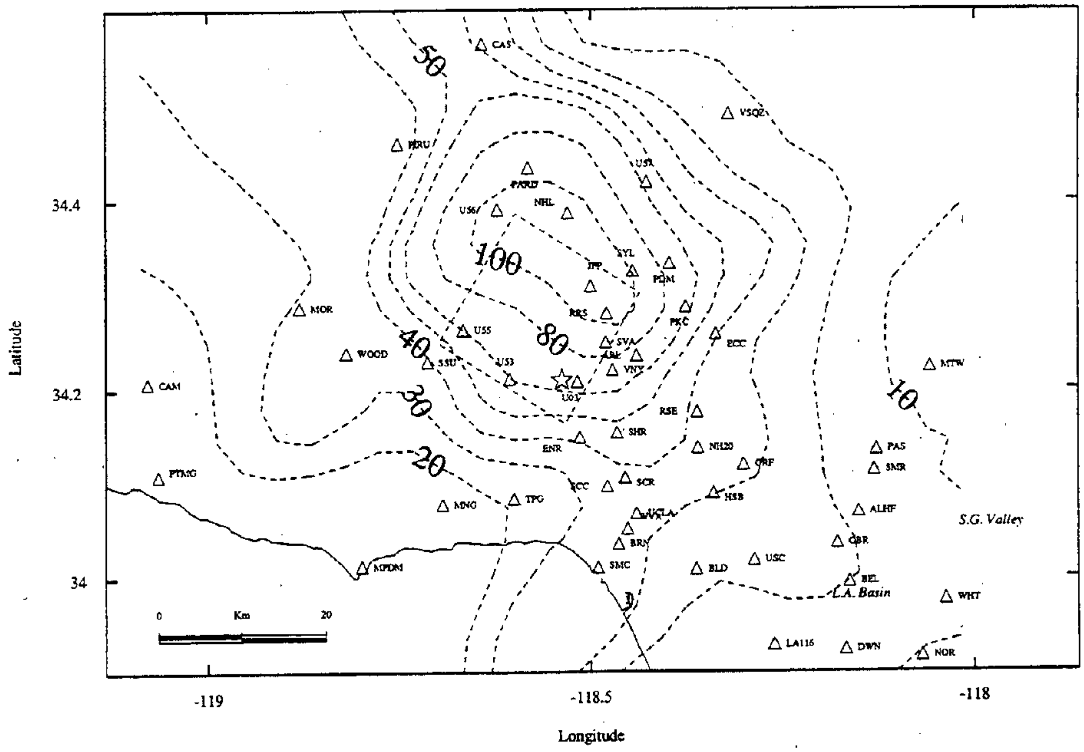

Recorded Ground Velocities

Fig. 1.3 Map showing ground velocities in the epicentral area. (Source: USGS)

Table 1.1 Peak Accelerations at Selected Sites From January 17, 1994

Location	**Epicentral Distance**	**Peak Accel. Horiz.**	**Vert.**
Los Angeles, 6301 Owensmouth Ave., Roof, 12 stories	5 km	0.48g	0.48g
Los Angeles, Sepulveda VA Hospital, Ground	7 km	0.94g	0.48g
Los Angeles, 5805 Sepulveda Blvd., Roof - 9 stories	7 km	0.76g	0.50g
Los Angeles, 16000 Ventura Blvd., Roof - 13 stories	8 km	0.41g	0.37g
Los Angeles, 15250 Ventura Blvd., Roof - 13 stories	8 km	0.61g	0.43g
Jensen Filter Plant, Administration Building, Basement	12 km	0.62g	0.40g
Jensen Filter Plant, Generator Building, Ground	12 km	0.98g	0.52g
Sepulveda Canyon, Spillway Building, Ground	14 km	0.43g	0.16g
Topanga, Fire Station, Ground	15 km	0.34g	0.19g
Los Angeles, Brentwood VA Hospital, Ground	18 km	0.29g	0.16g
Los Angeles, 10920 Wilshire Blvd., 19th Level	19 km	0.17g	0.24g
Los Angeles, 10751 Wilshire Blvd., Roof - 12 stories	19 km	0.40g	0.39g
Los Angeles, 10660 Wilshire Blvd., Roof - 19 stories	19 km	1.00g	0.51g
Los Angeles, Wadsworth VA Hosp., North Ground Site	19 km	0.26g	0.17g
Los Angeles, Wadsworth VA Hosp., South Ground Site	19 km	0.39g	0.14g
Los Angeles, 2029 Century Park East, 43rd Floor	20 km	0.32g	0.46g
Malibu Canyon, Monte Nido Fire Station, Ground	21 km	0.20g	0.17g
Los Angeles, 2121 Ave. of the Stars, Roof, 36 stories	21 km	0.43g	0.63g
Los Angeles, 1955 1/2 Purdue Ave., Basement	21 km	0.44g	0.16g
Los Angeles, 1955 1/2 Purdue Ave., First Level	21 km	0.50g	0.48g
Los Angeles, 1955 1/2 Purdue Ave., Third Level	21 km	0.63g	0.46g
Los Angeles, Griffith Observatory, Ground	24 km	0.29g	0.15g
Los Angeles, 1111 Sunset Blvd., Basement	31 km	0.13g	0.06g
Los Angeles, 1111 Sunset Blvd., 4th Floor	31 km	0.18g	0.09g
Los Angeles, 1111 Sunset Blvd., Roof - 8 stories	31 km	0.23g	0.16g
Lawndale, 15000 Aviation Blvd., Ground	38 km	0.18g	0.09g

Source: Porcella et al. 1994, USGS Open File Report 94-141

3. POWER SYSTEMS

ABSTRACT

Damage caused by the Northridge earthquake to high voltage equipment was generally consistent with that observed in other recent earthquakes. In this earthquake there was more damage to high voltage (230 kV and 500 kV) transformer bushings and damage to transmission-line tower foundations from liquefaction and on ridge shattering. This and other damage and the action of protective devices caused a loss of power to a large part of the greater Los Angeles area. The disruption of 1800 MW being exported to the Northwest also caused power disturbances in the Denver, Salt Lake City, Boise, and Seattle areas, with the longest disruption lasting about 3 hours. Power was 93% restored in 24 hours and 99.5% restored in 72 hours on an emergency basis. Total direct losses were $138 million to Los Angeles Department of Water and Power, and about $45 million to Southern California Edison. As a result of damage, changes were made to details in substation design, to bus configurations to improve power flow, to replace rigid bus with flexible bus and to provide more slack in conductors between equipment. More stringent interim equipment seismic specifications were adopted by one utility and expanded use of composite materials for transformer bushing, lightning arresters, and instrument transformers is planned.

INTRODUCTION

This chapter will summarize power system damage and describe some of the emergency operating procedures used to restore service. Based on observed damage, interim changes, and changes that are being considered to improve equipment and system performance are discussed below. Equipment and facilities that have been retrofitted will be identified as well as post-earthquake analyses and changes in response plans. Many of the emergency response actions have been used previously by several utilities although some were new to this earthquake. Many of these procedures have not been described in the literature. As each class of equipment is introduced, its damage or vulnerability will be identified, the impact of its damage will be discussed and emergency operating procedures, changes in specification and retrofitting will be described. It should be noted that practices and changes discussed below are not necessarily uniform among the utilities. The results presented are drawn from reports on power system damage that are still in the process of being prepared.

SYSTEM DESCRIPTION

The region impacted by the earthquake is served primarily by two large utilities, the Los Angeles Department of Water and Power (DWP) and Southern California Edison Company (SCE). Embedded in this large service area are a few much smaller municipal utilities that serve Pasadena, Burbank and Glendale. Figure 3.1 shows a schematic diagram of the DWP service area (none-shaded) with major substations and their general connectivity. The number of circuits and their voltages are not indicated.

The total generating capacity supplying the greater Los Anglese area is about 10,000 MW. Several large generating facilities are located away from the city with power carried into the area by the bulk power system. There were no generating facilities in areas of high ground motion. Most of the generating capacity near the city is located south of the epicenter and with more distant plants to the west and north. This total includes two generating stations owned by small municipalities.

Most of the bulk power is transmitted by Alternating Current (AC) circuits operating at 500 kV, 230 kV, or 220 kV, with a few circuits operating at 138 kV and other voltages. There are also two +/- 500 kV Direct Current (DC) circuits. Southern California Edison uses 220 kV circuits, but because the seismic performance of equipment operating at 230 kV and 220 kV is identical, both of these voltages will be referred to as 230 kV, the more commonly used voltage in the US.

The distribution systems of DWP and SCE are configured differently. The main distribution voltage of DWP is 34.5 kV which then supplies feeders at 4.8 kV. SCE has a more extensive sub-transmission system operating at 66 kV and feeders that operate between 4 kV and 33 kV with most at 12 kV and 16 kV.

NETWORK RESPONSE

After the blackouts in the northeast in 1964, the National Reliability Council established regional organizations to oversee the reliability of the nation's power grid. The Western Systems Coordinating Council (WSCC) of the National Reliability Councils (NRC) has jurisdiction of the power grid in the US west of Denver. The power grid in this area is a tightly integrated system. At the time of the earthquake about 1800 MW was being exported from Southern California to the Northwest over the AC and DC interties that link Southern California to Oregon and Washington State. At the time of the earthquake the Inter-mountain DC circuit was out of service for maintenance of the DC converter station at Sylmar East. As a result of the earthquake, the AC and DC interties were opened and the WSCC broke up into 3 islands. After the

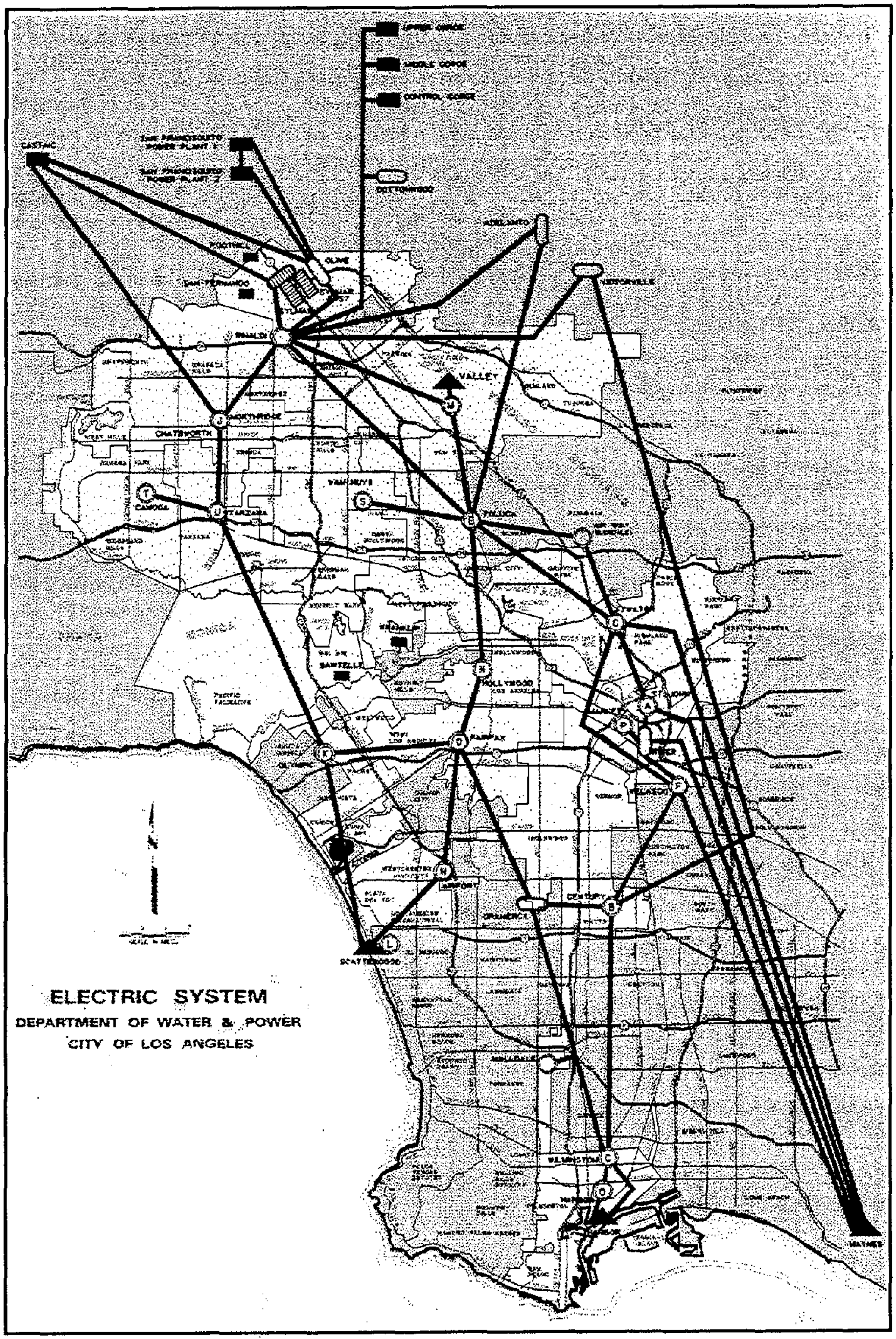


Fig.3.1 Schematic diagram of DWP power transmission system.

system breakup, the north island had more load than generation and this island's frequency started to drop. The Bonneville Power Administration (BPA) cut 688 MW of power to six direct service industrial customers for about an hour. Other Northwest utilities lost over 1200 MW of load following the earthquake. There were short-term outages in British Columbia, Montana, Wyoming, Idaho, Oregon, and Washington. The longest outage - which lasted about 3 hours - occurred in southern Idaho.

The long-term disruption of the DC intertie resulted in significant financial cost to BPA because of the need to purchase make up power that normally would have been transferred over the intertie.

OVERALL SYSTEM RESPONSE AND RECOVERY

In the greater Los Angeles area, the earthquake damaged several substations and a few transmission lines resulting in the loss of power to several areas. Several distribution lines were also damaged and this caused localized disruption to customers. As a result of the damage, there were major imbalances in supply and demand within the service area and large transient current flows that tripped protective devices incorporated into the network to protect equipment from damage associated with abnormal circuit conditions. As a result, a large area lost power.

Three conditions can contribute to power disruption other than direct damage to facilities. First, there can be large transient current flows associated with sudden changes in system configuration caused by damaged circuits or equipment. The resulting over-current or over- and under-voltage condition will cause system protective devices, such as circuit breakers, to open and isolate sensitive equipment like transformers. The imbalance in loads will cause generators to speed up or slow down changing the frequency in the network. In extreme cases, frequency load shedding relays will be tripped, and customers will be dropped temporarily in an attempt to prevent system collapse. Finally, large transformers are provided with devices to sense sudden changes in internal pressure. Transformers can develop an internal fault that generates gas and causes an increase in internal pressure. Since external over-current devices do not sense this problem, the change in pressure trips a relay that causes circuit breakers to isolate the transformer to prevent more extensive internal damage. Earthquake vibrations can also generate sudden changes in pressure that causes the transformer to be isolated. This results in power disruption. While each of these protective systems can cause disruption, they serve to prevent electrical damage to equipment that can be costly and very time consuming to repair and are needed for the safe operation of the system. This situation is not significantly different from the function of fuses or circuit breakers in the home. These devices may be activated when excessive load is put on a circuit, for example, if a hair dryer and an iron are operated at the same time. A circuit breaker will trip preventing the circuit from overheating and causing a fire.

When power is disrupted by an earthquake, substations that have the potential of being damaged are given a quick visual inspection for damage before equipment is re-energized. If the substation is unoccupied, as is frequently the case, service personnel must be dispatched to the substation to perform the inspections, and in some cases reset tripped devices. As a result, restoration may take several hours, even if there is no damage.

Figure 3.2 shows the DWP service area with the restoration times of major substations and their associated service areas. Power was restored to all substations on January 17th, except as noted. The restorations were associated with the inspections noted above, re-energizing circuits to the substation, or with the removal or bypassing of damaged equipment, which will be discussed below. As noted above, there may have been local outages within these areas due to damage to the distribution system. Not shown on this map in the Ventura plain, located west of the epicenter, that did not experience significant damage, but lost power for about 13 hours due to damage at a substation in the epicentral area. Figure 3.3 shows the percentage of customers with service retored as a function of time. Even with power restored, the system was relatively fragile, as much of the redundancy and reserve capacity designed into the system was reduced by system damage. The fact that the earthquake occurred in winter, when loads are much less than in summer reduced problems associated with limitations of the system.

SUMMARY OF EQUIPMENT PERFORMANCE

In each of the following sections the performance, the failure modes and the factors that may have contributed to the failures, and unresolved issues associated with each class of equipment will be discussed. The sections are ordered roughly on the basis of importance of the class of equipment to system performance, although this distinction has little meaning for the less important equipment. As each class of equipment is reviewed, emergency response procedures, changes in installation practices, seismic specifications and design practices are discussed. It should be noted that practices among the utilities vary and changes in practice as a result of the earthquake may not be used by all impacted utilities.

SUBSTATION TRANSFORMERS

Transformers are one of the most important items within the power network. Their function cannot be bypassed or eliminated. Substations frequently have two or more transformer banks, so that if one bank is taken out of service for maintenance, power is not totally disrupted. If single-phase transformers are used, a spare phase is often available at the site, and it may be pre-wired so that it can be put into service quickly. Transformers in this earthquake experienced problems with bushings, anchorage,

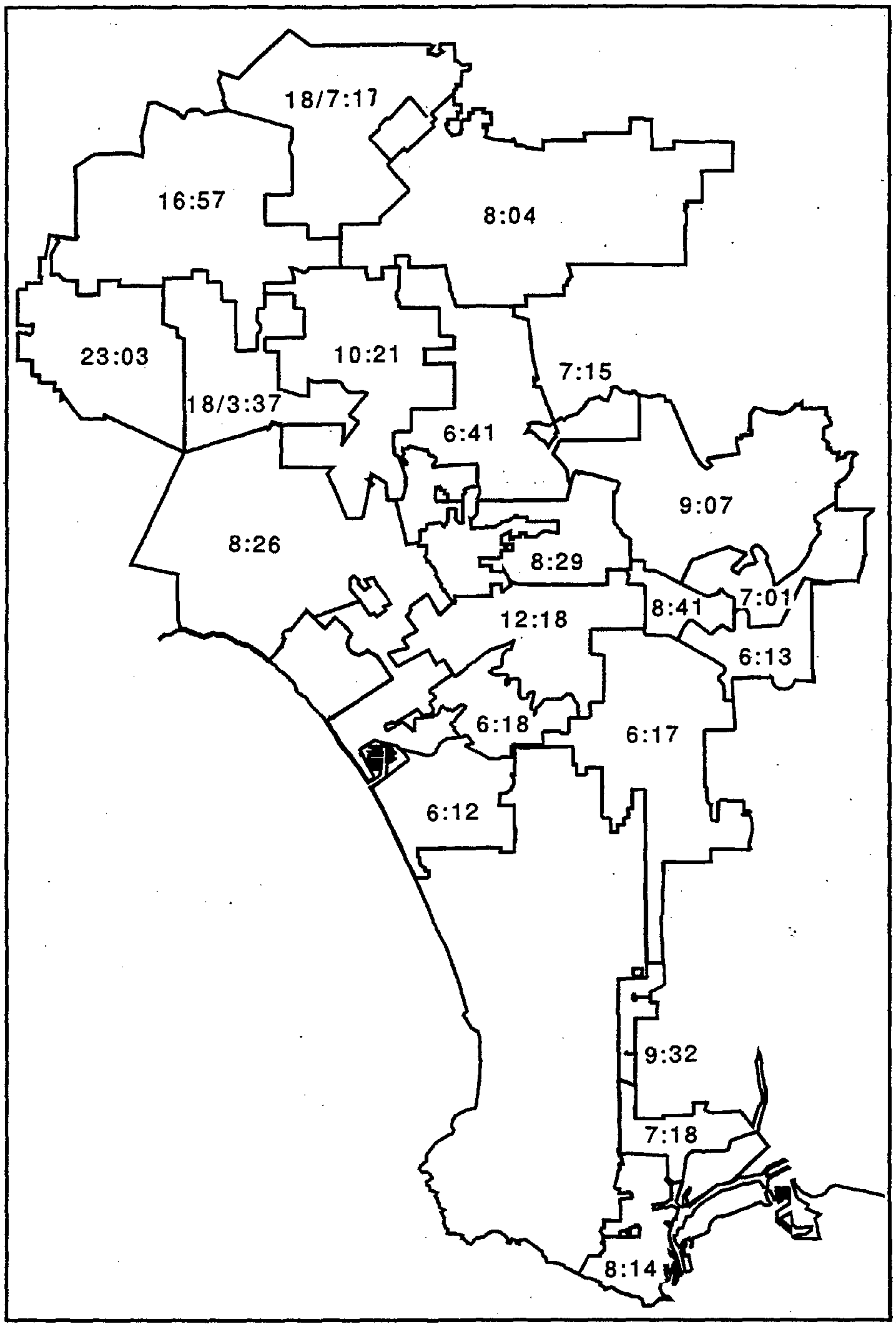


Fig. 3.3 Schematic diagram showing restoration times of power at major substations.

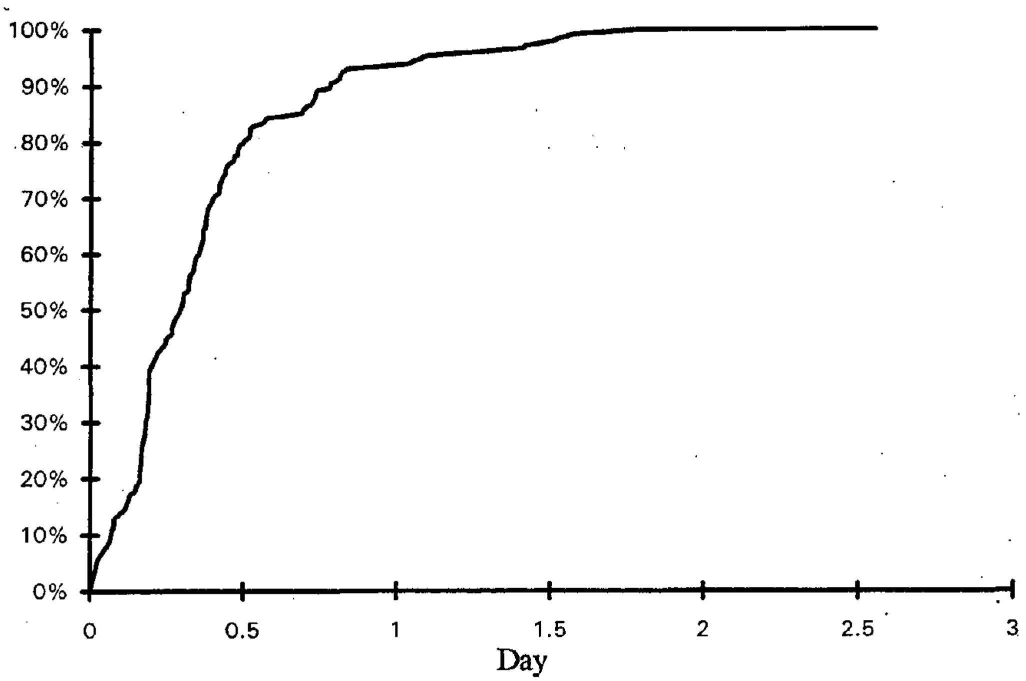


Fig. 3.3 Plot of the percent of customers with power restored as a function of time.

radiators, lightning arresters, and conservators. Grouped with transformers are some reactors which are constructed similar to transformers.

Bushings

Approximately forty-two bushings required maintenance or had to be replaced in the main event and seven others were damaged in an aftershock. Four transformer bushing failure modes were observed: cracked porcelain, shifting of upper porcelain relative to its mounting flange, damage to bushing support or turret, and internal degradation of bushing. Two 500 kV bushings experienced massive failures to porcelain, Figs. 3.4 and 3.5. These failures were probably due to large loads associated with the dynamic response of the bushing. The natural frequency of the bushing mounting, including the contribution of the turret, and the site motion may have contributed to the porcelain failure and oil leaks. Interaction loads with connecting conductors probably did not significantly contribute to these failures.

The second failure mode, which was much more common, was the rocking and slipping of the upper part of the transformer-bushing porcelain relative to its mounting flange, Fig. 3.6. In some cases the bushing re-seated itself and did not leak, but more often there was an offset and there were leaks at the interface between the porcelain and the flange. If the oil leak at the bushing is very small and the transformer is needed, it may be used with the leak until the units can be taken out of service and a repair made. Several factors contributed to these failures which were controlled by specific conditions at the transformer. Many failures were probably due to inertial loads imposed by the ground motion. In some cases, the flexibility of the turret, which

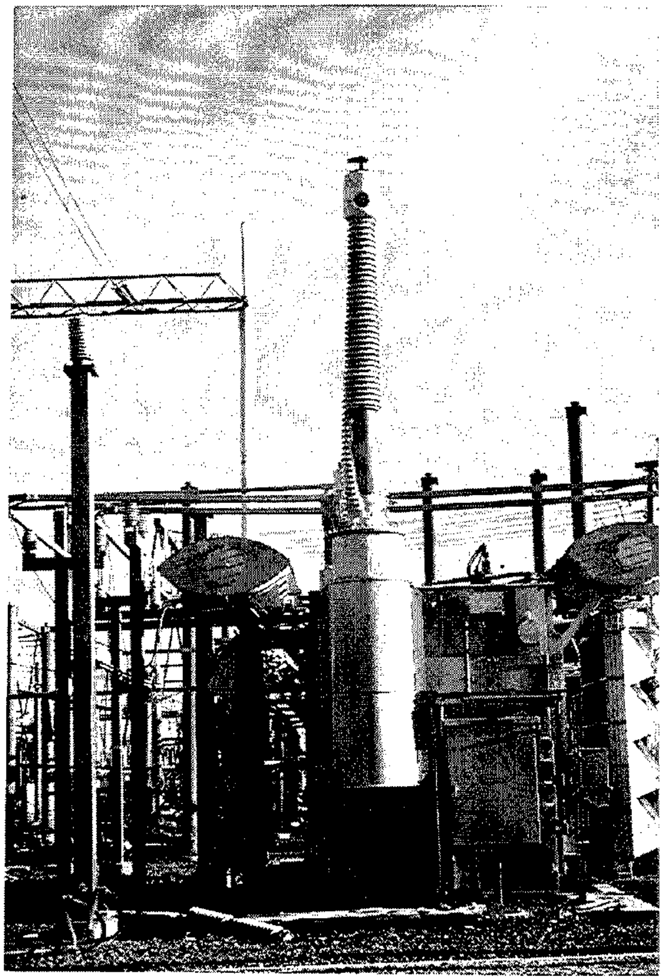


Fig. 3.4 Cracked 500 kV transformer bushing.

supports most bushings, probably contributed to the loads at the porcelain-flange interface. In some cases the failure of lightning arresters placed added loads on bushings and in one case bent the conductor binding post at the top of the bushing. (This will be commented on further in the Lightning Arresters Section.) In a few cases rocking of the transformer when anchor bolts stretched or the rocking of the transformer and its foundation due to soil-structure interaction probably increased bushing loads. The rocking of transformers also appears to have damaged bus supports on rigid low voltage bus were it is connected to the transformer's low voltage bushings. In a few cases, conductor interaction loads probably contributed to the bushing failures. There was one case where low voltage tertiary bushings failed due to interaction with rigid bus supported on tubular steel columns.

The third failure mode was the failure of the bushing support flange or turret. The failure of the flange support shown in Figs. 3.7 was probably due to a flaw in the casting, as this type of failure has not been observed before. The failure of the turret anchor bolts shown in Fig. 3.8 on a spare transformer was caused by the overload.

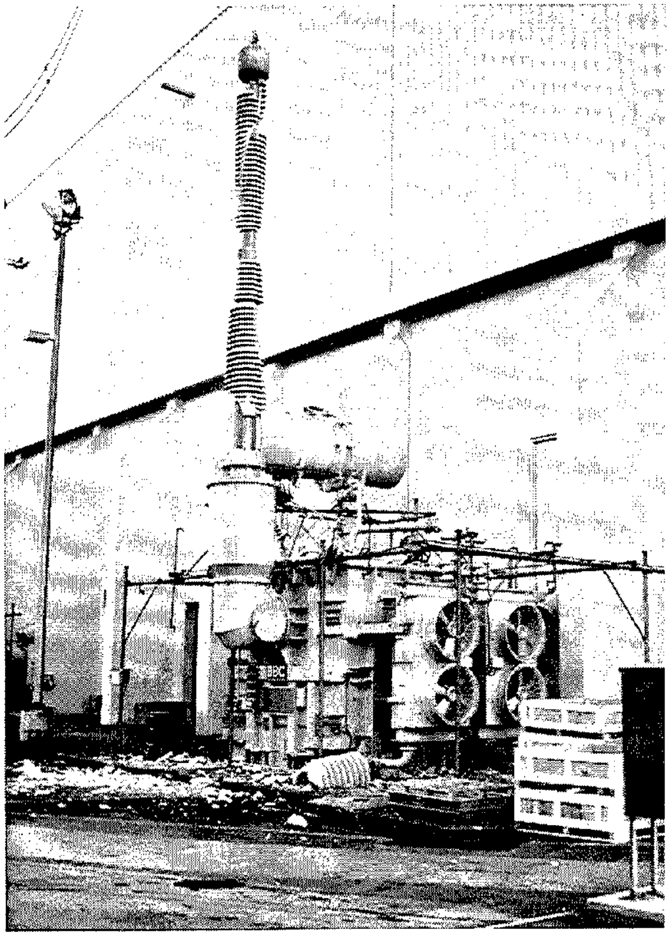


Fig. 3.5 Shattered reactor bushing.

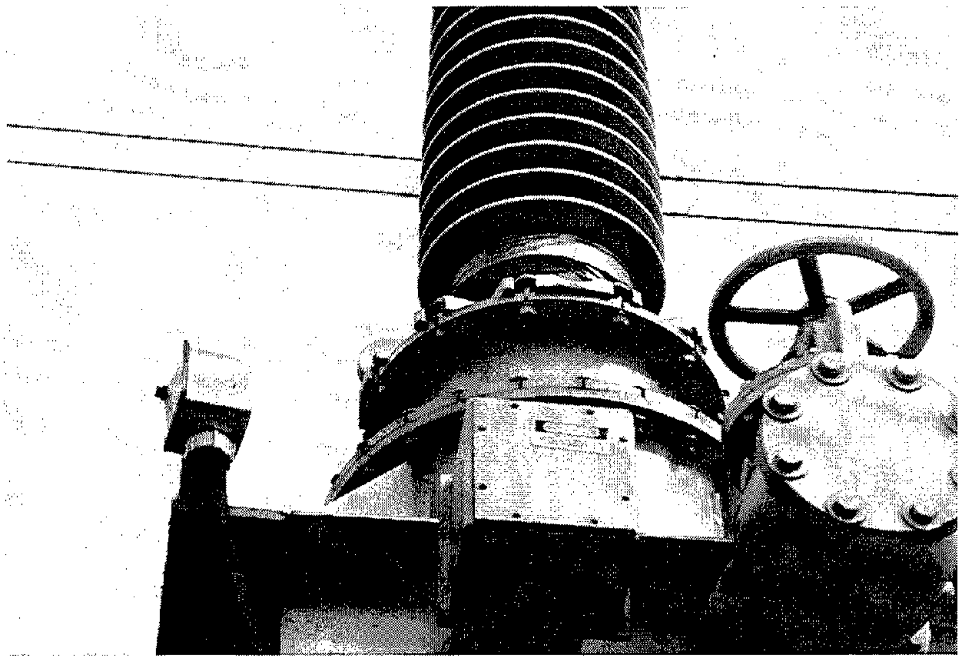


Fig. 3.6 Transformer bushing with porcelain slipped relative to its mounting flange.

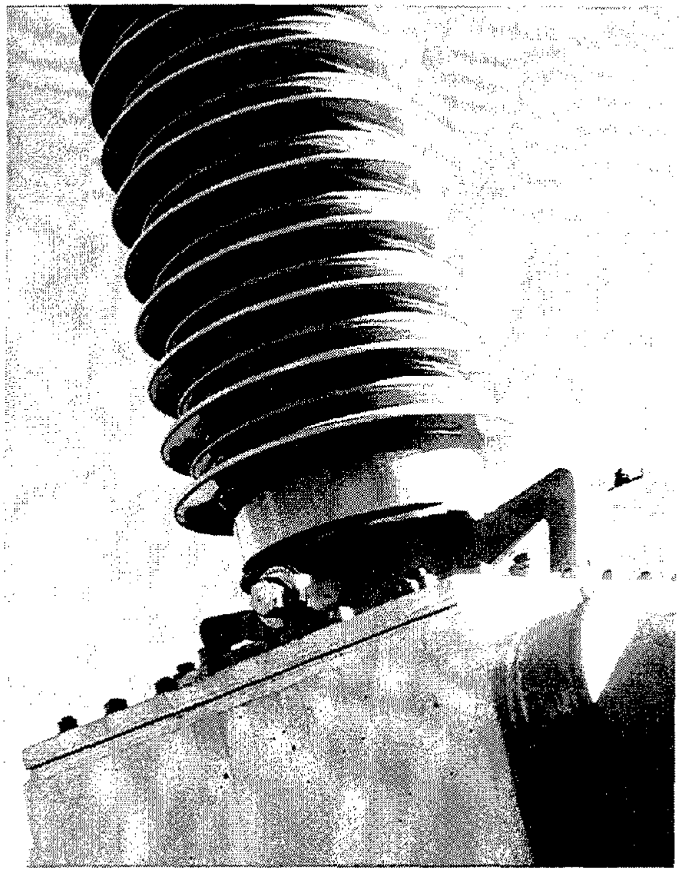


Fig.3.7 Fractured transformer bushing flange support.

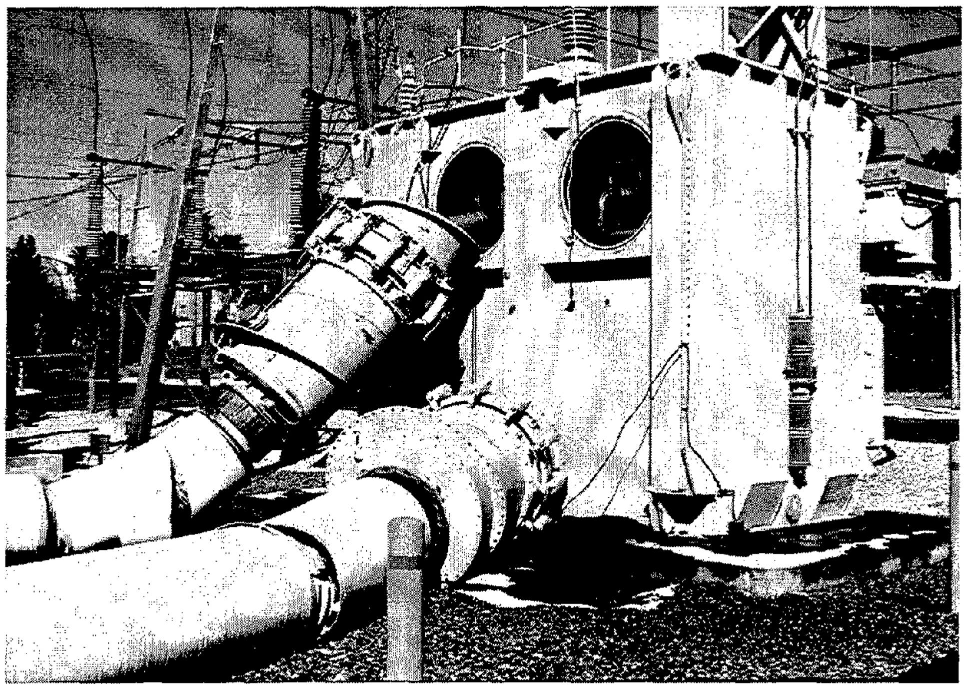


Fig.3.8 Bushing-turret mounting-bolts failed.

When installed, the turret is supported by the wall that the turret penetrates. The peak vertical acceleration recorded at this site was 0.83 g, well above the 0.5 g design value.

The forth failure mode is a delayed affect that is not well understood. In the weeks after the earthquake there appeared to be a degradation in the insulation between the bushing conductor and the flange so that eventually an arc developed causing the bushing to over heat and explode. This happened in two transformers and resulted in a transformer fire and a total loss of both transformers. Neither of these bushings were observed to have slipped relative to their mounting flange.

To repair a slipped bushing, it must be removed and restored at an appropriate maintenance facility, a lengthy process that can take about 6 weeks. To make a temporary repair to get the transformer back in service quickly, the oil around the base of the bushing is removed with a solvent and fast setting epoxy is applied to a thin wrap of linen around the porcelain-flange interface. If the leak persists, a vacuum line can be attached to the top of the bushing, and the cleaning and epoxy process repeated one or more times in an attempt to stop the leak. Bushings repaired in this way are then removed and restored when service conditions permit.

Because of potential problems observed in this earthquake associated with offset bushings, maintenance personnel now have bushing offset criteria, which, if exceeded, require that the bushing be removed for restoration. Prior to this time, if leaks could be stopped and the transformer was needed, it was kept in service. Because of the vulnerability of slipping at the porcelain-flange interface, some bushing manufacturers ship their bushings with retainer rings at the porcelain-flange interface. At one facility, this retainer ring was left on after the bushing was installed prior to the earthquake. This bushing survived the earthquake undamaged, while others at the site had slipped. The use of retainer rings as a retrofit is being used as a means to improve bushing performance; however, there are several technical issues associated with this retrofit. These issues include concern about contact stress concentration between the retainer ring and the bushing porcelain, effects of retainer ring corrosion, and distortion of the electric fields and resulting electrical stresses associated with the retainer ring. Because of their importance, some transformer bushings are in the process of being replaced with bushings made of composite material. A set of interim test requirements have been established which these bushings must satisfy that take into account system amplification and require an acceleration at the base of the turret of twice that of the ground design spectra. One of the difficulties in satisfying seismic specifications for transformer bushings is that they can not be tested on the transformer as an assembled unit, the preferred method of qualifying vulnerable equipment. This can not be done because of transformers' large size and weight - most transmission transformers weigh in excess of 500,000 pounds.

Each of the utilities in the area have transformer and bushing shops that can maintain and rebuild transformers and bushings. While the entire process of restoring bushings takes weeks, the availability of this in-house capability reduces shipping times and gives the utility direct control of repair priorities.

Anchorage

There were five types of transformer anchorage/support failures: welds to embedments failed, a weld tore the transformer case causing a leak, anchor bolts stretched and/or deformed, transformers and their foundation pads rocked, and two older transformers in storage at a site were inadequately anchored and tipped over, Fig. 3.9. Figure 3.10 shows one of two welds that failed at one end of a transformer. The transformer near the weld moved about 14 inches. The welds at the other end of the transformer did not fail. A mop that must have been near the transformer was found under the transformers so that the transformer must have lifted at least 1/2 inch off of the pad at the end with the failed weld. This is particularly interesting in that the heavy box-like construction of a transformer case suggests a very stiff structure that would not significantly deform. Several transformers that were bolted stretched their anchor bolts, Fig. 3.11. This 800,000 pound transformer had four-2" bolts along each side and one at each end. The bolts along one side stretched about 1/10", and due to the chair design experienced shear deformations of about 1/2". The motion and impact of the loose anchorage may have contributed to the slip in the transformer bushings.

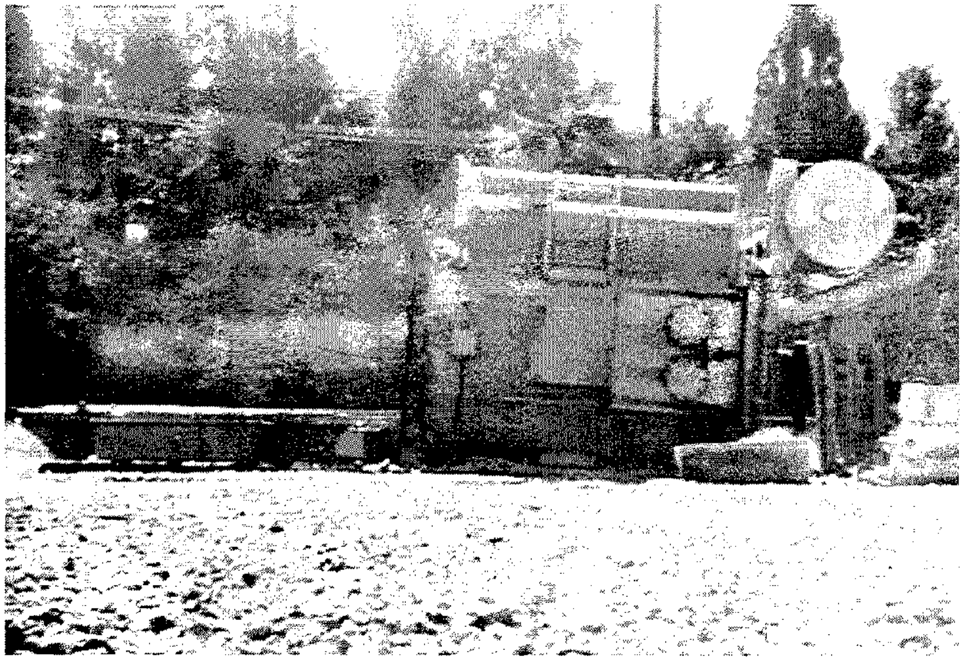


Fig. 3.9 Old spare transformer with inadequate anchorage tipped over.

The concrete around embedded plates in transformer pads at a low acceleration site (0.15 g) developed cracks. As a precautionary measure the anchorage has been strengthened. Most of the modifications to strengthen anchorage have connected the

Fig. 3.10 Transformer weld failed and transformer moved 14".

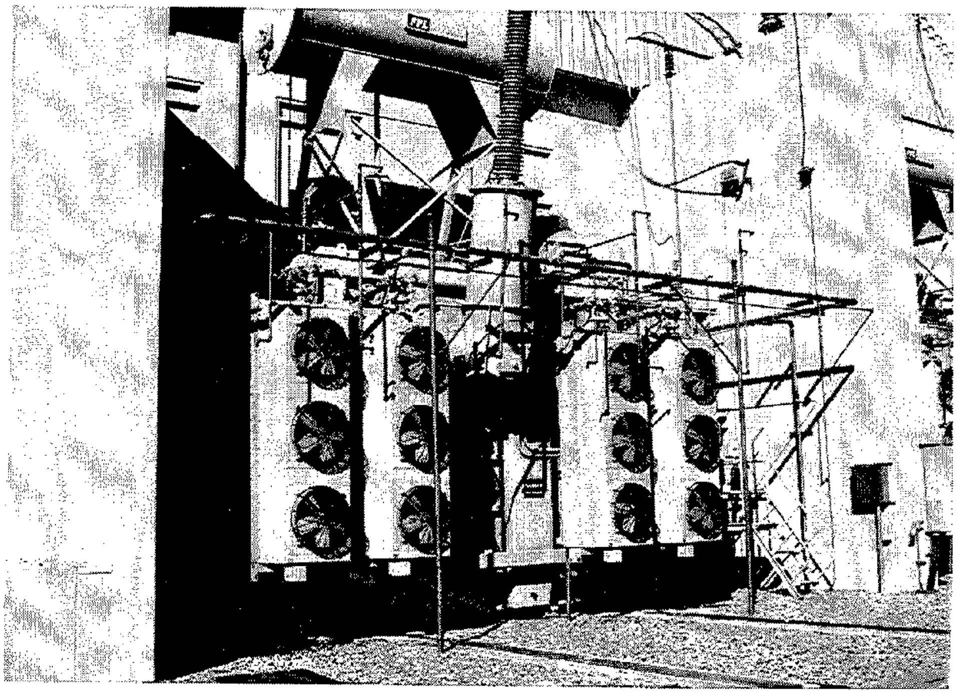


Fig. 3.11 Large transformer stretched and deformed its 2" anchor bolts.

new anchors to tabs used to move or ship the transformers. These tabs, incorporated into the original design by the transformer manufacturer, have the advantage that they are designed for large loads, however, they are often located several feet above the base of the transformer so that the transfer of the load to the pad is often inconvenient. The retrofit to the transformer shown in Fig. 3.10 is shown in Fig. 3.12. The base plate is held to the pad by four studs held with epoxy in holes in the pad. The base of the transformer is also welded to the anchor base plate. The original welds between the bottom of the transformer case and embedments in the foundation pad were also replaced with heavier welds. Figure 3.13 shows retrofits to transformer anchorage that showed signs of distress to ground motions of 0.15 g.

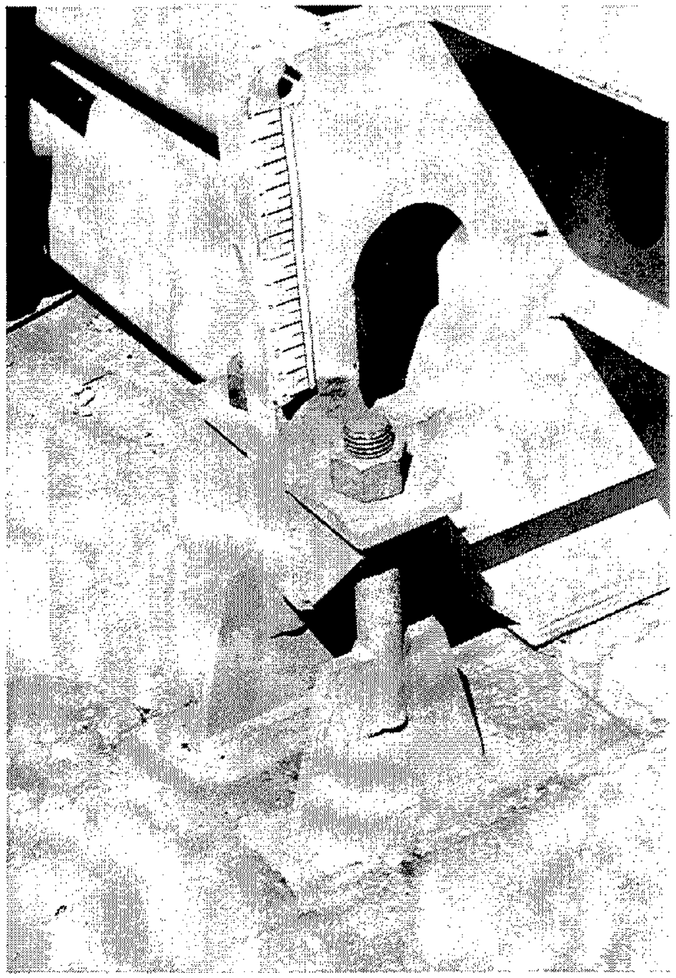


Fig.3.12 Retrofit anchor is connected to tap provided by manufacturer to move the transformer.

A few transformers appeared to have rocked back and forth with their foundation pads. In some cases, the transformers were tilted after the earthquake. In other cases, low voltage bus connections were broken, but the transformer was almost level after the earthquake. The approach to the problems introduced by soil-structure interaction causing the transformer and its pad to rock are still unresolved. These include the modification of low voltage connections so that they have more slack and the addition of piles that would be tied to the existing foundation pad.

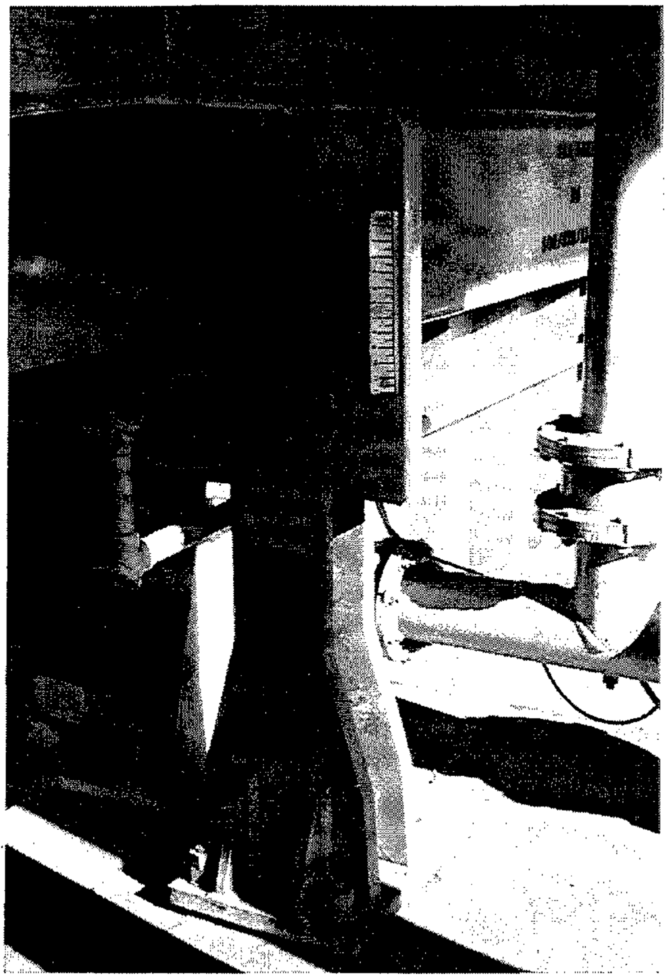


Fig.3.13 Distressed anchorage strengthened with linkage to existing tab.

Radiators

Transformer radiator damage in this earthquake included: a manifold-supported radiator that leaked at its upper piping connection, large single-element radiators that developed cracks in piping near the radiator-transformer body connection, and an independently supported radiator that failed its upper connection to the transformer.

In past earthquakes, unbraced, manifold-mounted radiators have developed leaks in the piping system, usually at the upper flange connecting the radiator to the transformer body. These leaks have usually been stopped by tightening the flange bolts, but flanges can be deformed sufficiently so that bolt tightening does not stop the leak. In this earthquake a rubber-like boot was placed around a leaking transformer-radiator connection to contain the leak, so that the transformer could be quickly returned to service, Fig. 3.14. This was an innovative use of a transmission-line splice shroud, normally used by line crews. It consists of a plastic sheet that is wrapped around the

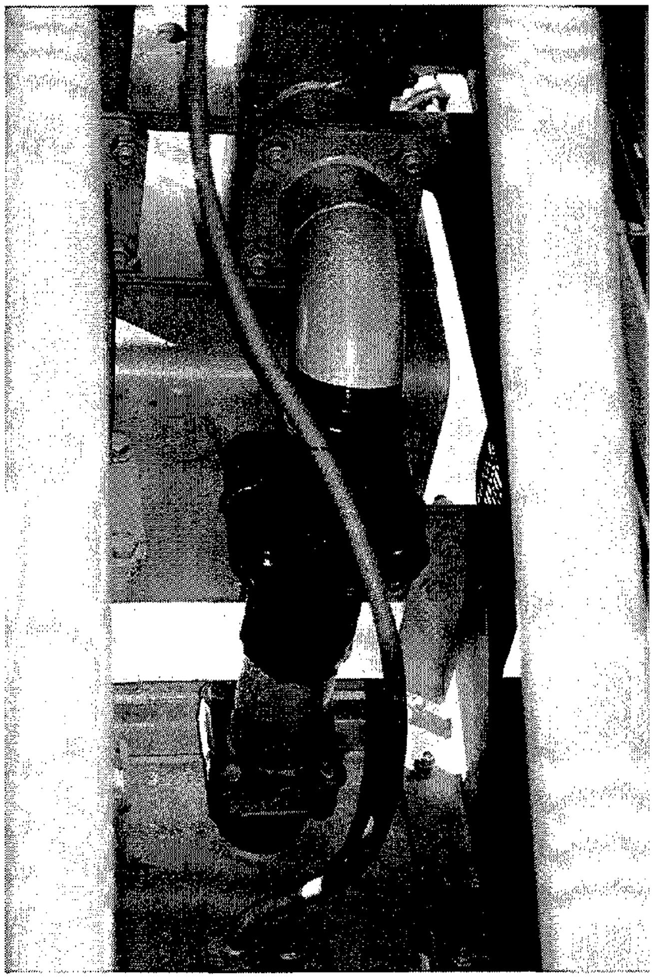


Fig. 3.14 Transmission-line splice shroud used to stop leaking transformer radiator connection.

pipe coupling. A metal strip joins and seals the longitudinal edges, a heat gun shrinks the material around the pipe and tape seals the ends where the pipe leaves the shroud. The use of this technique can avoid disruption, as it allows a transformer with damage that would normally require that it be shut down to continue to operate.

In this earthquake, large, single-element radiators caused some pipes to crack where they are connected to the transformer body. This occurred at a site with a peak ground acceleration of only 0.15 g. These radiators have been retrofitted by adding bracing at the top and bottom to increase lateral stiffness of the radiators and diagonal braces from the top of the transformer to the radiators to improve vertical support, Fig. 3.15.

Substations located adjacent to residential areas often have acoustical enclosures for transformers. When this is done, the radiators are typically located outside of the enclosure and are self-supported, Fig. 3.16. In one case, the motion of the radiator

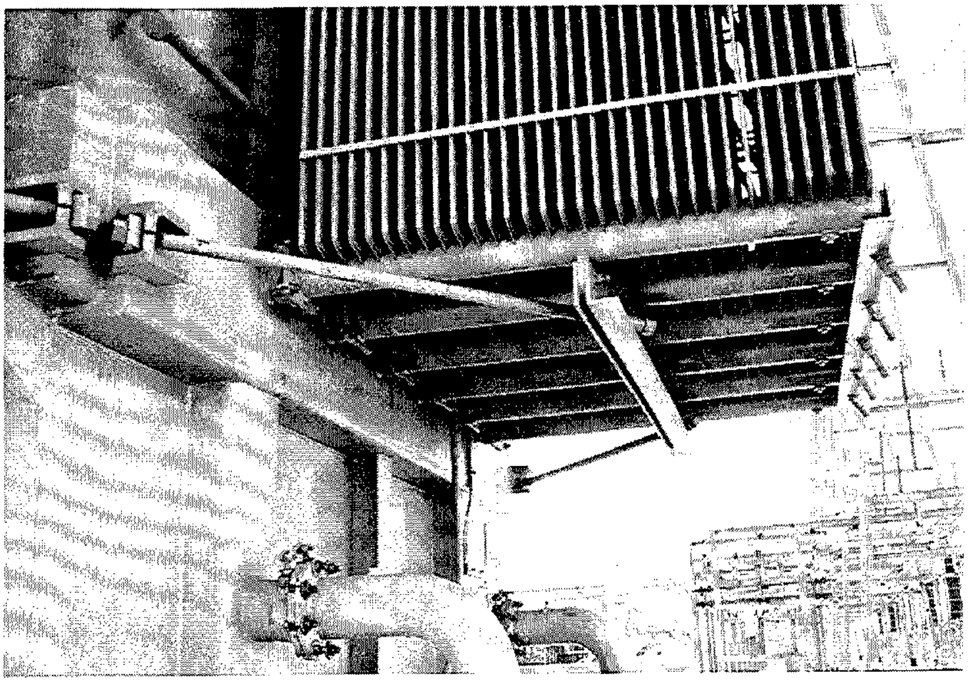


Fig. 3.15 Diagonal bracing added to radiators to reduce moments on pipe connections.

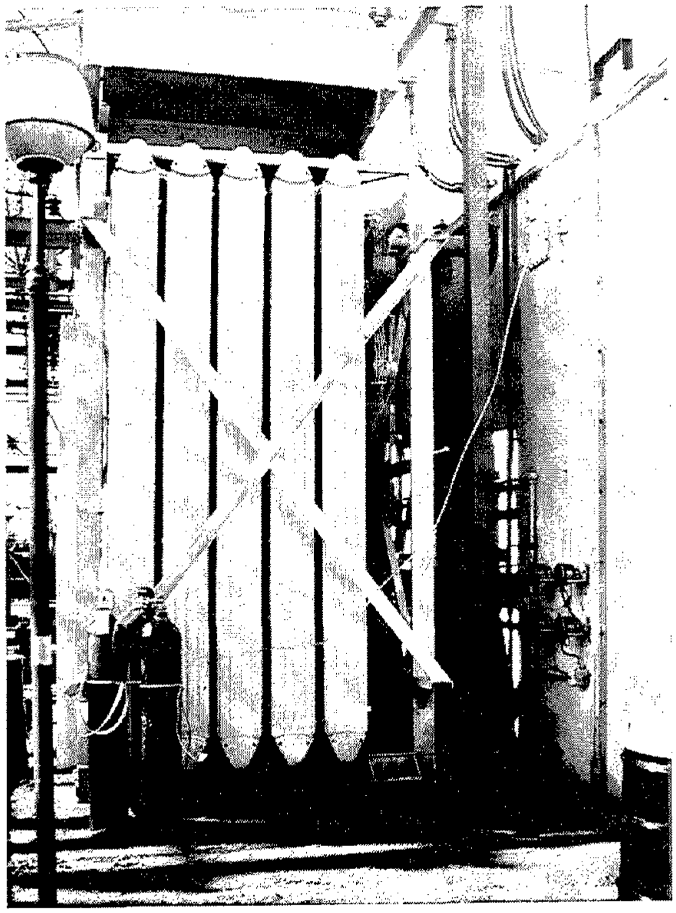


Fig. 3.16 Self-supporting radiator outside of acoustical transformer enclosure.

relative to the transformer caused the Dresser coupling between the transformer case and the top of the radiator to fail.

Lightning Arresters

To protect transformers from surges in voltage, lightning or surge arresters are located near the high and low voltage bushings. A arrester is typically supported in one of three ways: supported on its own support column, supported on a simple frame along with the lightning arresters for the other two phases, or supported on the transformer. Transformer supported lightning arresters can be supported on a boom connected to the transformer, on the top of the transformer case, or on a transformer radiator.

There are four types of anchorage detail used to connect the lightning arrester to its support. It can be mounted directly to its support structure, or it can be supported on standoffs. Standoffs are used in conjunction with strike counters that indicate the number of lightning arrester operations. There are several different standoff designs. The most frequently used standoff is fabricated from porcelain with a stud protruding from its top and bottom. In this type, loads must be carried by the porcelain. A newer design uses a porcelain bushing to insulate the anchor bolt from the lightning arrester. In this design, the tensile loads are carried by the bolt and the porcelain is subjected primarily to compressive loads. The third type of standoff is a tubular member that is part of the lighting arrester.

Lightning arresters have two failure modes: the standoffs fail or the body of the lightning arrester fails at the lower porcelain-flange interface. Figure 3.17 show the A and C phases failed in the body of the lightning arrester and the B phase failed at the standoffs. Lightning arresters are one of the most vulnerable items in a substation. Boom-supported and frame-supported units are the most vulnerable and the amplification of the support structure probably contributes to their failure. In many situations, interaction loads from conductors contribute to the failure. About half of the failures are in the standoffs and half in the body of the lightning arrester.

As noted below, lightning arresters can be removed and the system can continue to operate. The failure of the lightning arresters could have a serious impact, however. Some lightning arresters are positioned near the bushing so that if it failed, it could hit and damage the bushing. There are two ways to connect the lightning arrester to the system: a conductor directly to the bushing, or a conductor to the conductor connected to the bushing. Figure 3.18 shows the A and C phase lightning arresters connected to the bushing conductor and the B phase connected directly to the bushing. This was done because of lack of clearance due to the orientation of the overhead conductors. When the lightning arrester is connected directly to the bushings, it will have a tendency to fall towards the bushing if it fails. Even if it does not strike the bushing, the impact of the falling lightning arrester can damage the bushing conductor mounting hardware, Fig. 3.19.

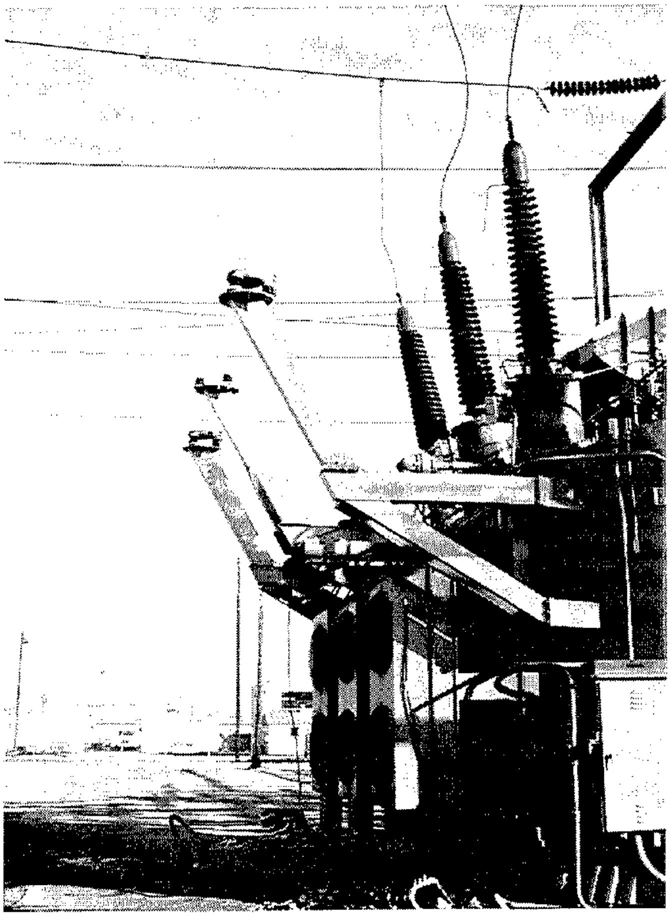


Fig. 3.17 Lightning arresters were supported on boom off of transformer failed at standoff or body of lightning arrester.

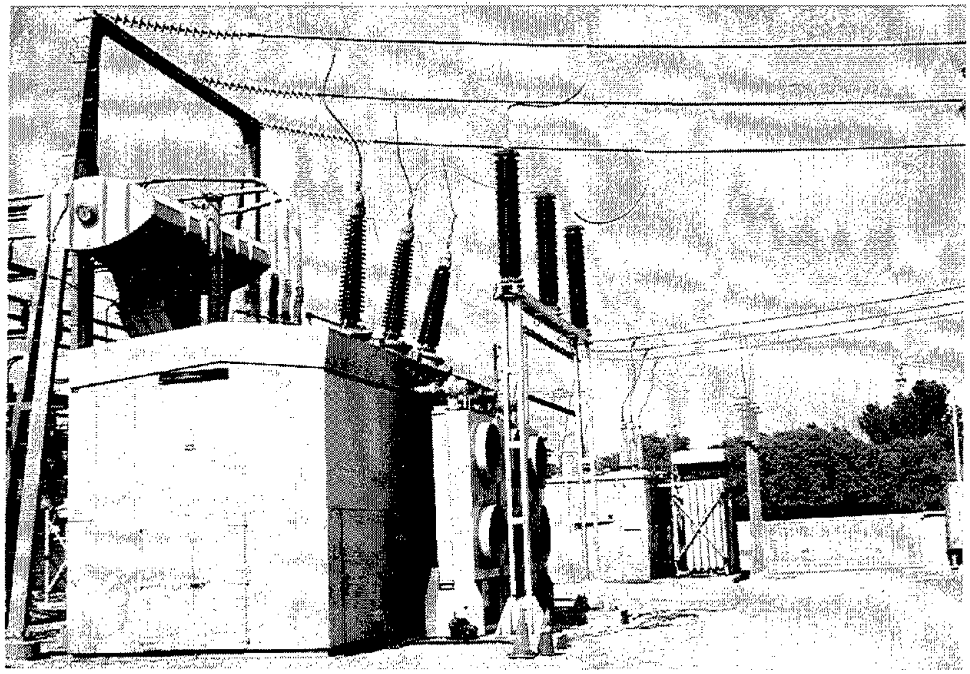


Fig.3.18 Lightning arresters can be connected to bushing or to bushing conductor.

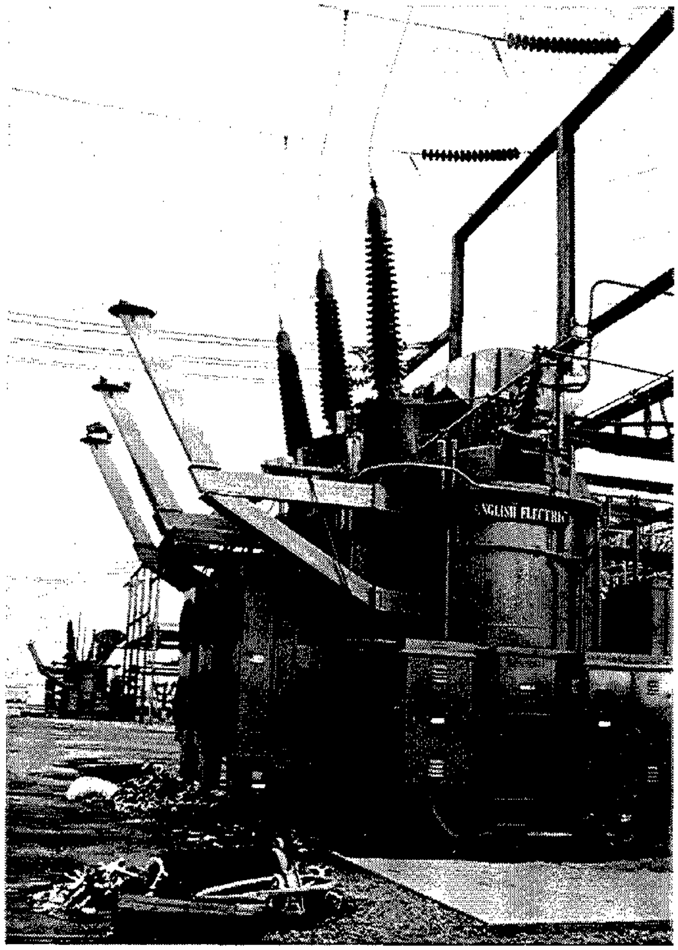


Fig. 3.19 The bushings mounting post was bent when lightning arrester failed, fell, and conductor pulled on post.

Damaged lightning arresters are typically cut from the line and the transformer put back into service without the lightning arrester. In California, lightning storms are relatively rare. In regions with frequent thunder storms, utilities may not take the risk of operating without lightning arresters.

The conductor to the lighting arrester does not have to be as large as the circuit conductor. To reduce the potential of a falling lightning arrester damaging a bushing, relatively thin conductor is being used with the intent that it will break and limit the loads applied to the bushing. Specifications now call for more slack in conductors. In many situations, strike counters are no longer used, so that standoffs are not needed. In this case the standoffs will be removed. Where standoffs are required, the bolt-through type will be used. Recently, high voltage lightning arresters made of composite material have become available, and these will be used in new construction.

Conservators

Conservators are large tanks located above the radiators that accommodate the change in oil volume with transformer temperature. In this earthquake one of the two structural supports of a conservator failed, but there was no leak and the tank did not fall. On another transformer, the motion of the conservator relative to the body of the transformer deformed a pipe flange that created a leak that drained the 1000 gallons of oil it contained in the conservator.

Other Transformer Damage

At one site with moderate ground motion, welds used to fabricate the transformer case cracked, causing a minor, but persistent leak, Fig 3.20. The leak was stopped by using a center punch to make indentations on each side and adjacent and parallel to the crack moving metal to close the crack.

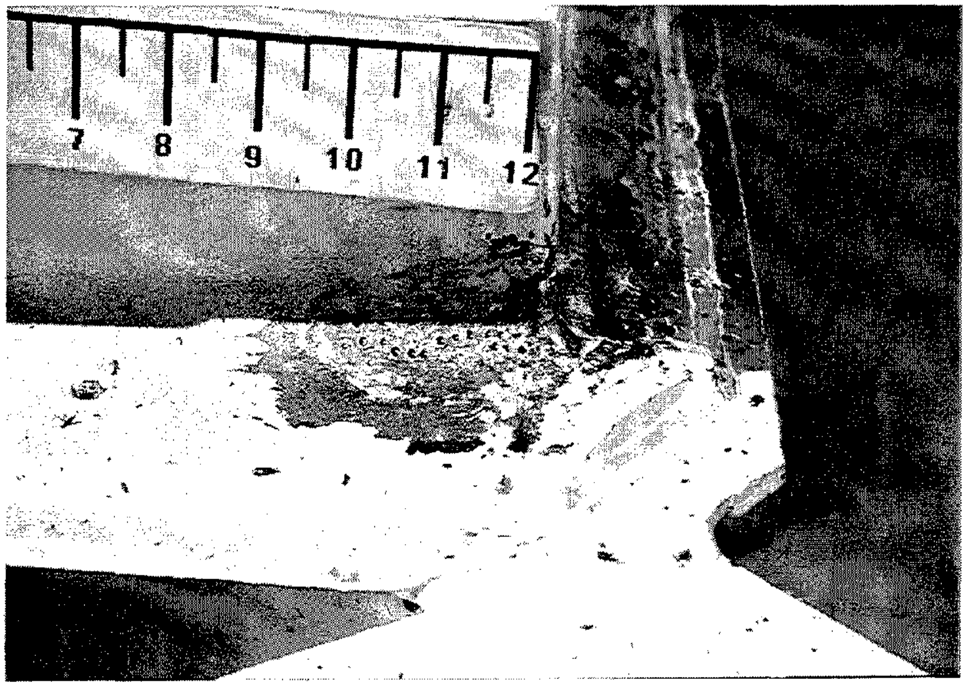


Fig. 3.20 Earthquake induced stress caused a weld to crack and leak oil.

CIRCUIT BREAKERS

Circuit breakers provide the important function of opening a loaded circuit. They are designed to operate even when there are large short circuit currents, and are thus needed for the safe operation of the system. Disconnect switches and circuit switchers can not operate under these conditions. There are two types of circuit breakers, live-tank breakers, in which the interrupting mechanism is contained in a tank at line voltage, and dead-tank breakers, in which the tank containing the interrupter mechanism is at ground potential. Live-tank breakers have their interrupter heads supported on porcelain columns and tend to be very vulnerable in earthquakes.

Most of the DWP live-tank circuit breakers were severely damaged in the 1971 San Fernando earthquake, and units in the AC switchyards were replaced with dead-tank breakers. None of the dead-tank breakers failed in this or any other US earthquake.

The performance of older live-tank breakers in this earthquake was consistent with past performance. That is, these units failed when subjected to moderate earthquake motions and were damaged or failed in small ground motions. Two designs were severely damaged by ground motions with a peak acceleration of 0.56 g, Figs. 3.21 and 3.22. The units shown in the right side of Fig. 3.22 are of the design that failed.

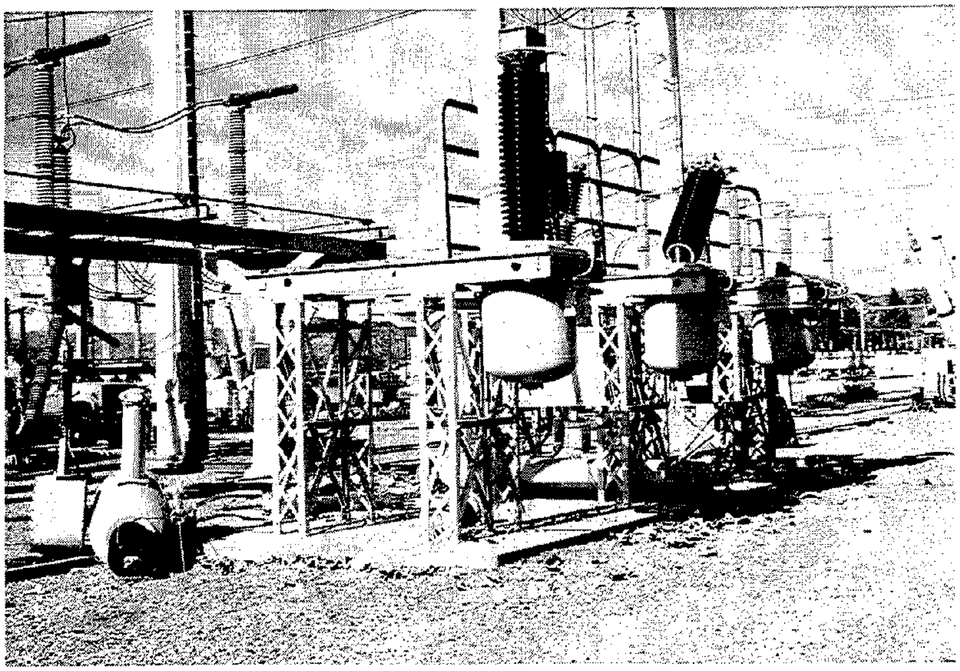


Fig. 3.21 Life-tank circuit breakers support the heavy interrupter head on a porcelain column that frequently fails.

At another site with a peak ground acceleration of 0.15 g, one of 3 units of a particular design had blown gaskets that developed a leak, Fig. 3.23. Based on this data and that observed in other earthquakes, the relative motion between interrupter heads can cause the gaskets to blow before the columns fail.

A review of the damage patterns suggests that circuit breaker failures were due to inertial loads. Loads associated with interaction through conductors probably did not contribute to the damage.

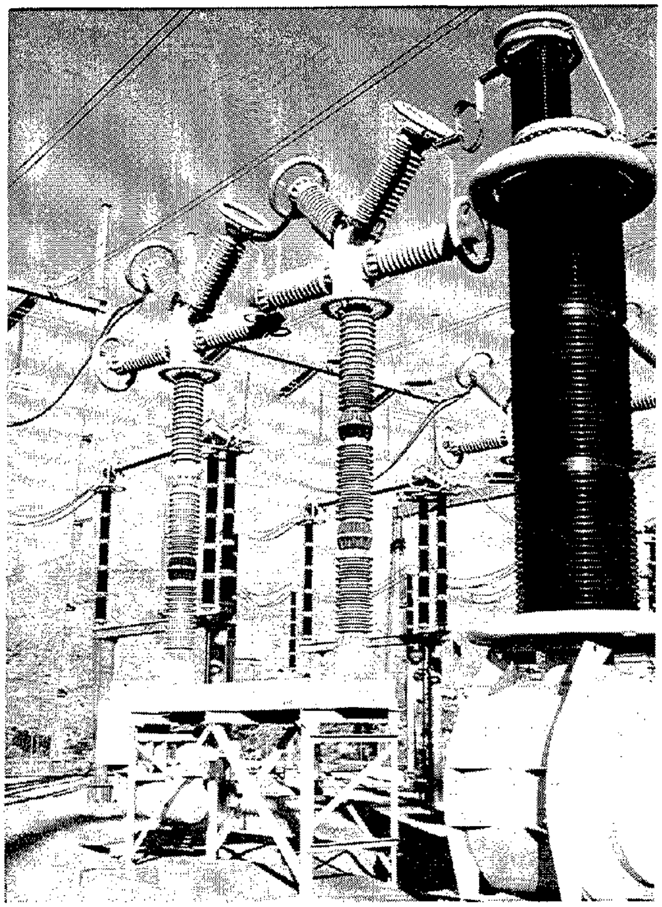


Fig.3.22 Leaking live-tank column gasket will cause a loss of pressure that will prevent the circuit breaker from operating.

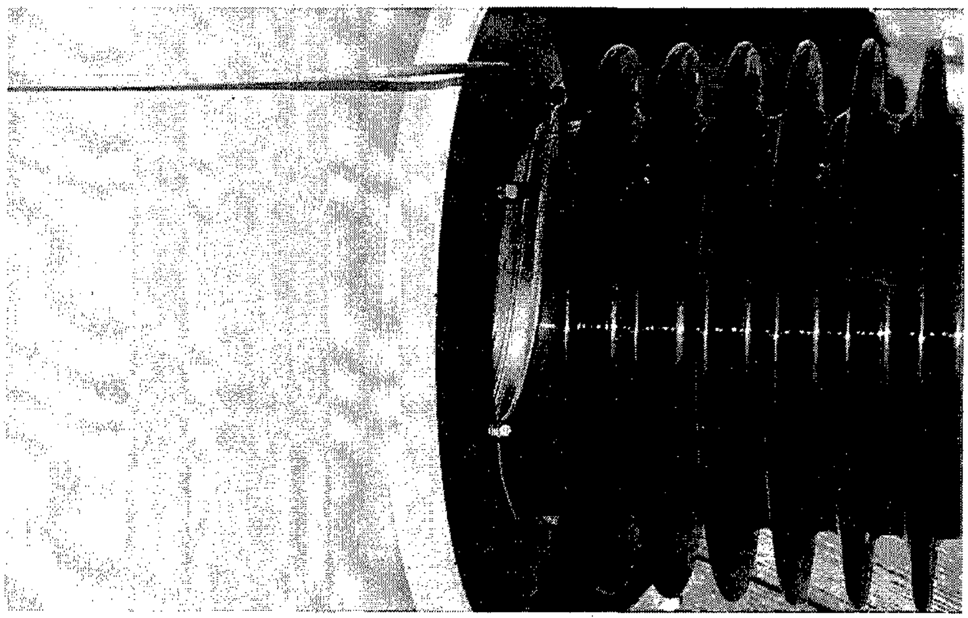


Fig.3.23 Motion between interrupter heads can cause the interrupter head bushing gasket to blow.

It is interesting to note that the bushings on transformers and bulk-oil circuit breakers are of the same design, but none of circuit breaker bushings slipped. A possible explanation for the better performance is that the bottom of the bushings on the circuit breakers are structurally connected when the circuit breaker is closed, thus providing additional support. An explanation of the difference in the performance of circuit breaker and transformer bushings is not clear.

DISCONNECT SWITCHES

Disconnect switches are used to re-configure the network, to isolate equipment, and to bypass equipment. They are operated only when the circuit is de-energized. Two basic disconnect switch designs were used in the earthquake impacted area: center break, and vertical break. Most disconnect switches are fabricated with two post insulator stacks on center-break type, and three post insulator stacks on vertical-break type. An unusual design using a tripod configuration and operating at 500 kV was also used, Fig. 3.24. The operating mechanism and support structure for each of the basic types can vary significantly between manufacturers and can exhibit different seismic performance. Most disconnect switches in the earthquake impacted area were center-break types.

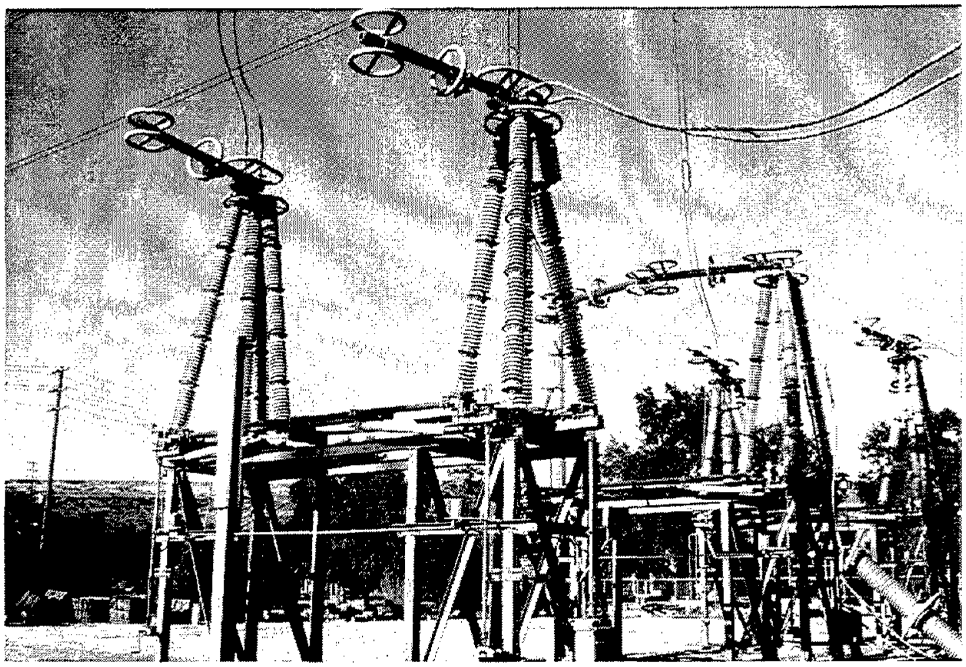


Fig. 3.24 This 500 kV center break disconnect switch is unusual in that it has tripod arm supports.

Disconnect switches failed from one of five failure modes in this earthquake. The most common is the failure of one or more of the post insulator columns used to fabricate the units, Fig. 3.25. A second failure mode is the deformation or slipping of the operating mechanism so that the disconnect switches of the center break type do not close. In this failure mode the switches appear to be aligned properly but are not completely closed. A third failure mode is that the base plate that supports the post insulator stack on a center break type is deformed so that insulator stacks are out of plumb. When the switch is in the closed position the arms are spread and electrical contact is not made, Fig. 3.26. Figure 3.27 show that the aluminum base plate is deformed. This is an unusual failure in that there is usually catastrophic failure of porcelain members rather than damage to metal components. The forth failure mode was the failure of post insulator columns that formed a tripod, Fig. 3.24. The failure pattern in these switches suggested that stresses associated with the assembly of the unit may have contributes to the failure. Finally, the fifth failure mode was associated with a manufacturing flaw in center-break units, in which tack welds used to hold a part served to initiate a fatigue crack in the support shaft. In this case the manufacturer provided new parts in which a different assembly method was used.

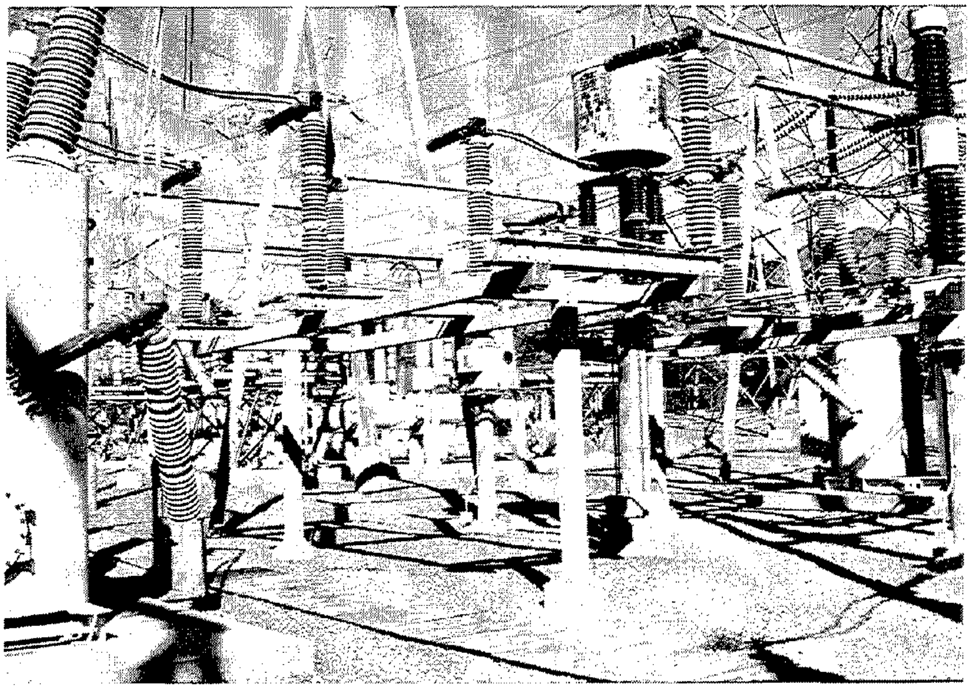


Fig. 3.25 The most common disconnect switch failure id the fracture of post insulators.

Several factors can contribute to disconnect switch failures. There were many examples where there was interaction between adjacent equipment because there was inadequate slack in the conductors or an adjacent item of equipment failed. For example, live-tank circuit breakers failed and pulled down disconnect switches. At one site, a damaged rigid bus fell on and damaged several disconnect switches. Bus drops and suspended items, such as current-voltage transformers and wave traps appeared to interact with adjacent disconnect switches. While the potential effect of a swinging

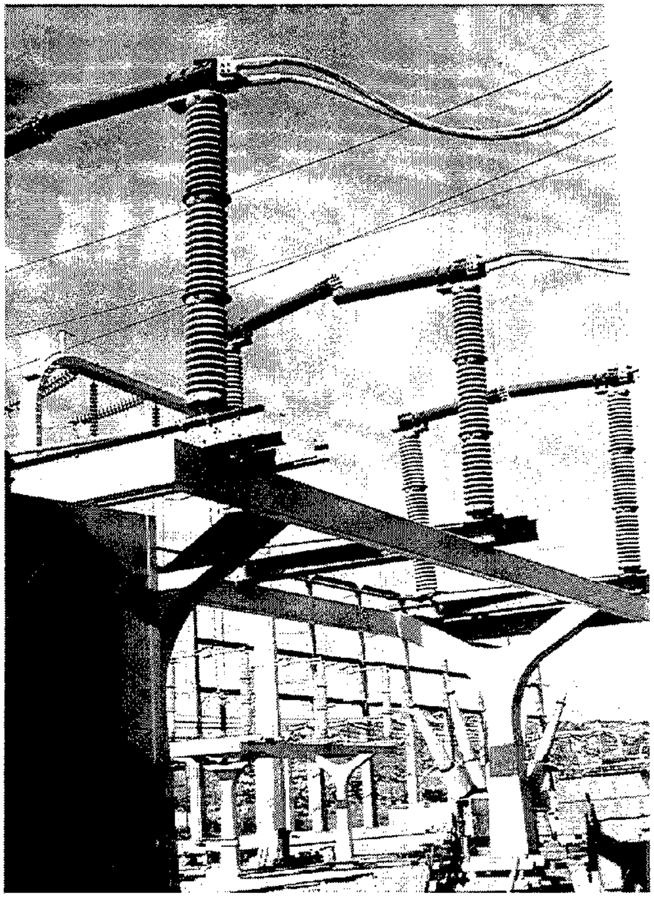


Fig. 3.26 Deformation of the plate supporting the post insulator stack prevented disconnect switch from closing.

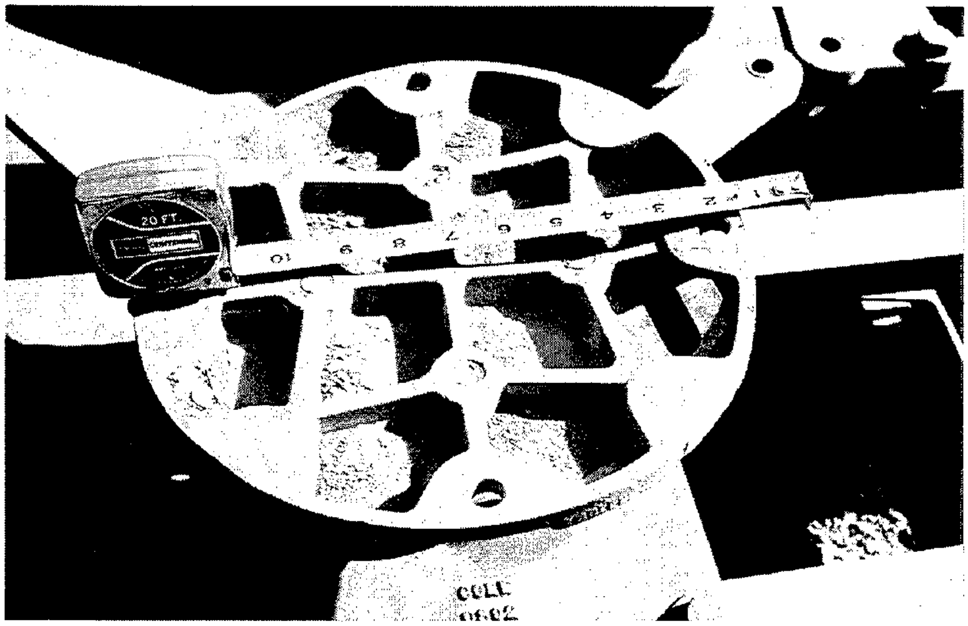


Fig. 3.27 The deformation of the cast aluminum base plate has not been seen in other earthquakes.

heavy wave trap is obvious, relatively light insulator strings appeared to have has a disproportionate effect. An explanation is not clear, but the vertical vibration of the bus support may have had a role in these failures. At one site there was some deformation of the ground in the switchyard. Some disconnect switch support structures have from two to six separate footings supporting the switch. Relative motion of the foundation pads may have deformed the support structure and interfered with the operation of the switch.

There were two emergency response actions taken to restore disconnect switch function, that is, to make contact across damaged disconnect switches. Because of the large number of damaged post insulators used to fabricate switches, it was common to cannibalized partially damaged switches or bus supports to get replacement post insulators. In one switch design, the stack of post insulators is tapered, that is, the insulators at the top are smaller than those at the bottom. Since the lowest insulator typically fails, there was a shortage of this particular element. While a flexible conductor could have been used to jump across a switch, none of these were observed. A second emergency procedure was to use cotton rope to hold deformed disconnect switch parts together to complete a connection so that service could be restored, Fig. 3.28.

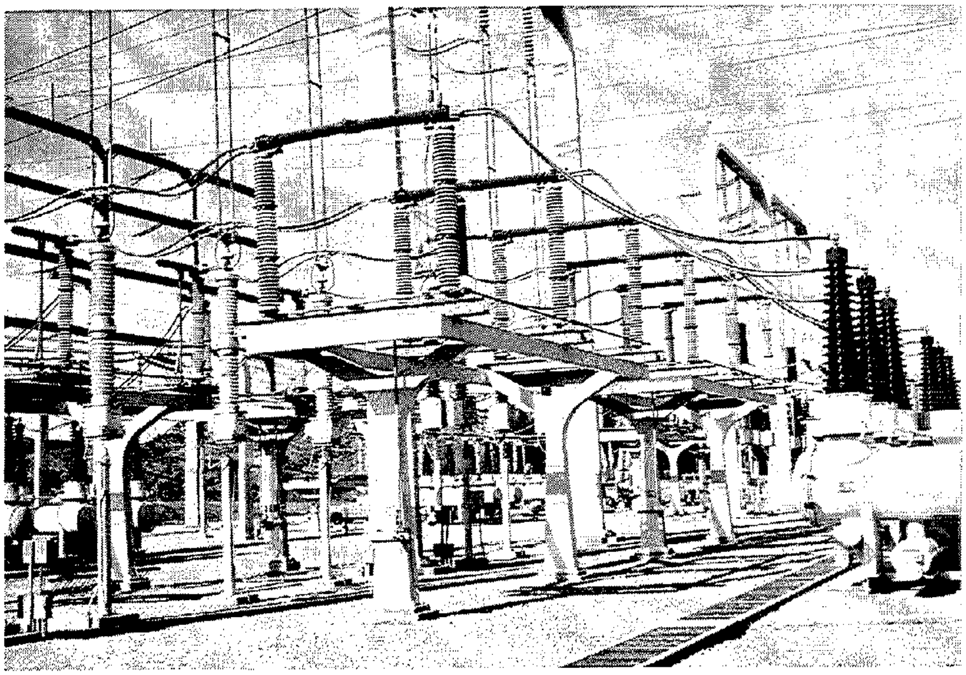


Fig. 3.28 An emergency operating procedure uses cotton rope to hold the disconnect switch arms together.

As a result of the earthquake, several design changes have been made relative to disconnect switches. In the future, switch foundation pads will be monolithic slabs. Busses are often configured so that a line drops between two disconnect switches and is connected to each. In some cases, the connection between the disconnect switch is made with a rigid bus. There were indications that this rigid connection contributed to disconnect switch failures. Existing systems are being modified by adding flexible connections to the switches and new construction will use all flexible conductor with generous slack. In general, more generous use of slack in conductor connections between equipment will be made.

CIRCUIT SWITCHERS

The function of circuit switchers are similar to circuit breakers, except that they can only operate under normal circuit conditions and they are relatively slow-acting. Circuit switchers are often used to connect capacitor banks to the network, but were also used to connect transmission lines to transformers.

Circuit switchers at several sites were severely damaged. At one location, where they connected a transmission line to transformers, conductor was strung across the damaged circuit switchers to restore service, Fig 3.29.

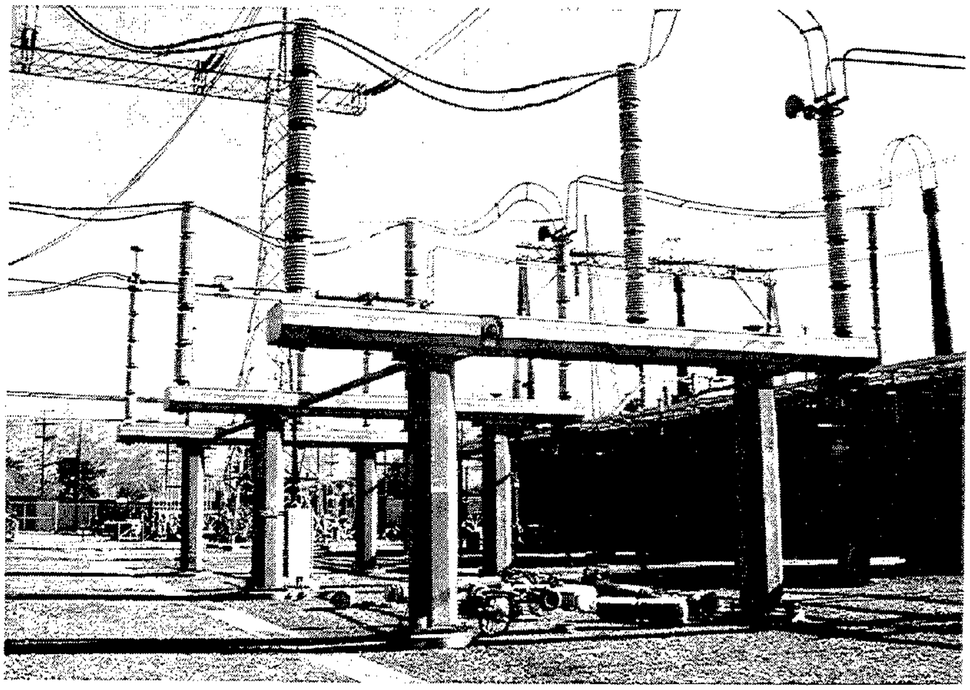


Fig. 3.29 Emergency procedure is shown stringing conductor across damaged circuit switchers to connect a transmission line to a transformer bank.

Because of the inability to find circuit switchers that meet current seismic specifications, the plan is to replace these devices with circuit breakers and disconnect switches.

INSTRUMENTATION AND CURRENT TRANSFORMERS

Instrumentation transformers that are considered here are used to measure voltage on high-voltage circuits for system control, protection, metering and monitoring. Current transformers measure currents in high-voltage circuits. The loss of these devices degrades the quality of system protection and can impact system control.

Potential transformers, current-voltage transformers, and some current transformers have similar structural forms, that is, they have long cylindrical porcelain members supported on steel columns or suspended from above. Units supported from below frequently failed where the porcelain joins its lower mounting flange, Fig 3.30. Some units supported from below used Bellville washers to change frequencies and/or increase damping. The performance of these units was mixed. Units with stiff (above about 8 Hz.) steel support columns performed well while those with standard columns with frequencies below 6 Hz. frequently failed. Suspended units had a different failure mode. The lower aluminum angle restraint anchor attachments on many of these units failed, and their swinging motion tended to damage low voltage electrical connections, Fig 3.31. The violent character of these motions is indicated by damage to the anchorage of restraint columns, Fig. 3.32 .. A review of the damage pattern suggests that the length of the suspension system influenced the response, so that there may have been a tuning of the system to the ground motion. Even in units where lower restraints did not fail, adjacent equipment was damaged in about 25% of the cases due to interaction effects. When the lower restraints failed, the damage to adjacent equipment rose to 78%. The damage associated with more massive suspended items, such as wave traps, was about three times that associated with lighter suspended items, such as current-voltage transformers. It is interesting to note that the porcelain on suspended units is seldom damaged.

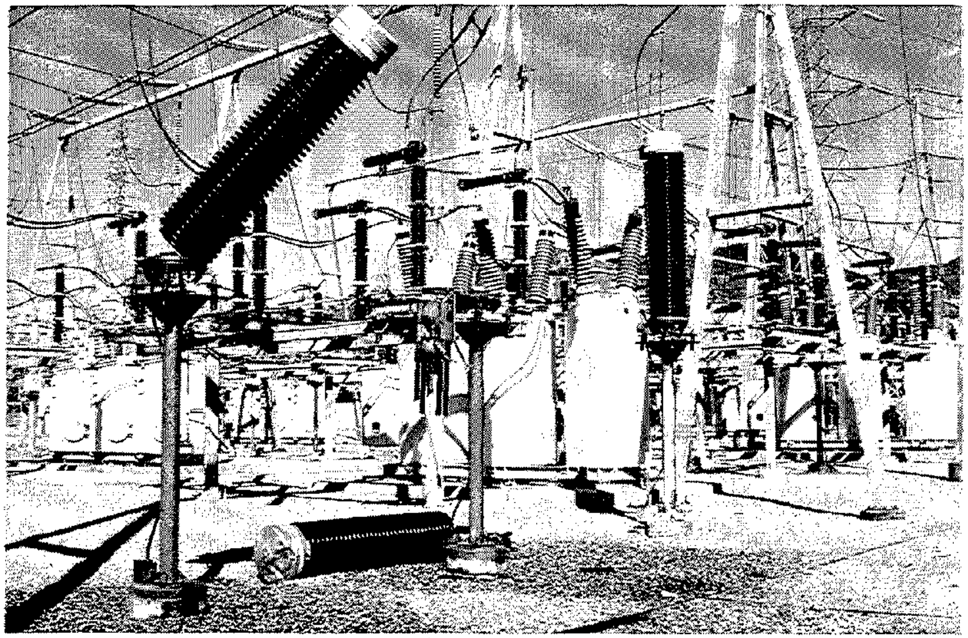


Fig. 3.30 Porcelain of a potential transformer failed at its lower support.

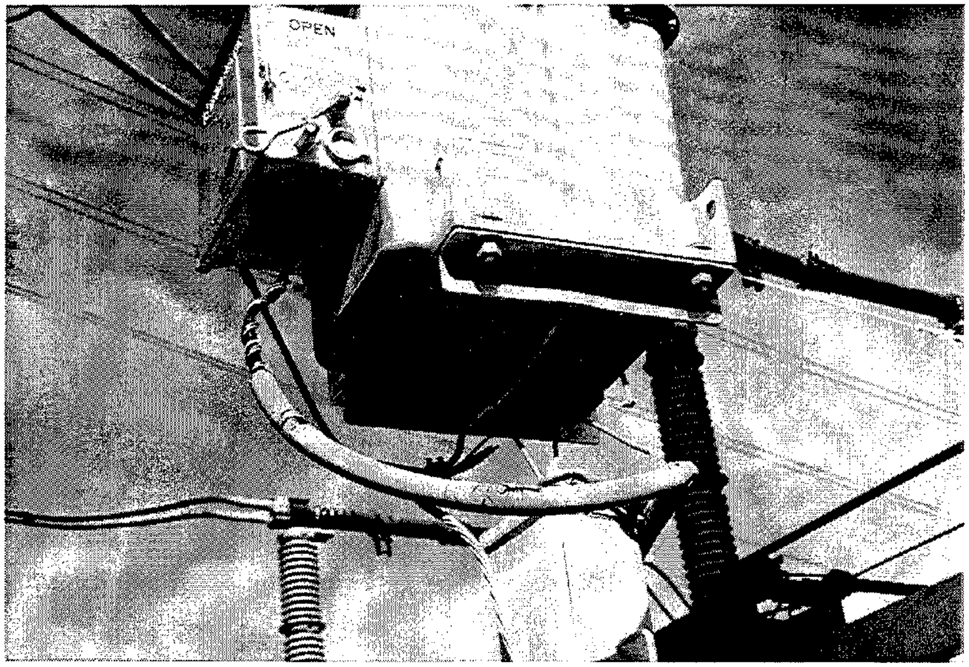


Fig. 3.31 Aluminum angle used to restrain suspended current-voltage transformers frequently failed.

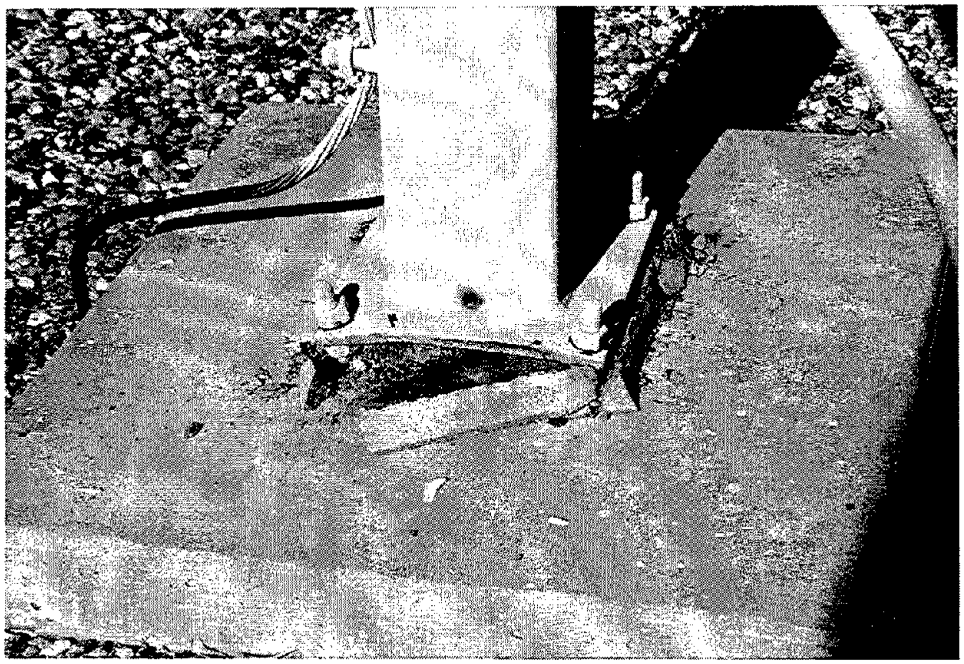


Fig. 3.32 Violent motion of suspended current-voltage transformers damaged base of column restraints.

When damaged current-voltage transformers are typically removed from the system and the system continues to operate. Suspended units with damaged restraints were often temporarily restrained with rope.

In the future, smaller leads will be used on instrumentation transformers so that if the items fail, they will break the electrical connection rather than pull down the adjacent item of equipment. Current-voltage transformers fabricated with composite materials are being evaluated. Methods are currently being explored to increase damping of suspended units.

WAVE TRAPS

Wave traps are inductors typically placed in transmission lines where they enter the substation. They serve to block high frequency carrier signals used for protective relaying and system protection that are carried on the transmission line.

Wave traps are typically mounted in the horizontal or vertical position and supported from below on post insulators, or suspended from dead-end or bus-support structures. When suspended they are restrained from below by cables connected to structure-supported post insulators or tethered to the ground or a structure by an insulator string and cable.

The performance of suspended units in this earthquake has been good, in the sense that most units were not damaged. However, their swinging motion often caused severe damage to adjacent equipment, Fig 3.33. Two suspended units had internal structural failures and fell to the ground. Support post insulators on units supported from below frequently fail, Fig. 3.34, or structural connections above the post insulators fail, Fig 3.35. Failures were often in aluminum bolts.

Damaged units were frequently cut from the circuit and service was restored without their use, even though this can degrade system protection.

In the future, wave traps will be subjected to vibration tests or more rigorous analysis to assure that they satisfy seismic specifications. Methods are currently being explored to increase damping of suspended wave traps. One company intends to eliminate wave traps by using a second microwave for communication circuit to replace the carrier frequencies.

CAPACITOR BANKS

There are two type of capacitor banks associated with the Sylmar facilities - power factor correction capacitors and harmonic filters capacitors. The power factor correction capacitors, which failed in 1971 due to poor quality control on support

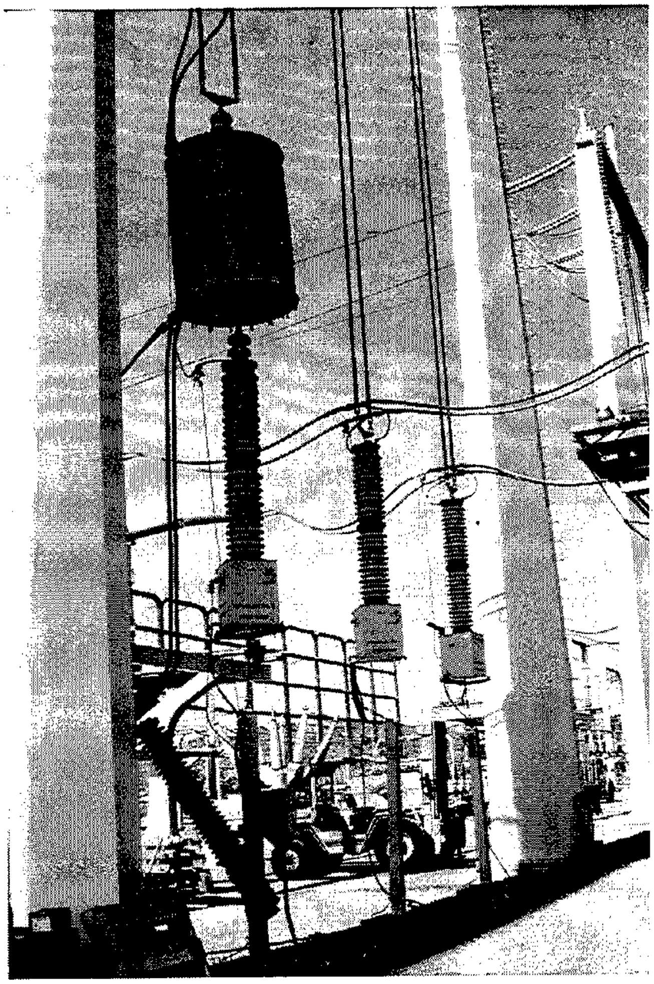


Fig. 3.33 Motion of a suspended wave trap damaged an nearby disconnect switch.

structure welds, had been replaced and were not damaged in this earthquake. Harmonic filter capacitors associated with Valve Hall 7 and 8 at Sylmar West were added after 1971. These capacitors were suspended, and in the earthquake broke their lower restraints, but were otherwise undamaged, Fig. 3.36.

Harmonic filter capacitors at Sylmar East were in a support structure made of post insulators. In the earthquake several post insulators fail, but the structure did not collapse, Fig. 3.37. The power factor correction capacitor racks are of different sizes to meet different electrical requirements. The base support porcelain members of the tallest racks at two locations on the site failed, Fig. 3.38. It is not known if the structural frequency was coincident with spectral content of the ground motion or if the taller structure overloaded its supports.

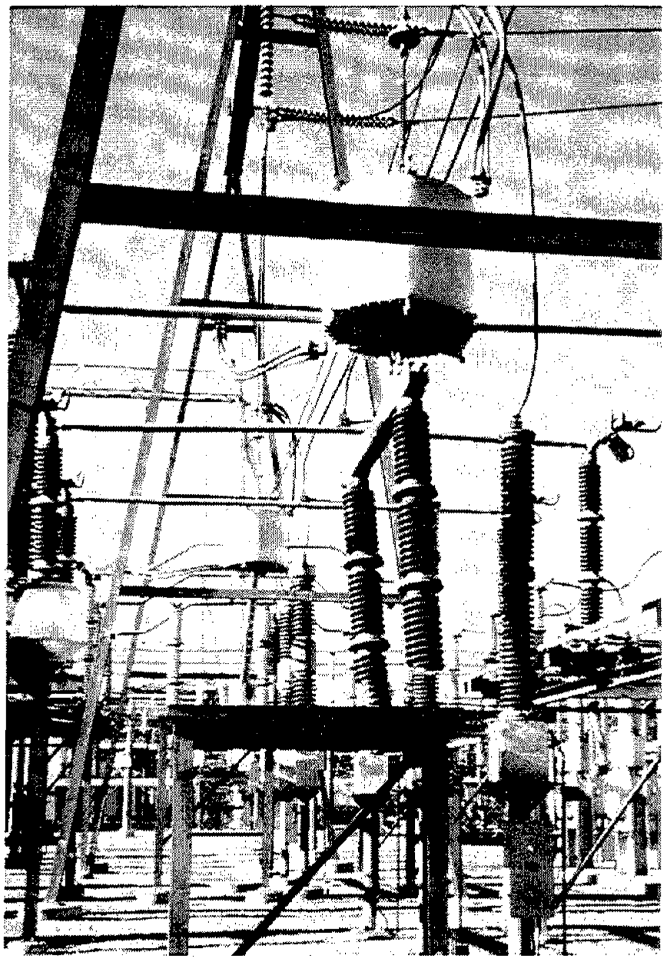


Fig. 3.34 A 230 kV suspended wave trap failed post insulator restraints below the wave trap.

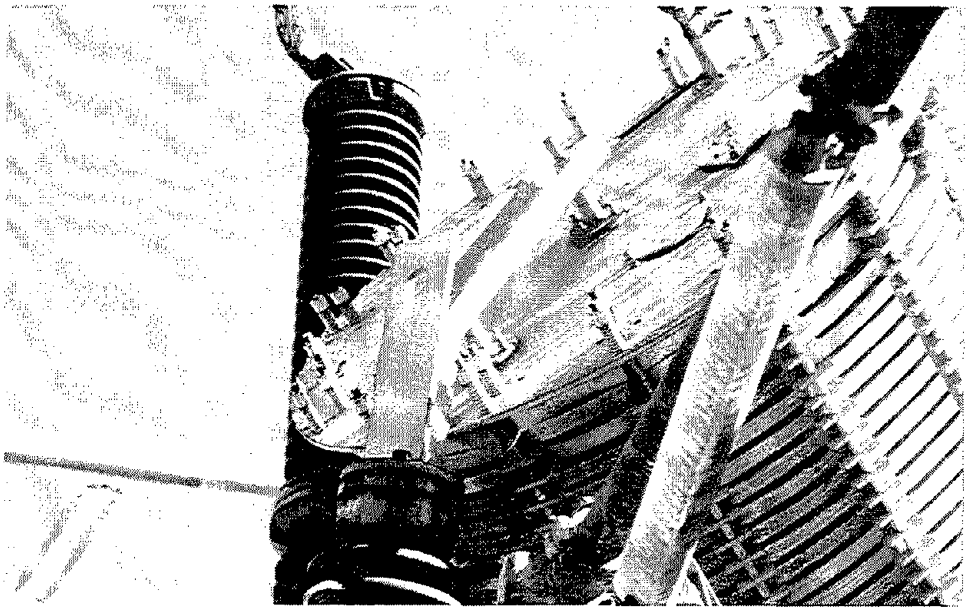


Fig. 3.35 Channel supporting wave traps failed just above the weld to the top of the post insulator.

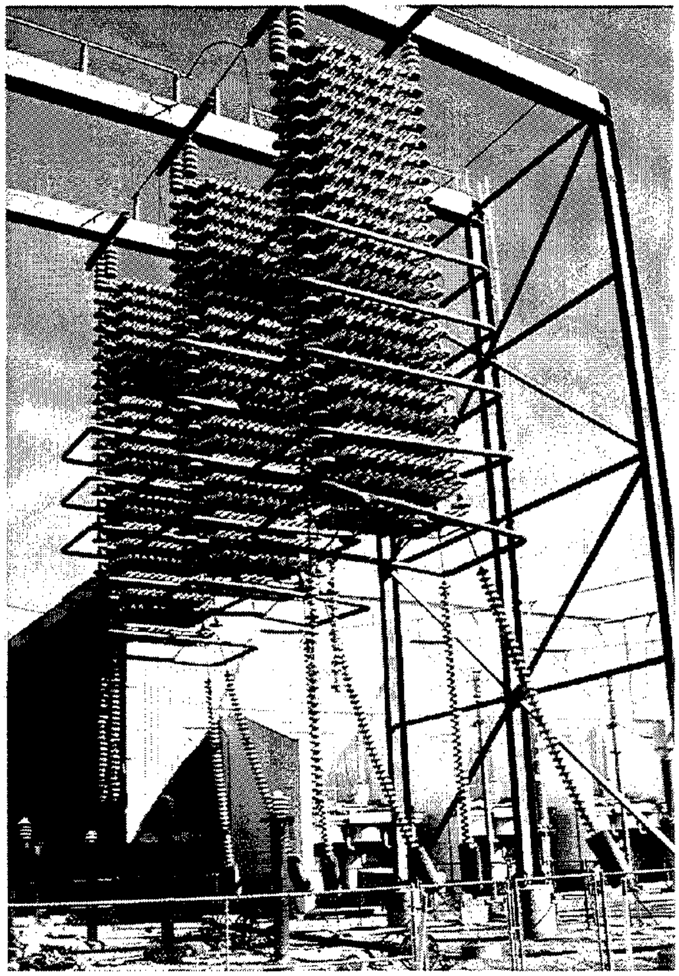


Fig. 3.36 Suspended harmonic filter capacitors failed their lower restraints, but were otherwise undamaged.

CONDUCTOR AND BUS SYSTEMS

Most of the high voltage bus and conductor used are flexible-type rather than rigid-type fabricated from aluminum pipe or heavy extruded aluminum sections. While there were exceptions, rigid bus in general performed poorly in that relative motion between equipment connected with rigid bus frequently damaged the porcelain member to which it was attached. A 230 kV bus at a major substation had a unique configuration in that the bus, which was a heavy aluminum H section, was suspended by short lengths of chain to allow it to swing. Its performance was very poor, Fig. 3.39. Rigid bus was also frequently used at line drops between disconnect switches, Fig. 3.40. An evaluation of the damage pattern suggests that the rigid bus in this configuration contributed to the failure of disconnect switches. Straight runs of rigid bus have little flexibility to accommodate motion between equipment. Incorporation of a dog-leg bend into straight runs of rigid bus will allow it to accommodate deflection between its ends.

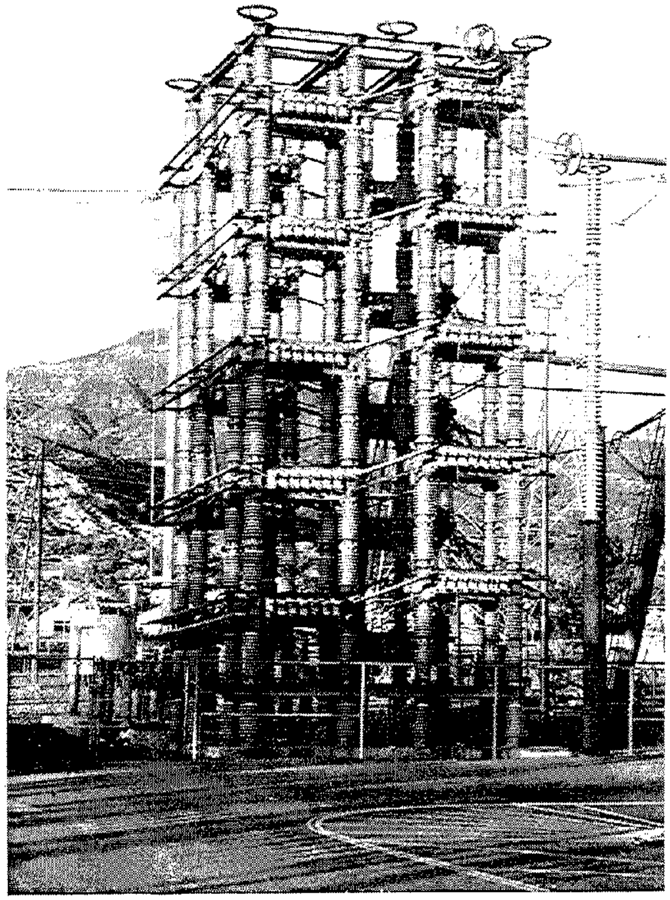


Fig. 3.37 Harmonic filter capacitor support structure was damaged, but did not collapse.

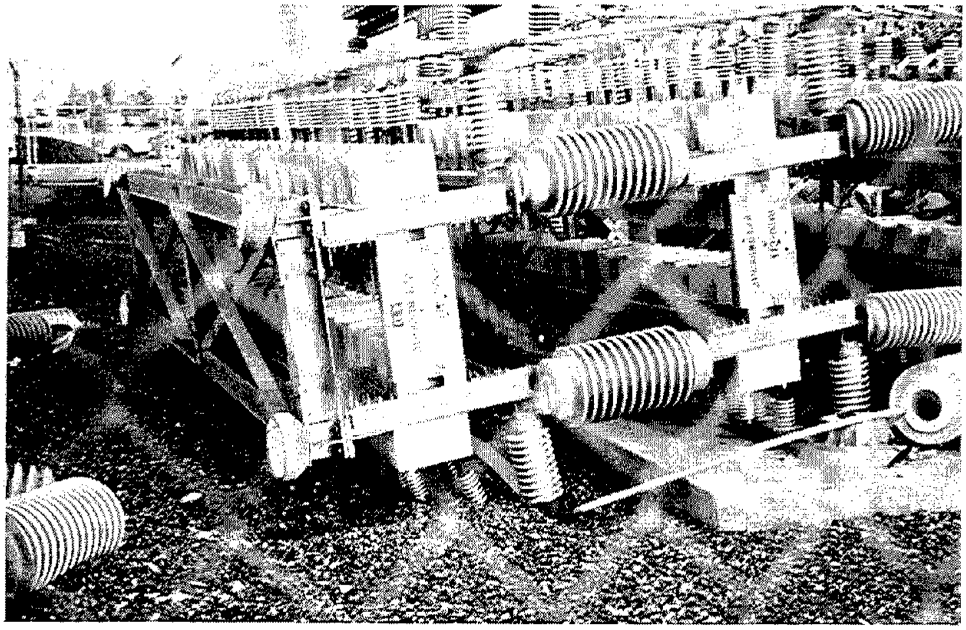


Fig. 3.38 The lower post insulators on the tallest power factor correction capacitors failed.

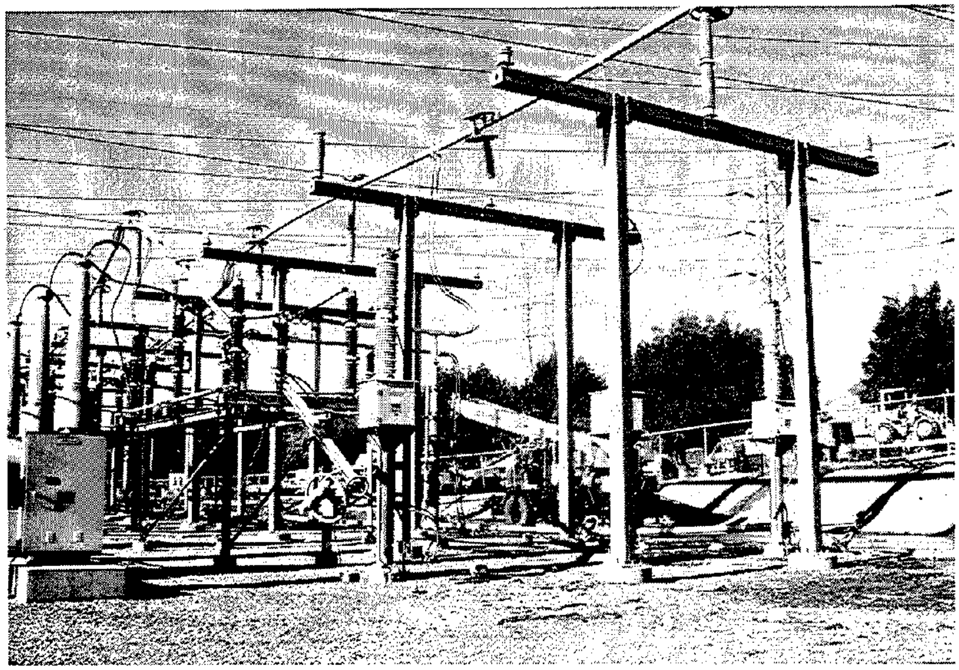


Fig. 3.39 Post insulators supporting rigid bus failed causing major disruption at the substation.

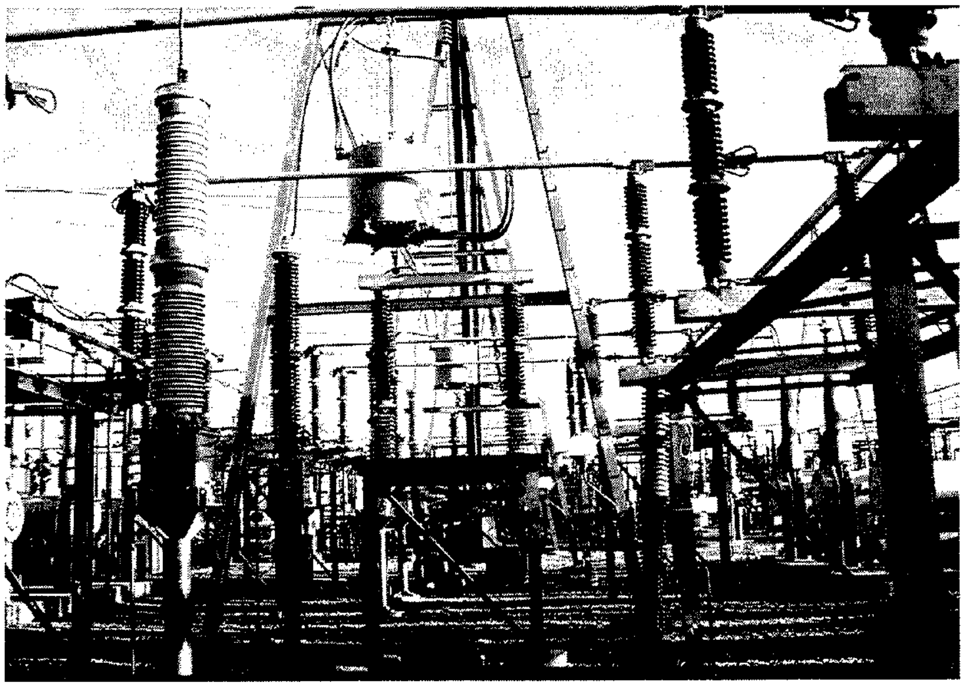


Fig. 3.40 Rigid bus used to connect disconnect switches at line drop contributed to disconnect switch damage.

One utility plans to replace its rigid bus with flexible bus. Also, at bus drop to rigid bus between disconnect switches will be modified by adding flexible links at the end of each run. Specifications for new construction also call for more slack in conductor between substation equipment.

Many of the substations have rigid low-voltage bus. Its performance has been poor due to brittle failure of the cast-aluminum hardware used to connect and support conductors, Fig. 3.41. To restore service, cotton rope was used to tie the bus to post insulators, thus replacing the function of the damaged hardware, Fig. 3.42. As a result of this damage, recommendations have been made that specifications for the hardware be increased to reflect the brittle failures observed.

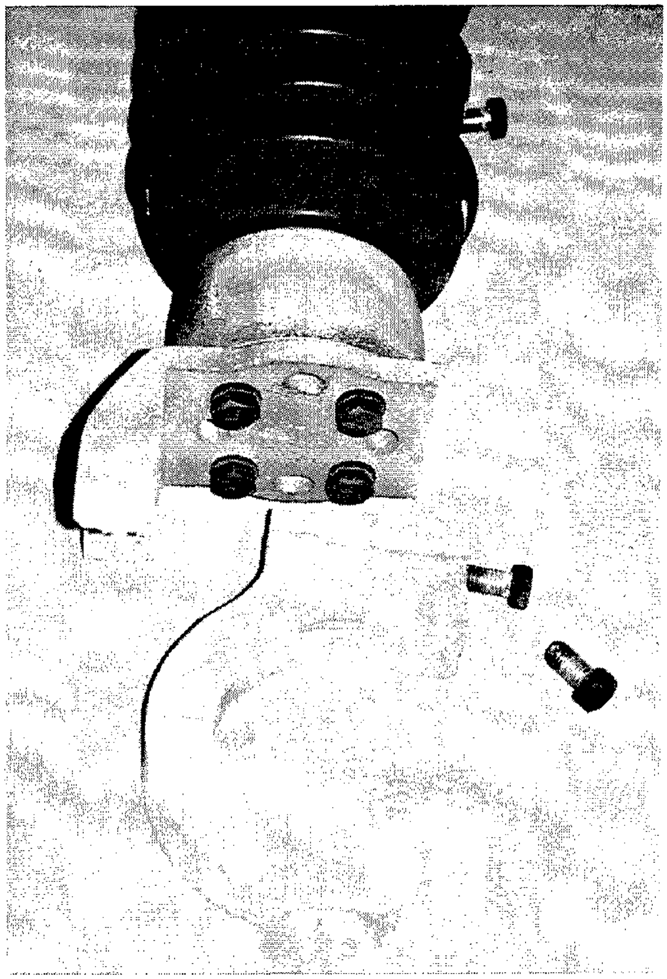


Fig. 3.41 Cast aluminum hardware used to support low voltage bus frequently failed.

STATION BATTERIES

There were no failures of station batteries, although there were a few examples of old wooden battery racks of questionable strength that were damaged. Old battery racks are to be replaced.

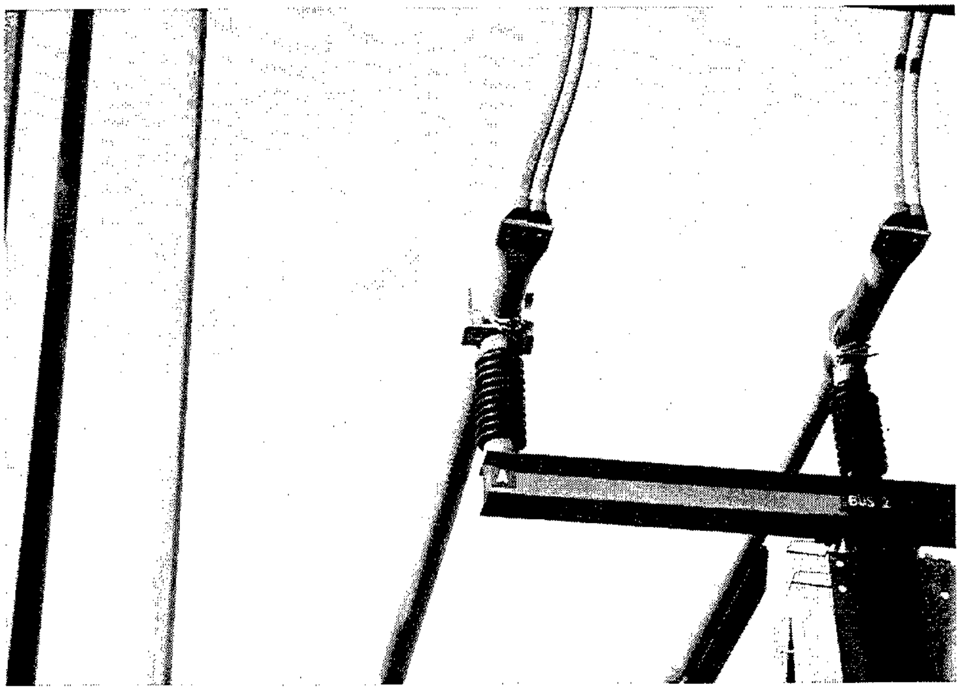


Fig. 3.42 An emergency procedure was to use rope to hold bus to supports.

TRANSMISSION SYSTEM

The earthquake performance of transmission towers has been very good. Several towers were damaged in this earthquake and three failures caused the loss of four circuits. A large construction crane was rigged to support one 230 kV circuit to restore a circuit to a pumped-storage facility. It was used until a replacement tower could be constructed, Fig. 3.43. Temporary supports were rigged for the other two circuits. At one substation that experienced liquefaction several large dead-end transmission towers were severely damaged. These inverted "U" shaped towers were fabricated out of plate to form large tubes. Several towers tipped slightly due to liquefaction, Fig. 3.44, and one leg of one tower had brittle fractures through its entire section near its base plate weld, Fig. 3.45. The footing of this tower was 34 feet deep. Bus support structures has a brittle fractures near welds and one had a crack through its 4" base plate.

DC CONVERTER STATIONS

The DC converter stations at Sylmar East and Sylmar West experienced damage in this earthquake, but the documentation and evaluation of this data is very preliminary and will not be reported here. It is worthy to note that Sylmar West facilities were also subjected to severe shaking in the 1971 San Fernando earthquake and experienced extensive damage in that earthquake. Following the San Fernando earthquake,

Fig. 3.43 A crane was used to temporarily replace a failed transmission tower to restore service.

equipment in the valve hall was evaluated and modified. While there was damage to bus work, reactors, resistors, and some damage to valve accessories, the extensive damage to the valves experienced in 1971 was avoided. There was relatively little damage to bus work in the "Bird Cages" adjacent to the valve hall, however, there was extensive damage to equipment in the Bird Cage and porcelain components of many bushings at the two facilities slipped relative to their flanges.

DISTRIBUTION SYSTEMS

The distribution system, as it is considered here, generally consists of radial lines emanating from distribution substations at voltages ranging from 4 kV to 22 kV. The DWP is different from most utilities in this regard, in that their distribution system in some areas has some redundancy so that it forms a grid.

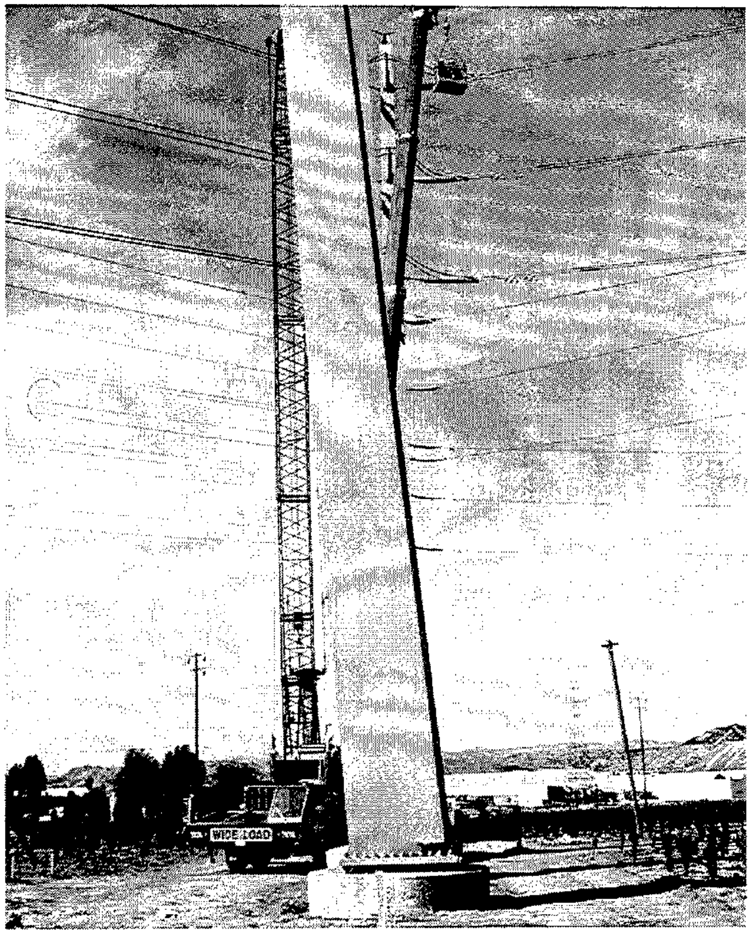


Fig. 3.44 Dead-end transmission tower tipped due to liquefaction and crack in tower.

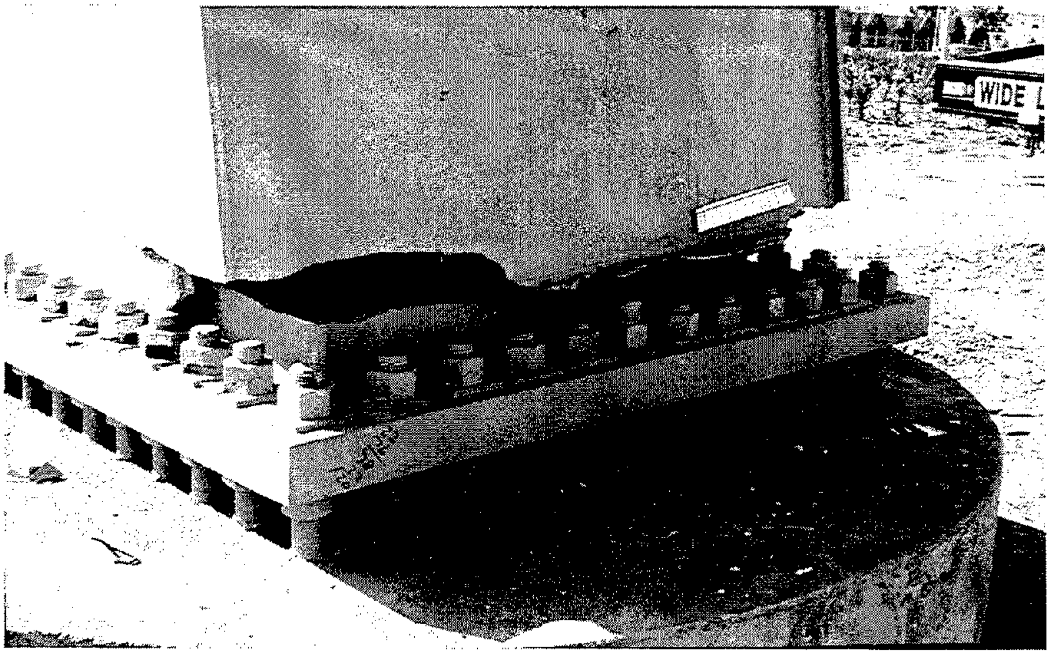


Fig. 3.45 Brittle fracture of dead-end structure associated with soil liquefaction.

In general, the performance of the distribution system was good. At the 35.4 kV voltage level, 92 overhead transformers of the 98,000 in the system fell or were damaged, 10 subway transformers fell over, and 10 transformer vaults had roofs damaged or collapse. At the 4.8 kV level, 1285 line spans were damaged, 213 lines relayed and were damaged, 152 lines went down, but did not relay, 238 jumpers were damaged and 250 small, pad supported distribution transformers moved on their foundation pads, Fig. 3.46. There was no damage to power lines or disruption of service as a result of the movement of these transformers, however, in the future these units will be anchored to their pads. There were 1423 service connection to meters that were damaged. It is interesting that only 2 wooden distribution-line poles failed as compared to hundred of concrete poles that were damaged by inertial loads in the recent Kobe, Japan, earthquake.

Fig. 3.46 Pad supported distribution transformers moved, but did not cause disruption.

GENERATING STATIONS

There was relatively little damage to generating stations, as has been observed in past earthquakes. The Caustic Pumped Storage Facility, with a peak capacity of 1247 MW, had minor damage to the control house and the failure of a water line cause the loss of the fire suppression system. Generation was not disrupted. There was damage to transformers and transmission lines noted above. The loss of the transmission lines isolated the plant from the grid. At the Burbank Generating plant there was a leak in a main steam line that was associated with pipe corrosion. A de-aerator tank at the Orman Beach station developed a small leak. Small leaks were detected at heater tubes at other plants, however, these may have been present prior to the earthquake.

SPARE PARTS STORAGE

Most small spare parts are kept at service centers where they are available to repair crews. Some large spares, such as bushings and porcelain components are frequently kept at substations, particularly if they are associated with specialized equipment located at the substation. Newer installations had well organized storage areas with special fixtures to anchor and protect spares, Fig. 3.47. Some older installations had special racks for spares, but some racks were poorly anchored and parts were not always well secured to the rack, Fig 3.48. A common practice throughout the county that is still occasionally used here, is the storage of spare parts in their shipping crates. While this is a good storage method, because shipping loads are typically larger than those generated in earthquakes, wooden shipping boxes quickly deteriorate, if left outside, Fig. 3.49. A protective cover is needed to prolong storage container life. One of the utilities is removing bushings from the type of rack shown in Fig. 3.49 and placing them in heavy duty wooden racks that are similar to shipping crates. Also, a major storage facility located outside of the earthquake area is being used for a large percentage materials stored for disasters.

COMMUNICATION SYSTEMS

Communication systems play an important role in the operation of utilities. They are needed for energy dispatch, that is, to control the output of generators so that supply balances demand. Communication is also needed for protective relaying, that is, information on abnormal system conditions is used to control circuit breakers for system protection. Radio communications are needed to dispatch repair crews.

In general, power system communication system were not affected by the earthquake. At one substation, modems used in the SCADA (Supervisory Control and Data Acquisition) system were unanchored, fell to the floor and were inoperable. Unfortunately, modems are typically anchored, but in this case a lack of anchorage caused damage.

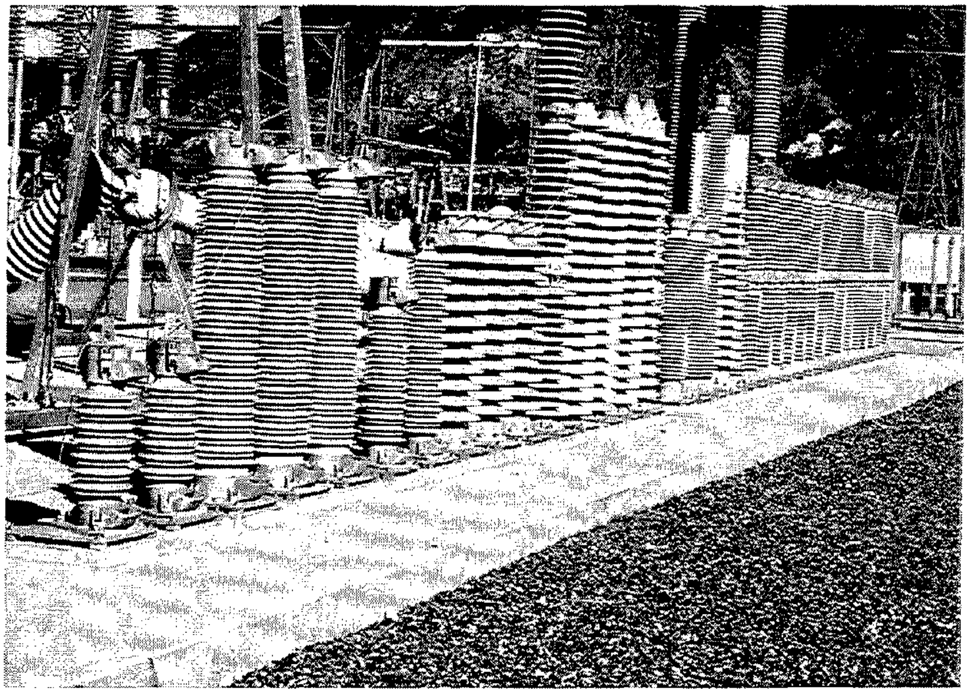


Fig. 3.47 Spare parts storage at new facility provided good protection.

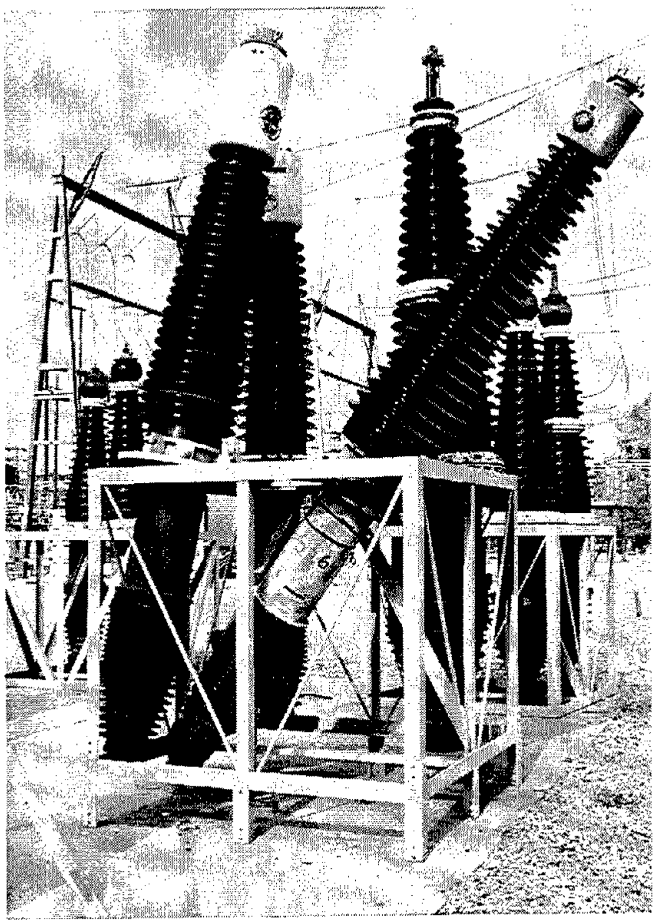


Fig. 3.48 Spare bushings stored at an older facility were not adequately anchored to their rack.

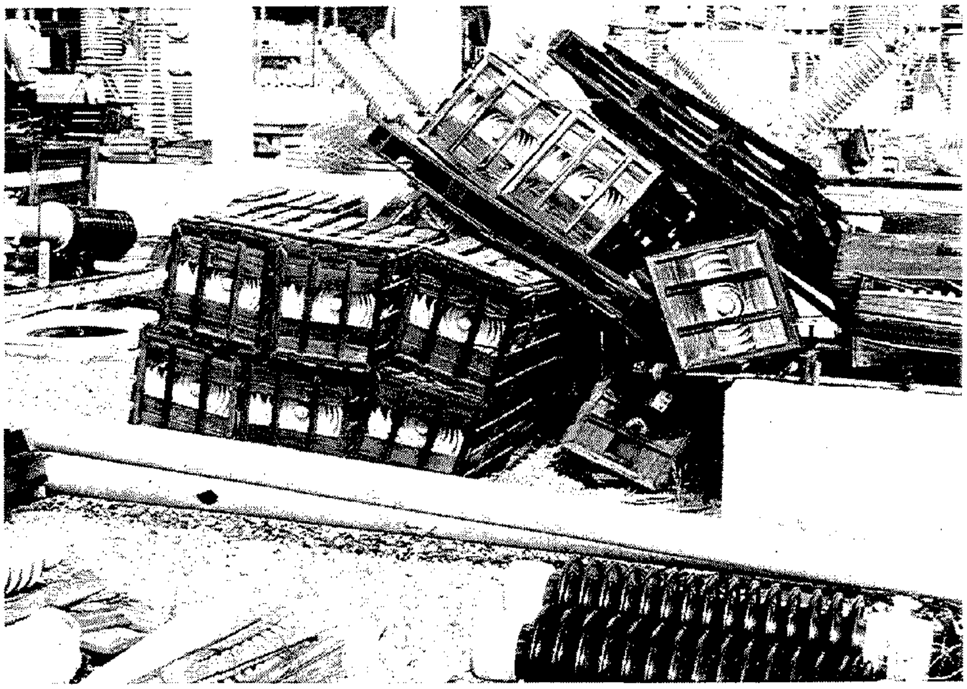


Fig. 3.49 Shipping crates provide good storage, but they deteriorate quickly in the elements.

SUMMARY OF DAMAGE TO SUBSTATIONS

A detailed summary of performance of 9 facilities follows. A brief description of each facility is given, and strong motion records and their response spectra are provided if available. The response spectra for damping values are 0.005, 0.01, 0.02, 0.05, and 0.10. A summary table of equipment performance for major classes of equipment at the facility follows. The numbers of undamaged and damaged items will be listed, and additional descriptive material and information about the failures are contained in comments. It should be noted that individual phases of equipment are counted separately, except when the three phases are combined in a single piece of equipment, such as a 3-phase transformer. Three-phase items are noted in the tables. Equipment in the tables operates at 230 kV, unless otherwise noted. For most facilities a detailed schematic diagram of the equipment is given showing the location and type of failures.

RINALDI SUBSTATION STATION

Peak acceleration at the site was 0.85 g, the peak velocity was 170 cm/sec., and the peak displacement was 33 cm. An aftershock on March 20 caused some transformer bushings, that had slipped in the main event and had been repaired, to slip again. Ground motion records and spectra for the main event are given in Fig. 3.50.

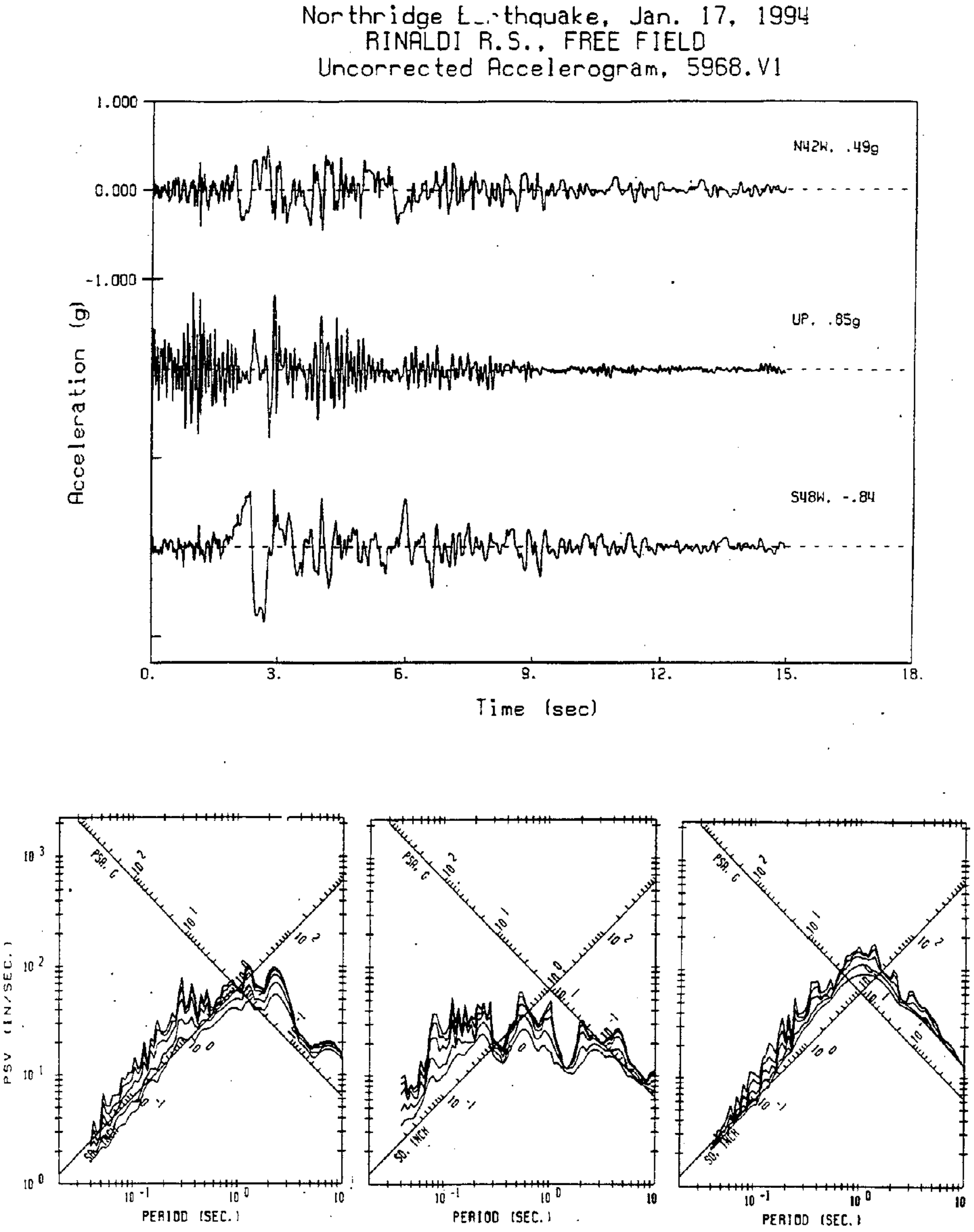


Fig.3.50 Ground motion records recorded at Rinaldi Substation and response spectra.

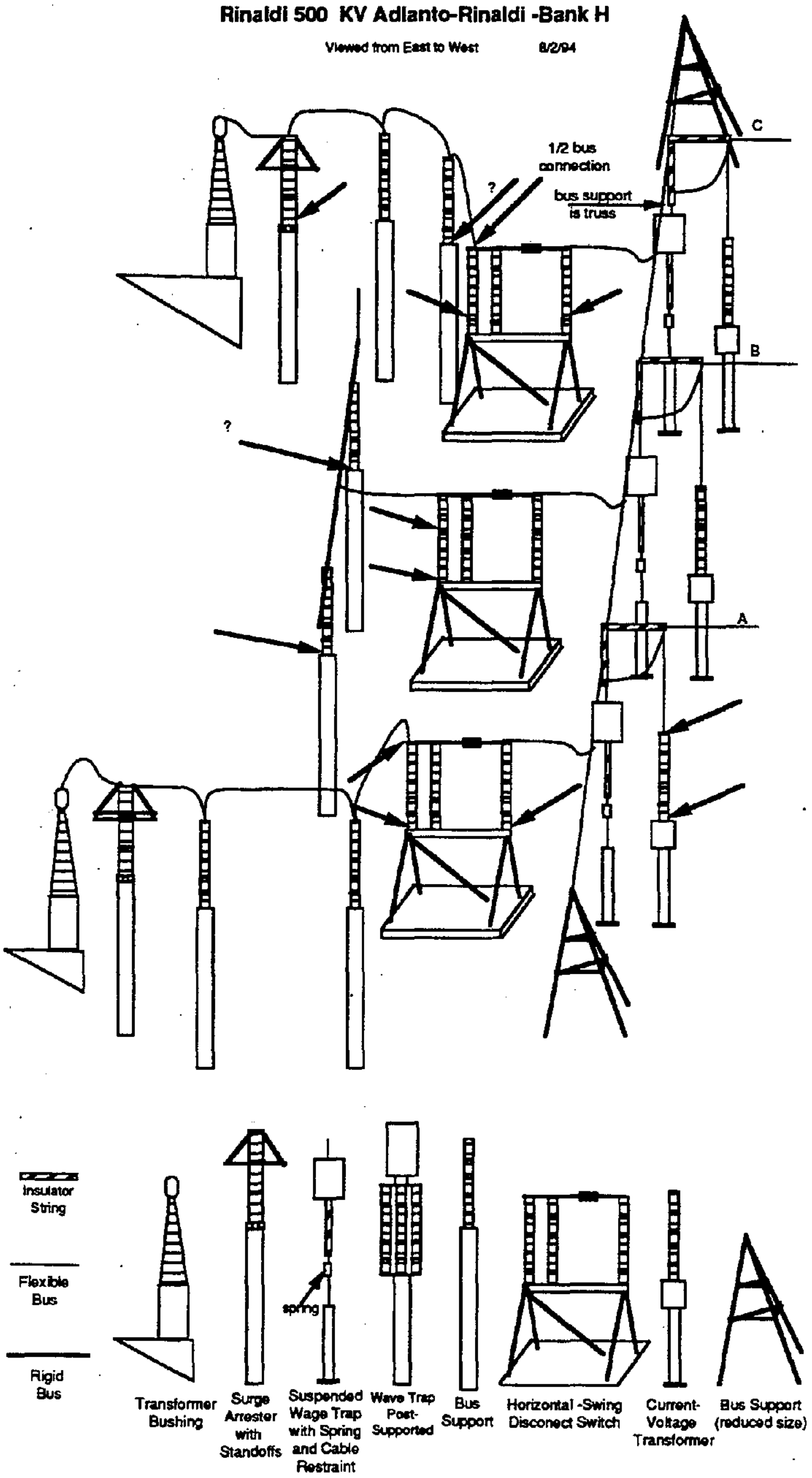


Fig. 3.51 Schematic diagram showing damage to 500 kV switchyard at Rinaldi Substation - Part 1. Note that arrows indicate damage locations.

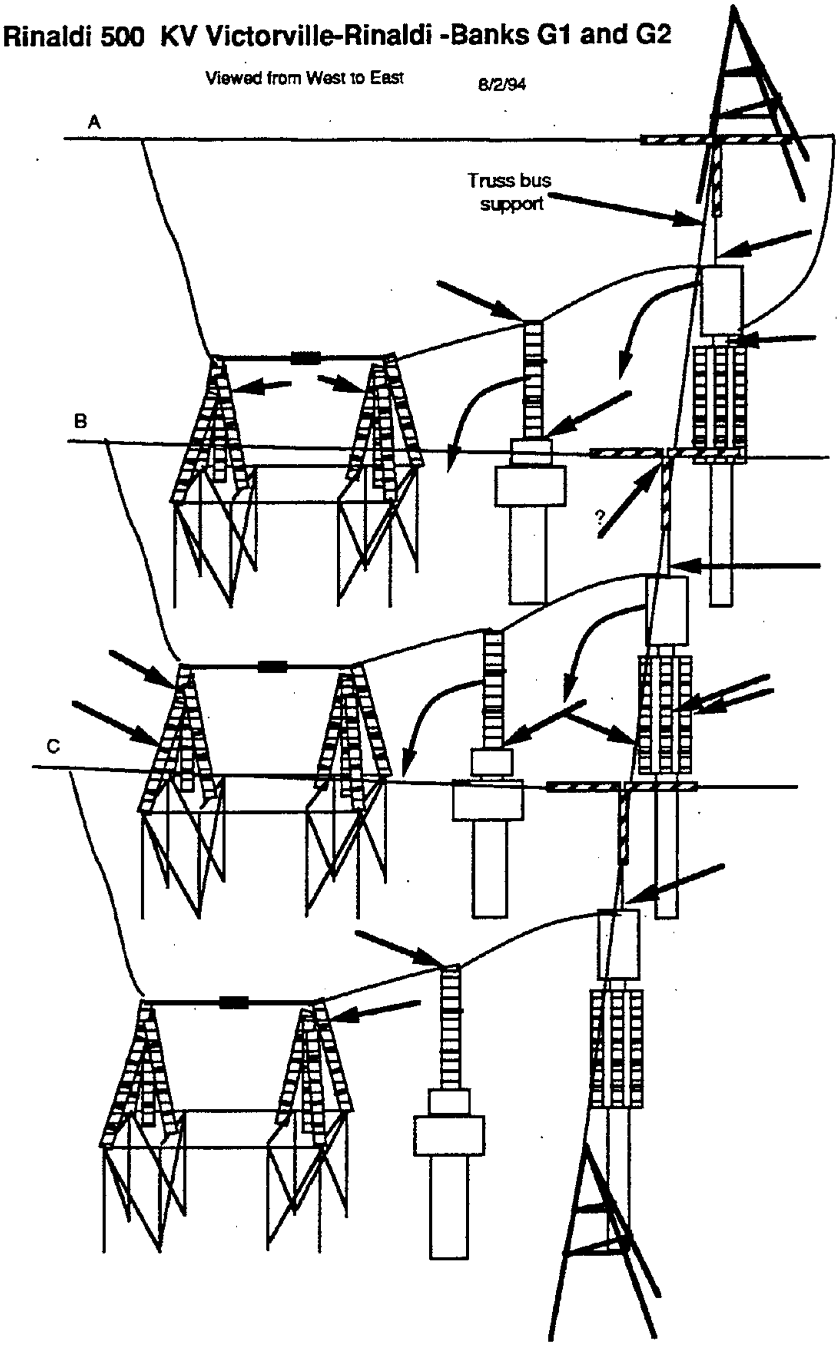


Fig.3.51 Schematic diagram showing damage to 500 kV switchyard at Rinaldi Substation - Part 2.

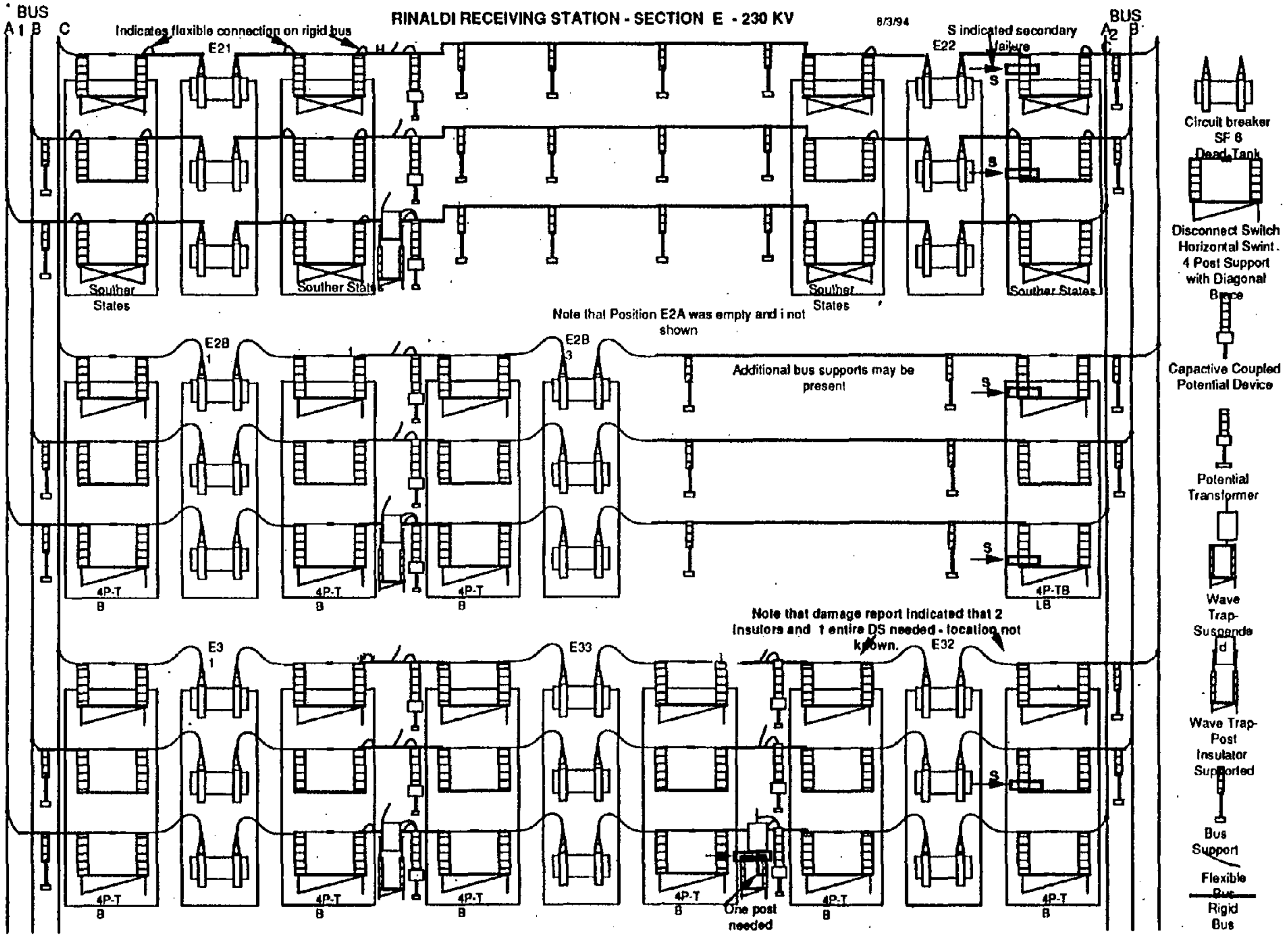


Fig. 3.52 Schematic diagram showing damage to 230 kV switchyard at Rinaldi Substation - Part 1. Note that boxes and arrows indicate damage locations.

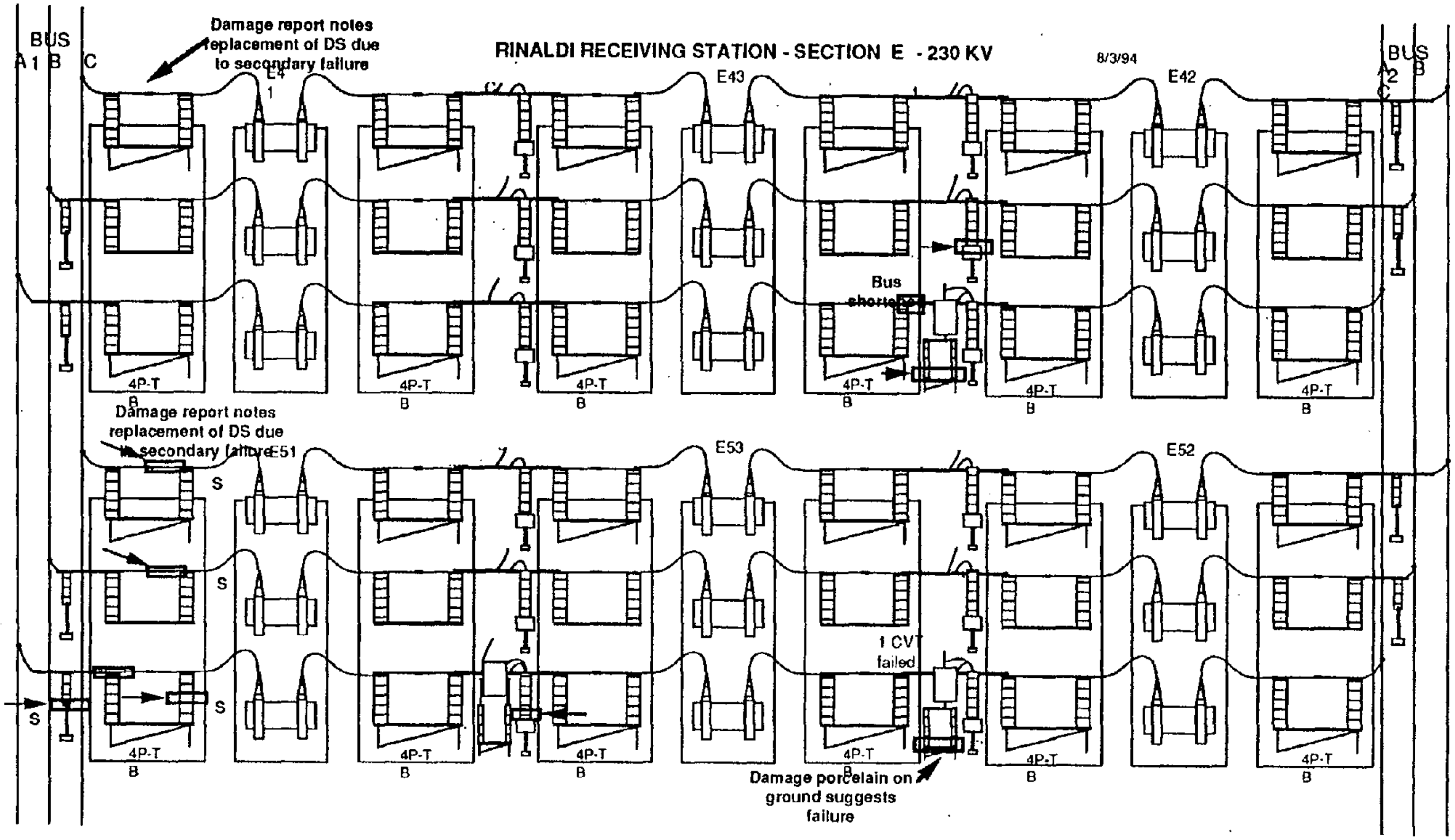


Fig. 3.52 Schematic diagram showing damage to 230 kV switchyard at Rinaldi Substation - Part 2.

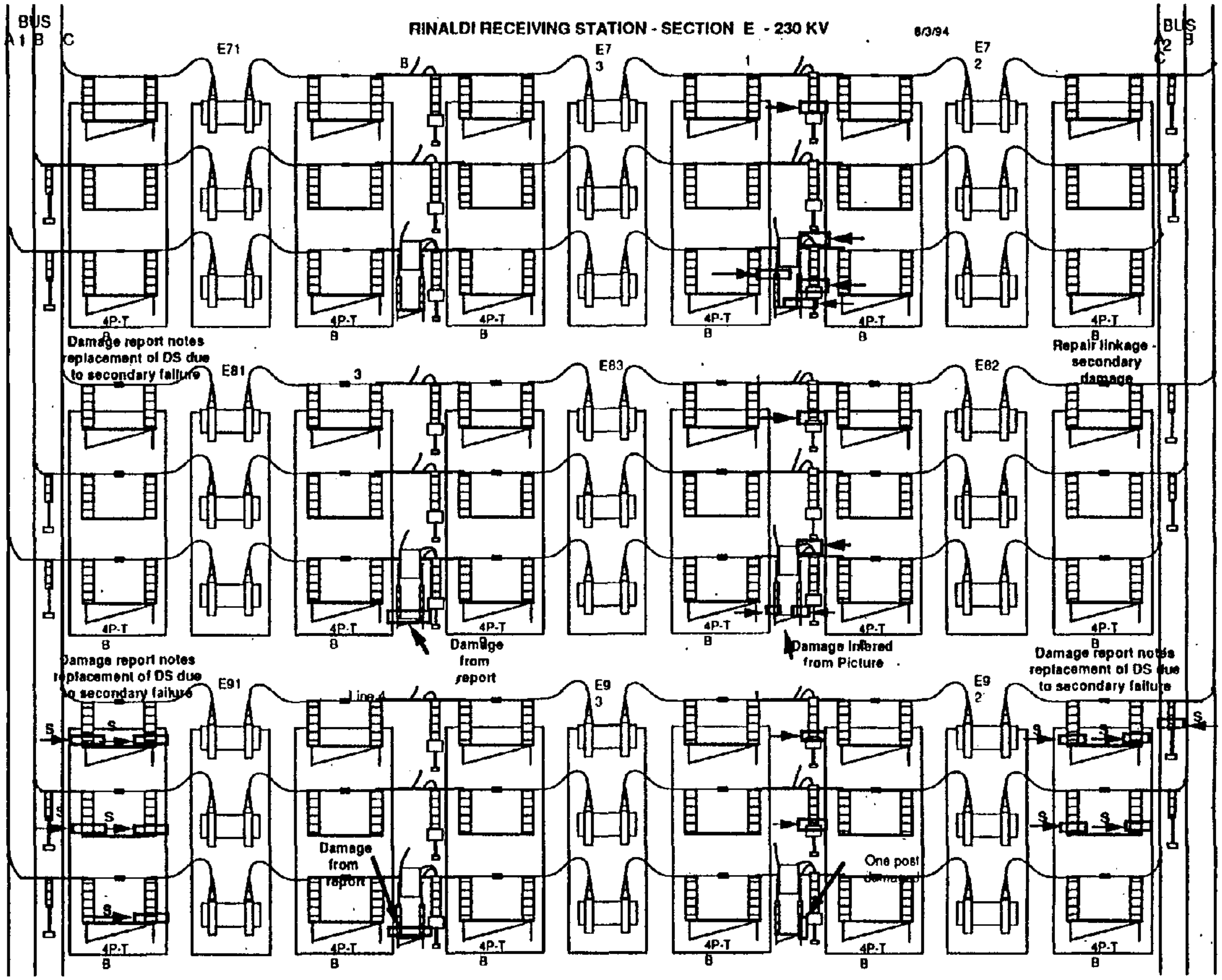


Fig. 3.52 Schematic diagram showing damage to 230 kV switchyard at Rinaldi Substation - Part 3.

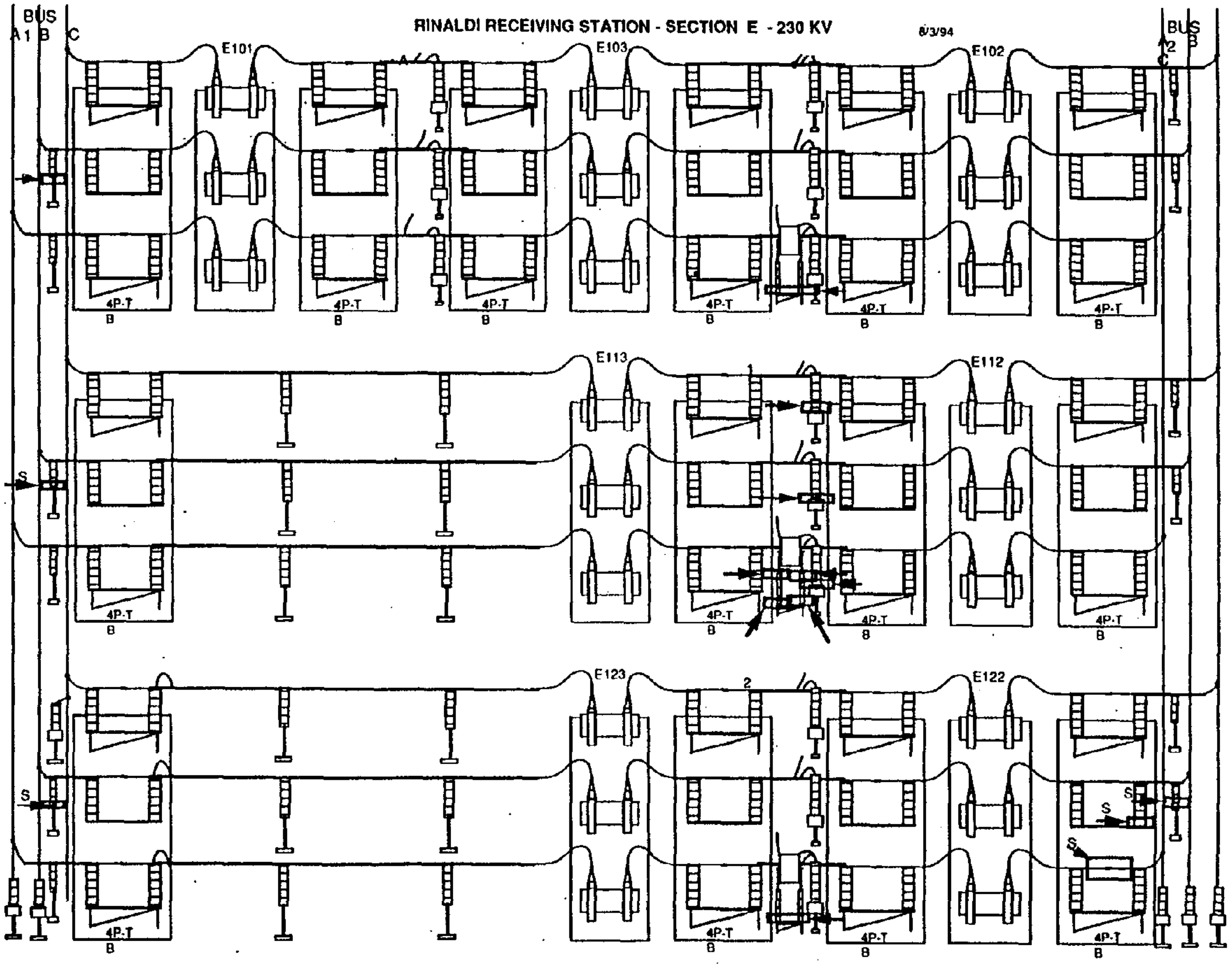


Fig.3.52 Schematic diagram showing damage to 230 kV switchyard at Rinaldi Substation - Part 4.

Rinaldi Substation has 500 kV and 230 kV switchyards. The 500 kV switchyard had both rigid and flexible bus. The 230 kV bus had heavy H-section rigid conductor suspended from post insulators in a breaker-and-half configuration. Rigid bus use typically used to connect disconnect switches at line drops.

In the 500 kV switchyard, suspended wave traps interacted with and damaged adjacent equipment. In the 230 kV switchyard post insulators supporting the rigid bus failed and sections of the bus fell on disconnect switches. There were also problems of equipment interaction with traditional pipe-type rigid bus. Several transformer bushings were damaged, but this data has not yet been tabulated. Figures 3.51 and 3.52 are detailed schematic diagrams showing damage to the 500 kV and 230 kV switchyards. Table 3.1 shows a summary of equipment performance.

Table 3.1 Summary of Equipment Damage at Rinaldi Substation

Item	Not Damaged	Damaged	Comment
Transformers			
Disconnect Switch - 500 kV		3	Vertical Break
Disconnect Switch - 500 kV		3	Center Break, Tripod Support
Disconnect Switch	10	2	Center break - Secondary failure to High Seismic
Disconnect Switch	146	15	Center Break - Secondary failures
Potential Transformer	6	0	
Current-Voltage Transformer - 500 kV	3	3	
Current-Voltage Transformer	40	14	
Wave Trap - 500 kV	3		Suspended/cable restraint
Wave Trap - 500 kV		3	Suspended/post restraint
Wave Trap	4	8	Horizontal/post supported
Wave Trap		3	Suspended/post restraint failed
Lightning Arrester - 500 kV	1	1	Post Support
Circuit Breaker	87		Dead-tank SF6

RECEIVING STATION J

Receiving Station J is a 230 kV substation with a double-bus double-breaker configuration. Strong motion data was not recorded at the site.

There was damage to transformer bushings and lightning arrester, two lengths of flexible conductor between dead-end structures fell when insulator strings failed, and porcelain on disconnect switches failed. Figures 3.53 and 3.54 are detailed schematic diagram showing damage to the 230 kV switchyard and transformers. Table 3.2 shows a summary of equipment performance.

Table 3.2 Summary of Equipment Damage at Receiving Station J

Item	Not Damaged	Damaged	Comment
Transformers	1	3	The 3-phase transformers had 9-230 kV leaking bushings, one bank had 3-34.5 kV leaking bushings, 2 banks had damage overhead conductors.
Disconnect Switch	54	18	6 lost porcelain, 12 damage unknown
Potential Transformer	6		
Current-Voltage Transformer	12		
Wave Trap	7	1	
Lightning Arrester	3	9	Boom-mounted off transformer
Circuit Breaker	72		Bulk-oil type

RECEIVING STATION T

Receiving Station T operates at 230 kV and has no circuit breakers or traditional switchyard. Strong motion data was not recorded at the site. Transformer bushings and disconnect switches were damaged. Table 3.3 shows a summary of equipment performance.

Table 3.3 Summary of Equipment Damage at Receiving Station T

Item	Not Damaged	Damaged	Comment
Transformers	1	2	3-phase - 6 leaking bushings, 6 failed arresters, failed conservator support
Lightning Arrester	3	6	3-post mounted, 6 boom mounted failed - 2 at standoff, 4 at arrester

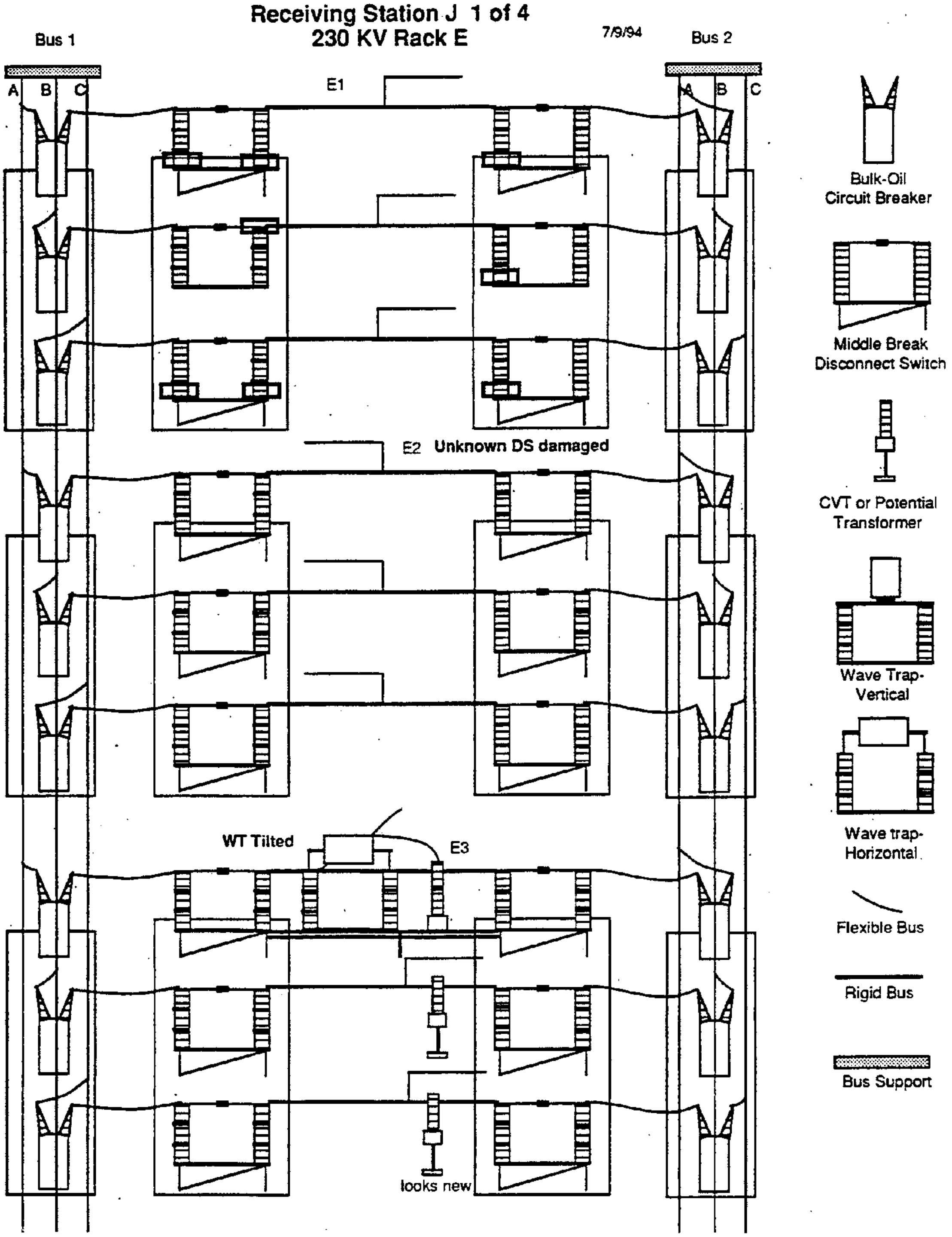


Fig. 3.53 Schematic diagram showing damage to 230 kV switchyard at Receiving Station J - Part 1.

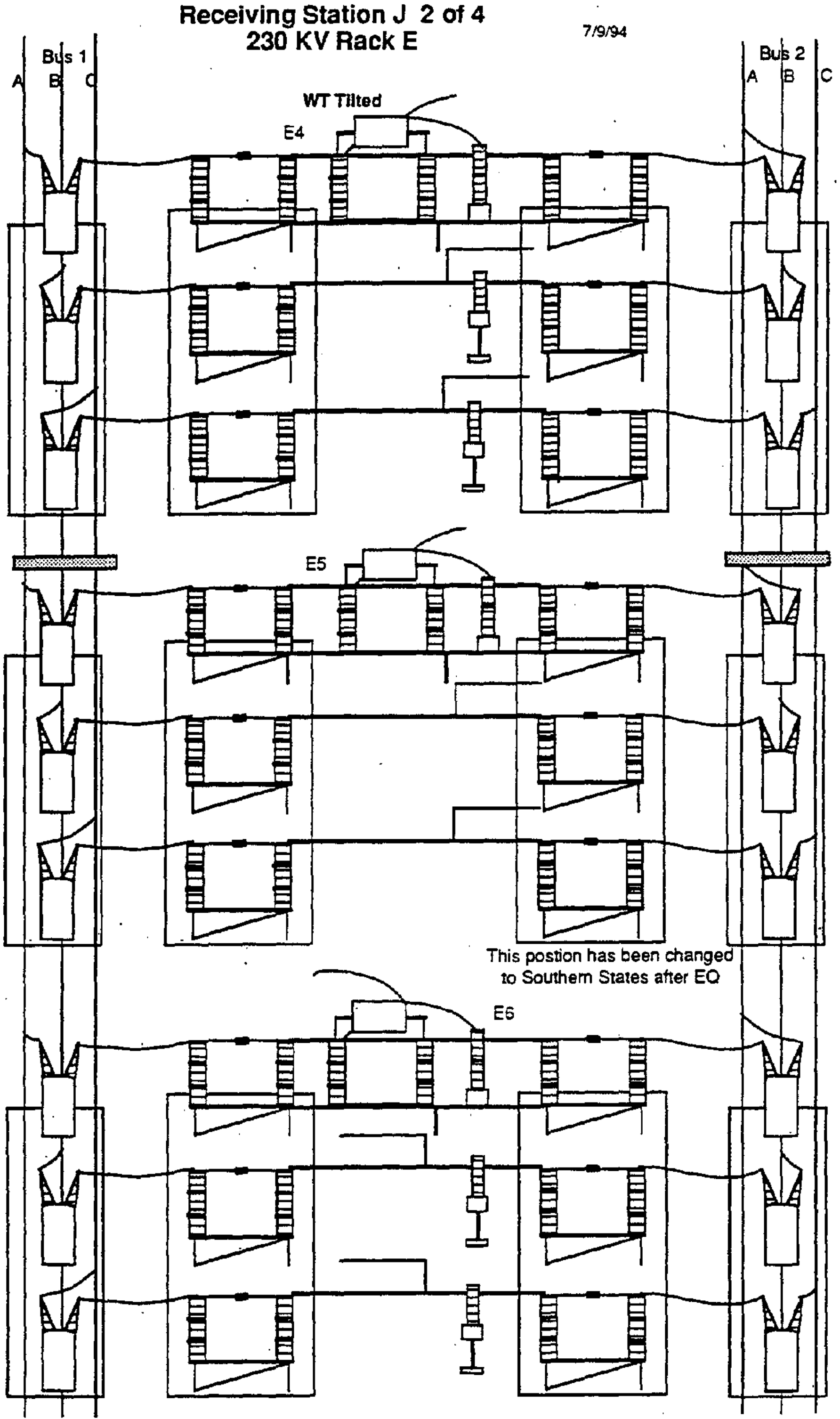


Fig. 3.53 Schematic diagram showing damage to 230 kV switchyard at Receiving Station J - Part 2.

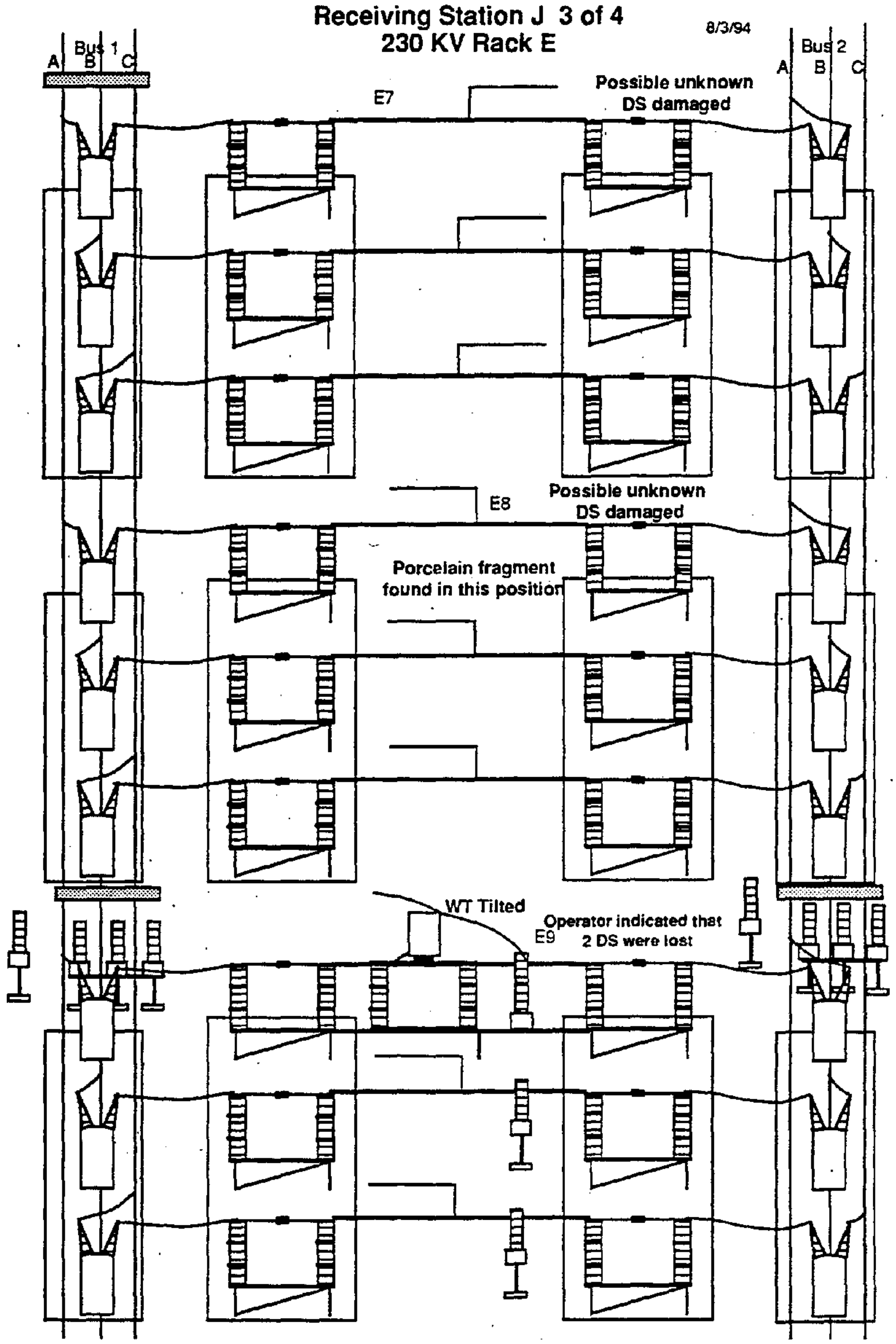


Fig. 3.53 Schematic diagram showing damage to 230 kV switchyard at Receiving Station J - Part 3.

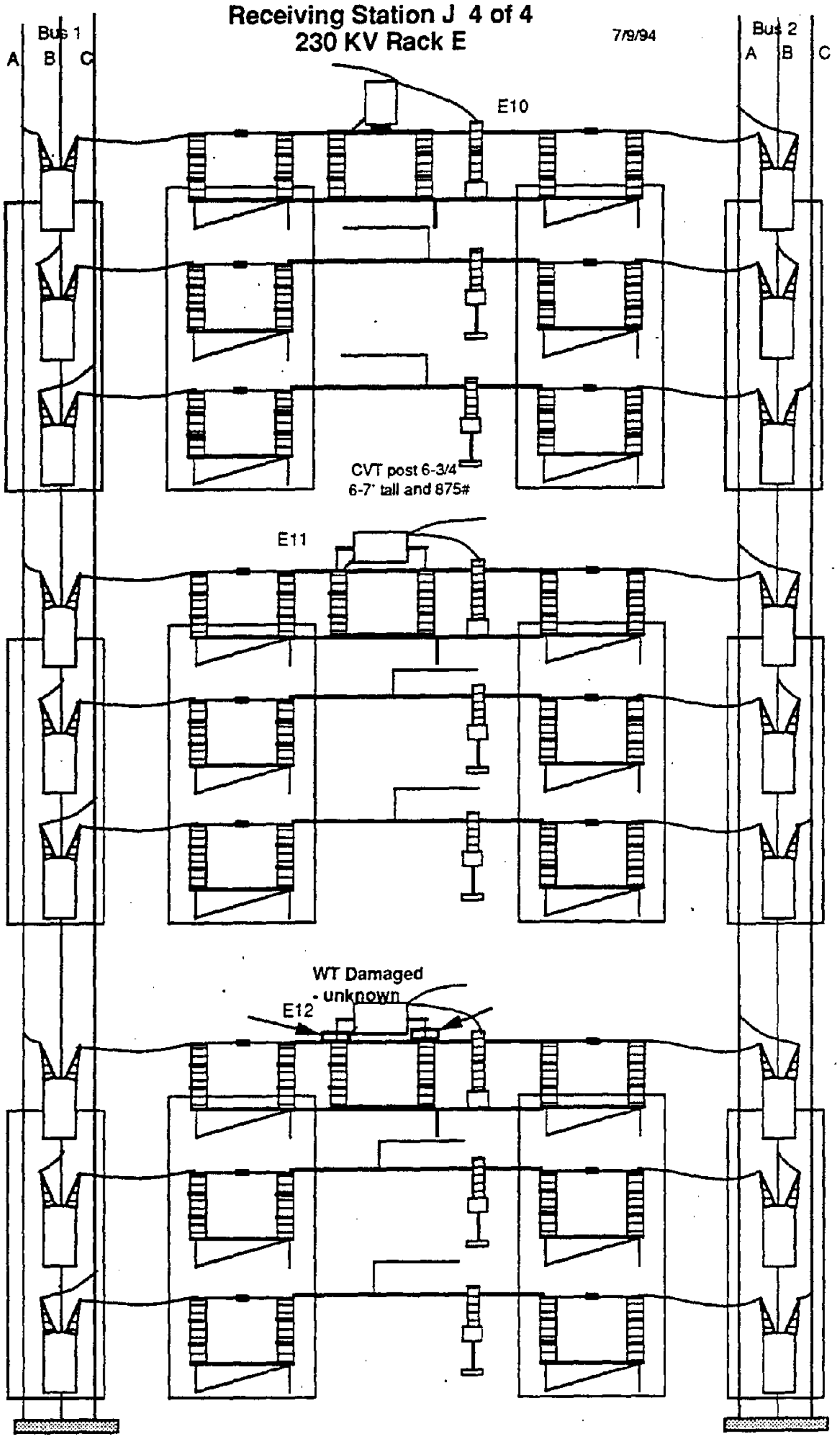


Fig. 3.53 Schematic diagram showing damage to 230 kV switchyard at Receiving Station J - Part 4.

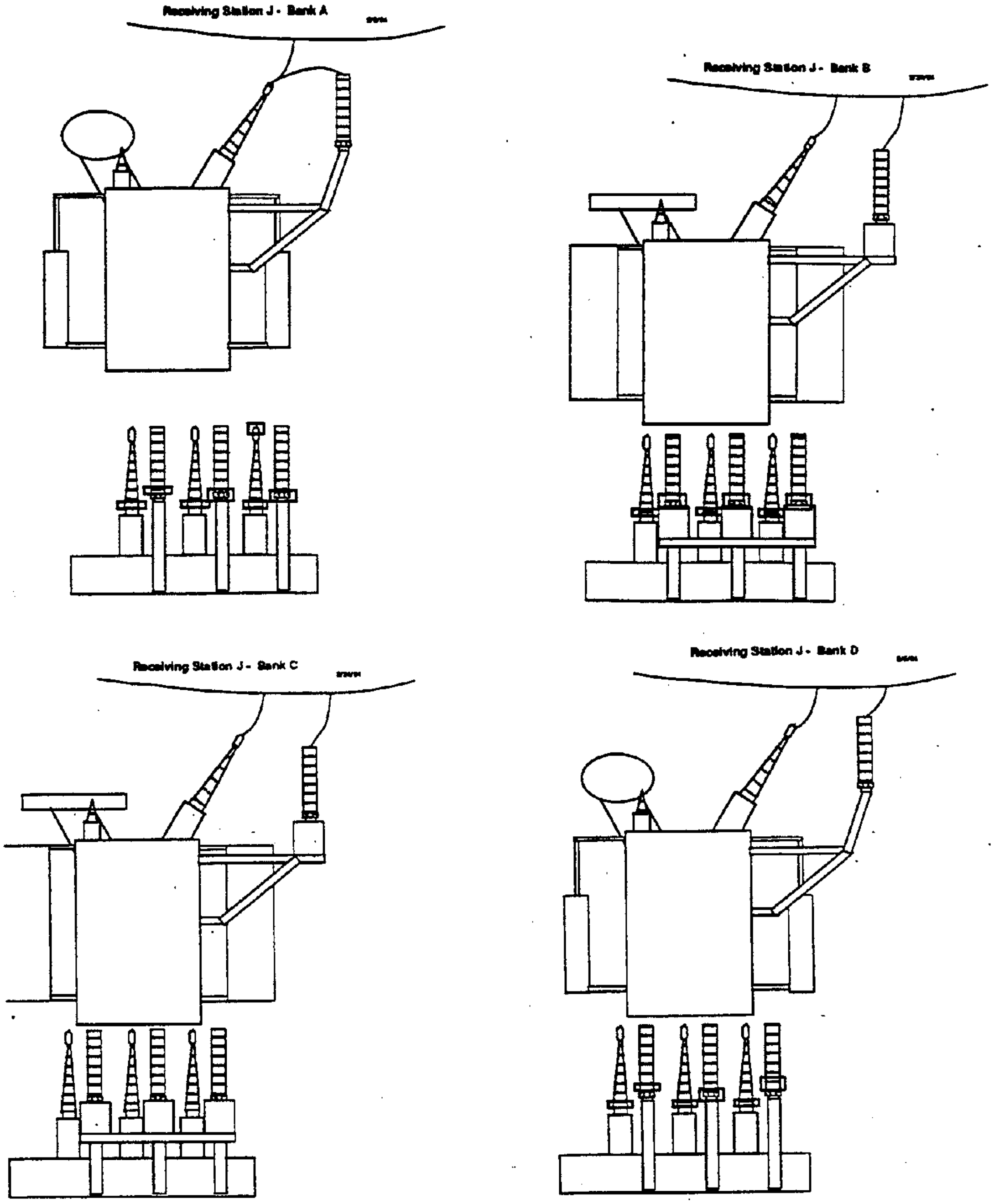


Fig. 3.54 Schematic diagram showing damage to transformers at Receiving Station J.

RECEIVING STATION U

Receiving Station U is a 230 kV substation with a breaker-and-a-half bus configuration. Strong motion data was not recorded at the site. There was damage to transformer bushings, lightning arresters, a wave trap, wave trap supports and disconnect switches. Figures 3.55 and 3.56 are detailed schematic diagram showing damage to the 230 kV switchyard and transformers. Table 3.4 shows a summary of equipment performance.

Table 3.4 Summary of Equipment Damage at Receiving Station U

Item	Not Damaged	Damaged	Comment
Transformers	1	3	1 bank had 3 leaking bushings, 1 bank had failed conservator support,
Disconnect Switch	24	26	Post insulators failed
Disconnect Switch		57	Bend operating mechanism
Disconnect Switch	3	9	Rigid bus with flexible end - post insulators failed
Potential Transformer	2		
Current-Voltage Transformer	15	3	
Wave Trap	1	3	Horizontal -post supported
Lightning Arrester	7	2	Mounted on pothead support structure - arrester failed
Lightning Arrester	3	9	5 failed at standoff, 4 at arrester
Pothead	9		
Circuit Breaker	54		Bulk-oil type

RECEIVING STATION E

Peak acceleration at the site was 0.52 g, the peak velocity was 32 cm/sec., and the peak displacement was 6 cm. Ground motion records and spectra for the main event are given in Fig. 3.57. Receiving Station E has 500 kV and 230 kV switchyards. The 500 kV switchyard has flexible bus. The 230 kV switchyard had a breaker-and-a-half bus configuration.

Lightning arresters, circuit switchers and a wave trap and disconnect switch were damaged. Suspended wave traps interacted with and damaged one post insulator restraint post. There was relatively little damage in the 230 kV switchyard. Figure 3.58 is a detailed schematic diagram showing damage to the 500 kV switchyards. Table 3.5 shows a summary of equipment performance.

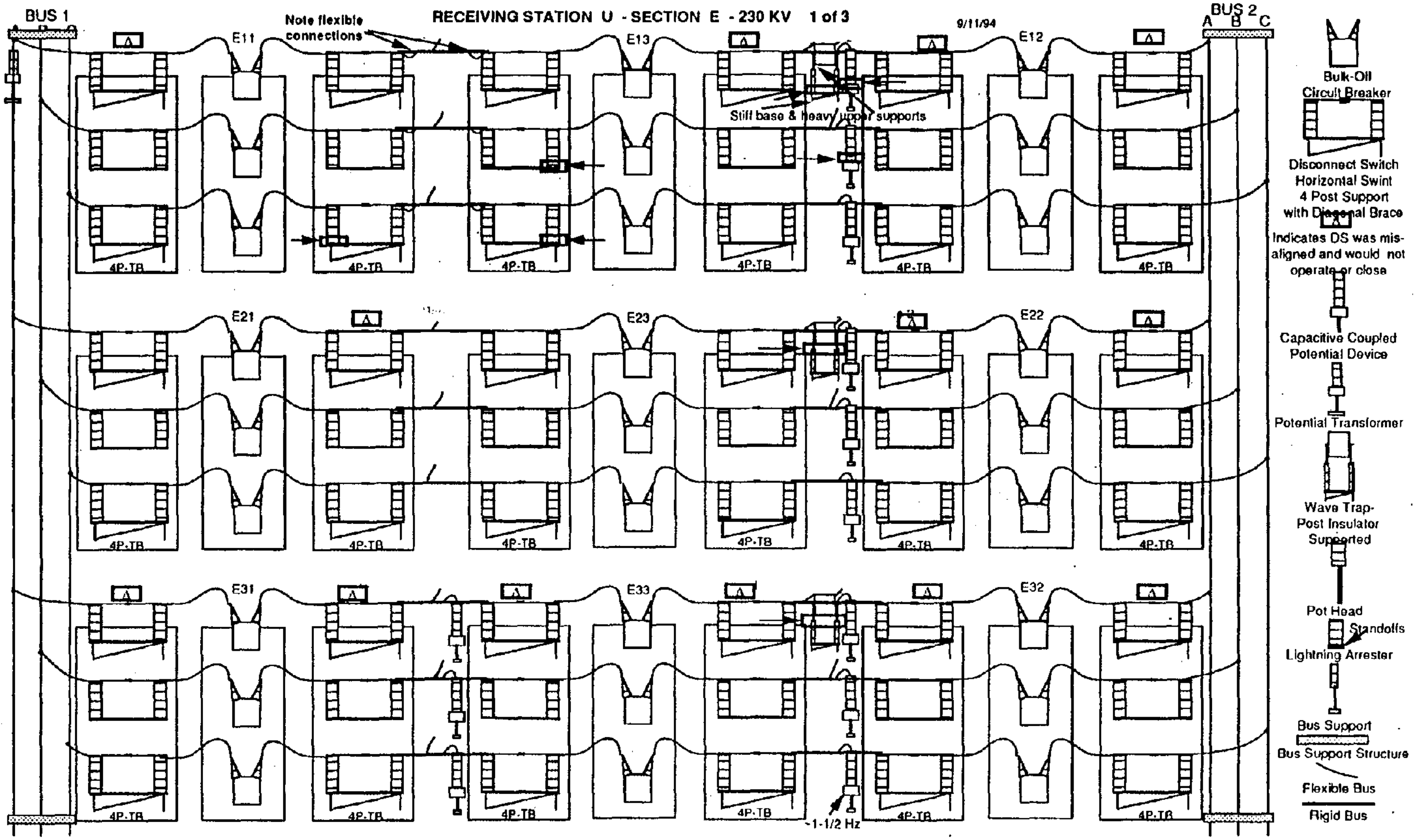


Fig.3.55 Schematic diagram showing damage to 230 kV switchyard at Receiving Station U - Part 1.

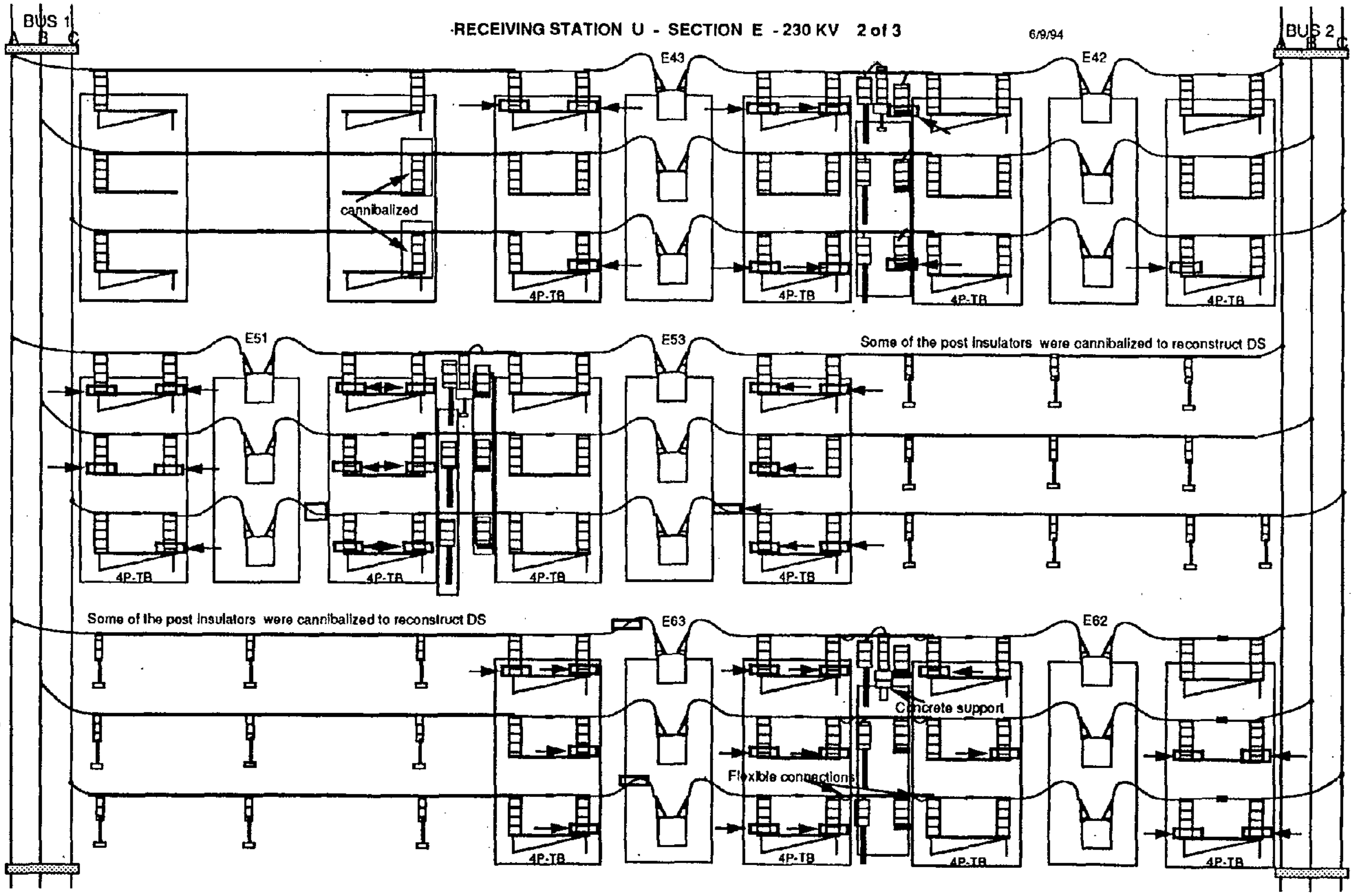


Fig. 3.55 Schematic diagram showing damage to 230 kV switchyard at Receiving Station U - Part 2.

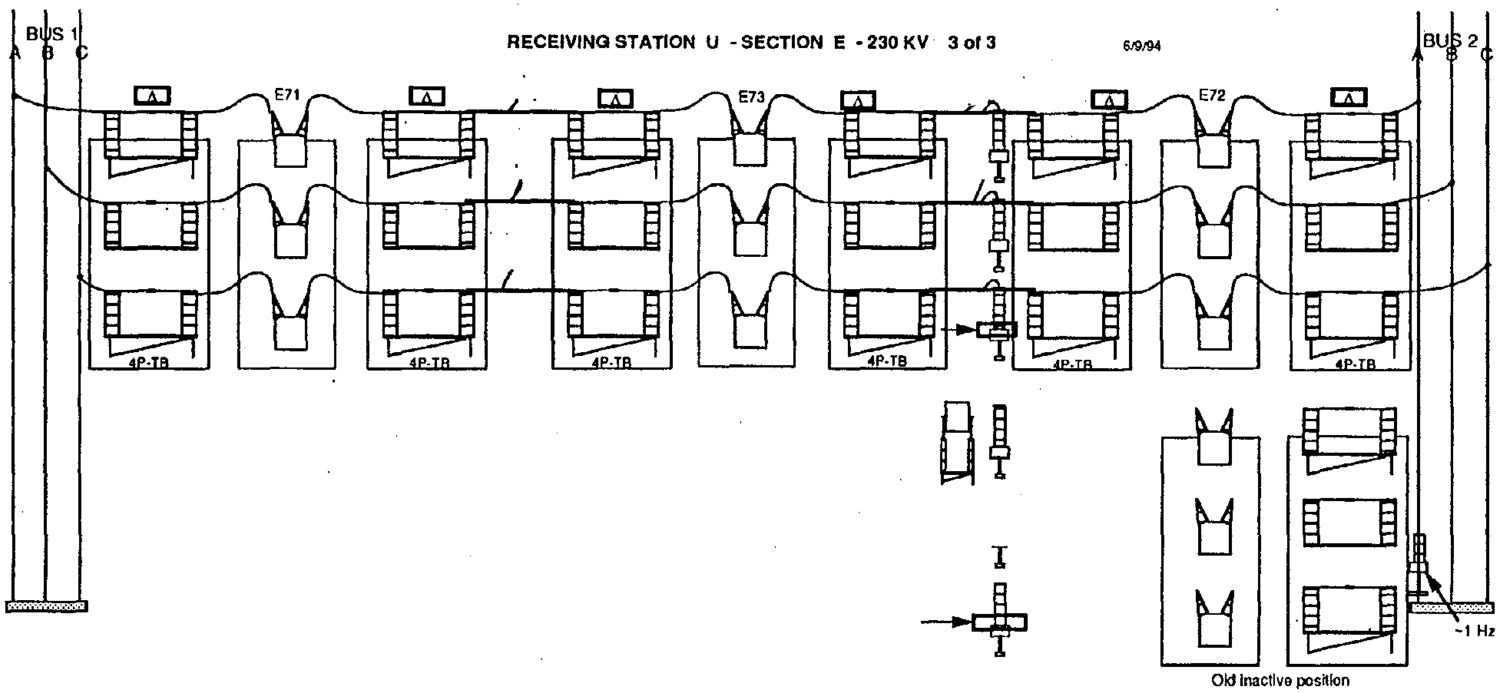


Fig.3.55 Schematic diagram showing damage to 230 kV switchyard at Receiving Station U - Part 3.

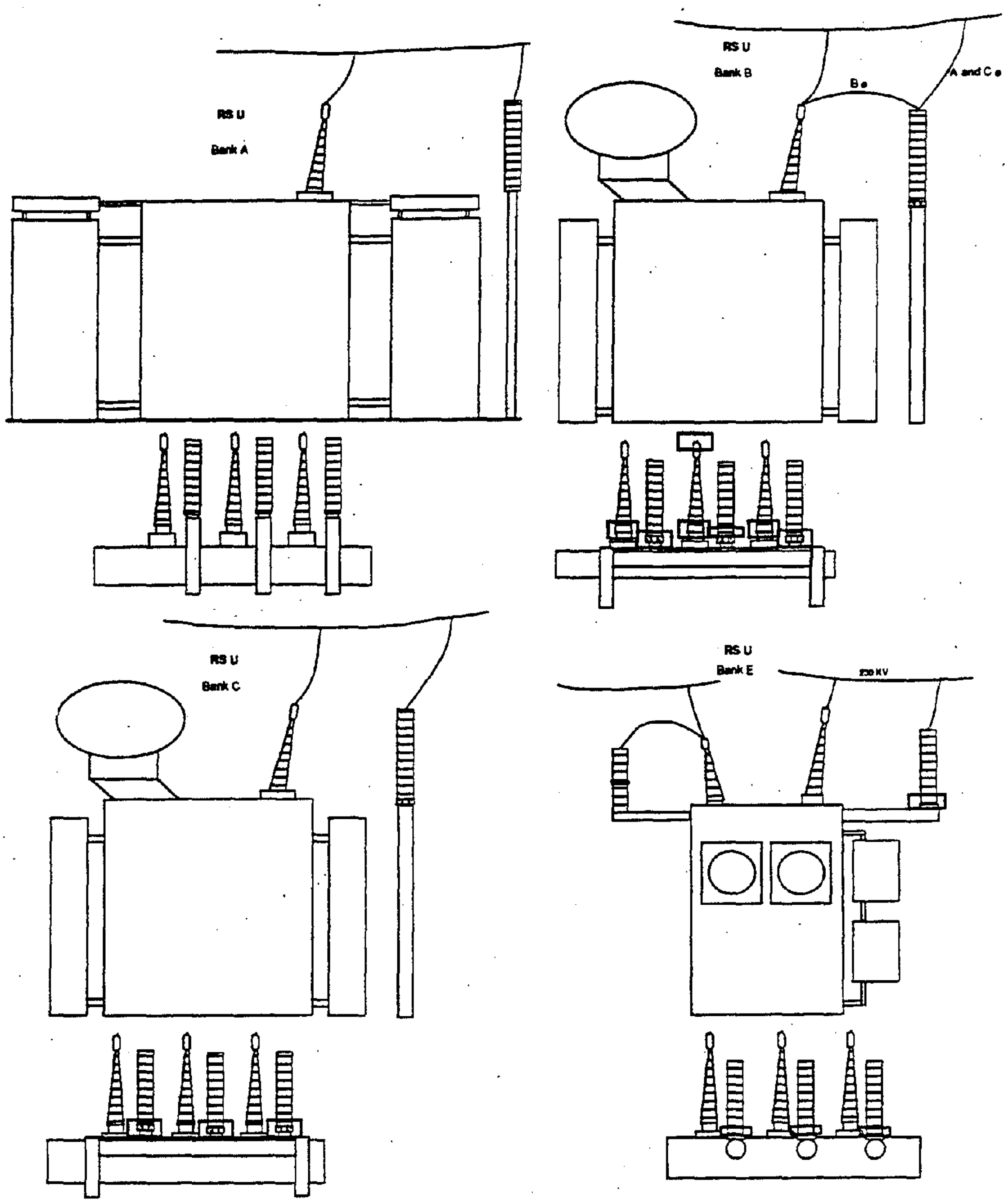


Fig.3.56 Schematic diagram showing damage to transformers at Receiving Station U.

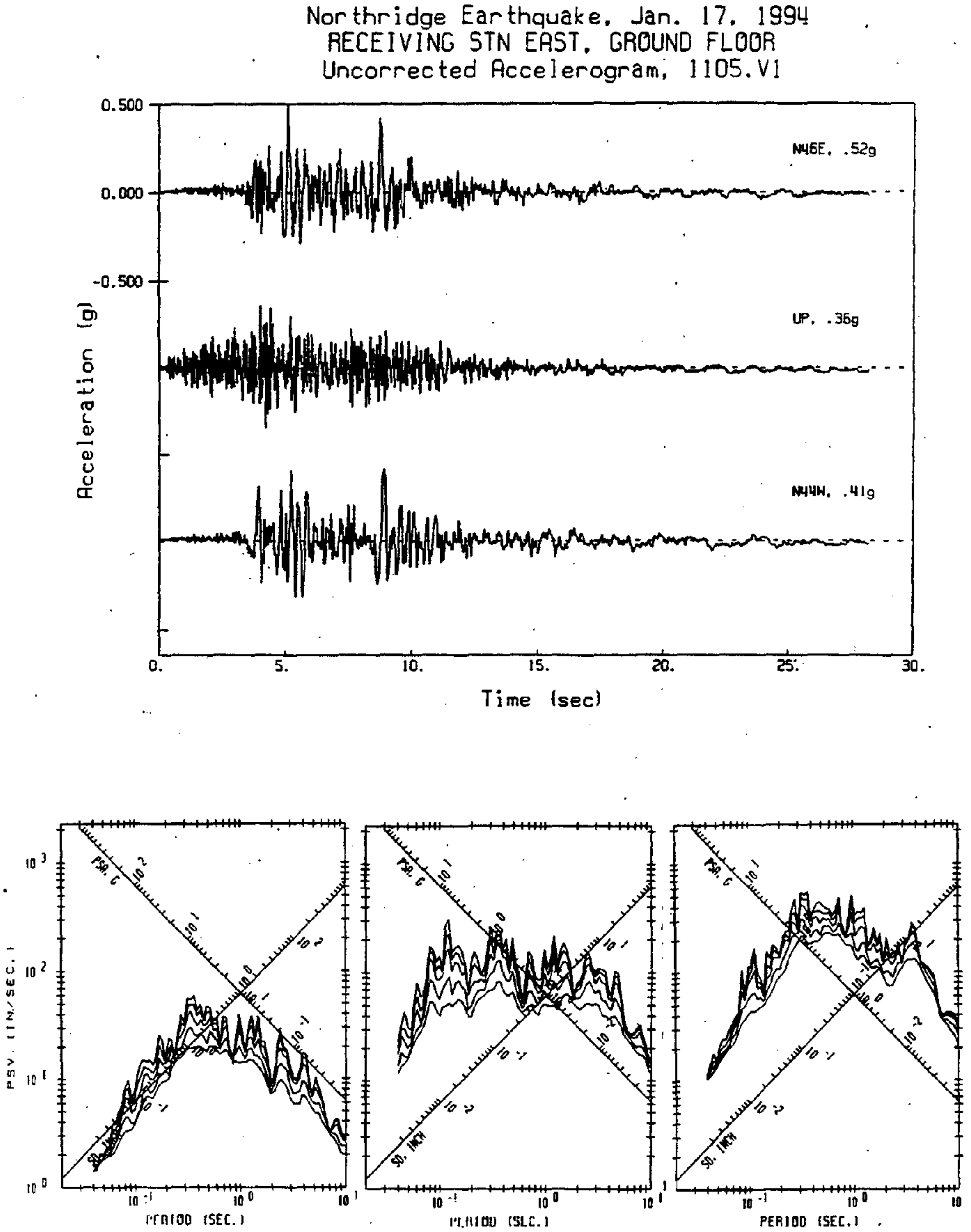


Fig.3.57 Ground motion records recorded at Receiving Station E and response spectra.

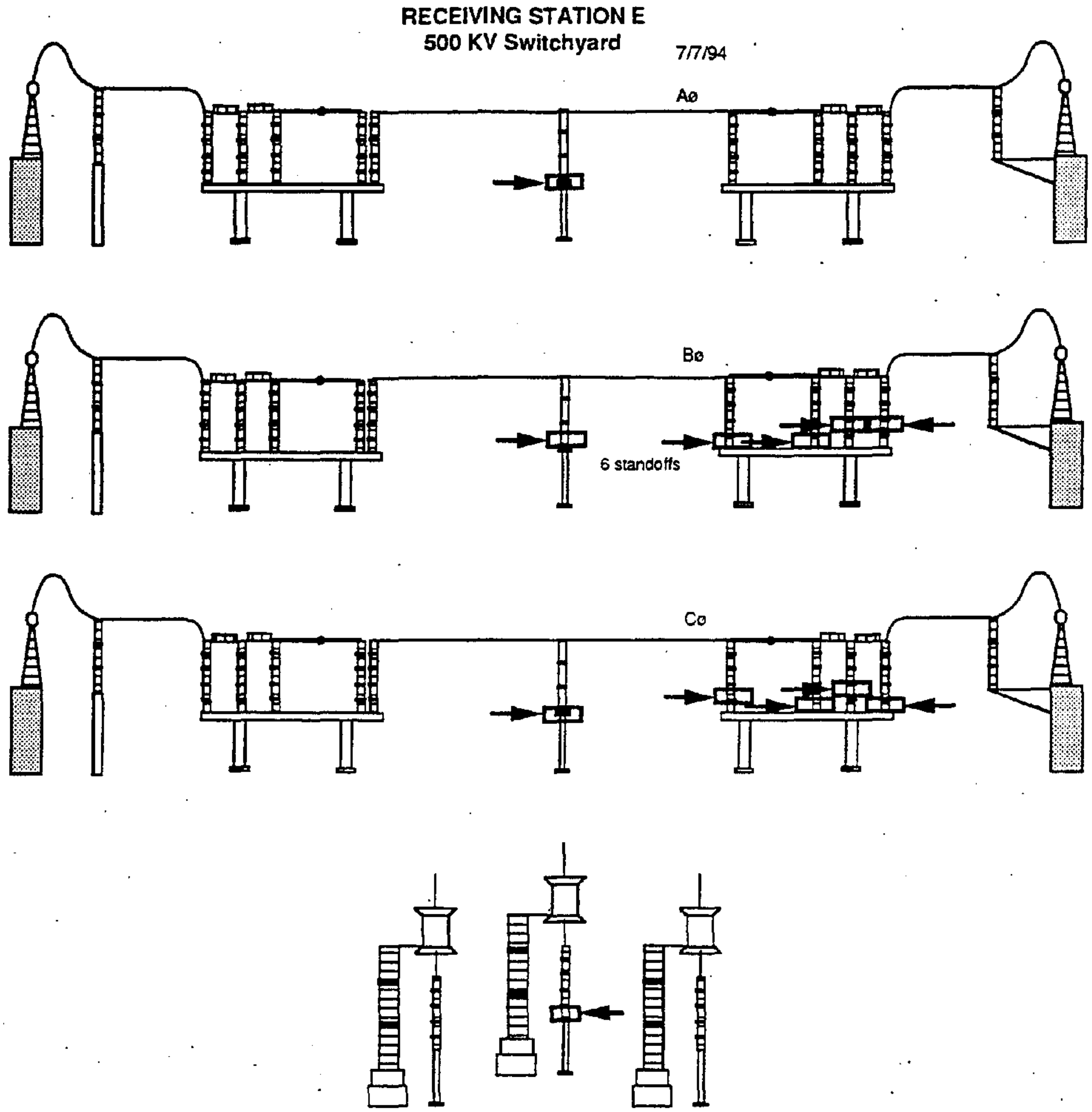


Fig. 3.58 Schematic diagram showing damage to 500 kV switchyard at Receiving Station E.

Table 3.5 Summary of Equipment Damage at Receiving Station E

Item	Not Damaged	Damaged	Comment
Transformers - 500 -230 kV	6		Single-phase
Transformers -230-34.5 kV	5	2	3-phase, lost arresters
Circuit Switcher -500 kV	3	3	Post insulators failed, base bolts stretched
Disconnect Switch	119	1	Post insulator failed
Potential Transformer	1	1	
Current-Voltage Transformer	27		Column and frame supported
Wave Trap	4	1	Post supported - post failed
Lightning Arrester 500 kV		3	Post supported
Lightning Arrester 230 kV	18	3	Boom supported
Pothead	9		
Circuit Breaker	114		Bulk-oil type

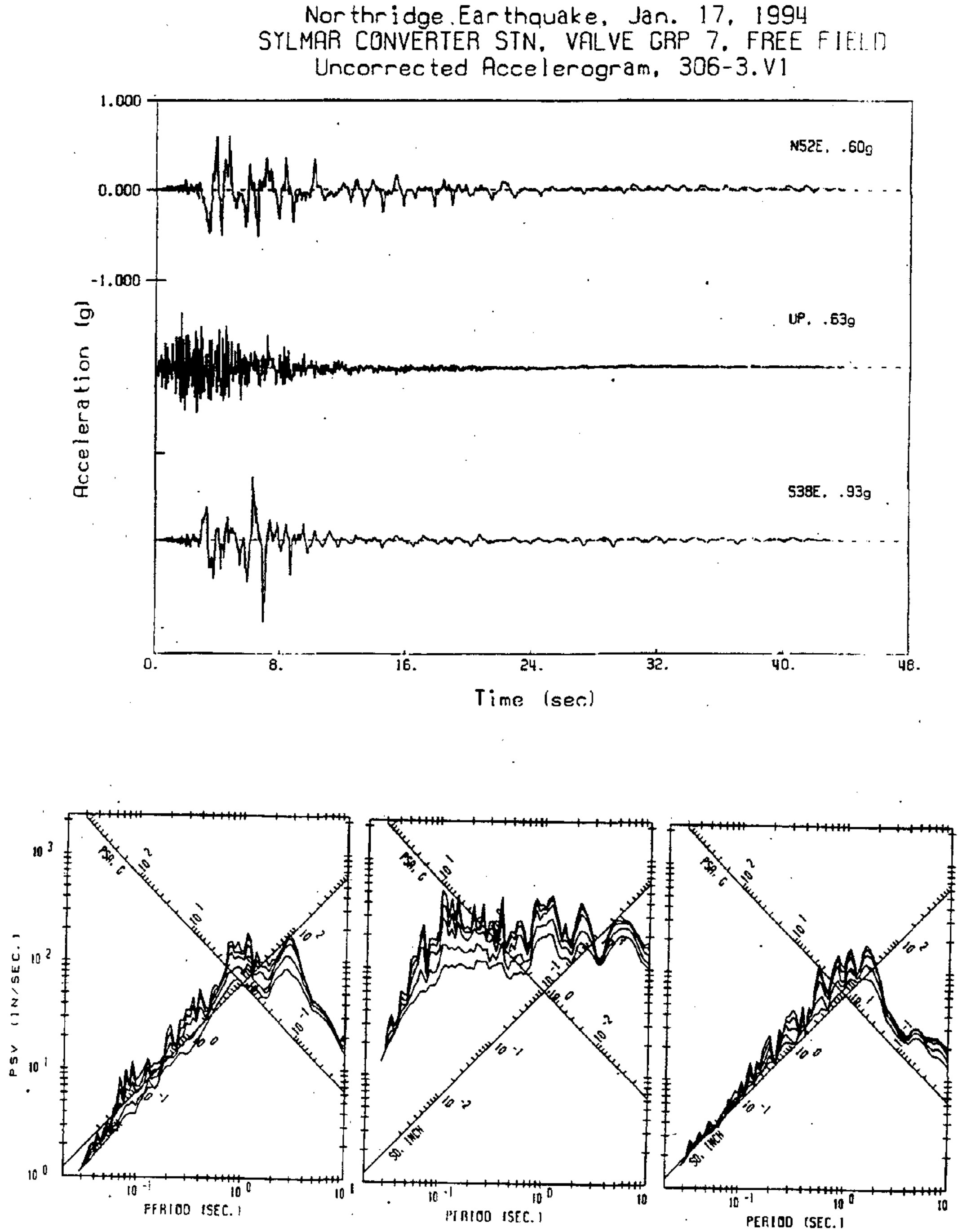
SYLMAR SWITCHING STATION

Peak acceleration at the site was 0.93 g, the peak velocity was 117 cm/sec., and the peak displacement was 40 cm. Ground motion records and spectra for the main event are given in Fig. 3.59.

Sylmar Switching Station is a 230 kV switchyard with a breaker-and-a-half bus configuration. The welds at one end of one of the transformers failed, but operation was not effected. Figure 3.60 is a detailed schematic diagrams showing damage to the 230 kV switchyard. Table 3.6 shows a summary of equipment performance.

CASTAIC GENERATING STATION TRANSFORMERS

Castaic Generating Facility is a pumped storage plant. The switchyard had no damage and it was not inspected. A strong motion record recorded at the dam abutment had a peak acceleration of 0.36 g, the peak velocity was 29 cm/sec., and the peak displacement was 10 cm. Ground motion records and spectra for the main event are given in Fig. 3.61. There was damage to two transformers. Figure 3.62 is a schematic diagrams showing damage to the 230 kV transformers. Table 3.7 shows a summary of equipment performance.



Northridge Earthquake, Jan. 17, 1994
SYLMAR CONVERTER STN, VALVE GRP 7, FREE FIELD
Uncorrected Accelerogram, 306-3.V1

Fig.3.59 Ground motion records recorded at Sylmar Switching Station and response spectra.

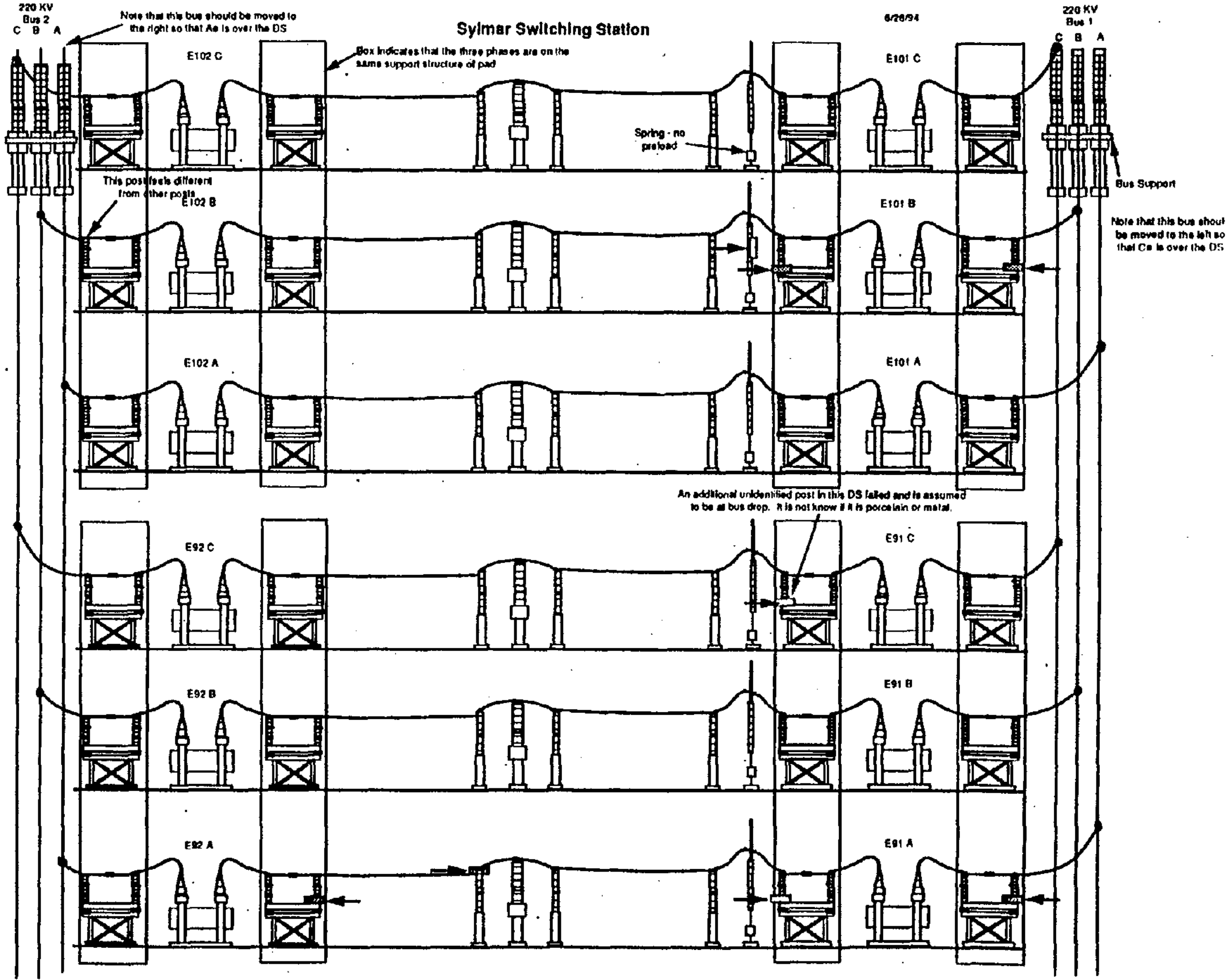


Fig.3.60 Schematic diagram showing damage to 230 kV switchyard at Sylmar Switching Station - Part 1.

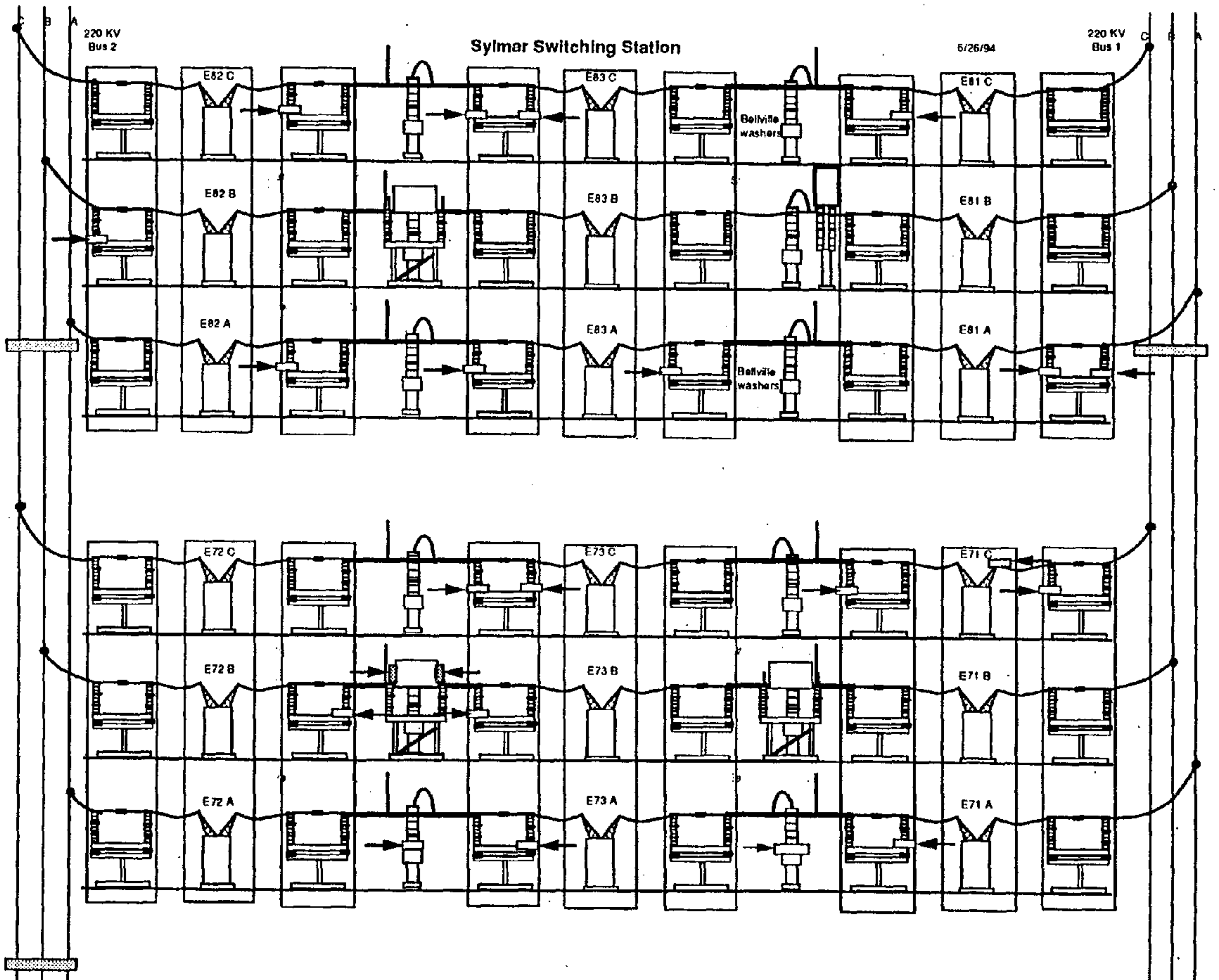


Fig. 3.60 Schematic diagram showing damage to 230 kV switchyard at Sylmar Switching Station - Part 2.

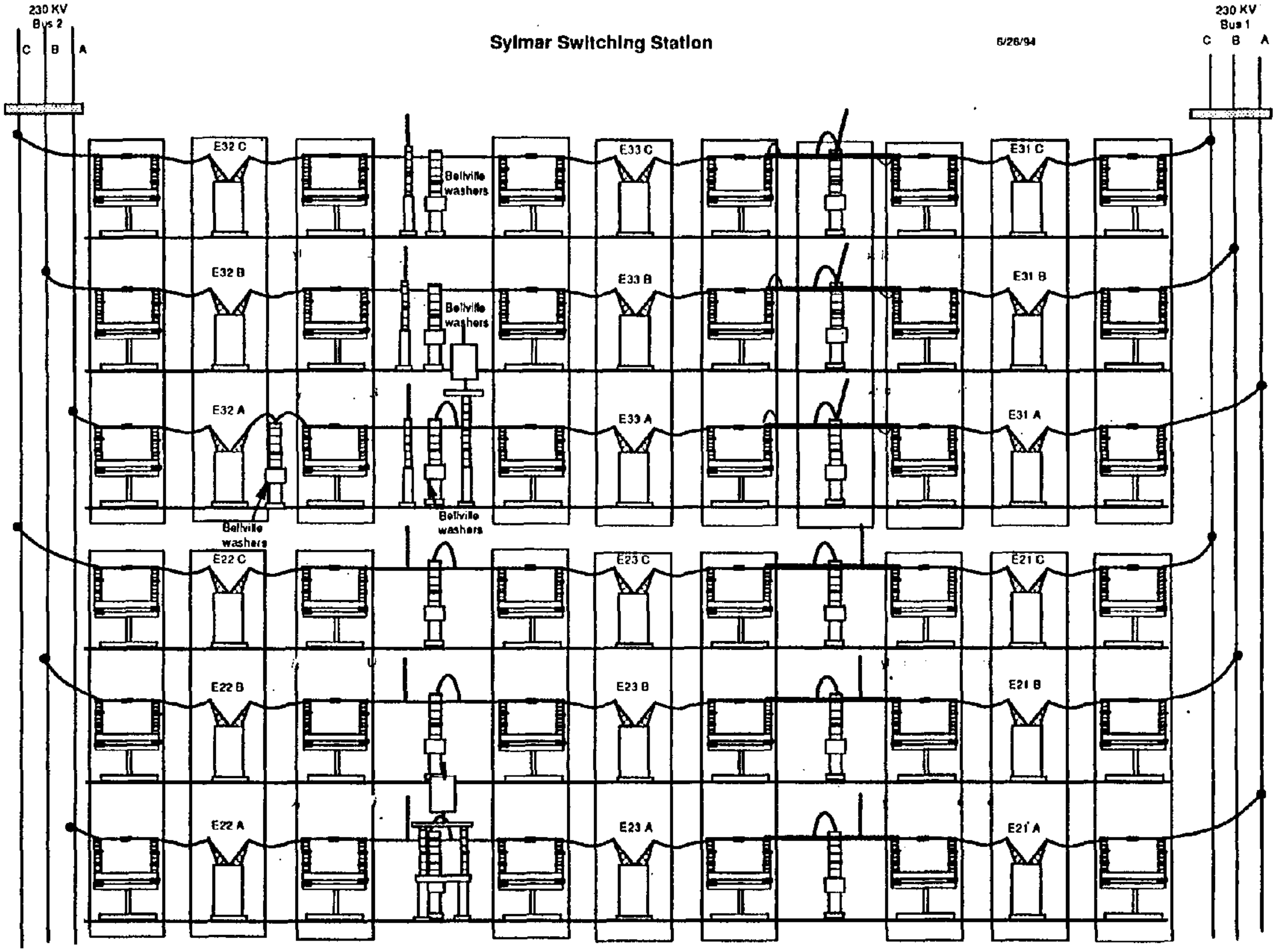


Fig. 3.60 Schematic diagram showing damage to 230 kV switchyard at Sylmar Switching Station - Part 3.

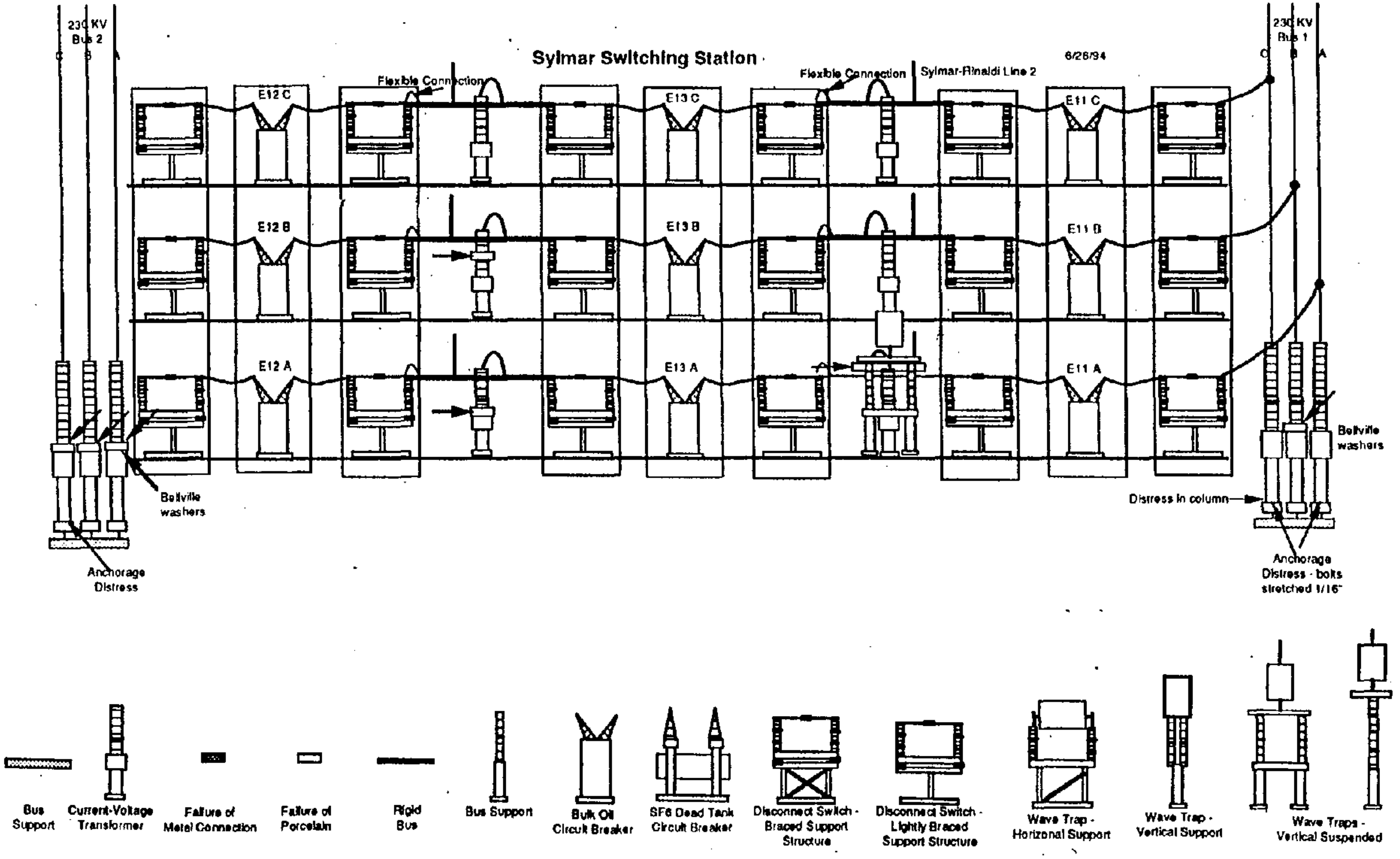


Fig.3.60 Schematic diagram showing damage to 230 kV switchyard at Sylmar Switching Station - Part 4.

Table 3.6 Summary of Equipment Damage at Sylmar Switching Station

Item	Not Damaged	Damaged	Comment
Transformers 230-220 kV	1	1	3-phase - welded anchorage failed
Disconnect Switch	18	6	Seismic Spec. - insulators failed
Disconnect Switch	83	19	Insulators failed
Potential Transformer	6		Still support column
Potential Transformer	2	4	Regular support with Bellvilles
Current-Voltage Transformer	6		Stiff support - Bellvilles
Current-Voltage Transformer	10		Stiff support
Current-Voltage Transformer	18	3	Regular support - 6-3/4" pipe
Wave Trap	1		Vertical -post supported
Wave Trap	2	1	Horizontal-post supported
Wave Trap	2	1	Suspended-restraint bolts failed
Lightning Arrester	12		Boom-mounted
Circuit Breaker	12		Dead-tank/SF6
Circuit Breaker	45		Bulk-oil type

PARDEE SWITCHING STATION

Pardee is a 230 kV switching station and has no transformers. There was a strong motion recording at the site with a peak acceleration of 0.56 g. Ground motion records and spectra for the main event are given in Fig. 3.63. The switchyard has a breaker-and-a-half bus configuration. All live-tank circuit breakers were damaged. Disconnect switches were damaged in an unusual way in that the plate that supported the post insulator stacks deformed so that the disconnect switches could not be closed. Dear-end structures were damaged. Figure 3.64 is a detailed schematic diagram showing damage to the 230 kV switchyard. Table 3.8 shows a summary of equipment performance.

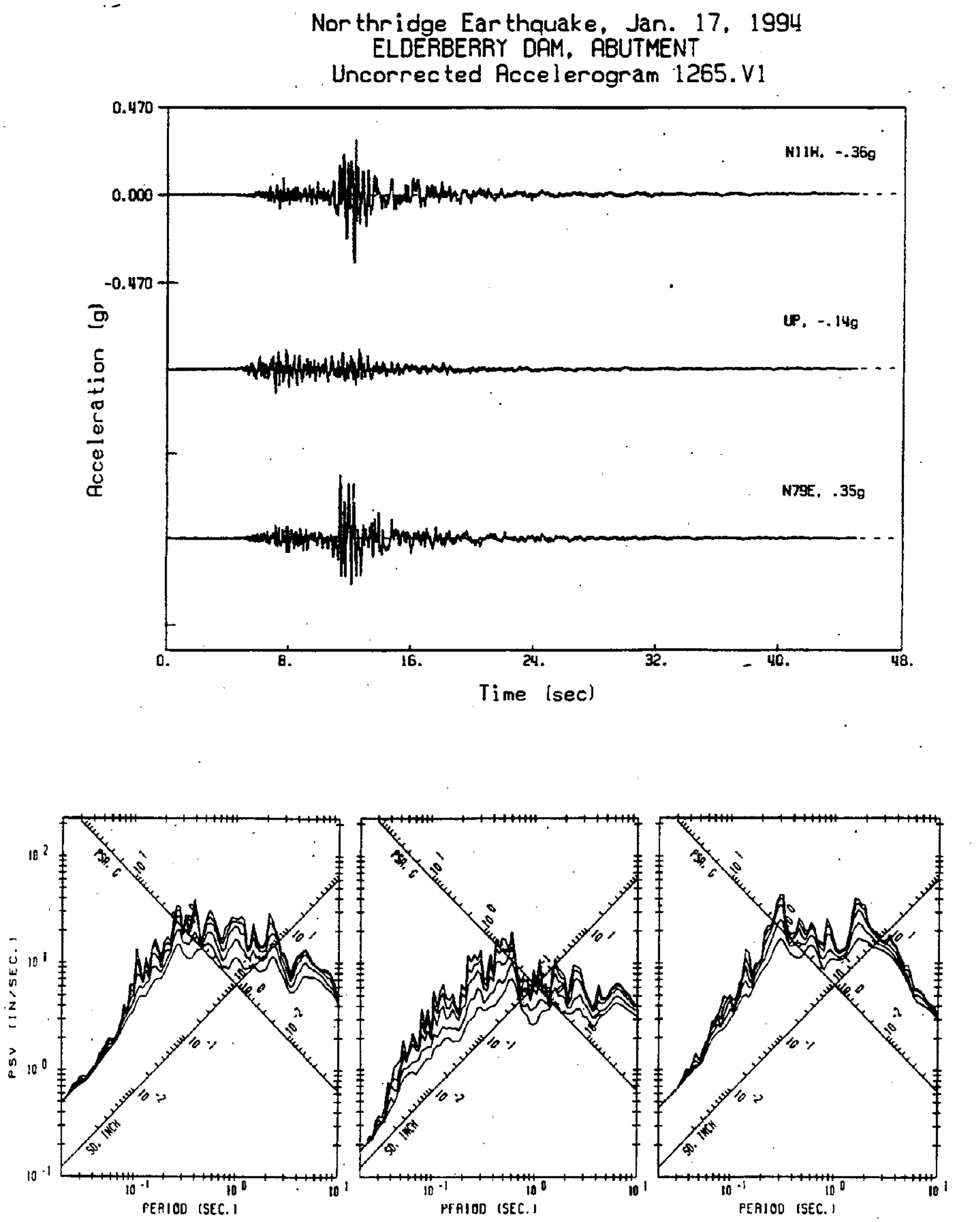


Fig.3.61 Ground motion records recorded at Castaic Generating Station and response spectra.

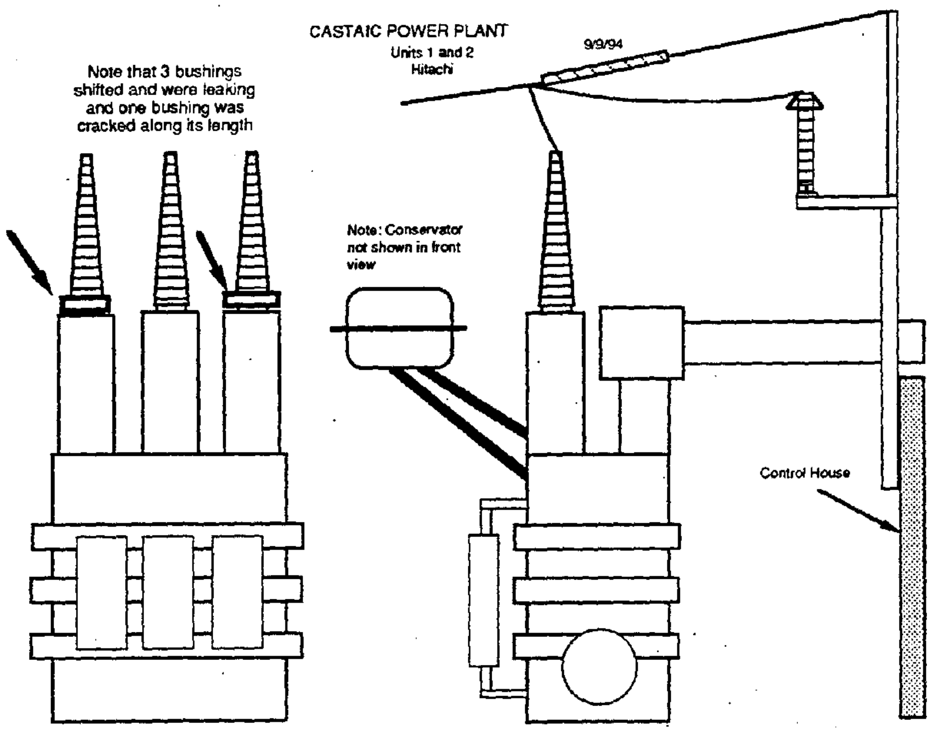
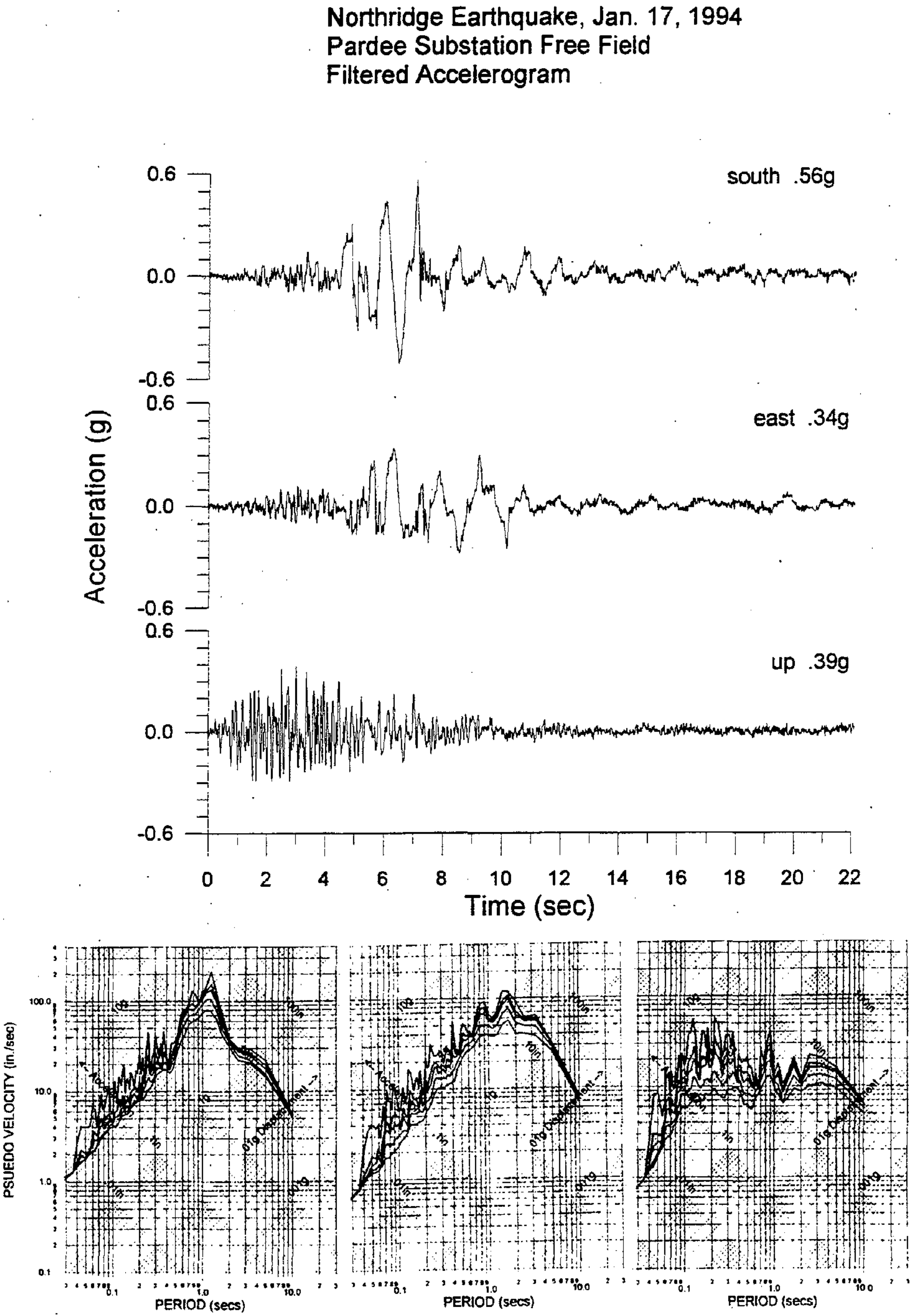


Fig.3.62 Schematic diagram showing damage to 230 kV transformers at Castaic Generating Station.



Northridge Earthquake, Jan. 17, 1994
Pardee Substation Free Field
Filtered Accelerogram

Fig. 3.63 Ground motion records recorded at Pardee Substation and their response spectra.

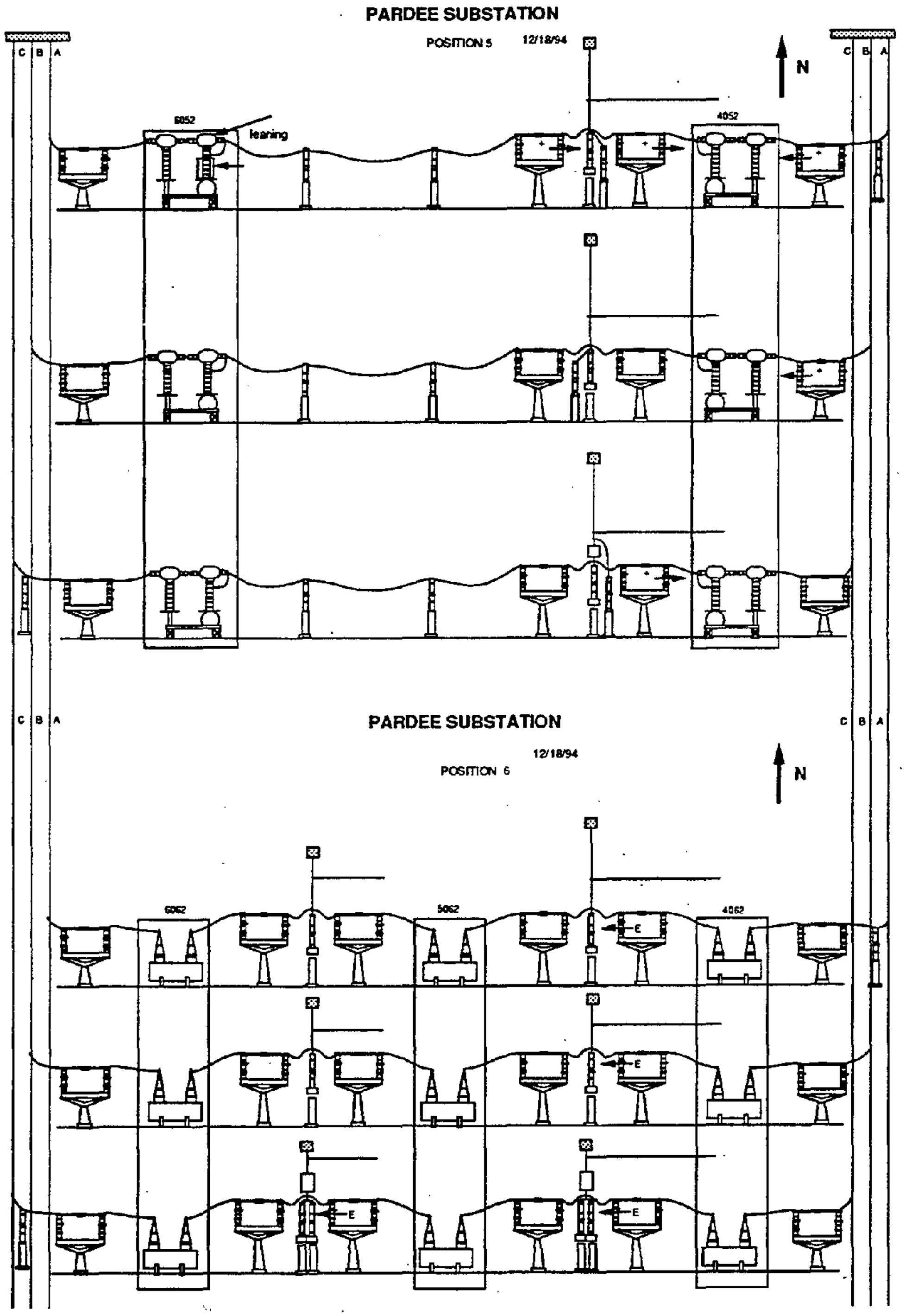


Fig. 3.64 Schematic diagram showing damage to 230 kV switchyard at Pardee Substation - Part 1.

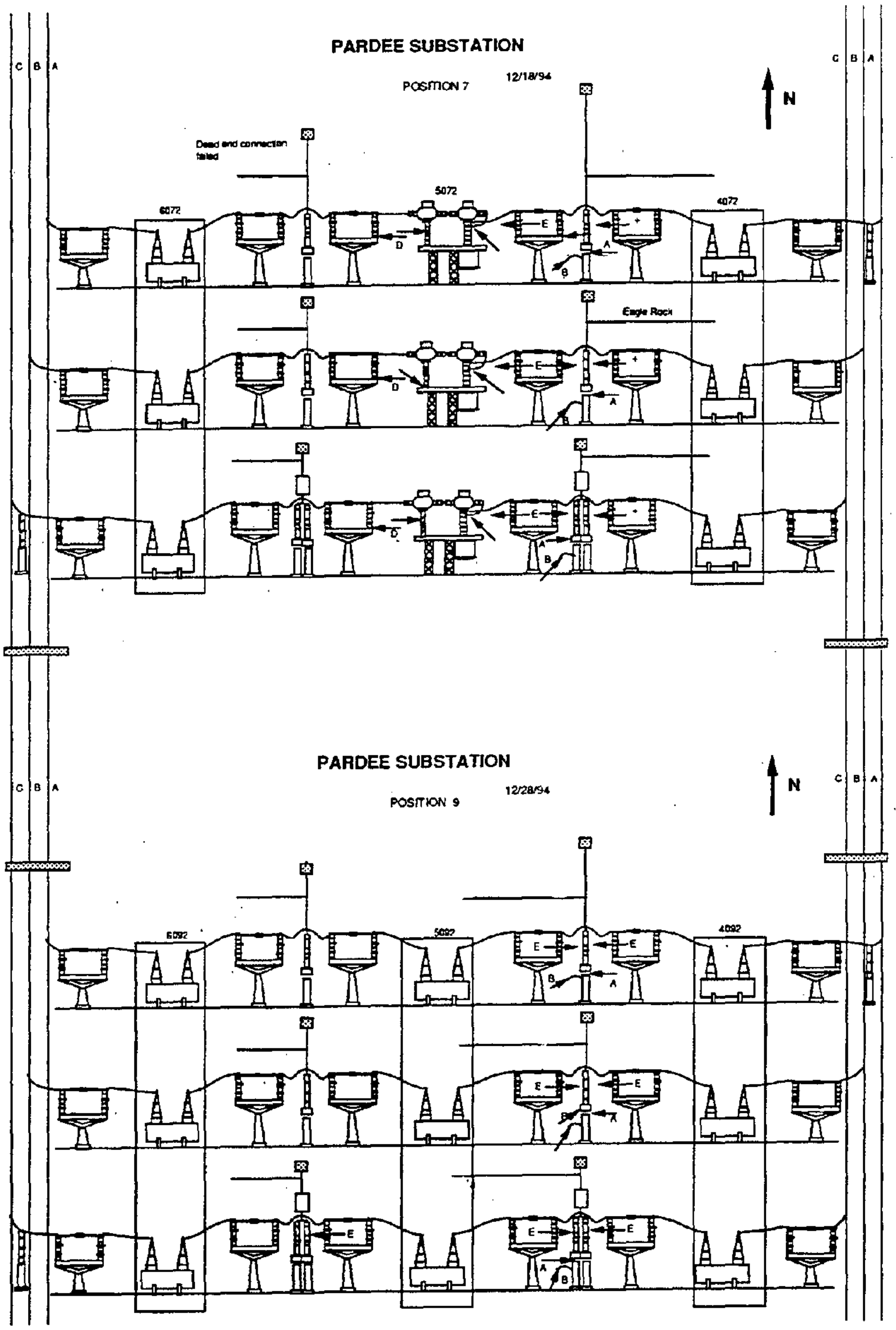


Fig. 3.64 Schematic diagram showing damage to 230 kV switchyard at Pardee Substation - Part 2.

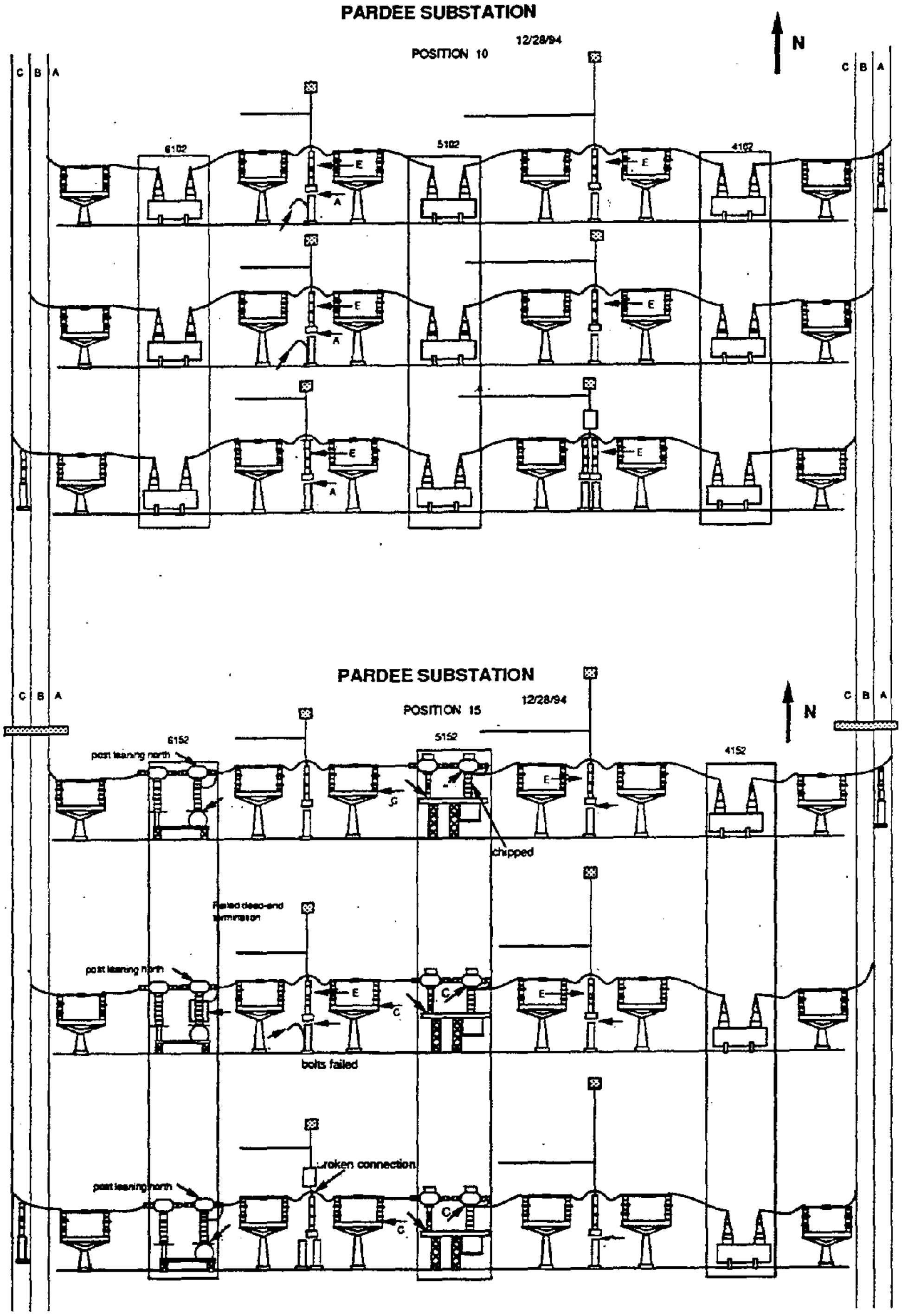


Fig. 3.64 Schematic diagram showing damage to 230 kV switchyard at Pardee Substation - Part 3.

Table 3.7 Summary of Equipment Damage at Castaic Generating Station

Item	Not Damaged	Damaged	Comment
Transformers - 230 kV	5	2	3-phase - 3 bushings leaked, 1 cracked
Lightning Arrester	20	1	

VINCENT SUBSTATION

Vincent Substation is a 500 kV substation with a breaker-and-a-half bus configuration. Ground motion records and spectra for the main event are given in Fig. 3.65. There was damage to transformer radiators, anchorage, and lightning arresters, but a detailed analysis is not yet complete. Figure 3.66 is a detailed schematic diagram showing damage to the 230 kV switchyard. Table 3.9 shows a summary of equipment performance.

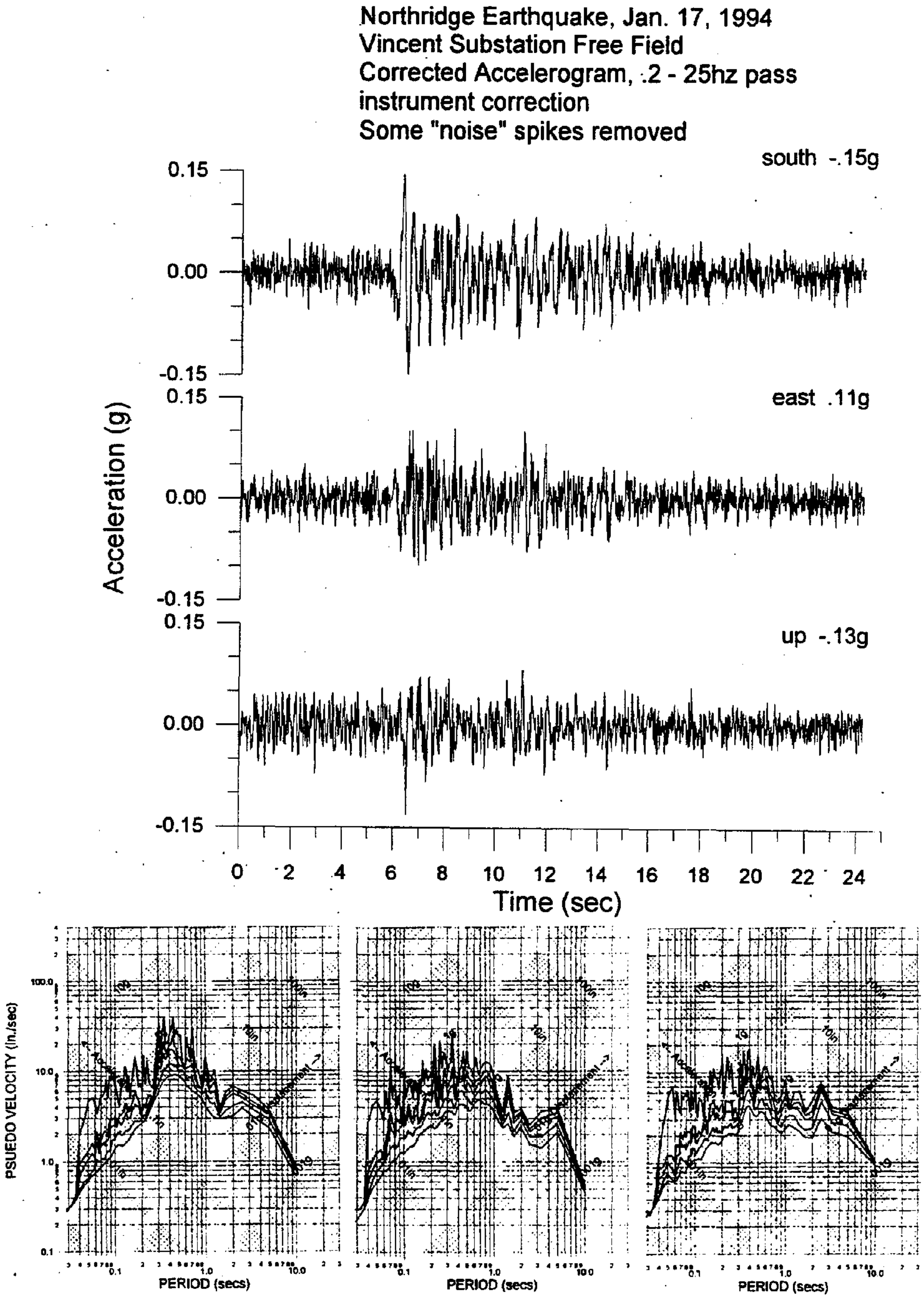


Fig.3.65 Ground motion records recorded at Vincent Substation and response their spectra.

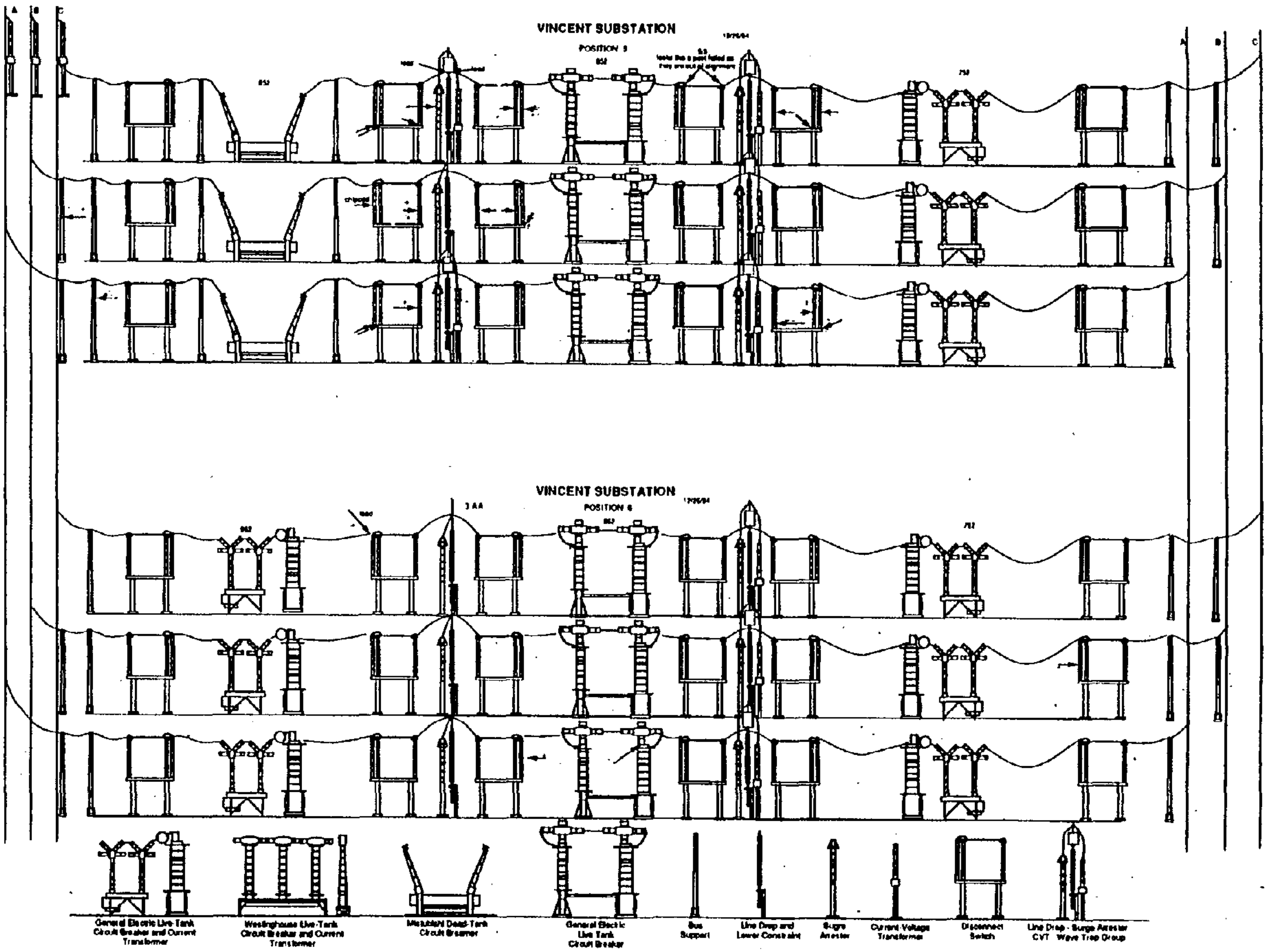


Fig.3.66 Schematic diagram showing damage to 500 kV switchyard at Vincent Substation - Part 1.

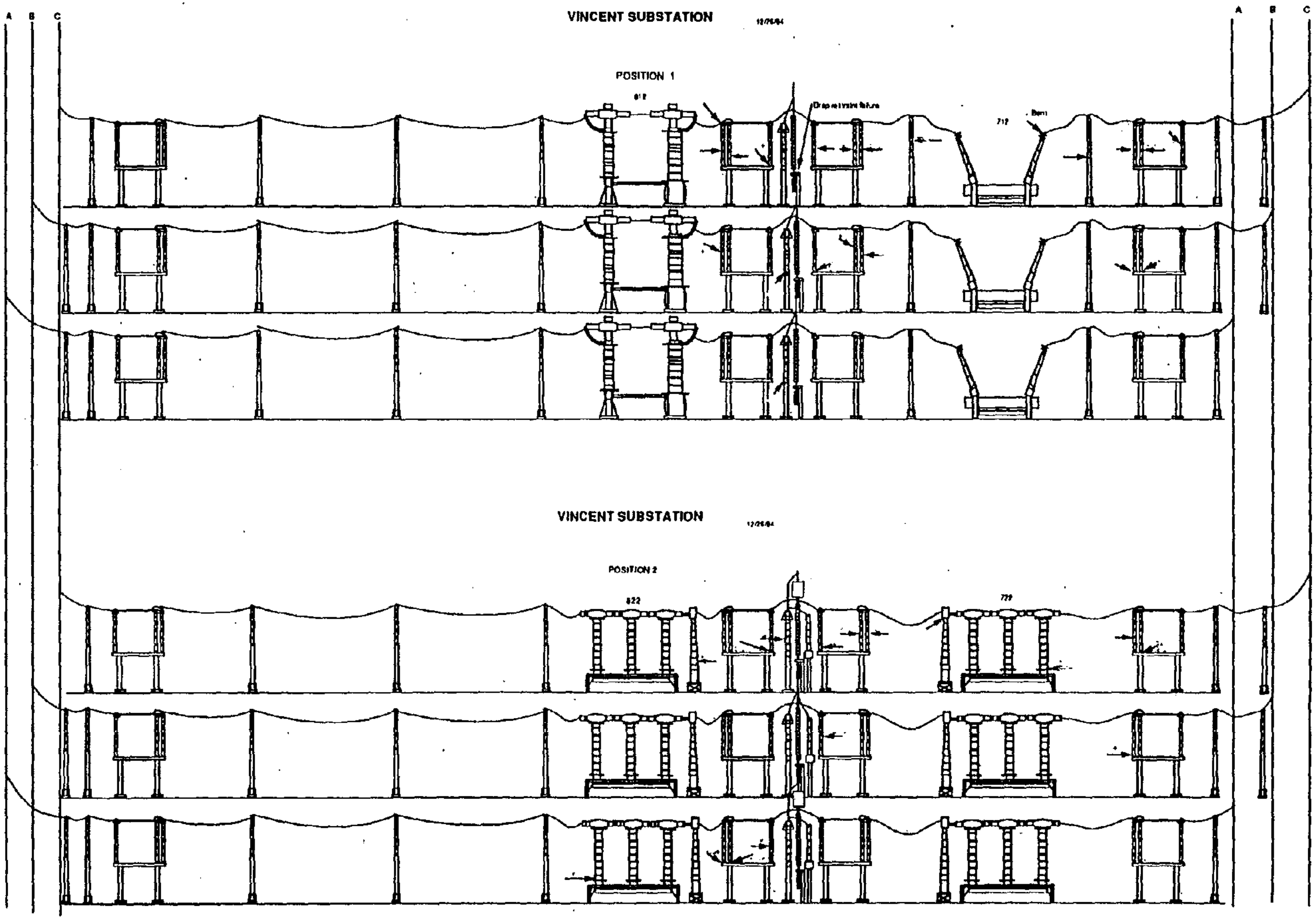


Fig.3.66 Schematic diagram showing damage to 500 kV switchyard at Vincent Substation - Part 2.

Table 3.8 Summary of Equipment Damage at Pardee Switching Station

Item	Not Damaged	Damaged	Comment
Disconnect Switch	79	56	Most failures due to post mounting plate deformation
Potential Transformer	6		
Current-Voltage Transformer	26	19	Restraint failures and 11 with failed low voltage connections
Wave Trap	13		
Circuit Breaker	45		Dead-Tank SF6
Circuit Breaker	2	23	Live-tank - column failure

EMERGENCY RESPONSE AND OTHER HEADQUARTERS ACTIONS

The emergency response actions taken to clear, bypass, repair or replace the various types of damaged equipment were discussed above. There were also emergency response and other activities associated with utility headquarters or that involved network and overall system functions. These included overall control of the restoration and recovery process, and providing logistic support and living needs for work crews.

Shortly after the earthquake, earthquake source data distributed by the CUBE (Caltech-USGS-Broadcast-of-Earthquakes) system were used to identify substations that were likely to be damaged. Inspection crews were then dispatched to unoccupied substations to evaluate damage. This provided a quick overview of the damage so that the restoration process could be started and better organized. A database consisting of log books of damage reports and pictures of each facility was formed. Within one utility an electronic database was developed within a day and evolved for about a week and the paper documentation was later transferred to the computer database. While an initial estimate of damage was obtained, damage not discovered until restoration had started were often not captured in the database. The database did not follow the restoration process so that time charges, spare parts and supplies required for the temporary repair and eventual restoration were often poorly documented. Also, interoperability of the damage database with other databases within the company was a problem. Good documentation is needed to recover losses from the Federal Emergency Management Agency or insurance companies.

A computer database for spare parts inventory was in place prior to the earthquake. Once it was installed, new acquisitions were added to the inventory database as they were acquired, but much of the inventory that existed prior to the establishment of the computer database did not find its way into the database.

Table 3.9 Summary of Equipment Damage at Vincent Substation

Item	Not Damaged	Damaged	Comment
Wave Trap - 500 kV	10		Suspended
Lightning Arrester - 500 kV	14	4	
Current Transformer - 500 kV	10	2	Failed porcelain
Bus Supports	60	4	Filed porcelain
Circuit Breaker - 500 kV	26	1	Live-tank - leak in gasket
Circuit Breaker - 500 kV	6		

Most of the damaged substation sites had strong-motion instruments that recorded ground motions. In the evaluation of the damage patterns at some of the sites, there were indications that the ground motion may have varied significantly within the site. To evaluate this effect and to collect after-shock data at sites that did not have strong-motion instruments, a request was made for the USGS to locate several instruments at sites to meet these needs. Eight instruments were deployed, two at sites that did not previously have strong-motion instrument and six at sites to explore site anomalies. In addition, a large power utility from Northern California deployed two instruments to record after-shock sequences and it collected ambient data to explore differences in soil conditions within two sites. This data has only been partially evaluated at this time but the plan is to use it in estimating equipment fragilities.

CHANGES IN EQUIPMENT SPECIFICATIONS

In the course of describing equipment damage, the following changes in equipment specifications were noted: transformer bushings, bracing of transformer radiators, connections to lightning arrester and current-voltage transformers, materials of high voltage lightning arresters, the design of lighting arrester standoffs, and factors of safety of cast aluminum hardware used to make bus connections. Seismic specifications of instrument transformers and wave traps have been tightened. Interim seismic equipment specifications have been developed but these have not yet evolved into consensus specifications for California utilities.

CHANGES IN EQUIPMENT, SUBSTATION AND NETWORK DESIGN

The elimination of circuit switchers, the use of lightning arresters and transformer bushings constructed with composite material, the use of flexible conductor and bus in substation, and the use of monolithic foundation pads for disconnect switches have been noted above.

The configuration of lines entering busses has been changed so that power flow is better distributed along the bus. This redistribution of power reduces the need for rigid high-voltage bus, which is being eliminated. This design change is being implemented at one substation and the existing rigid bus will be eliminated.

CHANGES IN RESPONSE PLANS AND PROCEDURES

The process for authorizing overtime for repair crew personnel in an emergency response situation has been changed to simplify the recovery process. The need to better document the restoration process and track labor costs and allocation of materials and spare parts was recognized after the earthquake. The procedure for doing this has not yet been implemented. To better evaluate equipment performance and factors that influence it there is a need to get more details about the damage prior to clearing of damage and restoration of service. The desire for better damage documentation and the need to restore service as soon a possible has not been resolved.

POST-EARTHQUAKE ANALYSES

After a damaging earthquake, the primary objective is to quickly and safely restore service. Even when there is extensive damage, site clean-up usually starts within an hour or two. In the case of the Northridge earthquake, where there was extensive damage, the clean-up process was relatively lengthy so that there was an opportunity to review and document some of the damage. The utilities assembled a team of people from another utility not impacted by the earthquake and consultants to document and analyze the damage. This process is continuing, and a report will be issued documenting the results. In addition it identifying damage, for most failures, the most likely failure modes and factors that may have contributed to the failure will be identified.

A method was developed by one of the utilities to use the damage record and the time to restore service from the Northridge earthquake to get a ranking of the relative importance of different types of damage. It is a relatively simple method which makes many assumptions to assign a cost to each failure by calculating lost revenue and repair costs. While primarily used as a ranking tool, it also gave a very rough estimate of the total utility costs associated with various types of damage that can be used to better assess the benefits of retrofitting. For some types of damage, the potential lost revenue is much larger than the cost of restoration.

There is a plan to make some field measurements to determine the natural frequencies of a broad range of damaged equipment. This data is needed to determine equipment fragilities.

There is a plan to use the earthquake ground motion data gathered in this earthquake in conjunction with measurements of equipment frequencies to make fragility estimates based on spectral information. Most fragility estimates to date have been based on estimates of peak acceleration at damaged sites. Prior to the Northridge earthquake there are only a few strong-motion records at substation sites that have had earthquake damage. It is known that most substation equipment is lightly damped and response would be very sensitive to spectral content of the earthquake. The data from this earthquake provides the first opportunity to do these types of analysis with real data.

There is a plan to develop improved methods of modeling the earthquake response of power networks. Current computer-based methods for evaluating power systems do not adequately take into account the redundancy in the networks and within substations. The new methods will address these and some other important issues.

A test plan is being considered to evaluate porcelain members to determine if the earthquake had any deleterious effect of the members.

RESEARCH NEEDS

Damage to lower voltage bus indicates that several transformers rocked in this earthquake. There is a need to evaluate the cost and benefits for new transformer foundation specifications and for upgrading existing foundations to reduce the risk of damage from rocking. A related issue is improving the seismic performance of high voltage transformer bushings. The most cost-effective methods for improving the seismic performance of bushings for new and existing transformers need to be identified. Factors which affect bushing performance are transformer foundations, slack in conductor and bus connections, modifying the bushing support to reduce dynamic amplification, adding retainer rings to reduce the chances of porcelain slipping, changing bushing design or installation to improve performance, changing the materials used in bushings. There is a need to evaluate if emergency restoration methods can be developed to reduce the time requires to repair a bushing that has slipped. There is a need to develop a standardized method for seismic evaluation and testing of transformer bushings. There is a need for a better method of supporting wave traps and current-voltage transformers so that they do not interact with and damage other equipment.

There is a need for appropriate procedures and software to facilitate the collection, cataloging, and evaluation of damage and restoration costs. Ideally, this could be done with a standardized package that could be used by the industry in normal operations so that it would be in place when a disaster strikes. Because of the unique characteristics of most organization's data bases and accounting systems, the output of this standard package would have to be interfaced with the various existing computer systems that exist in each utility.

ACKNOWLEDGMENTS

The authors wish to acknowledge DWP and SCE support to gather damage data and make it available for this report.

4. WATER SYSTEMS

ABSTRACT

In general, water system facilities seismically upgraded from the 1971 San Fernando earthquake performed well. The performance of dams, wells and pumping plants, except for the loss of power, was good. Over 30 tanks were damaged, but it is not known if modern seismic provisions were used in their design. Several communities were without water for as long as two weeks and boil water orders were in effect for in a few communities for about two weeks as a precautionary measure. The epicenter for the Northridge earthquake was in a more urbanized area than the 1971 event and there were more underground pipeline failures. The lessons learned were similar to those learned from previous earthquakes.

OVERVIEW OF THE WATER SUPPLY

Water supply to Southern California is provided by local groundwater basins, water reclamation and imported supplies from the Colorado River and northern California. The earthquake disrupted five of the major pipelines from northern California serving the Santa Clarita, Simi and San Fernando Valleys which supplied four water treatment plants. Three plants were in operation just before the earthquake; the fourth was under construction. Figure 4.1 is a map of the epicentral area showing communities, highways and the approximate location of water system facilities and some damage locations.

The breaks in the five steel and concrete pipelines and concrete conduits were repaired in two to 67 days. Some of the repairs were temporary to restore service and permanent repairs will made by the summer 1994.

Until these pipelines were repaired water utilities received supplies from local groundwater basins, storage reservoirs and Metropolitan Water District of Southern California (MWD) Colorado River Aqueduct and State Water Project - East Branch. Redundancy in the supply and pipeline system was important in the supply, to areas where the distribution system was in available, in which supply was disrupted from the

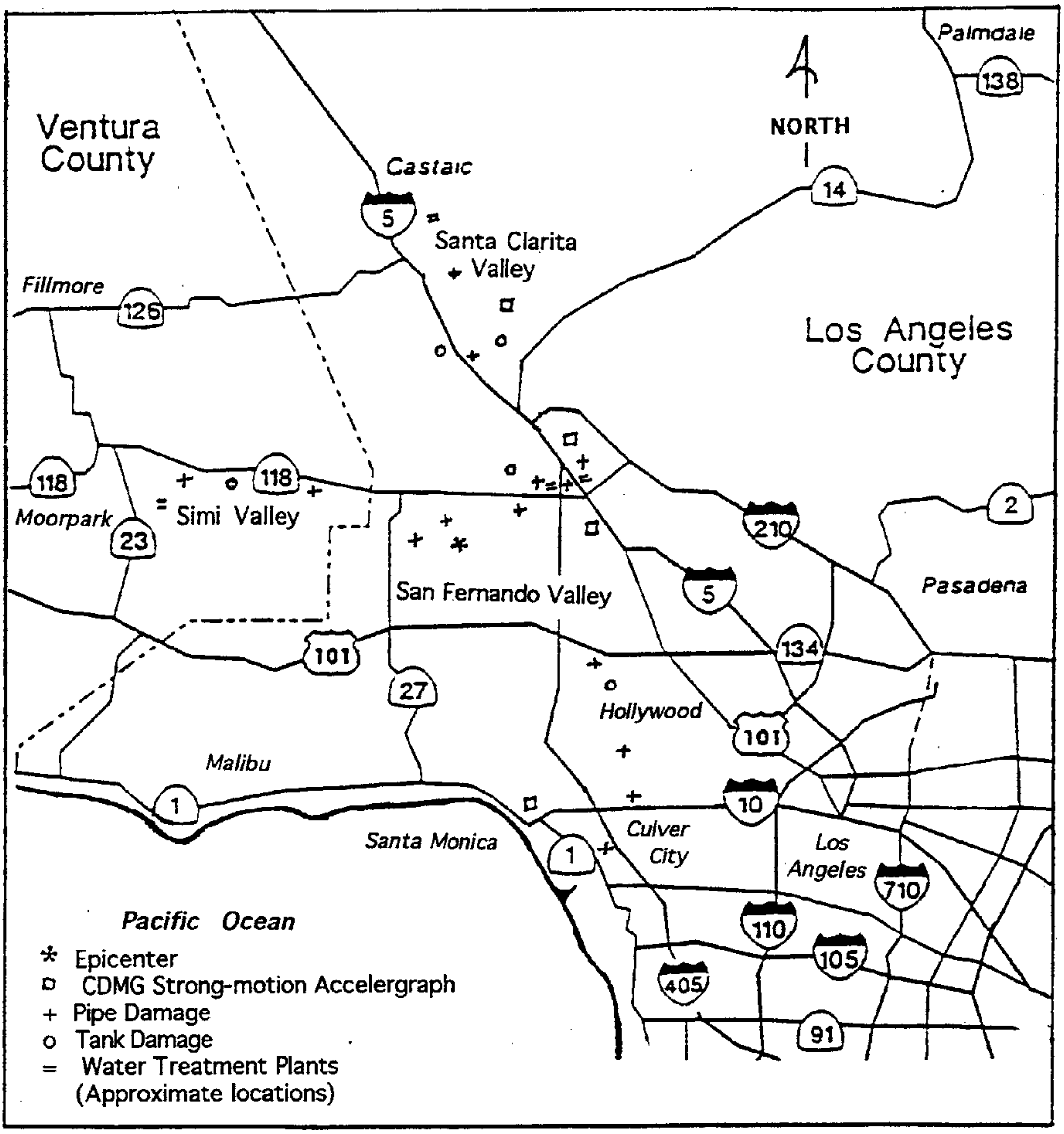


Fig. 4.1 General vicinity map showing the earthquake epicenter, communities, highways and approximate location of damage. (Caltrans)

three water treatment plants. Areas in the Santa Clarita, Simi, northern and western parts of the San Fernando Valleys were without water due to distribution system pipeline damage.

SUPPLY PIPELINES

CASTAIC CONDUIT

Santa Clarita Valley is served from the Castaic Reservoir, the terminus of the State Water Project-West Branch. The main conduit from the water treatment plant to the service area was video inspected and had 35 leak repairs in the 54-in. (1370-mm), 39-in. (990-mm) and 33-in (838-mm) modified prestresed concrete cylinder pipe (MPCCP). One repair occurred on the 54-in (1370-mm) MPCCP inlet pipe to the plant from Castaic Reservoir. Breaks occurred at welded fabricated compound (horizontal and vertical) bends and on long horizontal reaches where the rubber gasket joints pulled apart, Fig. 4.2.

Fig. 4.2 Excavating pulled joints and repair of 54-inch MPCCP with rubber gasket joints near Rye Canyon.

A pipe manufacturer fabricated new compound bend sections and a contractor welded these sections together with butt straps, Fig. 4.3. The pulled rubber gasket joints were welded in place. Backer rods were used to fill the annular space between the bell and spigot to facilitate the welding. The conduit was placed back in service March 25th. While the conduit was out of service the supply to the Santa Clarita Valley after the earthquake was supplied from local groundwater.

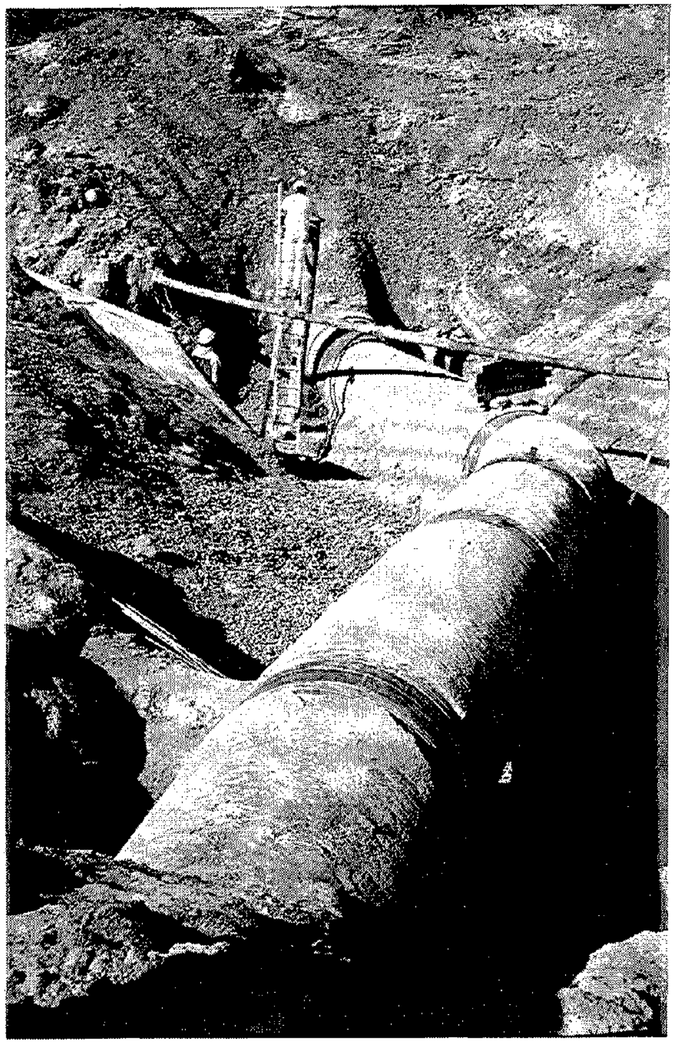


Fig. 4.3 Repaired 54-inch using contractor fabricated WSP compound bend with welded butt straps near Rye Canyon.

STATE WATER PROJECT-WEST BRANCH

The State Water Project-West Branch supplies the Jensen Water Treatment Plant from the Castaic Reservoir via the Foothill Feeder (Newhall and Balboa Tunnels). At the south portal of the Balboa Tunnel the 170-in (4320-mm) tunnel line branches into two-85-in (2160-mm) by 13/16-in (20-mm) welded steel pipes (WSP) at the inlet to the treatment plant. The west pipe performed satisfactorily; however, the east pipe circumferentialy cracked on the curved portion of a long bell, Fig. 4.4. The pipe was joined by an inside welded bell and spigot joint. The northerly part of the round crack moved horizontally about 3-in (76-mm) east with respect to the southerly part. Vertical movement was about 1/2-in (38-mm).

Fig. 4.4 Jensen influent 85-inch welded bell and spigot joint. Cut out cross section of circumferentialy cracked, at the curved section of the bell.

An approximately 10-feet (3.0-meters) of the damaged pipe was removed and replaced by two-5-ft (1.5-m) lengths of pipe fabricated at the MWD yard. The closure was made by three welded butt straps joints and completed the evening of January 19th, Fig. 4.5. The MWD East Valley Feeder and pumping plant was activated to provide supply from the Colorado River Aqueduct/State Water Project - East Branch to the areas in western Los Angeles County and eastern Ventura Counties, affected by this outage.

LOS ANGELES AQUEDUCT NO. 1

Water supply to the Los Angeles Water Filtration Plant is supplied from the Owens Valley by two aqueducts. Aqueduct No. 1 had damage at four locations; and it was

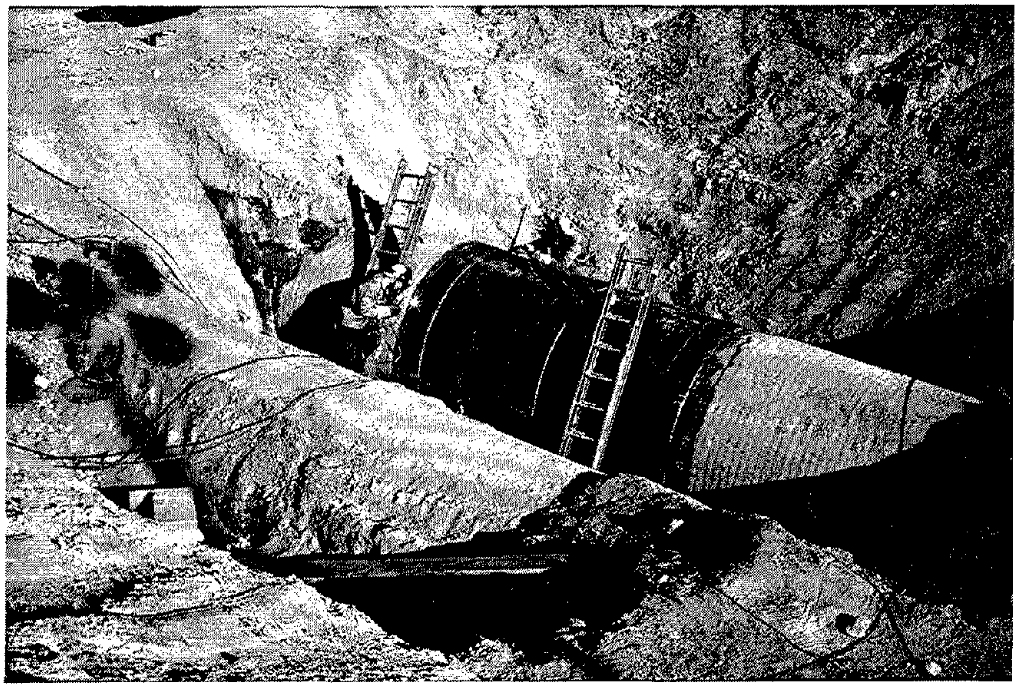


Fig. 4.5 Repaired Jensen influent 85-inch WSP, two 5 ft lengths of pipe, connected with three butt straps.

able to operate at very low flow for about a week after the earthquake to allow repairs to be made to Aqueduct No. 2, then shut off for repairs. It was operated again at one-half capacity, after temporary repairs were made, for about two weeks at the end of March, during a planned MWD shutdown. It was out of service from April 1st until summer for permanent repairs. The California drought and the court ordered restrictions limited the available supply.

Both aqueducts were shut down for a period of three weeks, the last week of February and first two weeks in March, to allow for the repair of the open concrete channel supplying the water filtration plant. The channel was fractured in many locations requiring replacing concrete sections, low pressure grouting the voids behind the walls and patching the cracks.

At the south end of Aqueduct No. 1 Soledad (inverted) Siphon at two locations occurred the partial cracking of the curved portion of the bell of an 120-in (3050-mm) by 3/8-in (10-mm) welded steel pipe, Fig. 4.6. The pipe was welded on the outside of a bell and spigot joint and was above ground and supported by concrete saddles, Fig. 4.7. The circumferentialy cracks were about 5-ft (1.5-m) long on the top of the pipe. The repair was made by removing a coupon of the damaged joints and replacing it with a welded steel plates, Fig. 4.8. At Quigley (inverted) Siphon there was split in the top of the 120-in (3050-mm) riveted steel pipe which was welded shut.

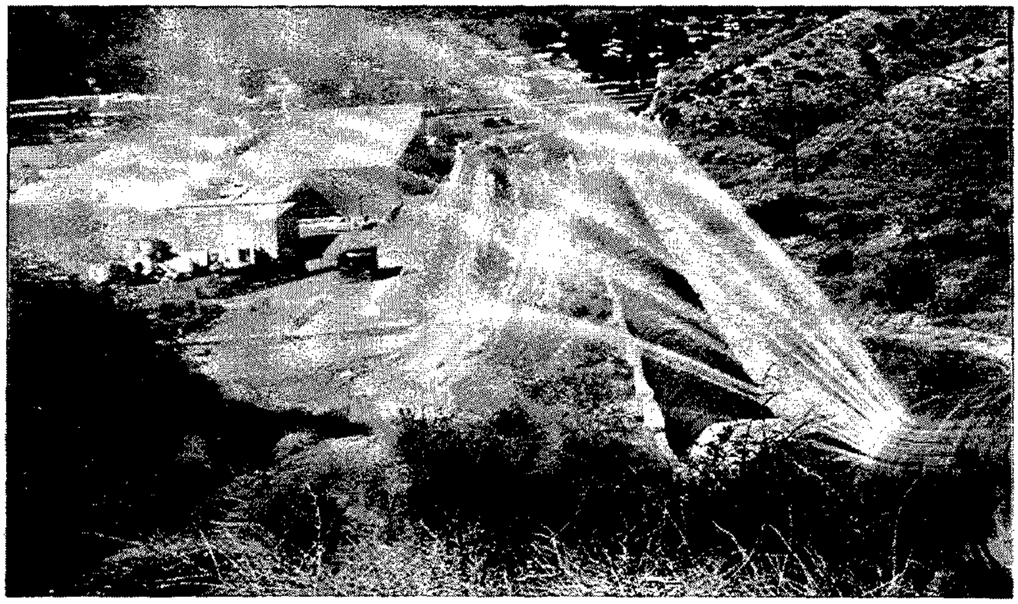


Fig. 4.6 Soledad Siphon 120-inch WSP leak. (LADWP)

Fig. 4.7 Soledad Siphon 120-inch WSP, with split bell, supported by concrete saddles.

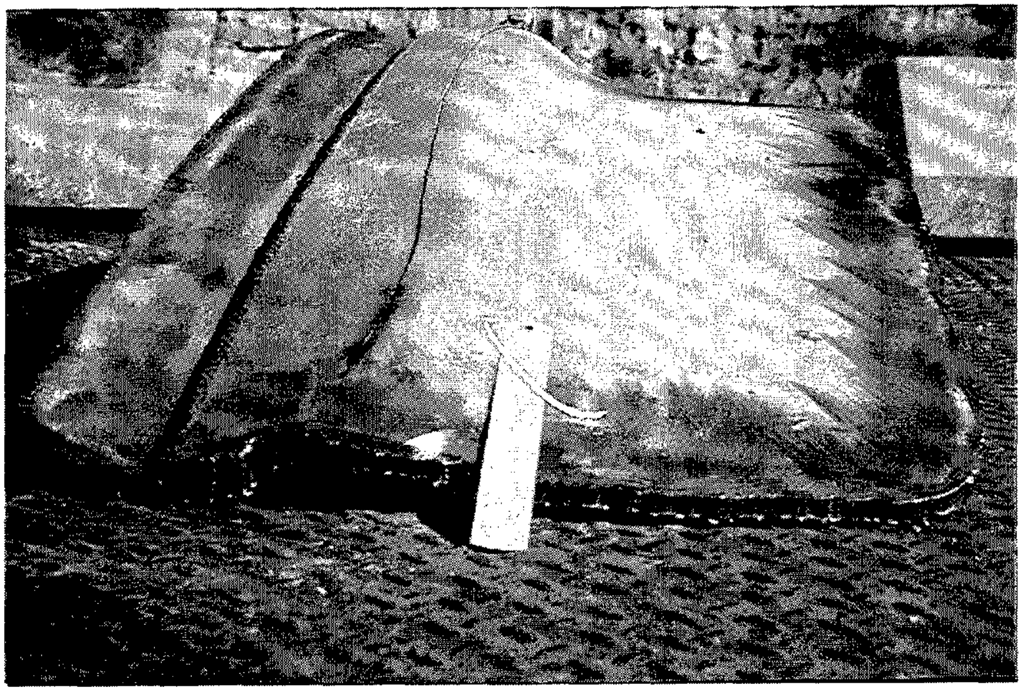


Fig. 4.8 Removed section of Soledad Siphon, 5-foot long split in top of pipe on the curve portion of the bell.

At two locations, Whitney and Elsmere Canyons, the 120-in (3050-mm) cast-in-place reinforced concrete (inverted) siphons were shattered, Fig. 4.9, temporary repairs were made by plugging the cracks from the outside. Permanent repairs were made by placing a steel liner inside the pipe and injecting the cracks with sealing compound from tapped holes in the liner from the inside of the pipe, Fig. 4.10. The steel liners were fitted with a "O" ring gasket at each end. Creek flow was a dewatering problem at Elsmere Canyon.

Tunnels were inspected and found in satisfactory condition except for minor cracking in the tunnel through Terminal Hill, which had circumferentialy cracking at the south end. The cracks were sealed with urethane resin.

Alternate supply was available from reservoir storage, groundwater, Colorado River Aqueduct/State Water Project - East Branch and the Los Angeles Aqueduct No. 2.

LOS ANGELES AQUEDUCT NO. 2

Aqueduct No. 2 was out of service for the first week after the earthquake for repairs, placed in service until the shutdown of both aqueducts for the open channel repair during the last week in February for three weeks. Put back in service in mid

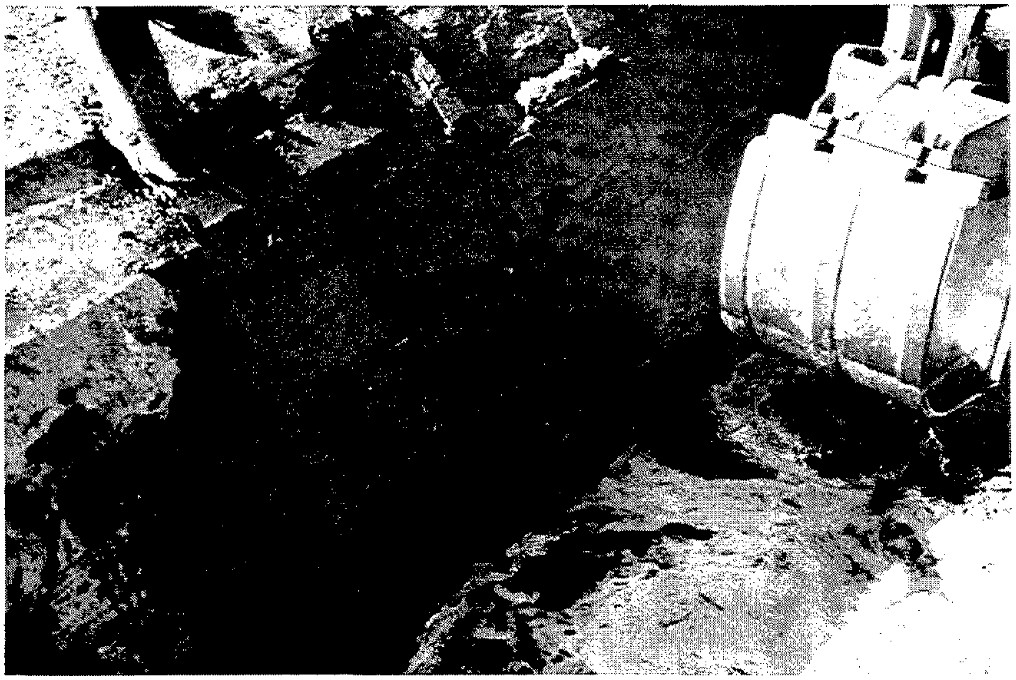


Fig. 4.9 Shattered Elsmere Canyon 120-inch concrete conduit. (J. Herbaugh)

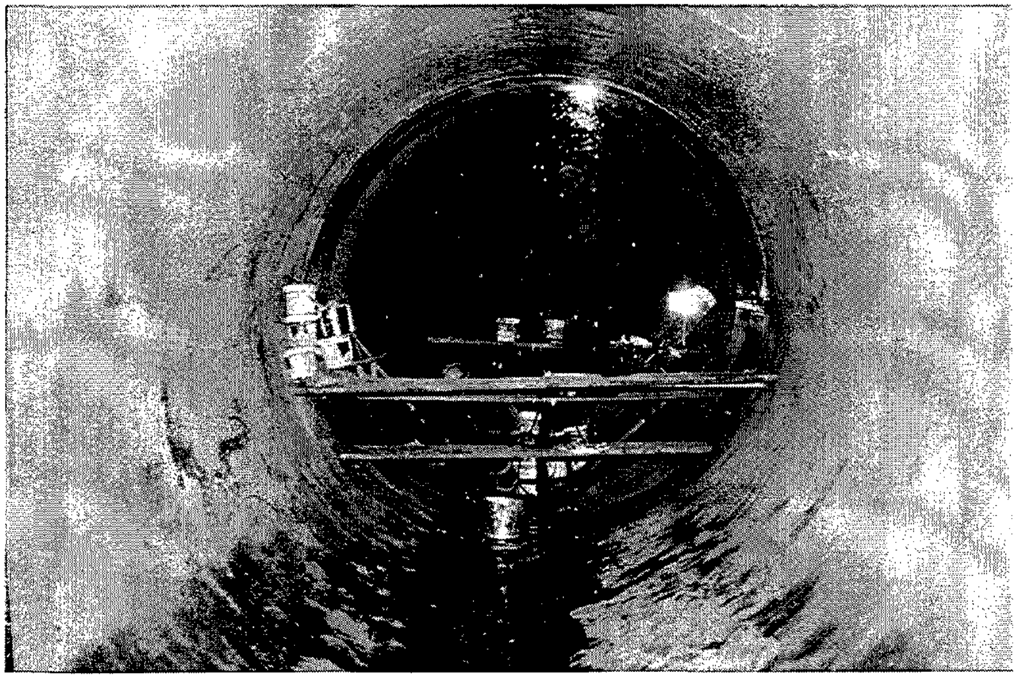


Fig. 4.10 Internal repair by steel liner of Elsmere Canyon 120-inch concrete conduit. (J. Herbaugh)

March until April 8th at which time it was removed from service for non earthquake related reasons.

At Terminal Hill the 77-in (1955-mm) welded steel pipeline was shut down twice to repair two pulled mechanical couplings, Fig. 4.11, and an eight-inch long split in the wye branch stiffener. This required the draining and filling the pipe twice during the first week after the earthquake. The pulled couplings were temporarily repaired by welded butt straps. Permanent repair was made by the installation of double restrained mechanical couplings, Fig. 4.12. The wye branch stiffener at this location was rewelded, Fig. 4.13.

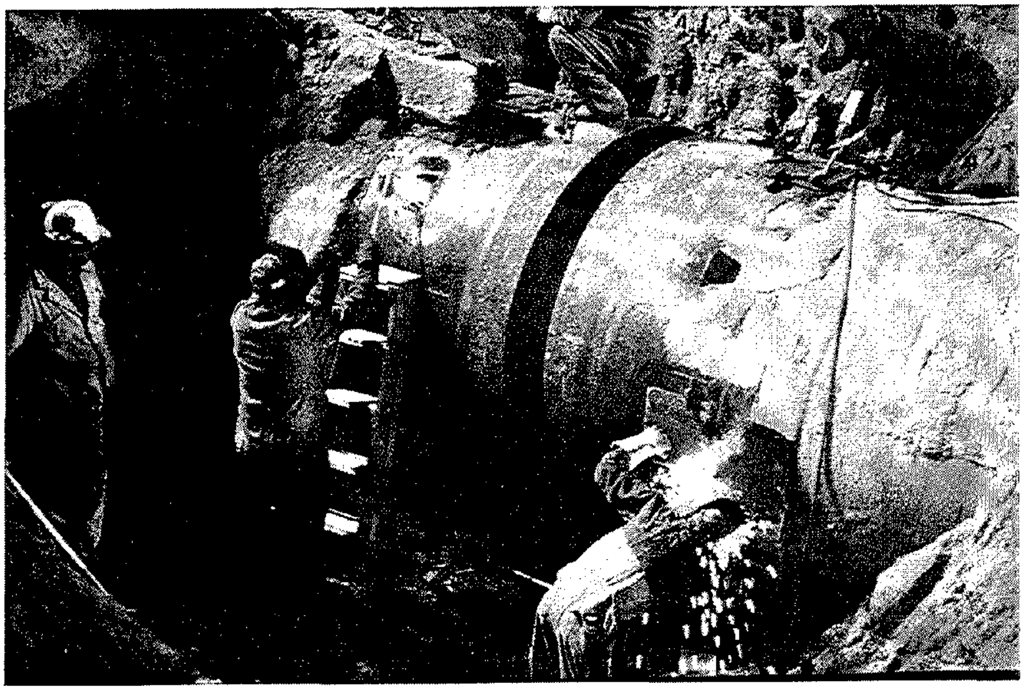


Fig. 4.11 Temporary repair in progress of 77-inch WSP pulled mechanical coupling at Terminal Hill. (LADWP)

Two 6-in (130-mm) compression bulges appeared on the north slope of Terminal Hill in the 77 in (1955 mm) pipe in above ground pipe supported on concrete saddles, Fig. 4.14. This represented almost 2-feet (0.6-m) of compression in the pipeline. At these bulges there were no leaks although significant movement occurred, Fig. 4.15. At Quigley Canyon a circumferentialy tear in the top of the buried 77-in (1955-mm) welded steel pipe was repaired by welding a interior patch plate.

Long travel times and traffic were a problem in getting access to the repair sites north and south of the damaged Interstate 5 and State Highway 14 interchange. All repairs were made by agency personnel. Compliance was required with the Occupational Safety and Health Act (OSHA) for entering confined spaces (tunnels and pipes). Alternate supply was available from reservoir storage, groundwater and the Colorado River Aqueduct/State Water Project - East Branch.

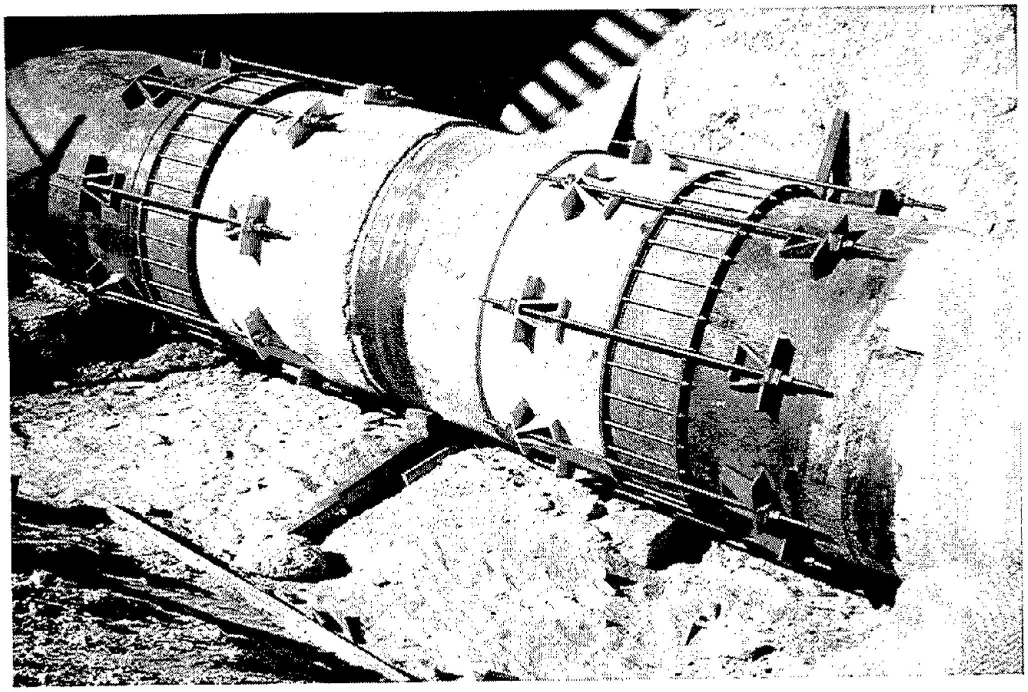


Fig. 4.12 Permanent repair of 77-in WSP by double restrained mechanical couplings.

Fig. 4.13 Repaired 77-inch WSP wye branch stiffener at Terminal Hill.

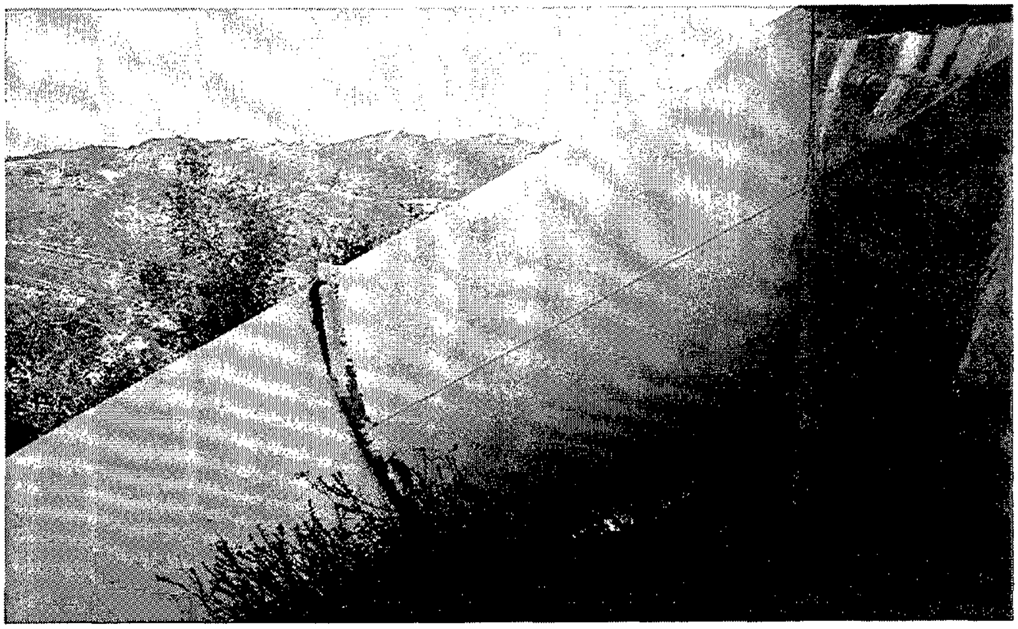


Fig. 4.14 North slope of Terminal Hill 77-inch WSP supported on concrete saddles.

Fig. 4.15 Compression bulge on 77-inch pipe at welded bell and spigot joint. Pipeline continued in service and did not leak.

THE 78 INCH NORTH BRANCH FEEDER

Simi Valley receives water supply from the MWD Jensen Treatment Plant. The supply is transmitted by two pipelines to the storage reservoir at the west end of Simi Valley. The common tunnel at the east end was inspected and found undamaged. At the west tunnel portal in Simi Valley the pipeline separates into 78 in (1980 mm) and 51 in (1295 mm) prestressed concrete cylinder pipelines with rubber gasket joints. Alternate supply was available from reservoir storage and groundwater.

On the 78-in (1980-mm) there were 15 to 20 major pulled joints and approximately 500 cracks requiring chipping and patching with cement mortar. The rubber gasket joints were welded shut and some of the joints were pressure grouted from the inside behind the weld. External repair plates (diapers) were used at some locations. Replacement was required of 22 damaged air and vacuum valves. The replacement valves were air freighted by the manufacturer within two days. The 78-in (1980-mm) line was placed back in service on March 4th.

THE 51 INCH CALLEGUAS CONDUIT

The 51-in (1295-mm) remained in service intermittently after the earthquake. The earthquake damage occurred at three corroded blind flanges and bolts at future service connections. The flanges, bolts and valves were replaced. Also an air and vacuum valve was damaged.

LARGE DIAMETER PIPELINES

Two of the three water lines in Balboa Blvd. were the Granada Trunk Line 48-in (1220-mm) WSP and MPCCP and the Rinaldi Trunk Line 68-in (1727-mm) WSP. The Granada line had four major pulled mechanical couplings and two tension and compression failures. Repairs were made by connecting a short length of pipe with two butt straps in the tension zone, a butt strap in the compression zone and interior butt straps (WEKO seals) at other locations. A flowing creek caused dewatering problems at one location. The line was put back in service on January 29th. The Rinaldi line had three pulled welded bell and spigot joints at the bell curve and a tension and compression failure on Balboa Blvd. Repairs were made by connecting a short length of pipe with butt straps in the tension zone, a butt strap in the compression zone and interior butt straps (WEKO seals) at other locations.

There were approximately one dozen other large diameter pipeline failures at other locations for the same reasons as described above. Repairs were made using the same methods, requiring the use of similar materials, equipment and personnel.

DISTRIBUTION SYSTEM

PIPELINES

The most significant damage to the smaller distribution pipeline network was within the earthquake affected area. It was reported there were approximately 1,400 repairs in mains and service connections to the meter by the water utilities in the San Fernando Valley and approximately 300 in the Santa Clarita and Simi Valleys. Pipes were broken by compression and tension and some pipes weakened by corrosion due most likely to ground shaking and ground failure. The most affected were older cast iron with rigid joints and older steel subjected to corrosion. Field personnel reported good performance by ductile iron pipe with rubber gasket joints, although there may be limited amount of the pipe installed in the area. There also were broken fire hydrants and air and vacuum valves, Figs. 4.16 to 4.18.

Fig. 4.16 Typical broken fire hydrant.

Fig. 4.17 Typical damaged to air and vacuum valves installation.

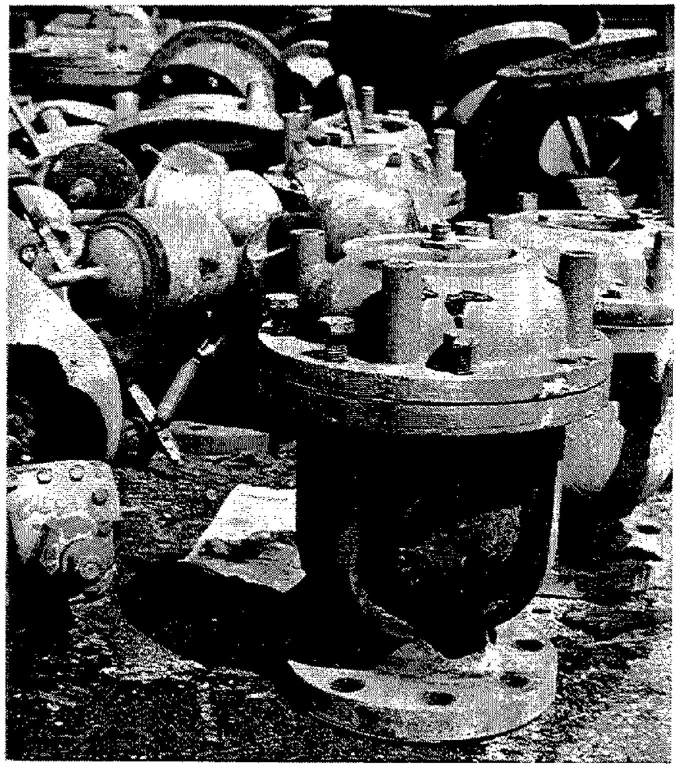


Fig. 4.18 Broken air and vacuum valves.

The repairs were time consuming requiring draining prior to repair, the repair, the filling the pipe for testing, and chlorination and invariably another leak was observed, requiring the repeat of the process. In a number of cases this process was repeated many times and was more time consuming in larger diameter pipes which required more time to drain and fill. In some areas dewatering of excavations was necessary. Food, water and housing were a problem to the restoration workers in the damaged areas, because of the loss of commercial power and potable water to restaurants and motels.

RESERVOIRS

There were 120 dams within 46 miles (74 kilometers) of the epicenter of the Northridge earthquake. Most of the dams are water supply storage reservoirs. Others are flood control and are generally empty or have minimum stored water. The California Department of Resources, Division of Safety of Dams (DSOD) has jurisdiction of 108 of these dams, the remaining 12 are owned by the federal government. All major DSOD dams were inspected by their owners immediately after the earthquake. Some of the major dams were further inspected by their staff or contract engineers. In the first five days 101 of the dams under state jurisdiction were inspected by DSOD engineers. The remainder were either dry, under construction, or outside the epicentral area. All were eventually inspected. All state and federal dams performed satisfactorily and no emergency situation existed, although damage to some non-critical appurtenances did occur.

Thirteen of the 108 dams nearest the epicenter had some minor longitudinal and transverse cracking, settlement, minor horizontal movement or increased seepage and one small storm water dam had a minor slope failure.

Pacoima Dam had cracking in both abutments and damage to its access ramps and stairways. The upper left abutment strong motion instrument recorded an acceleration of about 1.5 g on the horizontal and 1.4 g on the vertical component. At the same location in the 1971 San Fernando earthquake the record was 1.25 g on the horizontal and 0.7 g on the vertical component. Peak accelerations exceeding 2 g were recorded on the dam structure. Storage capacity was temporarily limited to 1,000 acre feet, the total capacity of the flood control basin is 3,770 acre feet, while civil engineers made further investigation of the abutments. The dam performed satisfactorily in the earthquake. Normally water is released from this dam to enhance the water supply by recharge into the San Fernando Valley groundwater basin.

Dams performed well in the Northridge earthquake. Since the 1971 San Fernando earthquake , most major dams in the state have been dynamically analyzed for the maximum earthquake credable earthquake expected at the dam site. Since 1971, some dams met this seismic criteria, others were rebuilt, modified, operated at a reduced level or have been removed from service.

STORAGE TANKS

Severe tank were damage in the Santa Clarita Valley (Valencia-Newhall area), which located north of and about eight miles (13 km) from the Northridge earthquake epicenter. Six of the seven Newhall tanks were damaged and were rendered nonfunctional following the earthquake. These tanks and their performance are described in Table 4.1. For the Newhall are tanks the principal modes of damage were broken inlet-outlet piping and valves, roof and rafter damage, and elephants foot buckling. Lateral movement or sliding/shifting did not appear to occur frequently or, if it did occur, it was in the order of two to four inches (5 to 10 cm).

Similarly, there were two structural failures in the Valencia area, with a third tank suffering damage from an adjacent tank failure, Figs. 4.19 and 4.20. Failure modes were severe shell buckling and uplift, inlet-outlet piping failure, roof/rafter damage and in one case shell ripping at the tank bottom, Figs. 4.21 and 4.22. The two tanks with structural failures have been removed. Figure 4.23 shows a tank with a damage roof and upper walls and one of seven temporary portable Baker tanks.

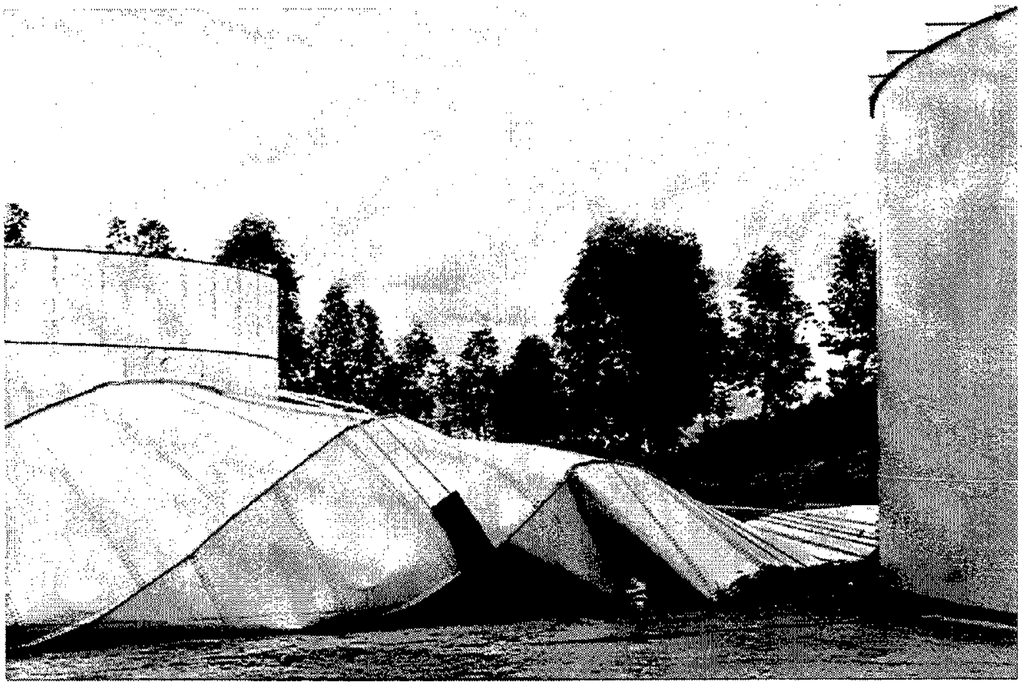


Fig. 4.19 Collapsed 0.50 mg bolted steel tank (MM I) in Valencia area. MM II, at the left, was damaged by outflow from MM I. Large tank to right was undamaged. (T. Cooper)

The Simi Valley area lies 10 to 12 miles (16 to 20 km) west of Northridge. This area also experience a significant number of tank functional failures, the causes of the failures again being shell buckling and inlet-outlet piping and valve damage. In

Table 4.1 Newhall, Valencia, Simi Valley and San Fernando Valley area steel tanks (T. Cooper)

	HT (FT)	DIA (FT)	VOL (MGAL)	ANCHORED	TYPE	YEAR BUILT	AWWA	REMARKS
NEWHALL AREA:								
1	30	60	.630	NO	WELDED	1964	YES	Tanks failed, inlet/outlet piping, NO336 pulled out, elephant foot
2	32	40	.300	NO	WELDED	1954	NO	Inlet/outlet piping, to be replaced
3	32	40	.300	NO	WELDED		-	Similar to Tank 2
4	32	40	.300	NO	WELDED	1962	YES	Roof rafters pulled out, inlet/outlet and drain piping failures
5	32	64	.750	NO	WELDED	1964	YES	Inlet/outlet piping, roof rafters, tank shifted
6	20	20	60	NO	WELDED	1960's	NO	Inlet/outlet and shell, to be replaced
7	32	90	1.500	NO	WELDED	1975	NO	Roof rafters and top shell, to be repaired, 1/2" bottom plate with no lower shell damage
VALENCIA AREA:								
LARWIN	40	60	.840	YES	WELDED	1986	YES	Used tank rebuilt on site in 1986
MM1	24	60	.500	NO	BOLTED	-	NO	Bolted tank, complete tear at bottom of lowest shell
MM2	24	73	.750	NO	BOLTED	-	NO	Bolted tank, damaged by outflor from MM1
SIMI VALLEY AREA:								
1	24	30	1.260	NO	BOLTED	-	NO	Prinipcal failures were in inlet/outlet piping, shell buckling and roof damage
2	24	30	1.260	NO	BOLTED	-	NO	
3	24	40	2.100	NO	BOLTED	-	NO	
4	24	40	2.100	NO	BOLTED	-	NO	
LOS ANGELES AREA:								
TOPANGA	29.5	36	2.100	NO	WELDED	1936	NO	Wood roof, no tank damage, replace broken inlet/outlet valve
ZELZAH	40	70	1.000	NO	WELDED	1948	-	Wood roof, roof collapsed, local buckling at top, replace broken valve
MULHOLLAND	33.5	52	.500	NO	WELDED	1931	NO	Wood roof, overflow pulled away
BEVERY GLEN	40.5	100	2.250	NO	RIVETED	1932	NO	Wood roof, roof collapsed--replaced with hypalon roof, dresser coupling pulled out, local buckling
COLDWATER	40.5	100	2.250	NO	RIVETED	1925	NO	Wood roof, roof shifted and collapsed, inlet/outlet piping failure
GRANADA HI	35	55	.600	NO	RIVETED	1929	NO	Wood roof, tank collapsed, removed
ALTA VISTA 1	29	54	.500	NO	RIVETED	1929	-	Wood roof , no damage
ALTA VISTA 2	36.5	95	1.800	NO	WELDED	1954	-	Wood roof, no damage
KITTRDG 3&4	51	190	10.000	NO	WELDED	1973	-	Wood roof, no damage
CORBIN	30	156	4.000	NO	WELDED	1987		Wood roof, minor draw line damage, partially buried

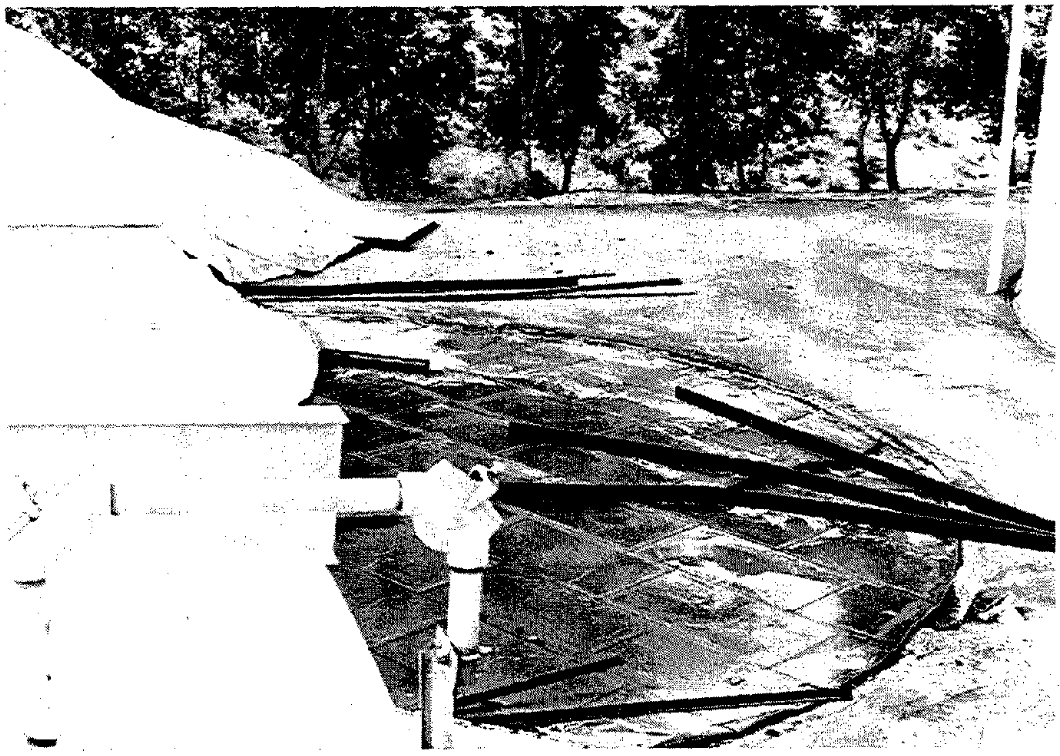


Fig. 4.20 Floor of collaspes bolted tank. Tear in side wall can be seen at edge of base. (T. Cooper)

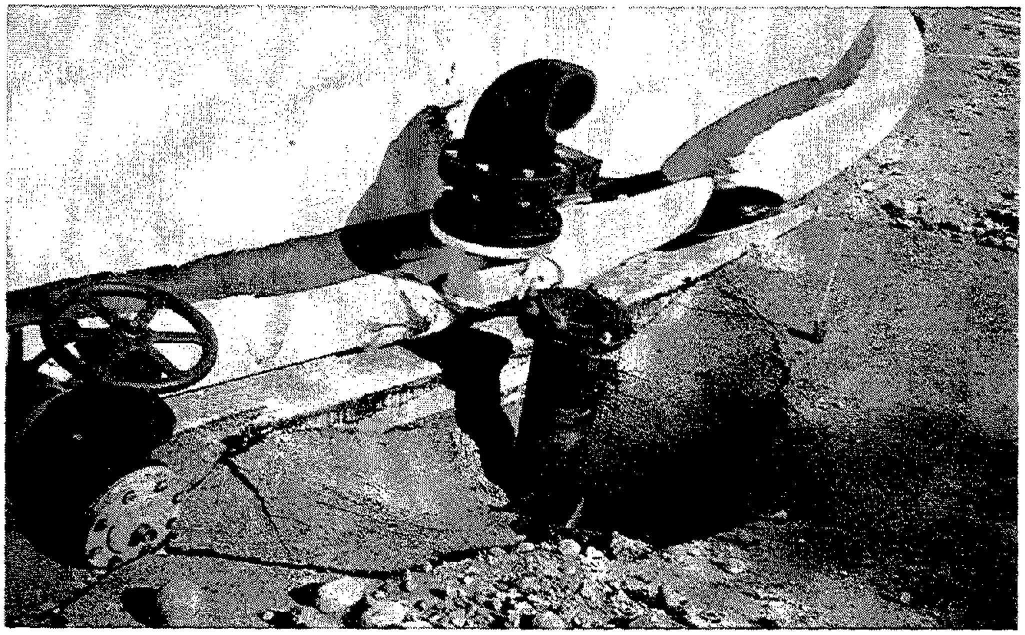


Fig. 4.21 Damaged 0.85 mg welded steel tank in Newhall area. Cast iron fittings failed and tank wall is torn across elephant foot buckle. Anchor straps are conealed by the elephant fot buckle.

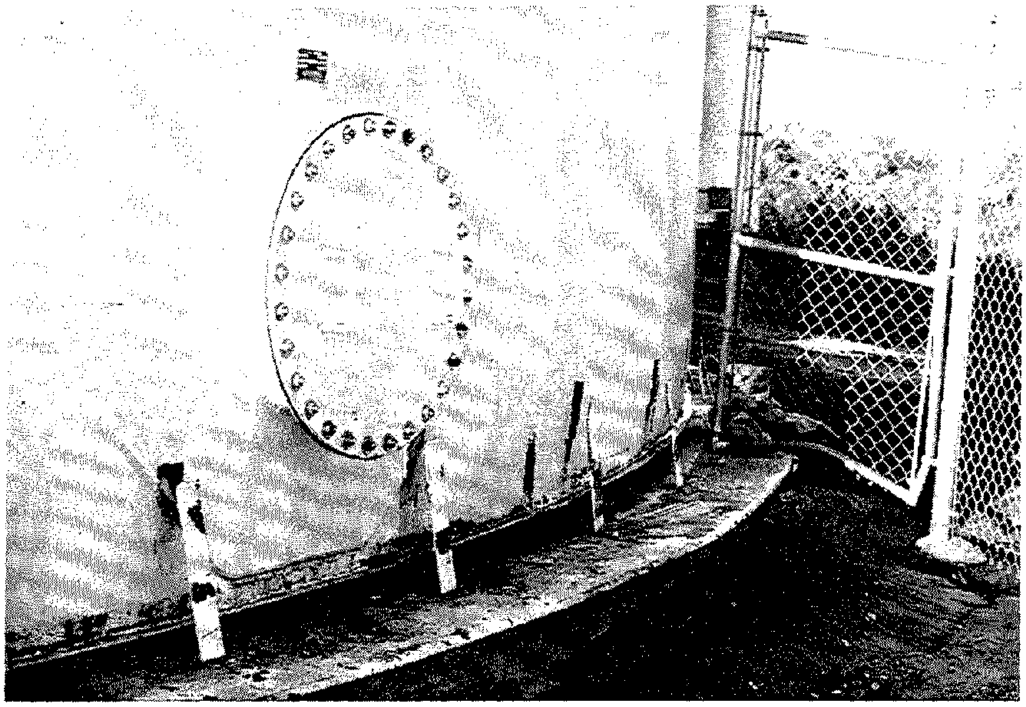


Fig. 4.22 Opposite side of tank shown in Fig. 4.2. Welds at anchbor straps failed. (T. Cooper)

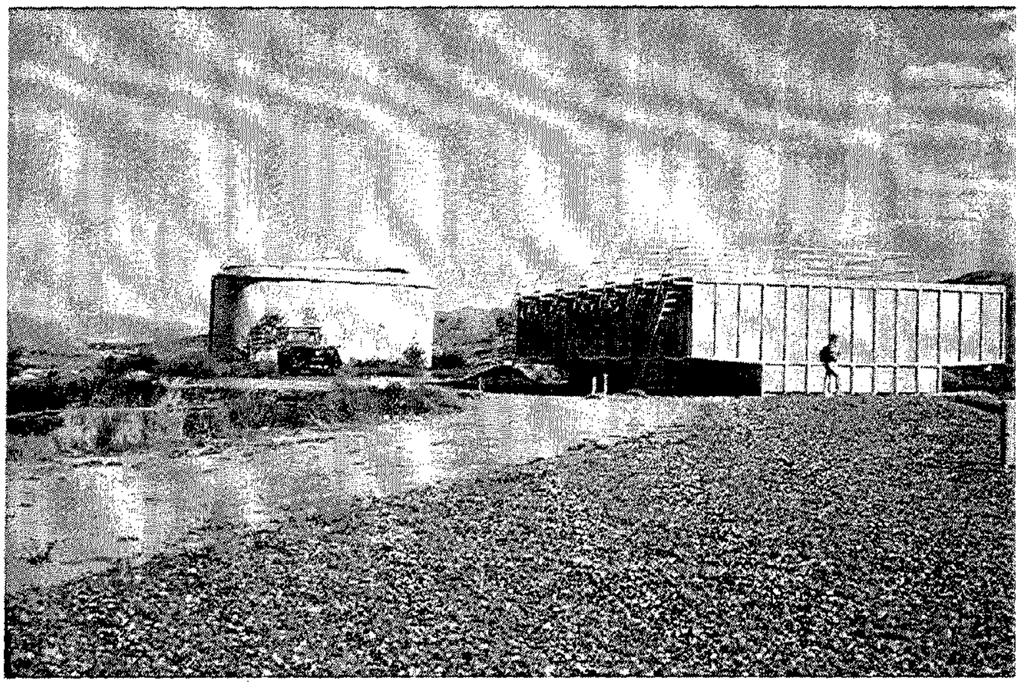


Fig. 4.23 Roof and upper part of walls are damaged of tank shown in Fig. 4.21. Temporary portable tank can be seen at left.

addition to the four Simi Valley tanks listed in Table 13.1. There were an additional ten tanks in the Simi Valley area which were damaged and rendered nonfunctional; however, detailed information on these tanks was not obtained. Many of these tanks were repaired and returned to service.

Tanks in the San Fernando Valley which had significant damage were in the Santa Monica Mountains south of Northridge. Inlet-outlet piping and valve damage, Fig. 4.24, erosion, Fig. 4.25 and roof problems, Fig. 4.26, were again the major causes of functional failure. All of these tanks have been repaired and returned to service. A damaged 1929 riveted steel tank in the Granada hills area has been removed.

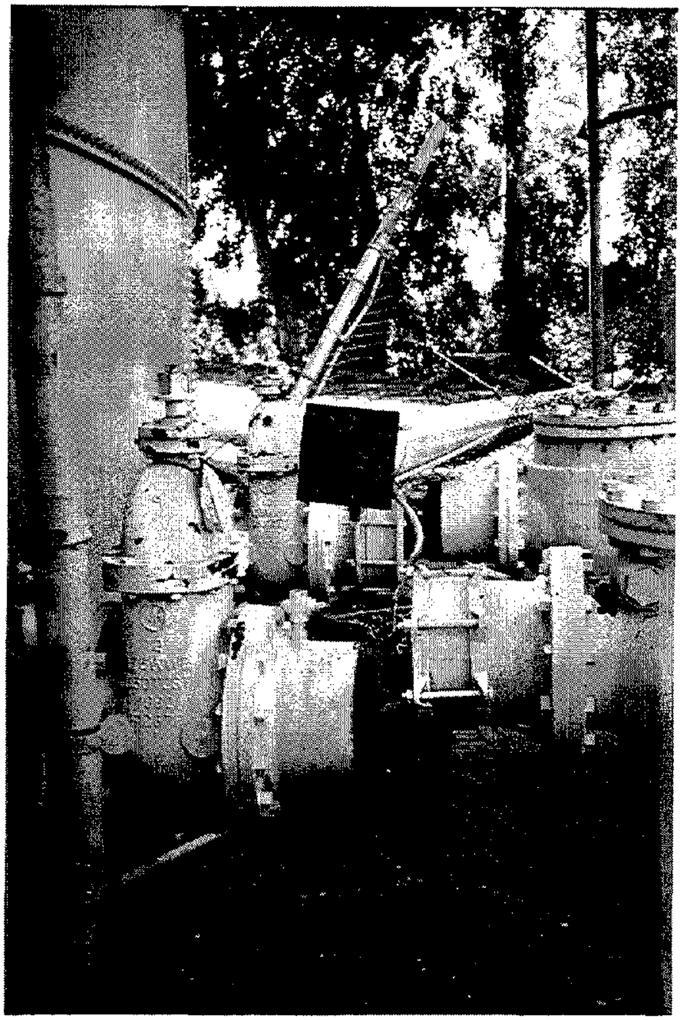


Fig. 4.24 Dresser coupling failed at the tank inlet and outlet. (A. Gibson))

At the L. A. County/USC Medical Center, three 7,500 gallon (28.4 ml) roof mounted water tanks on the Mental Health/Psychiatric Building leaked due to broken inlet-outlet piping. The resulting water leakage in combination with other non structural

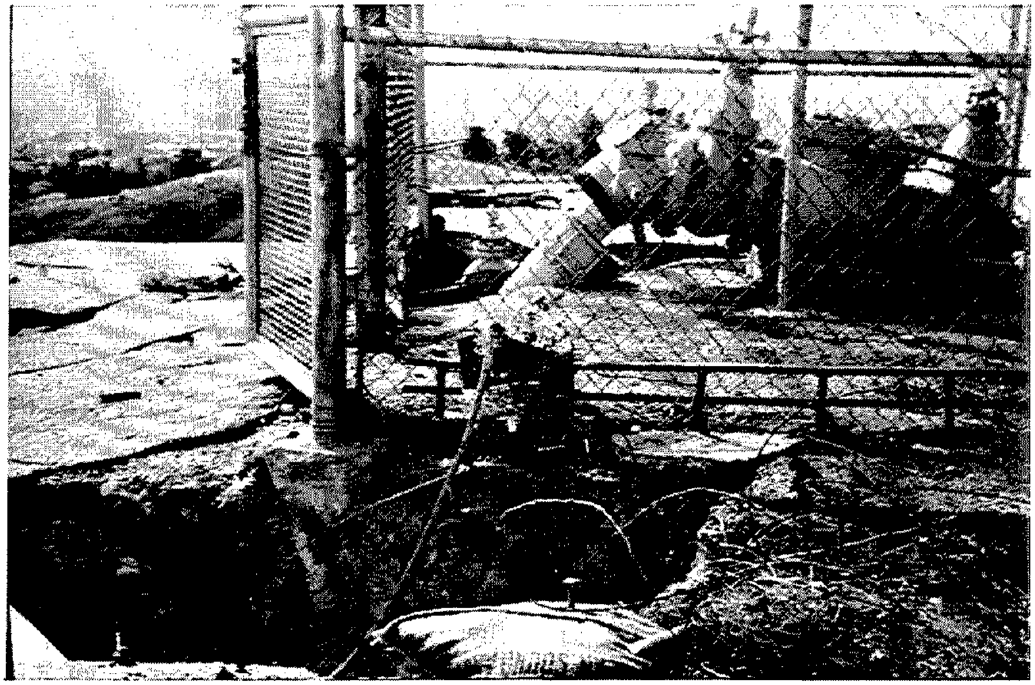


Fig. 4.25 Typical ground erosion from tank draining. (LADWP)

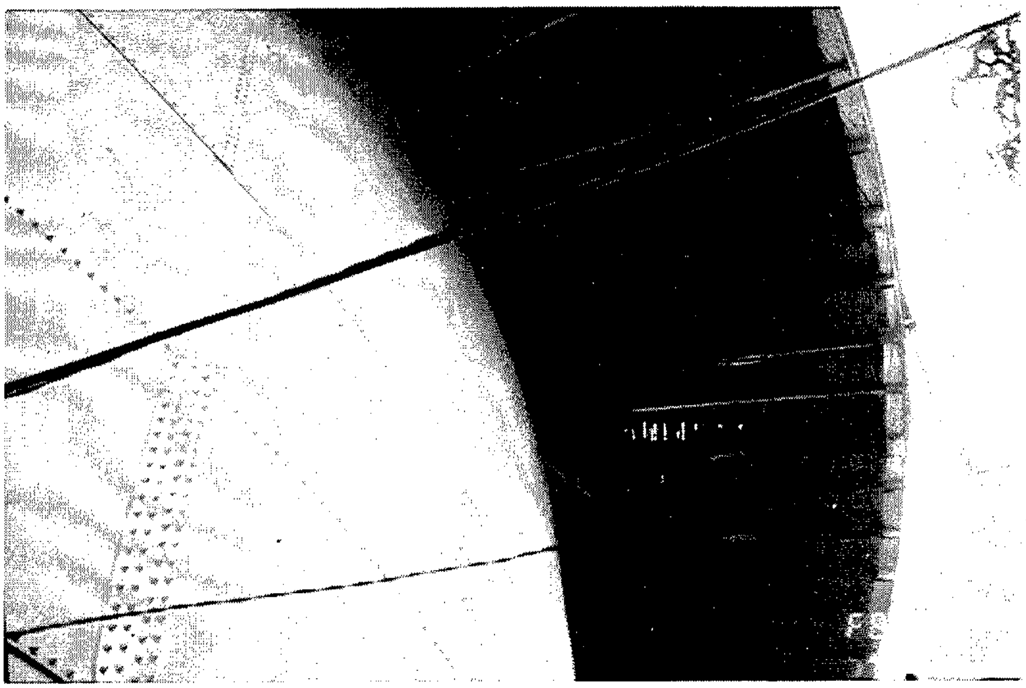


Fig. 4.26 Shifted wooden roof on riveted steel tank. (LADWP)

damage to elevators, etc. necessitated the closure of the building and the relocation of about 120 patients. Similar lifeline damage occurred at the Woman's Hospital and Pediatric Hospital at the Medical Center.

Summary of Water Tank Performance

About three dozen tanks were damaged and nonfunctional by this earthquake. The damage was more severe than in previous earthquakes and the loss of contents had the potential of disrupting fire supression. The principal modes of function failure were inlet-outlet piping failure due to uplift and roof damage due to sloshing. Also most of the failed tanks were not American Water Works Association AWWA D-100 seismic design basis tanks, many were of bolted construction and were of relatively small size. There were a number of smaller industrial tanks near the Northridge/Canoga Park area which also were damaged. To the credit of operating and maintenance personnel, many of the tanks without severe damage were returned to service in a short time.

Many of the steel tanks were not AWWA D-100 designs, and in earlier versions of the standards the seismic requirements were optional, so its is difficult to comment on the adequacy of current AWWA seismic design criteria. It is noted roof damage seemed to be more apparent in this event; the occurrence of roof rafters falling off supports was noted at several locations. The failure of the inlet-outlet piping was the principal cause of functional failure; the lesson here is to use steel valves and fittings and to provide flexibility in the piping to accommodate tank movement.

Larger concrete tanks, many semi-buried, did not appear to have suffered any damage and were designed and constructed to meet or exceed the AWWA Standards for Wire-Wound Circular Prestressed-Concrete Tanks (AWWA D 110). These tanks were located a greater distance from the strong shaking. A description these tanks and remarks on their performance are given in Table 4.2. Other tanks, both damaged and undamaged, are not included in this report.

BOOSTER PUMPING STATIONS AND GROUNDWATER WELLS

There was no reported damage to booster pumping facilities or groundwater wells, other than loss of commercial power, Fig. 4.27. Many wells did not have emergency power. Pumping stations with emergency power supply worked well. There was minor damage to the enclosures housing these facilities. The lack of damage to wells was important alternative supply to areas who lost their imported supplies.

In some areas, fire department engine pumpers were used to maintain pressure in area in which the leaks had been repaired. The pumping between fire hydrants by the engine pumpers was used when the primary supply was not available.

Table 4.2 Prestressed Concrete Tanks In The Los Anglese Area. (T. Cooper)

	HT (FT)	DIA (FT)	VOL (MGAL)	YEAR BUILT	REMARKS
FIRENZE	38.7	67	1.0	1958	Half buried, no damage, wrapped
MACLAY 1&2	20	300	10	1992	Two-thirds below ground, minor shell spalling, wrapped strand
ROSCOMARE 2	29.6	79	1.0	1956	Below grade, no damage wrapped strand
SUSANA	44	200	10	1990	Above ground, minor damage and chipping at roof, wrapped strand
TEMESCAL	27	83	1.0	1991	Below ground, no damage, wrapped strand
TRAILER	27	83	1.0	1985	Two-thirds below grade, no damage, wrapped strand
TUJUNGA	35	140	4.0	1992	Above ground, no damage, wrapped strand

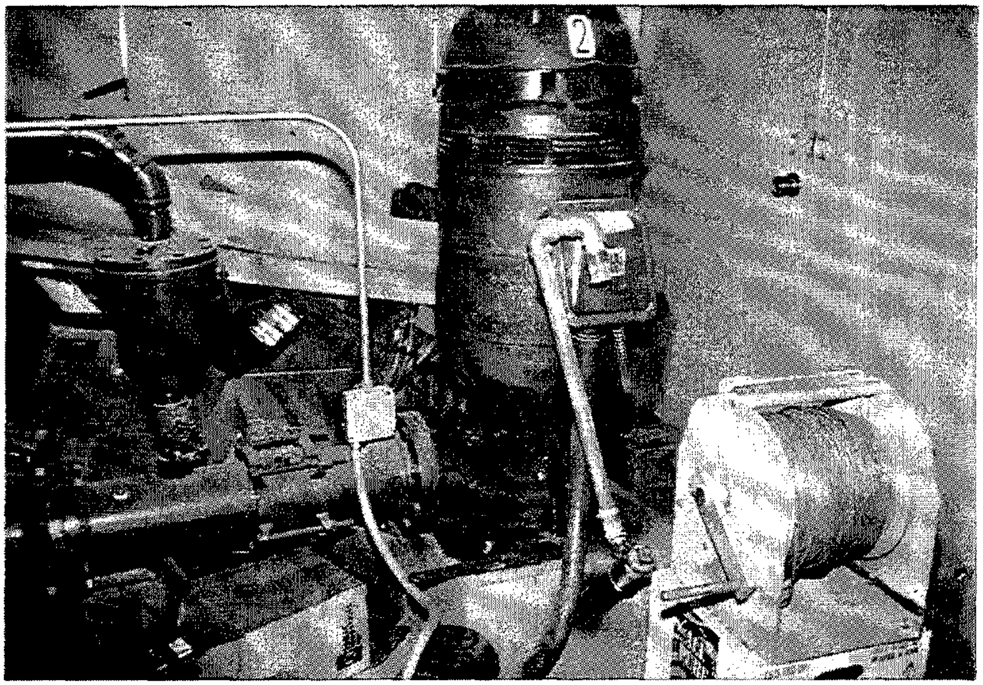


Fig. 4.27 This typical well pump installation had no damage.

WATER TREATMENT PLANTS

The operating plants have a capacity of 25 (95), 550 (2080), and 600 million gallons per day (mgd) (2270 million liters per day) (ml/d) The treatment plants received minor damage, such as ground settlement around the plants, Fig. 4.28; leaks at construction and expansion joints; leaks in plastic chlorine solution lines, Fig. 4.29, overturned filing cabinets and book cases; falling ceiling tiles; and sloshing damage to gratings and wood baffles in the basins, Figs. 4.30 to 4.32. Supply was available in most areas from storage and the other regional sources, but was not immediately available from the treatment plants because of the damage to the distribution systems. There was generally good performance of water treatment plants, since the damage could be repaired or mitigated in a short period of time. The Simi Valley water treatment plant (50 mgd) (190 ml/d) was not in operation and still under construction.

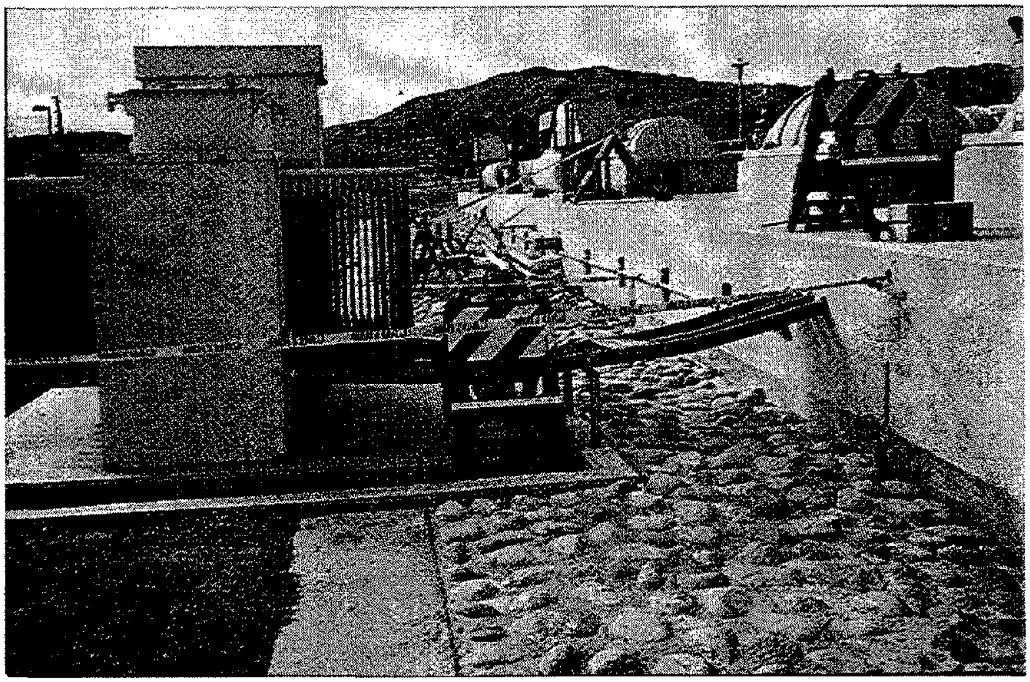


Fig. 4.28 Ground settlement adjacent to water treatment plant (U. of Tokyo)

LIFELINE COLLOCATION

A collocation of nine lifelines occurred on Balboa Boulevard, north of Rinaldi Street, in Granada Hills, an apparent tension and compression zone. Located within the street were 3-gas, 3-water, 2-sewer and 1-oil underground lines; 34.5 kv and 4.8 kv power, telephone, and cable TV overhead lines; and street lighting. Ground movement caused the breakage of some of the underground pipelines, a fire occurred in the street which ultimately burned the overhead lines and five homes, Fig. 4.33. At

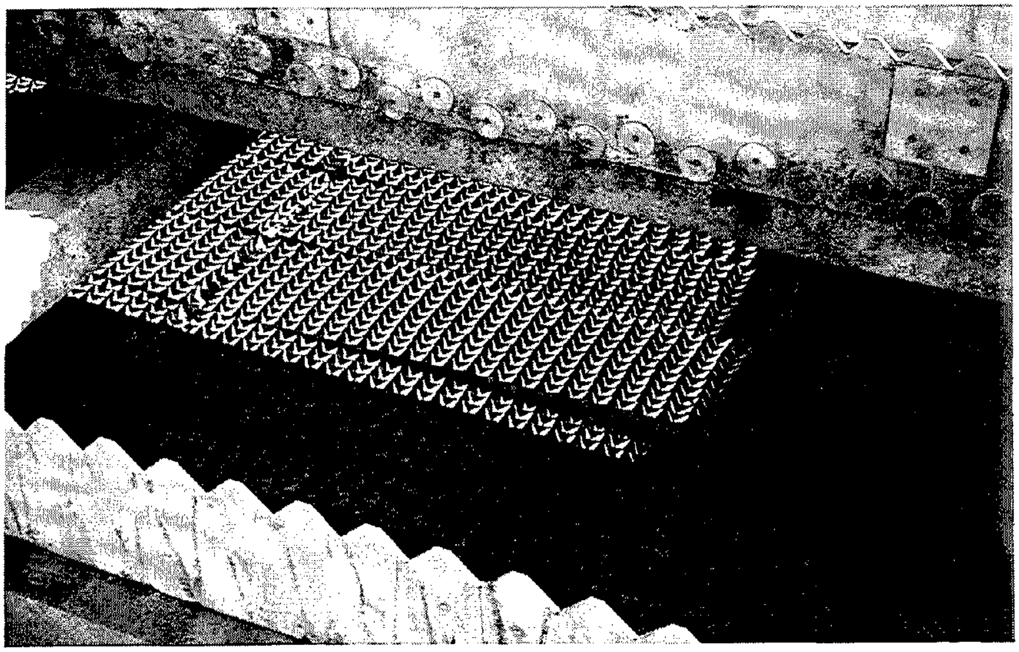


Fig. 4.29 Damaged PVC chlorine solution lines adjacent to water treatment plant.

Fig. 4.30 Grating dislodged by sloshing at water treatment plant.

this location there appeared to be a ground separation (tension) at a location on Balboa Blvd. south of Lorillard Street of approximately 9 to 12-in (230 to 305-mm). Approximately 1,000-ft (300-m) to the south there was ground compression of an equal amount, Figs. 4.34 to 4.37. At both of these locations the gas, water and sewer .

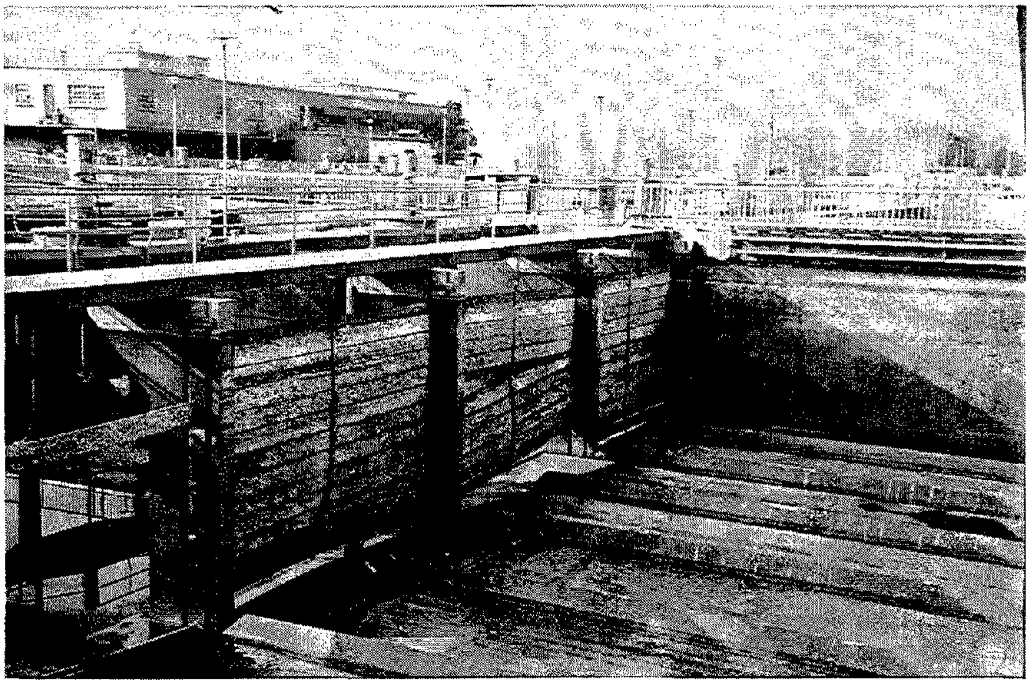


Fig. 4.31 Floating wood baffles dislodged by sloshing at water treatment plant. (MWD)

Fig. 4.32 Wood baffles damaged by sloshing at water treatment plant. (MWD)

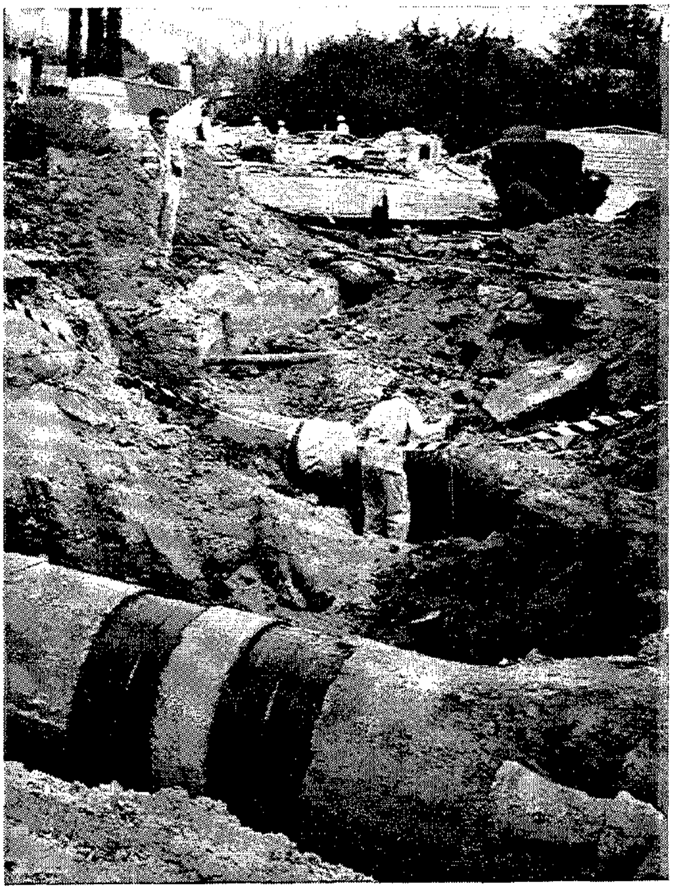


Fig. 4.33 Damaged pipes under Balboa Blvd. south of Lorillard St. in tension zone.

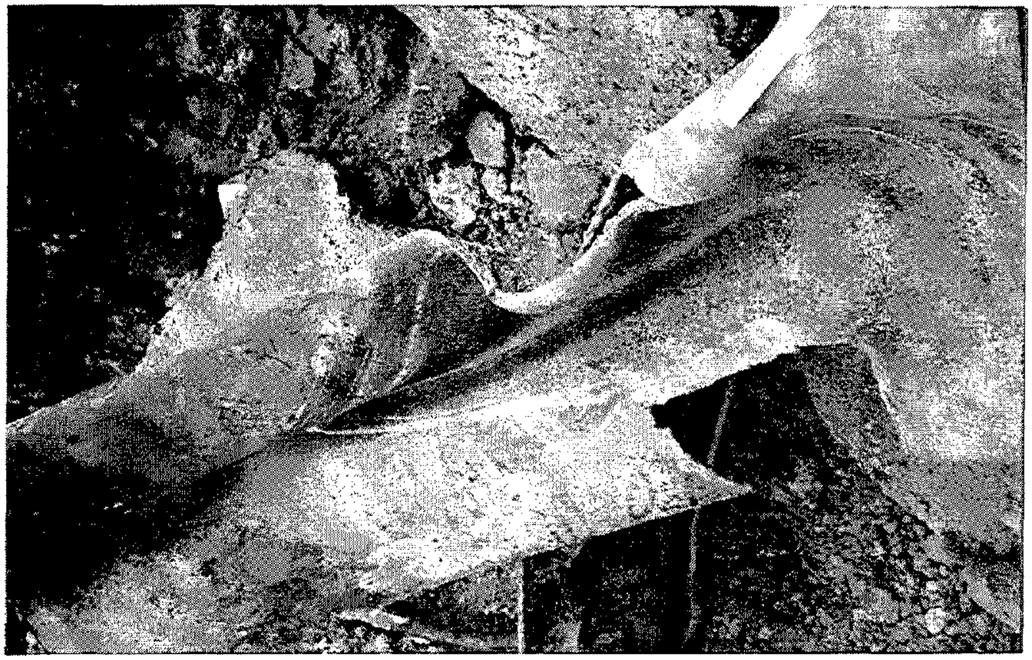


Fig. 4.34 Balboa Blvd. at Halsey St. compression zone 68-inch WSP buckled bell and spigot joint.

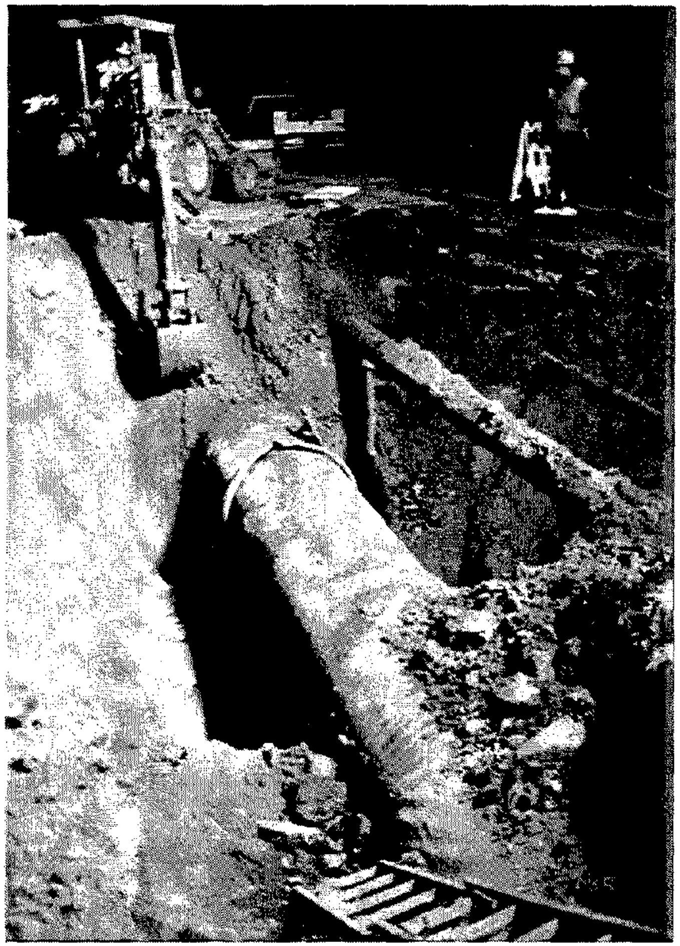


Fig. 4.35 Balboa Blvd. at Halsey St. compression zone, back hoe uncovering compression damage 48-inch WS pipe. (LADWP)

Fig. 4.36 48-inch welded steel bell and spigot joint from Balboa Blvd. at Halsey St.

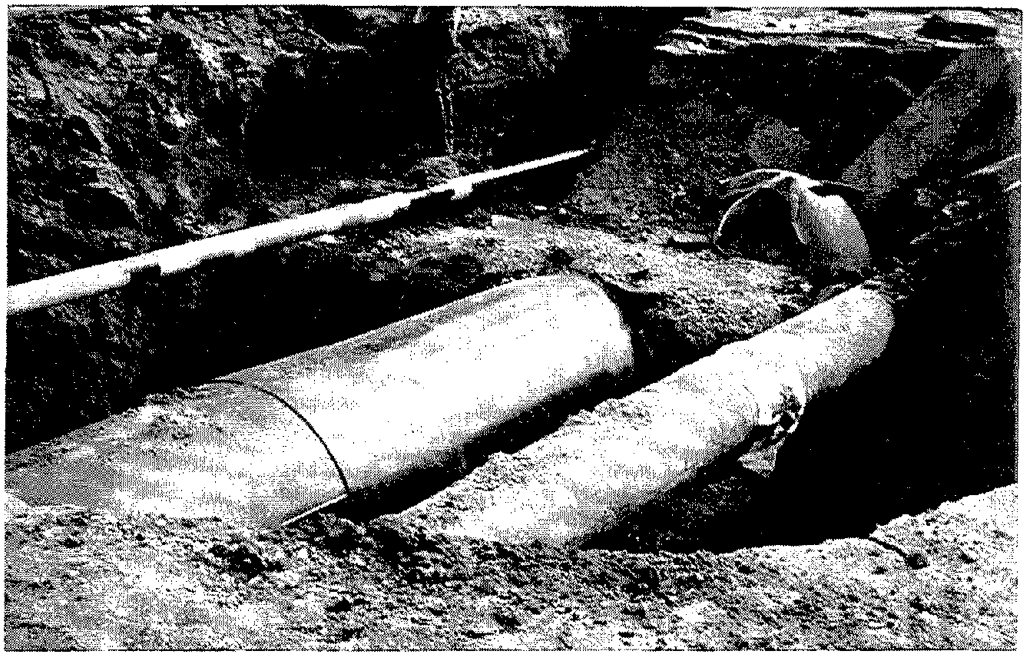


Fig. 4.37 Completed pipeline repairs at Balboa Blvd. at Halsey St.

WATER QUALITY

This earthquake disrupted treated water to many water systems including Santa Clarita, Fillmore, Moorpark, Simi Valley, Malibu and San Fernando as well as Los Angeles. Water supply was available, some treated and some untreated, from groundwater basins, storage, MWD Colorado River Aqueduct and East Branch of the State Water Project.

Three filtration plants were out of service due to supply pipeline damage; this meant a loss of over one billion gallons per day (3.8 billion liters per day) of water treatment capacity. The water supply to these facilities was restored in one to two days. Because of distribution system pipeline damage, water purveyors, in cooperation with the California Department of Health Services, Division of Drinking Water and Environmental Management (DHS), issued "boil water" notices immediately, as a precautionary measure. Although some service areas were not affected, the boil water notices gave water purveyors needed time to assess the damage to their systems. A standard "boil water" notice had been prepared by DHS in advance for use by the water agencies, in times of a emergency.

The notice generally stated customers should boil or treat their water before consuming. Rapid boiling for five minutes or treating the water with chlorine would disinfect the water adequately. Specifically, customers were asked to add unscented liquid commercial bleach to their water in the following amounts: 8 drops per gallon (3.8L)for water that appears clear, 16 drops per gallon (3.8L) for water that appears cloudy. Customers were told to mix the chorine and water and let the mixture set for 30 minutes before consuming.

The boil water notices were released by the water purveyors and DHS in the printed and electronic media. Local TV and radio stations became very important disseminators of changes in the boil water notice in the areas. A problem arose when customers from unaffected water systems began to unnecessarily boil water their water and call their water purveyors in panic. This required unaffected water purveyors to issue their own separate notice indicating their water was safe to drink. Even with the confusion water purveyors and DHS felt issuing "boil water" notices was better than taking a chance that someone may drink contaminated water.

In order to lift the "boil water" notice from any service area, the water agency requested permission from the local DHS district engineer. The authorization would only be granted after the water purveyor had completed the repairs to its distribution system, the distribution system was pressurized, had at least a 1 ppm (1 mgl) chlorine residual in the distribution system and had received satisfactory disinfection and bacteriological testing. The testing takes at least one day. It would be desirable to have mobile water quality Laboratory to make field testing of water quality and an expedited method for testing for contaminants in the water.

In areas like Santa Clarita Valley, where well water was chlorinated for the first time, some customers complained about the chlorine taste and odor. In Los Angeles, boil water area was gradually reduced as the system was restored and customers in the last boil water notice area were allowed to use their water on January 29th, in the Simi Valley on January 24th and in the Santa Clarita Valley on February 4th.

EMERGENCY WATER SUPPLY

Emergency water supply was provided by bottled water, beer and soft drink beverage companies, Figs. 4.38 and 4.39. MWD, U. S. Army Corps of Engineers, California National Guard and water agencies provided water using agency, contractors and rented tanker trucks. The tank trucks were disinfected and fitted with taps and hoses for easy dispensing. During the height of the operation in Los Angeles, 72 trucks were being dispatched to nearly as many locations providing over 100,000 gallons (378,500 liters) of water each day. The boil water order also impacted Los Angeles International Airport as noted in Section 10. Airports.

MUTUAL AID

Volunteer mutual aid was provided by almost a dozen water agencies from the local area and one came from the San Francisco Bay area. Mutual aid agencies provided their own personnel, equipment and materials. Fifty-two people assisted Los Angeles

Fig. 4.38 Beverage tank truck providing emergency potable water supply.

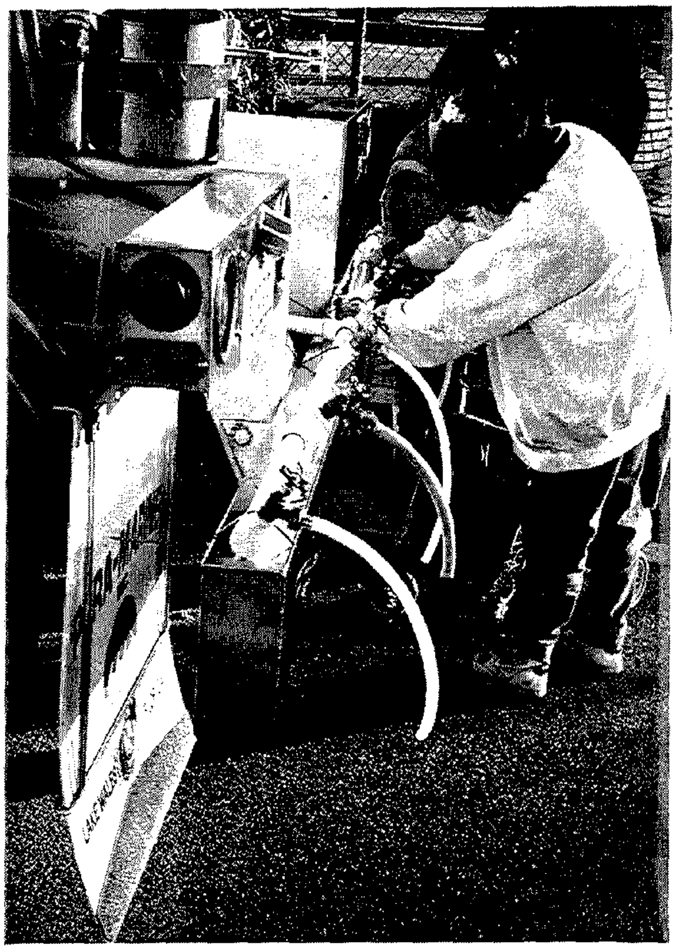


Fig. 4.39 Users filling their containers from the beverage tank truck.

in restoring their system. Contractors familiar with water utility work were also used. The mutual aid agencies had to deal with the limited housing and food in the epicentral area.

OBSERVATIONS AND RECOMMENDATIONS

- Seismic performance of dams, large buried reservoirs, and wells in the 1994 Northridge earthquake showed significant improvement from the 1971 San Fernando earthquake. Facilities constructed since the San Fernando earthquake that incorporated lessons learned from that earthquake performed well. These include concrete tanks and pumping stations that was subjected to very strong ground motions. The prestress-concrete water tanks were constructed using criteria more conservative that those contained in AWWA Standards for Wire-Wound Circular Prestress Water Tanks (AWWA D110).

- There is a need for performance criteria for water systems so that piping systems and other water system facilities and equipment can be evaluated and seismic specification established in a consistent manner. With performance criteria, water systems performance and the consequences of disruption can be evaluated. With this information a case can be made for getting public support to enhance system performance in a timely and cost-effective manner.

- The largest impact on water system performance was the failure of water lines, both large supply lines and smaller lines in the distribution system. Most pipeline damage has the result of ground deformations. This earthquake had no surface faulting, but there were many areas with ground deformations in locations that had not previously been predicted. Thus, a general level of improved materials and methods may be needed to improve system performance rather than concentrating on special problems of fault crossings. The uncertainty in predicting the location of damage increases the importance of system redundancy and alternate supplies from other sources, such as groundwater basins and alternate aqueduct systems for water supplies.

  Many of the pipe failures appear to be related to cracks in bells that are probably associated with their method of fabrication. There is a need to study the seismic strength of welded steel bell and spigot joints and methods to improve the seismic performance of the joint. The joint performance should be compared with the current (AWWA) Standard for Welded Steel Pipe.

- The performance of surface-supported tanks was poor and damage was similar to that observed in previous earthquakes. Many of the damaged tanks were old and predate current seismic design standards. The loss of tank contents was frequently associated with the failure of input and output pipe connections. These failures are due to the use of cast iron fittings and inadequate flexibility to accommodate the movement of the tank, which was typically lifting rather than sliding. The roofs and upper parts of side walls on several tanks were damaged due to sloshing. Several examples of elephant foot buckling were observed.

There is a need for follow up surveys to determine the performance of tanks constructed using current seismic standards and to determine the relative performance of anchored and unanchored tanks. Methods to address the damage due to sloshing should be identified for existing and new tanks. Based on the effect of tank performance on water system performance, the need for reducing the risk of tank damage by improving anchorage, stiffening to prevent buckling, and reducing effects of sloshing can be determined.

- Sloshing in large basins in water filtration and water reclamation plants caused damage in both the 1989 Loma Preita and the Northridge events. Although not critical, the damaged equipment can cause malfunction of other equipment. For example, sloshing caused the jamming of the chain drive sludge scrapers in seven out of 44 final clarifiers of a water reclamation plant. There is a continuing need to consider sloshing and shaking in the design of mechanical equipment and baffles in large basins of water and wastewater treatment plants.

- Air and vacuum valves on pipelines are configured in an inverted pendulum above the ground surface. In the Northridge event many valves toppled, had cracked bodies or damaged floats (balls). Also the damage may have been caused by transient pressures in the pipeline. A study is required to improve the performance of these valves in an earthquake.

- The disruption of commercial power emphasizes the need for reliable emergency power supplies. While emergency power for pumping stations and treatment plants performed well, there were indications that testing units under full load may enhance performance.

- The 1971 San Fernando and 1987 Whittier Narrows earthquakes experience has encouraged water agencies to prepare emergency response plans and establish emergency operations centers. These plans have been tested and implemented by lifeline agencies. Water system emergency response plans generally worked well in the Northridge earthquake. This was attributed to their periodic testing. It is important that plans address expected problems in communicating with personnel and with transportation problems. Because of transportation problems and the disruption of several lifelines, it is important that water system disaster plans make provision for supporting most needs of their workers, including food and temporary housing. In the recovery after an earthquake, outside contractors may be retained to speed the recovery. It is important that all personnel be aware of OSHA requirements for entering confined spaces, such as large diameter pipes, conduits and tunnels. To improve the performance of utility work crews, utilities should consider providing support for worker families that have been directly affected by the earthquake. For example, this could include providing assistance with getting shelter or help in evaluating damage to homes.

- Boil water orders were issued as a precaution. Because of the time needed to confirm that water is safe once an order is issued, the public may be needlessly inconvenienced. Consideration should be given to developing a mobile water quality laboratory to expedite, in the field after repairs have been made, the determination if the water is safe for drinking. More rapid methods for evaluating the safety of water should be explored.

- There is a need for adequate documentation of emergency response and recovery costs. For public utilities, as is the case for most water systems, a record is needed for reimbursement from FEMA. Documentation is also needed to substantiate insurance claims.

- The disruption of the water supply demonstrated that many critical facilities were not prepared with emergency water supplies or even a means for connecting an external source into their system.

  This is a need for better public education about the consequences of water system disruption and use of appropriate mitigation measures.

- While the performance of customer water is outside of the jurisdiction of water utilities, damage to these systems was costly and disruptive in the Northridge earthquake. The Oliveview Hospital, which was reconstructed after experiencing severe damage in the San Fernando earthquake had to be evacuated due to the failure of water systems within the hospital. The vulnerability of water systems in buildings should be evaluated and standards improved to reduce the losses and disruption from these systems.

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5. WASTEWATER SYSTEMS

ABSTRACT

The Northridge earthquake was the first event to test wastewater treatment plants in this area, since none existed in this area at the time of the 1971 San Fernando earthquake. As in past events damage did occur due to shaking and sloshing in the basins. Sewer pipeline damage was not obvious immediately after the earthquake as in the past. The loss of power was factor in the operation treatment plants and sewer pumping plants.

INTRODUCTION

An earthquake occurred at 4:31 a.m., Pacific Standard Time (PST), on Monday, January 17, 1994, the epicenter was located 20 miles (32 kilometers) from the center of Los Angeles, in the Northridge community (San Fernando Valley) of Los Angeles, California, USA. The magnitude was M 6.7 (Caltech). The impact of the earthquake was wide spread in western Los Angeles and eastern Ventura Counties. The earthquake had significant impact on lifelines, in addition to damage to residential and commercial buildings, and freeways. The estimated damage was approximately $20 billion and there were approximately 58 fatalities.

GENERAL

The area impacted by the earthquake is covered by wastewater treatment and collection systems generally restricted to within the drainage areas of Santa Clarita, Simi and San Fernando Valleys. Water Reclamation Plants treat wastewater for limited reuse or discharge into inland bodies of water, while wastewater treatment plants treat for discharge to the ocean.

The lifeline description, seismicity and the strong motion records are the same as described in the Water System Section 4. Figure 5.1 is a general vicinity map of the earthquake area showing the epicenter, communities, highways, and approximate location of treatment plants.

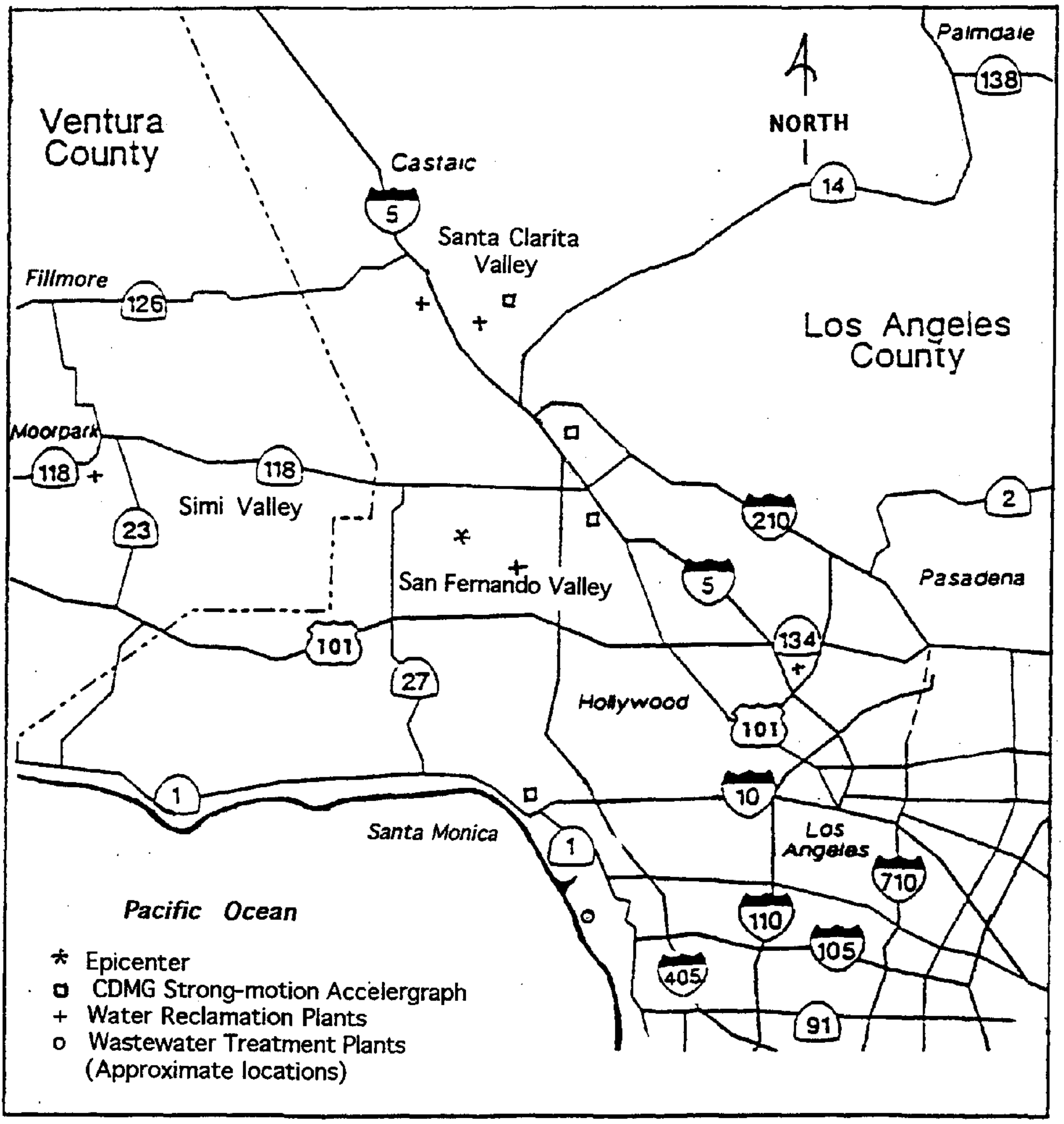

Fig. 5.1 Map of epicentral area showing communities, highways and approximate location of treatment plants.

WATER RECLAMATION PLANTS

VALENCIA WATER RECLAMATION PLANT

The plant in Valencia [(9 mgd (34 ml/d)] experienced vertical as well as horizontal accelerations causing damage to the treatment process and the treatment was temporarily reduced from tertiary to secondary treatment. The plant lost commercial power; however, the emergency generator started automatically after the earthquake. The sodium hypochlorite disinfection system shut down and attempts to restart the system were unsuccessful. The former gaseous chlorine system was inspected and place into service. The aluminum covers on all primary sedimentation tanks were bent, filter backwash wet well covers were damaged by sloshing (Figure 5.2) and all the solids collection systems (scrapers, etc.) failed. The chains driving the solids collection flights broke or came off the sprockets. Sloshing caused damage to the wood baffle walls which separate the aeration tanks and the baffle walls in the chlorine contact tanks. Damaged occurred to PVC aeration piping header and grid piping (Figure 5.3). There was a need in the pressure filters to repair the filter media and the leaks in the buried 42-in (1070-mm) reinforced concrete pipe bypass. The air diffusion equipment and the odor air scrubber unit was damaged (Figure 5.4). There was damage to chemical laboratory equipment and the automatic samplers. There was concrete cracking and joint separation through out the plant. The plant was never completely out of service and returned to full service on January 21st.

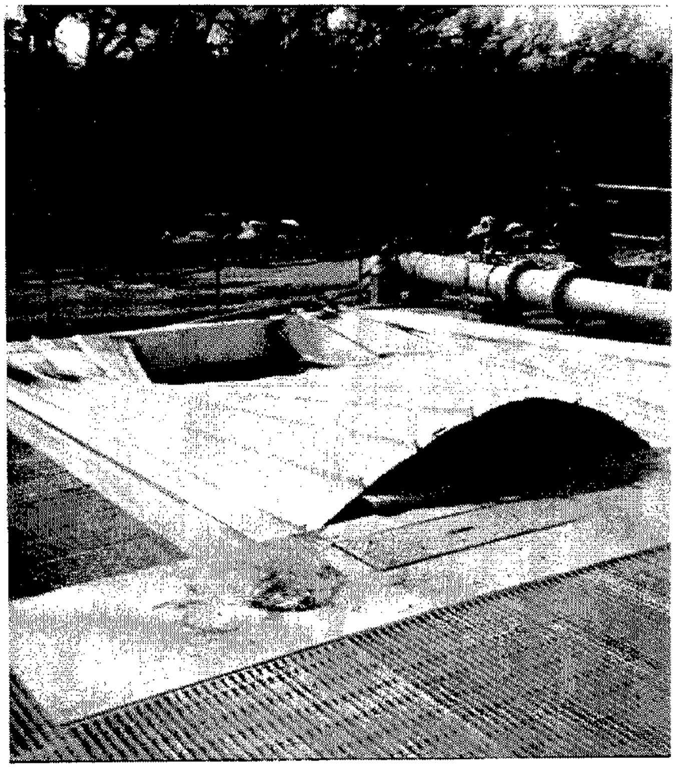

Fig. 5.2 Valencia Plant filter backwash wet well cover damage due to sloshing. (LA Co. SAN)

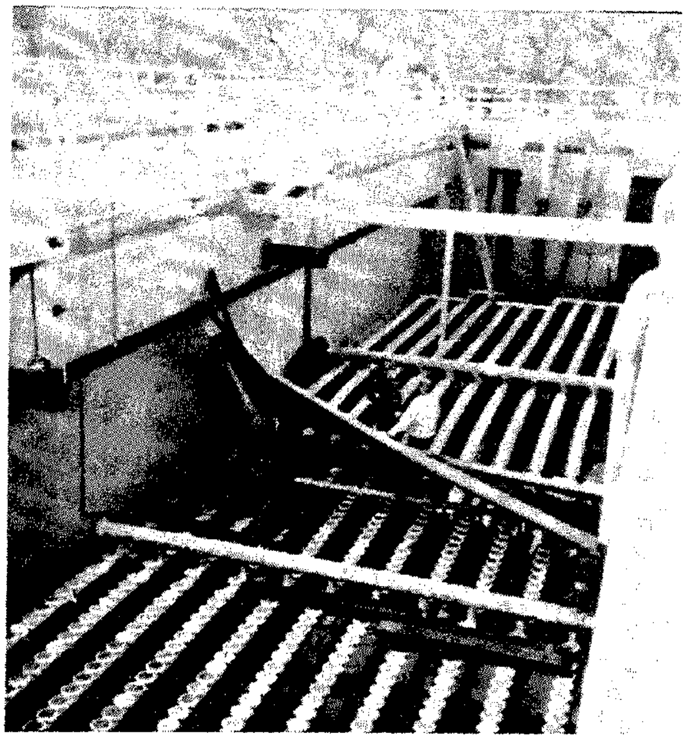

Fig. 5.3 Valencia Plant aeration tank damaged PVC aeration header and grid piping due to failure of pipe support to concrete wall. Header support moved 8 feet is laying against wall at the top of photo. (LA Co. SAN)

SAUGUS WATER RECLAMATION PLANT

The Saugus tertiary treatment plant [(5.5 mgd) (20.8 ml/d)] received damage to concrete structures mainly joints and cracks, in the secondary and primary sedimentation tanks, chlorine contact tanks, filter gallery, secondary effluent channel and aeration tanks. Also damage occurred to the process air piping (21 in) (535 mm) steel pipe. The commercial power service connection required repair. The damaged Saugus plant was never out of service. The Saugus and Valencia Plants are connected, this redundancy permitted the Saugus Plant to help to reduce the treatment load on the Valencia Plant.

LA GLENDALE WATER RECLAMATION PLANT

There are two water reclamation plants, LA Glendale and Tillman, in the San Fernando Valley area which provide tertiary treatment of the wastewater for reuse. Both plants lost power.

The Glendale plant 20 mgd (75 ml/d) lost power for 6 hours, did not have an emergency generator since it operates on a bypass of the main outfall sewer to another treatment plant. The plant was bypassed until power was restored. A 72-in (1829-mm) square plate came loose which directs the flow to the detention basin. A portion of the flow went directly to the serpentine effluent structure. Also there was broken auxiliary pipe. Emergency repairs were made on the day of the earthquake and the plant was returned to full operation. The integrity of water quality was not compromised.

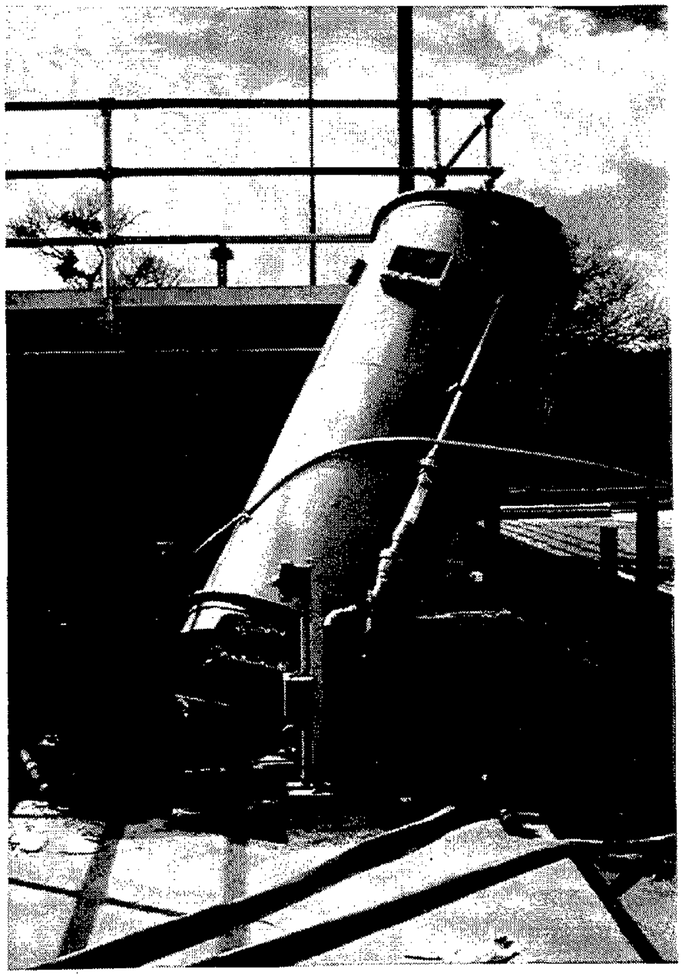

Fig. 5.4 Valencia Plant destroyed air scrubber. (LA Co. SAN)

TILLMAN WATER RECLAMATION PLANT

At the Tillman plant 80 mgd (805 ml/d) the emergency generator started automatically; however, the operator was concerned about its operation and shut it down. Tillman lost power for 7 1/2 hours; however, they did not loose their biological system. The Tillman Plant received minor damage, but not significant to hinder

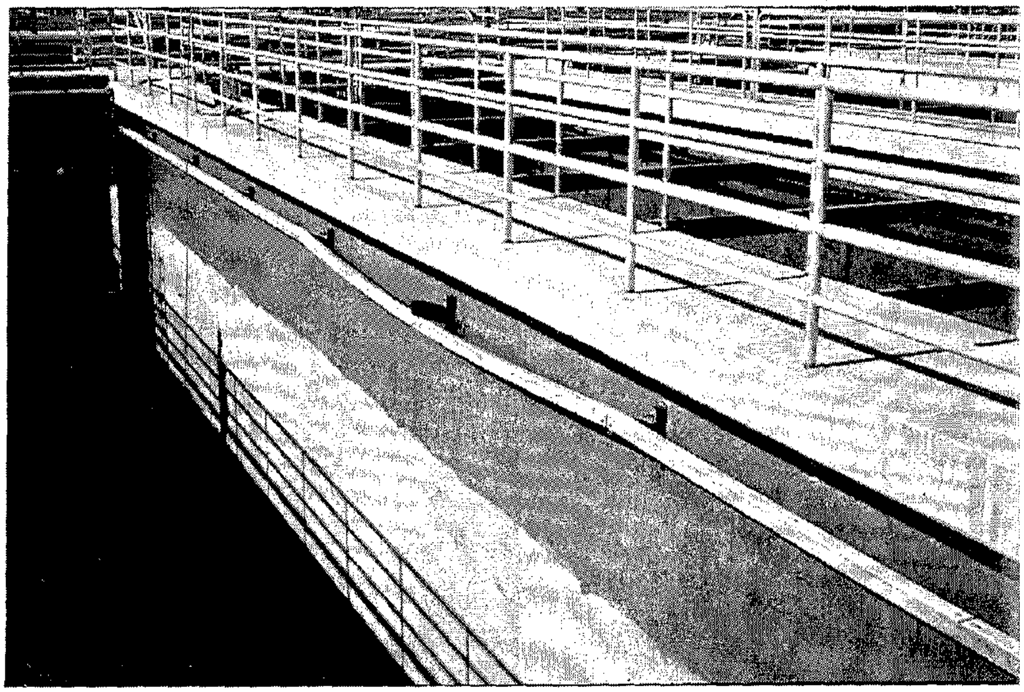

Fig. 5.5 Tillman plant final clarifier, sloshing unseated return sludge scraper chain rail.

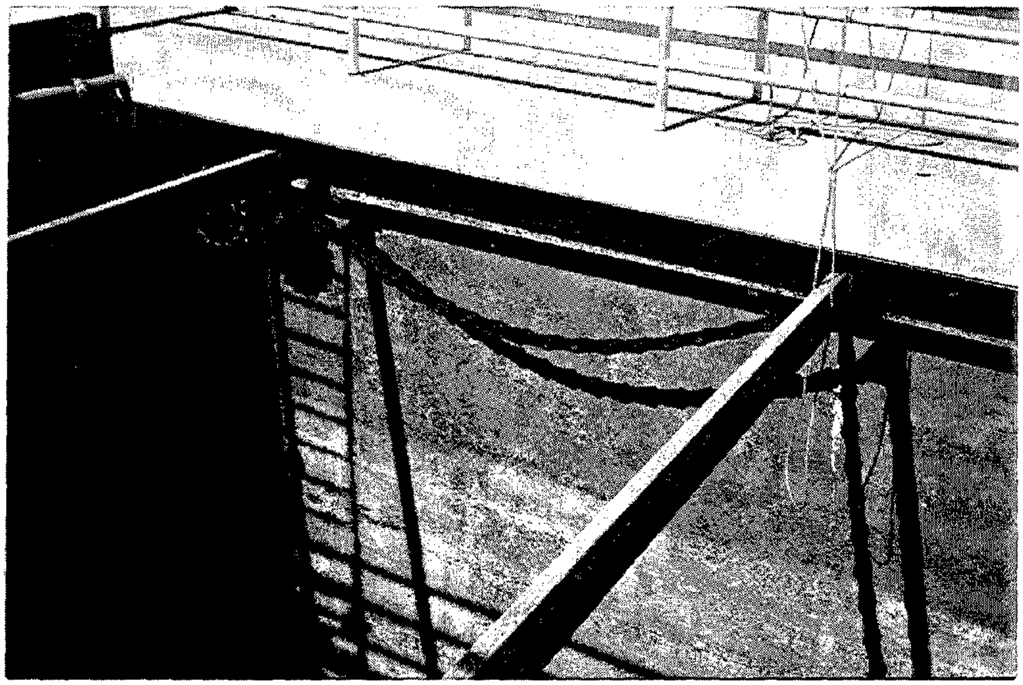

Fig. 5.6 Tillman plant final clarifier. Sloshing jammed sludge scraper chain drive.

operation when power was restored. Typical minor damage was dislodging by sloshing of the chain drive sludge scrapers on two primary and five final clarifier tanks out of a total of 44 (Figure 4.5 and 4.6), broken auxiliary piping, cracked concrete, broken windows, fallen ceiling tiles and warehouse supplies toppling.

HYPERION WASTEWATER TREATMENT PLANT

The Hyperion Wastewater Treatment Plant (360 mgd) (1360 ml/d) is located near El Segundo and had no damage and the energy/cogeneration operations remained on-line and provided power while all others in the city grid went off-line. The facility helped to restart the adjacent Scattergood Generation Station which was off line. The effluent pumping station lost power because it was not connected to the energy/cogeneration system; however, no process disruption occurred and power was restored within 30 minutes with an emergency generator. The plant is under an expansion construction activity.

In Simi Valley (12.5 mgd) (47 ml/d) and Moorpark (3 mgd) (11 ml/d) wastewater treatment plants continued to operate, received minor concrete cracking and loss of commercial power. Emergency generators operated.

SEWER SYSTEMS

The Los Angeles sewer collection system performed well, except, all 54 sewage booster pumping plants, within the city, lost power at the time of the earthquake. Standby generators or sewer bypasses prevented any sewage from spilling due to the power outage. An 18-in (457-mm) and 27-in (689-mm) in Balboa Blvd. north of Rinaldi St., in the tension and compression zones, were severely damaged. The lines were televised in this area and the mains serviceable were connected by temporally pumping from one manhole to an adjacent manhole to provide service. A contractor

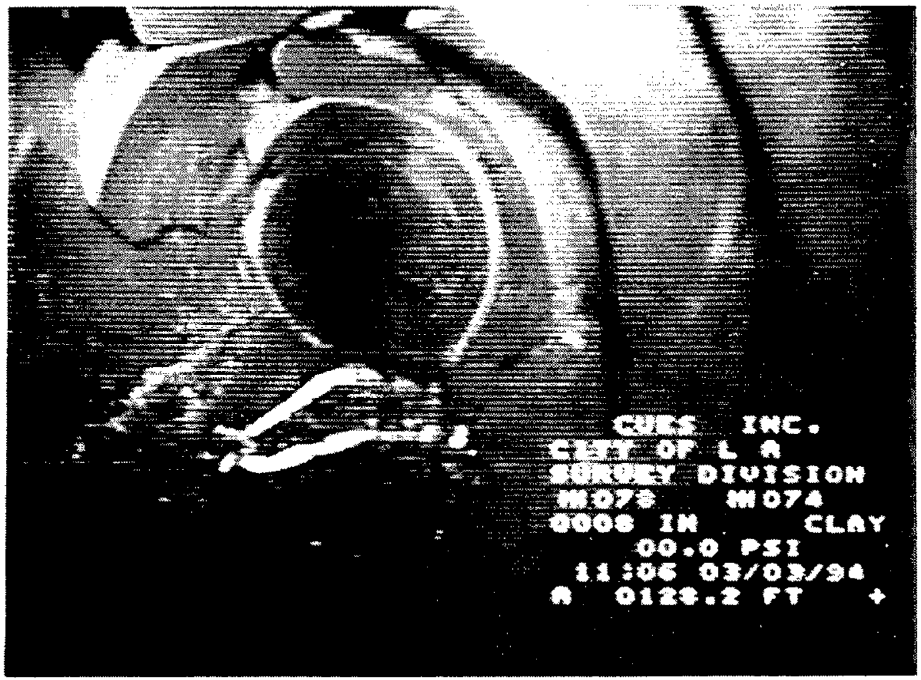

Fig. 5.7 Television photo of the interior of 8-inch VCP sewer. (LADPW)

made the repairs to the lines and service was restored. Sewer lines are normally flow by gravity. They may have been damaged, but if not obstructed will continue to flow, and show damage at a later date after a television survey (Figure 4.7).

Some of the sewers in Santa Clarita Valley were inspected by television. Repairs were required for at least four trunk sewers and other smaller sewers and manholes.

OBSERVATIONS AND RECOMMENDATIONS

Since wastewater systems have a similarity to water systems, the above are included under the Section 4 Water Systems.

6. COMMUNICATION SYSTEMS

ABSTRACT

Performance of the communications lifeline in the Northridge earthquake is summarized in this section. Observations and findings are compiled based on reconnaissance trips to the affected areas, site visits to central offices and private exchanges, communications with staff personnel, and miscellaneous reports and papers published by the operating companies and federal agencies for public consumption. The discussion covers mainly inside plant equipment and facilities including lifeline and other support systems, and outside plants. Network control and emergency response are also described based on information collected.

SCOPE OF RECONNAISSANCE

The main local exchange carriers (LEC) for Northridge and environs are GTE and Pacific Bell (PacBell), and the interexchange carriers (IEC) include AT&T, MCI and Sprint. LA Cellular and PacTel Cellular are the two main cellular service providers. There are over 80 switches in the affected area. Site visits were made to 11 central offices (COs) in the San Fernando Valley and Sylmar/Newhall area, Fig. 6.1. In particular, five of the COs visited are within a radius of 8 miles from the epicenter, and together they provide more than 200,000 access lines and carriers in that region. These locations also include the Regional Network Control Center and the Service Control Center for the telephone companies. Visits were also made to private exchanges located in large manufacturing and engineering companies in the area, and a private communications network that is quite extensive.

Damage and disruption to communications lifelines in the Northridge earthquake are light in comparison with the general devastation in the area. The final casualty count of the earthquake is 59 killed with more than 6,500 injured. Compared to these figures, not a single communications worker was killed and less than 10 suffered injuries of various kinds. Total dollar loss caused by the event is in the range $20-$30 billion (with about $12 billion insured) while total repair cost for PacBell is $26 million, with an additional $125-$150 million budgeted for equipment and facility upgrade (1). In Los Angeles and nearby counties, 55,000 residences were damaged, with at least 21,000 homes and apartments declared uninhabitable. Twenty-two State buildings were closed because of damage and 19 area hospitals were affected, of

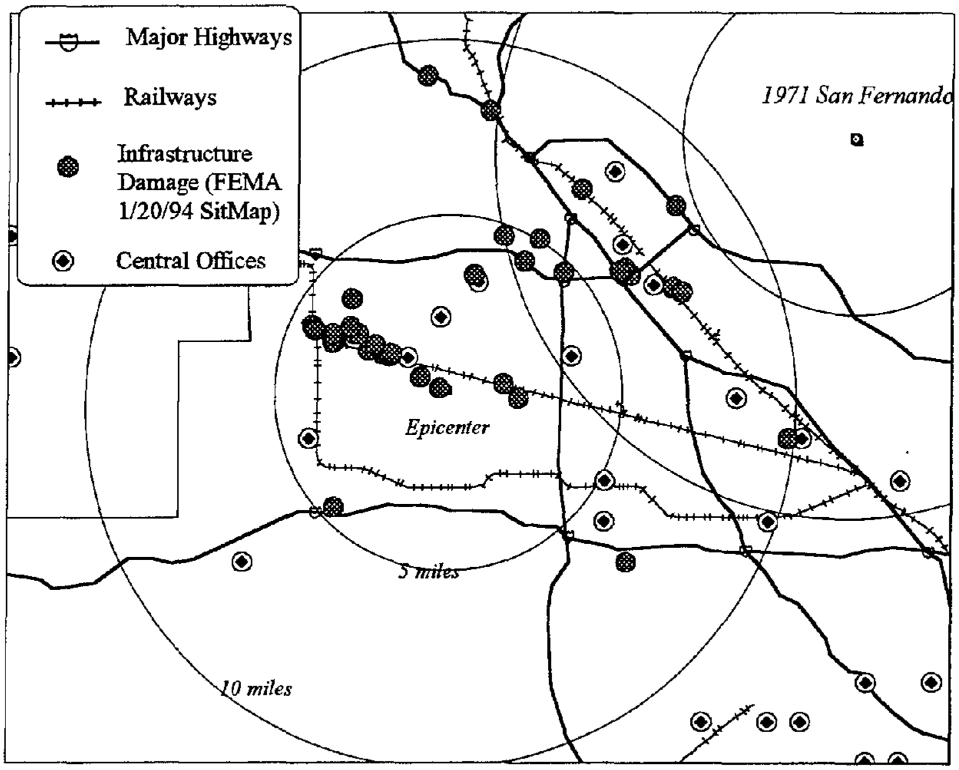

Fig. 6.1 Central offices in the San Fernando Valley nearest epicenter.

which five were totally evacuated. However, only 25-50 COs sustained some type of structural damage, and of which only 2-9 could be considered moderate to severe. No CO was shut down and evacuated.

The damage data and information presented in this section are compiled from several sources in addition to those gathered during our reconnaissance trips (Refs.1-3). We describe first the damage to the landline systems, then the cellular systems, and finally radio and television. Depending on the source of information, parts of the following description apply to all carriers in the area while others apply only to a single carrier. Efforts have been made to minimize potential confusion. Furthermore, some details have been omitted for non-technical reasons, but we believe that the report still conveys a fair picture of the impact of the Northridge earthquake on communications systems.

COMMUNICATIONS DISRUPTION

Local telecommunications infrastructure experienced five switch failures at four sites. Switch failure, as it is used in this report meanse there there was a loss of function, which typically was associated with a loss of power, or movement of a loose circuit board within the equipment. The outages ranging in duration from 3-13.5 hours and affecting approximately 224,500 access lines, or about 3% of the 6.5 million access lines in Los Angeles County. Eight switches were isolated from the SS7 Control Network for durations ranging from 3-8 hours, affecting 387,000 lines. Customers isolated by an SS7 failure still have dial tone but can call only numbers within their local dialing area including local emergency organizations. In addition, two interexchanges failed for approximately 8 hours, affecting approximately 1.9 million customers. Interexchanges connect customers to long distance carriers; customers can still make local and toll calls within the local carrier's network.These numbers are summarized in Table 6.1, and the main reason for most these failures is loss of electric power. Note that with reference to the total number of central offices and access lines in Los Angeles County, the percentage of disrupted COs and access lines is very small. Restoration was rapid, and essentially all customers had telephone service restored within the day. This is a result of continual improvement in equipment hardening against earthquakes and careful recovery planning on the part of the service providers.

Table 6.1. Broad Summary of Telecommunications Outage in the Northridge Earthquake.

Cause	**Total Circuits Affected**	**Duration (hours)**	**% Of County Total**
Switch Failures	224,500	1-13.5	3.5%
SS7 Isolation (A-Link Failure)	387,000	1-8	6%
IEX Failure	1,900,000	8	29%

Generally speaking, the extent of outage and damage corresponds to proximity to the epicenter as Fig. 6.2 shows. Exceptions include facilities in Sherman Oaks, Newhall and Santa Monica and they can be attributed to local geologic conditions. Note that with reference to the figure, some COs are affected by switch failure only, others are affected by SS7 isolation only, and some are affected by both. The reason is that control is implemented logically through a network separate from that of transmission and switching. Interexchange switch failures occurred at a single Point-of-Presence (POP), and affected all COs in the region connected to it.

Call congestion was a problem as is usually the case after a disaster. Table 6.2 traces the call volume in *one* central office in the affected area in the days after the event; the volume jumped to almost four times the daily volume in the immediate aftermath.

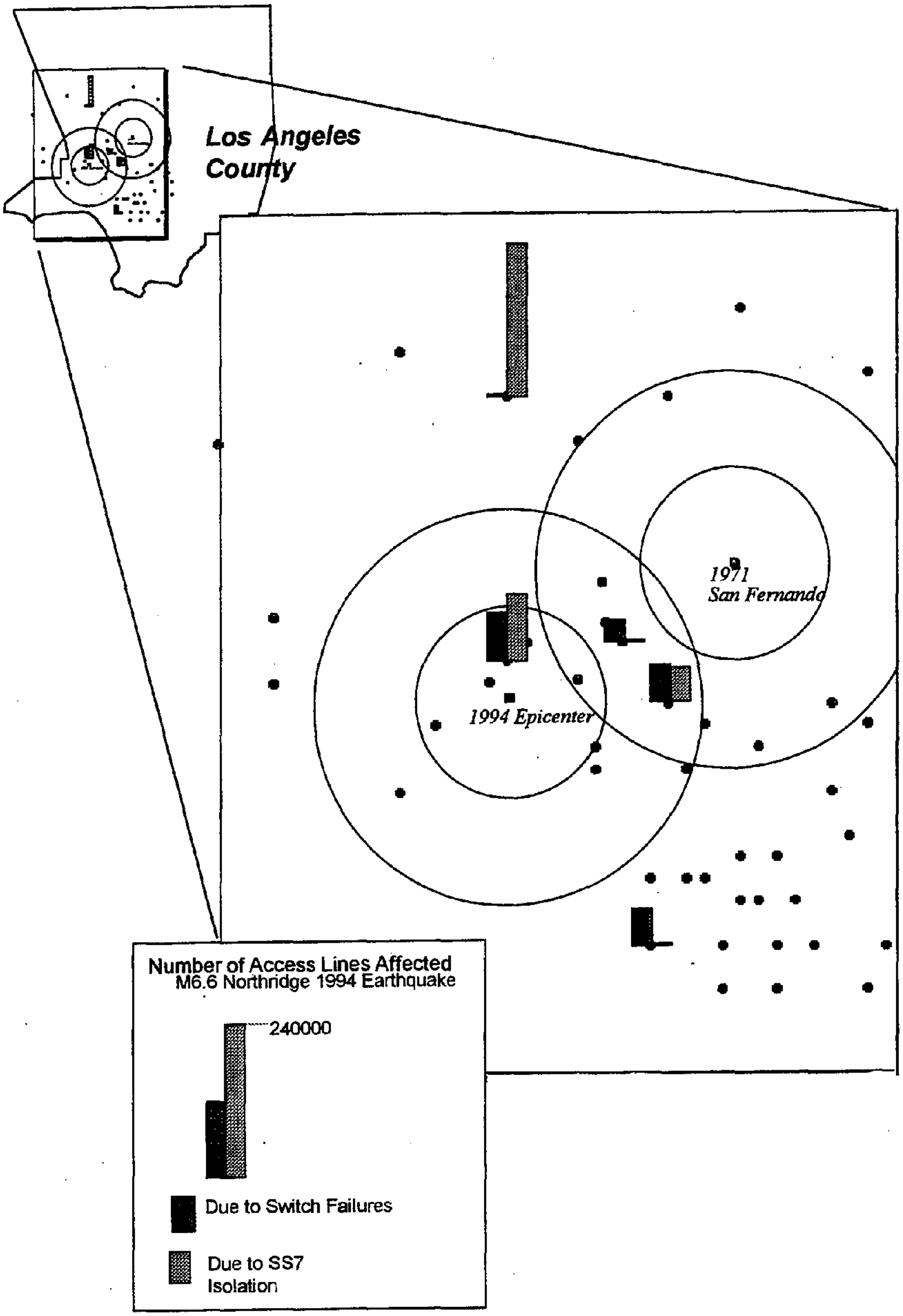

Fig. 6.2 Distribution of outages due to switch failure or SS7 isolation. The bars show the respective number of circuits affected.

Table 6.2. Call Volume On Selected Days In an Affected CO.

	Jan 17, 1994	Jan 18	Jan 19	Jan 20	Daily Ave (1993)
Call Attempt (in ,000s)	5,455	4,237	3,240	2,860	1,500
Performance Index (%)	86.9	95.2	96	97.6	99.3

DAMAGE OVERVIEW

A summary of the overall damage to communications systems belonging to PacBell in Northridge and vicinity is given in Table 6.3. The corresponding data from Loma Prieta of 1989, a more severe earthquake but further away from urban areas, are also included in the table for comparison.

BUILDING DAMAGE

Many exchange buildings were damaged, but only a few could be considered heavily damaged and they continued to operate. Significant physical damage occurred at sites as far away as Santa Monica. Damages were of varying types and at some locations, structural damage was on the verge of being a major factor in this earthquake. For example, at Northridge, the west wall of the facility separated from the second floor and roof. While the structural damages in others (as illustrated in Fig.6.3) were not catastrophic and were shored up within a few hours (some took several days), their potential in disrupting communications operation was confirmed. At a minimum, access to the facility could be denied, but, most likely, the domino effects could lead to severe damage of inside plant equipment. The Regional Network Control Center is located in one of these COs. A typical example involved a cable rack that fractured, causing a short of a 48-volt power cable. Cable rack damage in previous earthquakes was not considered service affecting because of the absence of mishaps, but the potential of service disruption was recognized. The incident in Northridge confirms this hazard. The power converters at the switch were tripped and all telephone services were disabled.

Other offices had fallen ceiling panels, dropped lighting fixtures and non-structural items. Minor buckling and cracking of the floor caused slight uplift of the equipment frame, but was not considered problematic. Ceiling debris was disruptive and a nuisance. Cabinets for storing spare parts separated from their wall anchors could slide and topple in a stronger earthquake, thus becoming a hazard to nearby equipment. Toppling of cabinets may also damage the spare equipment/parts inside them, and prolong recovery if these equipment/parts are needed as replacement.

Table 6.3. Comparison of Damages in Northridge and Loma Prieta, PacBell Systems.

	Loma Prieta	Northridge
Number of Buildings Damaged	195	25-50
Buildings with Significant Damage	9	2-9 (1-4 requiring environmental cleanup)
Outsite Plant	Aerial Drops in Marina District	4 Fiber Cables Damaged (At Piru CO, SR126, Southern Calif Edison gas-line fire; 2500 customers affected)
Support Systems	Intact, No Degradation	Functional With Some Degradation; South Network Management Center (NMC) unable to surveil network from Sherman Oaks; control transferred to Oakland; Significant monitors and workstations damage affecting operation services, repair and service representatives.
Financial Loss	$70 million (repairs only)	$26 million (repairs) $125-150 million (retrofit)
Call Volumes		
Call Attempts	180% Normal	225% Normal
Day 1 Call Completions	100 million (2x Normal)	154 million (2x Normal); return to normal January 25
Total CO Outages	2 (79K Lines)	3 (188K Lines)
Isolated Communities	1 (15K Lines)	8 (287K Lines)
Emergency 911 Network	Santa Cruz (<1 hr)	Negligible
TSP* Services	(did not exist)	13 orders, 317 circuits, 0 repair
Repair Service on Day 1	200% Above Normal	500% Above Normal

(* Telecommunication Service Priority, U.S. Government.)

EQUIPMENT DAMAGE

In general, main switch/transmission equipment performed extremely well despite evidence of strong shaking within the plant. Actual physical damage to switching machines and signal networks were reported although no further details were given.

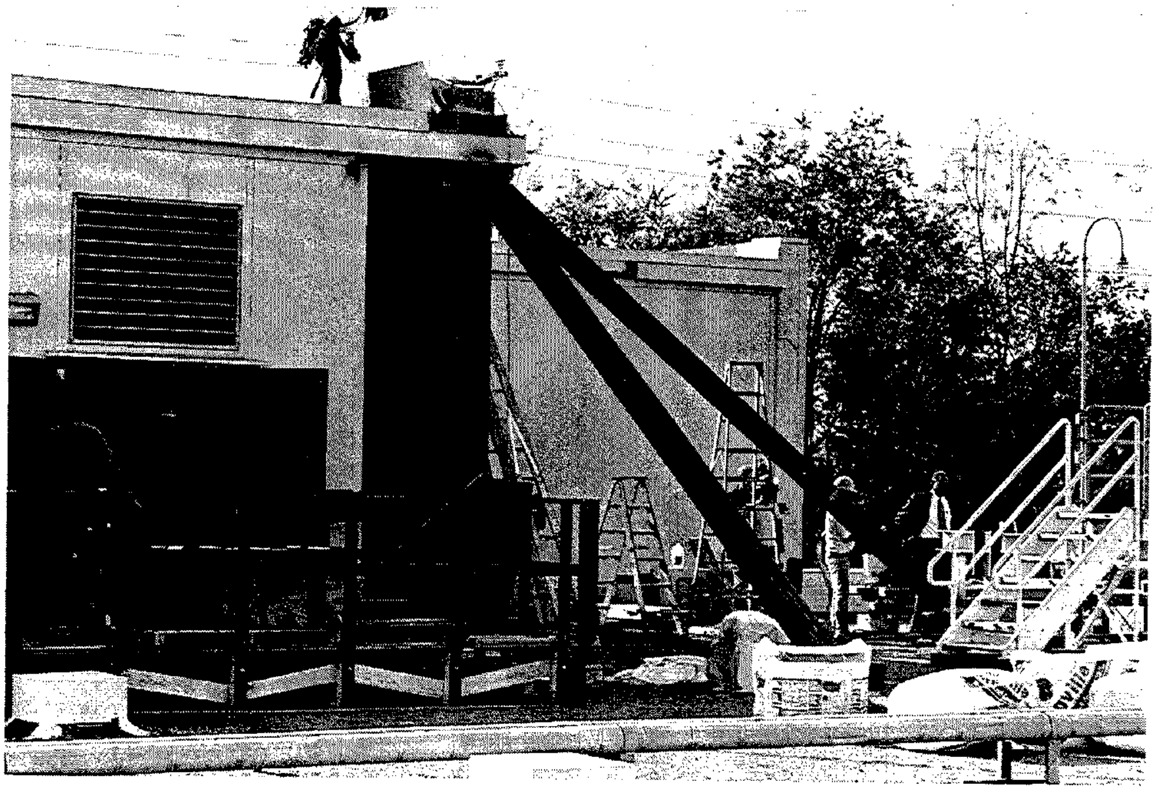

Fig. 6.3. Shoring up structural damage to a central office building.

Main cause of disruption was circuit boards being unseated from their shelf connectors inside the cabinet or malfunction of the boards (Fig.6.4), disk drive failures, shorts caused by unintended contacts, and loosened optical connectors. Effects of strong ground shaking manifested themselves in the form of buckled hanger rods, buckled and bent auxiliary bars (Fig.6.5), bent cable trays, indentation due to pounding, loose friction clips, loose anchor bolts, slide-out of equipment leveling shims, localized indentation of cabinet frame and buckled floors. The mechanical support and bracing system for equipment, when installed properly, showed that it could survive a much stronger earthquake.

None of the facilities visited have raised floors. Hence, performance of raised floor cannot be assessed although there is no reason why they would not perform as well as the overhead ironworks.

LIFELINE AND SUPPORT SYSTEM DISRUPTION

Most vulnerable components of inside plants were support systems. Many COs experienced power failure and backup generator problems; overload was the main cause of generator problems. We summarize first the disruption to water and power in the area in general, as these are the major lifelines that support communications. A summary of the effect of their disruption on commnications then follows.

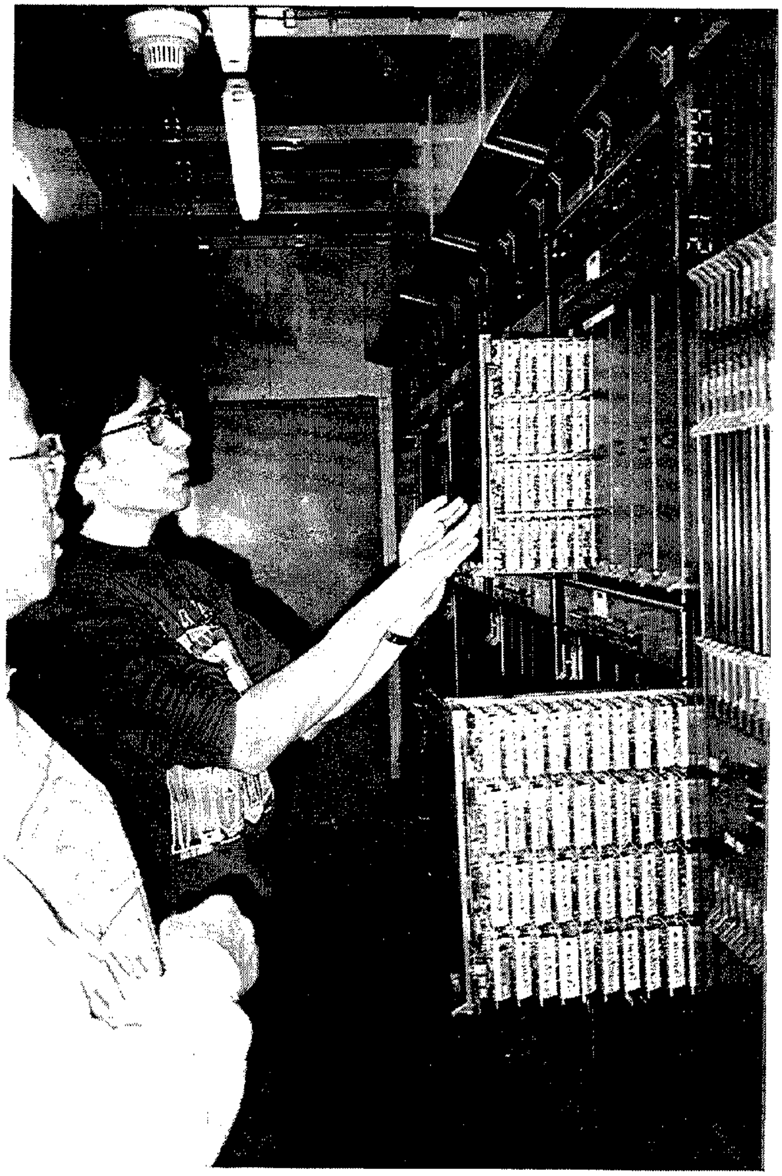

Fig. 6.4. Line disruption due to unseated or damaged circuit boards.

The Los Angeles Department of Water and Power, which serves most of the Los Angeles metropolitan area, reported approximately 350,000 customers without electricity after the initial shock. Southern California Edison, which services the suburban areas, reported 600,000 customers without electricity after the initial shock. Five water main breaks caused widespread damage to water systems. Over 200,000 residents, particularly in the northern San Fernando and Simi Valleys, lacked water service for several days. Ten days after the earthquake, 5,000 homes were still without water and 35,000 without gas. By January 25, electric power was restored to

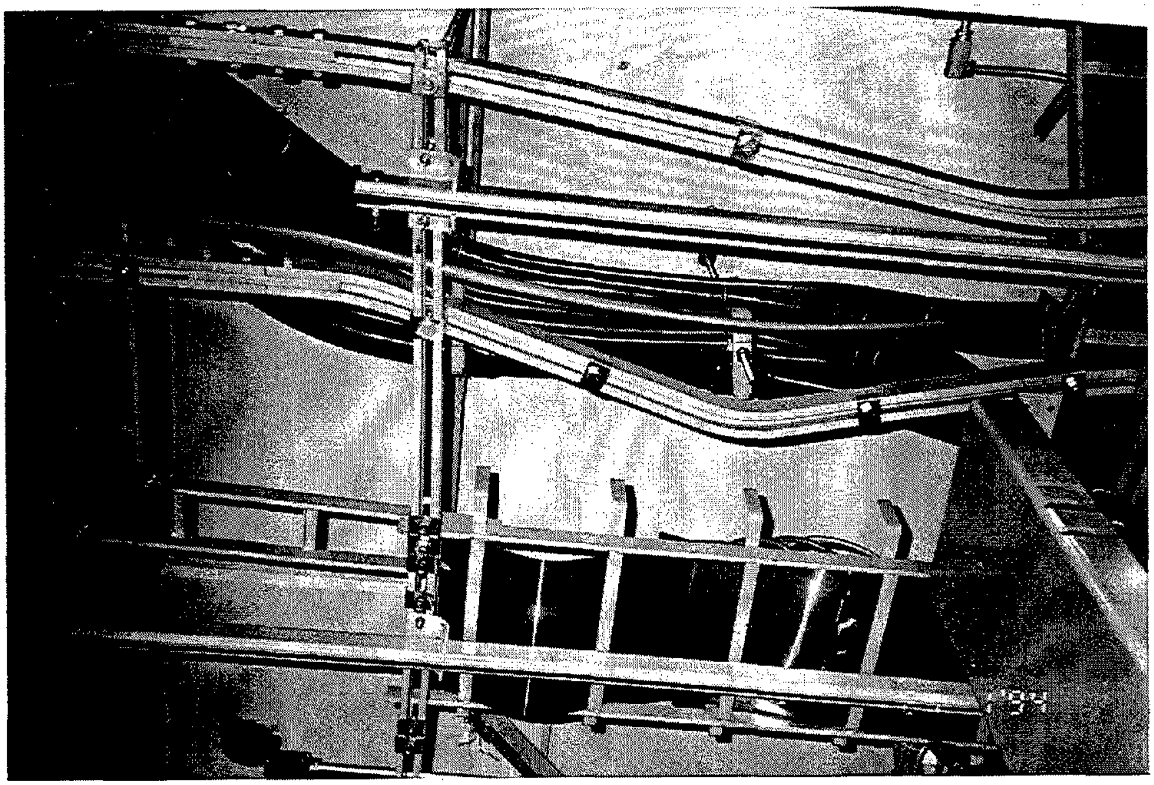

Figure 6.5. Buckled bars in overhead ironworks.

Two switches at the GTE Pacoima office, which sustained major damage, went down when commercial power failed and the office emergency generator was physically dislodged from its base during the earthquake, crimping the fuel line and rendering it inoperable. A backup generator was transported to the location and put in place following a safety inspection of the facility. A total of 35,000 customers were affeted, but full service was restored at 5 pm the same day. The GTE Granada Hills CO lost commercial power and remained on backup generator power for one week; no customers were affected. AT&T's (an IEC) Sheman Oaks switches lost commercial power immediately and could not be brought back to service because of backup generator problems. The switches were brought back on-line when AC power was restored to the site via an auxiliary generator. 15-30 PacBell COs lost commercial power but only three experienced backup generator problem and needed to depend on batteries only.

Other outages were caused by generators that automatically shut down due to related power problems. Network control was transferred to Northern California due to a combination of power/equipment failure at the Regional Control Center. Power at several COs was so low that contigency plans to shut off a portion of the equipment were close to being executed. Four days after the event, one CO was still non-functioning due to power outage. Contracted third-party generators remained on key sites as standby for potential power failure, and network control had yet to be returned to the Regional Center due to continued HVAC (heating, ventilation and air-conditioning) and power uncertainties. A week after the event, one CO continued to rely on temporary, contracted mobile generators and air-conditioning units.

There was evidence of toppling of battery racks and acid spills. Two battery racks in the CO nearest to the epicenter were damaged by ground shaking; one of them might have been caused by a collapsed wall. Low battery levels were caused by non-functioning emergency generators. Most battery problems were fixed by the second day.

Five MCI central offices were required to go on generator power with Sherman Oaks office on generators for 48 hours.

Water affects the effectiveness of environment control systems in most communications facilities, and is crucial for sites that use evaporative coolers and condensers. Most environmental systems within eight miles of the epicenter sustained some form of damage, from broken pipes to complete system failure. Compressors and chilled water delivery systems were invariably located at "penthouses", make-shift add-ons erected more as weather shelters than protective structures. Due to the combination of poor structural quality and location at the highest level in the building, these structures and the piping/equipment inside sustained significant damage, leading to failure of the HVAC systems even if power and water were available. Fans were used to cool equipment as a contingency. Emergency repair took a day or two, with thorough repairs requiring a week. Had the event taken place in the warm summer months, these damages would have been much more disruptive and more costly.

OTHER INTERACTION DAMAGES

A local switch incurred a total outage when excessive deflection of the bus bar led to inadvertent contact with a hanger bar, causing a power transient that tripped the power converters at the switch, thereby disabling all telephone service. Other outages were caused by disk drive failures, electrical shorts caused by pieces of equipment moving into positions that caused contact with other equipment; parts such as optical connectors that loosened during the earthquake; fiber cables that either burned during gas line explosions or were damaged by telephone poles that snapped.

CABLE SPANS

Outside plant assets directly and physically damaged by the Northridge earthquake were minimal because there were few instances of major ground failure along cable routes. Only indirect information on outside plant damage could be obtained as field inspection could not be arranged.

Functionally, as many as 100 cable spans were down during the first day although 75% were restored within 24 hours. GTE had a total of 44 cable spans down during the first day but approximately 75% were restored within 24 hours. Physical damage to interoffice and loop facilities were reported by PacBell. MCI reported part of an aerial cable between Sherman Oaks and Palmdale was burned and disabled resulting in traffic disruptions; service was fully restored in less than 4 hours. The most spectacular damages were caused by a gas line explosion, broken water mains and fallen telephone poles; cables located at or near these mishaps were completely disrupted (Fig.6.6). Two other cables in the area with a maximum of 32,000 lines each were also disrupted, but the exact cause could not be clarified.

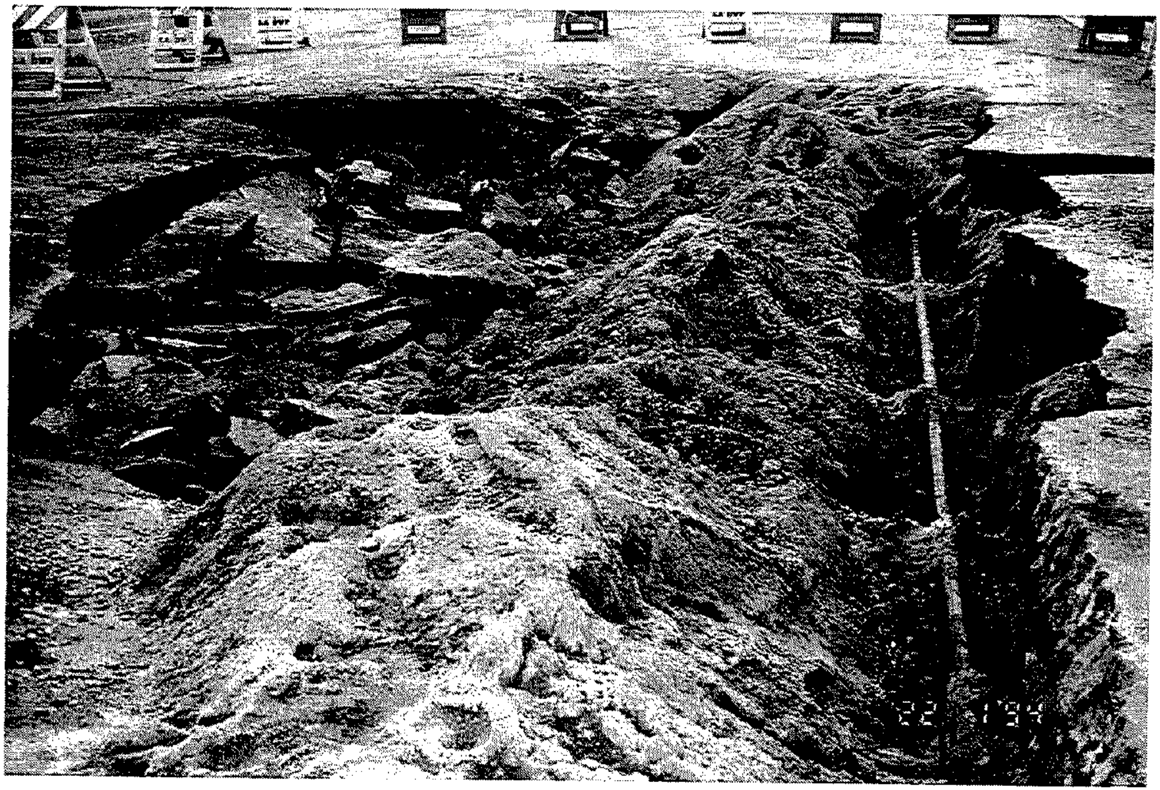

Fig. 6.6. Gas explosion led to fire, busted water mains and severed communications cables.

Carrier signals to a IEC CO is not restored as of one week after the event. The exact cause of the problem is not known, but it could be related to electric power and carrier problems, or physical access.

Logs of automated switch monitoring system documented the number of line interruptions and overall system performance continuously, including the day of the event. The interruption may be due to physical damage to cables, repeater failure, flooding of manholes, phones off the hook, etc. in addition to the circuit board problems mentioned previously. By the third day, most of the interrupted lines were cleared. Centrex lines at collapsed buildings were call-forward to a specific number to provide continuous service for the businesses affected.

NETWORK CONTROL & RESPONSE

One GTE SS7-SCP (Service Control Point) was also lost but service was not affected due to the redundancy. Emergency Operations Centers were activated. Call attempts into the area were 225% above normal and an estimated 5 million calls were blocked in the aftermath. Network management controls were implemented to reduce the flow of traffic into the affected area, preventing total switching office failures. The Regional Network Control Center (Network Management Center, NMC) lost control and monitoring capabilities, and control was transferred from Sherman Oaks to Oakland without affecting system performance.

On the other hand, there has been a rapid growth in the number of IECs in California and many of these carriers do not utilize network management controls. There is also no uniform standard for the application of network management controls; this can be a potential problem in future disasters.

Communications service was provided to the Disaster Application Centers (DACs) and FEMA's Central Processing Offices in Redwood City, CA, and to FEMA's teleregistration officesin Denton, TX, and Golden, CO. New phone lines were added to the Granada Hills hospital which served as a temporary consolidation location for three local hospitals. Coin phone trailers, providing free local and long distance calling, were dispatched to several community centers and other locations in the impacted area.

Service providers instituted a number of response measures to minimize the disruption of the earthquake. They installed emergency telephone banks in stricken areas and deployed and provisioned the 5K-Line "restoration express". Relief packages for customers, including free voice mail, call forwarding, etc., were established. They gave free installation to re-establish service at a temporary location for displaced customers. They gave free installation for businesses, set up a $1 million equipment loan program, and dispatched a tele-commuting "SWAT" team to meet complex business needs. In addition, $1 million worth of access time was donated to relief agencies.

A significant shift in the telecommunications traffic patterns developed after the earthquake, caused by the jump in telecommuting as a result of building and highway damages. Capacity was added where necessary to meet increased demand. Physical measures taken to restore capabilities included resetting power converters, manually configuring system processors and memory hardware, manually initializing equipment, installing auxilliary generators, patching optical carrier systems, replacing fuses, tightening loosened parts, and replacing damaged cables.

911 SYSTEM RESPONSE

The 911 switch located at Northridge continued to operate during and after the main shock, although the hugh volume of call attempts delayed call completion by the system. To most callers, the system might also have been perceived as being inadequate because of exhaustion of resources at the system's disposal. When all available emergency response vehicles and personnel had been dispatched, the system simply could not send out more even though communication was made.

CELLULAR SYSTEMS

Unlike the major damage experienced by cellular carriers during Hurricane Andrew, damage to cellular facilities during the Northridge Earthquake was minimal. Thirty-five cellular sites were out of service after the initial shock, of which 30 sites were restored within 8 hours. All were restored within 72 hours. The main causes of disruptions were loss of power and isolation from landline facilities and the damage totalled about $1 million (see table below). Undue delay was brought on due to safety concerns; water hazards created by flooding prevented restoration of electrical service. Because of this quick restoration and expansion of the radio capacity, the system overload seen in Hurricane Andrew was not a major problem.

Table 6.4. Cellular Site Outages.

No. of Sites	Problem	Solution
17	microwave dish misalignment	dishes realigned
15	severed landline interconnects	landlines restored
3	loss of primary and backup power	portable generators delivered to site within 72 hours

System usage immediately spiked following the earthquake, particularly in the most hard-hit portions of Los Angeles. Completed calls on the system as a whole increased by 119% on the day of the earthquake, and by 127% on the switches serving the most severely impacted areas. During the hours immediately after the shock, call attempts increased by more than 200 times. One month after the earthquake, system-wide usage remained more than 15% above normal.

Both carriers in the region, LA Cellular and PacTel Cellular, used transportable cell sites on wheels (COW) in highly congested or problem areas. About 900 cellular telephones were issued to Federal response personnel, along with free air time.

However, more than 100 cellular phones were compromised by hackers; fraudulent calls were a serious problem.

Twelve new temporary cellular base station facilities were deployed and more radio channels were added to accommodate demand and altered traffic flow. In the six weeks following the earthquake, LA Cellular constructed 20 new cells sites to meet increased traffic demand and altered traffic flow. More radio channels at many existing cell site locations were installed to accommodate increased call traffic demand. A total of 275 channels have been added to sites in the San Fernando Valley and 118 channels to sites in West Los Angeles.

PRIVATE NETWORKS

The LADWP (Los Angeles Department of Water and Power) system is one of the largest private network in the Los Angeles and San Fernando area, with two host offices (M1 and M2), a number of remotes, copper and optical fiber landlines, and the supplementary microwave/radio links (see Fig.6.7). The hosts are connected to the Public Switch Network by T1 links. The network provides voice and data transmission for the organization.

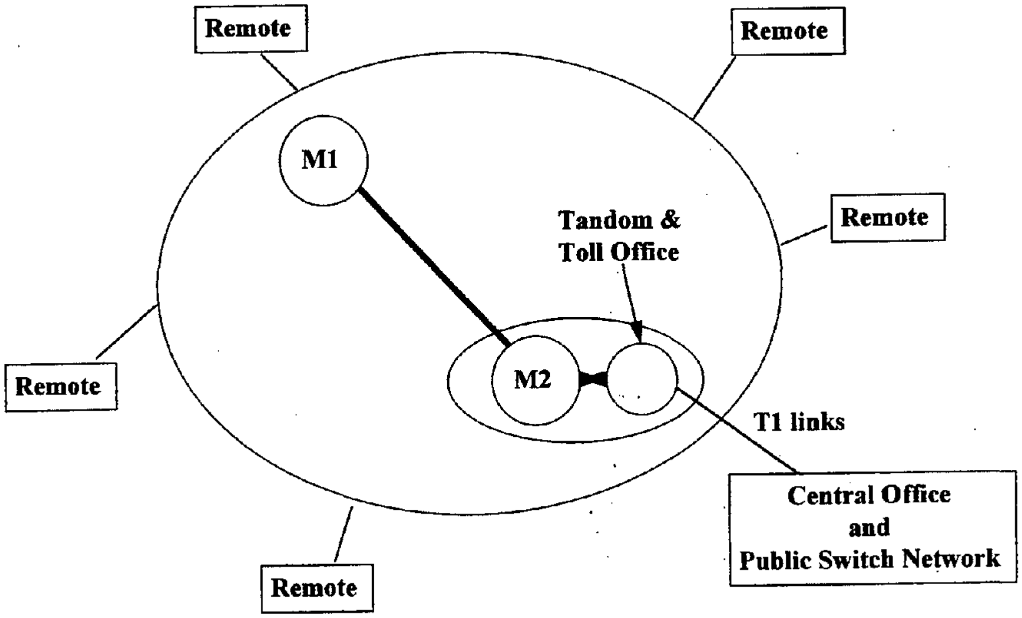

Figure 6.7. Schematics of a private network.

The overall performance of the system in the Northridge earthquake was very good. Most of the damages were incurred by the power and cooling support systems. For example, the pipe lines of the chilled-water facility on the third floor of the primary host M1 sustained extensive damage. A couple of the chillers (heat exchangers) were knocked off the vibration isolators and the snubber bolts sheared. Water pipes were broken and bent, and the room was flooded. Fortunately, one of the chiller units remained operational, and kept the computer and switching equipment rooms cool for several days before the general cooling system was restored. The switch and computer rooms and their equipment performed well. About 10% (500 cassette tapes) of the the tape library fell off the shelf, and when an old style tape rack fell, a number of the large 12" reel tapes were damaged beyond repair.

Most remotes rely on commercial power and battery backup only. In this earthquake, power failure outlasted the battery capacity at certain locations, resulting in switch failure. Lost of commercial power also affected transmission equipment; network trunking to four switches was lost for two days and lost memory had to be reprogrammed. At locations where backup generators were available for protecting the entire plants, some communications equipment were not connected to the station engine generator. Generator failures were reported due to an oil leak, erratic regulation from the governor, and ruptured oil lines. Backup generators at M1 and M2 performed well.

As a result of network trunks being down, the telephone switches routed calls strictly through the central office trunks. At two remotes these trunks were intermittent even a week after the earthquake.

At a radio repeater station located on Oat Mountain just north of Los Angeles, the equipment were stacked two levels high. The top units were displaced by the earthquake motion, and the connecting cables were pulled out and the connectors damaged. Consequently, the 900 MHz system was unavailable to field service personnel, and the lowband system was over-subscribed. Repair was made in one day. Equipment is now in two line-ups to prevent a recurrence of the Northridge mishap.

An aerospace firm with a large PBX (private business exchange network) and located about two miles from the epicenter was visited. Business operation was disrupted as evidenced by the many departments of the company, including the Purchasing Department, that set up temporary offices in the open area. Communications equipment survived in excellent shape, but the switch room suffered extensive damage to the chilled water pipes. One of the disrupted pipes was directly above the power equipment. The backup power generator could not function due to loss of commercial natural gas supply, and the switch operated on battery power. According to technicians of the firm, the phone system was the only working system in the company after the earthquake.

RADIO AND TELEVISION

Radio and television played an important role informing the public on emergency response and recovery activities following the earthquake. However, for most of the first two days after the earthquake, TV was not available to the public in the epicentral area because of the loss of commercial power. TV was available in emergency operation centers which had emergency power. For those with battery operated equipment, radios performed a major role in advising citizens of the need to boil water and of alternate transportation routes to get around the sections of collapsed freeway.

Approximately 12 stations lost their power supply because of absence of emergency backup power or because their emergency power supply did not operate satisfactorily. There was structural damage to one station. Another station broadcast eight minutes of mixed message when tape cartridges fell from their shelves on to the main control panel buttons, setting off signals of weather, traffic, news, etc. on the air simultaneously. At one station, the personnel were scared and left the building housing the station. Three radios and one TV station were off the air for various reasons and broadcast the signal from an AM radio station. The structure housing the California State Northridge student radio station was severely damaged. For several weeks this station operated from a tent on campus with equipment provided by commercial stations. Some cable TV stations were off the air because of the loss of power, building damage or downed cables and wires.

Good examples of emergency preparedness were evident at some stations: adequate emergency power, anchored equipment and shelving, removal of non-operating equipment, portable backup transmitter and antenna with an independent power source, an independent two-way station radio system, and emergency food, equipment and medical supplies.

The Federal Emergency Broadcast System (EBS) was not activated since all people within the epicentral area felt the earthquake and did not need an alert or warning of an impending event. Activated after the earthquake was the Emergency Digital Information System (EDIS) established by the California Office of Emergency Service (OES) which provides emergency response and recovery information to the media and the public. Participants in EDIS are the National Weather Service, United State Geological Survey, Federal Emergency Management Agency (FEMA), local city and county governments, utilities, California Highway Patrol, etc. EDIS provides service similar to a news wire service, which the media refers to as the Emergency New Network (ENN). KLCS-TV (Ch 58) reported the news from FEMA and OES through the EDIS and was called the "Recovery Channel".

COUNTERMEASURES AND RECOMMENDATIONS

In general, inside plant equipment performed very well due to the continual effort by the service providers in bracing and anchoring the equipment and frames. Disruption to the system was caused mainly by failure of the power and water support systems, and collateral hazards that are extremely difficult to avoid even though well-known.

For dependable backup power, we have the following suggustions:

- A 3-hour battery service is not sufficient in congested Metro areas, particularly at critical COs.
- Need an easier way to identify/read power plant status; need auto start/transfer for emergency engines.
- Regular reserve power testing will ensure working generators and improve consistency in performance.
- Monitor underground fuel storage tanks that supply generators, to ensure sufficient supply. This is already being implemented under the California Hazardous Material requirements.
- Incorporating the use of "tap boxes", to facilitate hook-up with portable generators.

For dependable cooling system, we recommend:

- Reinforcing support equipment mounts and strapping equipment to better withstand seismic shock.
- Install storage for emergency water supply for cooling.
- Relocation of water cooling towers from office rooftops.

Power cables and cable racks should be braced so as to preclude inadvertent contacts and electric shorts that can lead to devastating fires.

Backup communications system is vital to effectively coordinate efforts. In this regard, the cellular system should be strengthened; the structural assets should be hardened, and the support systems improved as indicated for the landline system. Radio channels should be widened. A fraud prevention program should be implemented to reduce unlawful use during the recovery period.

Finally, an integrated response plan should establish the network of utility coordinators for better coordination during emergencies. Inter utility assistance and industry mutual aid agreements are vital parts of the reponse plan.

ACKNOWLEDGMENTS

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Data described in this report came from various sources and we have attempted to distribute credits in the text. We recognize all who have contributed directly or indirectly, even if they are not mentioned in the following: Paul Neifer, Manager of

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1. Northridge Earthquake After-Action Report, Joint Government/Industry Northridge Earthquake Task Force, June 1994.

2. Caren, M. D., California, paper presented at Joint New Zealand/Los Angeles Workshop by Pacific Bell, August 15, 1994.

3. January 17, 1994. The Northridge Earthquake, Summary News Release by Pacific Bell, Los Angeles Region, undated.

7. BRIDGES AND ROADWAYS

OVERVIEW

There are approximately 12,000 State Highway bridges in California. About 1,200 of these bridges were in the area that experienced ground accelerations greater than 0.25g during the Northridge Earthquake. Most of these bridges performed well during the earthquake. Bridges constructed to Caltrans' current seismic specifications survived the earthquake with very little damage. Seven older bridges, designed for a smaller earthquake force or without the ductility of Caltrans' current design, sustained severe damage during the earthquake. Figure 7.1 shows the 4 locations where severe bridge damage occurred during the Northridge Earthquake. Table 7.1 identifies severely damaged bridges that were replaced after the earthquake. Another 230 bridges suffered some damage ranging from column and hinge damage to minor concrete cracks, bearing damage, or approach settlements. Table 7.2 identifies all state highway bridges damaged during the earthquake.

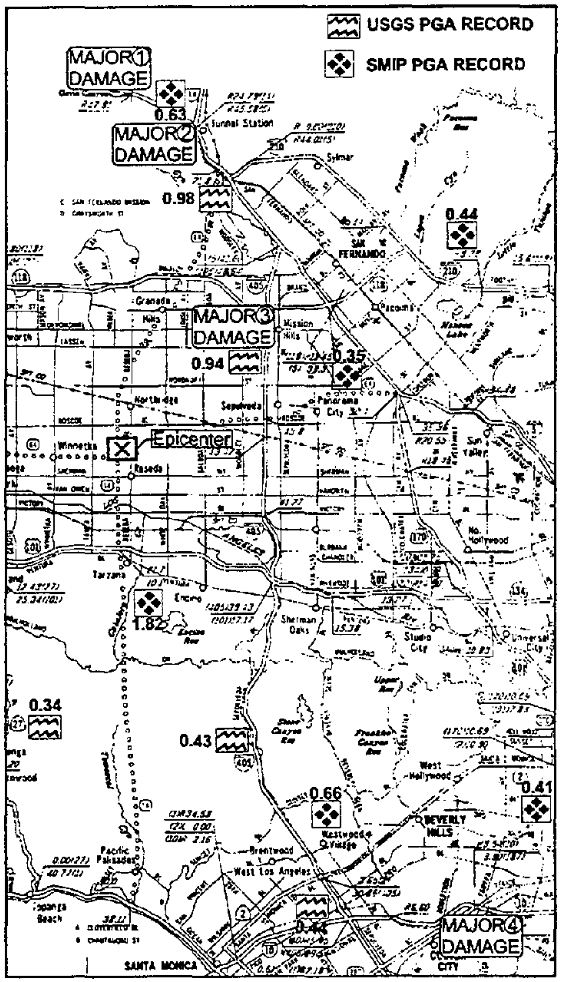
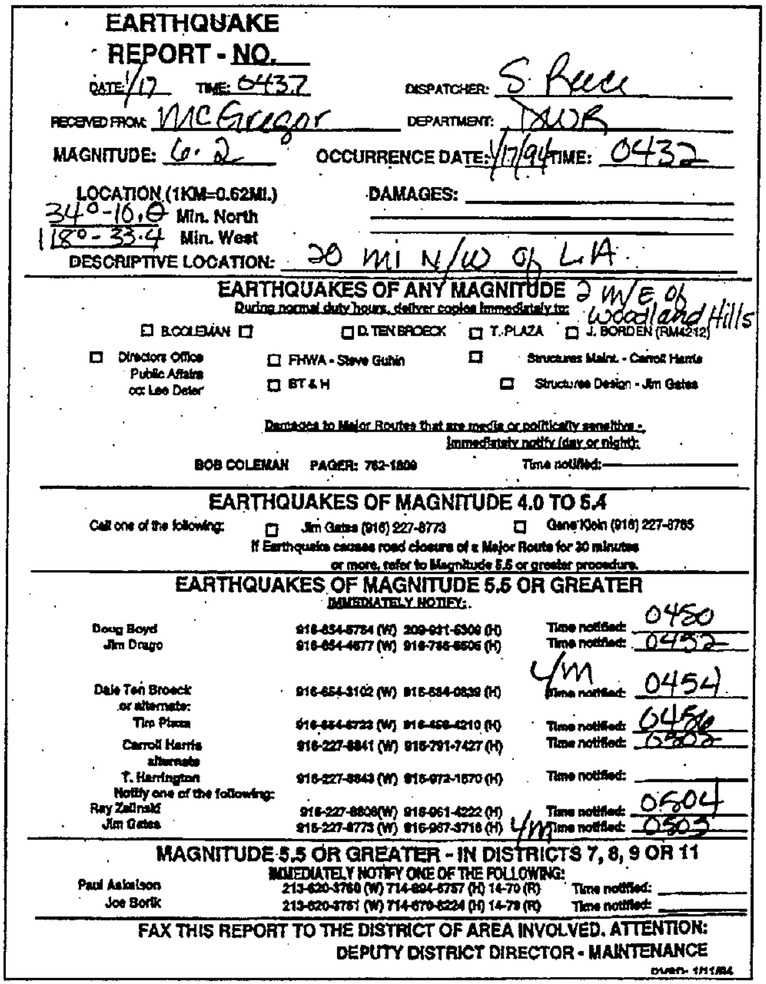


Fig 7.1. Map of Severe Bridge Damage.

After the earthquake, maintenance crews closed many of the major interchanges in the Los Angeles area. After the interchanges were inspected for damage they were reopened. Many were reopened after shoring was placed under them due to concerns about hinge damage. Because the earthquake struck early in the morning, there were few injuries and only one fatality related to bridge and highway damage.

EMERGENCY RESPONSE

Caltrans' Communication Center is operated 24 hours a day seven days a week. Their job is to alert the appropriate Caltrans' personnel of any emergency. They receive notification of earthquakes from 2 official sources. The Department of Water Resources (DWR) maintains a 24 hour seismic monitoring system. The Caltech and University of California Broadcast Earthquake (CUBE) System sends information through pagers onto computers throughout California. The CUBE system went down after the Northridge Earthquake, but DWR quickly informed the Communication Center. By 5:05 A. M. they had contacted Headquarters Maintenance Branch, the Director's Office, Caltrans Office of Emergency Management, Structures Maintenance, and Caltrans Office of Earthquake Engineering (see Figure 7.2). Carrol Harris and Tom Harrington of Structures Maintenance responded by organizing a team of 30 maintenance and design engineers to go down to Los Angeles and assess bridge damage. The engineers left Sacramento at noon and traveled down I-5 towards Los Angeles. Near Bakersfield they were met by CHP officers who escorted them through the various detours to a hotel in Pasadena. Then, every morning, each team of one design and one maintenance engineer would be assigned one or more highways to inspect. They would crawl around bridge bearings, climb through bridge decks, navigate snoopers to inspect bent caps, hinges, and soffits and evaluate the damage. They would determine whether a bridge could be reopened or needed replacement, shoring, or repairs. These were difficult decisions since closing a major route causes hardship to a community. However, the engineer's primary responsibility was to protect the



EARTHQUAKE REPORT - NO.

DATE: 1/17 TIME: 0437 DISPATCHER: S. Rue

RECEIVED FROM: McGregor DEPARTMENT: DWR

MAGNITUDE: 6.2 OCCURRENCE DATE: 1/17/94 TIME: 0432

LOCATION (1KM=0.62MI.)
34°-16.0 Min. North
118°-33.4 Min. West

DAMAGES:

DESCRIPTIVE LOCATION: 20 mi N/W of L.A. 2 W/E of Woodland Hills

EARTHQUAKES OF ANY MAGNITUDE

During normal duty hours, deliver copies immediately to:

☐ B.COLEMAN ☐ ☐ D.TEN BROECK ☐ T. PLAZA ☐ J. BORDEN (RM4212)

☐ Directors Office Public Affairs cc: Lee Deter
☐ FHWA - Steve Guhin
☐ BT & H
☐ Structures Maint. - Carroll Harris
☐ Structures Design - Jim Gates

Damages to Major Routes that are media or politically sensitive - Immediately notify (day or night):

BOB COLEMAN PAGER: 762-1809 Time notified:

EARTHQUAKES OF MAGNITUDE 4.0 TO 5.4

Call one of the following: ☐ Jim Gates (916) 227-8773 ☐ Gene Klein (916) 227-8765

If Earthquake causes road closure of a Major Route for 20 minutes or more, refer to Magnitude 5.5 or greater procedure.

EARTHQUAKES OF MAGNITUDE 5.5 OR GREATER

IMMEDIATELY NOTIFY:

Doug Boyd 916-654-5784 (W) 209-931-6309 (H) Time notified: 0450
Jim Drago 916-654-4677 (W) 916-786-8506 (H) Time notified: 0452
Dale Ten Broeck 916-654-3102 (W) 916-684-0839 (H) 4/m Time notified: 0454
or alternate:
Tim Plaza 916-654-6723 (W) 916-456-4210 (H) Time notified: 0456
Carroll Harris 916-227-8841 (W) 916-791-7427 (H) Time notified: 0502
alternate
T. Harrington 916-227-8843 (W) 916-972-1670 (H) Time notified:
Notify one of the following:
Ray Zelinski 916-227-8806(W) 916-961-4222 (H) Time notified: 0504
Jim Gates 916-227-8773 (W) 916-987-3716 (H) 4/m Time notified: 0503

MAGNITUDE 5.5 OR GREATER - IN DISTRICTS 7, 8, 9 OR 11

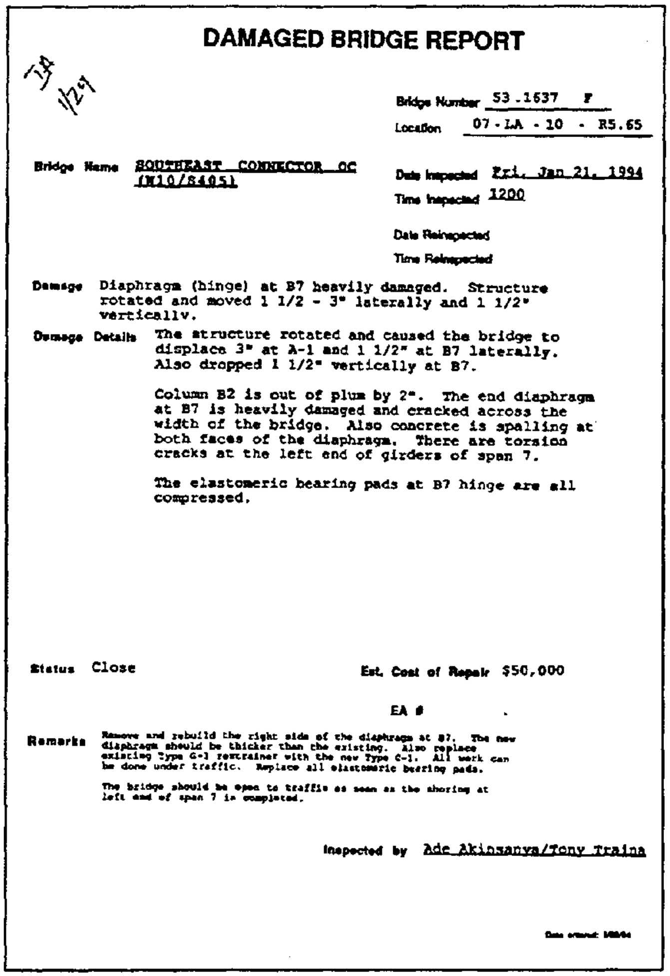
IMMEDIATELY NOTIFY ONE OF THE FOLLOWING:

Paul Askelson 213-620-3760 (W) 714-894-6757 (H) 14-70 (R) Time notified:
Joe Borik 213-620-3761 (W) 714-670-6224 (H) 14-79 (R) Time notified:

FAX THIS REPORT TO THE DISTRICT OF AREA INVOLVED. ATTENTION: DEPUTY DISTRICT DIRECTOR - MAINTENANCE

Fig. 7.2. Notification Report for the Northridge Earthquake.

public. Some heavily damaged structures were vulnerable from the many aftershocks that occurred in the days that followed. While assessment teams looked at bridges, support staff in Sacramento were busy copying as-built bridge plans and gathering other information for the teams. Li-Hong Sheng had written a computer program that created a list of all bridges within a radius determined by the magnitude of the earthquake. This was extremely helpful, as was the fact that all bridge records had been digitized. Each night, the teams' damage reports were given to Mohammad Behrooj and Erol Kaslan who were in charge of the investigation. The bridge evaluations were then sent to the District where emergency contracts were written to begin repairs (Caltrans has engineering and administrative support in Sacramento, and 12 local districts who are responsible for transportation in their geographic area.). District engineers were also busy inspecting and repairing all the highway damage that had occurred.



DAMAGED BRIDGE REPORT

38
1/24

Bridge Number 53.1637 F
Location 07-LA-10 - R5.65

Bridge Name SOUTHEAST CONNECTOR OC (N10/S405)
Date Inspected Fri, Jan 21, 1994
Time Inspected 1200

Date Reinspected
Time Reinspected

Damage Diaphragm (hinge) at B7 heavily damaged. Structure rotated and moved 1 1/2 - 3" laterally and 1 1/2" vertically.

Damage Details The structure rotated and caused the bridge to displace 3" at A-1 and 1 1/2" at B7 laterally. Also dropped 1 1/2" vertically at B7.

Column B2 is out of plum by 2". The end diaphragm at B7 is heavily damaged and cracked across the width of the bridge. Also concrete is spalling at both faces of the diaphragm. There are torsion cracks at the left end of girders of span 7.

The elastomeric bearing pads at B7 hinge are all compressed.

Status Close
Est. Cost of Repair $50,000

EA #

Remarks Remove and rebuild the right side of the diaphragm at B7. The new diaphragm should be thicker than the existing. Also replace existing Type C-1 restrainer with the new Type C-1. All work can be done under traffic. Replace all elastomeric bearing pads.

The bridge should be open to traffic as soon as the shoring at left end of span 7 is completed.

Inspected by Ade Akinsanya/Tony Traina

Date entered: [illegible]

Figure 7.3. Damaged Bridge Report.

The Damage Assessment Teams carried cellular phones, pagers, District 7's Log of Bridges on State Highways, two gallons of water, food, a strong flashlight, powerful binoculars, a tape measure, a notebook, and a camera with plenty of film. They would write in their notebooks during the day and transcribe their notes onto Damaged Bridge Reports in the evening. Clerical staff in the District would then type up the reports and distribute them. To facilitate this process, Bridge Maintenance recommended that all their engineers carry notebook computers that could fill out the forms and download them. Other recommendations made by the Damage Assessment Teams after the Northridge Earthquake were that K-rail should be placed at the ends of partially collapsed structures, an expert team should be trained and ready to assist a district immediately after an earthquake, and that clerical staff should be organized to assist the engineers in documenting the damage.

Besides the Damage Assessment Teams and District personnel, Caltrans also sent a Post Earthquake Investigation Team (PEQIT) to study the bridge damage and write a report. The PEQIT report is used by engineers to evaluate current seismic policy and as a record for future research. A PEQIT report has been written after every earthquake since the 1971 San Fernando Earthquake. Ray Zelinski selected Brian Maroney to head the PEQIT for the Northridge Earthquake. More information on PEQIT is available in their report (see the reference section at the back of this paper).

Other emergency work included the creation of detours by the Los Angeles Department of Transportation (LADOT), and the inspection of damage by the Federal Highway Administration (FHWA), and Federal Emergency Management Agency (FEMA). Both of these agencies provided money for repairs.

SEVERELY DAMAGED BRIDGES

Seven bridges sustained severe damage from the Northridge Earthquake. Their locations, listed below, may be especially sensitive to earthquake motions. Bridges in the 14/5 Interchange suffered severe damage during the 1971 San Fernando Earthquake. The part of the Santa Monica Freeway that was damaged was 16 miles from the earthquake epicenter.

Bridge Location	Bridge Name	Bridge #	Yr Blt	Length	Type
1) Gavin Canyon	Gavin Canyon UC	53-1797R/L	1967	741 ft	QBCCBC
2) 14/5 Interchange	Rte 14/5 Sep. & OH North Connector OC	53-1960F 53-1964F	71-74 71-74	1582 ft 1532 ft	QB CBC QBCCBC
3) 118 west of 405	Mission Gothic UC Bull Creek Cyn Ch Br	53-2205 53-2206	1976 1976	532 ft 256 ft	QBC QBC
4)I-10 downtown - Santa Monica Fwy	La Cienega-Venice UC Fairfax-Washington UC	53-1609 53-1580	1964 1964	871 ft 577 ft	CBC CBC

Table 7.1. List of Bridges Severely Damaged by the Northridge Earthquake.

LOCATION # 1 - GAVIN CANYON

This is the northernmost location of severe bridge damage. It carries north and south traffic over Gavin Canyon on Interstate 5 through steeply mountainous terrain. The ground is approximately 20 feet of sand above a rock layer of siltstone and shale at the bridge site with tall structural fills supporting the abutments. It is 9.2 miles from the epicenter of the Northridge Earthquake and near the surface projection of the Oak Ridge -Newhall fault (which may possibly have been the source of the earthquake). In any case, ground motion records indicate strong shaking in this area with a peak horizontal acceleration of about 0.8g.

Gavin Canyon UC: Description of Structure

These bridges were on I-5, two miles north of the 14/5 Interchange. They were composed of three frames. The end frames were reinforced concrete box girders that were supported on one end by diaphragm type abutments and cantilever over two column bents. The center frame was a prestressed concrete box girder on four columns (two bents) that supported the cantilever spans of the end frames. All the columns had 6'-3" by 10' octagonal sections with fixed ends and a flare on top. The bridges were retrofitted in 1974 with restrainer cable units at the 8" hinges connecting the three frames together.

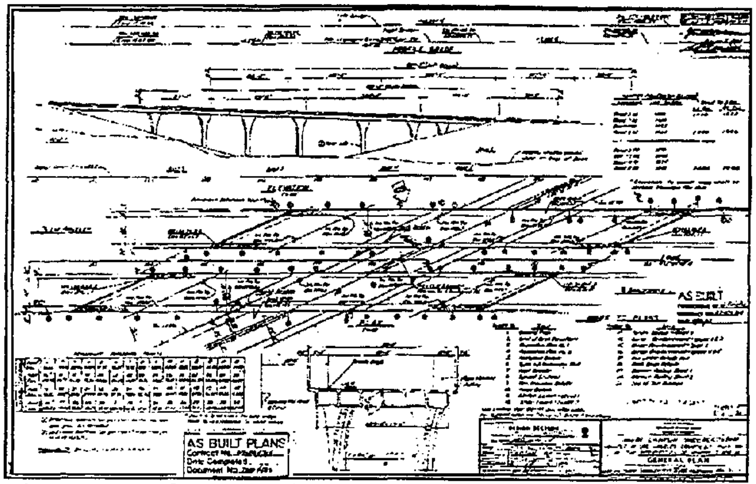


Figure 7.4. General Plan of Gavin Canyon UC.

Gavin Canyon U. C.: Description of Damage

Figure 7.5 shows the cantilever spans off of the hinge supports, broken, and with portions fallen onto the roadway below. There was also some minor damage at the abutments. There was no damage to the center span or to the columns.

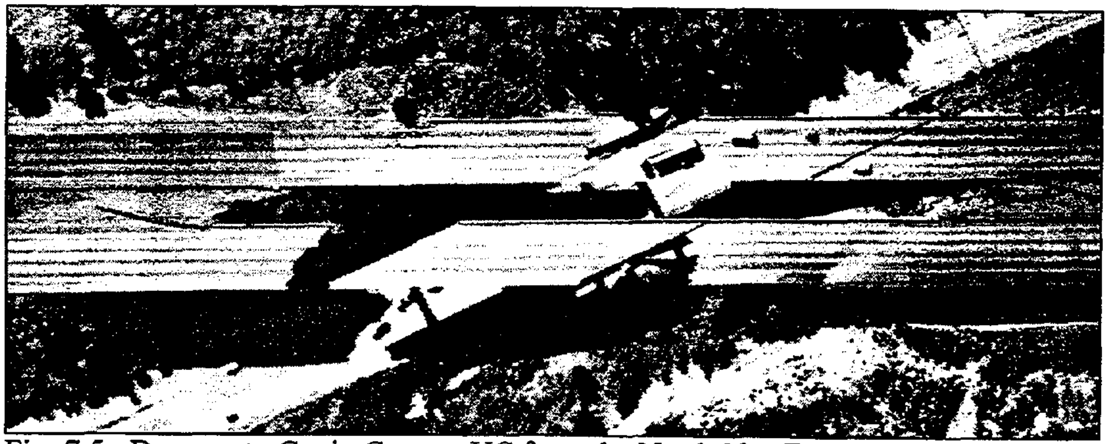


Fig. 7.5. Damage to Gavin Canyon UC from the Northridge Event.

Gavin Canyon UC.: Analysis of Damage

These bridges suffered major damage during the earthquake, largely due to a failure of the cable restrainers to limit superstructure movement. This failure may have resulted from a tendency of highly skewed bridges to rotate out of their hinge supports, a tendency not considered in the restrainer design. Or it may have been the result of an early restrainer design that didn't prevent the superstructure from moving the 8 inches of an inadequate hinge seat. The result was that the cantilever spans moved off the hinge seats, breaking off the acute corners of the cantilever spans. It may be that this three frame design with cantilever spans supported on hinges isn't a good choice for highly seismic zones. The end spans were much stiffer than the center span, which accentuated the problem. The replacement structure has no hinges.

LOCATION #2 - 14/5 INTERCHANGE

This interchange was under construction during the 1971 San Fernando Earthquake. The bridges were long, curving connector structures. Several bridges were damaged and replaced. The bridges are mostly long, curving connector structures. The site is surrounded by mountains and the bridges are supported by sandstone with some structural fills at the approaches. This site is about eight miles from the epicenter of the Northridge Earthquake and the peak ground acceleration is fairly close to that experienced at Gavin Canyon, two miles to the north. The Lamont-Doherty Earth Observatory took readings of aftershocks at this site and noted a large variation in ground motion. Whether this variation contributed to structural damage has yet to be investigated.

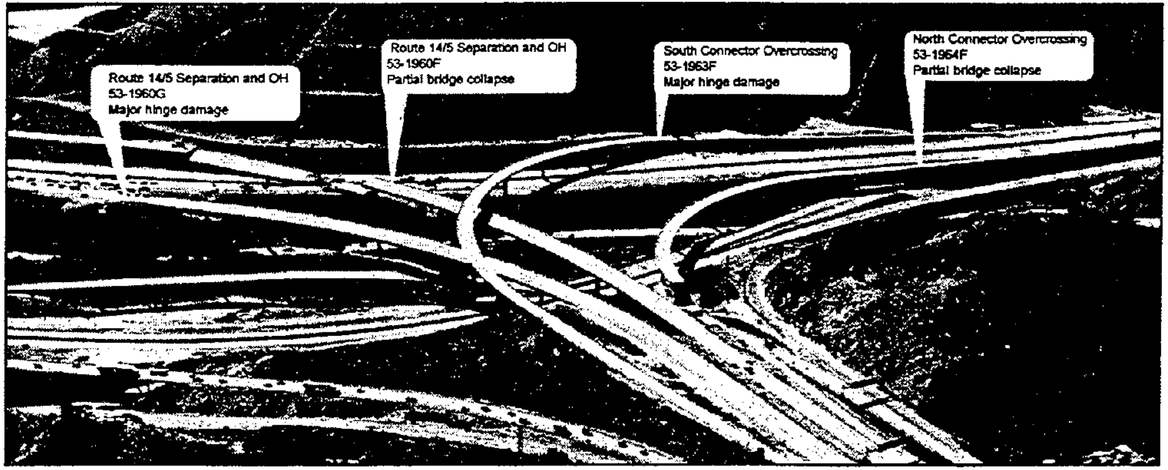


Figure 7.6. Bridge Damage at Location #2 - Route 14/5 Interchange.

Route 14/5 Separation and OH: Description of Structure

This structure connects southbound Route 14 to southbound I-5. It was a 1582 foot long curved bridge with 10 spans and 5 frames. All of the columns had been built and the end frames had stem and soffits on falsework when the 1971 San Fernando Earthquake occurred. Damage from that earthquake caused settlement of falsework and soffit cracks around pier #3. This damage was considered minor and

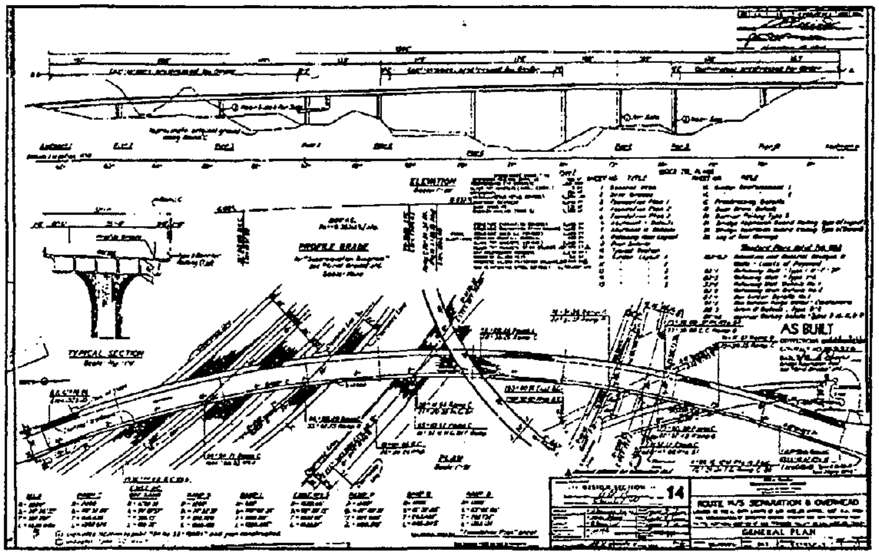


Figure 7.7. General Plan of Route 14/5 Separation and OH.

construction was completed in 1974 with a change order for the addition of restrainers at the 4- 14" hinges. The bridge had alternating prestressed and reinforced concrete box girder frames on single column bents. Figure 3.7 gives an indication of the varying column heights and span lengths. The columns had 12' by 4' or 12' by 6' octagonal sections with flares at the top and pile shaft foundations. The abutments were seat type on spread footings with elastomeric pads to support the superstructure.

Route 14/5 Separation and OH: Description of Damage

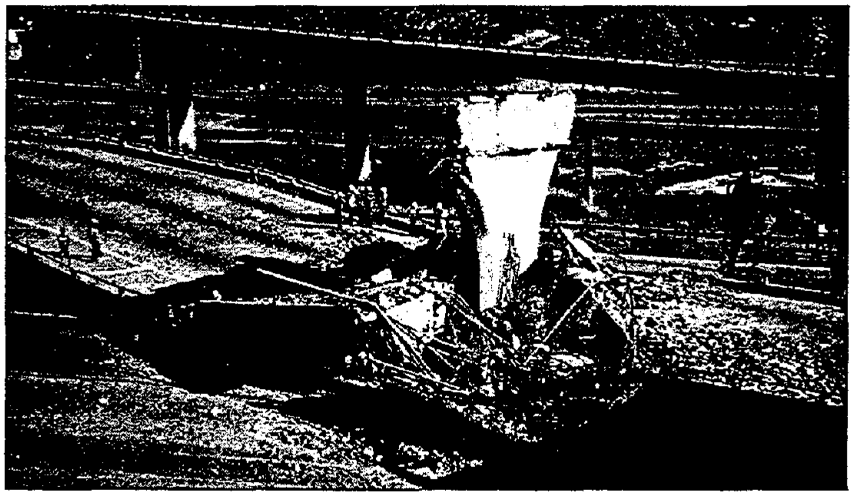


Figure 7.8. Damage at Pier #3 to Rte 14/5 Separation & OH.

This bridge is 8.2 miles from the epicenter of the Northridge Earthquake. A peak ground acceleration of at least 0.7g was estimated for this site. The first frame of the bridge collapsed and fell to the east. The only damage to abutment #1 was the failure of the right shear key as the superstructure moved to the right. At pier #2 the longitudinal column reinforcement remained attached to the bent cap while the column concrete was in rubble. Pier #3 remained standing while the superstructure on both sides of pier #3 and the bent cap lay on the ground. At hinge #1, all the restrainers and equalizing bolts had failed in tension and there were concrete spalls indicating banging of the hinge.

Route 14/5 Separation and OH: Analysis of Damage

Figure 7.7 shows that Frame #1 was short and stiff while Frame #2 was tall and flexible. In particular, Pier #2 was very short and had a large flare that further increased its stiffness. This extremely stiff column failed because it was unable to displace elastically to the same degree as the other columns. The ground around the columns of frame #2 show that it moved to the left (outwardly) about 6 inches during the earthquake. This apparently unseated stiff frame #1. Thus, the superstructure at Pier #2 and at Hinge #1 fell leaving Pier #3 standing. This was because there was no continuous reinforcement through the bent cap and perhaps because of the previously formed soffit cracks during the San Fernando Earthquake.

North Connector OC: Description of Structure

This was a 10 span, highly curved bridge on single column bents ranging from 25 to 75 feet in height. The bridge was 1532 feet long with alternating prestressed and reinforced concrete superstructure frames. Frame #1 was a drop in span supported by a seat type abutment. Frame #2 was a three pier frame supporting the other end of the drop in span. Frame #3 was two long spans with a single column. Frame #4 was similar to Frame #2 with three columns and short, cantilevered end spans. Frame #5 was supported by 2 piers and an end diaphragm type abutment. There are hinges in spans 1, 4, 5, and 8. The hinge seats were 14 inches. All the columns were 8' by 4' octagonal sections with flared tops and a mix of pile and spread footing foundations. The bridge was designed in 1968, modified after the San Fernando Earthquake, and constructed in 1975.

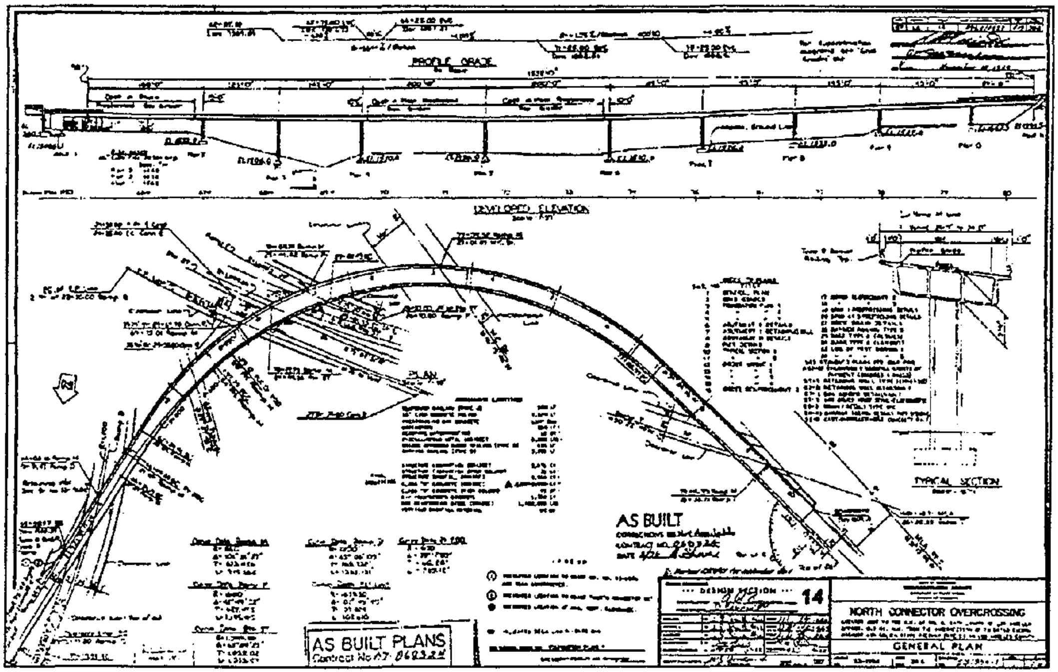


Figure 7.9. General Plan of North Connector OC.

North Connector OC: Description of Damage.

The first two spans along with Pier #2 fell during the earthquake. There was also a great deal of movement at hinge #2. There was no damage at Pier #3.

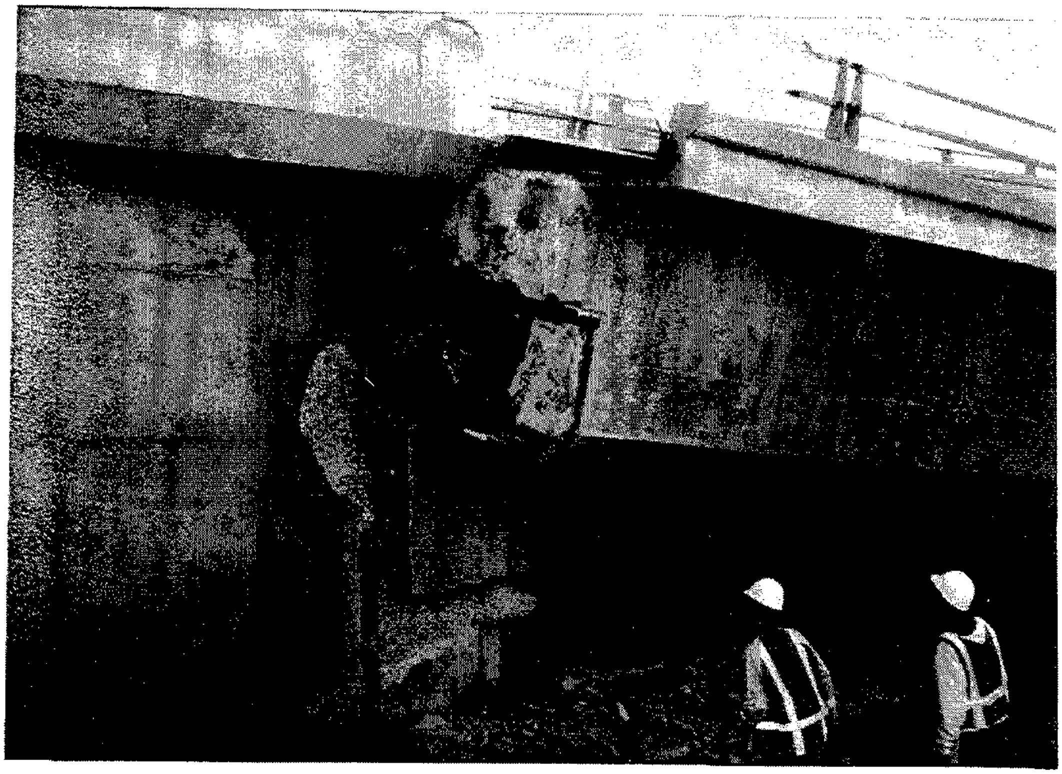


Figure 7.10. Earthquake Damage at Abutment #1 to the North Connector.

North Connector OC: Analysis of Damage

Pier #1 was too short and stiff to handle the bridge's displacement and failed, dropping the first two spans. Perhaps the end diaphragm abutment at the other end of the bridge, along with a frame with more piers, reduced the displacement, protecting short, stiff Pier #10 from a similar fate. Also the restrainers at hinge #1 don't appear to have prevented the movement at this end of the bridge.

LOCATION #3 - ROUTE 118 WEST OF ROUTE 405

Of the four locations, this is the closest site to the Northridge earthquake epicenter that experienced severe bridge damage. For several miles, every bridge along Route 118 west of I-405 suffered some damage from the earthquake. This damage ranged from approach settlements to superstructure collapse. Due to the extent of damage, a peak horizontal ground acceleration of at least 0.5g is estimated for this site. This is somewhat higher than what was recorded on instruments near this site. The ground is at least 90 feet of compact silts, sands, and gravels. All of the bridges at this location were built in 1976 which means that some of the new ideas about seismic design were incorporated into their designs. The bridges are all medium length prestressed concrete box girder structures.

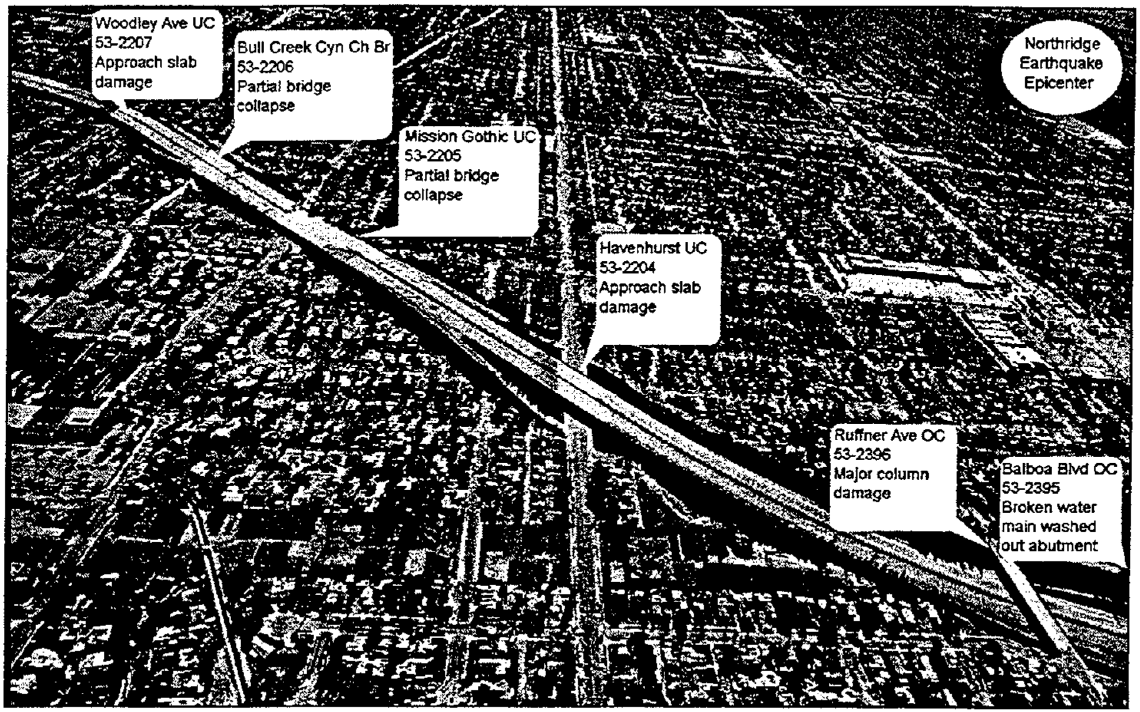


Figure 7.11. Bridge Damage at Location #3 -Route 118 west of Route 405.

Mission Gothic UC: Description of Structure

These two bridges had a rather unusual geometry with opposite skews at both ends. The left bridge had three spans and was 506 feet in length. The right bridge was four spans and was 566 feet in length. The cast in place prestressed box girder superstructures were supported by two column bents with prestressed bent caps. The columns had a six foot octagonal section with flares on top and pins at the footings. The columns had excellent transverse reinforcement of #5 spirals @ 31/2" up to the flare. All the abutments had four foot seats and supported the superstructure on elastomeric pads. All the foundations were supported by 16-inch CIDH piles. The bridges were designed in 1973 and built in 1976.

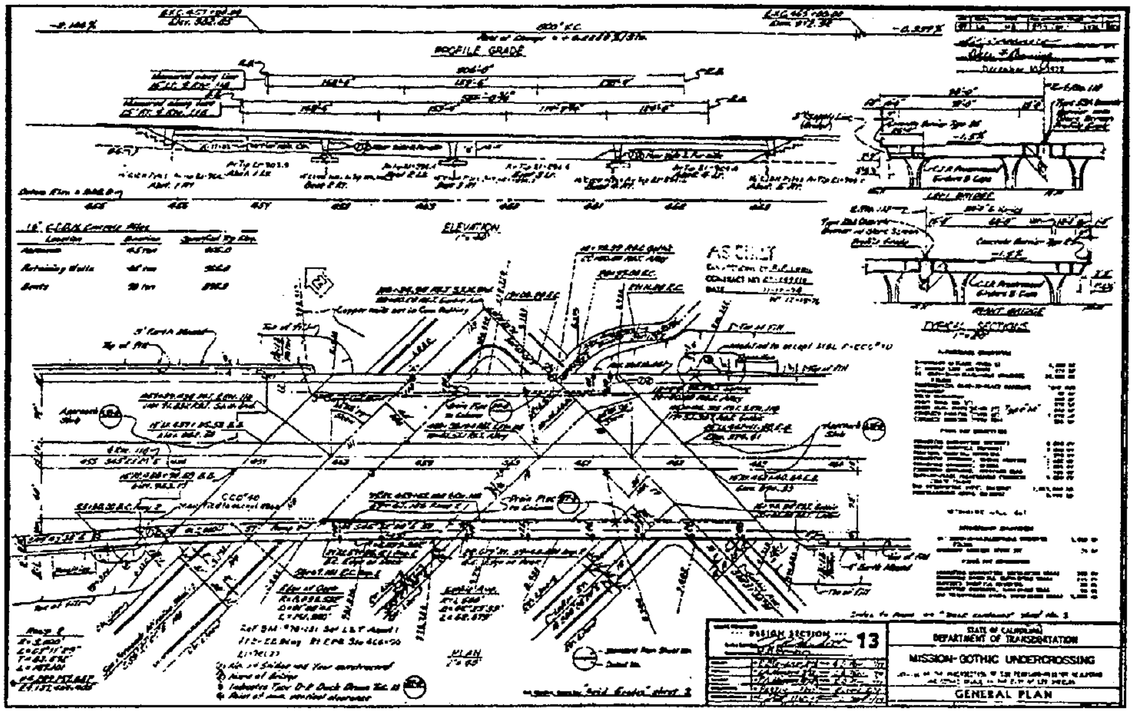


Figure 7.12. General Plan of Mission Gothic Undercrossing.

Mission Gothic UC: Description of Damage

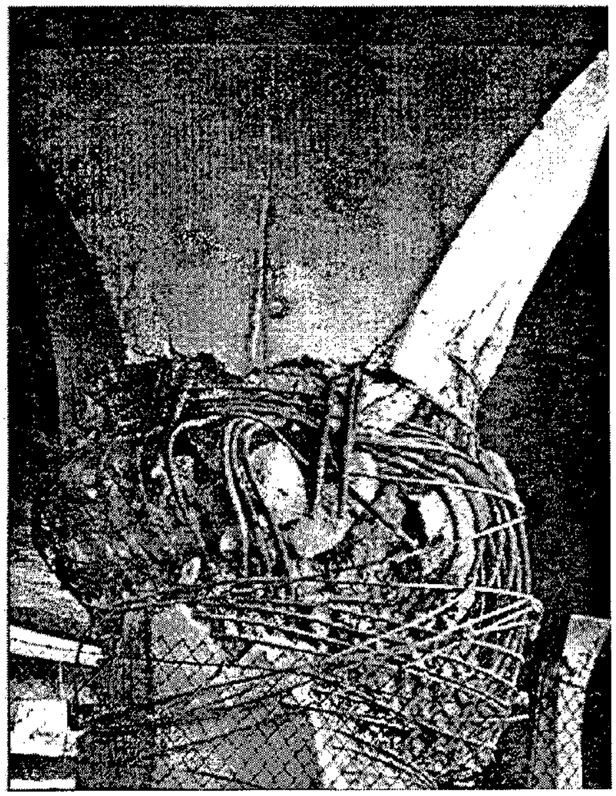


Fig 7.13 Left Bridge of Mission Gothic UC.

Both bridges suffered serious damage during the earthquake. The right bridge had a collapse of spans three and four. The columns at Bents #3 and #4 broke off below the flares, dropping the superstructure and unseating it at Abutment #4. The superstructure remained seated at Abutment #1 although there was 13 inches of transverse movement. At Bent #2, the left column also failed below the flare; however, the right column broke the bottom pin instead. The left bridge didn't collapse; however, most of the columns failed below the flare. There was two inches of transverse movement at Abutment #1 and over 10" at Abutment #4.

Mission Gothic UC: Analysis of Damage

There were two factors that controlled the dynamic behavior of these bridges. The first was the unusual geometry that allowed movement only to the south during the earthquake. This directional bias forced some columns to move in their stiff direction, which allowed only minimal elastic displacement. The other factor is the large flares that reduced the elastic length of the columns, causing a much greater plastic shear to develop (Vp=Mp/L). Thus, the largest plastic shear failed the weakest column section just below the flares and in one case at the column pin. Other factors that influenced the bridge damage was the wide spacing between columns, which forced fewer columns to carry more of the seismic load and a larger dead load. The progression of events after the damage at Bent #4 of the right bridge and Bent #3 of the left bridge is harder to determine. Probably, the increased displacements that occurred after these bents failed, broke the rest of the columns, and dropped the right superstructure from the east abutment.

Bull Creek Canyon Channel Bridge: Description of Structure

At Bull Creek there were two highly skewed bridges connected with a longitudinal joint on the centerline of Route 118. They were cast in place, prestressed box girder bridges. Both were three span structures with multicolumn bents and diaphragm type abutments on foundations seats. The foundations had 16" diameter CIDH piles. The superstructure widened from a minimum width of 200 feet and had a large skew. The columns had a four foot octagonal section without flares. At Bent #3, the columns were cast into a concrete channel. Bent #2 columns had an octagonal section for their entire length. The three spans were 90 feet, 101 feet, and 65 feet.

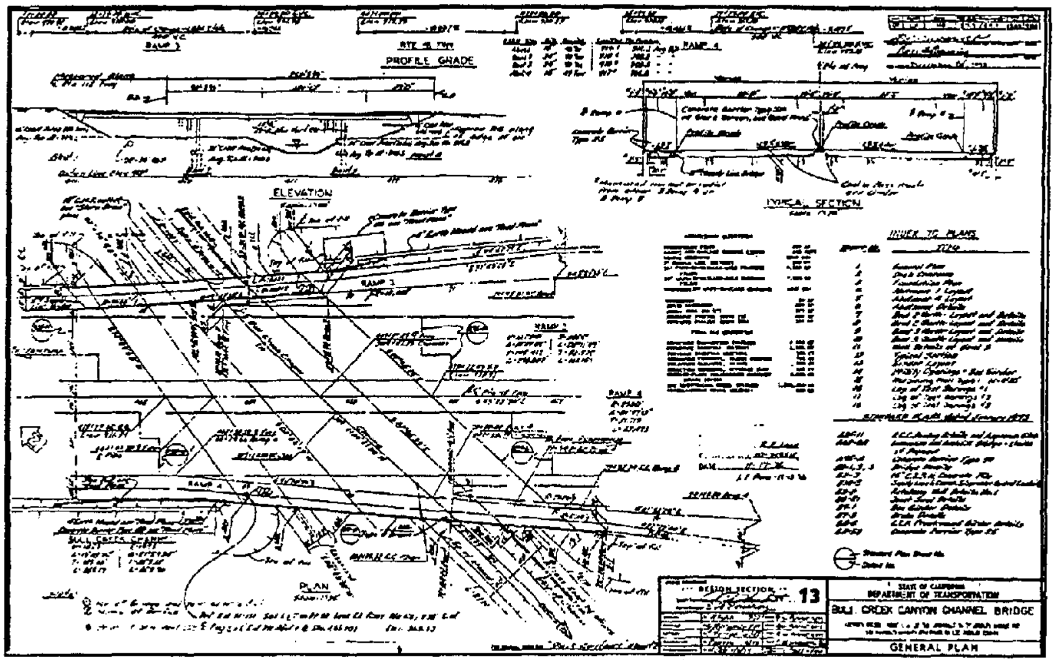


Figure 7.14. General Plan for Bull Creek Canyon Channel Bridge.

Bull Creek Canyon Channel Bridge: Description of Damage

At Bent #2, the right bridge had major column damage near the top of two of the five columns. This damage was the spiral reinforcement breaking, the longitudinal column steel buckling, and column concrete crushing into rubble. This occurred at one diameter below the soffit where the confinement steel changed from a 3 inch to 12 inch spacing. At Bent #3, both bridges had major column damage right above the concrete culvert (see Figure 7.15). The only other damage observed was some soil heaving at Abutment #4 of the right bridge, and some minor concrete cracks at the abutment shear keys and on the right bridge soffit at Bent #3. The bridges rotated clockwise during the earthquake.

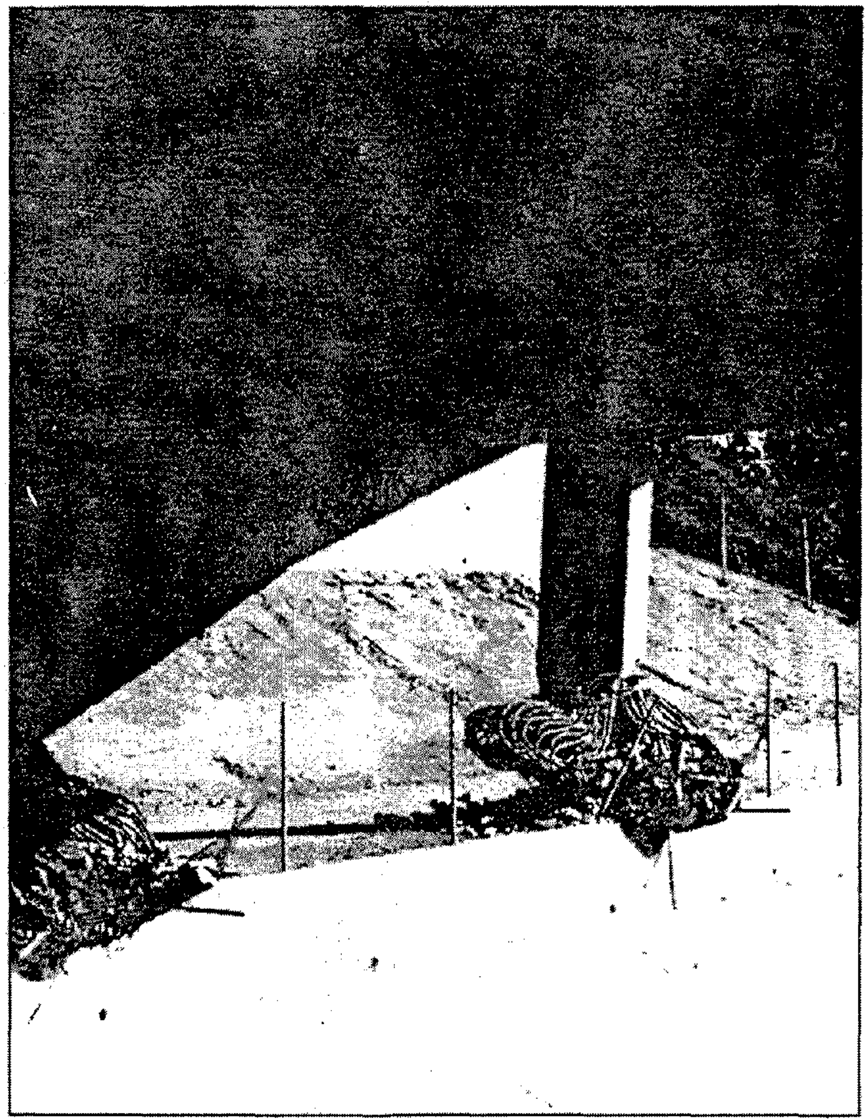


Figure 7.15. Earthquake Damage at Bent #3.

Bull Creek Canyon Channel Bridge: Analysis of Damage

Major damage was caused by Bent #3 being monolithically cast with the channel wall. This made the columns much shorter and stiffer. The result was that the bent was too stiff to displace with the rest of the structure. It immediately failed causing secondary damage to Bent #2 of the right bridge and other minor damage.

LOCATION #4 - THE SANTA MONICA FREEWAY SOUTH OF DOWNTOWN

Location #4 is 16 miles southeast of the epicenter of the Northridge Earthquake. The Santa Monica Mountains and a deep basin filled with alluvial deposits lies between. This site is on the southern edge of the basin, in an old stream basin softer than the surrounding area. Peak accelerations of less than 0.3g were recorded 2 miles away. However, the geology and damage suggests that higher accelerations occurred at this site. The damaged bridges were part of an east-west freeway built in the early 1960's.

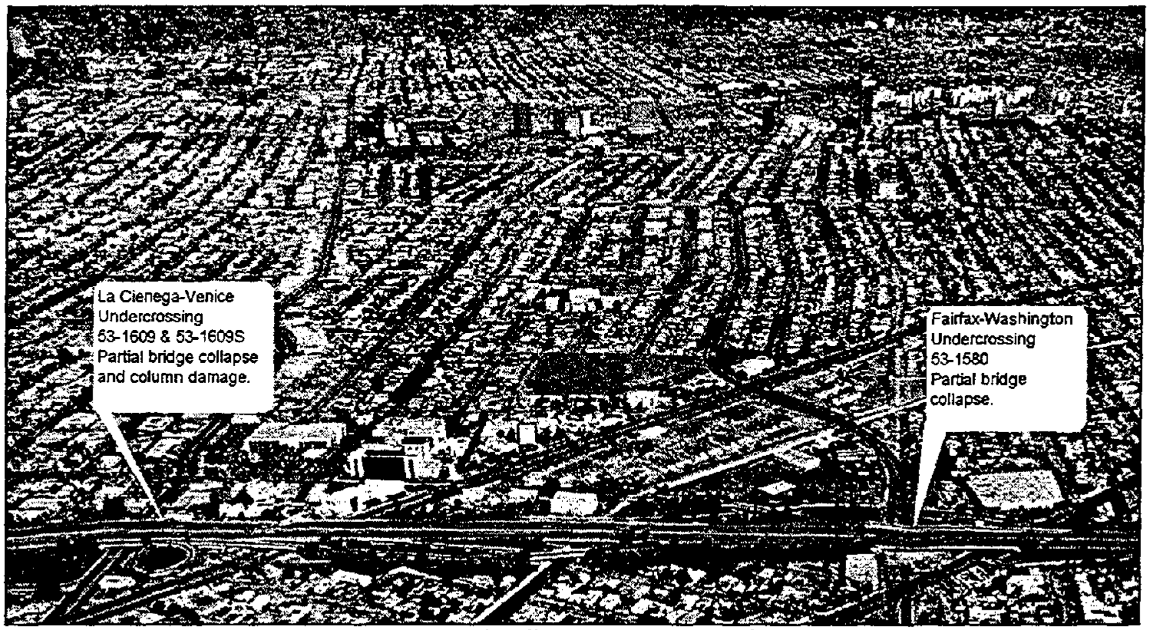


Figure 7.16. Location #4 -Santa Monica Freeway South of Downtown Los Angeles.

La Cienega-Venice: Description of Structure

These were 2 -9 span bridges connected with a longitudinal joint. The left bridge had a constant width of 70 feet and the right bridge widened to carry traffic onto an adjacent ramp (see figure 7.17). The bridges were supported by substructures on skews ranging from 5 degrees at Abutment #1 to 41 degrees at Abutment #10. The superstructures were 6'-3" deep, cast in place, reinforced concrete boxes composed of 3 frames and connected by 6 inch hinge seats. The bridges are 870 feet with spans of 51,116, 93, 111, 112, 105, 116, 115, and 51 feet. The end spans were slab and girders with crib walls to form closed bins at the abutments and pier walls.

Bents #3 through #8 had 3 or 4 (6 to 8 for both bridges) four foot diameter prismatic columns with #11 longitudinal reinforcement and #4 lapped hoops at 12 inches. Bent #4 had columns that were pinned at the bottom with a 6 inch ring of expansion joint material. There was a decreasing superelevation that caused a significant variation in the column heights of Bents #3 and #4. Piers #2 and #9 were concrete pier walls with lapped vertical reinforcement above the footing. All of the footings were inadequately reinforced and were supported on piles.

The soil profile shows at least 70 feet of sandy soil. The bridges were built in 1964 and seismically retrofitted in 1978. The retrofit was the installation of 1-1/4" diameter, high strength restrainer rods at the hinges.

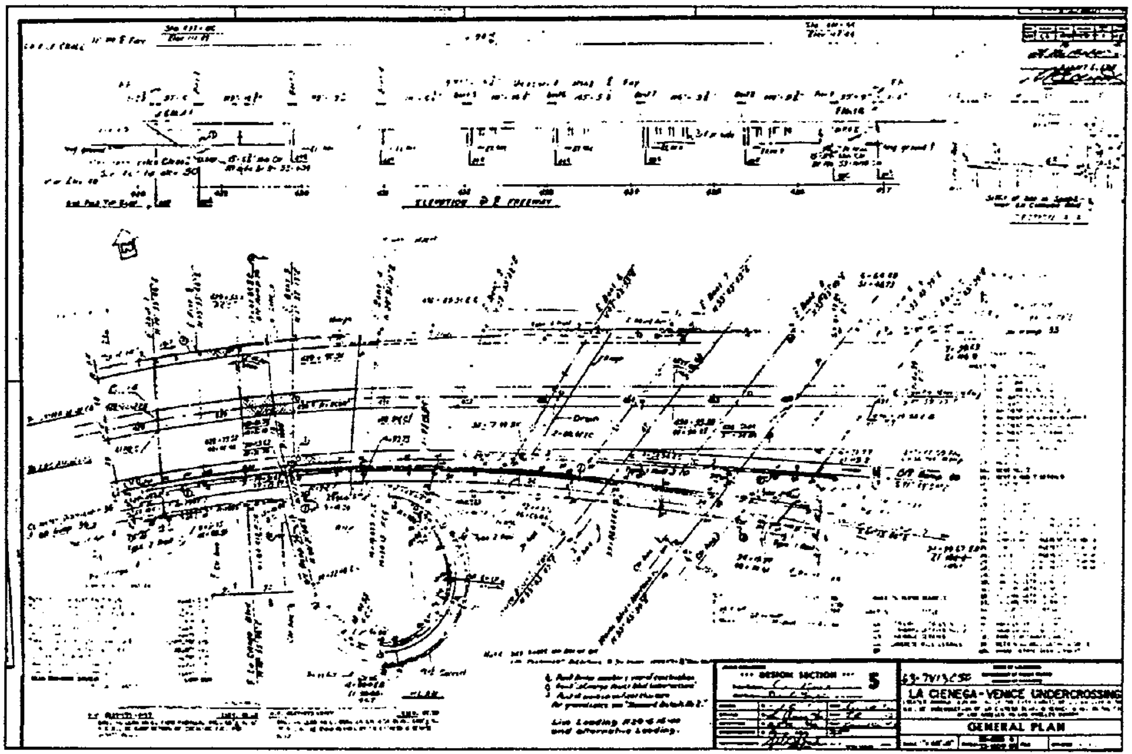


Figure 7.17. General Plan for La Cienega -Venice Undercrossing.

La Cienega-Venice: Description of Damage.

Most of the columns were severely damaged by the earthquake. Both superstructures dropped onto masonry storage buildings that were under the bridges. All of the columns at Bent #7 on the left bridge failed, 2 at the top and the middle one at the bottom. These columns were designed to be fixed at the bottom. Span #6 of the left bridge fell off of the hinge seat. The restrainers at that hinge sheared or were pulled through the concrete diaphragm. A separate but adjacent collector ramp structure also suffered some column damage. The column foundations were exposed after the earthquake and were found to be in excellent shape.

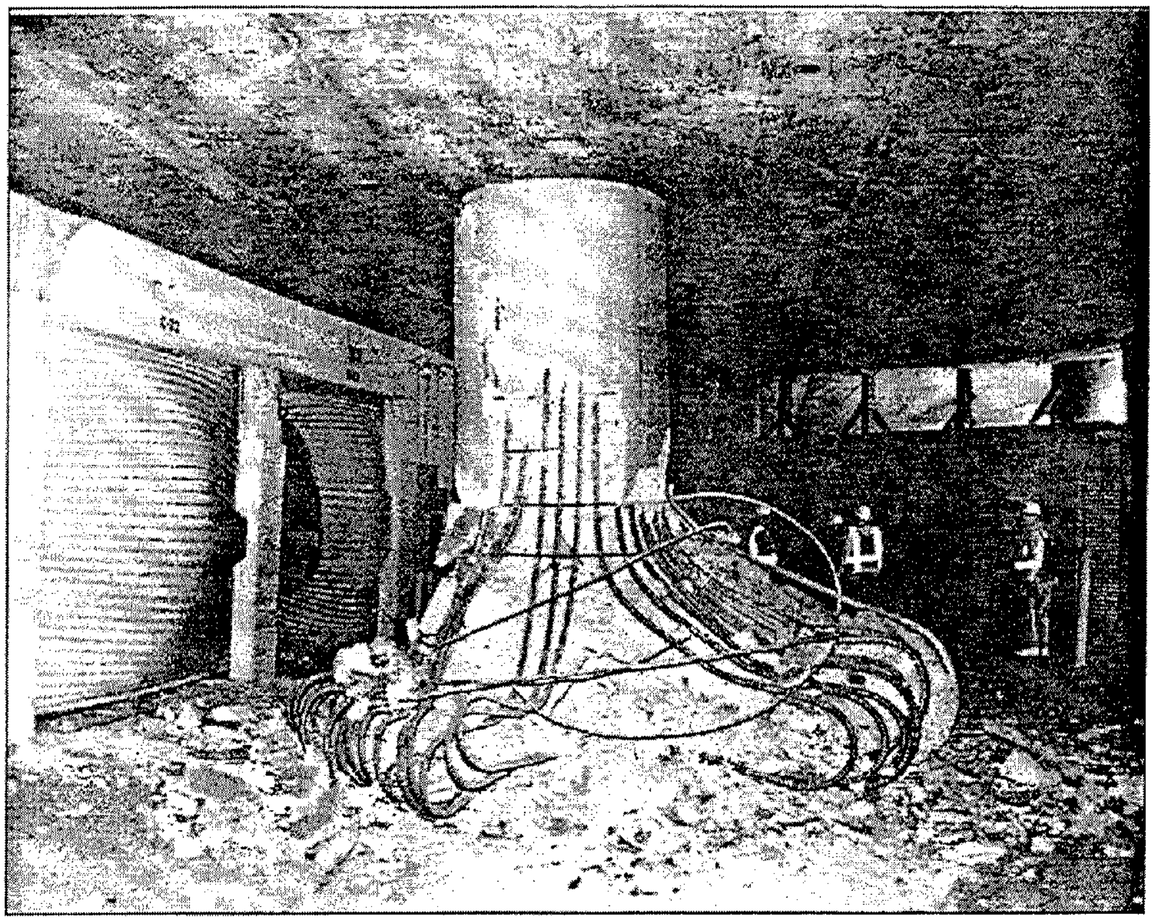


Figure 7.18. Damage to La Cienega-Venice Undercrossing.

La Cienega-Venice: Analysis of Damage

These bridges collapsed due to column failures. Specifically, #4 hoops at 12 inches failed before a plastic hinge could form and because they could not resist the large shear forces during the earthquake. In every column, failure began with rupturing of the #4 hoops, usually near the top or bottom plastic hinge zones. This is not surprising considering when these bridges were built. A seismic retrofit project for these bridges was about to begin at the time of the earthquake.

The bridges were 16 miles from the epicenter of the Northridge Earthquake. CSMIP Station #24157 recorded 10 seconds of significant shaking with a peak east-west acceleration of 0.25g and a peak north-south acceleration of 0.17g. This station was 2 miles to the southeast sitting on 3 feet of soil over rock. CSMIP Station #24389 recorded 10 seconds of strong shaking with a peak east-west acceleration of 0.27g and a peak north-south acceleration of 0.24g. This station was located 4 miles to the northwest on terrace deposits. It was surprising to see the extent of damage to these structures at those accelerations. Perhaps being located on a soft basin amplified the earthquake motions.

Fairfax-Washington Undercrossing: Description of Structure.

These were 2 cast in place, reinforced concrete, box girder bridges. They were 577 feet long. Each had 2 frames. The right bridge had 7 spans and the left bridge has 8 spans. Both bridges had varying widths with the right bridge varying from 72 to 74 feet and the left bridge varying from 72 to 110 feet. The bridges were supported by skewed supports varying from 5 degrees at Abutment #1 to 45 degrees at Abutment #8. The hinge seat width was only 6 inches. These bridges were very similar to La Cienega-Venice Undercrossing. The pier walls were adjacent to the abutments (with pinned bases on cast in drill hole pile foundations). The other bents had 3 to 4 -4 foot diameter columns (some pinned at the base and others with fixed bases all on cast in drill hole pile foundations) with #11 bars longitudinally and #4 bars at 12 inches transversely. The soil is similar to La Cienega with an excess of 70 feet of dense sand. The superstructure rested on 6 inch high bearing assemblies at the abutments. The abutments had spread footings. The bridges were built in 1964 and retrofitted with 5 and 7 cable restrainer assemblies in 1974.

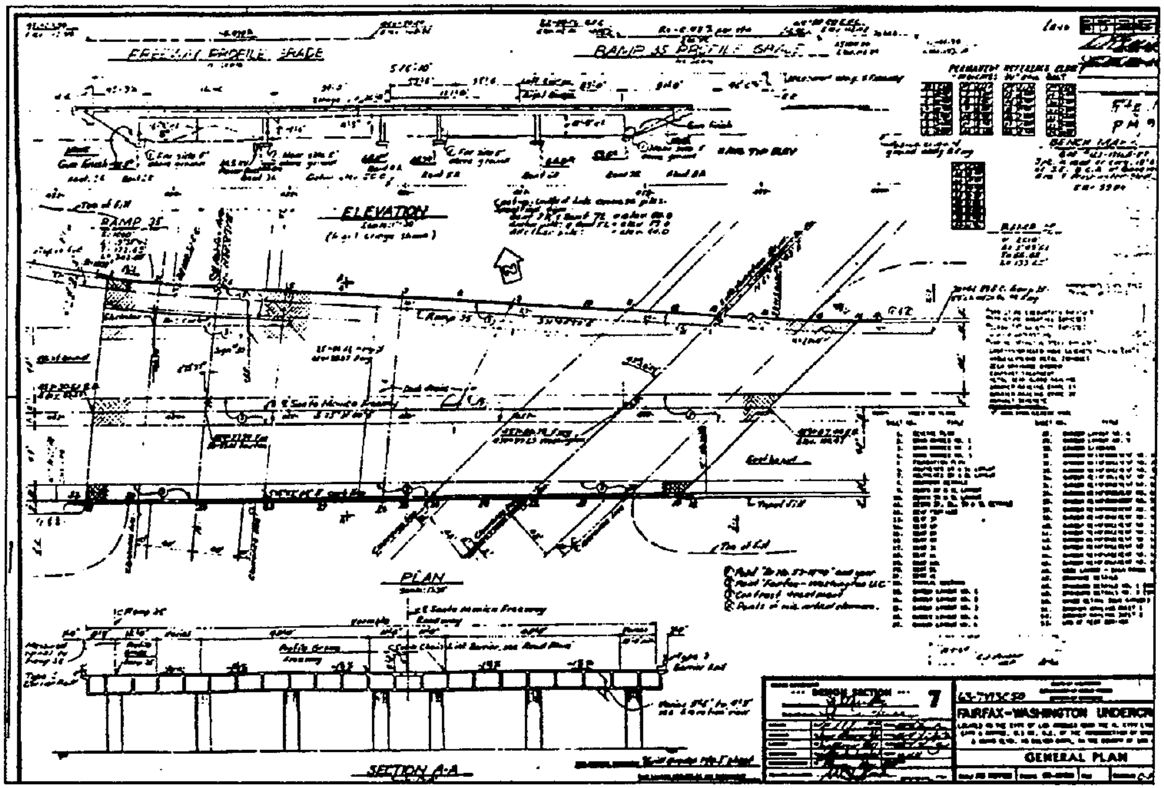


Figure 7.19. General Plan of Fairfax-Washington Undercrossing.

Fairfax-Washington Undercrossing: Description of Damage.

Damage to these bridges, although severe, was somewhat less than at the nearby La Cienega -Venice Undercrossing. The tops of all the columns in Bent #3 for both bridges had major damage. This caused the superstructure to sag about 10 feet at Bent #3 and lift about 5 feet above the rocker assembly at Abutment #1. The bottoms of the columns at Bent #3 were designed as fixed with lapped reinforcement above the footing. There was also some cracking of concrete on the columns at Bent #4. The restrainers did a good job of keeping the superstructures from falling off of the hinge seat.

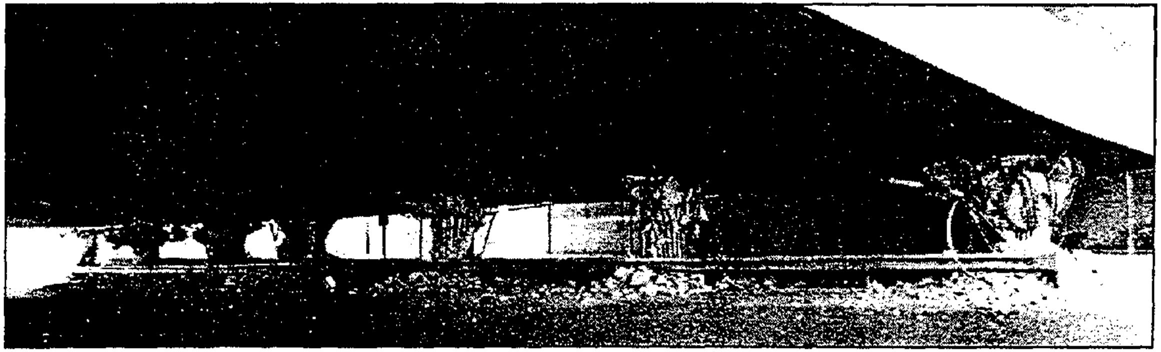


Figure 7.20. Damage to Fairfax-Washington Undercrossing.

Fairfax-Washington Undercrossing: Analysis of Damage

These columns failed in shear, probably after some plastic hinging occurred at the top of the columns. This hypothesis is based on the fact that there was no damage at the pinned bottoms of the columns which otherwise would have been more vulnerable to shear. This damage was similar to the nearby La Cienega -Venice Undercrossing, and it occurred for similar reasons. The columns at Bent #3 do not have sufficient confinement reinforcement. What is surprising is that such catastrophic damage could occur so far from the epicenter and at such a low acceleration. The footings and piles at Bent #3 were exposed and found to be in excellent condition.

OTHER BRIDGE DAMAGE

Besides the catastrophic bridge damage listed above, a great deal of other damage occurred, much of it minor but some more serious. Most of the damage was cracked and spalled concrete associated with superstructures banging against abutments and piers. More serious damage was restrainers punching through hinge diaphragms. In many instances shoring was placed under hinges until repairs were made. Table 7.2 below gives a complete description of all state highway bridge damage from the Northridge Earthquake.

Table 7.2. Highway Bridge Damage from the Northridge Earthquake.

Bridge #	Rt	Post mile	Bridge Name	Description of Bridge Damage
53-0498	1	36.89	BEACH PUC	Minor damage. Spalling at joints. PUC heaved inward causing longitudinal crack in #1 S'bnd lane. Cracking evident in other lanes.
53-0068	1	39.62	CASTELMARE POC	Slight spalling @ east abutment seat.
53-2602	1	36.25	MONTANA AV POC	Hinge separation - approx. 2". No recommendation. Supported on bottom also. No damage per Makoto Ogata on 3/9/94.
53-1580	10	R009.31	FAIRFAX WASH U	Superstructure sagged from abutment #1 to hinge.
53-1603	10	R004.24	CENTLA-PICO UC	Top of columns have spalled. Spalls @ top of col, radial cracks @ top of col along Centinela Blvd. (0"Lx8"Wx2"D). PCC spall w/ rebars exposed in N. rail. 3" settlement in approach slab over W. lane @ Centinela Ave. Off-ramp
53-1586	10	R010.43	LA BREA AVE UC	Spalls at R & L sides of B2 at the top corners of the curtain wall.
53-1599	10	R003.34	CLOVERFIELD OC	N.E. shear key cracked, bearing restrainer popped out with spall on wall; north abutment has minor shear key spalling. North abutment PN has 2' - 8'-3" spall; NW corner barrier separated. Raised median @ N. abut. cracked. Top of all columns (4)
53-1609S	10	R008.83	LA CNG-VEN SEP	Column has formed plastic hinge @ B3. Structure standing but unsafe. Needs to be Shored.
53-1609	10	R008.83	LA CNG-VEN SEP	Collapsed span hinge to adjacent span. Most of columns of mainline structure buckled. Some damage on ramp columns.
53-1572	10	R011.03	WEST BLVD OC	Hairline cracks at tops of columns. Slope paving cracked.

53-1301	10	14.23	SANTA MONICA VI (This is an extremely long viaduct 21918')	Minor Spalls at top of cols near I-110(PM 14.85) Primarily drop caps are damaged. Possible internal hinge damage: @ WB 10/NB 110; @ Los Angeles St. Only substructure & W/B deck inspected (work is now at Santa Fe Ave).
53-1637F	10	R005.65	SE CONNECTR OC	Cracks at exterior girders, Bent 7. Unknown internal damage.Crack @ hammerhead cap expansion joint. Damage to diaphragm (hinge) is excessive. Cracks at exterior girders and restrainers and diaphragm damage at Bent 7.
53-1485F	10	R009.22	CADILLAC RP SP	Approach settlement. Crack in slope paving; Abut 1 approach settled 1/2".
53-1557	10	R007.92	ROBERTSON-N UC	Damaged luminare (Maintenance contacted); lt ww at eb cracked; broken keeper plate bolts at bearing. Previously patched spall in EB gore area has popped off.
53-1288	10	31.72	BESS AVE POC	Minor damage to picket rails, some cracking of superstructure over Route 10.
53-1582	10	R009.74	HAUSER BLVD UC	Concrete spalls at Bent 3 curtain walls and wingwalls.
53-1587	10	R10.72	HARCOURT AVE UC	Minor concrete crack at Bent 3 curtain wall. No work required.
53-1570	10	R011.70	TENTH AVE OC	Minor horiz. concrete cracks at the top of all columns.
53-1571	10	R11.39	CRENSHAW BLVD. OC	Hairline Horiz. cracks @ top of all columns. Shear wall crack at north abutment.
53-1590	10	R12.10	FOURTH AVE POC	Minor concrete spalling of the external bolsters at both abuts.
53-1615	10	R006.31	NATIONAL BL OC	Rocker & keeper plate damage @ abuts, cracks in curtain wall, spalls at top of col. PEQIT (1/18/94); all keeper plates failed.
53-1333F	10	18.41	ECHANDIA OH	Abut. brg keeper plates sheared off. Barrier rail spall rt rail @ Abut. 1.

53-1459G	10	21.33	RAMONA BLVD UC	Hairline cracks @ bent 2, top of column.
53-2055K	10	20.95	CAMPUS RD RAMP	Minor cracking in columns at Bent 2.
53-1856	10	19.98	CITY TERRC POC	Hairline cracks near Hinge 2.
53-1634	10	R005.99	COVENTRY PL UC	Curtain wall damage.
53-1627G	10	R005.28	NORTHW CONN OC	2" offset of span at Bents 3 and 16; 1" spall at B4 and B5 col/soffit interface. Damaged rail tubes. Bent 3, Cells 1 & 4 hinge restrainer damage.
53-1584	10	R010.12	REDONDO BLD UC	Minor Damage. E/B Approach Lane #1 had 2" settlement, 2" gap in pier walls. Sidewalk Bulged at corners.
53-1553S	10	R007.08	MANNING A R OC	Cracks at east abut diaphragm. Spall at east abut deck joint.
53-1579	10	R009.12	BALLONA CREEK	Minor top of column spalls. Crack in wingwall. Retaining wall at A1 has moved out 5". Approaches settled 4" @ each end. There is plenty of evidence of structure movement.
53-1596	10	R002.61	14TH STREET OC	Bearing out of position at abutments.
53-1597	10	R002.84	17TH STREET OC	Minor spall and hairline cracks at top of all columns.
53-2540L	10	C021.07	WBD BUSWAY OC	Crack at top of column in outrigger Bent #5. Noticed 1 cm vertical crack on top of the right column over outrigger Bent #5. At the same bent, the cap outrigger to column connection, with previous patches due to earthquake, has fallen and the rebar is exposed.
53-1598	10	R003.07	20TH STREET OC	30' long transverse AC crack over N'ly Abut in bridge approach lanes #1 and #2.
53-1616	10	R006.40	OVERLAND AV OC	W Side S Abut Seat Cracks & Spalling. Top of Col Cracks.
53-1671K	10	R009.13	BALLONA CREEK	Approach Slab Settled 5". Horiz. crack below box girder in A1 Diaphragm.

53-1603	10	R004.24	CENTLA-PICO UC	Top of columns have spalled. Spalls @ top of col, circumferential cracks @ top of col along Centinela Blvd. Conc. spall (0"Lx8"Wx2"D) w/ rebars exposed in N. rail. 3" settlement in approach slab over w. lane @ Cintinela Ave. Off-Ramp
53-1442	101	31.05	LAS VIRGENE OC	Superstructure dropped 3"-6". Abut. 1&5 were thrust upward above sidewalks & A.C. approaches. Possible pile damage.
52-0266	101	7.89	WENDY DRIVE OC	Exterior girder fillet spalled.
53-1339F	101	11.63	134/101/170 SEP	Top of column spalling with some exposed rebar. Shear key failure. Numerous keeper plates broken.
53-0731	101	6.15	WILTON PLACE O	Shear cracks and spalls at curtain wall A1. Keeper plate bolts sheared off on one side. Spall at A3.
53-1336R	101	11.75	101/134/170 SEP	Shear key failure. Bearing restraint caused spall on abutments. Major column failure of Bent 5. Abut 9 rocker bearing damage. Minor spalls both sided of long span @ span 5 and span 7 hinges. Minor spalls @ Bent 6. Buckled bar @ col 4 of bent.
53-1102R	101	16.94	SEPULVEDA BL U	No Damage. Soundwall down (300'), otherwise no damage to bridge structure.
53-1095	101	25.88	SHOUP AVE UC	No Damage. Soundwall damage (300' out of alignment)
53-0676	101	5.81	WESTERN AVE OC	SE End of Bridge has buckled AC & Separation of Steel Girder at Abut. No damage per Makoto Ogata on 3/9/94.
53-0732K	101	6.41	VAN NESS AVE RP	South abut shear wall badly cracked and spalled. North abut shear wall cracked. Spall at barrier rail at N abut.

53-1337	101	13.27	TUJUNGA WASH	Out of plane hanger plate bending. Minor to moderate cross frames buckling at several locations. Abut joint wingwall cracks. Minor barrier rail damage.
53-1371	101	15.38	LOS ANGELES R	Top of column spalling. Keeper plate bolts have sheared off @ Abut 6 with loss of bearing. East abut not inspected. Curtain wall damage. WW (Bin Type Abut) Damaged.
53-1064	101	25.34	ROUTE 101/27 SEP	Minor concrete spalls and cracks at A1 s. widening conc header, Bent 2 s widen. columns #1 & 2 and at center widening, A3 sidewalk from gdr #6 N to end of bridge.
53-1224	101	10.86	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-2405R	105	R7.39	RTE 105/110 SEP	Bearing showed 4" movement. Abut face spall.
53-2655	105	R3.47	IMPERIAL HWY OC	Minor spalls at the E'ly 2 shear keys of the S'ly abutment.
53-2428	105	R14.95	MERKEL AVE OC	Minor concrete wingwall spall @ N'Wly corner.
53-2425	105	R14.65	PARAMOUNT BLVD OC	Minor Cocrete wingwall spall @ SW'ly corner.
53-2565S	105	R15.76	LAKEWOOD BL OC	Minor conc spalls in abut faces at NE'ly & SW'ly corners.
53-2572	105	R16.39	ARDIS AVE OC	Minor conc spall in abut face at W'ly side of N'ly abut.
53-2680	105	R7.68	NE TRANSIT CONN OC	Minor spalls at hinge #8.
53-0956	110	10.49	GARDENA BV UC	Minor exterior rail spalls at Joints.
53-0960	110	9.07	190TH ST UC	Minor spall at N abut wall.
53-2465	118	R007.05	ENCINO AVE OC	4" settlement on approach. Curtain wall damage. Cracks at ext. shear keys @ abut. 3 right and left side. Curtain wall connections damaged @ A1 (DBR). Soundwall Damage.

53-2395	118	R007.80	BALBOA BLVD OC	Minor spalls at top of column. Approach slab buckled. A1 & B2 damage is significant. Water mains washing out abut. Slope paving damage.
53-2396	118	R008.05	RUFFNER AVE OC	Column cracks.
53-2207	118	R009.04	WOODLEY AVE UC	Spalls at both abuts, seat damaged at SW abut, barrier rail damage at both abuts, median barrier damaged. Severe approach slab settlement
53-2204	118	R008.34	HAVENHURST UC	App slab buckled. West bound struct. appears to have rotated. Slope paving damaged.
53-2208	118	R009.33	GAYNOR AVE UC	Approach slab settlement; N. E. wingwall settled @ 1 FT. Wingwall and approach slab damage. Failed sidewalk & heavily damaged slope paving.
53-2215	118	R010.83	FOX STREET UC	Minor approach slab settlement. A1-midwidth cracking-1/8" vertical rt. WW 4" transverse separation. A2 left WW 3" longitudinal separation, 1/8" midwidth crack in diaphragm, minor cracking-1" settlement in approach slabs
53-2209	118	R009.57	HASKELL AVE UC	Severe approach slab settlement
53-2213	118	R010.07	SEPULVEDA B UC	Bridge slab buckled. A1 & A3 vertical cracking in diaphragm, slope paving cracking and settlement. Hairline cracks in all col. 2" settlement at both approach slabs (DBR).
53-2464	118	R006.80	WHITE OAK A OC	Shear keys cracked. Interior shear keys @ A1 & A3 damaged. Both keys remain partially effective. Steel is exposed (DBR)
53-2513	118	R006.58	ZELZAH AVE OC	Cracked slope paving & minor spalling.

53-2205	118	R008.63	MISSN GOTHIC U	EB Collapsed, WB structure damaged approx. 2ft sag, two columns buckled at first Bent, one column at second Bent. End spans are off supports; WB is in worst shape. Existing and replacement bridges are actually left and right.
53-2206	118	R008.84	BULL CR CYN CH	Right structure partially collapsed, superstructure not repairable. Left structure had all columns fail. Superstructure intact. Some columns poking through deck.
53-2095	118	R012.40	SAN FERN RD OH	Damage at abut 3; soffit spalled; cracked end diaphragm; column looks good
53-2103G	118	R013.89	PAXTON-FTHL UC	Minor spalling at hinge seats. Signs of movement @ hinge bad/torn joint seals , lamp of electrolier fell off.
53-2102G	118	R013.94	RTE118/210 SEP	Seal failure @ hinges, offset in hinges, spalls in soffit. Restrainer damage at span 5 (cell 1) and span 8 (cells 1,2,3 & 4). Minimal to moderate rotation of Abutment 11. Minor damage to exterior keys. Light standard bases are broken. Stan
53-2354S	118	R012.27	PAXTON ST UC	Minor abut spall and approach settlement
53-2210G	118	R009.70	CHATSWTH ST UC	Minor spalls at abutment. Minor vertical cracks down face of wingwalls
53-2324L	118	R011.42	RTE 118 5 SEP	Bridge rail cracking SW end of bridge. Some approach settlement in shoulders.
53-2342L	118	R011.31	SHARP AVE UC	Minor Abutment Damage
53-2342R	118	R011.32	SHARP AVE UC	Abut. 2 cracking and spalling; joint seal damage; 3" approach slab settlement
53-2343G	118	R011.32	SHARP AVE UC	Cracks and spalls at Abutments; 1 " approach settlement

53-2357	118	R011.05	ARLETA AVE UC	A-1: lateral movement at wingwall; A-2 minor crack and 1" wingwall displacement; cracked slope paving
53-2212F	118	9.85	CENTER CONN OC	Extensive cracking at Abut. 7 ,1/4-1/2 inch cracks (total 5) in pile cap. 2" transverse separation of backwall and wing wall at Abut. 1. Possible pile damage Bents 2-6. Hinge restrainer damage in Spans 2 & 5.
53-2214	118	R010.51	CHATSWORTH D U	A1: 4" lateral movement of right WW. 1/16" vertical crack in abut diaphragm @ midwidth. A2: 3" long. & 2" lat. movement of left WW. 1/8" vertical crack at midwidth of diaphgram
52-0300	118	R029.56	YOSEMITE ST OC	Evidence of plastic hinging. Cracking at tops & bottoms of columns. 4" approach settlement.
53-2499	118	R003.22	MASON AVE OC	Cracked slope paving. One small spall at A3 backwall. Approach settlement. Abutments have rotated, gap approx. 1 1/4 ".
53-2217H	118	R009.74	DEVONSHIRE UC	Minor abut. cracking. Minor soffit cracks. WW movement. Leaky joints
53-2182	118	R002.55	BROWNS CYN WA	Cracked or destroyed shear keys. Pads delaminated. All Keys at Both abutments cracked or destroyed. "Old" Bearing pads ruined.
53-2498	118	R003.13	RINALDI ST OC	Wingwalls separated from abutment diaphragms. Slope paving cracked near diaphragm. Possible pile damage.
53-2328G	118	R011.41	PACOIMA WASH	Abut 1 joint seal needs to be replaced. Sections of barrier at abut needs to be repaired. Spall on north/east wingwall needs to be patched. Significant signs of movement. Repair cracks in shear key and abut. face.
53-2500	118	R003.86	WINNETKA AV OC	Approach Settlement
52-0334L	118	T19.19	PRINCETON AV UC	Concrete spall on face of Abut. 1.

53-2694G	126	R005.80	RTE 126/ 5 SEP	Approach settlement. Minor spalls at column tops. Shear keys are cracked w/ some spalling. [EB: Moderate damage @ abuts. Spalling @ top of column]
53-0015	126	8.2	SFK SANTA CLAR	Sheared anchor bolts at abutments & bents 2&3 . Slight permanent displacement (approx. 1 1/2") has occurred at both abutments. Bent 3 appears to have moved to the north 1". Top of retaining wall adjacent to girders cracked due to lateral movement.
53-1345F	134	.04	RIVERSIDE DR UC	All (A1) keeper plates sheared (lower); (A3) parapet wall needs repair, right exterior shear key failed, rail displaced, lower bearing keeper plates sheared.
53-1452F	134	.03	RIVERSIDE DR UC	Abut 1 lower keeper plates sheared; Abut 3 L&R ext key sheared, curb spalled.
53-1493S	134	.00	RIVERSIDE DR OC	(Both abuts) All keeper plates failed, all bent cols minor spalled. Col spalled. Abut. 1 right curtain wall cracked, curb spalled. Joint seals failed.
53-1907G	134	R008.88	NW CONN OC	Deck overhang spalls at hinges. Spans 14L and 22L diaphragm, bearing and hinge restrainer damage.
53-1280	134	2.24	OLIVE AVE OC	Abut keeper plate failed.
53-1276	134	1.36	FORMAN AVE UC	Abut 1 Lt side parapet/ shear key failed.
53-1790H	134	R005.67	LA RIV BOH	"A" seals torn for entire transverse length near east side of structure. Rails separated adjacent to hinge. Crack at west abutment face.
53-1024R	134	L009.91	FIGUEROA ST UC	At Abut 1 the keeper plates failed and the right exterior shear key cracked. At Abut 3 the keeper plate failed. Cracks in Abut. 1.
53-1024L	134	L009.91	FIGUEROA ST UC	Keeper plates sheared at both abuts.
53-1023R	134	L009.72	MONTE BONITO U	Abut. 1 -rt ext. shear key cracked.

53-1917F	134	R009.04	SOUTH CONN OC	E Abut Shear Key Damage.
53-1272	134	0.35	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-1493S	134	0.00	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalled at hinge joint.
53-1336R	134	0.01	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls at hinge joint.
53-1960F	14	R024.73	RTE 14/5 SOH	Spans 1 & 2 collapsed (at southern end); Collapsed spans have been demolished.
53-1964F	14	R024.97	NORTH CONN OC	Spans 1 &2 collapsed (most north. span demolished), Span 3 broken stirrups, Span 4 hinge damage with 2 to 4 inches of bearing, minor damage all hinges.
53-2200S	14	R030.81	RTE 126 /14 SEP	Failed column. Concrete cracks @ wingwall & abut. backwall. Concrete broken at hinges. Minor cracks and spalls @ top of column (DBR).
53-1936R	14	R025.13	SIERRA HWY UC	Minor spalling at Abut. 1 rt WW.
53-2171	14	R030.55	CEDAR VL WY OC	Spalling north column, south face at Bent 2, and west side of abutments.
53-1960F	14	R24.77	RTE 14/5 SOH	At both hinges the hinge restrainers, diaphragms & equalizing bolts failed. At H3 diaphragm punching damage was visible (DBR). Shear key failure & backwall spalling at Abut. 9. 1 of 4 restrainers at H1 failed, 2 of 4 restrainers at H3.
53-2166R	14	R030.90	VIA PRNCSSA UC	Wingwalls damaged due to movement of shoulder slab at Abut.
53-2166L	14	R030.90	VIA PRNCSSA UC	Wingwall damaged due to movement of shoulder slab (E. side of S. Abut & W. side of N. Abut)
53-2201K	14	R030.91	VIA PRNCSSA UC	Abut. and rail damage at N. Abut E. side & So. Abut W. side due to movement of the shoulder slab.
53-2027R	14	R031.88	SANTA CLARA RI	2 hinges opened 4", conc breakage of hinge seats & rails, distortion of filling mat'l, minor spalls at top of column (bents 5 & 6).

53-2027L	14	R031.88	SANTA CLARA RI	2 hinges opened 4", concr. breakage of hinge seats & rails, distortion of filling mat'l, minor spalls at top of column (bents 5 & 6).
53-1963F	14	R24.82	SOUTH CONN OC	Damage to hinge 1, span 4 (2-3" of seat remains). 6" movement @ abut, severe damage. Approach slab off seat w/ no fill beneath.
53-1962F	14	R024.81	TRUCK CONN OC	Minor cracking and spalling at abut 1 (south end) . Minor spall on barrier at 1st hinge.
53-2029L	14	R031.62	HUMPHREYS OH	Shattered concrete at junction wingwall - abutment wall acute corners - SE & NW.
53-2029R	14	R031.62	HUMPHREYS OH	Spalls at rail and wingwall at abutments.
53-2076L	14	R028.08	PLACERITA R UC	Minor spall at southern abutment. Rebars are exposed.
53-2076R	14	R028.08	PLACERITA R UC	Spalling of concrete at the abutment. It seems the spalled concrete is an old patch.
53-1644	170	R015.63	CHANDLER BV OH	Minor crack at center approach railing
53-0490	170	R018.65	WHITSETT AV OC	Permanent disp. at Abuts. (5"); Plastic hinging at B-2 & B-4 Cols; Struc. has rotated counterclockwise.
53-1344	170	R014.78	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-1122G	170	R020.52	RTE 170/5 SEP	Joint seal failed at abutments and hinge. Large spall near hinge in shoulder (10' x 2'). Four keeper plates broken at A1.
53-1339F	170	R14.51	RIVERSIDE T UC	Broken keeper plates. Rail spalls. Deck spalls adjacent to joint at hinge.
53-1921F	2	R18.81	NE CONNECTR OC	Longitudinal disp. at abut, spalled shear key, abut/ret wall separation, torn water stops at abut/wingwall joint. Diaphragm damage at span 3 (cell 3).

53-2104F	210	R06.08	RTE118/210 SEP	Spalling at hinge seats. Restrainer damage at span 3 (cells 1 thru 5), span 5 (cells 1 thru 5) span8 (cells 1 & 4). Hinge movement, bad seals on armored joints torn in tension.
53-1988F	210	R00.12	NORTH CONN SEP	Minor wingwall cracking at left side of Abutment 1.
53-1925	210	R03.01	TYLER ST POC	Spalling at Abut 1 seat. Approx 75% loss of bearing area.
53-2219K	210	R18.53	WALTONIA DR UC	1" movement @ both hinges. Minor crack @ departure AC. Joint seal type "B" is loose in joints.
53-1896	210	R03.57	ASTORIA ST POC	Cracking and spalling of abutment 1 seat. Approx. 30% loss of bearing seat.
53-2117	210	R07.16	TERRA BEL ST U	Appr. slab settled 2" in lanes 1&2 at E. & W. Abuts. Shear keys are cracked per S1 3/3/94.
53-2009	210	R46.36	SAN DIMAS A UC	Settlement of N/B approach (AC - no slabs) and movement @ south end slope. Some top of col spalls.
53-0302R	22	1.42	SAN GABRIEL R	Minor spalling at pier wall between rt & lt bridges
52-0118	23	23.62	SANTA CLARA R	Minor to moderate shear cracks and spall in the pier walls. Moderate shear cracks in the top of pier wall #4 (west end) and top of pier wall #8 (east end). 24"L x 20"W spalls at top of pier wall #2 (east end) and top of pier wall #3 (east end).
53-1500	405	46.24	DEVONSHIRE UC	Minor diagonal crack at abut. Right exterior key cracked at base.
53-1506	405	47.75	RINALDI ST UC	Bent 3 major damage. Horiz & vert cracks in closure wall. (PJW) Excavated Bent 3 footing (1/23/94) only minor damage to piles. Not more than one pile lost.
53-1507	405	47.24	SAN FERN BL UC	Approach settlement @ 14". Rail slamming and spalls. 2" sag at midspan. Abut & WW cracks to 1/8". Deck spalls @ joints.

53-0739	405	37.03	MULHOLLAND DR OC	Bearings damage at abuts; spall on wingwall barrier; joint seal failure at both abuts. EB & WB AC settlement.
53-1501	405	46.74	CHATSWRTH ST U	Approach fill settlement. Minor cracks & spalls at ext shear keys at B3R & B2R. Barrier rail spall at A1L. Vertical joints at abutment closure walls have shifted.
53-2216G	405	46.8	SE CONN OC	Severe damage at abut 1, spalls under 5 of 10 girders from shear keys; most hinges have damaged bearings, restrainers & diaphragms. Approach settlements & offsets; (Ref Br # 53-2212F Report with same abut 1).
53-1439	405	44.24	PARTHENIA ST U	Bt 2 rt rail spalled. Abut 4 north bound approach settlement.
53-1255	405	25.93	JEFFERSON BV U	Damage to bents common with Bridge #53-1851. All ext. col. connection to bent caps 2,3,4 suffered damage. Col #7 @ B2 & B3 suffered the most damage.
53-0704	405	29.85	EXPOSITION OH	Spalls/cracks in Col. 4, 5, 6, 7. Cracks at Bent caps 3, 5, 7.
53-1852F	405	25.91	SOUTH CONN OC	N side spall at hinge seat extender bolster.
53-1629F	405	29.62	NE CONNECTR OC	W. abut. rockers are out of position, keeper plates broken. Metal tube railing at abut. pulled apart & butted against next rail sect. E. abut. 1'x1' spall in safety walkway. Span 3 hinge restrainer damage in Cell 1.
53-0704F	405	29.85	EXPOSITION OH	Bent 1 span 1 has 2" movement toward B2. No damage.
53-1250	405	23.71	LA CIEN BV S O	Abutment bearing damage. Keeper plates sheared off.
53-1630G	405	29.43	SW CONNECTR OC	Abutment rockers and keepers are out of place. Bolster damage.
53-2211	405	46.83	RT 405 118 SEP	Vertical cracks at bent walls. Diagonal cracks at columns. Incipient spalls at abut. shear keys.

53-0740	405	38.59	SEPULVEDA BV U	Spall at the overhang soffit @ B2 (1'x3').
53-1362	405	41.27	W VAN NUYS OH	Minor cracks at abutment 1.
53-1449	405	41.36	VICTORY BV UC	Bearing pad delamination at bent 2 (face of bin abutment).
53-1490	405	36.72	RIMERTON RD OC	Minor damage. Crack in closure wall right side A1.
53-1638G	405	29.42	SEPULVEDA B UC	2' of Sidewalk at N'ly rail broken over east abutment.
53-0706	405	30.18	EXPOSITION OH	Spalls/cracks in Col. 4, 5, 6, 7. Cracks at Bent caps 3, 5, 7.
53-2217H	405	46.64	RT 405 118 SEP	Vertical cracks at bent walls. Diagonal cracks at columns. Incipient spalls at abutment shear.
53-1797L	5	R047.83	GAVIN CANYON U	Spans 2 & 4 collapsed, as of 11:15 AM 1/18/94 bridge being removed.
53-1117	5	34.65	TUXFORD ST UC	Minor damage. Some cracking. Keeper plate bolts sheared at abut 3.
53-1796	5	R46.58	WELDON CYN OC	Light cracks top of column @ bent 2. Minor cracks @ A1, left horiz. cracks top B7 col., incip. corner spall top A3 right, 1/16" diag. crack @ top A3 left (DBR)
53-0687L	5	R53.70	SANTA CLARA R	Abut 1 backwall cracked, both abutments have bearing pad & anchor bolt damage, SE of Abut 8 restrainer cables failed, cracks in all piers (P7 heaviest damage). Some local buckling of stiffeners and cross frames..
53-1989F	5	R 44.01	SW CONNECTR OC	Shear key spalls. Minor spalls at Bents 2 & 3. Insufficient seat width at Abut 1. Superstructure lower than approach. Longitudinal gaps in abuts.
53-1797R	5	R047.83	GAVIN CANYON U	Spans 2 & 4 collapsed, as 11:15 AM 1/18/94 being removed.

53-2329G	5	39.31	SOWEST CONN OC	Abut cracks, approach slab settlement, failed joint seal at N. abut, crack in entire length of col. Girder bearing damage at hinges at span 2 (cells 1 & 5), span 4 (cells 1 & 5) and span 6 (cells 1 & 5). Restrainer damage at span 6.
53-1986	5	R044.43	BALBOA BV OC	Minor column damage, approach slab buckled.
53-1985F	5	R044.01	RTE 210/5 SEP	Minor to moderate damage at both abuts. Shear keys slightly damaged. Spalls at hinge joint.
53-1990G	5	R043.83	SAN FERN RD OH	Approach slab rotation. Joint seals failed (both abuts). Spalls at abut 1. John Bither assigned a tentative B-PS&E of 3/18/94.
53-1128	5	39.19	PACOIMA WASH	Failed columns at B2 & B3, significant column damage on most of the columns of both bents.
53-1548	5	41.55	RTE 5T/405 SEP	Minor cracks at two columns.
53-1068	5	23.66	GLENDALE BV OC	2" horizontal superstructure rotation. Minor sidewalk spalls.
53-0387	5	R50.80	BUTTE CANYON	Spalls and cracks at abutments.
53-0687R	5	R053.70	SANTA CLARA R	Spalls at both abuts. At A8 gir 4 & 5 restrainer cables failed, cracks and spalls in all piers. Some local buckling of stiffeners and cross frames.
53-1815	5	R052.47	VALENCIA BV OC	Abut 1 displaced approx 6" left of orig., Abut 3 is 1" left of orig., spalls at both abuts. 27" water line supports damaged. Damaged roller brgs. Retrofit will not be done by S14, just repairs per Fritz Hoffman 3/9/94.
53-2057	5	R051.44	MCBEAN PKWY OC	Minor spalls at both abutments.
53-1807	5	R056.12	HONOR RHO R OC	Cracks and spalls at abutments and bents. Gdr seats cracked at gdrs #1 & 4.
53-1809	5	R056.60	HASLEY CYN R O	Shear cracks @ B2 on span 1 & 2 sides, both L & R columns.

53-1087	5	29.16	OLIVE AVE OC	Minor spalling at bent joints where there was debris in joints. Broken keeper plate bolts.
53-1088	5	29.39	MAGNOLIA BV OC	Minor pier cap spall under a bearing. Broken keeper plate bolts.
53-1908L	5	R059.49	LK HUGHES R UC	1 1/2 " or less settlement at both approaches.
53-1984L	5	R044.87	W SYLMAR OH	Additional damage to all shear keys and expansion joints due to after shocks.
53-1984R	5	R044.87	W SYLMAR OH	Spalls at hinges and abutments. Shear keys have failed. Additional damage to all shear keys and hinges due to after shocks.
53-1333	5	18.52	ECHANDIA OH	Sheared brg keeper bolts at A1 N. Minor Spalling of R & L Rail at A1.
53-1783	5	R050.33	PICO LYONS OC	Cracks/spalls, bearing & restrainer damage @ abut 1. Severe cracks, cracked girder web & restrainer damage @ abut 3. Minor cracks @ col 2, bent 2. Retrofit will not be done by S14, just repairs per Fritz Hoffman 3/9/94.
53-2330F	5	39.36	NE CONN OC	Restrainer and bearing damage at span 5 (cell 1) and restrainer and diaphragm damage at span 5 (cell 3). Deck spalling @ abutment jts.
53-2346F	5	39.26	PACOIMA WASH	Abut 1 shifted right & spalled 3 ft of concr. near deck level adjacent to WW.
53-1133	5	41.57	RTE 5/405 SEP	Minor cracking at Abut 1 wingwall.
53-1132	5	40.46	RINALDI ST UC	Miinor cracking in soffit near A-1; Several cracks and spalls in lt. and rt. ext. diaphragms at A-1. Right bin wall near B-3 pushed 2" toward A-1. Minor damage at tube rail at abut 1.
53-1130	5	39.98	BRAND BLVD UC	Shear cracks and spalling in both external shear keys at Bts. 2 & 5.
53-1126	5	38.5	VAN NYS BL UC	Apparent broken water line washed out left side of A2 undermining bin walls & 2 LF of pile cap.

53-0848R	5	C045.49	SIERRA HWY SEP	Bearing, shear key and pedestal damage, both abutments. Large deck crack at widening closure pour. Some barrier damage.
53-0730	5	R043.84	SAN FERN RD OH	Internal and external shear key failures. Minor top of column fractures.
53-0848G	5	C045.49	SIERRA HWY SEP	Minor shear key damage at both abutments.
53-1115	5	42.65	ROXFORD ST UC	Minor cracking at left curtain walls and right side of Abut 1 shear key. Minor approach settlement.
53-1181S	5	24.61	GRFTH PK OR OC	Joint seal (Type A) damage at hinge in span 3.
53-2327F	5	39.30	SOEAST CONN OC	Moderate damage at both abutments. Restrainer and bearing damage at span 6 (cells 1 & 4) and span 8 (cells 1 & 4). Bearing damage at span 11 (cells 1 & 4).
53-1332F	5	18.53	ECHANDIA OH	Minor damage. Large diagonal crack in curtain wall at side of A-9. Also incipient spalling. 1' x 1' spall at REOD overhang at abut 9. Minor spall at left rail at abut 1.
53-1316	5	18.38	S CONNECTOR UC	Minor damage. Slight cracks ext. shear keys both A-1 and A-2.
53-1312	5	18.78	MISSION RD UC	Spalling at A1. Rt. diaphram and wingwall joint separated. Wingwall not plumb, top pulled away @ 4". No settlement of app. fill.
53-1359R	5	17.21	HOLLENBECK LAK	A1 bearing keeper plate bolts sheared.
53-0368	5	18.96	ALHAMBRA AV OH	Minor spalls at abut 5 under girders.
53-1317F	5	18.62	MISSION RD R U	A1 backwall moderately spalled - many rocker brg. keeper plates damaged with sheared bolts.

53-1792L	5	R049.03	CALGROVE BV UC	Appr pvmt & shoulder disp. A1 appr lanes settled 2". A1 rt appr shoulder heaved & buckled & PCC shoulder spalled at bridge. A1 Lt appr shoulder AC settled 8" to 12" w/18" voids. A3 rt appr shoulder settled 3". Slope paving damaged.
53-1222K	5	36.34	SHARP AVE ONRP OC	At abutment 4, total 4 locations, the anchor bolts are sheared off for the lower keeper bar for the rocker bearing. There are 3 minor spalls (30cmx30cm area) on the soffit of the EQ restrainer outrigger.
53-1110	5	31.23	BUENA V-WIN UC	No bridge damage. Approach slabs to be replaced EA 1Q7501
53-1118W	5	35.01	LANKERSHIM PP	Hairline Cracks in Backwalls. No damage per Makoto Ogata on 3/9/94.
53-1359L	5	17.21	HOLLENBECK LAK	1' x 2" spall at A1 lt edge of deck. Some exposed reinforcement.
53-1626G	5	R55.48	RTE 126/5 SEP	Cracks at abutment / soffit interface. Minor top of column cracks & spalls. A5 continuous stub wall spall.
53-1424	5	20.31	ELYSIAN VIAD	Minor/mod. Bent 8 shear key has minor spalls.
53-1792R	5	R49.03	CALGROVE BV UC	Appr pvmt & shoulder disp. A1 appr lanes settled 2". A1 rt appr shoulder heaved & buckled & PCC shoulder spalled at bridge. A1 lt appr shoulder AC settled 8" to 12" w/18" voids. A3 rt Appr shoulder settled 3". Slope paving damaged.
53-1625L	5	R53.55	RTE 5 126 SEP	Spalls at both abuts, @ A8 gir 4 & 5 restrainer cables failed, cracks and spalls in all piers. Local buckling of stiffeners and cross frames.
53-1625R	5	R53.55	RTE 5 126 SEP	Spalls at both abuts, @ A8 gir 4 & 5 restrainer cables failed, cracks and spalls in all piers. Local buckling of stiffeners and cross frames.

53-0848L	5	C45.49	SIERRA HWY SEP	Bearing, shear key and pedestal damage, both abutments. Large deck crack at widening closure pour. Some barrier damage.
53-1728	60	R03.88	BELVEDERE POC	Minor spall at top of bent column adjacent to WB Rte 80.
53-1717H	60	R03.26	NE CONNECT OC	Abut 12 Keeper Plate Anchor Bolts Sheared. Rocker Bar Fell Over.
53-0075L	60	R01.26	WHITTIER BV UC	Abutment 1 left shear keys gdrs #4 & 5. spalled sections @ 1'X1'X1.5'. The stiffeners which are connected to the cross bracing at the abutment have moved 0.64 cm (1/4"). The paint on the bottom flange of all girders has flaked.
53-0081	60	R01.48	LORENA ST OC	A1 keeper plate anchor bolts sheared. Same damage at A3.
53-1987F	71	R00.58	E CONNECTOR OC	Crack in support side of hinge @ Bent #2. Crack width is about 0.5" at the top and tapers down to 0" at the bottom. Crack runs vertically 6" from the edge of the hinge seat.
53-1714G	710	24.61	SE CONN OC	No damage per DBR. Steel rockers damaged.
53-1716F	710	24.64	NW CONN OC	No damage per DBR. Steel rockers damaged.
53-1851	90	2.54	RTE 90 405 SEP	Numerous shear cracks and some spalling at common bent with Br #53-1255. Multicolumn bent @ median has damage to top of bent caps on transverse internal shear keys. Cracks/spalls at portion of bent cap face adjacent to keys.
53-1854G	90	2.55	NW CONNECT OC	Minor abutment spalls. No damage per Makoto Ogata on 3/9/94.
53-1855F	90	2.73	JEFFERSON B UC	Minor damage - barrier rail pipe@ hinge slipped out of sleeve.
53-2240	91	R011.64	RTE 91/710 SEP	Minor rail and WW damage due to skewed south. abutment. Rail pocket spalls, a 4" bow in 20' metal rail; a 1' x 1' spall in upper corner of SW wingwall, and a 1/2" crack at bot of ext gdr @ 2' long. (DBR)

DAMAGE TO BRIDGES WITH SEISMIC RETROFITS.

Date of Retrofit	**Superstructure Stability**	**Substruct. Strength**	**Substruct. Ductility**	**Substruct. Stiffness**	**Bridge Energy**
OLD <1989	Restrainers Shear Keys Bearing Replacements Catcher Blocks			Isolation	Dampers Fuses
NEW >1989	Pipe Seat Extenders	Footing & Abutment Retrofits *(tiebacks, large piles, Waffle Slabs, etc.)* Column Retrofits *(Shear Walls & Super columns)*	Steel Column Shells Column Fiber Wraps	Abutment Retrofits	

Table 7.3. Summary of Seismic Retrofit Strategies

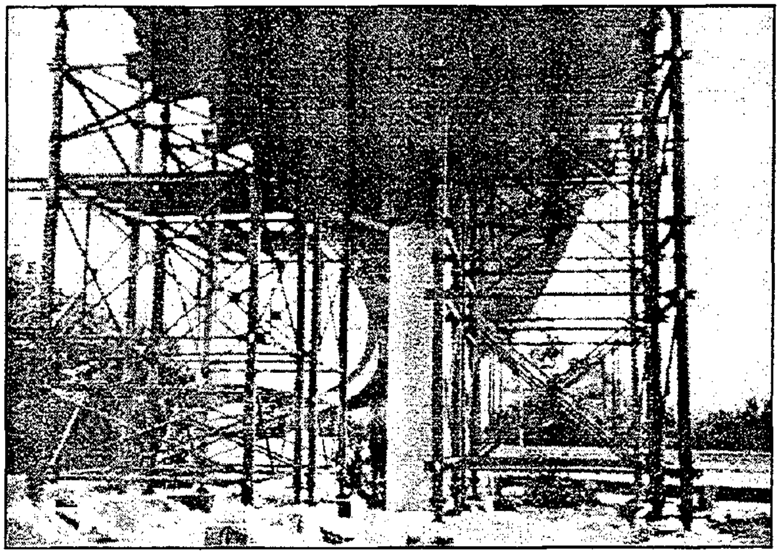


Fig 7.21. Damage to the Southeast Connector Overcrossing

After the 1971 San Fernando Earthquake, Caltrans' began its Phase 1 bridge seismic retrofit program. The primary purpose of these retrofits was to prevent the superstructure from falling off of its supports. After the 1989 Loma Prieta Earthquake, Caltran's began its Phase 2 seismic retrofit program. These retrofits addressed a wider range of problems and were more sophisticated in their approach. The Phase 2 retrofit program specifically addressed the problem of nonductile columns. Since Caltrans' retrofit program would require several pages to even marginally describe, interested readers should investigate the references in the back of this report (Yashinsky 1995). Table

7.3 indicates what retrofit strategies are available and when they began being used. About halfway through this second retrofit program, the 17 January 1994 Northridge Earthquake occurred. There were 132 bridges in the area of shaking that had a post San Fernando earthquake retrofit. Several of these bridges suffered major damage including Gavin Canyon Bridge and portions of the 14/5 Interchange. There were at least 80 bridges in this same area that had a post Loma Prieta Retrofit. None of these bridges suffered significant damage. The most serious damage was on the Southeast Connector OC (Bridge #53-1637F). This is a long, tall, prestressed concrete bridge with a retrofit that includes steel shelled columns and restrainer and abutment work. The bridge has hinges supported on columns (see figure #21). During the earthquake, the restrainers holding the hinge together smashed the hinge diaphragm and surrounding concrete. The bridge was closed to traffic until shoring was provided around the column. However, the retrofit may have prevented more serious damage from occurring. Bridges with a Phase II retrofit performed very well. If the second retrofit program had been completed at the time of the Northridge Earthquake, it is likely that only 1 or 2 bridges would have suffered severe damage.

DAMAGE TO CITY AND COUNTY BRIDGES

In contrast to the many state owned bridges that suffered damage, there was very little damage to any city or county bridge during the Northridge Earthquake. This may have been because, in general, state bridges tend to be longer, taller structures.

EMERGENCY RELIEF PROJECTS

PROJECT # REPORT #	EA	DT	AGENCY	CO-RTE-PM	LOCATION	F.CLASS	ON FED HWY?	EST ER OPENING AMT	ESTIMATED RESTORATION AMT			TOTAL ESTIMATED AMT	TOTAL OBLIGATED AMT
									PE	CE	CONST		
ER-2800(008) MN-LACO-1	928894	07	Los Angeles County	LA - 0 - CRS	McBEAN PARKWAY OVER SANTA CLARA RIVER (1.20 MILES E OF I-5) Bridge	U-MA	yes	530,000				530,000	496,400
ER-2800(008) MN-LACO-2	928895	07	Los Angeles County	LA - 0 - CRS	SIERRA HWY, (NB); 0.5 MI S OF SOLEDAD CANYON RD. OVER SPTC. Sierra Hwy OH bridge.	U-OPA	yes	5,000	10,000	15,000	100,000	130,000	17,705
ER-2802(010) MN-LACO-5	927551	07	Los Angeles County	LA - 0 - CRS	WHITES CNYN RD BRIDGE OVER SANTA CLARA RIVER & OVER SPTC. ALSO VIA PRINCESSA ; SIERRA HWY TO MAY WAY.	U-MA	yes	105,120				105,120	105,120
ER-2801(008) MN-SCla-1	928911	07	Santa Clarita	LA - 0 - SCTA	SAND CANYON RD. BRIDGE APPROACHES OVER SANTA CLARA RIVER.	R-MJC	yes	325	312	468	3,122	4,227	
ER-2801(010) MN-SCla-1	928912	07	Santa Clarita	LA - 0 - SCTA	SIERRA HWY 500' S SOLEDAD 500' N SOLEDAD; RR BRIDGE; BRIDGE OVER SANTA CLARA RIVER	U-OPA	yes		1,254	2,055	12,545	15,854	
ER-2800(030) MN-LA-3		07	Los Angeles	LA - 0 - LA	WILBUR: ENTIRE LENGTH, bridge	U-MA	yes	50,000	14,059	21,088	90,591	175,738	
ER-2800(001) MN-LA-1	928921	07	Los Angeles	LA - 0 - LA	NORDHOFF ST. BRIDGE OVER SP RR TRACKS BETWEEN CORBIN AVE. & TAMPA AVE.	U-OPA	yes	587,000				587,000	278,800
ER-2800(022)	928923	07	Los Angeles	LA - 0 - LA	WILBUR AVE. @ COLLINS ST. PEDESTRIAN OVERCROSSING.	U-MA	yes	84,700				84,700	84,100
ER-2800(002) MN-LA-7	928983	07	Los Angeles	LA - 0 - LA	AVE 43 BRIDGE OVER ARROYO SECO CHANNEL & PASADENA FWY.	U-MA	yes		300	400	3,000	3,700	91,412
ER-2800(004) MN-LA-1	928984	07	Los Angeles	LA - 0 - LA	BALBOA BL (EAST RDWY) BRIDGE OVER LA RIVER BETWEEN VICTORY BL AND BURBANK BL.	U-OPA	yes		1,000	1,500	10,000	12,500	
ER-2800(005) MN-LA-2	928985	07	Los Angeles	LA - 0 - LA	DEVONSHIRE ST BRIDGE OVER PACOIMA WASH DIVERSION CHANNEL AT ARLETA AV.	U-OPA	yes		1,500	2,200	15,000	18,700	32,085
ER-2800(006) MN-LA-3	928986	07	Los Angeles	LA - 0 - LA	FRANKLIN AV BRIDGE BETWEEN ST GEORGE ST AND MYRA AV.	U-MA	yes		1,500	2,200	15,000	18,700	
ER-2800(007) MN-LA-1	928987	07	Los Angeles	LA - 0 - LA	GRAND AV BRIDGE BETWEEN 2ND PL AND 4TH ST	U-OPA	yes	1,600	5,500	8,250	55,000	70,350	0
ER-2800(008) MN-LA-4	928988	07	Los Angeles	LA - 0 - LA	LA TIJERA BL BRIDGE OVER SPRR & CENTINELA CREEK BETWEEN THORNBURN ST. & SAN DIEGO FWY.	U-OPA	yes		2,300	3,450	23,000	28,750	0
ER-2800(009) MN-LA-4.1	928989	07	Los Angeles	LA - 0 - LA	LINDLEY AV BRIDGE OVER LA RIVER BETWEEN VICTORY BL AND ERWIN ST.	U-MA	yes		1,660	2,490	16,600	20,750	82,774
ER-2800(010) MN-LA-2.1	928990	07	Los Angeles	LA - 0 - LA	MAGNOLIA BL BRIDGE OVER TUJUNGA WASH BETWEEN BELLAIRE AV AND COLD WATER CANYON.	U-MA	yes		928	1,392	9,280	11,600	0
ER-2800(011) MN-LA-9	928991	07	Los Angeles	LA - 0 - LA	MASON AV BRIDGE OVER LA RIVER BETWEEN HART ST AND VANOWEN ST	U-MA	yes	1,000	3,000	4,500	30,000	38,500	34,349
ER-2800(012) MN-LA-5	928992	07	Los Angeles	LA - 0 - LA	NATIONAL BL (NORTH) BRIDGE OVER BALLONA CREEK @ JEFFERSON BL.	U-OPA	yes		2,000	3,000	20,000	25,000	
ER-2800(013) MN-LA-3	928993	07	Los Angeles	LA - 0 - LA	RESEDA BL BRIDGE OVER LA RIVER BETWEEN KITTRIDGE ST AND VICTORY BL.	U-OPA	yes		880	1,320	8,800	11,000	0
ER-2800(014) MN-LA-8	928994	07	Los Angeles	LA - 0 - LA	SAN FERNANDO RD BRIDGE OVER TUJUNGA WASH BETWEEN TRUESDALE ST AND BRANFORD ST.	U-OPA	yes	1,000	2,300	3,500	23,500	30,300	
ER-2800(015) MN-LA-7	928995	07	Los Angeles	LA - 0 - LA	TAMPA AV BRIDGE OVER LA RIVER BETWEEN KITTRIDGE ST AND VICTORY BL.	U-OPA	yes		2,000	3,000	20,000	25,000	
ER-2800(016) MN-LA-6	928996	07	Los Angeles	LA - 0 - LA	VANOWEN ST BRIDGE OVER LA RIVER BETWEEN OSO AV AND MASON AV.	U-OPA	yes		2,800	4,200	28,000	35,000	
ER-2800(017) MN-LA-6	928997	07	Los Angeles	LA - 0 - LA	WHITE OAK AV BRIDGE OVER LA RIVER BETWEEN VICTORY BL AND ERWIN ST.	U-OPA	yes		500	750	5,000	6,250	
ER-2800(018) MN-LA-3	928998	07	Los Angeles	LA - 0 - LA	WINNETKA AV BRIDGE OVER LA RIVER BETWEEN ARCHWOOD ST AND GILMORE ST	U-OPA	yes		800	1,200	8,000	10,000	0
ER-2800(020) MN-LA-10	927530	07	Los Angeles	LA - 0 - LA	BARHAM BLVD. BRIDGE OVER LA RIVER	U-OPA	yes	148,000				148,000	148,000
ER-2800(021) MN-LA-11		07	Los Angeles	LA - 0 - LA	VICTORY BLVD. BRIDGE OVER LA RIVER BET. LINDLEY & ETIWANDA AVE.	U-MA	yes		3,440	5,160	34,400	43,000	
ER-2804(003) MN-VEN-1	928975	07	Ventura County	VEN - 0 -	SANTA SUSANA PASS ROAD BRIDGE AT RAIL ROAD.	R-MA	yes		1,200	900	9,500	11,600	11,600
							Statewide Summary:	$1,493,745	$59,233	$88,023	$540,338	$2,186,339	$1,382,345

Table 7.4. List of Local Agency Bridges Eligible for Federal Funds.

Only 4 local bridges suffered any significant damage from the earthquake. The most serious damage occurred to Wilbur Avenue Pedestrian Overcrossing (Br. #53C-1387). This reinforced concrete, box girder bridge is 3 miles south of the epicenter in the town of Tarzana. During the earthquake the bottom of the columns were severely distressed and it appeared that a few more cycles of movement would have caused collapse.

The Sierra Highway OH (Br. # 53C-1776R) is an older concrete T-beam Bridge. It was retrofit with cable restrainers at the hinges. During the earthquake, a restrainer broke, and the end diaphragms, which sat on footings, were smashed.

McBean Parkway (Br. #53C-1840) is a precast I girder bridge on pier walls and seat type abutments. During the earthquake the superstructure smashed through the backwall and about 6 inches into the soil.

The Old Road Bridge (Br. # 53C-0327) had large steel plate girders attached to deep floor beams on pinned bearings. During the earthquake, one floor beam buckled and the other floor beam tore the bearings out of the piers.

DAMAGE TO STEEL BRIDGES

There were several steel bridges that experienced damage during the Northridge Earthquake. Most of this damage was from the superstructure banging against the abutments. In many cases damage to anchor bolts and bearings also occurred. Better connection details between steel superstructures and concrete substructures may eliminate some of this damage. As mentioned above, there was also a tendency for the steel floor beams to experience distress during the earthquake. All the seismic force is transferred by these diaphragms into the substructure.

The Santa Clara River Bridge (Br. #53-0687L) is a highly skewed, 741 foot long, 7 span structure. During the earthquake, many of the anchor bolts connecting the girders to the concrete piers pulled out (see Fig 7.22). There was also banging and spalling of the abutments. The most interesting damage was cracking of the girders where they connected to the cross frames. The cross frames were staggered due to the bridges skew. These cracks were probably initiated through fatigue and propagated by the earthquake. It has long been known that staggered cross frames are a serious maintenance problem for steel bridges. Pico-Lyons Overcrossing (Br. #53-1783) is a 2 span continuous plate girder bridge. During the earthquake the restrainers, anchor bolts,

Fig. #7.22. Santa Clara River Br.

and bearings were damaged. Other bridges with very minor damage include McBean Parkway OC (#53-2057), Valencia Blvd. OC (#53-1815),and the Old Road Bridge mentioned above. More detailed information on the performance of steel bridges during the Northridge Earthquake can be obtained from a report by Professor Astaneh-Asl of the University of California (Astaneh-Asl 1994).

SOIL BEHAVIOR RELATED TO BRIDGE AND HIGHWAY DAMAGE

In general, it appears that weak soil was not a significant factor in causing bridge damage during the Northridge Earthquake. The one exception was at the Santa Monica Freeway where softer soils may have amplified the earthquake motion. In general, the bridge sites were on medium sands over denser sands and sandstone. There were some layers of clay and silt at Route 118. However, weak soils did not play anywhere near the role they did during the Loma Prieta Earthquake.

HIGHWAY DAMAGE

There was a great deal of highway damage as a result of the Northridge Earthquake. As of May 1994, 122 million dollars was spent on highway repairs compared with 144 million in bridge repairs. The highway costs included repair of the many bridge approaches that settled during the earthquake. The area of highway damage was even more widespread than the area of bridge damage, extending north of Castaic on I-5, south on Highway 405 to Ballona Creek, west on Route 126 to Fillmore, and east on Route 14 to Santa Clarita. Much of the damage was highway slabs that buckled due to soil settlement and road slip outs caused by landslides. There was also damage to drainage pipes and culverts under highways. Highway 2 near La Canada had to be cleared of several minor landslides. A portion of Route 126 at the Los Angeles/Ventura County line was built on an ancient slide that required periodic regrading after the earthquake. The most serious damage was settlement of bridge approaches, particularly on Highway 118. Other damage included soil heaves on I-5 from Castaic to the Hollywood Freeway. There was also a slip out on I-5 on the 5 mile grade near Castaic. This caused highway damage and many of the drains under the highway were damaged. On Route 14 both north and south of I-5 the roadway buckled and was later covered with an asphalt blanket. There was a slough under a portion of Highway 14. At highways 405 and 5 in Granada Hills the pavement slabs buckled. There was a great deal of damage to the Santa Monica Freeway due to soil movement. There was also a great deal of damage to city and county roads. There was a landslide on the Sierra Highway maintained by Los Angeles County near the 5/14 Interchange. Approximately 5 miles of the Santa Susana Pass Road maintained by Ventura County east of the Southern Pacific Station Museum was torn up. Automobile sized boulders were reported on the roadway and large sections of the road slid off. The approaches to the Nordoff Street OH owned by the City of Los Angeles settled several feet.

BRIDGE REPAIR AND REPLACEMENT

After the earthquake, many of Los Angeles' major traffic arteries were closed. Interstate 5, the major connector of northern and southern California was down, as well as a portion of Interstate 10, the world's busiest freeway. It was imperative to get the transportation system up and running as soon as possible. There were several factors that helped Caltrans quickly reopen damaged highways after the Northridge Earthquake. Many lessons had been learned repairing bridge and highway damage after the Loma Prieta Earthquake. A great deal of the credit goes to the head of Caltrans' Structures Division. Having steered Caltrans through the Loma Prieta Earthquake 4 years before, Caltrans' Chief Bridge Engineer provided the experience to overcome many obstacles. Other factors included:

COOPERATION BETWEEN AGENCIES

There was an effort by the Federal Government, the Governor's Office, and by the City of Los Angeles to work closely with Caltrans to expedite all details of reconstruction. The Governor immediately toured the area and signed emergency executive orders to override the usual lengthy contract process for construction. The federal government quickly evaluated the extent of bridge and highway damage and made funds available. All participating agencies met together daily to receive updated information, plan strategies, and take the newest information back to their offices. A Caltrans engineer worked in LADOT's emergency center and an LADOT engineer worked in Caltrans traffic management center so that detours would match current highway reconstruction.

ESTABLISHING DETOURS

LADOT did an excellent job of creating detours from the closed highways onto city streets. They restriped roads, and added traffic signals to control a 200 percent increase in road use. Helicopters and video cameras monitored traffic while message signs alerted drivers to changing conditions. An Automated Traffic Surveillance and Control (ATSAC) system automatically changed the timing of traffic signals to accommodate the number of vehicles. Special, more direct routes around damaged highways were created, but limited to high occupancy vehicles. This reduced the amount of vehicles on heavily congested roads.

ACCELERATED DESIGN PROCESS

As soon as a bridge was identified for repair or replacement, a project manager was given the job of producing a set of bridge plans, specifications, and estimates (PS&E). A peer review panel was established to oversee all the designs and to ensure that they met the current seismic criteria. In all cases, these designs surpassed current criteria and incorporated many of the lessons being learned from Northridge (see the next section, Code Implications). To expedite the design, the projects were given to a Caltrans engineer or to a consultant. On some projects, both a concrete and a steel bridge alternative were designed to give contractors the widest possible choice in submitting a bid. In a few cases, a design/build contract was awarded.

EMERGENCY CONTRACTS

Instead of the lengthy bid advertising process, Caltrans preselected experienced contractors who had agreed to work on only one emergency contract. They were asked to submit bids within hours or days after the PS&E package was produced. Also, incentive/disincentive contracts were written to expedite early completion of bridge construction. The winning contractors typically reduced their bid amount to reflect the number of days they felt they could reduce construction time. For instance, 140 days was the time allowed for reconstruction of the bridges on the Santa Monica Freeway. If a contractor thought construction could be completed in 130 days, the bid could be reduced by 10 times $200,000 or 1 million dollars. The contract was awarded to the bid with the lowest (A: Construction cost) + (B: Number of days to completion times the incentive/disincentive). These contracts included commitments to obtain a goal of 20 to 40% participation by disadvantaged businesses (DBE's). C.C. Meyers was awarded the first contract for repair of the Santa Monica Freeway with a bid of $14.9 million and a DBE participation of 42.7%. He completed the contract in 66 days by excellent project management, use of lots of equipment, and round the clock construction. On April 11, 1994, the Governor reopened the Santa Monica Freeway. By November 4th, 1994 all the highways closed after the Northridge Earthquake had been reopened to traffic.

PROJECT	INCENTIVE/ DISINCENTIVE
Santa Monica	$200,000/day
Gavin Canyon	$150,000/day
5/14 (major)	$100,000/day
5/14 (minor)	$20,000/day
118	$50,000/day

Table #5. Incentive/Disincentive Contracts

CODE IMPLICATIONS

Changes to the Caltrans seismic bridge code may come from Caltrans' continuing research program, from bridge engineers developing better analyses procedures, seismic designs and retrofit strategies, or from geotechnical engineers and seismologists developing more realistic earthquake forces. However, all of this work is stimulated by careful studies of bridge damage after powerful earthquakes.. Not only does this give engineers an understanding of how existing bridge designs perform, but it gives insight into where new research should be directed. For instance, Caltrans has long been interested in the performance of flared columns during earthquakes. However, actual damage during the Northridge earthquake provided the impetus for Caltrans to continue research on flared columns. Thus, a cyclical push over test of a flared columns, better analysis procedures for flared columns, and a study of how to improve the architectural features of columns began, in part, because of the Northridge Earthquake.

After the 1971 San Fernando Earthquake, and at the direction of the FHWA, the Applied Technology Council (ATC) formed a group to look at seismic bridge specifications and recommend changes to improve bridge safety for earthquakes. These recommendations are commonly referred to as ATC6. They were studied by engineers and many of the recommendations were adopted nationally and by Caltrans.. After the 1989 Loma Prieta Earthquake, Caltrans funded the ATC to study Caltrans specifications and design procedures and to propose new changes. This is known as the ATC32 Project. However, the work of the ATC32 Committee has not been completed. Lessons learned from the Northridge Earthquake will no doubt be incorporated into the ATC32 document.

Also, after the Loma Prieta Earthquake, the governor recommended the establishment of a Seismic Advisory Board made up of scientists and engineers outside of Caltrans to provide input into the Caltrans current seismic design procedure. The establishment of criteria for 2 levels of design for important bridges, a safety evaluation using the maximum credible earthquake, and a serviceability evaluation using a smaller, probability based earthquake, came from recommendations of this Board.

The basis of Caltrans Bridge Design Specifications is the American Association of State Highway and Transportation Officials (AASHTO) Standard Specifications for Bridges. However, other criteria were added by Caltrans that reflects the much larger and more frequent earthquakes that devastate California. This includes higher response spectra, a map of California giving peak ground accelerations, and methods for determining the demands and capacities of bridge members for earthquakes. Not all seismic code requirements find their way into Bridge Design Specifications. Recommended seismic practice is also outlined in Memos to Designers. For instance, recommendations for seismic retrofit design and joint shear requirements are in Memos to Designers Section 20-4. Chapter 14 of Bridge Design Aids includes instructions for modeling bridges for seismic analysis, instructions for designing earthquake restrainers, minimum hinge seat widths for earthquakes, and several other earthquake issues. Other earthquake requirements never make it into a manual but are incorporated into computer programs used by designers. Procedures for obtaining spring stiffnesses for foundations, for modeling the nonlinear behavior of bridge foundations, and obtaining the displacement capacity of columns, beams, and frames are found in various computer programs.

Thus, proposed changes to Caltrans seismic bridge code may come from many sources, may be reviewed by several groups, and may end up in a variety of media. However, the impetus for most new criteria comes from large earthquakes like Northridge. These earthquakes are the final arbiters of Caltrans seismic codes and procedures.

AREAS OF STUDY

The Northridge Earthquake validated much of Caltrans' current seismic procedures. In particular, current retrofit strategies performed very well during Northridge. However, the Northridge Earthquake also provided some new areas of concern and new ideas for retrofit and new bridge design. Some of these ideas Caltrans has been dealing with for a while. Others have shifted in importance due to the earthquake. Still other ideas Caltrans is just beginning to consider. Such is the nature of progress. In the last 20 years Caltrans made a major effort to provide sufficient ductility to bridge members. Now the Northridge Earthquake has put an emphasis on understanding bridge system behavior, the effect of vertical accelerations on bridges, and some problems with skews and other geometric issues. The following are proposed design revisions developed by Caltrans design and seismic engineering staff. It should be understood that the final revisions may differ significantly from these proposals.

BALANCING MEMBER STIFFNESSES

Much effort was spent on this issue after the Northridge Earthquake. In particular, the original structures on the 5/14 Interchange had problems with stiff columns adjacent to more flexible columns attracting very large forces. Caltrans wanted to make sure that problem wasn't repeated in the replacement structures. What makes this difficult, of course, is that length plays such a significant role in column stiffness ($k=L^3/nEI$.). This problem was solved for 5/14 by varying the length and width of columns with drilled shaft foundations and using 'isolation casings' to give the columns more equal stiffness (see Figure 7.3).

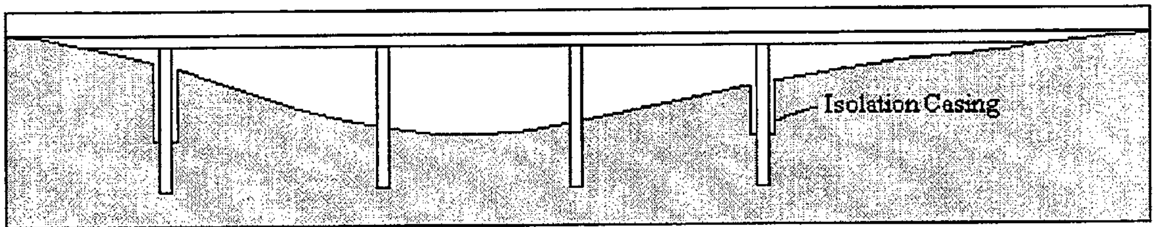


Figure 7.23. Maintaining Constant Column Stiffness by Using 'Isolation Casings'.

Another method was used to balance column stiffnesses on the Alemany Interchange Retrofit Project. In that project, isolation bearings were placed on stiff columns to change substructure stiffness and maintain a similar response between columns. In general this problem is being addressed with the following proposals.

1: Keep all column stiffnesses in a frame approximately equal. Keep all column stiffnesses in a bent approximately equal.
2: Use isolators or sliding bearings on short, stiff columns next to an abutment.
3: Develop procedures for determining effective moments of inertia for columns during earthquakes.
4: Make a better determination of actual column stiffness by studying the as-build condition of the bridge. This would include consideration of superelevations, type of pin or moment connection, differences in soil stiffness, column flare and other architectural elements, and location of curbs, barriers, and other nonstructural elements.
5: This issue goes hand in hand with establishing ductility levels on a bridge. If stiff columns are unavoidable at a location, then higher ductilities must be used to handle the increased demand at that location.
6: Engineers must present their preliminary bridge design before a group of experienced bridge engineers. The engineer should use these Type Selection Meetings to discuss balancing member stiffness and to develop strategies for maintaining similar flexibilities throughout the structure.

VERTICAL GROUND MOTIONS

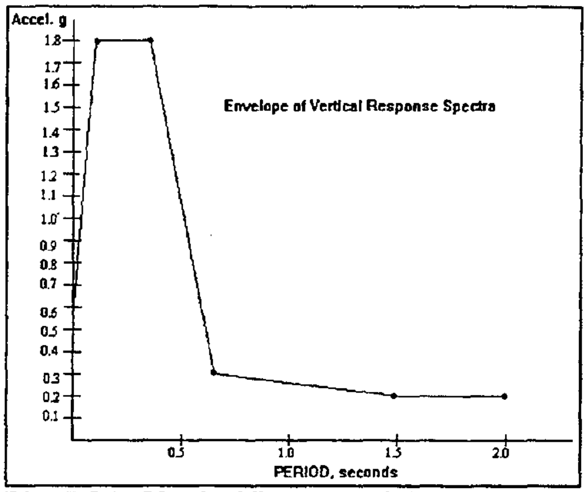


Fig. 7.24. Vertical Response Spectra

High levels of vertical acceleration were recorded during the Northridge Earthquake. This was in a frequency range that could excite structures to ductilities of 2 or higher. The high vertical acceleration usually was accompanied with very large horizontal shaking. This high vertical acceleration appears to be related to the near field behavior of thrust faults. Since blind thrust faults may be a problem for California, it may be prudent to develop some criteria to deal with them. A vertical response spectra was used for the replacement of the 5/14 Connector OC Bridge #53-2795G (see figure 7.24). This vertical response spectra has a maximum acceleration of 1.8g for short periods between 0.1 to 0.35 seconds. It is an envelope of 5 vertical acceleration records obtained during the Northridge Earthquake. No decision has been made so far on including this type of response spectra in a future bridge code. Caltrans recommended that engineers working on the 5/14 Interchange Replacement Project also design the superstructure for a vertical force of 1.5g in an upward direction and 0.5g in a downward direction. Moments and shears for this loading were combined with moments and shears for an unfactored dead load and compared to all other loading cases. The superstructure was designed for the critical loads. End conditions were carefully considered so that if a bridge had a seat type abutment, the end condition would be a cantilever for the upward direction. However, tiedowns should probably be provided where uplift is a problem. The moment capacity of columns would also be much lower as the axial load becomes smaller. Areas that are especially vulnerable for vertical loads would be Outriggers, C-Bents and very long spans. The end result of all of this was the addition of a nominal amount of mild steel being placed in the soffit near the supports and the top deck at midspan for superstructure moments caused by upward vertical loads. Other areas that should be examined are the bent cap to superstructure connection, girder stirrups, and bearing devices. It is proposed to have an additional Group VII load case as shown below:

Proposed EQ Load Case 3 = 1.0(DL) + 1.0(Vert. ARS) + 0.3(Long. ARS) + 0.3(Trans. ARS)

COLUMN FLARES

This was an area of concern before the Northridge Earthquake although no damage had at that time occurred due to flares. The problem was that engineers had long assumed that the flare was a non-structural element that would spall off during an earthquake. In reality the flare, was reducing the length of the column and increasing the plastic shear demand. A 2 inch gap between the soffit and the flare was one solution used to address these problems (see Fig 7.25). However, testing at the University of California at San Diego showed that a 2 inch gap was too small and caused a high strain in the longitudinal steel. A 3 prong approach is being used to address this problem. The first is to develop a simple procedure for designers to use to determine the plastic moment, shear, and hinge location for flared columns. This would require considering different plastic hinge locations on the flare. The plastic hinge will form at the location that results in the smallest

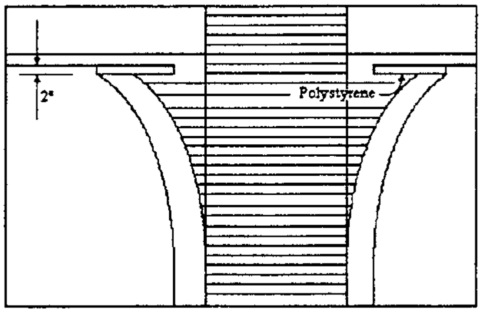


Fig 7.25. Old Column Flare.

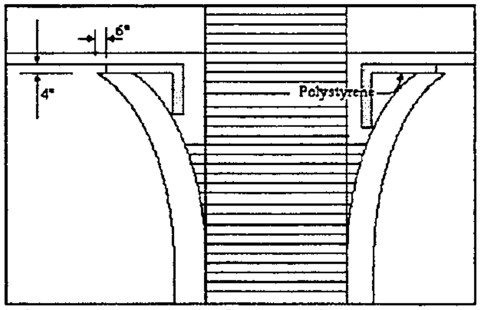


Fig 7.26. New Column Flare.

plastic shear. A second approach is a research project to test different flared columns and validate their behavior. The third step is to develop better flared column details. Fig 7.26 shows one proposed flare detail. A research project at the University of California at San Diego on Architectural Concrete and Bridge Columns is also developing architectural details that improve the seismic performance of columns. Alternatively, Caltrans' architects are evaluating ornamental facades for bridges using nonstructural material that should not affect bridge behavior during earthquakes.

SKEWS

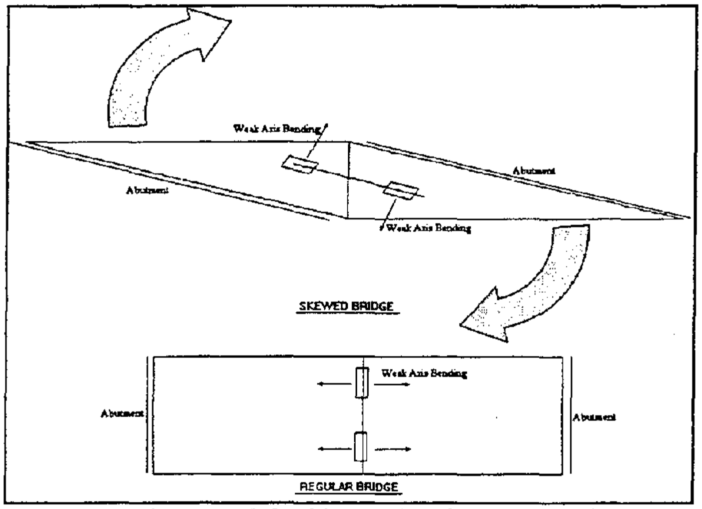


Figure 7.27. Skewed Bridge Behavior.

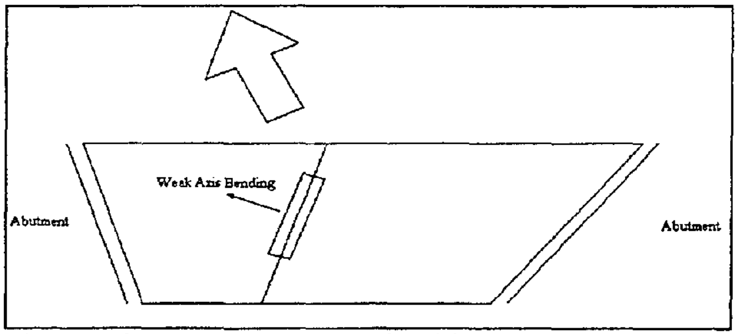


Figure 7.28. Opposite Skewed Bridges.

Highly skewed bridges can cause problems during earthquakes. Skewed bridges are extremely weak for one direction of rotation. In Figure 7.27, the abutments of skewed bridges are very stiff in the counterclockwise direction but have very little stiffness in the clockwise direction.. This clockwise rotation will cause the superstructure to slide out of its abutment seat. Also the columns of skewed bridges experience more biaxial bending during earthquakes. Finally, there is some question as to how effectively the current modeling procedure for bridges captures skew behavior. Possibly using 2 beam members or a grid to represent the superstructure would give more realistic displacements and forces for earthquake loads. This is the recommendation of the new LRFD AASHTO Specifications currently under review. Certainly the partial collapse of the Gavin Canyon Bridges shows a need for better analysis techniques for skewed bridges. Whenever possible, skew should be eliminated or made as small as possible. Also, seat type abutments and hinges should be avoided or provided with much larger seats for bridges with high skews. Also, bridges with abutment skews in opposite directions (see figure #28) like Mission Gothic Undercrossing should be avoided since they are extremely weak in one direction of movement.

IMPROVED ABUTMENT DESIGN

Very flexible abutments allow more of the earthquake force to go to the columns. Seat type abutments may have contributed to bridge damage at several locations during the Northridge Earthquake. For many years, Caltrans has discouraged using end diaphragm abutments due to a history of maintenance problems. Since the Loma Prieta Earthquake, retrofits that attach large diameter CIDH piles to abutments to give them added strength, stiffness, and ductility have been used. A proposed new abutment design improves on this pile retrofit concept. This new design separates the lateral load supports from the vertical load supports of the abutment. The goal is for the large pileshafts to take the lateral force leaving the abutment wall undamaged. The design provides about 12 inches of pile shaft movement before the backwall is engaged. This new abutment design was used on the replacement bridges at the 5/14 interchange.

IMPROVED HINGES

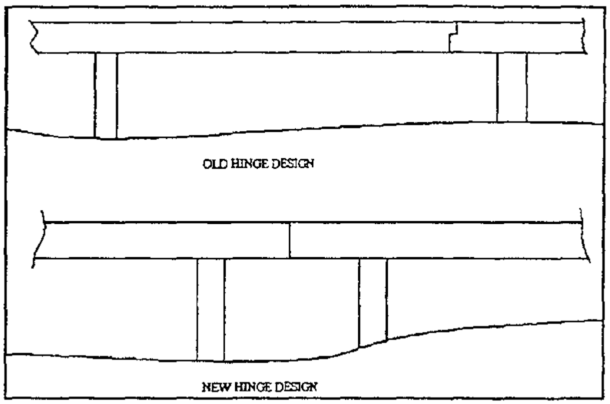


Figure 7.29. Old and New Hinges.

Hinges have long been a problem for Caltrans. The phase 1 retrofit program began after the 1971 San Fernando Earthquake to prevent large hinge movements with cable and rod restrainers. These retrofits had some success in controlling large movements during the Northridge Earthquake. But the current hinge design makes it extremely difficult to make repairs and replace damaged bearings. Newer, more repairable hinge details are being developed. Another new expansion joint design provides much better seismic response with no danger of unseating (see figure 7.29). This new design was used on a replacement bridge in the 5/14 interchange. This hinge may be particularly appropriate at locations where large displacements are expected.

OTHER ISSUES

There are many other issues related to bridge analysis and design that the Northridge earthquake has raised. Issues relating to superstructure design such as cap to superstructure connections, flexural reinforcement for prestressed bridges, and superstructure joint shear are being examined. Research into earthquake force issues such as faulting, site specific response spectra, and near field events are being studied. Other code related issues include hinge restrainers, pier walls, bent caps, footings, piles, and ductility factors.

CONCLUSION

This is an extremely brief report on a very complicated subject. Much more information exists in the many large reports that have come out since the earthquake. In particular, the reports by the Earthquake Engineering Research Institute (Hall 1994), the Earthquake Engineering Research Center (Moehle 1994), the National Center for Earthquake Engineering Research (Buckle 1994), the National Institute of Standards and Technology (Todd 1994), and Caltrans' Post Earthquake Investigation Team (Zelinski 1994) provide much more insight into bridge behavior during the Northridge Earthquake. A report by the University of California at San Diego provides results of structural analyses performed on many of the damaged bridges (Priestley 1994). A report on the performance of steel bridges was prepared by the University of California at Berkeley (Astaneh-Asl 1994). Strong ground motions are essential in understanding bridge behavior and highway damage during the earthquake. We were fortunate to have records from California's Department of Mines and Geology (Shakal 1994), the US Geological Survey (Porcella 1994), and from Los Angeles Department of Water and Power (Lindvall 1994). Japanese engineers are equally concerned with bridge and highway damage from earthquakes and several fine reports have been produced in Japan (Goto 1994) (Ohmachi 1994).

Severe bridge damage from the Northridge Earthquake fits into 2 categories. In general, damage caused by columns with inadequate lateral reinforcement was prevalent. However, severe damage also resulted from bridge geometry that exacerbated existing weaknesses. This damage was caused by:

- Short stiff columns next to long flexible columns in the same frame or in the same bent.
- Skewed bents and abutments that caused bridge frames to rotate off of their supports.
- Abutments with opposite skews that forced bridge movement in a weak direction.
- Column flares that significantly increased the plastic shear and stiffness of columns.

- Conditions such as columns cast into slabs that make one bent much stiffer than the other bents.

Many of these failures could have been prevented by using seismic retrofit strategies that existed at the time of the Northridge Earthquake. However, Bull Creek and Mission Gothic point to areas that may require more study. These bridges were reviewed and taken out of the retrofit program before the Northridge Earthquake. Better screening methods are needed to identify bridges that can suffer severe earthquake damage. As built conditions need to be more carefully studied before a seismic retrofit is begun. Also, better analysis tools are needed to capture the behavior of skewed bridges, flared columns, and other geometric anomalies that may cause higher than expected loads on bridge members.

Since the 1971 San Fernando Earthquake, the seismic safety of bridges has been a high priority at Caltrans. Caltrans has been funding research to answer many of the questions raised by Northridge and other earthquakes. Caltrans is not waiting for the formal completion of a code document before going ahead with the important work of making its bridges safer for earthquakes. As soon as research is completed on any of the issues discussed in this report, Caltrans shares that information with its engineering staff. Classes, informal discussions, workshops, papers and phone calls go back and forth between researchers and engineering staff to improve the safety of new and retrofit bridge design. This allows Caltrans to test new ideas in actual practice to see if they are practical. Peer Review Panels and Caltrans' Seismic Advisory Board carefully monitor decisions, seismic retrofits, and new bridge designs. Before any bridge is built, a type selection meeting is held with participation from The Office of Earthquake Engineering to make sure that the latest criteria is being used and that the general plan reflects a safe seismic design. All seismic retrofits must go through a similar strategy meeting where the analysis and final retrofit are closely examined.

A new improved code and design procedure is gradually taking shape through work by researchers, the ATC32 Committee, and with input from Caltrans engineers and the Seismic Advisory Board. Thus, new designs and retrofits will take advantage of the lessons learned from Northridge and the other earthquakes that Caltrans has carefully studied both in California and around the world.

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8. RAILROADS

BACKGROUND

The Sante Fe Railroad (SF) currently owns approximately 300 miles (483 kilometers) of track in the Los Angeles (LA) basin, none of which is located in the San Fernando Valley. Most of the track that was previously owned by SF has been purchased by local transit agencies.

The Southern Pacific Railroad (SP) currently has 3 main routes in the area: Burbank to Santa Barbara; Saugus to Ventura; and downtown LA to Santa Monica. A portion of the latter 2 routes are not in operation. In addition, they have the Metrolink route from Burbank to Palmdale.

The Union Pacific Railroad (UP) operates 24 trains per day on their LA to Riverside line, and routes from LA to Sima (Long Beach). Many of their routes have been sold to local transit agencies.

The Metropolitan Transit Authority (MTA) operates 2 commuter lines in the LA basin. The Blue Line is a light rail commuter train that opened in 1990. Its route consists of 22 miles (35 kilometers) of track and 7 elevated structures (bridges) from Long Beach to LA. Ridership on the Blue Line currently is approximately 40,000 per weekday (20 hours of operation). The Red Line is a heavy rail subway with 4.4 miles of tunnels in the downtown LA area from Union Station to Westlake. Ultimately, the Red Line will consist of 22 miles (35 kilometers) of track reaching to the San Fernando Valley.

The Green Line, which is under construction, will consist of 20 miles of light rail track running from Norwalk to El Segundo. Train operations are controlled at MTA's Communications Control Facility (CCF) located in a 6-year old building on Imperial Highway. Communication modes included telephone and radio (station to station). The CCF is monitored 24 hours per day using a Supervisory Control and Data Acquisition (SCADA) system to contact personnel during off duty hours.

Metrolink is operated by the Southern California Rail Authority that in the last few years purchased track from Southern Pacific, Union Pacific, and Sante Fe. At the time of the earthquake, they were responsible for 200 miles (322 kilometers) of track. Prior to January 17th, they operated 61 trains per day throughout the system with a ridership of 18,000 passengers per day.

The Harbor Belt Line is a subsidiary of the major railroads and includes 68 miles (109 kilometers) of track in LA Harbor. They were not in operation at the time of the earthquake. They have 4 trains that move freight cars in the Harbor area.

The LA Junction Railway consists of 63 miles (101 kilometers) of track in the cities of Industry, Vernon, Maywood and Commerce. Their system includes 2 bridges and 1 tunnel. They operate 3 trains per day on weekdays and 1 train per day on the weekends. They are owned by the Sante Fe Railroad.

RESPONSE

The earthquake occurred on January 17, 1994, a holiday, and most transit agencies were not in full operation. Sante Fe is a subscriber to the California Institute of Technology's (CalTech) - USGS Broadcast Earthquake's (CUBE) system, which is connected to earthquake monitoring facilities at CalTech. Earthquakes of magnitude 5.0 or greater are monitored at the computer operations center in Schaumburg, IL. Normally, trains within a 30 to 50 miles (48 to 81 kilometer) radius of the epicenter are stopped for magnitude 5.0 events or greater. In this instance, the notification limits were extended to 75 miles (121 kilometers). Stoppage notifications are made by the dispatcher in Schaumburg by microwave radio, telephones, or railway signals.

Southern Pacific also uses the CUBE system and suffered delays in the receipt of information. When the magnitude exceeds 5.0, dispatchers are notified by radio or best available method. Track and signal inspection teams were notified and mobilized within minutes after notification.

Local Union Pacific field personnel were on duty during the earthquake and notified the dispatchers in Omaha, NB, of the event. The dispatcher immediately notified all trains to stop by microwave and radio. Track inspectors were sent out and completed their inspections by 9:50 a.m. This process has continued for each aftershock greater than 5.0 magnitude.

Sante Fe stopped 7 of their trains, 1 Amtrak train, and 2 Union Pacific trains that were on their tracks. They had track inspectors fully mobilized within 30 minutes after the earthquake. Within 3 hours after the earthquake, the Amtrak train was cleared to move on inspected track. Other trains began moving at restricted speeds by following track inspection vehicles. Union Pacific indicated that their only delays resulted from the stop orders and track inspection schedules. Train congestion is heavy during each inspection period.

MTA had 2 trains in operation at the time of the earthquake, both of which were in a pre-operation inspection (sweep) mode. Subway tunnels fro the Red Line have 3 sensors installed to measure ground accelerations. At 0.1g, a warning is issued to the trains. At 0.2g, all trains are stopped. This event had a recorded ground acceleration of 0.27g.

MTA's operating trains were notified by radio immediately after the event by the Central Control Facility (CCF). MTA's inspectors were fully mobilized within 1 hour. There were power outages, but no structural damage. There was no damage to the San Fernando Valley portion of the Red Line currently under construction. However, there were gas alarms in the Red Line tunnels caused by seeping water bringing in methane and/or hydrogen sulfide gas.

MTA provided additional track inspections after each aftershock, even though the seismic device did not register a high acceleration. Also, electricity from the Blue Line provided partial power, via a breaker and buss, to the Red Line at the 7th and Figueroa Metro Station. This allowed the 2 trains to return to Union Station. They could not proceed to Westlake because the grid west of 7th and Figueroa has a separate electrical system.

Some routes were augmented using busses driven by Blue Line operators. Inspection was completed on the Blue Line by 7:30 a.m. and full services was restored. The Red Line was ready for operation by 1:30 p.m., but was closed until the next day as a precautionary measure in case of a major aftershock.

Ridership on the Red Line was approximately 21,000 per weekday for 18 hours of operation. This load was increased by 35% after the event due to increased traffic from Metrolink reach Union Station.

Metrolink uses radio communications to have the operators stop trains for all earthquakes with a magnitude of 5.0 or greater. They did not run any trains for 1 day to allow for inspection of tracks and tunnels and coordination with the other railroads. They were in full operation the second day with the exception of the Chatsworth Line (the site of the SP derailment). They immediately expanded the operation of the Santa Clarita Line by increasing each train from 3 to 8 coaches and providing additional trains. They borrowed coaches from CalTrain along with unused coaches that were to be collected for future routes.

Ridership on the Santa Clarita route increased from 1,000 passengers per day to 20,000 per day in the first week. After 4 weeks, the ridership stabilized at 9,000 per day. System-wide, they raised operations to 75 trains per day. In addition, they increased their system by 60 miles (97 kilometers) by adding service to Lancaster.

Additional platforms were constructed and parking areas were graded by the U.S. Navy Seabees LA County, contractors, etc. The Los Angeles Department of Water and Power constructed the new Northridge Station.

The Harbor Belt Line inspected all of their track by 6:00 a.m. and were in full operation at their normal starting time of 8:00 a.m. on January 17th.

The LA Junction Railway is a part of the same system as Sante Fe and receives information directly from CalTech. They were not operating at the time of the earthquake. The morning foreman reported to work at 5:30 a.m. on January 17th and began inspections. A total of 12 inspectors completed inspections by 7:00 a.m. There was no damage or delays.

DAMAGE, RESTORATION AND USER IMPACTS

A 64-car Southern Pacific freight train traveling through Northridge at the time of the earthquake derailed, spilling 8,000 gallons (30,283 liters) of sulfuric acid from tank cars and 2,000 gallons (7,571 liters) of diesel fuel from the engine. The locomotive operator reported seeing a 3-foot (1 meter) high ripple (wave) in the track that apparently caused the derailment when it passed under the engine. The tracks were cleared and service restored by 2:00 a.m. on January 19th. Debris was cleared by January 21st. In addition, Southern Pacific had some rockslides to clear.

Southern Pacific control signals have either emergency generators or battery backup systems for commercial power failures. Because of the duration of the outages exceeded 6 hours in some locations, portable generators were used to restore electrical power to battery supplied track signals so that trains could continue moving.

There was no damage to Sante Fe, Union Pacific trackage.

MTA's Blue Line had some minor damage to catenary poles which did not directly affect operations. MTA had minor delays on the Blue Line due to the power outages. There were minor construction delays on the Green and Red Lines due to power loss and road congestion. MTA's track inspections consisted of a train inspection, a walking inspection and then a gas sweep. This normally takes 3 hours however, some inspections were delayed due to power outages.

Metrolink stopped service for 1 day. All trains were in operation the second day after the earthquake after coordination with other track users.

HINDRANCES TO RESPONSE

Apparently, the CalTech direct computer link on the CUBE system went down causing delays in receiving magnitude and epicenter information. Sante Fe has a direct telephone line to CalTech which allowed them to call immediately after they lost the signal. Sante Fe has a 24-hour facility in the City of Commerce which notified the Schaumburg dispatcher of the earthquake.

Union Pacific found that overloaded telephone circuits delayed some contacts with field personnel. In addition, the curfew required that their special agents contact local authorities to allow travel and inspection during the restricted hours.

MTA's restoration operations were hindered by aftershocks which caused train stoppages and track inspections. The on-line electrical loads were so large that the generators could not start all facilities at once. The emergency generator system had to be manually "load shed" so that ventilation fans and other systems could be operated during the power outages. An automatic load shedding system is currently being installed. Full power was restored by 10:00 a.m. on January 17th.

PERFORMANCE OF EMERGENCY RESPONSE PLAN

Santa Fe uses an emergency plan prescribed by CalTech which is based on the CUBE system. There has been a number of earthquake events over the last few years to allow for sufficient practice of the response procedures. This resulted in almost immediate response from both their Schaumburg dispatchers and local inspectors. Their inspections were completed in time to loan inspection teams to local transit agencies. Sante Fe is testing a ground motion detector that is installed adjacent to the track that would immediately notify trains by signal to stop.

Southern Pacific used their written emergency response plan. They have access to the CUBE system and use a message pager known as "Advantage". With the exception of delays with CalTech, the response procedures performed well. They are currently working out a program with UC Berkeley to provide a second source of earthquake data.

Union Pacific has a contingency plan in place for earthquakes. There has been enough events that it is well used and, accordingly, went smoothly for this earthquake. There is a general plan in Omaha that contains regional instructions. There are local plan supplements that contain data on sources of emergency materials and equipment that are available 24 hours a day.

MTA's emergency response plan performed well. As with the other companies, emergencies are frequent enough to allow for continual evaluation of emergency procedures. Prior to the earthquake, there was a study being prepared on the tunnels for the Red Line. The scope of the study will now include a performance evaluation of the tunnels during the earthquake. Their acceleration monitoring sensor worked well and they are planning to install them on the Blue Line in the future. MTA's employees are directed to report to their post (or nearest MTA facility) in an emergency. There were no major personnel related problems and no overtime was necessary.

CONCLUSIONS

All railroad companies in the area were well prepared to handle an earthquake of this magnitude. The emergency response procedures have been well rehearsed which provided for prompt response and restoration of services.

RECOMMENDATIONS

Develop and/or improve out-of-area seismic notification stations so that out-of-state dispatchers can be notified in the event that local monitoring and communications systems are damaged or without power.

REFERENCES

The names of contacts at the following railroads provided information contained in this report.

Sante Fe:	Mike Martin, Manager Public Affairs
Southern Pacific:	Tom Eisenburg, Signal Terminal Manager Charlie Redmond
Union Pacific:	Mark Davis, Regional Director, Public Relations
Harbor Belt Line:	Roy Igo, General Manager
LA Junction Railway:	Bill Edwards, Assistant General Manager
MTA:	Steve Chester, Media Relations Wyman Jones, Rail Safety Engineer J. David Byrd, Rail Operations Super. Rufus Francis, Manager, TS Safety
Metrolink:	Brendon Shepard, Spokesman

9. PORTS

ABSTRACT

Compared to earthquake damage sustained by port facilities in the San Francisco Bay area after the Loma Prieta Earthquake and, more recently, port damage in Kobe, damage to the Port of Los Angeles (POLA), as a result of the Northridge earthquake, would be considered light. The Port of Long Beach, located adjacent to POLA, reported no damage. However, the Northridge earthquake did provide the POLA with an event that did not damage the port significantly, but did allow the emergency response of the port to be tested. Based on this learning experience, improvements to the Port's emergency response plans have been adopted in an effort to better respond to future earthquakes as well as other natural disasters. A description of the POLA and a summary of damage sustained as a result of the Northridge earthquake are given below followed by a summary of changes to the emergency response plans that have been adopted as a result of this earthquake. This discussion follows up on the original investigation done by Robert Hayden of Hayward Baker, Inc. immediately after the Northridge Earthquake in January 1994. Information for the original investigation and for this re-investigation was provided by Doug Thiessen, civil engineer, at the Port of Los Angeles.

PORT DESCRIPTION

The two major port facilities near Northridge include the Port of Los Angeles (POLA) and the Port of Long Beach. Both ports are located in San Pedro Bay. The Port of Long Beach, located approximately 39 miles form the epicentral region, did not suffer any damage during the earthquake and, hence will not be discussed in detail. The POLA occupies 28 miles of shoreline on the south side of Los Angeles and is located approximately 37 miles from the epicentral region as shown in Fig 9.1. The harbor is protected by 4.5 miles of break water which is owned and maintained by the Army Corps of Engineers. The wharves and piers are accessed through approximately 8 miles of dredged shipping lanes as shown in Fig. 9.2. Containerized freight is the major item handled by this port although facilities for bulk liquid cargo (petroleum products, and others) including storage tanks are located at this facility. Thirty-five container cranes are currently in use. Most of the Port is constructed on hydraulic fills with pile-supported wharves extending over revetment slopes. Transportation of goods inland occurs over highway, by rail and through pipelines.

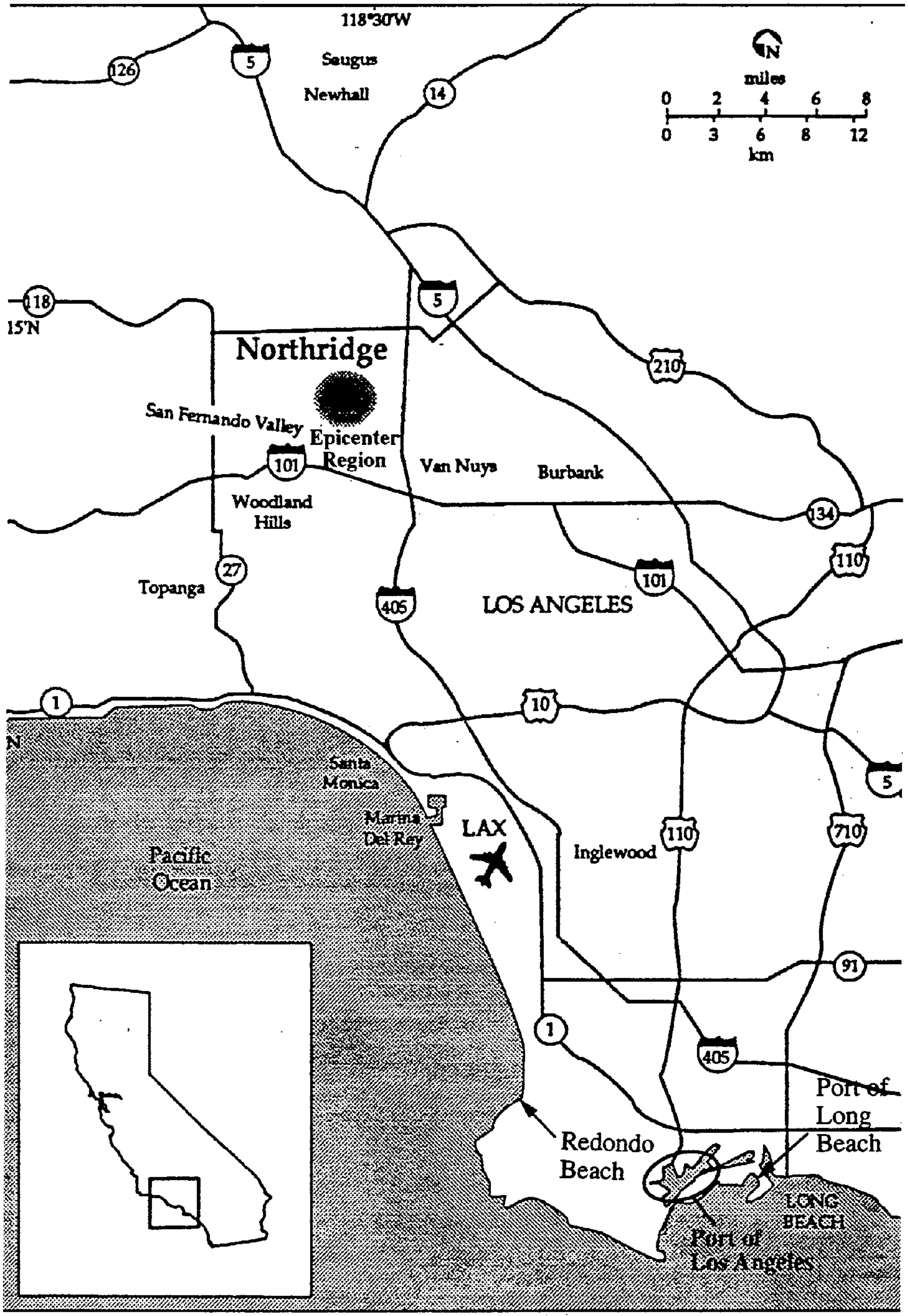

Fig. 9.1 Location of the Ports Relative to the Earthquake Epicenter

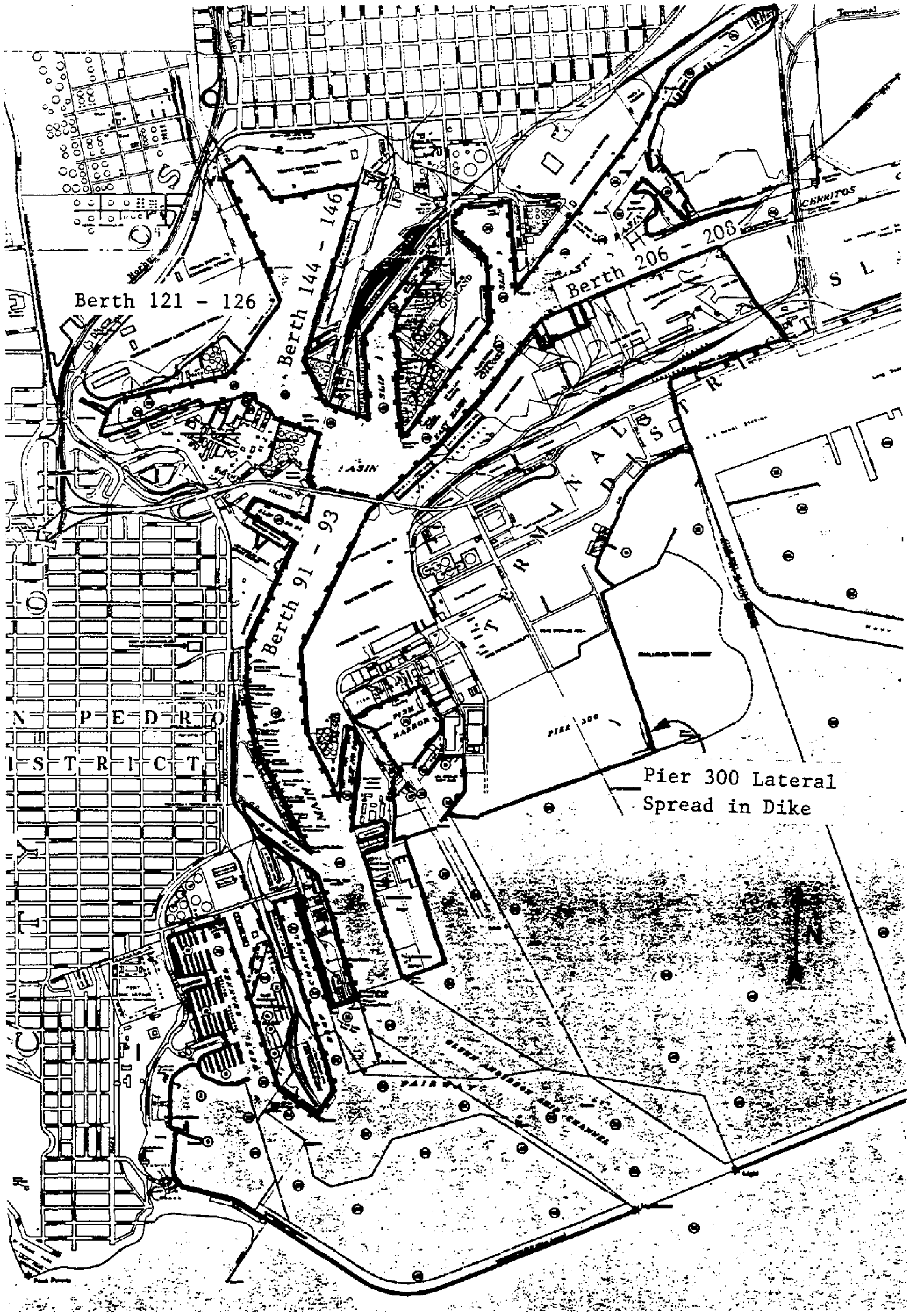

Fig. 9.2 Port of Los Angeles

Several wharves are located on Terminal Island. This island is accessible to vehicle and rail traffic by bridges. Cross-channel submarine pipelines carry all utilities (water, gas, telephone, and electricity) to the islands. All the terminals are leased to private companies with varying maintenance agreements. POLA has a staff of 750 people including a construction and maintenance division of 250 people and an engineering staff of approximately 100 people. The annual cargo handled by the POLA is approximately 69 million metric revenue tons.

The King's Harbor Marina in Redondo Beach suffered liquefaction damage. However, this facility does not serve a lifeline function and therefore will not be discussed further.

REVIEW OF DAMAGE SUSTAINED BY THE PORT OF LOS ANGELES

Almost all damage was identified immediately after the earthquake, however some pavement damage has continued to reveal itself for almost a year after the earthquake. A summary of the damage and its effects on operation of the Port is given below. Ground motion instrumentation is not in place at the Port. However, as a result of Northridge, plans are being made for the installation of strong motion instrumentation. At the Vincent Thomas Bridge, which provides the highway crossing from San Pedro to Terminal Island, the uncorrected peak horizontal ground acceleration was measured at 0.25 g's and the vertical acceleration was measured at 0.08 g's. Free field ground accelerations were not measured. This bridge is owned by CALTRANS. The California Division of Mines and Geology owns and maintains the instrumentation on this structure.

SUMMARY OF DAMAGE

POLA container terminals at Berths 121 - 126 incurred liquefaction related damage to the wharf. Ground displacements resulted in the crane rails breaking by two distinct modes. Horizontal shear type failures were observed in the crane rails at expansion joints and tension failures were caused by lateral movement of the wharf decks. All crane rails are supported by concrete piles located under the wharf deck. Only minor horizontal cracking was found in the observable portions of the piles. These cracks will be repaired by epoxy injection. Crane rail failures were attributed to seaward movement of piles as rigid bodies rather than damage to the piles. Damage was observed to asphalt at expansion joints used to accommodate thermal expansion between adjacent wharf aprons. Berths 121 -126 were built in 1981.

An area of subsurface loose silty and sandy soils (ASTM D-2487 Unified System Soil Classification ML-SP) approximately 200 ft in diameter, behind the dike and wharf apron at container Berths 121 - 126 liquefied. Sand boils penetrated 7 inches of asphalt, coming to the surface through weakened zones in the asphalt. Ten cubic yards of displaced sand were removed from the site. Post-earthquake Cone

Penetrometer Testing indicated that the loose fill sands that liquefied had a relative density in the range of 20 to 50 percent. The wharf sustained lateral displacements ranging from 2 in. at Berth 121 to approximately 3 in. at Berth 126. Lateral spread cracks in the asphalt, some 500 to 600 feet in length and 1 to 2 in. in width were found in this region. Pavements in this area settled 6 to 8 inches. Cracks in the asphalt continued to form for a year after the earthquake. Formation of these cracks are attributed to truck traffic repeatedly loading surfaces where the underlying soil had liquefied, settled, and created voids not immediately noticed.

Buildings at Berths 144 - 146, 206 - 209 and buildings at the passenger terminal located near Berths 91 -93 suffered architectural glass and stucco damage. These same locations had small leaks in water lines located in the fill material and buildings. The water leaks were found through out these areas.

Pier 300, a new fill area located on Terminal Island where a container terminal is being constructed, had liquefaction and sand boils in a limited area where the fill material had not been pre-loaded and densified. The soil in this area was not compacted because of economic considerations, the current intended use of this area (parking area for container freight), and planned future modifications to this area. Engineers at the POLA expect that a more intense earthquake in the near future will cause further liquefaction problems, but benefit-cost analyses have shown that it will be more cost-effective to repair this damage when and if it occurs. From 4 to 6 inches of lateral spreading was observed in the east dike at Pier 300. A 30- to 40-foot-high temporary pile of dirt covering approximately 40 acres near the dike produced an additional surcharge on the dike that is assumed to have contributed to the displacements caused by the earthquake.

EFFECTS ON OPERATION OF THE PORT

The damage sustained by the POLA had little adverse effect on the operation of the facility. One ship had to be diverted from its intended berth while damage to Berths 121-126 was repaired.

EMERGENCY RESPONSE PLANS

The Northridge Earthquake provided sufficient stimulus to have a significant impact on the emergency response planning for the port. A summary of the emergency response plans before the earthquake and changes that were brought about as a result of the earthquake are discussed below.

Plan Existing Before Northridge

Formal earthquake emergency response plans exist for the City of Los Angeles as a whole. The plan entitled "City of Los Angeles Emergency Operations Master Plan and Procedures" outlines the duties and responsibilities of the various city departments including the Harbor Department. The plan also contains annexes which reference earthquake warning procedures as well as earthquake response procedures. Although general written emergency response procedures existed at the time of the Northridge Earthquake, a formal plan had not yet been completed at the POLA.

Another plan in existence at the time of the Northridge Earthquake is the city's Recovery and Reconstruction Plan. This plan basically describes an ad hoc committee which is formed to expedite disaster recovery efforts throughout the city (i.e., permit fee waivers, purchasing procedures, debris removal, etc.).

Effectiveness of Existing Plans

Even without formal earthquake emergency response plans port officials felt that their staff responded well to the earthquake. Port officials feel fortunate that Northridge was not a serious event for their facility. This event allowed the staff to respond and provided information with which to make improvements to the earthquake response procedure without having to suffer through a catastrophic event.

Changed Made to the Plans as a Result of Northridge

The City of Los Angeles and all of its departments are in the process of meeting new state-wide emergency planning and training requirements. The new law is referred to as Standardized Emergency Management System (SEMS). This new emergency management system requires the use of the nationally approved Incident Command System (ICS). The Harbor Department has included the ICS in its plan and has recently provided orientation training to its senior managers and division heads.

Whenever a major disaster occurs the City of Los Angeles activates its Emergency Operations Center (EOC) in downtown Los Angeles. The Harbor Department activates its own EOC at the Port Police communications center in San Pedro (25 miles from the City EOC). A Port Police Officer and the Emergency Preparedness Coordinator are dispatched to the City EOC and represent the Harbor Department in all situation assessment meetings that are called by the head of the Emergency Operations Organization (Mayor). As damage assessment reports are compiled by the Port Warden (with the assistance of the Chief Harbor Engineer) they are relayed to the Harbor Department representative at the City EOC who in turn reports to the Operations Commander of the EOC.

As of April 1995 the Emergency Procedure Plan for the Los Angeles Harbor Department has been completed and distributed to all appropriate offices and personnel of the Department. This plan identifies an earthquake as the worst possible disaster for the Port. Included in this plan is the addition of an Emergency Response Coordinator. In the event of a major earthquake the Chief Port Warden becomes the incident commander until life safety and security issues are under control. After these issues are considered under control, the Chief Harbor Engineer would normally take over as the incident commander. The engineering and maintenance crews assist in dealing with the life safety issues on an as-needed basis with Port Police and, concurrently, they begin assessment of the damage during this phase.

Disaster drill and training are another direct result of the Northridge event. Port police have been taking part in drills. An earthquake fair has been planned to provide information regarding earthquakes and to allow port personnel to ask related questions.

A toll-free 800 number has been established that will allow employees to call in to get information and job assignments after an earthquake. Tenants can also use this number to notify the maintenance personnel about damage. It should be noted that the city of Los Angeles requires all city employees to call in after an event such as an earthquake.

Other emergency plans that were adopted as a result of the Northridge Earthquake include issuing cellular phones to senior managers in an effort to avoid communication problems that result from phone line congestion and the maintaining of a list of qualified contractors for emergency repairs. Plans are being considered for redundant data storage of important record such as a geographic information system and personnel records. Currently, these records are stored on a central computer at one location.

POST-EARTHQUAKE DAMAGE ASSESSMENT

Informal procedures are in place to assess the damage after an earthquake. The informal procedure that has been adopted appeared to work well after the Northridge Earthquake.

SYSTEMATIC WALK DOWN PROCEDURES

The POLA has purposely not implemented any formal walk down procedures to identify damage. Initial damage is first reported by the port police and by tenants. In order to get a quick overview of the port in a short amount of time, engineers and maintenance crews first perform land-side drive-by inspections. Water-side drive by inspections are then performed by boat. Subsequently more refined inspections take place including inspection of the underside of wharves and detailed inspection of top side of the wharves. Tenants have typically notified the port maintenance crew of damage to buried utilities which is apparent from loss of service.

UNDERWATER FACILITIES

Divers were hired to perform underwater inspections. Because of the cost associated with divers, their inspections were limited to areas where surface inspections indicated that there might be below-water-line damage. Typically they inspected for loss of embankments, damage to piles, and potential shoaling to dredged shipping lanes caused by slope failures.

REPAIR OF DAMAGE

In general, damage to the POLA was considered light. Repairs to Berth 121-126 began almost immediately after the earthquake. These repairs include those needed to restore the crane rails, repair of expansion joints between adjacent wharves, repair to utility lines, pavement repairs and sealing cracks in the asphalt. The crane rail expansion joint at Berth 121 was strengthened to accommodate a 2 in. longitudinal displacement at the wharf's expansion joint. At other locations the rails were cut, straightened, re-welded and re-grouted. All repairs to crane rails were done in the field with restoration of service as the primary objective. These repairs did not represent significant engineered design changes to the original rail system. Electric power trenches were realigned. Pavements were cold planed (the top 2.5 in. of asphalt are ground off) and resurfaced to restore the original grades. Berths 121-126 were put back in temporary service after an initial five day repair period. Subsequently, two three-day repair periods were scheduled around ship arrivals to finalize the work in this area. All emergency repairs were completed by January 30, 1994. Other long term repairs will be done in the future.

Although not needed for damage sustained during the Northridge Earthquake, California regulations require owners of facilities that handle petroleum products (the oil companies themselves) to maintain equipment to contain oil spills. Equipment at these facilities consists of floating booms (continuous, approximately 12-in-high floating barriers) that are deployed around the spill from a hose reel mounted on a boat . Private companies are then contracted to skim the oil contained within the boom off the water with specialized equipment. The POLA does not maintain any of this equipment (booms or skimming equipment).

WHO PERFORMED REPAIRS

Repair were performed both by port maintenance crews and contractors. The Port tries to use its own personnel when it can because of their knowledge of the facility and for economic reasons. However, the Port does not maintain certain heavy equipment, hence, contractors provided specialty equipment such as that needed to cold plane and pave the asphalt. A contractor repaired the crane rails. For cranes owned by tenants, crane maintenance people were hired to repair damage to the cranes. Divers were hired to inspect underwater structures. Geotechnical engineers were hired to perform field investigations and to consult on soil liquefaction problems.

ADMINISTRATIVE PROCEDURES REQUIRES TO START REPAIRS

When the Governor of California declares a state disaster, the City of Los Angeles goes into a disaster operations mode. In this mode routine procurement requirements for hiring contractors by low bids are waved. Contracts are then awarded verbally. Engineers may select capable contractors that they have had good working relations with and whose work they have previous experience with. Because these contractor have done previous work for the POLA, records of their rate schedules are on file at the POLA. Although no problems were encountered, this documentation would make it difficult for contractors to charge higher fees during the emergency response. Engineers at the POLA feel that this system worked extremely well immediately after the Northridge Earthquake.

NEED FOR ENGINEERING PRIOR TO REPAIR

The nature of the damage was such that engineering was done in the field relying on the judgment of experienced engineers. This mode of operation was adopted in the interest of getting the job done in a timely fashion so the facility could be used by the tenants. In the areas around Berths 121-126, where liquefaction related damage had occurred, engineers decided not to remove the asphalt and re-compact the soil. This decision was based on the desire not to significantly disrupt the tenants use of the facility as the damage was located in a critical area of the facility. Another factor contributing to this decision was that the tenant will vacate this facility in 1997. At this time more extensive repairs (placement of stone columns designed to relieve excess pore water pressure) are planned that will directly address the potential soil liquefaction problems.

OBSTACLES TO REPAIR

No major obstacles to repair were reported other than the need to perform repairs around shipping schedules. Ideally, the construction crews would have liked unobstructed access to the area requiring repair, but the need to maintain the operation of the facility required that repairs took place around ship schedules. Again, this need was based on a desire to minimize the disruption of service to the tenants. In general, most container facilities have the reserve capacity, both in storage and in freight handling, to absorb an unplanned 1 - 2 ship per week increase in traffic. Therefore, when a single ship is re-routed to another facility, as was done after Northridge, the storage capacity and loading/unloading capacity is available at such a facility. At the time of Northridge the tenants at Berths 121 - 126, where damage caused the ship to be re-routed to another facility, as well as the tenants at the alternate berths were operating on their normal schedules.

Availability of Other Lifeline Functions

Most lifelines serving the port were functional within three hours after the earthquake and, hence, did not pose a serious problem to repair operations. Electric power was restored within 3 hours after the earthquake. Minor water leaks were repaired within 2-3 days after the earthquake. Phone lines were congested for 2 days after the earthquake requiring the use of cellular phones when performing initial inspections and for coordination of repair operations. Radios were also used extensively by the Port police and the construction and maintenance crews. All radios worked immediately after the earthquake and continued to work during the emergency response period after the earthquake.

Availability of Equipment, Supplies, and Personnel

No major problems with equipment, supplies or personnel were reported by the port engineers. Although the damage sustained by the POLA was considered relatively minor by their engineers, it did tax their personnel, supplies and equipment to get the repairs done on short notice so as to minimize the impact to tenants.

CHANGES BASED ON EARTHQUAKE EXPERIENCE

Engineers at the POLA did not consider this earthquake severe, and as such it did not fully test their designs. Therefore, although this event did provide to some extent a training exercise without severe damage, it did not allow enough experience to be gained such that beneficial changes could be made to design practices, modes of operation, or administrative procedures.

FACILITY DESIGNS

No major changes to the POLA's facility design were adopted as a result of the Northridge Earthquake. The consensus opinion of port engineers was that facilities designed to codes and standards established in the last 15 years performed well during the earthquake. The engineers point out, however, that this earthquake was not severe and it did not provide a design basis test of their facilities. Some design details such as those associated with expansion joints and those associated with electrical and water line connections at the wharf apron/ fill interface have been improved and strengthened to better resist seismic ground motion. These improvements include the use of commercially available flexible utility line connections at these locations.

MODES OF OPERATION

Again, based on the response to the Northridge Earthquake, no major changes in the modes of operation were adopted. This earthquake provided a good training experience for port personnel and the feeling was that their personnel responded well. Engineers at the port feel that this event did help to identify the resource limitations of their abilities to repair damage with their own crews after a significantly larger earthquake.

ADMINISTRATIVE PROCEDURES

The primary change to administrative procedures that was developed as a result of the Northridge Earthquake was to formally adopt the FEMA Damage Category Recording Process with dedicated full time accountants assigned to track the paper work associated with this recording procedure during repairs. Adoption of this procedure speeds the process by which reimbursement from FEMA was obtained. Having full time accountants dedicated to tracking this paper work minimized the changes needs to the documents submitted to FEMA and in the long run save time and minimized inconveniences in this process.

SUMMARY

Damage sustained by the POLA after the Northridge Earthquake was relatively minor when compared with damage experienced by other port facilities during recent earthquakes such as Loma Prieta and Kobe. The damage was repaired such that the Port was functional within five days after the event. During repairs, one of the primary considerations that influenced engineering decisions was to minimize the interruption of services to the tenants . Many of the repair decisions, particularly the more costly ones associated with liquefaction problems, were based on future planned modifications to the facilities (when it will be more cost-effective to make the repairs) and benefit-cost analyses. In some cases, the engineers are aware that another earthquake in the near future will cause similar problems as experienced during Northridge, but the benefit-cost analysis and the lack of life-safety concerns show that it is more economical to repair this damage when and if it occurs. Few design changes have been adopted as a result of Northridge as the earthquake was not severe enough to fully test the design basis for the facilities.

Although the Northridge Earthquake did not damage the POLA significantly, it did allow the emergency response of the port to be tested. Based on this learning experience, improvements to many aspect of the Port's emergency response plans have been adopted in an effort to better respond to future earthquakes as well as other natural disasters. One of the primary changes has focused on methods to better handle administrative requirements of FEMA.

10. AIRPORTS

ABSTRACT

Three commercial airports experienced significant ground shaking from the Northridge earthquake: Van Nuys, Los Angeles International, and Burbank Airports. Airports were closed to traffic for up to one and a half hours until runways and tunnels that cross under runways could be checked for damage. Several windows at the Van Nuys Airport control tower cracked or fell from the structure. At Los Angeles International Airport (LAX) transfer switches on two of the airport's emergency generators failed to operate and had to be switched manually to restore power to part of the terminal. Disruption caused by the loss of power for some terminal functions almost caused international flights to be diverted to another airport, but commercial power was restored in time. Because of the boil water order issued by the Los Angeles Department of Water and Power, LAX trucked in water from El Segundo. The vibration isolators used on some emergency generators do not have snubbers and are vulnerable to earthquake damage. Batteries used to start emergency generators are typically not restrained to their racks and the racks are not anchored. Uninterruptable power supplies are typically unanchored in the bases of cabinets or adjacent to cabinets.

INTRODUCTION

Figure 10.1 shows the locations of the three airports relative to the epicenter of the Northridge Earthquake. The size of the three airports varies significantly with LAX the largest airport in the region and Van Nuys primarily servicing general aviation. The original airport investigation of airports was conducted by Glaude Griffin (1).

AIRPORT EARTHQUAKE PERFORMANCE

VAN NUYS AIRPORT

The airport was closed for about one and a half hours to inspect runways. Sherman Way Avenue, a major east-west thoroughfare, passes under the south end of the

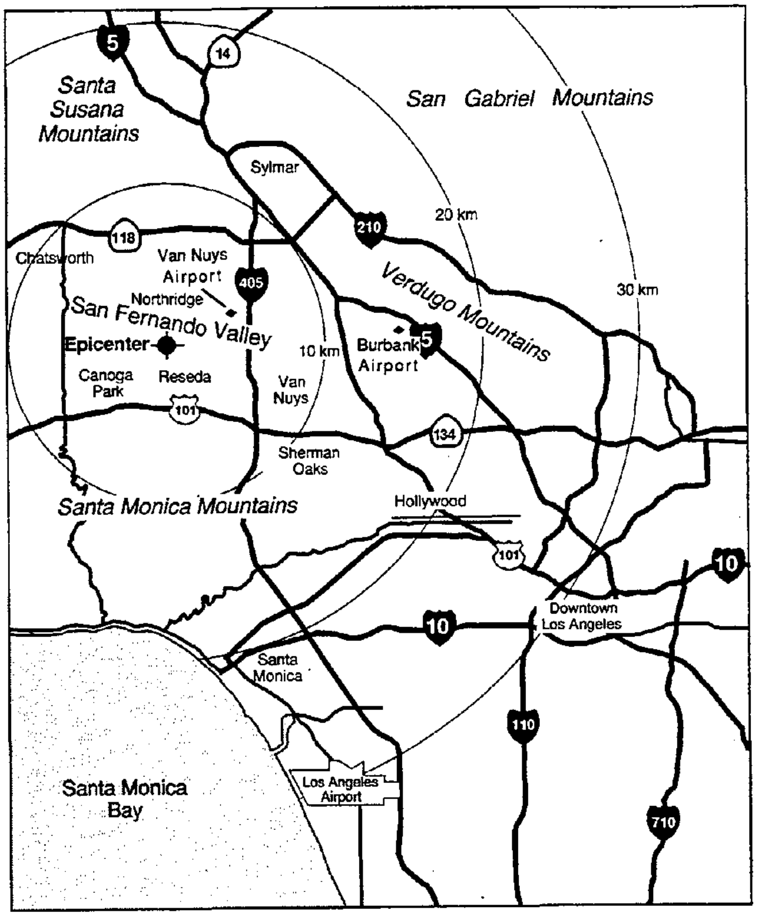

Fig. 10.1 Map of epicentral area showing the location of major airports. (Source: USGS)

runway through a tunnel. There were minor cracks and spalling at construction joints in the tunnel and an engineering assessment was needed before air planes were allowed to use the runway over the tunnel. The cost to repair damage to FAA facilities at the airport control tower was about $160,000.

The control tower is a modified Type O design, one of the standard designs used by the Federal Aviation Administration (FAA). It was modified by extending the standard 49 ft (15 m) height tower to 60 ft. (18 m) and adding an elevator. The roof of the tower, like all US control towers, is supported only by the window mullions rather than internal, view-obstructing columns. Also, FAA requirements limit the thickness of the mullions to 4" by 6" so that the view of the field is minimally obstructed, although there are a few exceptions to this limitation. The windows were heavy single pane 3/4" (2 cm) thick glass.

Figure 10.2 shows an overview of the control tower and cab. The gashes in the tower siding were caused by the window as it fell, suggesting that they came out as a unit or fractured and large pieces fell to the ground. A fragment of the window is shown in Fig. 10.3. Each of the five sides of the cab has two window panes separated

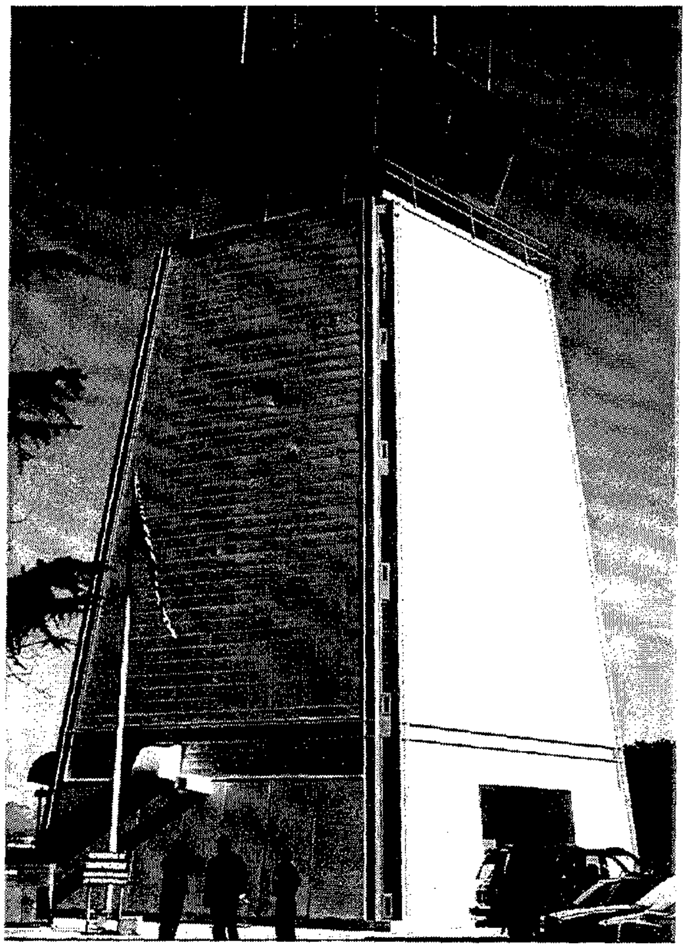

Fig. 10.2 Overview of the Van Nuys control tower with gashes in siding caused by windows falling from the cab.

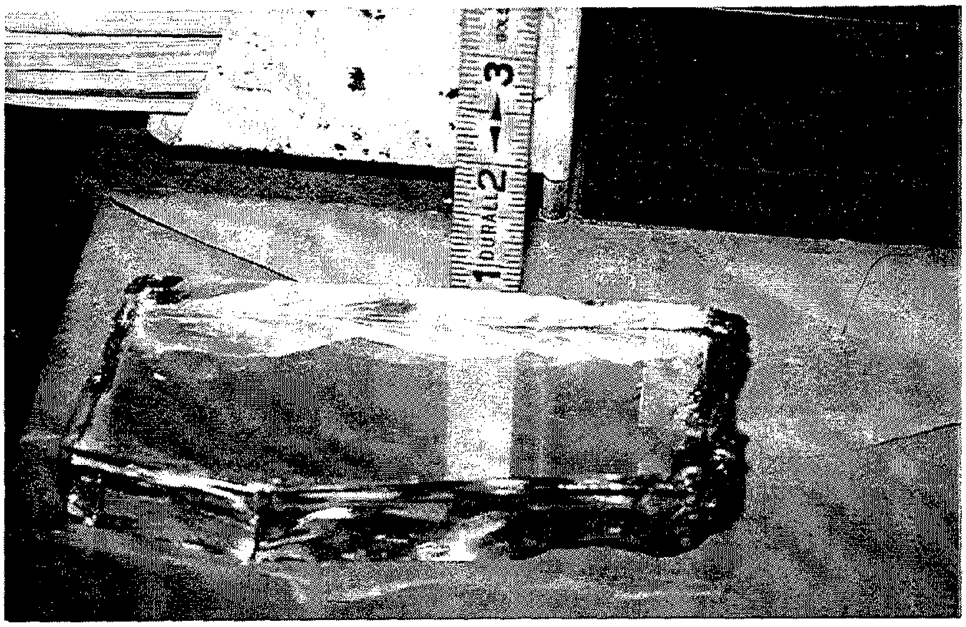

Fig. 10.3 Fragment of control tower window glass that is 3/4" (2 cm) thick.

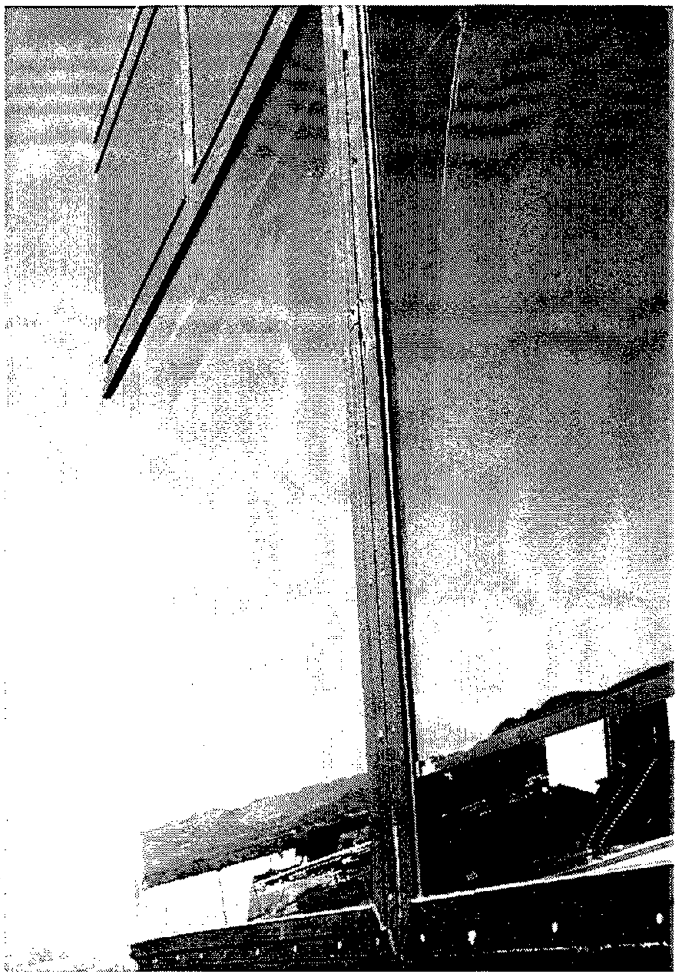

Fig. 10.4 Window retaining plates held by aluminum screws to mullion and lower window frame.

by a mullion. Note that there are no corner mullions. Figure 10.4 is a view of one of the mullions from outside the tower. The window retainer plate is held by seven aluminum machine screws (which appear to be about 10-23 size). The clearance between the edge of the window glass and the mullion is not known. .

The control tower engine-generator was anchored at the time of the visit, but was unanchored at the time of the earthquake. The batteries used to start the engine-generator were not secured to their battery rack and the rack was not anchored, Fig. 10.5. The utility transformer that supplied power to the control tower is located adjacent to the tower was unanchored, but did not move during the earthquake. The control tower is normally closed during the early morning hours. A uninterruptable power supply in the base of a cabinet was unanchored, but continued to operate, Fig. 10.6. Air handling equipment in the tower was on vibration isolators that were unanchored and appeared to have moved as much as 4" (10 cm) as a result of the earthquake, Fig. 10.7.

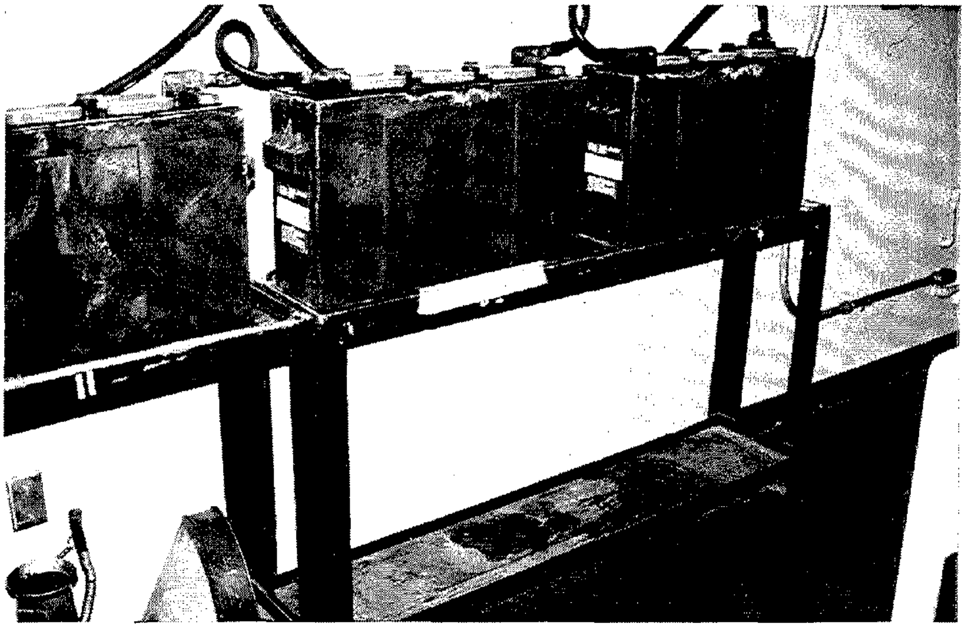

Fig. 10.5 Batteries used to start the emergency engine-generator are unsecured to their rack and the rack is not anchored.

Fig. 10.6 A uninterruptable power supply in the bottom of a cabinet was unanchored. It did not move and continued to operate after the earthquake.

It was reported that the engine-generator for a Very High Frequency Omni Directional Range (VOR) station located near the airport moved about 4" (10 cm) and almost broke its fuel line.

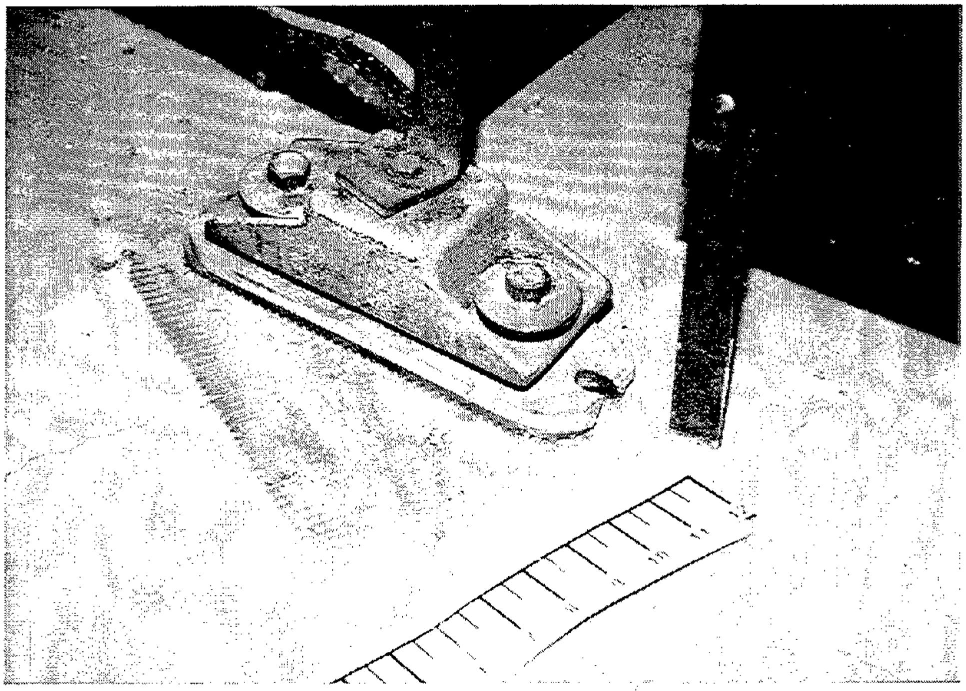

Fig. 10.7 Vibration isolation pad used to support air handling equipment was unanchored and moved about 4' (10 cm).

LOS ANGELES INTERNATIONAL AIRPORT

The runway and taxiways were checked using vehicle headlights. A decision was made to delay the airport opening slightly to wait for daylight so that a more thorough check could be made. In addition to the runways, the Sepulveda Boulevard tunnel under the runways was checked and found to be undamaged. Two air cargo flights that were scheduled to arrive shortly after the earthquake were diverted. Some international flights were due to arrive and they were about to be diverted to another airport when commercial power was restored. Due to the loss of power and the need to transport water, there were minor delays in departing flights. The total cost to repair damage to airport facilities including terminal buildings, runways, and parking garages was about $100,000.

Power Systems

LAX is provided power by three power line feeders from different substations. The airport and the many leased facilities associated with it, such as maintenance shops and freight forwarders, have over 50,000 personnel on site, so the airport is the size of a small city. The airport lost commercial power with the rest of the city at 4:31 am. Commercial power was restored at different times to different parts of the airport, and initially was intermittent. Power was restored to all facilities by about 8:30 am.

The FAA has one emergency generator and the airport has a generator for each terminal with a total of nine units. There are a variety of units, some dating back to the 1960s. Some are diesel and others have been converted to gas with bottled gas back-up. These units primarily provide egress lighting. They do not provide power to the many lease areas within the terminal buildings. For example, airline computer facilities, jetways, and baggage handling equipment are not supplied with emergency power by the airport. The FAA generator operated and provided power to communication, radar, runway lights, and other FAA functions. LAX emergency generators started, but transfer switches on two of the nine airport generators failed to operate and units had to be switched manually. The transfer switches were installed in the 1960s. This units are designed to sense ground faults. It is suggested by service personnel that water leaks created a ground fault situation and the switch would not transfer the load. This had happened previously in other situations where there was a loss of power. With the loss of commercial power and the malfunction of the transfer switches on two emergency generators, parts of the terminal were without power for normal operations. The loss of power caused at least two significant problems. Security locks with magnetic codes on badges to gain access to certain areas within the airport would not function without power, so that airport and airline personnel could not get into some areas. It was reported by one airline that airplanes could not be refueled because fuel pumps of the consortium that supplies this service to all airlines. It was suggested that the problem may have been due to lack of emergency power, but fuel service company has four diesel generators and all reportedly work. It is standard practice to check the system for fuel leaks before pumping fuel, and this takes one to two hours. This may have accounted for the delay in refueling aircraft.

Another concern of one of the major airlines was the loss of power to jetways used to load and unload passengers. Jetways have automatic controls to keep the jetway aligned vertically with the door of the aircraft. Without power these controls would not operate and there was a concern that rocking of the plane in the earthquake could have damaged open airplane doors that extended into the jetway. These were inspected and no problems were found. This airline has one mobile generator and many small portable units. This units operated without problems.

Water Systems

The Los Angeles Department of Water and Power provides water to the airport. Due to damage to the water distribution system there was concern that there could be contamination of water due to damage to both water and sewer lines, so as a precaution a boil water order was issued. The airport water supply was not disrupted, and they had the capability of adding disinfectant to the water, but chose to get water from neighboring El Segundo, which had potable water. LADWP supplied a tanker truck and food service suppliers provided transport for water from El Segundo. Within the terminal, drums of potable water and cups were provided.

The catering services that provide in-flight food were located in El Segundo, so their water supply was not disrupted. One of the major airlines had the food service vehicles get water at El Segundo for supplying departing aircraft. As soon as the boil water order was issued, one of the major airlines requested incoming flights to carry extra bottled water for use after they departed LAX. There is no regulation for a potable supply on aircraft, and bottled drinks can meet passenger needs for liquids.

A potentially more serious problem is the need for "blue" water used for sanitary facilities on the aircraft. Potable water is not required for this use. One of the major airlines indicated that they have about 2000 g storage tank that is good for about 10 days. If aircraft could not be serviced at airports affected by the earthquake, they could still operate by making a service stop at a nearby airport en route.

From three to five water leaks in the fire suppression system caused minor clean up problems in terminal facilities. A hot water pipe in one of the snack bars in Terminal 7 broke in three locations. Access could not be gained to shut the water off and it flooded a bag area on the floor below. This was a minor inconvenience that could be worked around. A dresser coupling on the sprinkler system started to leak some time after the earthquake.

BURBANK AIRPORT

The control tower at Burbank Airport is a relatively new facility that was put into service in 1990. In the 1971 San Fernando earthquake the control tower windows were damaged in the main event and replaced and damaged again in an aftershock. The windows were not damaged in this earthquake. Repairs to the tower were about $15,000.

The Burbank Airport was closed for approximately five minutes after the earthquake; however, there is normally little or no traffic at that time of night and no flights were diverted. The runways and taxi ways were undamaged. The terminal was closed for about two hours for inspection and to clean up fallen ceiling tiles. There was minor damage to HVAC ducts that were inadequately suspended. Likewise, wires supporting the ceiling broke allowing it to swing.

An older parking garage sustained some damage to column bases, requiring repairs, which were completed on January 20th. This structure had been seismically upgraded in 1990 and it was not necessary to close it for the repairs (1).

OBSERVATIONS AND RECOMMENDATIONS

Emergency power at some airports is only provided to life-safety functions, so that the loss of commercial power can be very disruptive to airport operations. The loss of baggage handling equipment, jetways, and reservation terminals would severely impact operations.

There is a need for guidance or standards for the installation of emergency power generators and their support systems.

Control tower windows are still vulnerable to earthquake damage.

Duct work and suspended ceilings have been damaged in a relatively new (1990) California facility. This suggests that the adequacy of these elements in other regions of the country, such as the Northwest and in the New Madrid area will also be deficient.

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11. OVERVEW OF TRANSPORTATION SYSTEMS

INTRODUCTION

The January 1994 Northridge earthquake caused extensive damage throughout the Los Angeles area, closing highways that carried some of the highest daily traffic volumes in the world for several months. Although catastrophic travel conditions were widely predicted, except for the first few days after the quake, excessive delays were not experienced and the transportation system continued to function throughout the reconstruction period. Detours were quickly established to take traffic around the closed freeway sections, utilizing city streets and sections of freeways that were not damaged by the quake. New carpool lanes were established to encourage ridesharing in an effort to reduce vehicular demand. Rail and bus enhancements were also implemented. This report discusses the impacts of the freeway closures, the effectiveness of the various mitigation measures, and how commuter behavior changed in the corridors that were most directly affected. On the affected corridors in which convenient local street detours were available (I-10 and SR-118), motorists appeared content to continue driving. On the corridors where alternate routes were few or nonexistent (I-5 and SR-14), rail ridership increased substantially. Bus utilization did not appear to have a major effect in any of the corridors. Users of the newly established carpool lanes experienced some time savings, but interestingly, overall carpool volumes did not appear to be much higher than pre-quake volumes, indicating that few new carpools were formed to take advantage of the lanes.

The magnitude 6.8 earthquake that occurred in Southern California on the morning of January 17, 1994 resulted in widespread damage throughout the Los Angeles area. Of the variety of structure types that sustained major damage, the collapse of several highway facilities were among the most visible to the rest of the world. Substantial disruptions to areawide travel occurred during the first few days after the quake, but the catastrophic traffic conditions that were widely predicted never materialized. Although unfortunate, the prolonged closures of several major transportation links provided a unique opportunity to examine motorist response to traffic disruptions of this magnitude and whether certain traffic management strategies are more effective than others under these circumstances.

This report describes the types of traffic management and mitigation measures that were implemented, how motorists responded to the commute choices that were available to them, and the traffic conditions that resulted. Recommendations on the types of actions and measures which worked well and could be successfully applied to similar situations in other areas are presented.

BACKGROUND

SETTING

The freeway system in and around the Los Angeles area of Southern California is considered to be the most extensive, if not necessarily the most modern, in the world. The area is criss-crossed by 27 freeways totaling 615 miles. The freeway system is further supplemented within the Los Angeles basin by a comprehensive local roadway network, which for the most part is on a grid system.

The Los Angeles basin area is physically separated from central and northern California by the San Gabriel and San Bernardino Mountain ranges. Access over the mountains is provided via Interstate 5, which runs the length of the state from the Oregon to Mexican borders, and also by State Route 14, providing access to the Antelope Valley communities of Lancaster and Palmdale. Except for these two freeways, there are no other convenient major public roadways that provide access over the mountains.

Public transit service in the Los Angeles area is provided primarily by the Los Angeles County Metropolitan Transportation Authority, with additional service available from a number of other operators. The Metrolink commuter rail system, in operation since 1992, provides train service connecting Ventura, Los Angeles, San Bernardino, and Riverside Counties.

PRE-QUAKE TRAFFIC MANAGEMENT FACILITIES

The freeway system and state highway system is operated by the State of California Department of Transportation (Caltrans) out of their Los Angeles "District 7" office. Traffic management activities are coordinated through the Traffic Management Center (TMC) in the Caltrans office in downtown Los Angeles. The TMC is staffed 24 hours a day, every day of the year by Caltrans traffic operations and maintenance and California Highway Patrol personnel. Extensive traffic monitoring and management capabilities were already in place on most of the major freeways well before the quake, including loops capable of monitoring speeds and flows, closed-circuit television cameras, and meters at most on-ramps. Permanently mounted overhead changeable message signs were also already in place approaching key freeway junctions. Emergency response Traffic Management Teams (TMT) also are deployed out of the downtown Los Angeles Caltrans office, providing the capability to fine-tune the traffic management response to individual incidents or closures.

The City of Los Angeles operates its Automated Traffic Surveillance and Control System, which was constructed in 1984. The system, consisting of a network of traffic signals that can automatically adjust signal timing in response to real-time traffic conditions, video surveillance of key intersections, and fixed changeable message signs, is housed in the city's Department of Transportation headquarters a short distance from the Caltrans TMC in downtown Los Angeles.

DAMAGED FACILITIES

Major damage affecting transportation facilities was confined to four major highways and interchanges (see Figure 1). The Santa Monica Freeway section of Interstate 10, connecting the westerly cities of Santa Monica, Beverly Hills and Culver City with downtown Los Angeles, suffered major damage at two overcrossings. Two of the connectors at the 5/14 interchange in Sylmar collapsed, severing the only freeway link over the mountains to Lancaster and Palmdale, as well as causing damage to the through-movement on Interstate 5. Except for the extensive damage at the interchange, Route 14 to the north was unaffected. Interstate 5, however, also suffered damage at several locations north of the 5/14 interchange, effectively closing the only other major highway link over the mountains. State Highway 118 in Granada Hills was closed when the eastbound roadway collapsed at two locations. Additional damage at other locations resulted in the closure of the entire section of Route 118 from I-405 to I-210 (about 4 miles) in both directions. At all of these locations, closures were immediate and total, with no freeway traffic able to pass through the damaged zones.

At a fifth location, State Route 1 (the Pacific Coast Highway), closures occurred during the first few weeks after the quake because of mud slide. However, repairs on Route 1 were completed by mid-February. Minor damage also occurred at many other highway locations. However, except for the locations described above, none of the closures lasted more than a few weeks.

The local street network was, for the most part, not significantly affected by the quake. Temporary closures were implemented at freeway overcrossings where major damage occurred and at locations where the structural integrity of nearby buildings was in question. This is similar to the experience after the 1989 Loma Preita earthquake in Northern California, where the only sustained damage to transportation facilities was on freeways. Outside of Los Angeles County there was relatively little damage to any roadways. In Orange County to the southeast of Los Angeles, the highway network remained relatively unscathed, although some damage occurred to other types of structures. Airports were also unaffected.

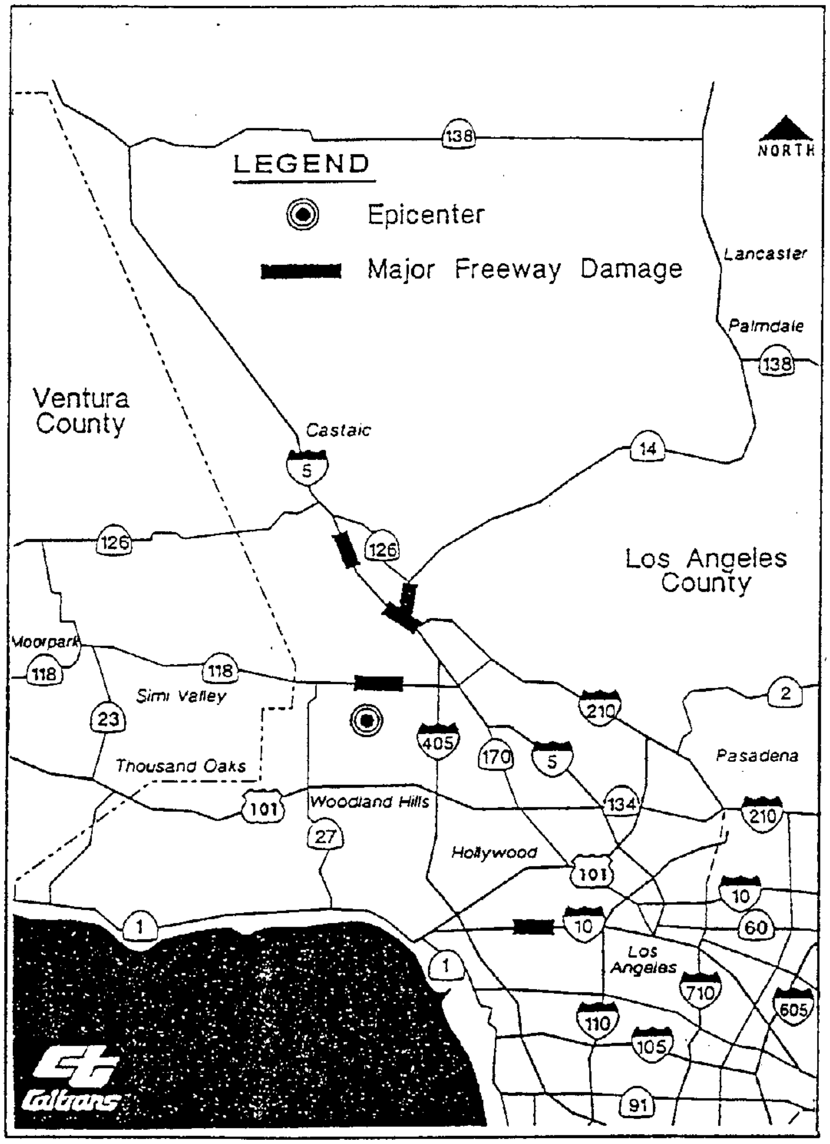


Fig. 11.1 Map showing locations of major bridge damage.

INITIAL RESPONSE

The primary effort within the first hours after the quake consisted of assessing the extent of damage to the roadway system and the provision of basic detours around the affected areas. This function was performed by all available and qualified personnel, but was handled mainly by Caltrans maintenance, construction, and structures staff. Traffic operations TMTs were dispatched to provide assistance in diverting traffic around the closures. Coordination of these efforts, as well as the dissemination of traffic closure information to the public, was handled through the TMC.

Power outages were widespread immediately after the quake, disabling traffic signals on the street system and hindering communications throughout the region. Electrical service to the Caltrans TMC was out, but backup generators and telephones continued to work.

The earthquake occurred very early on a Monday morning, when most of the population was still at home. Furthermore, that Monday was also Martin Luther King's birthday, a national holiday, and thus, many work trips would not have occurred anyway. As expected, areawide traffic volumes were substantially lower than normal in the first few days following the quake, which aided the recovery effort. By the week after the quake, however, workers began returning to their jobs and volumes increased dramatically, although overall volumes were still lower than normal. By mid-March, traffic conditions had generally stabilized throughout the area such that there were only minor day to day variations in peak period travel time.

Early rough estimates indicated that repairs would take from six months to a year. Interstate 5 was expected to reopen in August, Interstate 10 would reopen the month after, and State Route 118 and the 5/14 interchange would reopen towards the end of the year. Incentive clauses were incorporated into the repair contracts in order to encourage contractors to complete the work as quickly as possible. Nevertheless, throughout the reconstruction period, there was considerable uncertainty as to when each of the freeways could be reopened.

Once a determination was made as to which facilities would remain closed for extended periods, the task confronting traffic operations personnel was essentially the same as the underlying problem to congestion problems of any size: how to best balance capacity and demand.

MITIGATION MEASURES IMPLEMENTED

Initially, motorists that were originating or were destined for areas outside of the Los Angeles basin were encouraged to circumvent the area completely. Recommended routes were Route 101 to the west and Interstate 15 to the east. Use of these long distance detours added as much as 50 miles and several hours to trips. Although this was reasonable and would probably have been acceptable for a relatively short period of time, it was obvious that additional measures would be needed to handle traffic through the duration of the reconstruction period.

CAPACITY INCREASING MEASURES - ALTERNATE ROUTES & DETOURS

The use of local street detours was the mitigation measure that was implemented immediately after the quake and was the measure that ultimately proved to be the most effective. The Los Angeles Department of Transportation estimates that signals were re-timed at 300 intersections, and 1,000 directional signs and 7,500 temporary parking restriction signs were installed on the detour routes.

Interstate 10

Separate detours were implemented for High Occupancy Vehicle (HOV) and single occupant vehicles (see Figure 2). A two-or-more definition was instituted for the HOV detour. HOVs were given preferential treatment by allowing them to stay on the freeway as far as the interchange closest to the closure site and to reenter the freeway immediately past the closure. Single occupant vehicles, on the other hand, were required to exit the freeway two interchanges upstream of the closure and reentered the freeway further downstream of the closures than HOVs. Moreover, once on local streets, the HOV detour utilized streets that were significantly closer to the freeway than the streets utilized by the single occupant vehicles. As a result, the single occupant vehicle detour was about 5 miles longer than the HOV detour. In each direction on the freeway leading up to the detour off-ramps, one lane was designated as an HOV lane to permit HOVs to bypass some of the freeway congestion. This detour scheme was implemented on January 25th, and was revised on February 1st to increase efficiency.

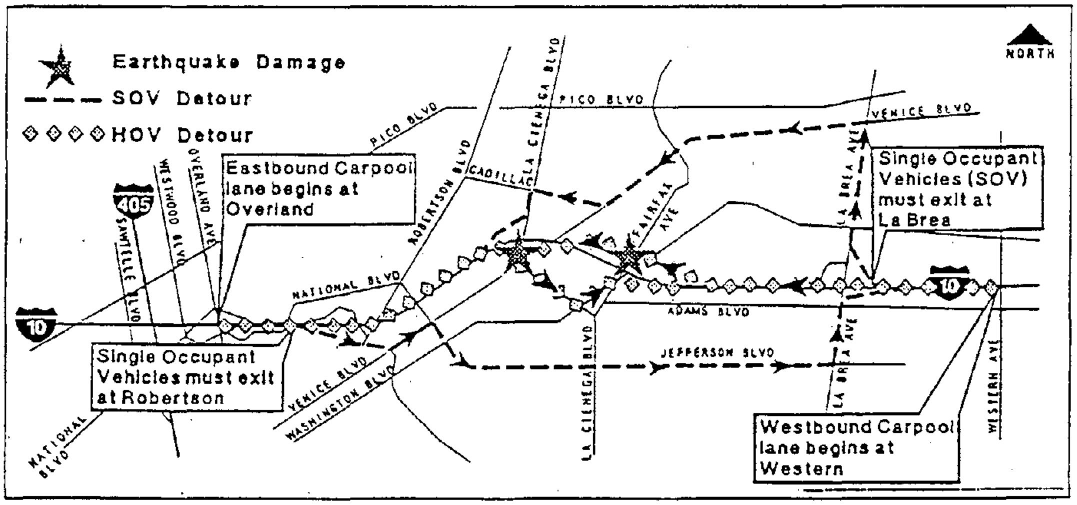


Fig. 11.2 Map of detours implemented on Interstate 10.

5/14 Interchange

Southbound traffic through the interchange was diverted onto local streets, which were initially converted to one-way operation during peak periods. Northbound traffic through the interchange used the undamaged truck lanes, which was modified to provide two mixed flow and one HOV lane. HOV lanes were opened on the southbound and northbound approaches to the interchange from State Route 14. By the end of January, the southbound local street detours were restriped to provide additional capacity without having to resort to one-way operation.

Interstate 5

A detour utilizing the Old Road, a high capacity local street paralleling the freeway, was implemented by January 29. All traffic was taken off of the freeway, onto the Old Road which accommodated two lanes in each direction, and then directly back onto the freeway downstream of the closure.

State Route 118

Initially, detours were established on local streets, which was relatively easily accommodated by the comprehensive street network in the area. Signal timing and phasing changes, lane restriping, and detour signing were implemented to support this detour. By February 21st, repairs had been sufficiently completed on the westbound roadway to allow it to be reopened to traffic. The roadway was then striped to provide three lanes in each direction, with a concrete barrier separating the two directions of traffic.

OTHER TRAFFIC MANAGEMENT ACTIVITIES

In the week after the quake, Caltrans personnel established a list of strategies that made up the earthquake relief Traffic Management Plan (TMP). These strategies were refined and implemented rapidly in the following weeks. Tow trucks, which had been assigned to some of the routes that were damaged as part of the Freeway Service Patrol program were re-deployed to patrol the detour routes. Highway Patrol enforcement was also increased through the COZEEP (Construction Zone Enhanced Enforcement Program) to provide traffic control support to expedite repair operations. Peak period helicopter service was leased from the Los Angeles Police Department to provide more rapid and accurate traffic surveillance capabilities. A public awareness campaign was instituted, focusing on providing information on alternative transportation options. Communications equipment, such as cellular phones, pagers, and two-way radios, were leased to facilitate contacts with field units.

EpiCenter

An Earthquake Planning and Implementation Center was constructed and field instrumentation was installed where traffic surveillance and motorist information systems were critically needed but were not available. This included the installation of changeable message signs, highway advisory radio systems, closed-circuit television cameras, vehicle detector systems, and a video image processing system —

all operated from the EpiCenter at the Caltrans Los Angeles District 7 office. Satellite linkups were installed to permit communications with equipment at remote sites where conventional linkups could not be implemented quickly enough.

DEMAND REDUCTION MEASURES

Transit Enhancements

Six of the bus transit systems operating in Los Angeles County added new emergency service, which consisted of the implementation of new routes and extension and revision of the schedules of existing service. Most of the bus service changes were implemented on routes on or near Interstate 10. Metrolink added extra trains and line extensions into the Antelope Valley and Westward to Camarillo to provide additional capacity for commuters isolated by the closures of Interstate 5 and Route 14. Within the first week, seven new trains were added, and service began operating out of new stations in Lancaster and Palmdale. Numerous shuttles were also put in service to connect Metrolink and Amtrak lines with major employment centers.

Park & Ride Lots

Three new park and ride lots were created at strategic locations in order to encourage the formation of carpools or use of transit. These lots were either newly constructed or made use of leased space on existing lots, and were located in the vicinity of the 5/14 interchange.

TRAFFIC CONDITIONS DURING THE RECONSTRUCTION PERIOD

Fortunately, because of the distance separating the damaged facilities and because of their geographical locations, the effects of each of the closures were generally independent of each other. The closure of the through-movement on Interstate 5 was, of course, closely inter-related with the closure of the 5/14 interchange. The Interstate 10 and State Route 118 closures, however, operated independently of each other and from the Interstate 5 and 5/14 interchange closures. Thus, there was no compounding effect which would have substantially exacerbated the already serious impacts of the individual closures.

INTERSTATE 10

The two-way average daily traffic (ADT) on Interstate 10 prior to the quake was approximately 310,000 at the point of the closure. Based on an average vehicle occupancy of 1.4 persons per vehicle, this translates to 434,000 people typically using the freeway on any given weekday, all of whom had to make decisions about how their trips would be made during the reconstruction period. The closure of the Santa Monica Freeway has been the most thoroughly studied of the closures to date, and in many respects, provided the most diverse spectrum of opportunities for commuters to choose from during the reconstruction period. Motorists could:

1. Continue to drive their automobiles and use the freeway, and then divert to the primary designated detour route.
2. Continue to drive, but divert to parallel freeways, such as the recently opened Interstate 105 (the Century Freeway) located about 8 miles to the south.
3. Continue to drive, but divert to other city streets or arterials that were not officially designated as alternate routes.
4. Form a carpool to take advantage of the new HOV lane and HOV detour.
5. Shift to transit, utilizing existing bus routes or one of the new routes implemented in response to the quake.
6. Change the time of day of travel.
7. Eliminate trips altogether.

Not unexpectedly, daily volumes dropped drastically in the first few weeks until the primary detours were established. ADTs were down by about two-thirds within the first week. Once the detours opened, volumes began climbing steadily, stabilizing at about 130,000, which accounts for 42 percent of the pre-quake ADT.

Extensive traffic counts were performed on parallel local arterials and freeways and a home interview survey was conducted in order to determine where the remaining trips had diverted to. Of the 310,000 daily vehicle trips that occurred on this section of Interstate 10 prior to the quake, 47,000 (about 15 percent) were eliminated altogether during the reconstruction period. Distribution of vehicle and person-trips are summarized in Table 1.

TABLE 1 Changes in Travel Route or mode on I-10

	Vehicles	People
PRE-QUAKE	310,000	434,000
RECONSTRUCTION		
Primary I-10 Detour	130,000	208,000
I-105	5,000	7,000
Other streets	128,000	155,000
Transit		2,000
Telecommuting		2,000
Trip eliminated		60,000
Reconstruction totals	263,000	434,000

Non-HOVs using the primary mixed flow detour during the peak commute periods experienced average delays of only 10 minutes compared to pre-quake travel times. Travel times on the HOV detour were even less, ranging from 3 to 5 minutes more than pre-quake travel times. In fact, once back on the freeway downstream of the closure, travel conditions were better than prior to the quake, since the output of the detours was approximately one-half of the pre-quake demand. As a result, in many cases the total trip travel time for HOVs was less than prior to the quake.

The number of vehicles that diverted to local streets other than the designated primary detour was virtually the same as the number that used the primary detour. Use of the most easily accessible alternate freeway, Interstate 105, was minimal, representing less than 2 percent of the total pre-quake vehicle trips. The low increase in volume was probably directly related to the high levels of delay on the north-south freeways that would have been used to take motorists from Interstate 10 to Interstate 105. Both Interstate 405 (the San Diego Freeway) and Interstate 110 (the Harbor Freeway) are heavily congested during peak periods.

Transit Utilization

Because of the relative ease of use of the local street detours and the comparatively minor delay associated with their use, increases in transit ridership in the Interstate 10 corridor were minimal. Daily boardings increased by about 2,000 passengers immediately after the quake, and then stayed at virtually the same level throughout the reconstruction period. By mid-March, transit operators began consolidating some of the new lines because ridership levels were not sufficient to justify the operating costs.

Effect on Ridesharing

Of particular interest on Interstate 10 was whether or not there would be a noticeable increase in ridesharing in response to the availability of the HOV detour. Prior to the quake, the number of vehicles carrying two or more occupants during the peak hour ranged from 1,000 to 1,400 vehicles. During the reconstruction period, HOV volumes ranged from 1,000 to 1,300 vehicles, although HOVs represented a much larger proportion of the total traffic flow because of the lower overall volume. After the reopening of Interstate 10 on April 12th, peak hour HOV volumes ranged from 1,200 to 1,500.

Thus, although it appears that there was an increase in ridesharing as a result of the HOV detour strategy, the increase was relatively minor. Several factors may have contributed to this. The time savings offered to users of the HOV lane and HOV detour may not have been large enough to instigate a significant change in travel mode. Moreover, the time saved on the HOV detour may not have been large enough to offset the additional time it would have taken to form a carpool each day. In addition, the amount of time savings may have been relatively small in relation to what the total trip times were. Nevertheless, the implementation of the HOV detour was clearly successful in reducing overall person-delay in the corridor.

INTERSTATE 5 AND THE 5/14 INTERCHANGE

The closures of Interstate 5 and the 5/14 interchange presented a substantially different set of travel options to commuters. At this time, however, the home interview survey and traffic performance data are still being analyzed and only preliminary conclusions can be made.

With few, if any, alternative roadways to use instead of the closed freeways, motorists had a much smaller set of choices to select from compared to Interstate 10. Motorists could:

1. Continue to drive on the freeway in single-occupant autos.
2. Form carpools to take advantage of the State Route 14 HOV lanes.
3. Shift to one of the new Metrolink rail lines.
4. Change the time of day of travel.
5. Eliminate trips altogether.

Travel patterns on Interstate 5 and State Route 14 are highly directional. The primary flow during the morning commute period is southbound, heading towards the Los Angeles basin, and is reversed in the afternoon commute period. In the off-peak direction during commute periods, and during most other times of the day, demands are low enough that virtually no recurrent congestion occurred in spite of the reduced freeway capacity.

Conditions on Interstate 5

The capacity of the two lanes in each direction on the Old Road was generally adequate to handle all but the peak period demands. Peak period travel times were extremely variable during the first month after the quake, with motorists experiencing individual delays as high as one hour. By early March, conditions had generally stabilized, with 10 to 15 minutes of delay in the southbound morning peak and 5 to 10 minutes in the northbound afternoon peak. Vehicles using the detour at times other than the peak period experienced no congestion at all, and use of the detour at those times added only about 2 minutes to trips.

Conditions on State Route 14

The combined capacity of the freeway lanes and improved parallel local streets was also adequate to handle traffic demands, except during the commute periods.

Peak period individual delays in the days following the quake were as high as 40 minutes. By early February, after the detours had been improved, delays through the interchange decreased significantly, stabilizing at about 10 minutes in the southbound morning peak and about 20 minutes in the northbound afternoon peak. During the off-peak, there was no congestion on State Route 14 or on the local street detours. At these times of the day, use of the detour added virtually no time to trips.

Time savings for users of the HOV lanes ranged from 5 to 20 minutes during peak periods. HOV lane volumes were approximately 1,500 vehicles during the peak hour. Violations of the two person per vehicle minimum occupancy ranged from 1 to 14 percent dependent on the level of Highway Patrol enforcement.

Transit Utilization

Prior to the quake, the northerly terminus of Metrolink service was at the Santa Clarita station near the 5/14 interchange. Daily ridership was about 1,000 boardings per day. The extensions into Lancaster and Palmdale opened on Friday, January 21st. By the following Tuesday, daily ridership peaked at almost 22,000 boardings, leading to expectations that the rail line would relieve much of the expected freeway congestion and that these ridership levels could be sustained over a long term period. A week later, however, ridership had dropped off to about 13,000, steadily declining through the reconstruction period as shown in Figure 3.

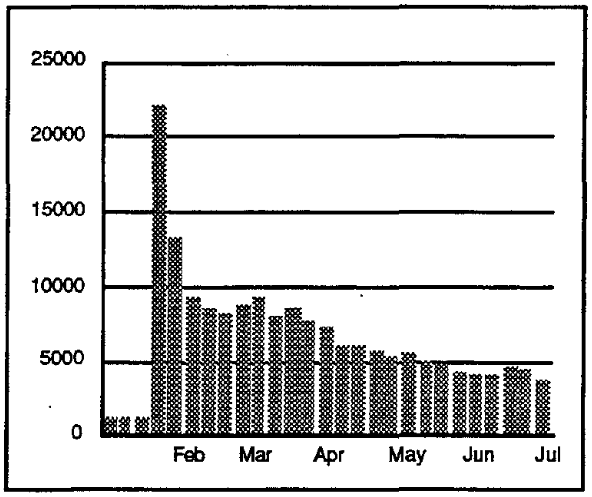


Fig. 11.3 Ridership on the Santa Clarita Metrolink Line During Reconstruction.

By the time the through-movement on Interstate 5 opened in mid-May, daily boardings were less than 5,000. Just before the major connectors at the 5/14 reopened in early July, ridership was at about 4,300 per day. In spite of the inability to sustain the very high ridership levels immediately following the quake, the Metrolink extensions still proved vital in reducing demand on the freeway.

STATE ROUTE 118

The two-way average daily traffic volume on State Route 118 immediately to the east of the closure was about 123,000 prior to the quake. Until the freeway detour was opened on February 21st, all traffic was being diverted onto the local street detours. As a result, daily volumes on the adjacent freeway sections were less than 50 percent of the pre-quake volume. Some of the local streets were carrying as much as an additional 30,000 vehicles per day. Peak period delays using the designated local street detours were as high as 30 minutes.

Once the freeway detour opened with three lanes in each direction, virtually all delay was eliminated. Daily freeway volumes are still slightly below pre-quake levels, with the local street system absorbing the difference.

IMPACTS TO TRUCK TRAVEL

The closures of Interstate 5 and State Route 14 raised considerable concern with respect to impacts to commercial truck traffic and commodities movements. Truck intercept surveys were conducted in May at truck inspection facilities at entry points to the Los Angeles area. Telephone surveys were conducted during May and June with 300 shipping companies in the Los Angeles basin. At this time, the survey data is still being analyzed. However, these preliminary conclusions can be made:

- Between 30 to 50 percent of the truck trips into the Los Angeles area were canceled immediately following the quake.
- Until the detours were firmly established, long distance detours via State Routes 58 and 138 and Interstate 15 were used by about one-fourth of the truckers to enter and leave the area. Truck rerouting was the most common action taken by shippers in response to the closures.
- Once the detours were in place, truck volumes returned to pre-quake levels and virtually all trucks returned to their normal routes.
- Rescheduling of shipments was employed by almost one-half of the firms surveyed, with one-fourth reporting less frequent deliveries and pickups.
- Estimated increases in operating costs were estimated to be about 8 percent. A more detailed review of the economic impacts on these firms is currently being conducted by the University of California, Irvine.

COST OF DELAY

Motorist delay costs associated with the closure of Interstate 10 are conservatively estimated to be about $990,000 per weekday. Delays due to closures at the 5/14 interchange were about $436,000 per weekday. This correlates very closely with the independent estimate by the Governor's Office of Planning and Research and with the early-completion incentives offered to the repair contractors. These estimates do not include the economic impact of disruption to commercial traffic movements, loss of business due to trips being eliminated, and loss of jobs.

Delay cost estimates were developed by establishing screenlines across the affected corridors, determining the daily volume of traffic that crossed the screenline prior to the quake, and then calculating the aggregate increase in delay based on data collected on the detour routes. Costs were based on standard factors established by the State of California.

FINDINGS AND RECOMMENDATIONS

PROVIDING IMMEDIATE TRANSPORTATION SOLUTIONS TAKES PRECEDENCE OVER THE OPPORTUNITY TO CHANGE MOTORIST BEHAVIOR

Although the opportunity clearly presents itself to use disasters affecting transportation facilities as an opportunity to make long term changes in driver behavior by establishing new HOV lanes or new & increased use of transit, undeniable political realities must be considered. Whether it is truly feasible to provide "less" vehicular capacity than can actually be provided in order to encourage a modal shift needs to be carefully considered in the context of whether the alternative measures will be able to provide congestion relief, whether they will be adequately used, and whether the benefits of sustained mode shifts compensate any long term negative perceptions that may develop.

STABILIZATION OF TRAFFIC CONDITIONS CAN TAKE SEVERAL WEEKS TO SEVERAL MONTHS

Large fluctuations in traffic conditions can be expected during the initial period following the disaster. Depending on the magnitude of impacts to the system, it may take weeks or months before conditions stabilize into a regular pattern. Consequently, it may not be feasible, nor would it be necessarily cost effective, to attempt to develop the initial traffic mitigation strategies on a real-time basis. A more efficient approach would be develop large-scale strategies based on known pre-disaster travel patterns, and then make adjustments based on data collected over a reasonable period of time.

WHERE SUFFICIENT ALTERNATE ROUTES EXISTED, MOTORIST CONTINUED DRIVING; WHERE CONVENIENT DETOURS WERE NOT AVAILABLE, TRANSIT OPTIONS BECAME MUCH MORE ATTRACTIVE.

The difference in response to the Interstate 10 closure compared to the Interstate 5 and 5/14 closures indicate that where alternate routes are available, motorists were content to continue driving. Increases in bus ridership in the Interstate 10 corridor were very minor. The magnitude of the time savings offered to HOV lane users was probably insufficient to generate any substantive degree of modal shift. Moreover, the closures were not sustained over a long enough period to elicit major mode shifts.

The dramatic increase in Metrolink ridership in the Interstate 5 and State Route 14 corridors immediately following the quake clearly point to the importance of providing transit options on corridors where alternate routes are limited or unavailable. However, once the freeway detours were opened and overall traffic conditions stabilized, ridership decreased sharply. What this means with respect to the long term viability of transit in the Los Angeles area will be the subject of much debate in the future. Whether this experience can realistically be applied to other areas is another important question that cannot be answered at this time.

A REVIEW IS NEEDED OF ISOLATED COMMUNITIES THAT ARE CURRENTLY SERVED BY A SINGLE TRANSPORTATION FACILITY.

Although the detours that were established were successful in providing access to the Antelope Valley, traffic handling could have been substantially more difficult had there been more damage to the highway system or if the Metrolink extensions were not feasible. A review is needed to determine to what extent additional capacity is needed over the San Gabriel and San Bernardino Mountains, if nothing else, to be able to respond to emergencies such as this one. This review could be expanded to include a search for other similarly isolated communities and to provide an estimate of what the economic impacts of prolonged closures might be.

AVAILABILITY OF ACCURATE TRANSPORTATION DATA IS CRITICAL IN DEVELOPING EMERGENCY RESPONSE

A database of information should be developed in anticipation of such disasters, integrating data from all transportation providers. Data concerning traffic volumes, travel times, origin & destination information, and transit ridership & schedules should be compiled and stored at a single accessible location. Computer modeling may be useful for this purpose.

After the disaster, a comprehensive data collection effort should begin immediately in order to provide timely and accurate information to the public, to develop mitigation measures, and to determine delay costs with which repair contract incentive clauses my be based.

EMERGENCY RESPONSE PROCEDURES NEED TO BE EXPANDED TO HANDLE MAJOR DISASTERS

"Standard" emergency response measures were already in place and worked well. These include the availability of emergency response teams, widespread use of communications devices such as cellular phones & pagers, and fully-equipped remote field offices. A variety of interagency agreements were already in place which expedited the work between transportation providers.

However, the magnitude of this disaster revealed several areas that require improvement. Detailed procedures should be established in advance to determine how personnel from other locations can be transferred rapidly to the disaster site. These procedures should include a quick approval process for renting or leasing equipment. Media relation training should be given to key staff who will be on the front lines of the recovery effort. Hiring of public relations consultant firms can be extremely beneficial in satisfying the insatiable thirst for disaster information, freeing up personnel to expedite recovery work. Earthquake drills involving all agencies could also be expanded.

AREAS WITH WELL-DEVELOPED TRAFFIC MANAGEMENT CENTERS ARE ABLE TO ACCOMMODATE SUDDEN CHANGES EASILY.

Properly equipped and well-staffed traffic management centers are an invaluable tool in dealing with transportation emergencies of this magnitude. The availability of devices such as closed-circuit television cameras and roadway detection loops were critical in being able to monitor freeway conditions quickly and frequently. This resulted in more accurate information being given to the public, either via the freeway changeable message signs or through the media. However, the availability of traffic management equipment is by no means a substitute for engineers with the necessary training and experience to develop appropriate operational solutions quickly.

12. GAS SYSTEMS

ABSTRACT

There were approximately 151,000 gas outages as a result of the Northridge earthquake. At the recovery effort peak, there were 3,400 personnel of the Southern California Gas Company involved in restoration, including 460 from neighboring utilities. There were 35 non-corrosion related repairs in the transmission system, of which 25 were at cracked or ruptured oxy-acetylene girth welds in pre-1932 pipelines. There were only 27 repairs in polyethylene distribution piping, even though there were 24,045 km (14,935 mi.) of polyethylene pipe in service at the time of the earthquake. Such performance provides strong evidence of the favorable seismic response of polyethylene piping. Observations emphasize the vulnerability of mobile homes, and suggest the need for improved seismic codes for this type of structure.

INTRODUCTION

This section provides a description of the Northridge earthquake response of gas systems, beginning with an overview of the gas facilities of the Southern California Gas (SoCalGas) Company. General performance statistics are summarized. Specific treatment is provided for gas transmission facilities at the Aliso Canyon Gas Storage Field, Potrero Canyon, and Balboa Blvd. in Mission Hills. Information is summarized with respect to recovery activities, residential gas service performance, and seismic gas shutoff valves. The overall performance of the gas transmission system is evaluated. Observations, lessons learned, and recommendations are summarized.

SYSTEM DESCRIPTION

The natural gas system in the Los Angeles metropolitan area is owned and operated by SoCalGas. It is the largest U.S. gas system in terms of customers, with approximately 4.7 million metered services. According to company statistics for 1993, there are 6,123 km (3,803 mi.) of steel transmission pipelines and 43,162 km (26,809 mi.) and 24,045 km (14,935 mi.) of steel and plastic distribution mains, respectively. The transmission pipelines are predominantly 200 to 900 mm (8 to 36 in.) in diameter and are operated at pressures generally exceeding 1 MPa (150 psi). The distribution system is composed of pipelines predominantly 50 to 300 mm (2 to 12 in.) in diameter, limited to pressures of 0.42 MPa (60 psi) or less. The plastic piping is made of medium density polyethylene. SoCalGas identifies an additional category of pipeline, referred to as distribution supply line, which is predominantly 50 to 300 mm (2 to 12 in.) in diameter and is operated typically in the range from 0.7 to 2.8 MPa (100 to 400 psi).

In this work, transmission and distribution pipelines are defined in accordance with the Federal Code of Regulations [Office of the Federal Register, 1990] and General Order No. 112-D pertaining to the State of California [Public Utilities Commission of the State of California, 1988]. In essence, a transmission line transports gas from a gathering line or storage facility to a distribution center or storage facility, and operates at a hoop stress of 20% or more of the specified minimum yield strength (SMYS) of the pipe steel. A distribution line is a pipeline other than a transmission or gathering line. Distribution supply lines may be classified as transmission or distribution lines, depending on hoop stress level and function. The maximum allowable operating pressure (MAOP) of a transmission line is the highest pressure it is intended to operate at and often is larger than transmission pressures under normal operating conditions.

OVERVIEW OF SYSTEM PERFORMANCE

There were approximately 151,000 gas outages as a result of the earthquake. SoCalGas estimates that approximately 88% of the outages are attributable to customers shutting off their own services. Service was restored to approximately 84,000 customers within one week of the earthquake, and to over 119,000 within one month of the earthquake. Of the remaining 32,000 customers, a large portion restored their own services or had a plumber do so. Service could not be restored to 9,100 customers because of structural property damage.

There were approximately 154 instances of damage to metallic distribution mains and services where no corrosion or construction-related damage was observed. There were 27 instances of damage to polyethylene pipes, the majority of which were at socket fusions and older style transition fittings. In addition, there were 536 instances of damage to metallic distribution piping where corrosion or material-and construction-related defects were observed, or where damage was of unknown origin. There were 35 non-corrosion related repairs in the transmission system, of which 25 were at cracked or ruptured oxy-acetylene girth welds in pre-1932 pipelines. Figure 12-1 shows a plan view of selected transmission pipelines in the area of most severe ground shaking. Locations of damage in the form of pipeline breaks, leaking flanges, and a fractured flange are shown in the figure. Figure 12-2 is a map of the area just north of the earthquake epicenter, showing the Aliso Canyon Gas Storage Field and the locations of two gas transmission line breaks on Balboa Blvd.

Flange leaks occurred at the four locations shown in Figure 12-1 at sections of above ground piping. There was also a break in an oxy-acetylene weld in Line 85 at a location approximately 39 km (24 mi.) northwest of Newhall, which is not shown in the figure. Damage was mainly in the form of flange separation and leaking gaskets. One of the flanges shown in Figure 12-1 was fractured. At the damaged locations, Line 85 is a 650-mm- (26-in.)-diameter pipeline with a pipe wall 6.4 mm (0.25 in.) thick, SMYS of 224 MPa (33,000 psi), and MAOP of 2.2 MPa (317 psi). The ruptured oxy-acetylene weld and four leaking flanges occurred in a partially reconditioned portion of Line 85. The weld failure was at an original oxy-acetylene weld.

There was a break at a weld in Line 85 near Taft, approximately 120 km (75 mi.) north of the epicenter. This section of the pipeline was constructed in 1931 with electric arc welds. The line had an MAOP of 2.5 MPa (360 psi). There was a leaking flange at an aboveground section of Line 119 north of the area shown in Figure 12-1. This section of the 550-mm- (22-in.)- diameter pipeline was constructed in 1931 with a wall thickness of 7.9 mm (0.312 in.). The SMYS of the steel and MAOP were 208 MPa (30,000 psi) and 2.5 MPa (360 psi), respectively.

A fractured oxy-acetylene girth weld was repaired in Line 122 at the location shown in Figure 12-1. Although this pipeline is not operated as a transmission line, it nevertheless is described in this report because of its relatively high operating pressure of 1 MPa (150 psi). The 375-mm (15-in.) pipeline was installed in 1927 with oxy-acetylene girth welds, 6.4-mm- (0.25-in.)-thick wall, and steel of unknown grade.

As indicated in Figures 12-1 and 12-2, there was damage to gas storage field facilities and transmission pipelines in Potrero Canyon and Balboa Blvd. A description of the earthquake effects in each of these areas is provided in the next three sections.

GAS STORAGE FIELDS

The Aliso Canyon Gas Storage Field, which covers some 14.7 km ADVANCE \U 3.60 2 ADVANCE \D 3.60 (3,600 acres) and 56 km (35 mi.) of access road, is used to store gas in an underground reservoir that once was used for oil production. Gas is injected during low demand summer months and withdrawn during high demand winter months. Earthquake effects in the facility included deformation of aboveground pipe supports, displacements of runs of injection and withdrawal lines, and structural damage to a fin fan unit used to cool compressed gas before its injection into storage wells. The supply of gas from Aliso Canyon was interrupted for five days.

As shown in Figure 12-1, there was a break in Line 104 inside the Aliso Canyon Gas Storage Field. The pipeline is 250 mm (10 in.) in diameter and has an MAOP of 1.6 MPa (228 psi), but it is operated at 1.4 MPa (200 psi). It was constructed with

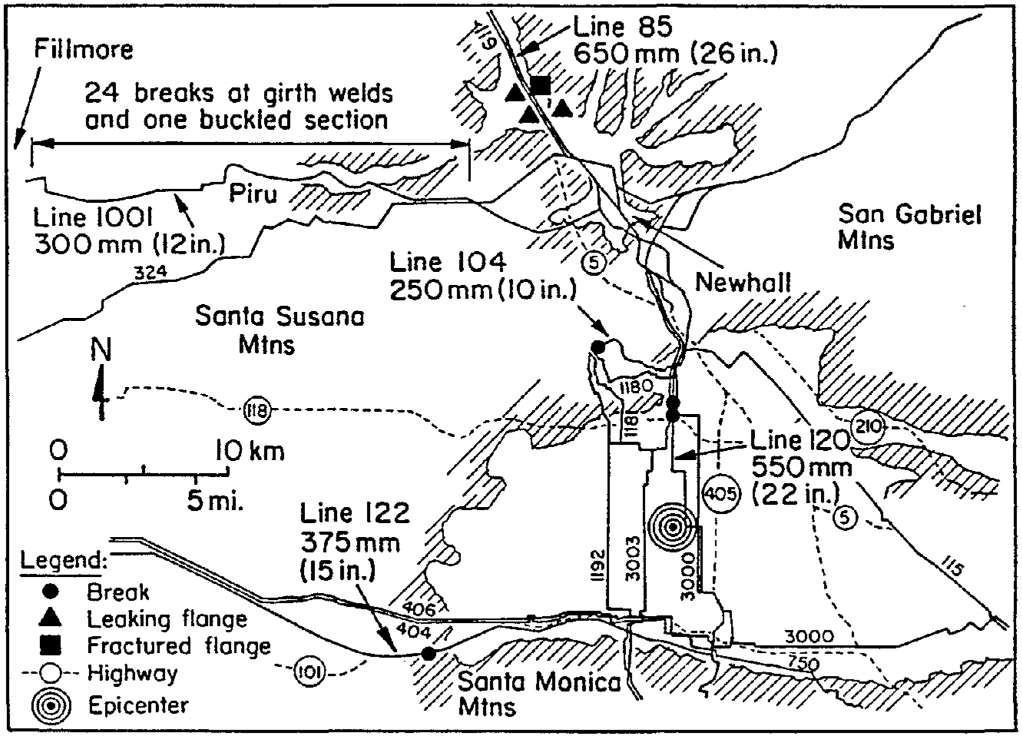


Fig. 12-1. Map of gas transmission pipelines in the area of strong ground shaking.

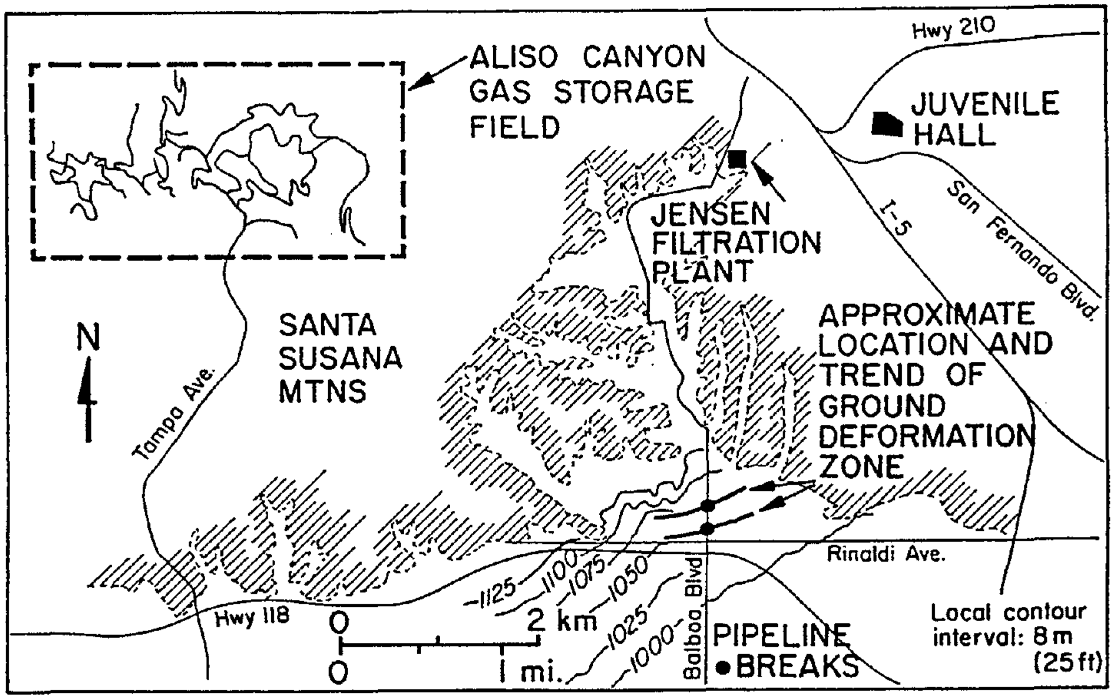


Fig. 12-2. Map of the area north of the Northridge earthquake epicenter.

electric arc girth welds in 1941. The pipe has a 5.2-mm- (0.203-in.)-thick wall of unknown grade steel.

Figure 12-3 shows a plan view of Line 104 in Aliso Canyon relative to the site topography. The rock in the area covered by the figures is highly fractured, friable siltstone and sandstone with 0.6 to 3 m (2 to 10 ft) of silty sand cover in many places. Pipe damage appears to be related to slope displacement perpendicular to the pipeline, which also caused an adjacent 100-mm- (4-in.)-diameter, steel fuel oil line to fail at an aboveground vertical bend. Slope displacement adjacent to the access road in the northeast part of the figure threatened Line 104, and the pipeline was excavated in the slope area to free it from the adjacent soil.

Three water tanks in the facility were damaged. The tank supplying water to the main plant was not damaged, but pipelines conveying water from the tank developed leaks, thereby cutting off supply. Of approximately 12 oil storage tanks in the facility, six were damaged. One tank collapsed and another at the same location sustained a split seam. Damage at other oil storage tanks was relatively minor and consisted of buckling and warping of steel plates. The fuel gas system used for heaters and plant instruments was disrupted in several locations. A number of transformers fell from poles, disrupting electrical service.

Because of failed water tanks and associated piping damage, water supply inside the facility was disrupted. Because of damage to Los Angeles Department of Water and Power trunk and distribution mains, water supply from outside the facility also was disrupted. Vacuum trucks were dispatched to locations of leaking trunk lines outside the facility, where water was collected and brought back to Aliso Canyon for use at the storage field facility.

Figure 12-4 shows a plan view of surficial ground movement and gas facilities near the location of a leaking flange in Aliso Canyon. Downslope movement at the Wye structure caused deformation at the flange of a withdrawal pipeline, thereby breaking the seal at the gasket. Local soil and rock failure exposed the drilled shaft foundations of aboveground pipeline supports north of the Wye structure. Withdrawal and injection lines along the access road were deformed by fallen debris in the landslide area at the eastern side of the figure.

With the exception of a leaking flange in an area of slope movement, there were no leaks or ruptures of aboveground withdrawal and injection pipelines. Serious damage to aboveground pipes was scarce, even though there were many deformed pipe supports and sections of line undermined and distorted by local landslides.

There was damage at the Honor Rancho Storage Field near Newhall. Earthquake effects at this installation were considerably less than those at Aliso Canyon. There was disruption of the fire loop system, brine filtration equipment, and access roads. A

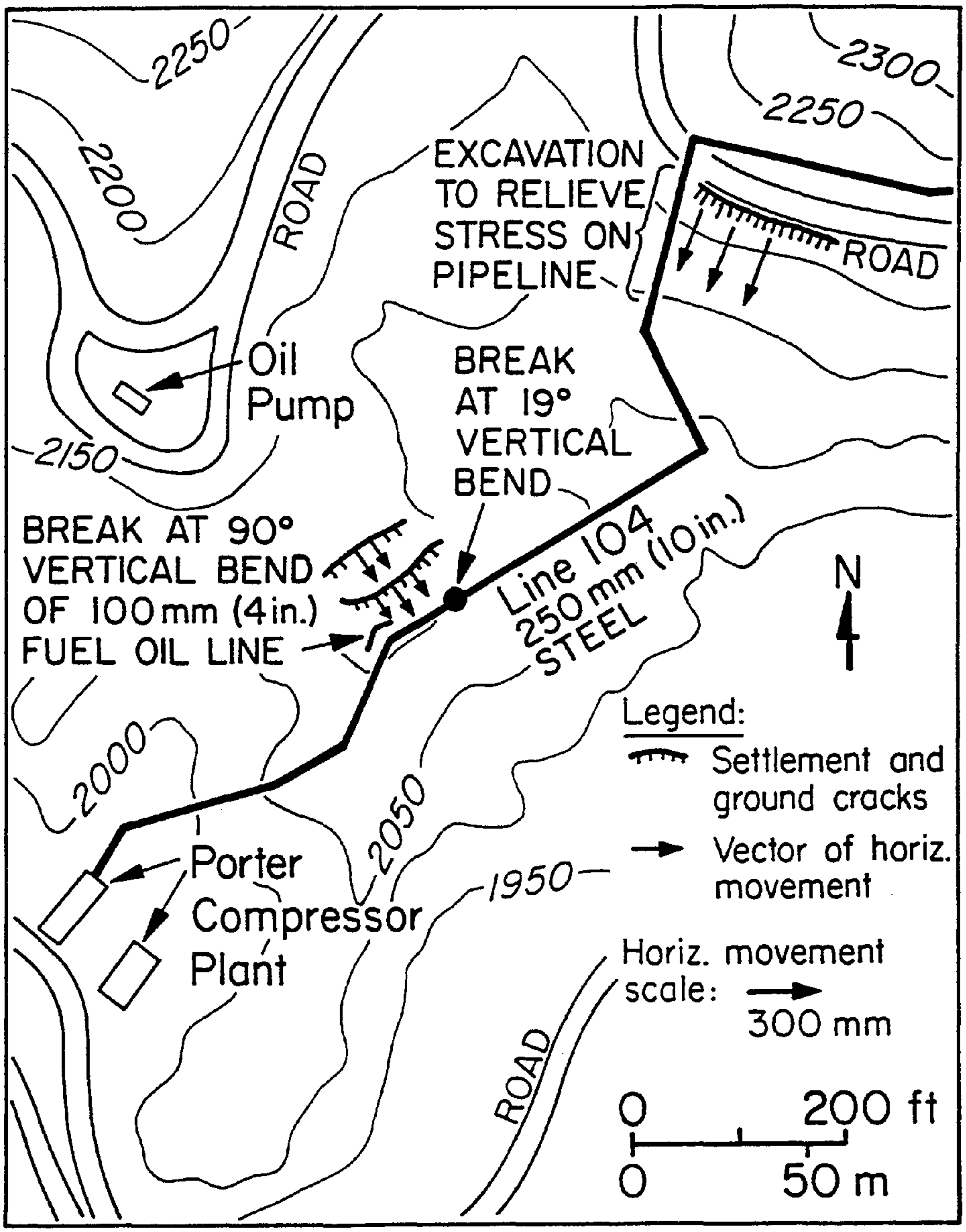


Fig. 12-3. Plan view of Line 104 in the Aliso Canyon Gas Storage Field.

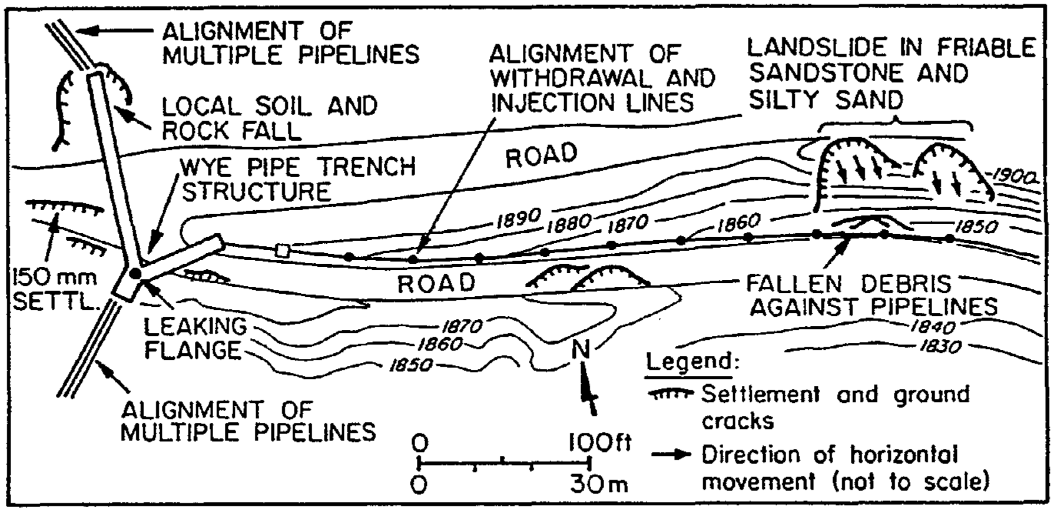


Fig. 12-4. Plan view of Wye pipe trench structure and aboveground pipelines influenced by local landslide activity at Aliso Canyon Gas Storage Field.

400-mm- (16-in.)-diameter water main, water tank, gas piping, and electrical transformer also were damaged.

POTRERO CANYON

As shown in Figure 12-1, there were 24 breaks at oxy-acetylene girth welds and one location of buckled pipe in Line 1001, which conveys gas between Newhall and Fillmore, many of which were in Potrero Canyon. Line 1001 was constructed in 1925, and was operated at the time of the earthquake at 1.7 MPa (245 psi) internal pressure. The pipeline is 300 mm (12 in.) in diameter, with 5.6-mm- (0.22-in.)-thick wall of unknown grade steel.

Of the 25 repairs in Line 1001, 18 were southeast of the Santa Clara River, both near and within Potrero Canyon. Six breaks in oxy-acetylene welds were located in areas north of the Santa Clara River and east of Piru. One oxy-acetylene weld ruptured at the eastern city limits of Fillmore, leaving a crater approximately 2.7 m deep and 4.5 m by 6 m (8.9 ft x 14.8 ft x 19.6 ft) in area. Gas escaping at the location of this break under Highway 126 was ignited by a downed power line.

Significant permanent ground deformation was reported in Potrero Canyon [Stewart, et al., 1994]. The canyon is filled with alluvial and colluvial deposits to a maximum depth of about 80 m (262 ft). Sand boils were observed at several locations along the canyon, and prominent ground ruptures were plotted [Stewart, et al., 1994]. Along the southern margin of the canyon, ground cracks were both compressional and extensional, with minor left lateral offsets. Multiple ground fractures within zones 2 to

18 m (6.6 to 59 ft) wide accommodated as much as 600 mm (24 in.) of vertical movement.

Figure 12-5 shows the location of Line 1001 in Potrero Canyon in relation to ground deformation features and sand boil locations mapped by Rymer, et al. (1995). Ten locations of pipeline repair are shown in the figure, all of which were separations and cracks at oxy-acetylene welds. Approximately half the locations of pipeline repair coincide with mapped ground cracks.

Both permanent ground movements and strong shaking were experienced in the canyon. A nearby strong motion station on soil recorded peak horizontal acceleration of 0.46 g [Stewart, et al., 1994]. Rymer, et al (1995) report 115 cm/sec (45 in./sec) peak ground velocity at the east end of the canyon with a pulse duration of nearly 2 sec. They suggest that a strong up-dip projection of energy from the causative fault played an important role in generating the ground deformation observed in the canyon.

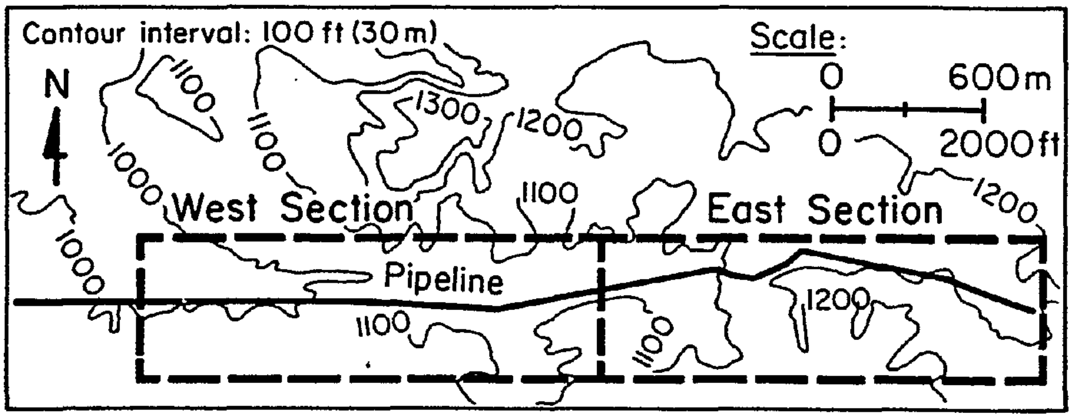
Line 163.10 is located at the eastern end of the canyon. It is a 400-mm- (16-in.)-diameter pipeline of Grade B steel, constructed in 1950 with shielded electric arc welds and 6.3-mm (0.25 in.) wall thickness. No damage was detected in this pipeline.

BALBOA BOULEVARD

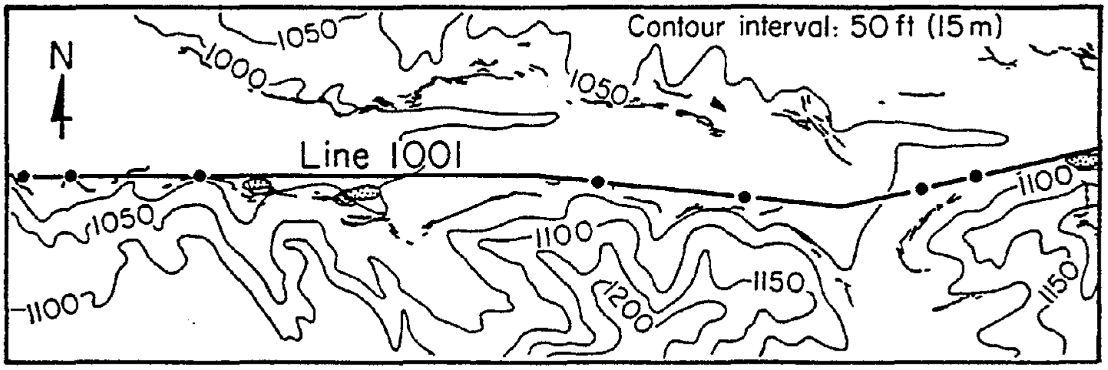
Figures 12-6 and 12-7 show maps of the pipelines in Balboa Blvd. near the zones of permanent ground deformation. There were six transmission and water trunk lines at this site. There were two 750-mm- (30-in.)-diameter gas transmission lines with 9.5-mm-(0.375-in.)-thick wall, constructed of X-52 steel in the 1950s which were not damaged. There was a 400-mm- (16-in.)-diameter petroleum pipeline, operated by the Mobil Oil Corporation, which was not damaged. The pipeline was composed of X-52 steel and installed in 1991. Two water trunk lines, the 1,240-mm- (49-in.)-diameter Granada and the 1,730-mm- (68-in.)-diameter Rinaldi Trunk Lines, failed in tension and compression in the tensile and compressive zones of ground deformation, respectively.

Gas pipeline damage on Balboa Blvd. occurred in Line 120, a 550-mm- (22-in.)-diameter steel pipeline constructed in 1930 with unshielded electric arc girth welds. At the time of the earthquake, the line was operated at about 1.2 MPa (175 psi). The pipe had a wall thickness of 7.2 mm (0.281 in.) and was composed of Grade B steel. The pipeline failed in tension in a zone of tensile ground deformation about 300 m (900 ft) north of a zone of compressive ground deformation where the pipe failed by compressive wrinkling.

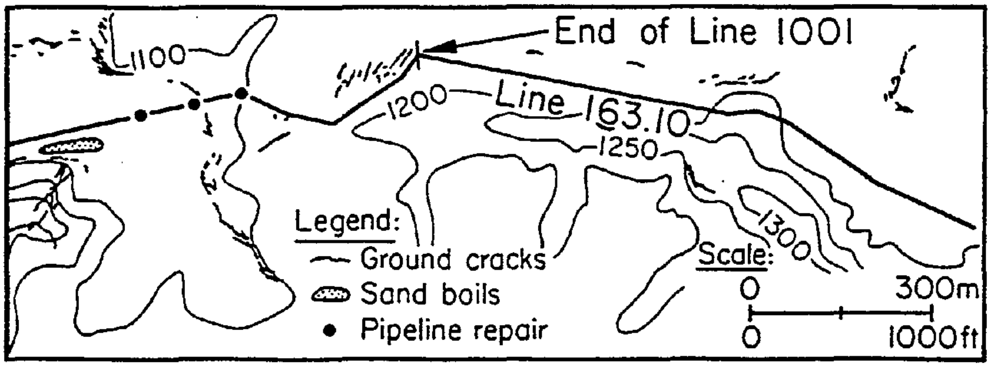
As shown in Figure 12-2, the ground rupture zones occurred in the toe area of an alluvial fan and are oriented subparallel to the surface elevation contour lines. The pattern of ground deformation suggests that lateral deformation of the alluvial fan



a) Potrero Canyon



b) West Section



c) East Section

Fig. 12-5. Map of locations of pipeline repair and ground deformation features in Potrero Canyon. [Based on map prepared by Rymer, et al. 1995.]

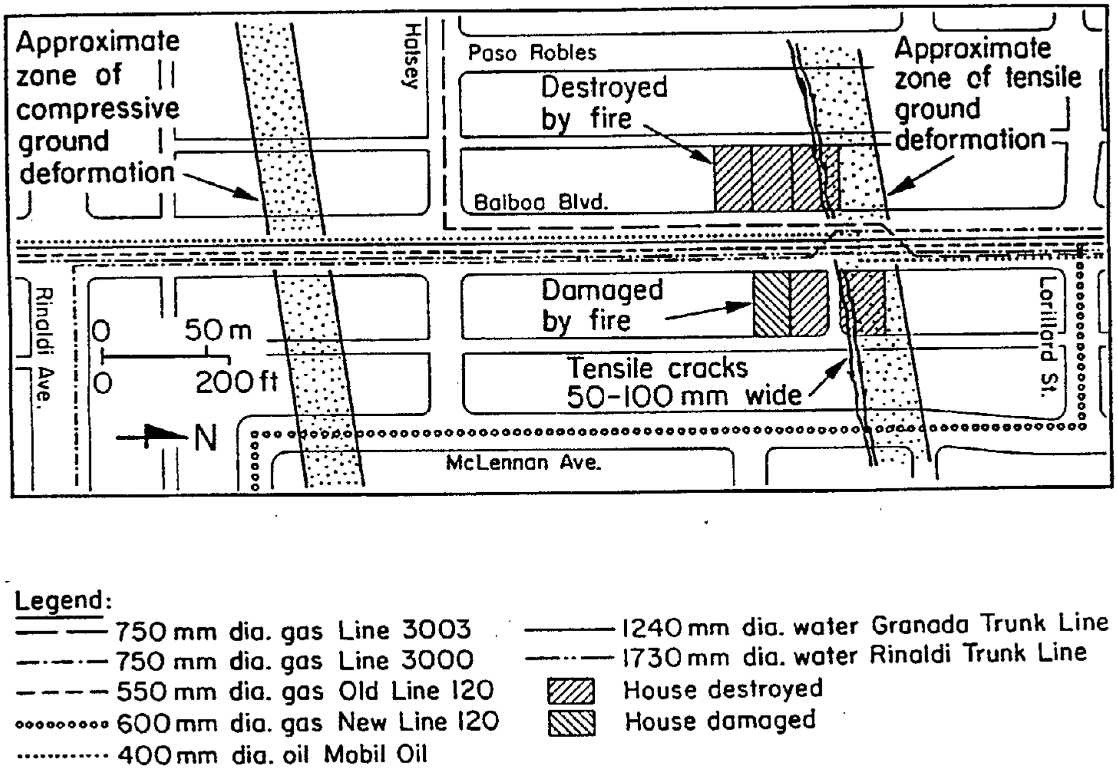


Fig. 12-6. Map of major pipelines, fire damage, and ground deformation on Balboa Boulevard.

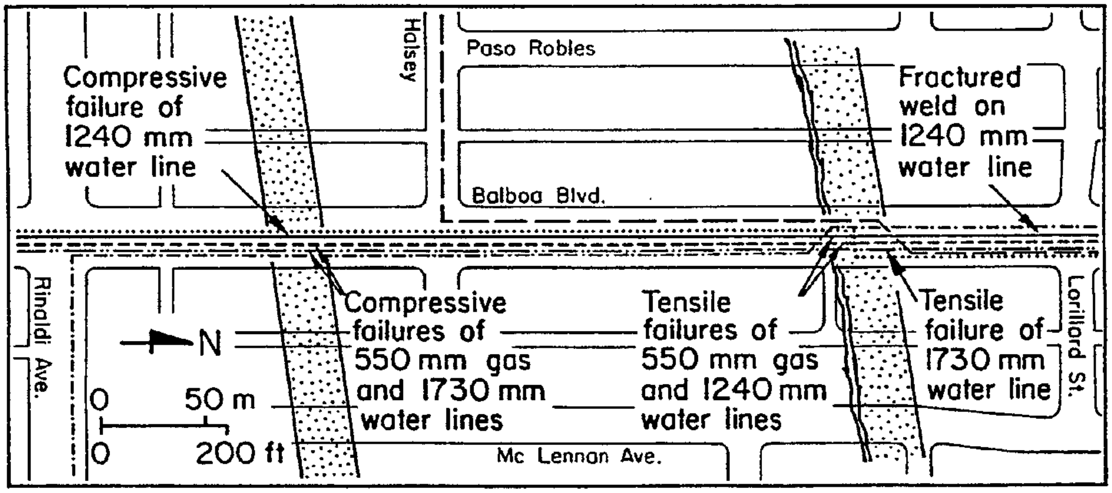


Fig. 12-7. Map of major pipelines, ground deformation zones, and locations of pipeline damage on Balboa Boulevard.

sediments took place. There is no clear evidence of liquefaction at this site. Nearby boreholes show loose silty sands at depths of 9 to 12 m (30 to 40 ft), but water levels are indicated at depths exceeding 20 m (60 ft) in dense materials.

Gas escaping from Line 120 was ignited by sparks from the ignition system of a pickup truck that had stalled in the area of tensile ground deformation flooded by the ruptured water trunk lines. The gas fire spread to adjacent properties, destroying five houses and damaging an additional structure.

Line 120 had been scheduled for replacement in the Granada Hills area. A new 600-mm- (24-in.)-diameter pipeline, with electric arc girth welds, X-60 steel, and 6.4-mm- (0.25-in.)-thick wall, had been constructed parallel to the older 550-mm- (22-in.)-diameter line along McLennan Ave. It had not been opened for gas flow at the time of the earthquake. Even though it crossed similar zones of tensile and compressive ground deformation, it was not damaged.

A 150-mm- (6-in.)-diameter gas distribution pipeline along the eastern side of Balboa Blvd. was ruptured in tension and compression in the tensile and compressive ground deformation zones, respectively. This pipeline was operated at a pressure of approximately 0.3 MPa (45 psi). Gas escaping from the tensile rupture caught fire.

A detailed examination of sections of Line 120 and the Granada Trunk Line, which were removed from the compressive ground deformation zone, each disclosed a compressive shortening of approximately 250 mm (10 in.). In each case, the compressive shortening and line failure occurred at a welded joint. Observations of Line 120 in the tensile ground deformation zone showed a separation between the failed ends of the pipe of approximately 250 mm (10 in.). Failure occurred at a welded joint.

RECOVERY

The earthquake damage was concentrated in three of the SoCalGas five customer operations regions and one transmission and storage operations region. The regions were: 1) Northern, where the epicenter was located in the San Fernando Valley and where damage was most acute, 2) Mountain View, where there was extensive damage in the east San Fernando Valley and in the Santa Clarita/Valencia area; 3) Pacific Region, where there was considerable structural damage in the western portion of the Los Angeles Basin; and 4) Aliso Canyon, the company's largest underground storage field.

Within an hour of the quake, the company's Emergency Operations Center (EOC) was staffed and functioning at the headquarters facility in downtown Los Angeles, as was a command center at Mountain View Region headquarters. Additional command centers were opened shortly thereafter at regional headquarters offices located in

Chatsworth (Northern) and Torrance (Pacific) to direct operations in the most affected areas.

SoCalGas had prepared for a 1993 union labor strike by training over 200 headquarters management employees in service restoration work. In addition, every former gas service employee, distribution field employee, and customer call center representative had received brush-up training to ready them to return to their former jobs. Many of these employees reported to operating bases in the earthquake area on the day of the earthquake and remained throughout the recovery effort. By the fourth day of the Northridge recovery effort, the company was able to put approximately 1,000 of these trained personnel into the field to augment over 1900 regular work-force personnel assigned to restoration.

Recovery assistance was obtained from 460 employees sent by neighboring utilities representing Long Beach Municipal Gas Department, Pacific Gas and Electric, San Diego Gas and Electric, and Southwest Gas. At the recovery effort peak, there were 3,400 personnel involved in the recovery effort, including those from neighboring utilities.

In addition to the workers in the field, the call centers and other offices provided 24-hour support, and responded to more than 400,000 telephone calls and in-person customer requests over two weeks. In January, the company responded to a record 853,000 calls.

Restoration activities were focused first on assessing the safety of the system, then getting service back on line as quickly as possible where outages were experienced. The response involved a three-part effort: 1) leakage surveys were performed on all pipelines in the affected areas; 2) neighborhoods were investigated, going from meter to meter, to identify both structures and appliance connections that were safe to return to service; and 3) trained technicians restored service to structures identified as being safe in the neighborhood investigations.

The central purchasing unit assigned procurement agents and support personnel to 12-hour shifts. This unit purchased over $600,000 of materials for immediate delivery from 53 suppliers and three neighboring utilities. The company trucking unit made approximately 100 unscheduled deliveries during the recovery period, moving 463 different items. Included in these shipments were 8,000 meters and 4,000 regulators.

Restoration of services to approximately 103,000 customers was accomplished by 26 January, at which time personnel from neighboring utilities were released. By 28 January, the supplemental workforce employees began to return to regular assignments. By 7 February, gas service had been restored to over 119,000 customers. Of the remaining 32,000 customers, a large portion restored their own service or had a plumber do so. As mentioned previously, service could not be restored to 9,100 customers because of structural property damage.

Earthquake restoration costs estimated several months after the earthquake by SoCalGas were between $53 and $68 million. This price includes approximately $35 to 45 million for operation and maintenance costs and between $18 and 23 million for capital costs.

RESIDENTIAL GAS SERVICE PERFORMANCE

SoCalGas service personnel found approximately 1,541 unstrapped water heaters which were damaged or leaking. Only 144 strapped water heaters were found damaged or leaking, many of which showed evidence of not having been adequately strapped. During restoration, service personnel were instructed to install flexible connectors when such work was needed to bring the water heater back into service.

While SoCalGas usually provides service directly to residential customers, this is not always the case with mobile home parks. Many of these are "master metered" where the gas distribution system within the park is privately owned and operated by the park owner. Other parks are individually metered and are serviced directly at the coach by the company.

It is believed that 172 mobile homes were destroyed by natural gas related fires. These fires typically started at a single coach and then spread rapidly to others. According to SoCalGas investigators, broken water lines caused by the earthquake hampered the firefighting response. Two primary causes of mobile home fires involving natural gas were identified: 1) coaches dislodged from their foundations, breaking risers supplying gas, and 2) overturning of appliances, primarily water heaters, which fell and broke interior gas lines. Coaches that had installed adequate earthquake bracing systems were the least damaged.

SEISMIC GAS SHUTOFF VALVES

Statistics pertaining to gas leaks have been compiled (Strand, 1995) on the basis of fire-department incident reports, interviews with various fire agencies, and information released by SoCalGas. It should be recognized that some of these data are general in nature, and that specific data about the causes of observed gas leaks and leakage rates often are not available.

After the Northridge earthquake, fire departments responded to over 1,000 reported gas leaks and at least 50 gas-related fires at structures in Fillmore, Los Angeles, Pasadena, Santa Clarita, Santa Monica, and Simi Valley (Strand, 1995). There were 14,062 natural gas leaks reported in customer facilities. A gas leak was found at 162 (19.3%) of the 841 structures where SoCalGas reset seismic gas shut-off valves (SGSVs).

A survey of the performance of over 400 SGSVs at over 160 locations was performed (Strand, 1995). Most surveyed SGSVs within 29 km (18 mi.) of the mainshock's epicenter tripped. At California State University at Northridge (CSUN), one of the four SGSVs did not trip. The unit that did not trip has not been evaluated to determine if it was defective. Many of the Los Angeles Unified School District's (LAUSD) SGSVs tripped. The LAUSD's SGSVs closest to the epicenter tripped numerous times during aftershocks. The M 4.5 aftershock of December 5, 1994, for example, tripped them at 35 San Fernando Valley schools; however, these valves are of an older design and their trigger levels may have drift. Aside from the SGSV that did not trip at CSUN, the surveyed SGSVs closest to the epicenter that did not trip are 14-18 km (8.5-11 mi.) away in the Santa Monica Mountains. At the Long Beach Naval Station [51 km (31 mi.) away], built on fill, all 38 SGSVs installed in 1989 tripped for the first time. Two SGSVs surveyed in downtown Long Beach [53 km (32 mi.) away] did not trip. The furthest surveyed SGSV that tripped is in Costa Mesa [79 km (48 mi.) away].

When data reported by Strand (1995) are combined with available information on tripped SGSV locations collected by SoCalGas, the tripped locations are within an area approximately bounded by lines extending between Oxnard, Santa Clarita, Upland, and Rancho Palos Verdes. This boundary encompasses on the order of 4,200 km^2 (1600 $mi.^2$); however, not all SGSVs within this area tripped. Based on contours of peak ground acceleration from uncorrected records, nearly all of the structural damage and all natural-gas fire incidents responded to by the Los Angeles Fire Department fall within the 0.3 g - 0.4 g contours.

Four SGSVs reported in Strand (1995) that tripped as a result of the Northridge earthquake are associated with gas-system damage downstream of the SGSV location. A SGSV at an industrial plant in Chatsworth tripped on the 102-mm (4-in.), natural gas service line that supplies an interior gas system that was broken in several places. A SGSV installed in 1989 on a natural gas line that supplied five buildings at Santa Monica College tripped for the first time. On the roof of one of those buildings, a 38-mm (1.5 in.) Schedule 40, black-iron gas line broke in a threaded area near a coupling, about 90 cm (3 ft) from a running electric motor, when a HVAC unit shifted about 35 cm (14 in.). A SGSV tripped on the main providing gas to the CSUN campus, where the gas systems in several buildings suffered significant damage. A SGSV tripped on a natural gas service line to a mobile home in Santa Clarita that fell off its foundation and broke the flex piping beneath it in four places. In the wake of the Northridge earthquake, Los Angeles passed legislation (Ordinance 170158) that has required an approved SGSV to be installed on all gas-serviced new construction and significant (i.e., over $10,000) commercial remodels permitted after June 30,1995. However, technical details associated with instrument requirements contained in the bill are currently under review.

SUMMARY OF GAS TRANSMISSION PERFORMANCE

Table 12-1 summarizes information about installation date, pipe dimensions, construction characteristics, and repairs of pre-1942 transmission lines damaged as a result of the 1994 Northridge earthquake. The highest incidence of damage was at oxy-acetylene girth welds, with the preponderance of this damage occurring in a single pipeline, Line 1001. There were four instances of damage to electric arc welded lines, of which three were at unshielded electric arc welds on Lines 85 and 120. As previously discussed, repairs to Line 120 were made in an area of significant lateral ground deformation on Balboa Boulevard. The single repair to Line 104 occurred at an overbend in an area of landslide movement. Metallurgical examination indicates that the welds in Line 104 were administered by shielded electric arc welding techniques.

Table 12-1. Summary of Repairs to Pre-1942 Transmission and Supply Lines as a Result of the 1994 Northridge Earthquake

Installation Date	Line No.	Nominal Diameter mm (in.)	Wall Thickness mm (in.)	SMYS[e] MPa (ksi)	Welds	Repairs
1925	1001	300 (12)	5.6 (0.22)	166 (24)	oxy-acetylene	25
1927	122	380 (15)	6.4 (0.25)	NR[d]	oxy-acetylene	1
1930	119	550 (22)	7.9 (0.312)	207 (30)	electric arc[c]	1[b]
1930	120	550(22)	7.9 (0.312)	240 (35)	electric arc[c]	2
1931	85	650 (26)	6.4 (0.25)	228 (33)	partially reconditioned[a]	1,4[b]
1931	85	650 (26)	6.4 (0.25)	228 (33)	electric arc[c]	1
1941	104	250 (10)	5.1 (0.203)	166 (24)	electric arc	1

a - Originally oxy-acetylene; many welds reinforced in 1932 with electric arc welded bands and plates. Break occurred at oxy-acetylene weld.
b - Leaking and fractured flanges
c - Using belled end pipe and underlying steel ring
d - Not recorded
e - Specified Minimum Yield Strength

There were no repairs nor disruption of supply experienced in post-1941 gas pipelines, even though several such lines were located in the epicentral area and subjected to large ground deformation. For example, lateral and vertical ground movement on Balboa Blvd. did not damage two 750-mm- (30-in.)-diameter gas transmission lines constructed in the 1950s, despite the fact that substantial ground deformation at this site contributed to failure of several other trunk and transmission lines with weld types different from the full penetration circular girth welds, standardly administered in post-1941 gas transmission and distribution supply lines.

OBSERVATIONS, LESSONS LEARNED AND RECOMMENDATIONS

The types of transmission lines most vulnerable to the effects of the Northridge earthquake are similar to those which were most severely affected by previous southern California earthquakes (O'Rourke and Palmer, 1994a,b). Repair statistics indicate that oxy-acetylene welded pipelines are the most vulnerable types of line.
This observation does not mean that oxy-acetylene welds are intrinsically weak. On the contrary, the metallurgical quality of an oxy-acetylene weld is not significantly different from that of an electric arc weld, provided the work is performed by qualified welders according to proven procedures. Well-made oxy-acetylene and electric arc welds are about equal in strength, although the heat-affected zone adjacent to an oxy-acetylene weld is somewhat larger and the joint ductility somewhat less than those associated with an electric arc weld. The reason for the higher incidence of weld damage is associated with poor weld quality. As described by O'Rourke and Palmer (1994a, b), oxy-acetylene welds, which ruptured as a result of the 1971 San Fernando and 1994 Northridge earthquakes, had characteristics such as poor root penetration, undercutting and overlapping at the toe, and lack of good fusion between the pipe and weld. These types of features result in a flawed weld, and are not representative of the welds achieved under the quality control standards currently in effect.

Electric arc welding first was introduced during 1929 for SoCalGas transmission lines. Between 1929 and 1931, both electric arc and oxy-acetylene welding were used. Since 1931, electric arc welding has been used on 400-mm (16-in.) and larger diameter pipelines.

Electric arc welded pipelines have shown substantially better performance than oxy-acetylene welded lines. Electric arc welds before the early 1940s were often made with unshielded arc techniques, and thus do not exhibit the same integrity and ductility of welds performed with the shielded arc techniques adopted for high pressure pipelines around 1941. Pre-1942 unshielded electric arc welded pipelines have shown relatively good performance during previous earthquakes in areas where permanent ground deformation has not been reported (O'Rourke and Palmer, 1994a, b). Some damage, however, has been sustained in unshielded electric arc welded pipelines in response to lateral spread near the Juvenile Hall during the 1971 San Fernando earthquake (O'Rourke and Palmer, 1994a, b) and at Balboa Blvd. during the 1994 Northridge earthquake.

Post-1941 electric arc welded pipelines in good repair have never experienced a break or leak as a result of traveling ground waves during a southern California earthquake. SoCalGas' repair record shows that modern electric arc welded gas pipelines in good repair are the most resistant type of piping, vulnerable only to very large and abrupt ground displacement, and generally highly resistant to traveling ground wave effects and moderate amounts of permanent deformation.

The performance of polyethylene distribution piping during the Northridge earthquake was very good. Only 27 repairs, primarily at socket fusions and older style transition fittings, were made in this type of piping even though there were approximately 24,045 km (14, 935 mi.) of polyethylene pipe in service at the time of the earthquake. Such overall performance provides strong evidence of the favorable seismic response characteristics of polyethylene pipelines.

Observations after the Northridge earthquake emphasize the vulnerability of mobile homes to earthquake damage, and suggest the need for improved safety codes and building standards for this type of structure. Experience derived from the earthquake indicates that the risk of fire can be reduced by bolting coaches to earthquake bracing systems to avoid slippage of the coach and the severing of service lines. In addition, the adequate strapping of water heaters and the installation of flexible connectors between water heaters and interior piping will diminish the risk of damage and associated gas leakage.

ACKNOWLEDGMENTS

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13. LIQUID FUEL SYSTEMS

ABSTRACT

Three petroleum pipelines that traverse the epicentral area were investigated. Two constructed after 1950 when improved welding methods were used were undamaged. The pipeline constructed in 1925 that used acetylene welds had eight failures and about a dozen damaged welds in its 32 mile (50 km) length. The two terminal facilities investigated were largely undamaged, including seven fuel storage tanks and oil-contaminated water tanks.

LIQUID FUELS PIPELINES

There are three crude oil pipelines coming from the San Joaquin Valley to Los Angeles. Two of these survived the earthquake with no apparent damage. The third, a 10 inch (26 cm) pipeline had significant damage evident at eight locations; these eight locations were over a distance of about 32 miles (50 km). All failures were in acetylene welds, which were part of the initial construction when the pipeline was installed in 1925. There were approximately a dozen more damaged welds detected during the repair and testing of the pipeline. Examination of the welds and the review of records indicated that there were also a number of damaged welds in the 1971 San Fernando earthquake. The pipeline was not in operation at the time of the earthquake, and has not been returned to service.

As a result of the weld failures there were spills ranging from 1 bbl (0.15 m^3) to 3500 bbls (550 m^3). A major spill of 3500 bbls (550 m^3) near Newhall ultimately drained into and impacted approximately 16 miles (25 km) of the Santa Clara River. The other major spill, of less than 1000 bbls (160 m^3) was in the City of San Fernando. This spill ran into gutters and storm drains and ultimately into the Los Angeles River. In the course of its journey the crude oil caught fire, injuring a motorcyclist and setting fire to seventeen parked cars. The fire also ignited four houses, destroying one.

Of the crude pipelines surviving the earthquake, one 16 inch (40 cm) pipeline was constructed in 1993 to the latest industry standards; the other, a 12 inch (30 cm) pipeline, was constructed in the 1950's, using then current codes, welding criteria and methods (arc welding.) The 16 inch pipeline was inspected (by line-a-log) following the earthquake. No damage was detected and the line was in compliance with the inspection criteria. No damage was evident on the 12 inch (30 cm) pipeline and both lines were returned to service.

There are two products pipelines from local refineries to Valley distribution terminals. There were no reported leaks or problems with these pipelines, and they have been returned to service.

Figure 13.1 shows the general area, the location of the two terminals, and the significant pipeline breaks.

LIQUID FUELS TERMINAL FACILITIES

There are two Liquid Fuels (distribution) Terminals in the Northridge area. Both terminals are supplied by pipeline to on-site storage tanks; trucks are then loaded with liquid fuel from the storage tanks via a loading rack. Terminals had only minor or insignificant damage. There was no reported or apparent damage to the pipelines supplying these terminals. Also, both of these terminals were in operation in 1971, at the time of the San Fernando earthquake. There was no reported damage resulting from that previous event.

SEPULVEDA TERMINAL

This terminal consists of three principal tanks for fuel storage, and two tanks for drainage water storage and treatment prior to discharge. The terminal is location about four miles (7 km) east of the epicenter. This terminal was constructed in the mid 1960's. Table 13.1 lists the dimensions and service of the tanks at the Sepulveda Terminal.

Table 13.1 Description of tanks at the Sepulveda Terminal.

Designation	Diameter (ft)	Height (ft)	Capacity (bbls)	Service	Storage During Quake
A	65	36	20k	Fuel	2/3 full
B	72	36	25k	Fuel	1/3 full
C	60	36	18k	Fuel	1/3 full
AG-1	12	24	450	Wastewater	empty
AG-2	12	24	450	Wastewater	full

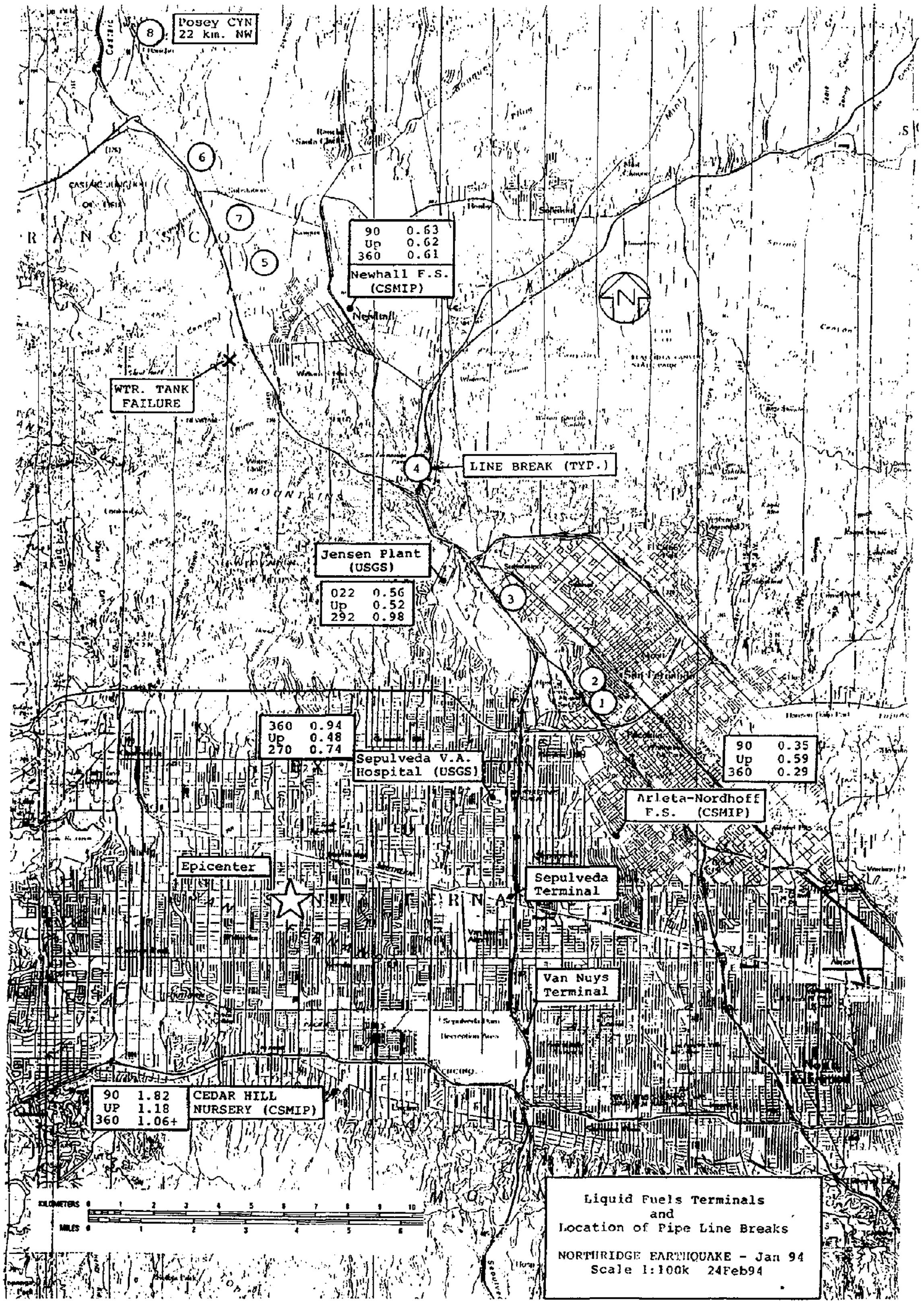


Fig. 13.1 Liquid fuel terminals and pipeline break locations.

All tanks were constructed to the then current American Petroleum Institute (API) 650 standard for tanks. The fuel tanks are cone roof with an internal floating pan. The three fuel tanks are on concrete ring foundations but with no anchorage between the tanks and the foundations. At the time of the earthquake, Tank A was about two-thirds full. Tanks B and C were one-third full. It was difficult to ascertain if the tanks lifted off their foundations; if they did, it was a small amount, as there were no obvious signs or indications of uplift. No shell buckling was evident. There was sloshing in the tanks as some fuel spilled on to the top of the pans, but without sinking the pans. This spillage was removed and the tanks remained in service.

One of the water storage tanks was full and one was empty at the time of the earthquake. The tanks are identical and are on a common foundation. The tanks each have 16 one-inch anchor bolts equally spaced around the tank base, with substantial chairs on the tanks. For the full tank it was evident that paint between the anchor bolt nut and the chair plate had cracked or parted on all 16 anchor bolts. The paint crack is taken as an indication that the anchor bolts worked. Judging from the paint crack distance, the movement was well within the elastic range. For the empty tank there was not even the paint cracking. There was also no indication of shell buckling on either tank.

VAN NUYS TERMINAL

This terminal consists of four operating tanks for fuel storage, plus one wastewater holding tank. Additionally, there are five tanks which were being taken out of service, of which two were full (or near full) at the time of the earthquake, the others being empty. Table 13.2 lists the dimensions and service of the tanks at the Van Nuys Terminal.

Table 13.1 Description of tanks at the Van Nuys Terminal.

Designation	Diameter (ft.)	Height (ft.)	Capacity (bbls)	Service
1	29	48	5,500	Fuel
2	36	48	8,500	Fuel
3	67	48	30,000	Fuel
4	72	48	34,000	Fuel
5	15	30	900	Wastewater

All tanks were constructed to the API 650 standard in effect at the time of construction (circa 1963). The tanks are set on a rock base with no concrete foundation and no anchorage. The fuel tanks are cone roof tanks with internal pans. There was no significant damage to any of the tanks. Moreover, it appears that Tank No. 2 may have uplifted since a stone was found under the steel base ring plate. A bolt sheared on an overhead walkway between two tanks, but the walkway did not fall or fail, the sheared bolt was replaced. On the occasion of one of M5.5 aftershocks, an operator observed a 16 foot (5 m) oscillation on the tank level gage.

The site also had five tanks with high aspect ratios, 10.5' by 33' (3.2 m x 10 m). These tanks were being taken out of service. Two of these were near full at the time of the earthquake. Neither suffered significant damage although there was damage to the ladder and walkway at the top of the tanks. These tanks also were on a rock base with no concrete foundation or anchor bolts.

OBSERVATIONS AND RECOMMENDATIONS

As has been observed in previous earthquakes, acetylene welds using methods that predated the early 1930s perform poorly.

There is a need to perform a detailed survey to compare the performance of anchored and unanchored tanks and to evaluate the performance of seismic provisions in tank design standards.

14. THE APPLICATION OF NEW TECHNOLOGIES

ABSTRACT

This paper provides a brief overview of how new technologies were used after the Northridge earthquake to improve lifeline response and recovery. Technologies that are discussed include real-time availability of earthquake source data, improved loss estimation techniques, Geographic Information Systems and satellite-based monitoring systems. This paper also identifies areas in which further integration of these methods into emergency response would improve the survivability or reliability of lifeline facilities or services.

INTRODUCTION

At the time of the Northridge earthquake, a number of new technologies, including real-time availability of earthquake source data, improved loss estimation techniques, Geographic Information Systems and various satellite-based monitoring systems, were either available or under consideration as emergency management resources. The potential benefits from these technologies for earthquake hazard mitigation, response and recovery however, was largely conceptual. One of the major lessons learned from the January 17, 1994 earthquake was that these technologies could confer significant advantages in understanding and managing a major disaster, and that their integration would contribute a significant additional increment of utility.

The technologies discussed in this chapter developed as discrete entities, in diverse disciplines and at different rates relative to one another. At the time of the Northridge earthquake, near real-time broadcasts of earthquakes had been available to utility and lifeline operators in southern California since 1990, although emergency management application of this information remained mainly experimental. Loss estimation, on the other hand, has been in use for two or three decades by both government and the private sector but has evolved, in recent years from a single event scenario format to a more versatile automated one.

Geographic Information Systems (GIS), like loss estimation, have a history spanning the last quarter century but only within the last several years have they been applied as an emergency management tool, and only in the Northridge earthquake were they used extensively in disaster response and recovery. As part of the "defense conversion" in the aftermath of the Cold War, satellite monitoring systems have been made available for peacetime purposes and have already been successfully applied in weather and storm surveillance and have been applied, to a limited extent, in other natural hazard analysis.

In this chapter, we will examine these various new technologies, their contributions to response and recovery after Northridge and their actual or potential application to improving lifeline performance. Although this discussion will treat these technologies as discrete scientific developments, we will attempt to identify areas in which there has been convergence and where further integration could produce significant improvements in the survivability and continued functionality of lifeline facilities and services.

NEW TECHNOLOGIES

REAL-TIME SEISMOLOGY

Although real-time seismic monitoring has been applied to promote public safety in Japan, similar applications have been slow to materialize in the United States. Following the Loma Prieta earthquake, a survey was conducted to assess the perceived utility of an earthquake early warning system which would provide a few seconds of warning in advance of damaging levels of shaking . Researchers found that most groups which were expected to enthusiastically endorse this new technology were lukewarm, at best, considering a few seconds warning too little time to take meaningful action in advance of a major earthquake. Nor was such a system regarded as a cost-effective strategy for hazard reduction and thus, unlikely to receive much support from users (Holden et al., 1989).

Despite this somewhat disappointing beginning for real-time monitoring, Caltech and the U.S. Geological Survey pushed ahead with plans to upgrade the Southern California Seismic Network (SCSN) to provide real-time broadcasts of earthquakes and seek the support of government agencies, large utilities and corporations for the potential post-event benefits these broadcasts might provide. Gradually, participants were recruited to participation in the Caltech-USGS Broadcast of Earthquakes (CUBE) and by the time of the Northridge earthquake, there were 18 Level III participants in the Earthquake Research Affiliates of Caltech (ERA), the organizational vehicle for provision of real-time earthquake broadcasts from SCSN. These participants made an annual contribution of $25,000 to the Caltech Development Fund (which helped support the purchase of new seismic monitoring equipment) and received reports of earthquakes via pagers which carried the magnitude, location, time and other earthquake data within 2-5 minutes of occurrence.

For approximately four years, CUBE reliably broadcasted earthquakes up to about M5.5 to participants. At 4:31 a.m. on January 17, however, the CUBE system experienced both hardware and software difficulties which resulted in delays of approximately one hour in providing information on the Northridge earthquake. A study currently under way is designed to determine how response of CUBE participants was affected by the performance of CUBE after the Northridge earthquake, and in general, how receipt of real-time earthquake information from SCSN has been integrated into the response plans of these organizations (Goltz, 1995).

Preliminary results from this study indicate that the CUBE system usually provides the first data upon which action may be taken. To assist in determining whether a response is justified, many CUBE participants have customized the Q-pager software (which displays spatial and other data on an earthquake) by adding overlays to the basic southern California map on which earthquake epicenters are plotted. These overlays include facilities such as transmission lines, dams, power stations or other critical structures. In a few instances, participants reported monitoring the patterns of small earthquakes in a particularly critical location under the assumption that these earthquakes may be precursors to a large damaging event.

Statewide real-time broadcasts are now available and have been adopted by those agencies (OES and Caltrans) and companies (utilities and railways) with statewide jurisdiction, facilities or distribution networks. These statewide broadcasts are available through a cooperative agreement between Caltech (CUBE) and the University of California at Berkeley (REDI or Rapid Earthquake Data Integration). In March, 1995, CUBE participants received software which permits the mapping of ground acceleration data broadcast in real-time from the SCSN. Most users consider this to be a very important development in that the potential impact on facilities can be more precisely estimated and mobilizations of personnel for inspections can be expedited.

The development of real-time monitoring and broadcast of seismic information appears to be in transition from concept and pilot project to a practical operational system. Under the strictest definition of real-time availability, the Northridge earthquake must be considered a missed event. It appears, however, that the January 17 event exposed a plethora of technical vulnerabilities in the CUBE system and triggered a concerted effort to remedy most, if not all of them. It does not appear that the failure of the CUBE system to provide rapid and accurate information on the earthquake had a dampening effect on the interest and enthusiasm of users.

LOSS ESTIMATION

The Northridge earthquake was the first earthquake disaster to occur in the United States in which important emergency response and early recovery decisions were based on loss estimates as well as actual data gathered through standard reconnaissance procedures. The utilization of loss estimation techniques in the immediate post-earthquake context is a key development and marks a significant departure from conventional applications. For the last two decades, earthquake loss studies have addressed the pre-earthquake planning needs of utility operators and government agencies. Although the needs of these users vary, understanding risks and maintaining public safety have generally required similar scenario events, that is, those with the greatest impacts on the local population and economy.

Historically loss estimation studies for planning purposes have identified scenario earthquakes as the focal point for estimate development. These studies use existing knowledge of regional geology and seismology to generate maps with estimated intensities and, based on projected ground motion and other factors, estimate damage to buildings and structures, lifelines and impacts on population. Some studies also address potential secondary hazards such as fire, flood and hazardous materials releases. Presented in report or document form, often with fold-out and sometimes overlay maps, these earthquake scenarios have been employed by government and utilities to prepare and mitigate potential earthquake losses. Thus, the typical loss study has been single-event focused, applied in the long-term pre-event period and utilized primarily by those concerned with seismic safety planning and risk management.

Even before the Northridge earthquake, technological developments were rapidly rendering these scenarios and the formats in which they are presented obsolete. The advent of high speed computing, satellite telemetry and Geographic Information Systems (GIS) have made it possible to electronically generate loss estimates for multiple earthquake scenarios, provide a nearly unlimited mapping capability, and perhaps most important, develop estimates for an actual earthquake in near real-time given the source parameters of magnitude and location. For the last five years, real-time broadcasts of earthquake data including magnitude, location, depth and time of occurrence, have been available in southern California on an experimental basis from the Southern California Seismic Network operated jointly by the California Institute of Technology and the United States Geological Survey.

Currently under development for the California Governor's Office of Emergency Services (OES) is a GIS-based system capable of modeling building and lifeline damage and estimating casualties in near real-time given the source parameters of an earthquake (Eguchi, et al, 1994). The Early Post-Earthquake Damage Assessment Tool (EPEDAT) will be completed in mid-1995, will utilize real-time seismic information from the Southern California Seismic Network and will operate on a personal computer. EPEDAT will utilize fault and seismicity data to locate the most likely source of an earthquake, as broadcast by CUBE. Applicable ground motion and soil amplification models will be employed to estimate the expected intensity patterns in the affected area. These intensities will then be overlaid onto the computerized data files containing an aggregate listing of buildings and lifelines in the region. Based on damage and casualty models already developed under contract with the State of California, and the intensity patterns computed, building and lifeline damage as well as casualties will be estimated for the impacted area. EPEDAT will also allow the user to update early estimates with actual reconnaissance data. Thus, as more accurate and specific data become available, they can be incorporated to refine or correct initial predictions.

Real-time loss estimation offers direct and tangible benefits over conventional loss studies. For the first time, loss estimation can be used in the emergency response and early recovery phases of a disaster as a decision support tool. Based on rapid receipt of magnitude and location, estimates of ground shaking and intensity can be calculated and mapped giving emergency responders a sense of the overall scope of an event minutes after it has occurred. Reconnaissance efforts can focus on those areas projected to be hardest hit based on estimates of intensity. Inspection teams can be dispatched, staging areas can be identified, medical emergency resources mobilized and sheltering needs considered, as responders are guided by estimates of damage, casualties and displaced persons. Recovery can be hastened by calculation of total dollar loss estimates and breakdowns of losses by facility or structural type, usage or other categorizations expedite governmental disaster assistance.

Immediately following the January 17 earthquake, data and models which will be the basis for EPEDAT in Southern California were utilized and, though the system was not fully operational at the time, produced timely and accurate information which was used by state and federal officials to support key policy and program decisions. Estimates of dollar losses and ground shaking intensity were used by the California Office of Emergency Services to define the general regional scope of the disaster during the critical 24-48 hours after the event. The shaking intensity map was instrumental in approximating the locations of heaviest damage, used in briefing state agency executives, including the Governor, and in making decisions regarding shelter needs, locating Disaster Application Centers and "fast-tracking" the federal Disaster Housing Assistance Program. A total dollar loss estimate of $15 billion, generated within 24 hours of the earthquake, served as the basis for negotiation of a supplemental Congressional appropriation of $8.6 billion in federal disaster assistance.

GEOGRAPHIC INFORMATION SYSTEMS (GIS)

In the context of emergency management, GIS technology has rapidly evolved over the last decade and, in the aftermath of the Northridge earthquake, is regarded as a vital response and recovery decision support system. An obvious advantage for response and recovery officials is the ability to gain both a regional and highly localized assessment of situations requiring rapid decision making. Such decisions are facilitated by the interrelationship of structural, demographic, economic and environmental data in mapped as well as tabular formats. The utility of GIS has been enhanced by technological developments in related areas including remote sensing, global positioning, software and hardware improvements and desktop applications (Topping, 1993).

A GIS unit had been established within the California Governor's Office of Emergency Services prior to the Northridge earthquake; after the January disaster, however, this unit was greatly enhanced with additional personnel, new equipment and technical expertise available on a consulting basis. Co-located in the Pasadena Disaster Field Office with its GIS counterpart in the Federal Emergency Management Agency, this unit provided an important source of information in both the response and recovery phases of the Northridge earthquake. In addition, this unit has taken major strides toward development of a disaster management database for California.

In the immediate aftermath of the Northridge earthquake, GIS was used to develop a shaking intensity map based on model estimates. This map was instrumental in gaining a rapid assessment of the regional scope of the disaster and supported key decisions regarding the location of shelters and disaster application centers and documenting the state's request for a presidential disaster declaration (Goltz, 1995). As recovery programs were initiated, GIS was instrumental in identifying and displaying language and demographic characteristics, geographically locating disaster assistance applications and in hazard mitigation planning (Topping, 1994).

For lifeline operators, GIS also played an important role in Northridge response and recovery. The wastewater collection system for the City of Los Angeles consists of a complex network of underground sewers, both gravity driven and forced mains. In total, over 7,000 miles of sewer pipe traverse the City of Los Angeles. As in past earthquakes, damage to underground sewer pipes has been difficult to detect because the effects are not immediately visible, unless ground failure has occurred. In some cases, leaks and breaks are only detected when adjacent water mains are filled and wastewater spills onto the ground and street because of blockages caused by internal damage or collapse. Other indicators of severe sewer damage include street settlement, crushed or buckled curbs, damage to sidewalks and failed water mains.

In an attempt to quickly identify areas of severe sewer damage after the Northridge earthquake, the City of Los Angeles relied on GIS (Solorzano et al., 1994). First, GIS was used by the Bureau of Engineering to identify areas of extensive building damage, water main repair and surface disruption (i.e., damage to sidewalks, roads, etc.). This information was then overlaid onto maps of the sewer system in order to prioritize close circuit television (CCTV) surveys. Areas that fell within relative high risk areas (e.g., areas with extensive building damage) were surveyed first. This assessment revealed that approximately 16% of the inspected sewers required emergency repair, 49% sustained some damage and the remaining 35% sustained no damage.

Similarly, the Los Angeles Department of Transportation used a GIS-based Automated Traffic Surveillance and Control system (ATSAC), installed several months prior to the earthquake to monitor traffic flow, to plan detour routes and implement signal timing strategies in the Santa Monica I-10 Freeway corridor. The ATSAC system is also used to control the message signs along the freeways and, after the earthquake, these signs were used to advise motorists of the various detour routes and traffic conditions (LADOT, 1994).

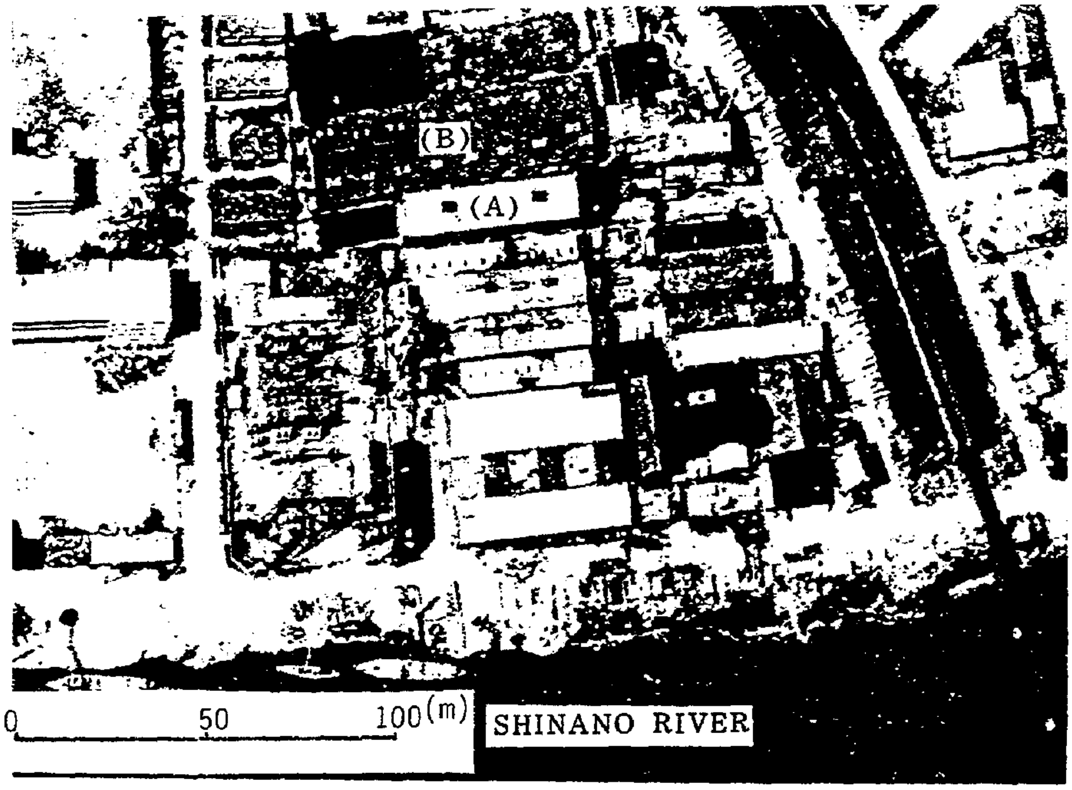
AERIAL AND SATELLITE-BASED MONITORING SYSTEMS

Images, measurements and other data obtained from the vantage point of high altitude aircraft and satellites has recently entered the technological arsenal of emergency managers. These technologies have been employed to monitor geological changes and as a source of damage assessment during and after major emergencies including fires, bombings and flooding. These technologies including aerial photography and satellite imagery have recently been proposed for assessing the effects of large earthquakes (Crippen, 1992; Crippen and Blom, 1993). Using SPOT satellite images acquired approximately one month after the 1992 Landers earthquake, the Jet Propulsion Laboratory in Pasadena was able to capture spatial details of terrain movements along fault breaks associated with the earthquake that were virtually undetectable by any other means.

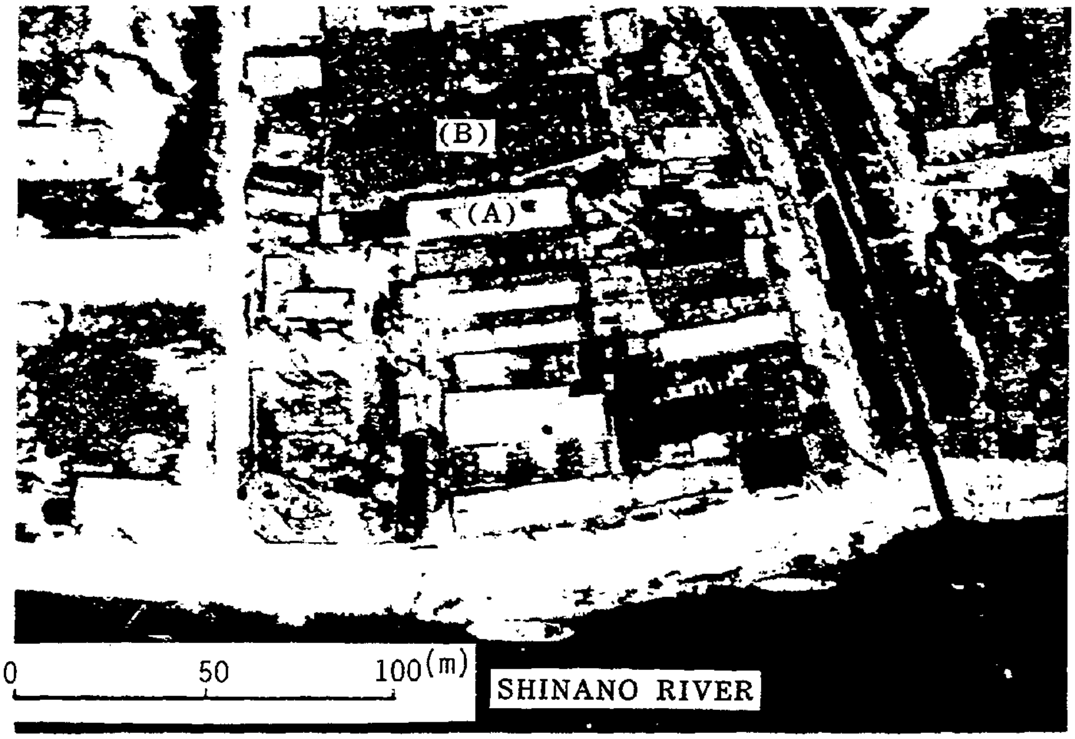
The Japanese have used aerial photographs to identify areas of significant ground failure after several large earthquakes. By comparing pre- and post-earthquake aerial photos of liquefaction affected areas, they have successfully mapped areas of ground movement including both magnitude and overall displacement. Figure 14.1 shows aerial photographs of the Kawagishi-cho and Hakusan area before, and four hours after, the 1964 Niigata, Japan earthquake. Evident in these photographs is significant planar distortion of buildings after the event. Also clearly visible is the change in curvature of the shoreline after the earthquake.

Another example of aerial reconnaissance after an earthquake is shown in Figure 14.2. This photograph shows earthquake damage detected after the 1971 San Fernando earthquake. Explosion craters resulting from gas leakage along Glen Oaks Boulevard in Sylmar can be clearly detected. Also visible in the center of this photo are ground cracks that resulted from extensive ground shaking during the earthquake. In this particular area, over 100 pipeline breaks were recorded in water and natural gas pipelines (Eguchi, 1982). It has been demonstrated historically that extensive ground distortion generally leads to significant damage to underground lifeline components (Eguchi, 1991).

Until recently, it was not clear how satellite data could be used effectively to identify areas of earthquake impact. In general, the data that are publicly available are limited by the level of resolution possible. For example, the SPOT image pixel size used to detect ground movement during the 1992 Landers earthquake (See Figure 14.3) is 10 meters (Crippen and Blom, 1992), which is larger than many of the displacements observed during the event. However, through the use of image matching by correlation analysis, JPL has been able to computationally detect displacement vectors revealing horizontal ground strain patterns. The most effective



(a) Before the Earthquake (1962)



(b) After the Earthquake (1964)

Fig. 14.1 Aerial photographs of Kawagishi-cho and Hakusan before and after the 1964 Niigata, Japan earthquake (Hamada and O'Rourke, 1992)

Fig. 14.2 Cratering caused by gas leakage and explosions along Glenoaks Boulevard after the 1971 San Fernando Earthquake.

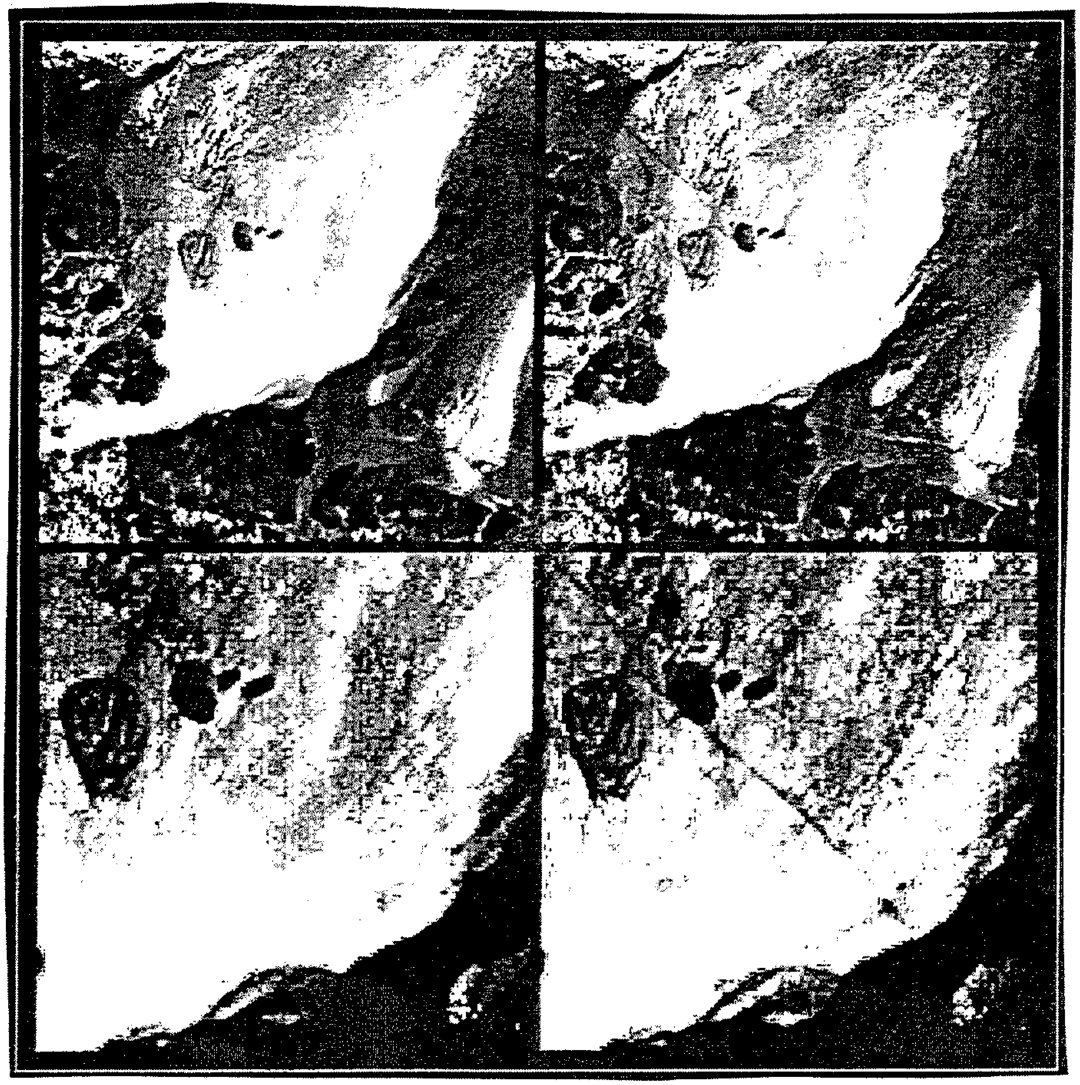


Fig. 14.3 Landers earthquake ground cracks Emergson fault, southwest of Galway Lake, Mojave Desert, California.

means of using this data in a post-earthquake situation is in identifying large areas of tectonic ground movement. Data resulting from satellite imaging may suggest areas for detailed aerial reconnaissance. A technique derived by Gabriel and others (1989) has been used to map small elevation changes over large areas using differential radar interferometry. This technique could be used to supplement satellite imaging (which only estimates horizontal changes) to identify areas of significant tectonic changes or perhaps ground failure settlement.

Global Positioning Satellite (GPS) systems were employed after the Northridge earthquake to assess the extent of crustal deformation and displacement. Based on measurements taken before and after the earthquake, the extent and nature of co-seismic displacements were determined. These data indicated that measurable displacements were produced over a 4,000 square kilometer area including much of the San Fernando Valley and adjacent mountainous areas (Hudnut et al, publication pending). Although these measurements were not available immediately following the earthquake, they could be made within sufficient time in future earthquakes for lifeline organizations to make response decisions based on the probable location and magnitude of displacements.

DISCUSSION AND CONCLUSIONS

Lifeline operators, both public and private, have been receptive and, in many cases enthusiastic, users of new emergency management technologies. The application of these technologies in the Northridge earthquake was, for many organizations, the first real test of their actual or potential utility in a major regional crisis. In some cases, existing systems proved to be successful and of critical importance, in others, performance was disappointing but important lessons were learned and vulnerabilities exposed. In addition, many new applications were discovered and the potential integration of these technologies moved from the conceptual to actual pilot testing. In this final section, we will identify areas in which the further application or integration of technologies could improve lifeline performance.

Expanded application of real-time earthquake monitoring holds considerable promise in improving performance during and hastening recovery after an earthquake for lifeline organizations. Most of the participants in the Caltech USGS Broadcast of Earthquakes are utilities and rail transportation providers. While most CUBE users, including lifeline organizations, have used the receipt of real-time source data for determining response needs, some have worked toward linkage of real-time notification with automated shutdown or other procedures which would ensure continued service after a major earthquake. Telecommunications companies, for example, have developed methods of rerouting network traffic away from areas likely to have sustained earthquake damage based on real-time broadcasts. Lifeline organizations have also been advocates of expanded real-time information including strong ground motion, estimates of displacement and early warning systems.

Earthquake loss estimation studies and scenarios such as those developed by the California Division of Mines and Geology have been used by lifeline organizations for planning and hazard mitigation purposes. Most, if not all, of these planning scenarios have included relevant vulnerability information which specifically address transportation and utility lifelines. Although new rapid loss estimation techniques which are linked to real-time earthquake monitoring systems have been developed for state and federal agencies, lifeline organizations, both in the United States and Japan, have expressed considerable interest in these new systems which provide a range of geotechnical, economic (e.g. damage, dollar loss) and population impact (e.g. casualties, displaced persons) data within minutes of the occurrence of a major earthquake.

In our earlier discussion of the application of GIS technology, we cited two examples of the use of GIS systems by lifeline operators in the Northridge earthquake. The experience of the two Los Angeles city agencies suggests that GIS-based systems in lifeline organizations are more fully integrated with operational processes than is the case in other organizations. Recall that the Department of Transportation used their GIS-based system to assess traffic conditions, implement control mechanisms and provide public information in one operation. This level of system integration suggests that lifeline organizations are likely to provide key innovations in the application of GIS technology to the management of emergencies.

Aerial surveillance and satellite imagery could be potentially beneficial sources of rapid information on above ground lifeline systems. Although high altitude aerial reconnaissance was attempted in the Northridge earthquake, neither the mission nor the results of this effort are known and to date have not appeared in after action assessments or other media known to the authors. The value of aerial photography and remote imaging are questionable for underground lifelines. The potential benefits of GPS data for pipelines and other underground systems, however, is quite significant.

The convergence of these new technologies after the Northridge earthquake mark an important development for emergency management in general, and for the performance of lifelines in particular. Of particular significance is the integration of real-time monitoring of seismic activity, loss estimation methodologies and GIS systems. The potential benefit lies in the ability of lifeline operators to obtain early warning of potentially damaging ground motion and implement procedures to lessen impacts and to respond rapidly to an earthquake, based on both empirical information and model estimates.

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15. HOSPITALS WITH EMPHASIS ON LIFELINES

ABSTRACT

As a result of damage suffered by the electrical and water lifelines in various hospitals, over 1000 patients were evacuated from hospitals. Specifically, many hospitals suffered total or intermittent loss of their normal supply of electrical power. By itself, this loss was not a major problem because most emergency generators performed well. However, several hospitals subsequently lost emergency electrical power because of electrical shorts and grounds caused by leaks in domestic water and fire sprinkler systems and rupture of roof mounted tanks. These leaks were caused by failure of nonload bearing partition walls. At least three fires and one death were caused by electrical shorts and grounds.

Waste water, and natural gas systems were not a significant problem for hospitals in this earthquake. And exterior and interior communications were not a problem for most hospitals because emergency radio circuits were used.

Most hospitals had emergency response plans and exercised them twice a year. The plans worked well for managing incoming casualties, but most hospitals had not planned that they themselves would be the casualty.

INTRODUCTION

Within the first five days after the earthquake, approximately 10000 people were treated for earthquake-related injuries and were released the same day from local hospitals and medical centers. Additionally, approximately 1300 people were admitted to hospitals for care. Approximately 220 of these people were in critical condition. The official death toll for this earthquake is 58.

Before the earthquake occurred, there were 1750 beds in intensive care units in Los Angeles County. As a result of the loss of some ICU beds due to earthquake damage and the occupancy of some ICU beds by patients injured during the event, only 216 of these beds remained unoccupied four days after the event (Los Angeles Times, 1994). Damage caused by the earthquake necessitated the evacuation of over 1000 patients from damaged hospitals.

Six hospitals were evacuated in the aftermath of the earthquake. These hospitals were St. John's Hospital in Santa Monica, the Veterans Administration Medical Center in Sepulveda, Olive View Medical Center in Sylmar, Holy Cross Medical Center in Mission Hills, and the Psychiatric Hospital and the Pediatric Hospital in the Los Angeles County Medical Center Complex. A number of other hospitals were forced to curtail services for several days due to earthquake related damage.

REVIEW OF FACILITIES

The following sections provide details of the response to the earthquake of nine hospital facilities. This includes details of personnel emergency response, lifeline systems performance, and structural response.

LOS ANGELES COUNTY MEDICAL CENTER, LOS ANGELES

This facility is located about 22 miles (36 km) from the epicenter. It is composed of over 30 buildings built at different times and composed of various lateral force resisting systems. At this location, the peak free-field horizontal acceleration was about 0.49 g. The soil at this site is described as siltstone. This facility is located across the street from the University of Southern California Medical Center.

The Mental Health/Psychiatric Building is a non-ductile reinforced concrete frame structure which was built about 1952-54. It has never undergone any seismic retrofitting. At the time of the earthquake, it had about 125 beds. On the roof of this building, three 5000 gallon (19000 liter) domestic water tanks lost their contents when the tanks moved in their saddles. The motion ruptured the rigidly attached inlet and outlet piping. The tank contents then flowed down into the interior of the building. This building was without water for about 3 days. Additionally, many columns were severely damaged. In some columns, there were horizontal cracks across the entire cross section. In other columns, vertical cracks were wide enough to allow the passage of outside breezes. There was no evidence of transverse reinforcement in the damaged columns. The interior water problems, combined with the column damage, necessitated closure of the building and relocation of about 100 patients. The structure was still red tagged 15 months after the earthquake. The term red tagged means that the building has been determined to be structurally unsafe for human access.

The Pediatric Building is a non-ductile reinforced concrete frame structure, with a capacity of about 180 beds. Because of significant column damage, all 67 patients in the building at the time of the earthquake were evacuated. It was still red tagged 15 months after the earthquake.

The Women's Health Building is a ten story reinforced concrete structure with a capacity of about 180 beds. On the roof, two 7000 gallon (26500 liter) domestic water tanks lost their contents. However, since structural damage was limited to a few small cracks in a side stairwell, this building was not evacuated.

Several one and two story shop and warehouse buildings were damaged so extensively that they were torn down after the earthquake. These buildings were built around 1910-1920 with concrete encased steel columns and unreinforced masonry infill walls. These brittle columns were unable to withstand the lateral forces imposed by this earthquake.

Overall, for the entire facility, there were no problems with the commercial supply of electrical power, nor with telephone communications. One 8 inch (20 cm) raw water main into the facility ruptured, but it was quickly isolated. Other water mains were put into service so that the supply of water to the facility remained stable throughout the recovery process. There were no problems with the sewer system, nor with hazardous waste. There were no problems with the supply of natural gas, nor with medical gases inside the facility. With the exception of the evacuated buildings, the HVAC systems suffered no problems. Ambulance access into the facility was not impaired.

The facility has an "emergency response plan" which worked well during this earthquake.

UNIVERSITY OF SOUTHERN CALIFORNIA MEDICAL CENTER, LOS ANGELES

This 40 acre (16 hectare) facility is located about 22 miles (36 km) from the epicenter. It is composed of about 23 buildings built at different times and composed of various lateral force resisting systems. At this location, the peak free-field horizontal acceleration was about 0.49 g. The soil at this site is described as siltstone. This facility is located across the street from the Los Angeles County Medical Center.

The facility has approximately 2000 students and 900 faculty/staff. The main patient care facilities are located in the Cancer Hospital (60 beds) and in the USC University Hospital (270 beds), a teaching hospital. There is no Emergency Room associated with this facility. Consequently no patients were treated for earthquake related injuries. There were no reported injuries on site. There is housing for only 96 students on this site. Many of the faculty and students also perform functions in the Los Angeles County Medical Center across the street from this site.

In general, the lifeline systems and equipment of this facility performed extremely well. Commercial electrical power, water, waste water, and natural gas all remained uninterrupted during and after the event. Internally, there were no reports of problems with the HVAC systems nor the fire suppression systems. The telephone system was inoperable, but communications were maintained by microwave and radio circuits. Handheld transceivers were used extensively. The elevators in most buildings were inoperable for about two days due to misalignment and the great demand on a limited number of personnel to realign them. There were no problems with ambulance or rolling stretcher access.

The USC University Hospital building is an eight story braced steel frame structure supported on 68 lead-rubber isolators and 81 elastomeric isolators, which was completed in 1991. The peak structural accelerations were 0.13 g at the base and 0.21 g at the roof. This building remained completely functional during and after the earthquake. There were no reports of damage to equipment or lifelines inside this building. The isolators performed so well that there was a total of only $500 worth of damage to the building and that damage was in the form of cracks in non-structural partition walls.

In the Norris Medical Library Building, there was only cosmetic damage. Some light fixtures were shaken loose from their supports and were found hanging by their electrical supply cable. This building is a two story reinforced concrete frame structure with concrete shear walls completed in 1968. It has never had any seismic retrofitting.

In the Raulston and Mudd Buildings, fallen ceiling tiles caused several spills of hazardous materials. These spills were cleaned up and the affected areas released for occupancy within the first hour after the earthquake. The Raulston Building is a five story reinforced concrete structure completed about 1950. It has never had any seismic retrofitting.

In the Seaver Building, an unreinforced brick chimney sheared at the roof line and shifted about 6 inches (15 cm). It was removed. This building contains a cafeteria, bookstore, and a dormitory.

The emergency response plan worked extremely well. However, difficulty was encountered in obtaining keys in order to inspect laboratories for hazardous material spills.

OLIVE VIEW MEDICAL CENTER, SYLMAR

This 377 bed facility is located about 9 miles (15 km) from the epicenter. This is a replacement structure for the hospital of the same name that was heavily damaged by the 1971 San Fernando earthquake. The original reinforced concrete frame structure was torn down after 1971 and replaced on the same site by a six story steel frame structure with steel plate shear walls. This structure became operational in 1977. At this site, the soil is classified as alluvium and the peak free field acceleration was 0.91 g. The peak horizontal accelerations recorded on the structure were 0.82 g at the base and 2.3 g at the top of the structure. The steel frame/steel shear plate system performed well, with the exception of one cracked weld at a shear plate connection to the roof deck, and one sheared bolt.

All 300 patients in the building were evacuated within the first 14 hours after the earthquake. This was necessitated by the water damage in the structure and by the intermittent loss of electrical power. However, the hospital never officially "closed" because many functions of the hospital continued to be performed in the parking lot. This included the treatment of about 100 people for earthquake related injuries within the first 24 hours after the event. About 30 hours after the earthquake, the facility began to readmit patients into the hospital structure. The building was never red tagged.

Within the first 8 hours, the facility lost electrical power three times. The first time occurred when the commercial power supply was lost. After this, the two 920 KW diesel generators commenced providing electricity, but they stopped after about 20 minutes. This was because one diesel shut down automatically due to high temperature, and the other one ran out of fuel. It is believed that the fuel loss was due to the fact that batteries in the "Uninterruptable Power Source" (UPS) had been removed before the earthquake. The UPS was the initial source of power for the fuel pump. This second power outage lasted for about two hours until the 3MW gas turbine generators were made operational. These supplied power to the facility and to the diesel fuel pumps. The diesel and gas turbine generators operated simultaneously for about 5 hours until the gas turbines shut down due to loss of cooling water to their bearings. This third power outage occurred because the water main into the facility was isolated by Los Angeles County Department of Power and Water personnel without warning. Two hours later, tank trucks were brought onto the facility to supply water for domestic and power plant use.

In the interior of the hospital building, there was significant water damage due to the rupture of domestic lines which punched through nonstructural walls, the rupture of chill water lines in damaged HVAC ducts, and the shearing of fire sprinkler heads by the movement of false ceiling tiles. It took about 8 days to repair these water lines.

In the hospital building, communications and command and control were a major problem. The emergency response plan specified the duties of various administrative people at the Emergency Operations Center (EOC). But many of these people could not get from their homes to the facility for several hours. The staff on the night shift needed to be trained to take action without a functioning EOC. Phones calls could be made into the hospital building, but none could be made from within to the outside.

Cellular phones temporarily solved this problem, until those phone circuits became saturated. Cellular phones were vital in the procuring of water trucks in the first hours of the event.

There were no problems with the waste water system. There were no hazardous material spills. The natural gas supply was not interrupted. There were no problems with ambulance access. Elevators became misaligned and thus were inoperable.

Only minor damage occurred in the HVAC plant, which is physically separated from the hospital building. Some steam lines moved axially in their seismic cable restraints. A liquid oxygen tank, supported by four legs with a 1-1/4 inch (3 cm) bolt in each leg, sheared its anchor bolts and moved sufficiently to rupture its piping. This caused a small explosion. The cooling towers located next to the oxygen tank were not damaged by this explosion. These towers, which are about 30 feet (9 m) tall (10 feet below grade and 20 feet above the ground), are constructed of concrete with ceramic tile interior.

NORTHRIDGE HOSPITAL MEDICAL CENTER, NORTHRIDGE

This facility is located about one mile (1.6 km) from the epicenter. It consists of eight buildings constructed between 1968 and 1990. They are all reinforced concrete frame structures with glass and masonry facade. The older buildings were retrofitted after the 1971 San Fernando earthquake. This retrofit included epoxy injection to strengthen beam-column joints and shotcreting of some structural members.

Only a few spaces were damaged enough to prevent their continued use after the earthquake. However, the facility was hampered in carrying out its functions because all commercial utility lifelines (except natural gas) were lost. As a result, patient triage was conducted in a parking lot for about five days after the earthquake. During the first five days, this facility treated more than 1000 earthquake victims. Additionally, some patients were sent from this facility to Pasadena Hospital and four neonatal patients were evacuated to Huntington Hospital. Two months after the earthquake, only one space, which functioned as an Outpatient Registration Center, remained unusable due to structural damage.

Commercial electrical power was lost and not returned to service for about four days. The three emergency electrical power generators did function properly. However, the switchgear from one generator failed due to non-earthquake related causes. All generators were supported on isolators and their battery racks were restrained at top and bottom. The cooling system for the generators had no leaks. The fuel tank for the generators was located underground and there were no leaks in the fuel system. The emergency power generating system was able to supply enough power for all essential equipment. The emergency generators are tested weekly under full load. All switchgear and transformers are anchored and no problems occurred with this equipment.

Telephone communications were also lost. Communications inside the buildings were maintained by an "emergency intercom system" which was battery powered. Communications with off-site organizations were maintained by means of handheld/battery powered radios.

The normal supply of fresh water was lost due to broken water mains in the area. Tanker trucks were used to provide an emergency supply of water. None of the interior domestic consumption water lines suffered any damage. However, a rupture occurred in one underground 6 inch (15 cm) line for the fire suppression system. Additionally, several fire suppressor sprinkler heads were sheared off by lateral movement of false ceiling tiles.

The waste water system in the area surrounding the facility suffered numerous broken lines. Consequently, the sanitary waste disposal systems of the facility were inoperable for about three days. This caused a major hindrance in the performance of the functions of the facility.

The facility is heated by steam from its own boiler plant. There was no damage to the boiler plant nor problems with any of the equipment in it. The chill water system performed well, as did all but one unit of the air conditioning system. One unit located on the roof of a three story building suffered damage when the bolts anchoring the unit's isolators to the roof sheared. There were two 0.75 inch (2 cm) diameter bolts for each of the four isolators on this unit.

There were no problems with the natural gas system. And all medical gas cylinders were restrained and thus they suffered no damage.

Numerous elevators became inoperable as a result of earthquake induced misalignments. One, located in the parking garage, was still inoperable two months after the event. The parking garage is a four story reinforced concrete frame structure with concrete masonry unit (CMU) shear walls. Minor spalling of some split-faced CMUs occurred along the east face of the east shear wall.

Curb misalignments and accessway differential settlement were not large enough to cause any access problems for ambulances or rolling stretchers.

FILLMORE MEDICAL CLINIC, FILLMORE

This facility is located about 25 miles (40 km) from the epicenter. It consists of one single story building (wooden frame with stucco exterior) constructed about 1969.

During a normal 24 period, about 90 people are treated at this facility. After the earthquake, this number remained about the same because the Red Cross set up an additional treatment facility in this rural town. This clinic has no overnight care facilities, and patients who need this type of medical attention are sent to nearby hospitals.

This clinic lost commercial electrical power. And since the clinic has no emergency power generators, it remained inoperable for about three days. The electrical power loss caused a loss of all HVAC systems.

Telephone communications were also lost. There were no emergency communication circuits, either inside the building or with outside organizations.

The normal supply of fresh water was not affected by the earthquake. The waste water system was also unaffected.

There were no problems with the natural gas system. And all medical gas cylinders were restrained and thus they suffered no damage.

File cabinets were anchored down, but their contents were unrestrained and patient files were strewn about the floor by the earthquake. Many desktop computers were also unrestrained. They moved on their desks, but none fell to the floor. Shortly after the event, all computers were restrained to the desk tops by VELCRO. There was one spill of a medical liquid. One large bottle of iodine fell off a shelf and broke. There were no restraints on the shelf.

Differential ground settlement was insufficient to cause any access problems.

The clinic has an "emergency response plan," and it is exercised twice a year. Before the earthquake occurred, the most recent drill took place in the autumn of 1993.

ST. JOHN'S HOSPITAL, SANTA MONICA

This facility is located about 15 miles (24 km) from the epicenter. It is the largest hospital in Santa Monica, with 501 beds. It is also the largest employer in Santa Monica, employing over 2000 people. It was completely closed for a three month duration following the earthquake. It took over 6 months for all functions to be restored to full operation.

During a normal 24 hour period, about 60-80 people visit the emergency room. In the 24 hour period following the earthquake, about 175 people visited the emergency room. When the earthquake occurred, the facility had about 295 patients. On the day of the event, about 130 people were discharged to their homes. Over the two day period following the quake, about 30 people were admitted to the facility as a result of earthquake related injuries. On the third day following the event, January 20, all patients were evacuated from the facility. In this evacuation, about 65 people were discharged to their homes, while about 130 were sent to other hospitals. The evacuation took about 7 to 8 hours.

The facility consists of a main building with five wings and one separate (Ross) building. The Ross building and the east and west wings of the main building were yellow tagged but the north, south and main wings were red tagged. The yellow tagged buildings were all steel frame structures. The term yellow tagged means that limited access to the building was allowed because the building's structural damage was determined to be non-life threatening. The entire facility had never undergone any seismic retrofitting.

In the red tagged main wing, the lateral force resisting system was a non-ductile reinforced concrete frame which was built in 1942. The structural frame performed well, but the nonload bearing partition walls, which were made of hollow clay tile, failed in a brittle manner, causing numerous interior plumbing leaks. These leaks caused electrical shorts and three electrical fires.

The red tagged north wing was a non-ductile reinforced concrete frame built in 1954. This wing, which is long in the east-west direction, had a soft second story. Significant structural damage occurred in this wing. This included shear cracks in the exterior window pier columns, and interior beam, floor and column damage, Fig. 15.1.

The red tagged south wing, built in 1968, was a reinforced concrete frame with shear walls. This wing suffered major structural damage because the shear wall was discontinuous at the bottom of the second story. The first story was wider than the second and upper levels. Large cracks occurred in the shear wall about 4 to 6 feet (12-18 m) above the bottom of the second story as a result of the shear wall discontinuity.

The facility had intermittent electrical power losses following the quake. The emergency generator started up and assumed the electrical load. But due to numerous electrical shorts caused by interior water leaks in the facility, several breakers tripped open. Thus several functions in the hospital were without any electrical power. Additionally, the supply of cooling water to the emergency generator was lost, when the chill water tanks on the top of the main wing toppled over. The generator is a 1400 KW diesel which is shock mounted and is tested weekly under load. The battery racks were restrained at both the bottom and the top.

The loss of the chill water tanks also caused the loss of the air conditioning system. The heating system also was inoperable due to the numerous interior plumbing and ductwork problems.

Figure 15.1. St. John's Hospital. Shear cracks in columns of soft story of north wing.

The facility had no problems with the fresh water system directly. But because of off-site ruptures in the waste water system, the potability of the fresh water supply was questionable. Consequently, water had to be boiled before use.

There were no problems with the telephone communication system or with any of the emergency radio systems.

The facility has an "emergency response plan," and it is exercised once a year in the county wide drill, and one additional time per year, alone. Before the earthquake occurred, the most recent drill took place in the autumn of 1993.

VETERAN'S ADMINISTRATION MEDICAL CENTER, SEPULVEDA

This facility is located about 4 miles (7 km) from the epicenter. The peak ground motion recorded at this site was 0.94 g horizontal and 0.48 g vertical. There are 22 buildings on the 44 acre (18 hectare) site. A majority of the buildings were constructed during the period from 1952-1955. Most buildings suffered only minor damage, but four buildings, Bldgs. #3, #40, #20, and #25 suffered major structural damage.

There was only one earthquake related injury. One patient fell out of bed and broke a hip.

The facility has an "emergency response plan," and it is exercised often. This readiness was evident in the rapid evacuation of patients from damaged structures. During the evacuation, all patients in the damaged structures, except those in the intensive care unit (ICU), were evacuated within 2 hours to a parking lot. When portable generators had been set up in a parking lot, all ICU patients were evacuated. Thus, within 3 hours all 331 patients in the damaged buildings had been evacuated.

VA centers in West Los Angeles and Long Beach provided assistance in equipment and personnel. Eighty-five patients were transferred to the Loma Linda VA Center and about 246 were transferred to the Long Beach VA Center. A mobile medical clinic arrived from Prescott, AZ, within 28 hours after the earthquake, and it had treated 77 patients by the end of January 18, the first day after the earthquake. During January 19, the second day after the event, the mobile clinic treated 154 patients. A second mobile medical clinic arrived from the VA Center in Spokane, WA, at 11:00 PM on January 19. On the third day, over 200 patients were treated in these two mobile clinics.

The facility lost commercial electrical power for a period of about 12-14 hours. During the earthquake, many of the batteries which are used to start the emergency generators toppled over and snapped their cables. The batteries were not restrained in their racks, Fig. 15.2. However, personnel were able to start up all six generators. All generators are shock mounted and their cooling water systems had no leaks, Fig. 15.3. The generators operated properly until numerous electrical grounds occurred as a result of interior water leaks in the facility. (These leaks occurred when interior nonload bearing partition walls were damaged by the pounding of the various wings of Building #3 at their joints with the main body of the structure.) These electrical grounds caused almost all circuit breakers to trip open. Thus most functions in the entire facility were without any electrical power. This condition lasted for two days, until the grounds were repaired and the facility was energized one building at a time. Power was restored to all but two buildings by about 60 hours after the earthquake. However, Bldgs. #3 and #99, remained without electrical power for five days, because switchgear and transformers had been knocked off their supports. For example, one 750 KVA transformer sheared its 0.75 inch (2 cm) anchor bolts and the support pad underneath one 300 KVA transformer sank. In total, there was over $1.5 million in electrical equipment damage.

The facility has automatic shut off valves for the natural gas supply system. They functioned according to design.

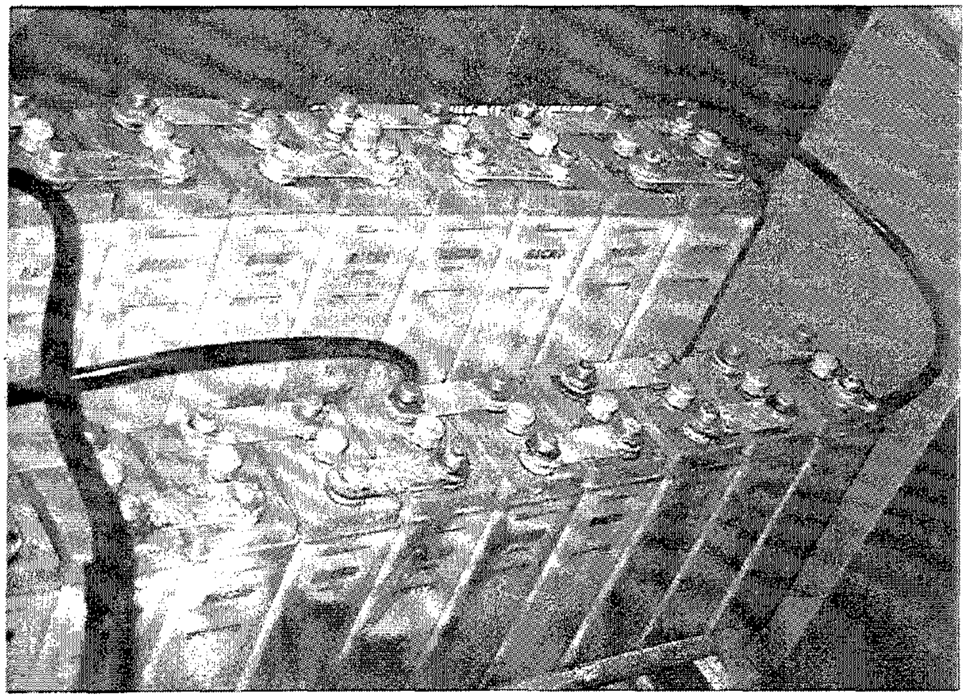


Figure 15.2. VA Hospital. Emergency generator batteries, which were not restrained at top and bottom, toppled over.

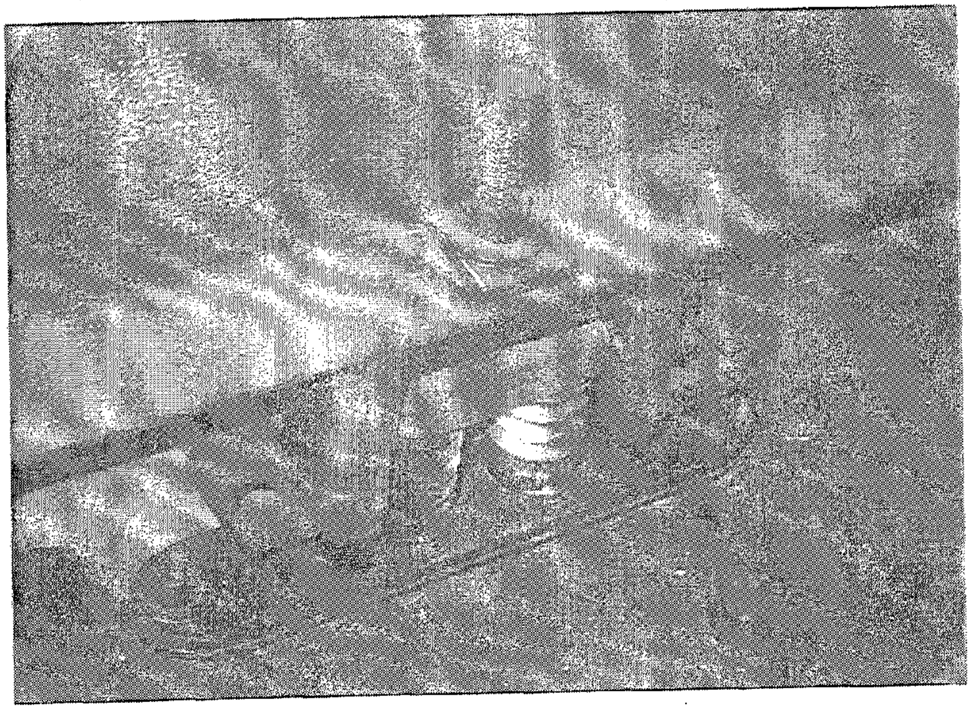


Figure 15.3. VA Hospital. Shock mounting for emergency generators.

There were no reported problems with the telephone communication system nor with any emergency radio system.

It was observed that medical gas cylinders were restrained by chains. But one set toppled over when the chain broke as a result of the earthquake. One large liquid oxygen tank, measuring about 8 feet (2.4 m) in diameter and about 15 feet (4.6 m) tall, and restrained by a single 1.0 inch (2.5 cm) diameter anchor bolt on each of its three legs, suffered no damage, Figs. 15.4 and 15.5.

Building #3 suffered major damage and all patients in it were evacuated. It is a reinforced concrete frame structure with reinforced masonry infill walls. It has a main wing, which is six stories plus a penthouse, and several five story wings, Fig. 15.6. Seismic joints are located at the intersections of the wings with the main wing and with each other, Fig. 15.7. Significant pounding damage occurred at the joints between the southeast and east wings, between the west and southwest wings, and between the main wing and the southwest wing, Fig. 15.8. At these locations, the joints opened a larger amount in the upper stories and consequently the exterior pounding was worse in the upper stories. It was also observed that the interior lifeline damage was worse in the upper floors of the structure than at the first floor. For example, on the fifth floor, the cover plate over the seismic joint between the main wing and the southwest wing, buckled upward over 6 inches (15 cm). This would significantly impede the movement of patients on rolling stretchers. At this same location on the first floor, the plate moved horizontally less than 1 inch (2 cm).

The pounding caused significant damage to the floor diaphragms and nonload bearing partition walls. The concrete cover on many floor joists was spalled off and the reinforcement bars were buckled. The fracture of brittle partition walls caused many leaks in the interior plumbing system. These leaks caused many electrical shorts and grounds, which caused circuits breakers to trip open and prevented the energizing of circuits when emergency electrical power was available.

Building #2 is located about 200 feet from Bldg. #3. Compared to Bldg. #3, it is similar in plan, and oriented in the same direction with respect to the epicenter, Fig. 15.7. The main wing is five stories plus a penthouse, and the wings are four stories. But the major difference between Bldgs. #2 and #3 is that the seismic joints in Bldg. #2 are along the main wing, not at the intersections of the main wing with the other wings, as in Bldg. #3. At the intersection between the main and east wings, the seismic joint opened up by about 4 inches (10 cm), nearly uniformly from top to bottom. There was no evidence of pounding at the main wing joints, nor anywhere else in Bldg. #2. The east and southeast wings essentially formed a cruciform which responded as one structure to the ground motion. The west and southwest wings performed similarly. Bldg. #2 had several broken glass windows, but no major damage. This building remained occupied and operational.

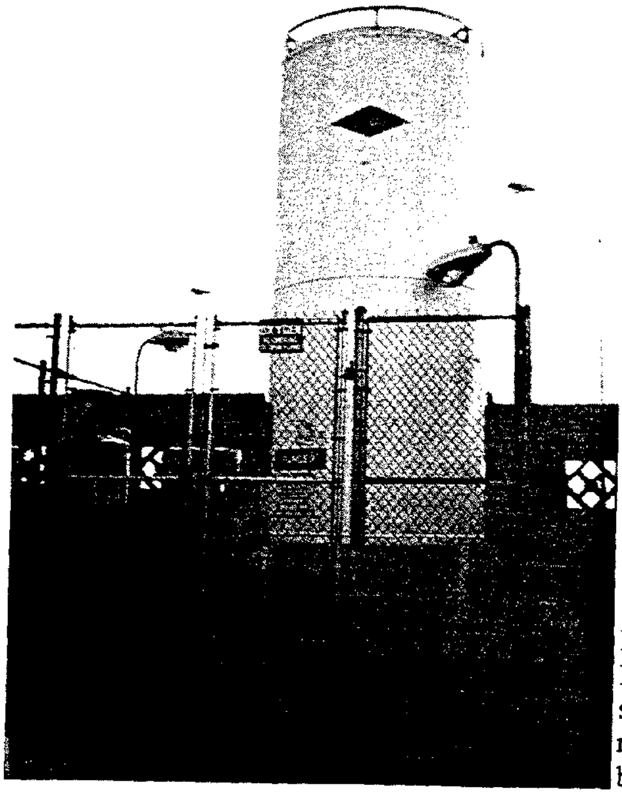


Figure 15.4. VA Hospital. Liquid oxygen tank. (Left)

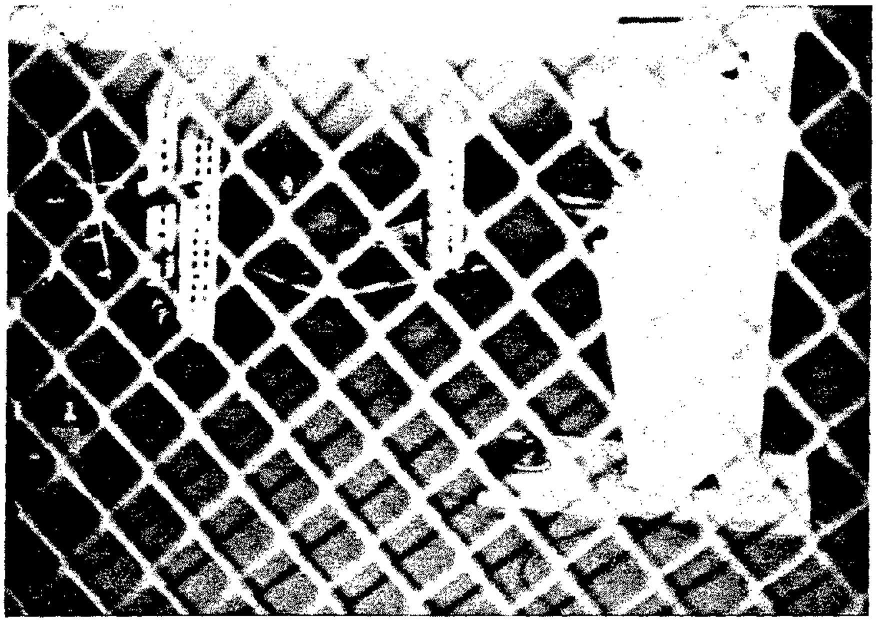


Figure 15.5. VA Hospital. Liquid oxygen tank was supported on three legs each restrained by a single 1 in. bolt. (Below)

Figure 15.6. VA Hospital. View of south side of building #3.

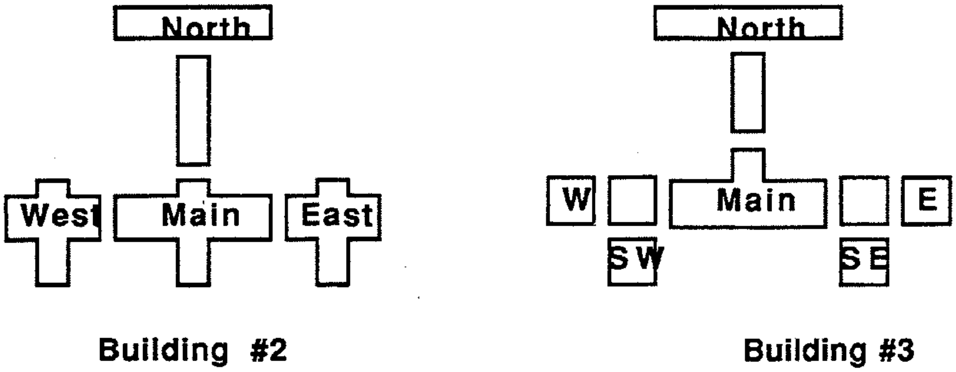


Figure 15.7. VA Medical Center. Plan view of Buildings #2 and #3.

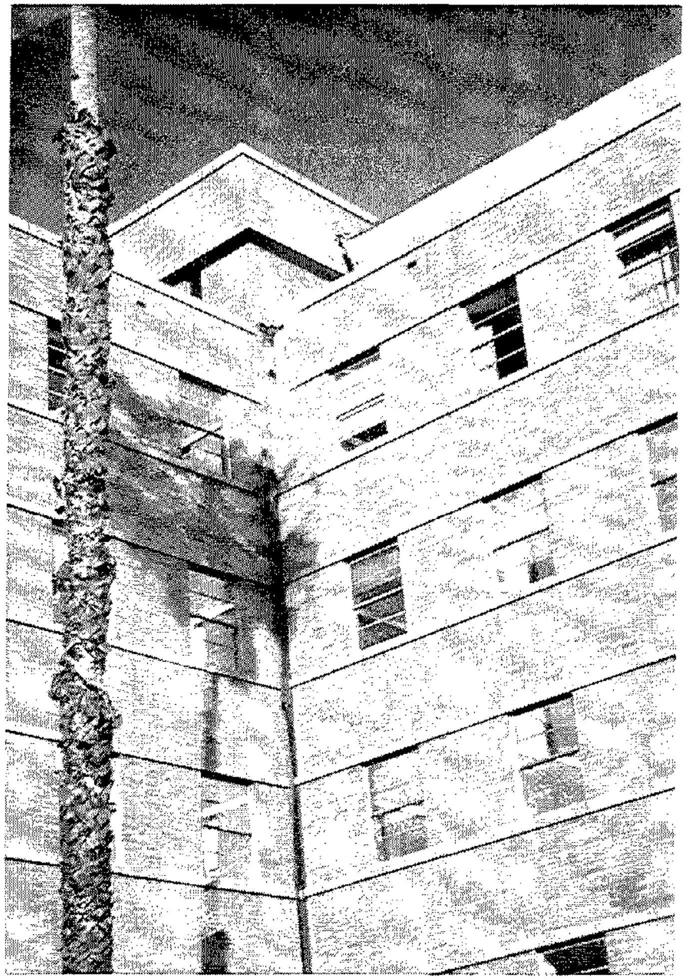


Figure 15.8. VA Hospital. Bldg. #3. Pounding damage at seismic joint between southwest and west wings.

Building #40 contains the boiler plant and the chill water plant. In this building there was no damage to any chill water equipment since most equipment was bolted to the floor. However, the 12 inch (30 cm) chill water pipe out of the plant developed leaks at a flanged joint located about 8 feet (2.4 m) outside of the building. One horizontal air compressor tank jumped out of its spring-shoe supports, while an identical unit next to it did not move because it was solidly bolted to the floor, Figs. 15.9 and 15.10.

At several locations, it was observed that there was about 4 inches (10 cm) of relative axial displacement between pipe hangers and the supported chill water lines, Fig. 15.11.

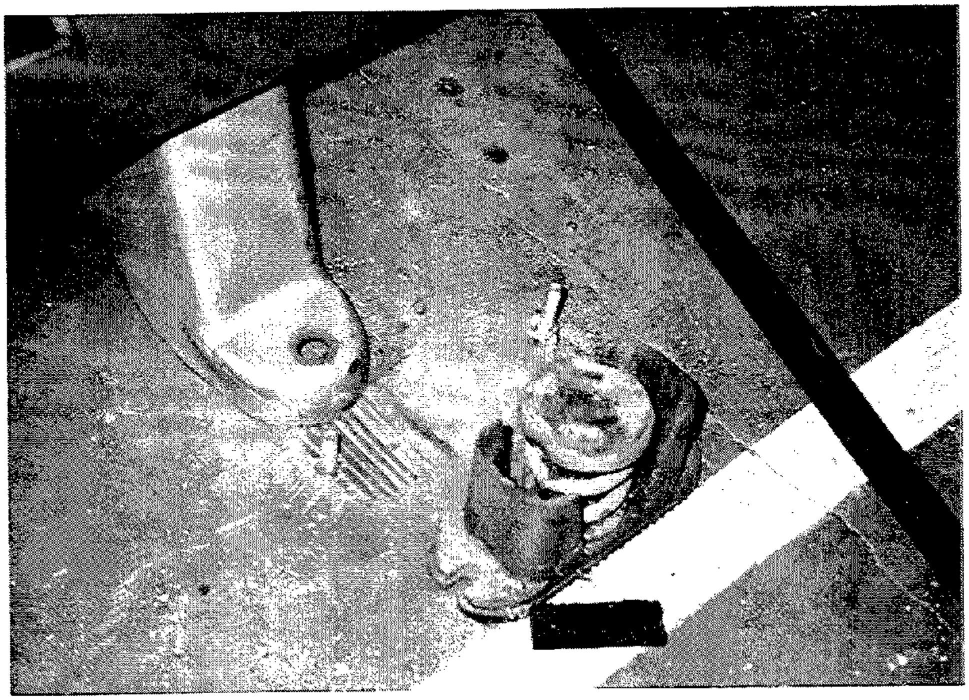


Figure 15.9. VA Hospital. Air compressor tank jumped out of this spring-shoe support.

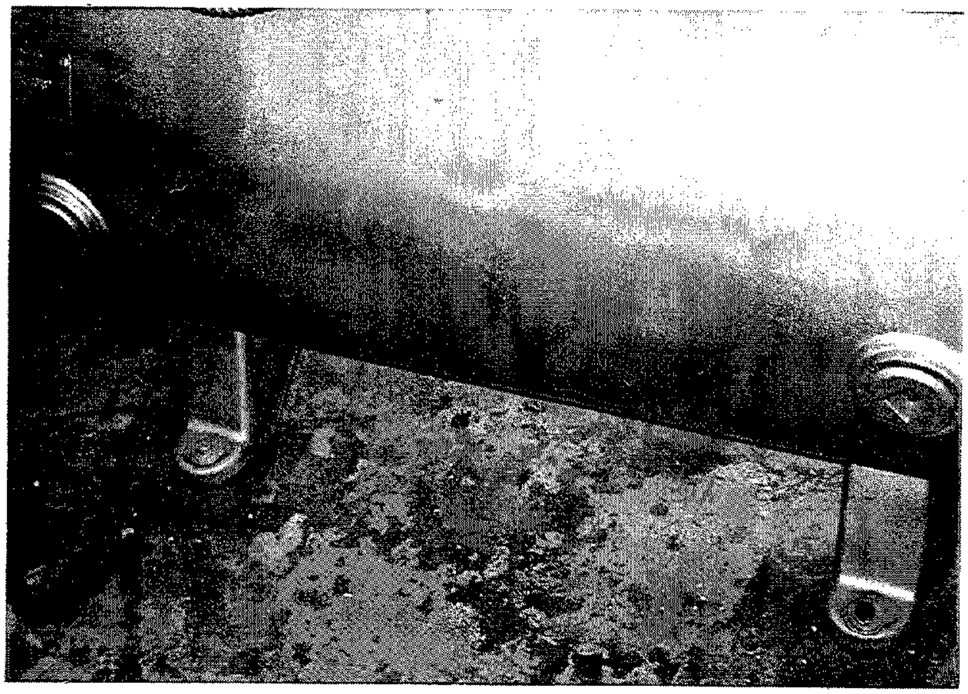


Figure 15.10. VA Hospital. Air compressor tank bolted solidly to floor.

At one location, a 12 inch (30 cm) steam pipe had moved about 4 inches (10 cm) laterally on a roller support, Fig. 15.12.

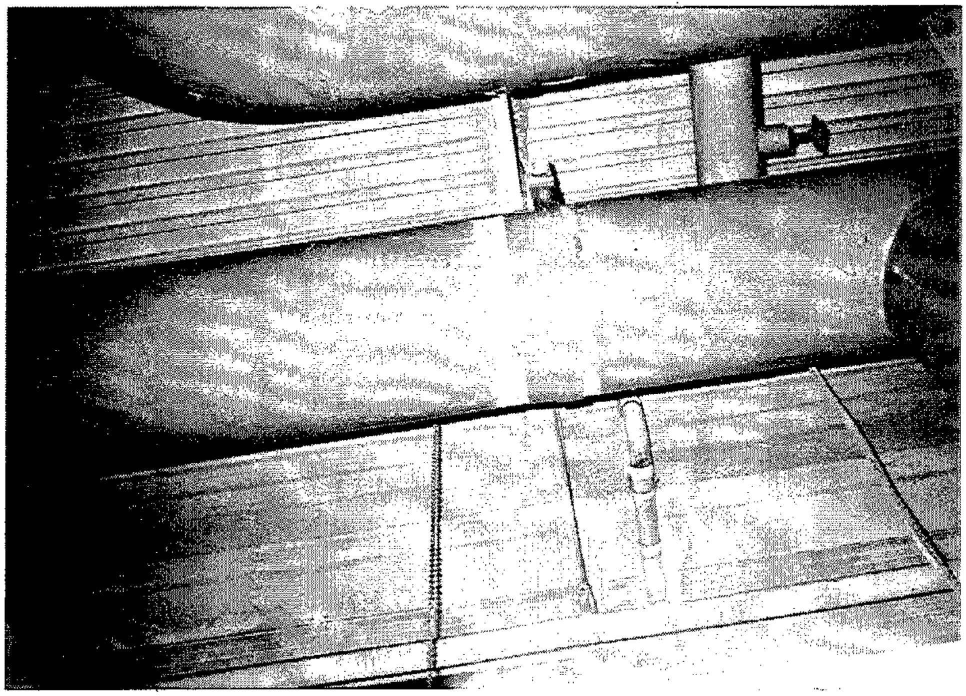


Figure 15.11. VA Hospital. View looking upward of relative axial motion between chill water pipe and pipe hanger.

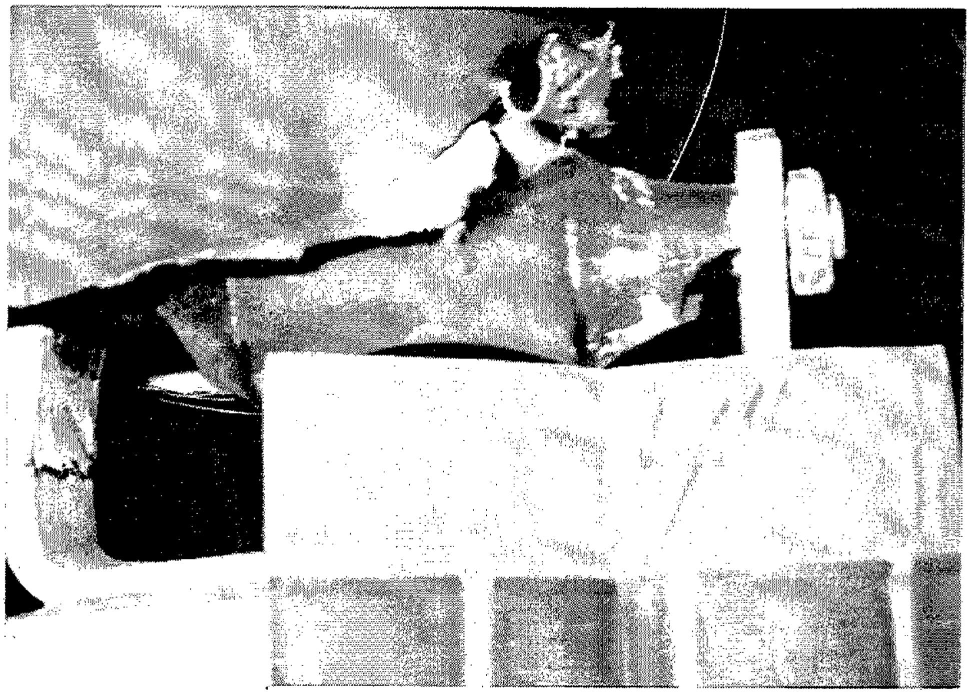


Figure 15.12. VA Hospital. A 12 inch diameter steam pipe moved laterally off its roller support.

One of the two boilers lifted off its supports causing cracks in the refractory brick. One support for a catwalk pulled out of a concrete column. The support pad was anchored by two 0.5 inch (13 mm) bolts, Fig. 15.13.

The portion of Building #40 containing the boiler plant was built in 1954 with a reinforced concrete frame and reinforced clay brick infill walls about 40 feet (12 m) high. The walls are double wythe, solid grouted, with #3 horizontal bars and #4 vertical bars. The part of the building containing the chill water plant was of more recent construction with solid grouted reinforced concrete masonry block walls about 20 feet (6 m) high. A seismic joint is at the intersection of the two parts. There were large diagonal shear cracks in the clay brick walls indicating that severe pounding occurred at this joint. The frame in the older part is stiffer along the west side than along the east side. See Figs. 15.14 and 15.15. Consequently, there was an eccentricity between the center of mass and center of stiffness of the building. Thus torsion occurred causing large cracks in the masonry at the northeast corner. See Figs. 15.16 and 15.17. At this corner, several bricks were knocked completely out of the wall so that the entire two wythes were exposed. See Fig. 15.18. Additionally, two 16x18 inch (40x46 cm) reinforced concrete columns along the north wall suffered cracks completely through their cross-section. See Fig. 15.19. On one of these columns, some concrete spalled off at a 6 inch (15 cm) lap splice, and the #7 reinforcement bars buckled, Figs. 15.20 and 15.21. There were no lateral ties observable in the columns.

HOLY CROSS MEDICAL CENTER, MISSION HILLS

This facility is located about five miles (8 km) from the epicenter. It consists of a 225 bed hospital structure, which is a four story reinforced concrete frame plus a penthouse, and a separate structure containing the boiler and chill water plant. The facility was constructed in about 1976. There has never been any seismic retrofitting.

All services were interrupted by the earthquake. About 50 patients were evacuated to other hospitals.

The fracture of partition walls and the collapse of false ceilings in many spaces inside the structure caused numerous ruptures in plumbing lines and heating coils in the HVAC ducts. This type of damage occurred in the spaces of all departments, thus affecting all services offered by the facility. The services offered were partially restored in all departments within one week. Full capacity was restored in all departments within three weeks of the earthquake.

The HVAC ducts and booster pumps for the chill water and heating water systems in the penthouse were damaged by the collapse of structural members in the penthouse. This caused the loss of all HVAC throughout the facility. Additionally, several heating

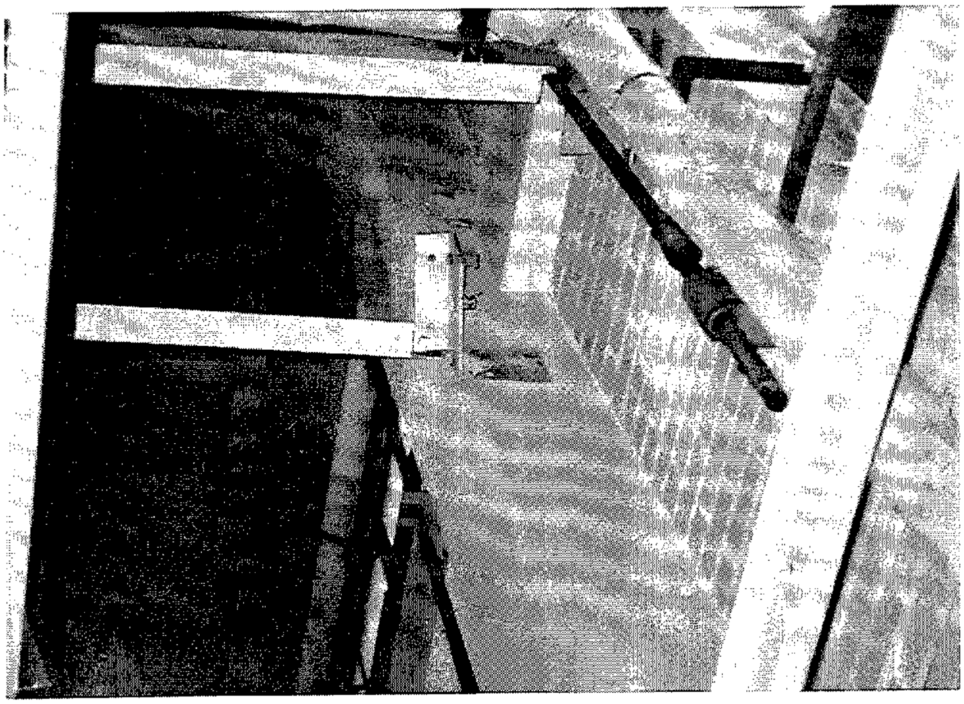


Figure 15.13. VA Hospital. Bldg. #40. Support pad for a catwalk pulled out of its support column.

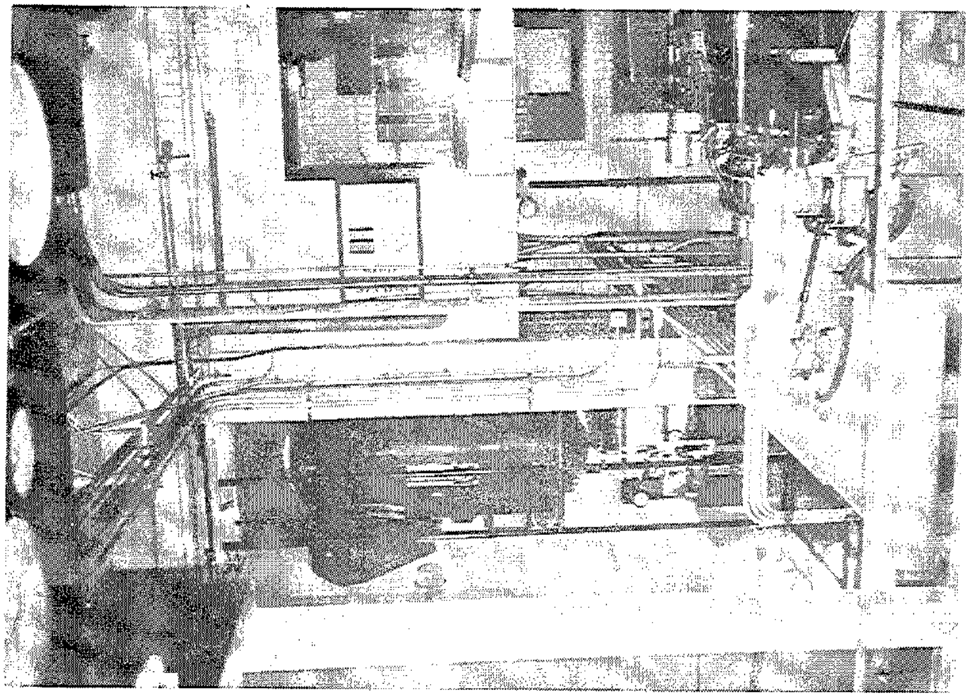


Figure 15.14. VA Hospital, Bldg. #40. West portion of interior frame.

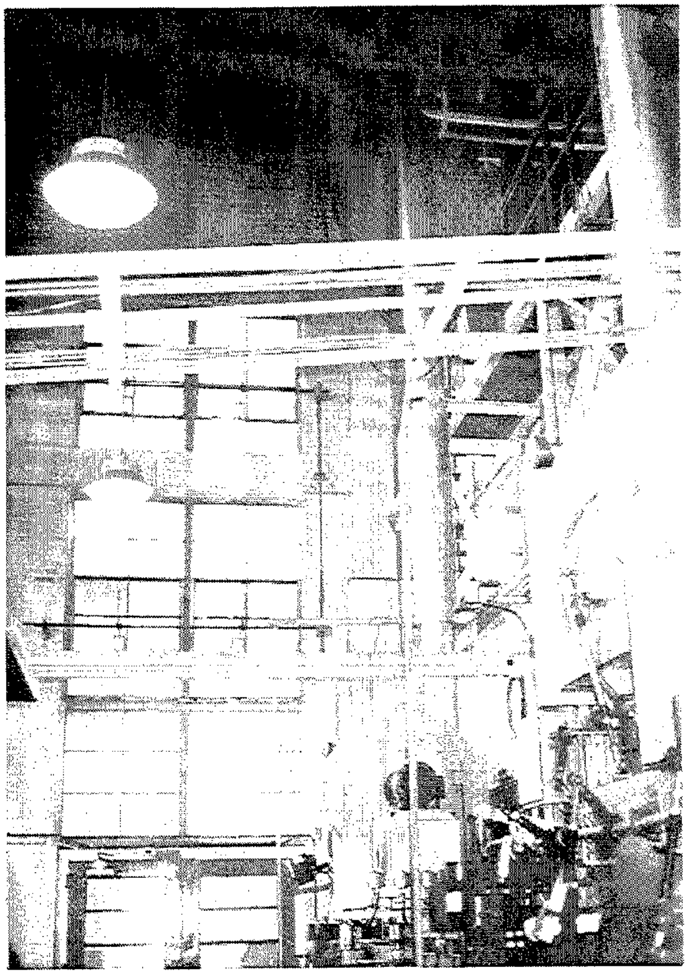


Figure 15.15. VA Hospital Bldg.#40. East portion of interior frame.

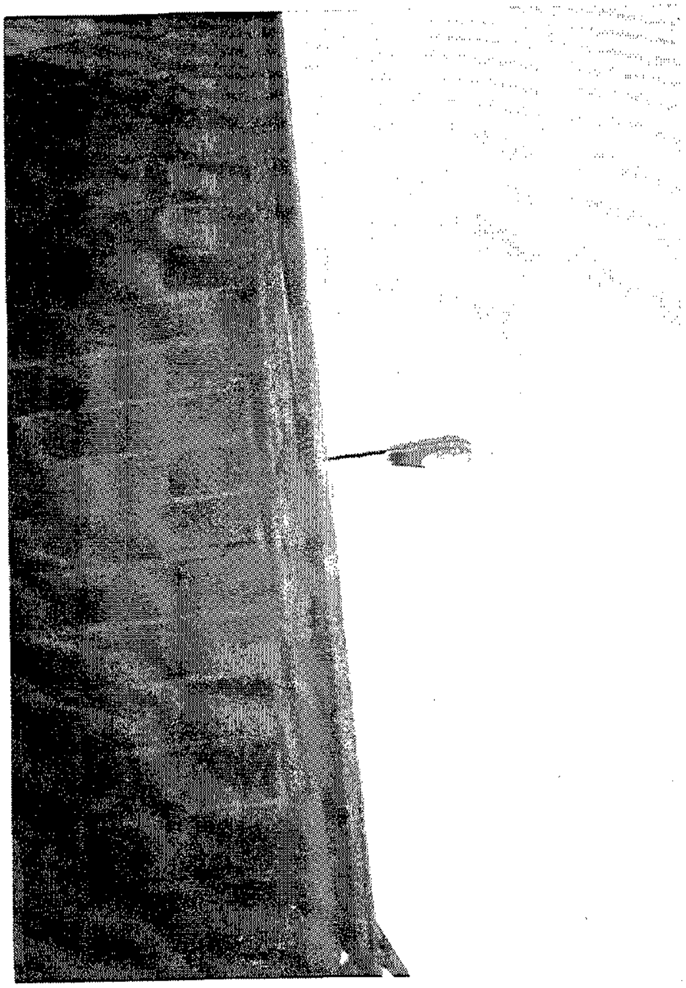
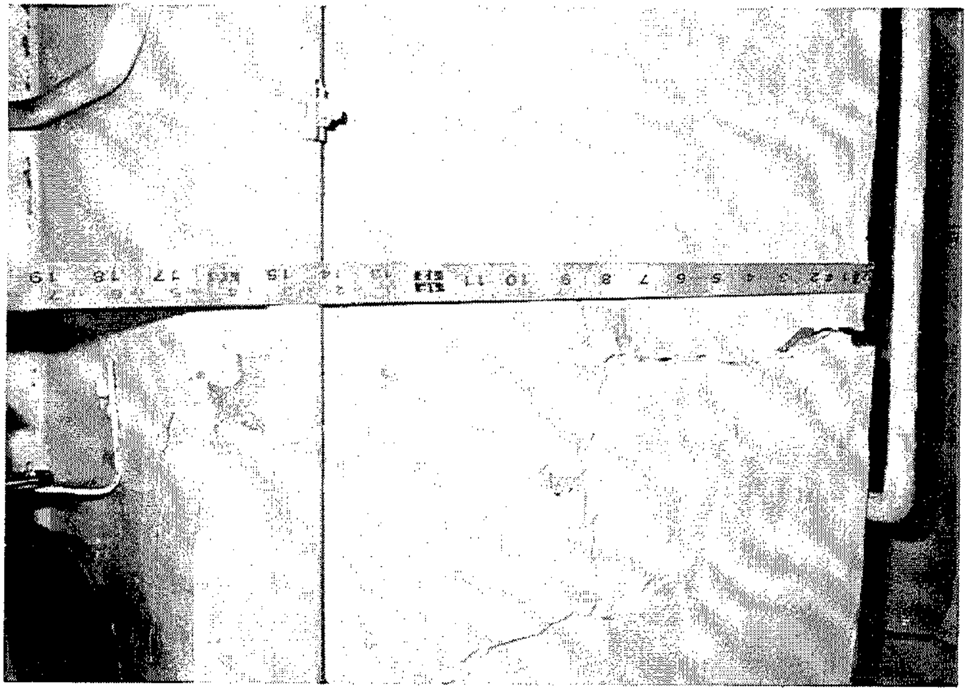


Figure 15.16. VA Hospital. Bldg. #40. Exterior of infill wall at northeast corner. Cracks due to frame torsion.

Figure 15.17. VA Hospital. Bldg. #40. Interior of infill wall at northeast corner.

Figure 15.18. VA Hospital. Bldg. #40. Exterior of infill wall at northeast corner. Double wythe solid grouted, reinforced. (Left)

Figure 15.19. VA Hospital Bldg. #40. Interior column along north wall. Crack through entire cross section. (Below)



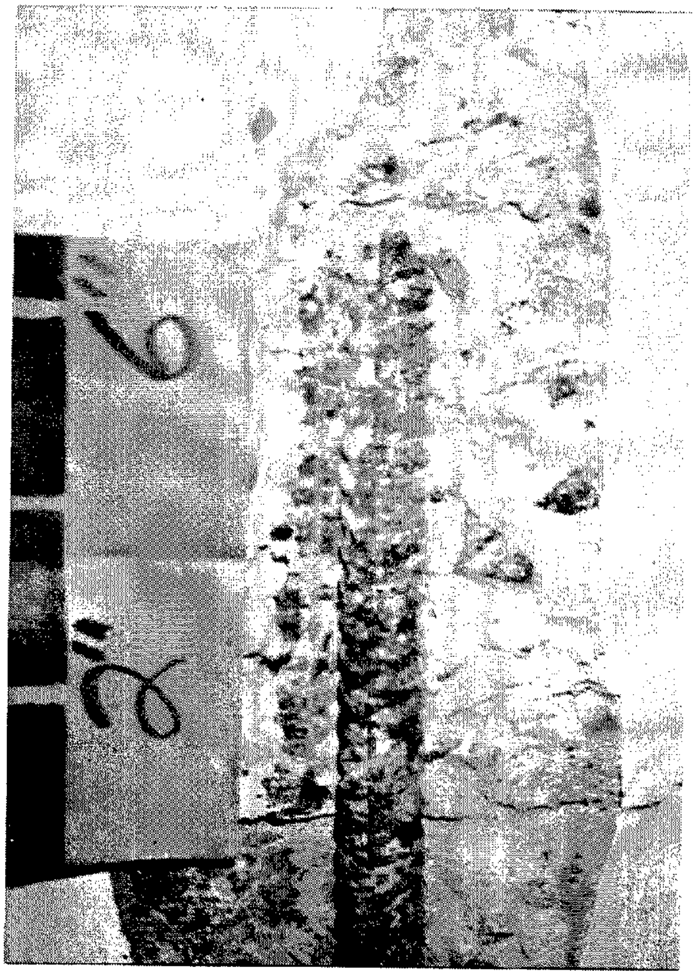


Figure 15.20. VA Hospital Bldg. #40. Same interior column as Figure 15.19 along north wall. Concrete spalled at 6 inch lap splice.

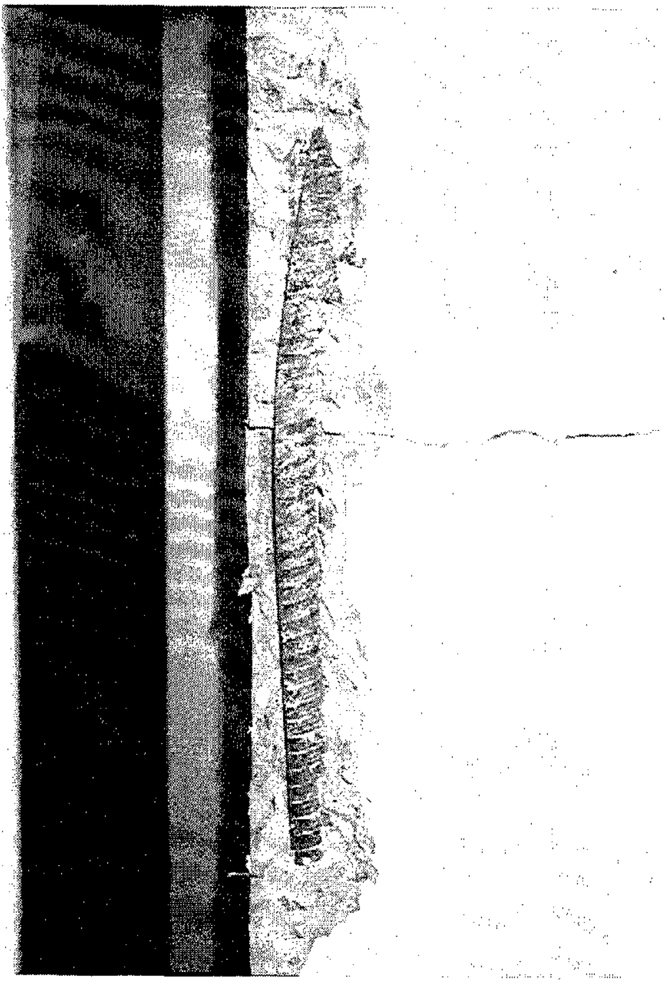


Figure 15.21. VA Hospital Bldg. #40. Same interior column as Figure 15.19 along north wall. Reinforcement bar (#7) buckled due to lack of lateral ties.

water circulating pumps in the boiler plant twisted on their supports, even though they were anchored by 0.75 inch (2 cm) diameter bolts. However, no lines ruptured.

Commercial electrical power was lost for a period of about 6 hours. The emergency generators successfully assumed the electrical load. There are two 300 KW generators and one 800 KW generator. They are all shock mounted and tested under full load weekly. There was no problem with the batteries which are located on the floor. The tank for the fuel system is underground and there were no leaks. All transformers and switchgear were anchored and no problems occurred with any of this electrical equipment. However, because of grounds caused by plumbing leaks and the subsequent opening of some electrical circuit breakers, one person died due to loss of electrical power to his respirator.

Telephone communications were lost intermittently. The intercom system in some spaces of the facility failed because some amplifiers were damaged by falling ceiling debris or water leaks. The emergency radio communications with outside organizations had no problems.

The normal supply of fresh water was lost. The waste water system in the area surrounding the facility continued to function, but there were several rooms that had clogged toilets due to fallen ceiling debris.

A large liquid oxygen tank, measuring about 6 feet (1.8 m) diameter and 15 feet (4.6 m) tall and anchored by four legs, suffered a buckling of one leg. This leg was anchored to a concrete support pad and had an unbraced height of about 12 inches (30 cm). The entire tank was replaced.

The elevators were made inoperable by activation of an automatic seismic shutoff switch. They were returned to service on the day of the earthquake.

There were no problems with ambulance or rolling stretcher access to the facility.

The facility has an "emergency response plan," and it is exercised once a year in the county wide drill, and one additional time per year alone.

GRANADA HILLS COMMUNITY HOSPITAL, GRANADA HILLS

This facility is located about 1.5 miles (2.4 km) from the epicenter at 10445 Balboa Blvd. in Granada Hills. It is located adjacent to the collapsed Kaiser Permanente office building.

This facility consists of a 3 story plus penthouse main hospital building, a 3 story medical office building, and a 4 story parking structure. The reinforced concrete frame parking structure collapsed due to failure of the beam-column joints. The office building is a steel frame structure with reinforced concrete masonry unit (CMU) walls. The walls pulled away from the steel frame. This structure was unusable until it was repaired. The repairs took about 12 weeks. The main hospital building suffered no structural damage. In all three of these buildings, there were no injuries due to the earthquake.

The hospital remained open in the aftermath of the earthquake, but some functions of the hospital were disrupted due to lifeline problems in the hospital building. These made it necessary for the facility to treat over 1000 people in the parking lot, and it forced the hospital to stop accepting trauma patients. However, this was the only hospital to remain open in Northridge after the earthquake, and about 30 patients were admitted to the hospital in the first two days after the event.

The penthouse above the third story of the hospital building contains the boiler and chill water plants. Three of the four circulating water pumps pivoted on their spring supports, but no leaks developed due to this motion. One cooling water tower shifted, but it developed no leaks. This tower was anchored to the roof diaphragm. One bank of chill water coolers toppled over, even though it was anchored to the roof diaphragm. No significant leaks occurred from this.

But some tanks in the penthouse lost their contents and this caused significant water damage to the hospital. A 2500 gallon (9475 L) domestic water storage tank moved axially along its saddle supports until one end came off its saddle. This broke the piping system at this tank and caused the water to flow down into the third and second stories. The saddles were anchored to the roof diaphragm. Additionally, two 500 gallon (1900 L) hot water tanks became detached from their four anchored supports and ruptured, spilling their contents down onto the third and second stories. These water problems did not cause any electrical shorts nor disrupt intercom communications inside the building.

Commercial electrical power was lost for a period of about 6 days. The two 500 KW emergency generators functioned properly because they were all shock mounted and tested under full load weekly. There was no problem with the batteries which are located on the floor. The tank for the fuel system is underground and there were no leaks. The cooling system for the generators is self-contained with the generators; there were no leaks in this cooling system. All transformers and switchgear are anchored and no problems occurred with any of this electrical equipment. One portable 500 KW generator was brought on site but it was never needed.

Telephone communications were lost for about 1-1/2 days. But handheld radio communications were maintained with outside organizations through the Hospitals Emergency Amateur Radio (H.E.A.R.) disaster network. Interior communications within the hospital building were not disrupted.

The normal supply of fresh water was lost due to broken water mains in the area. But the waste water system out of the facility into the local sewer system remained operable. The sewer system in the immediate area was not affected by the earthquake. There were no problems with any hazardous material.

The natural gas supply was lost. There were no problems with medical gases in the facility because the bottles were restrained.

There were no problems with ambulance or rolling stretcher access to the facility.

The facility has an "emergency response plan," and it is exercised once a year in the county wide drill, and one additional time per year alone.

SUMMARY OF TYPICAL LIFELINE RESPONSE

Table 15.1 summarizes the performance of the nine hospitals discussed in this chapter. It identifies the major sources of damage which caused disruptions in the functions of the hospitals.

Over 1000 patients were evacuated from various hospitals due to damage suffered by the electrical and water lifelines in those hospitals.

Many hospitals suffered total or intermittent lost of their normal supply of electrical power. By itself, this loss was not a major problem because most emergency generators performed well. However, several hospitals subsequently lost emergency electrical power because of electrical shorts and grounds caused by leaks in domestic water and fire sprinkler systems and rupture of roof mounted tanks. These leaks were caused by failure of nonload bearing partition walls. At least three fires and one death were caused by electrical shorts and grounds.

Telephone communications with outside organizations were lost by many hospitals, but communications were maintained by radio circuits. Some hospitals lost interior communications because of grounds due to interior water leaks.

The incoming supply of fresh water and the removal of waste water were not a significant problem for most hospitals in this earthquake. No significant problems were reported with natural gas systems, and no fires were caused by natural gas at hospital facilities.

Most hospitals had emergency response plans and exercised them twice a year. The plans worked well, for incoming casualties, but most hospitals had not planned that they themselves would be the casualty.

OBSERVATIONS, LESSONS LEARNED, AND RECOMMENDATIONS

Emergency response plans should be reformulated to include actions to be taken in the event that some or all of the hospital functions are disrupted by earthquake damage. It should also designate responsibilities, chain of command, and actions to be taken until the Emergency Operations Center is operational. Emergency response plans should be should be tested at least twice a year.

The following list contains recommended actions for hospital facilities. These are based upon the lessons learned from the good and poor performance of lifeline equipment and systems observed in the aftermath of the Northridge earthquake.

Table 15.1 Hospital Functionality After the January 17, 1994 Northridge Earthquake

Hospital	Functionality	Cause
L A County Medical Center -Psychiatric Hospital	•Evacuated 100 patients. •Red tagged for over 15 months.	•Water damage caused by roof tank rupture. •Reinforced concrete column damage
L A County Medical Center - Pediatric Hospital	•Evacuated 67 patients •Red tagged for over 15 months.	•Reinforced concrete column damage
USC Univ. Hospital	•Excellent performance	•Base isolated steel frame, only $500 damage
Olive View Medical Center	•Evacuated 300 patients •Continued functions in parking lot.	•Intermittent loss of emergency power. •Domestic water lines ruptured due to lines punching through walls.
Northridge Hospital	•All functions interrupted. •Remained open. •Triage in parking lot	•Water mains in area ruptured. •Wastewater mains in area ruptured. •Fire main ruptured.
Fillmore Medical Clinic	•Inoperable for 3 days.	•Lost commercial electrical power. •Has no emergency power equipment.
St. John's Hospital	•Evacuated 195 patients •Completely closed for 3 months. •All functions restored in 6 months.	•Domestic water lines ruptured due to failure of non-structural walls. •Failures of non-ductile reinforced concrete frames. •Electrical fires.
Veterans Administration Medical Center Sepulveda	•Evacuated 331 patients.	•Domestic water lines ruptred due to failure of non-structural walls caused by pounding of wings of structure. •Loss of emergency power due to electrical grounds and batteries toppling over.
Holy Cross Medical Center	•Evacuated 50 patients. •All services interrupted •All service restored in 3 weeks.	•Water mains in area ruptured. •Domestic water lines ruptured due to failure of non-structural walls. •Patient died due to loss of power to respirator.
Granada Hills Community Hospital	•Loss of some functions. •Remained open. •Treated patients in parking lot.	•Water damage caused by roof tank rupture. •Water mains in area ruptured.

Emergency Response Plans must provide for:

- delineation of chain of command
- specification of personnel authorized to order evacuation, red/green tagging of buildings
- standardized inspection forms
- off-site and on-site sources of casualties
- off-site and on-site sources of lifeline damage
- only half of the specified personnel may arrive
- food supplies for specified personnel for 2 days
- keys for inspecting hazardous material locations
- exercising twice annually

All equipment must be positively anchored, including;

- pumps
- fans
- file cabinets
- gas cylinders top & bottom
- switchgear
- transformers
- cooling towers
- compressors
- computer terminals
- tanks
- anchor legs to roof/floor diaphragm
- anchor saddle tanks to saddle

Emergency generators must:

- be shock mounted
- be tested under full load weekly
- be able to be started manually
- have operators trained to start manually
- have its startup batteries restrained at top and bottom
- have a self-contained cooling system
- have a fuel tank which is anchored
- be connected by flexible couplings to
- fuel system
- cooling system
- electrical system

Communications within the facility and with outside organizations must be able to be maintained by radio circuits. Therefore hospitals must have:

- spare batteries
- handheld/portable transceivers
- personnel trained in radio use

Ceilings tiles must be supported to prevent

- falling
- shearing of fire sprinklers

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16. FIRE DEPARTMENT EMERGENCY RESPONSE

ABSTRACT

Damaged lifelines due to the Northridge Earthquake affected the fire department emergency response efforts in many ways. These lifelines were principally water, communications, electrical power and gas.

The Northridge Earthquake principally affected the City of Los Angeles Fire Department (LAFD). Other fire departments in the area were also affected but to a lesser degree. The earthquake created the potential for a conflagration. One of the greatest dangers to property as a result of an earthquake is fire. Earthquake preplanning and the resourcefulness of LAFD personnel helped avert this possibility. Even so, hundreds of mobile homes and both single- and multiple-family dwellings were destroyed by fire.

LAFD EARTHQUAKE EMERGENCY OPERATIONAL PLAN

The LAFD Earthquake Emergency Operational Plan (EEOP) was formulated in 1973 as a response to the San Fernando Earthquake. The current plan was updated and revised in 1987. The immediate implementation of the EEOP during the Northridge Earthquake provided guidance to all involved and helped limit damage. (Mittendorf, 1994)

The EEOP assumes a catastrophic situation and provides for the following:

1. Each Battalion Command assumes responsibility for command and control of all emergency operations in their geographic area, and can function as an independent operational system.

2. Movement of all apparatus and personnel to predesignated safe location sites (away from buildings).

3. Special communications procedures which rely on radio instead of telephone.

4. A base for interdepartmental and interagency coordination and assistance.

5. Reconnaissance patrols (drive-throughs) by each station along preestablished routes of "special consideration" to verify the status of potential hazards.

6. Recall of off-duty personnel.

7. Suggestions for alternate water supplies if needed.

Water supply is a crucial factor for fighting fires, but after an earthquake the water supply may be limited or nonexistent. This was the case for many areas immediately after the Northridge Earthquake. The EEOP suggests the following if water is lacking:

"Water supply may be disrupted in a localized area due to breakage of water mains or a large segment of the City could be affected by trunk line or supply disruption. Department of Water and Power has emergency interconnections with other water agencies to help alleviate major supply disruptions. Localized disruptions may be resolved by Department of Water and Power's manipulation of gate valves to augment a damaged system or they may request Fire Department pumpers to boost water from one zone to another. In the event of failure of a portion of the water system, commanders should consider the following:

1. Cause notification of Department of Water and Power and the Engineering and Hydrant Unit.

2. Consider a surface relay of water from an adjoining hydrant zone.

3. Local water storage facilities, swimming pools, tanks, etc., may provide a source of fire fighting water.

4. Using reserve hose in storage at fire stations and from Supply and Maintenance.

5. Five-mile length of 6-inch portable water main is stored locally by Office of Emergency Services (O.E.S). An additional ten-mile length is stored outside of the area (5-6 hours away).

6. Water tank trucks are available through our Department and other agencies.

7. Consider helicopter for water drops and filling of portable 1,000-gallon tanks.

8. Consider judicious use of water by selective extinguishment and/or perimeter control of a burning area."

LAFD RESPONSE

At the time of the earthquake there were 788 LAFD personnel on duty. During the quake firefighters were injured, and several fire stations suffered major damage. Most of the city was without electrical power.

Structural damage was noted in 35 station buildings. Although most were repaired quickly, Station 90 was closed for one month for roof repair, Station 70 was out of service for six months, and Station 78 was condemned and demolished. (Ward, 1995)

Once equipment and personnel were safely outside of buildings, reconnaissance patrols were sent out as designated in the EEOP. The timing of the earthquake at 4:31 a.m., was advantageous for the LAFD because their 24-hour shift change occurs at 6:30 a.m. each day. So soon after the earthquake occurred the new shift came to work and the other "old" shift continued to work due to the emergency, doubling the number of personnel available. This enabled reserve equipment to be easily put into service.

By 7:00 a.m., more than 100 active incidents were being handled in the field. Luckily there was no significant wind the morning of the earthquake, otherwise many of the small fires could have quickly spread. By 10:00 a.m., 5 1/2 hours after the earthquake, the LAFD had no major structure fires remaining and all other fires were under control. (Manning, 1994)

LIFELINE INTERACTIONS

The major problem related to other lifelines was lack of water due to the many broken water mains. Disruption to communications, electric power, and gas were also ranked high in affecting fire department response and causing fires.

COMMUNICATIONS

Communications became a weak link in the effort to coordinate and respond to the large number of incidents caused by the earthquake. Even so, there were no incidents in which damage could be attributed to poor communication. But if the earthquake had been larger, or occurred during the day, causing a greater number of incidents, the lack of good communications would have contributed to damage and an inefficient allocation of resources. (Ward, 1995)

The LAFD telephone system continued to work and provided the overall command and control function. The normal Operations Control Dispatch channel for the San Fernando Valley however, was knocked out by the earthquake. The Department's normal command channel was also inoperable. The areas hardest hit experienced occasional difficulty communicating with Department Command by radio because of the very high radio traffic. This necessitated some decisions made in the field without Department Command direction. (Creasey, 1994)

Many cellular phone relay sites in the northwest area of the Valley were inoperative after the earthquake. This made filling logistical requests very difficult, as long lists were relayed over the 800-MHz radio. There was also a lack of 800-MHz radios for distribution because the Department's usual store were on loan to various civic service organizations.

L.A. Cellular provided 50 cellular phones for use. Many of the chief officers were using the loaner cellular phones in their backup sedans. During the day the batteries became discharged, making the devices inoperable. Most of the backup sedans did not have a cigarette lighter outlet to plug in a phone power jack. (Fulmis, 1994)

Communication between area hospitals and the Emergency Medical Services branch of the LAFD was poor or nonexistent which made coordination extremely difficult. (Cowen, 1994) The Hospital Emergency Administration Radio System (HEARS) functioned poorly. This prevented the LAFD from knowing the status of the area hospitals, such as which hospitals were accepting patients or evacuating patients, and which ones were damaged and needed help. (Ward, 1995)

During the first 24 hours, the LAFD had in excess of 2,200 incidents. They received a total of 6,785 telephone calls for assistance (285% above the daily average). The 911 emergency telephone system received 30,109 on the day of the earthquake (227% over the daily average). (Miller, 1994)

As a result of the experiences with poor communication during the aftermath of the earthquake, the State of California has been asked to fund a satellite emergency communication system. (Ward, 1995)

ELECTRICAL POWER

The earthquake occurred at night and was followed almost immediately by the loss of electrical power, which resulted in an almost total blackout. Power lines lying across streets and properties created a hazard for fire fighters.

The power outage hampered the quick exit of equipment from fire stations because electric apparatus door openers did not function. Later in the day refueling became a problem since electric fuel pumps were inoperable. Portable generators were distributed to solve this problem.

When electric service was restored to an area, new fires were not uncommon, due to appliances and lamps that were left in unsafe conditions as a result of the earthquake. Approximately 40 fires were determined to be of such origin. (Prince, 1995)

WATER

Approximately 150 square miles of the San Fernando Valley were without water; nearly one-third of the city area. The quake was so severe that fire hydrants were snapped off. (Schneider, 1994) Large and small-diameter mains ruptured and left many areas without water for fire fighting.

During the first hours, where water pressure was lost, some fires were fought using water from swimming pools, and others required long hose lays from hydrants in zones that remained pressurized. The hardest hit part of the city has many swimming pools which firefighters used extensively to replenish the tanks on their apparatus. (Apparatus is the term used by firefighters for their "fire engines and trucks".) All LAFD engine companies carry "siphon ejectors", specially for pumping from swimming pools and other open bodies of water. (Ward, 1995)

LAFD has five helicopters. Some of the helicopters performed water drops on structures due to the large number of fires and the lack of water in many areas. Water drops were only made on working structure fires in cases where the fire department was not already on the scene and the potential for occupants at that time of day would be nonexistent. This strategy proved beneficial in mitigating the potential for conflagrations. (Anthony, 1994) A total of 15,120 gallons of water was dropped on fires by the helicopters. (Ward, 1995)

Due to the lack of water, 29 water tankers were placed strategically throughout the San Fernando Valley. As a precaution, a tanker was dispatched any time there was an indication of an actual fire. The tanker capacity ranged from 1400 to 5000 gallons. Also, extra hose was carried by all engine companies. (Anthony, 1994)

The LAFD played a major role in providing water service in the affected areas without water. Up to 25 engine companies established temporary pumping stations using the fire engines to transfer water from the low pressure zones to the high pressure zones which were dry. This lasted up to eight days. Strategic locations of fire hydrants from adjacent pressure zones had been established in the past. The pumping locations were well distributed along the periphery of the system, providing coverage to the entire zone. Optimal locations were from areas with large-diameter mains and where the hydrants had minimal traffic impact. The initial attempts to accomplish cross-zone pumping proved ineffective due to the excessive number of leaks/breaks and the inability to isolate them. (Anthony, 1994)

At one location a water tank (Granada High Tank) was damaged and the water damaged an adjacent 800 MHz emergency repeater site. (Ward, 1995)

GAS

Fires associated with the rupture of a 20-inch diameter natural gas line on Balboa Boulevard caused the direct loss of five single-family residences. The rupture created a large fire with flames reaching 100 feet into the air. A 56-inch diameter water main parallel to the gas main also ruptured and flooded the street. During the two-hour incident water from swimming pools was used to control the spread of fire since there was no pressure in the water system. Three engine companies contained the fires on both sides of the street. When personnel from the Southern California Gas Company arrived the gas was shut off and the fires were extinguished. (Patrick, 1994)

Natural gas-fed fires destroyed more than 100 mobile homes. Lack of water to fight the fire, a light wind, and the inability to shut off the gas contributed to the large number of units destroyed. (Bowie, 1994)

TRANSPORTATION

Damage to streets and freeways hampered the ability of the LAFD to respond quickly to incidents, but other lifelines were more significant. In the most affected area the Antelope Valley Freeway had collapsed onto the Golden State Freeway, and sections of the Simi Valley Freeway also had fallen. Numerous freeway overpasses had buckled.

SUMMARY OF FINDINGS AND CONCLUSIONS

1. From the perspective of fire fighting the major lifeline interdependencies were (in order of importance): water supply, electrical power, communication, and gas.
2. A reliable communications system is necessary to coordinate an overall response in an widespread emergency. Better communications systems may have improved the response to the Northridge Earthquake.
3. Fire departments can provide some water system pumping needs in an emergency. Preplanning and coordination with the water purveyor is essential for success.
4. Manual methods to open station apparatus doors as a backup to the electric power should be considered.

5. When restoring electric power, coordination and communication between the electric utility and the fire department could reduce the risk of fires.

6. Redundant gas shutoff valves or "earthquake" shutoff valves on main supply lines for mobile home parks would reduce the risk of fire after an earthquake.

7. A backup system for hospital communication is needed.

8. The LAFD EEOP functioned well, but the initial "drive-throughs" were not completed in a reasonable time in the hardest hit areas because units were diverted to known emergencies. During major disasters other city resources could be used in conducting the drive throughs.

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17. CONCLUSIONS

- Detailed technical conclusions are contained in the sections associated with each lifeline.

- The magnitude 6.7 Northridge earthquake caused significant lifeline damage and losses of the hundreds of millions of dollars to lifeline organizations.

- Most of the lifeline damage observed in this earthquake has been observed in previous events. It did serve to reemphasize many lessons. It also pointed out interdependencies of lifelines. The importance of emergency power, support systems, such as air conditing and ventilating systems, and cooling water needed for the continue operation of critical systems were observed.

- As a result of damage and the resulting lifeline response, several lifeline organizations are reevaluating seismic designs for equipment and facilities, seismic specifications for equipment, operating procedures, and emergency response plans.

- The impact of the loss of major freeways on traffic congestion was less than anticipated. The use of advanced methods of controlling surface traffic alleviated congestion on the Interstate 10 corridor. There were limited alternate routes around Interstate 5, but commuter rail increased several fold and a year after the earthquake volume is twice pre-earthquake levels. The use of telecommuting and modified work schedules also helped reduce traffic congestion.

- The large secondary losses associated with the disruption of lifelines that has been predicted for catastrophic earthquakes has not yet occurred in the US. The 1995 Kobe, Japan, earthquake, where direct lifeline losses were very high and secondary losses were even larger, demonstrated that even an earthquake of moderate magnitude (M_W = 6.8) in a region that has not established and enforced adequate lifeline standards and practices can cause very large direct and secondary losses.

- The Northridge earthquake, like many other recent California earthquakes, occurred on a previously unidentified fault. While it did not have pronounced surface faulting, there were many areas that experienced significant ground deformations that caused damage to buried water, sewer, gas, and liquid fuel lifelines. The difficulty in predicting these affects adds uncertainty to risk analyses used by utilities and the emergency response community. This suggest a more important role for emergency response planning and response capabilities by these groups.

- The importance of secure emergency power and water supplies, particularly for non-utility systems, needs to be communicated more effectively to the emergency response community, industry, and commercial organizations.