NATIONAL CENTER FOR EARTHQUAKE
ENGINEERING RESEARCH
State University of New York at Buffalo

GEOTECHNICAL AND LIFELINE ASPECTS OF THE OCTOBER 17, 1989 LOMA PRIETA EARTHQUAKE IN SAN FRANCISCO

by

T. D. O'Rourke, H. E. Stewart, F. T. Blackburn, and T. S. Dickerman
Department of Structural Engineering
School of Civil and Environmental Engineering
Cornell University
Ithaca, New York 14853

Technical Report NCEER-90-0001

January, 1990

This research was conducted at Cornell University and was partially supported by the National Science Foundation under Grant No. ECE 86-07591.

NOTICE

GEOTECHNICAL AND LIFELINE ASPECTS OF THE OCTOBER 17, 1989 LOMA PRIETA EARTHQUAKE IN SAN FRANCISCO

by

T.D. O'Rourke[1], H.E. Stewart[2], F.T. Blackburn[3] and T.S. Dickerman[4]

January, 1990

Technical Report NCEER-90-0001

NCEER Contract Number 89-4006

NSF Master Contract Number ECE 86-07591

1 Professor, Department of Structural Engineering, School of Civil and Environmental Engineering, Cornell University
2 Assistant Professor, Department of Structural Engineering, School of Civil and Environmental Engineering, Cornell University
3 Assistant Fire Chief, San Francisco Fire Department
4 Assistant Manager, City Distribution Division, San Francisco Water Department

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
State University of New York at Buffalo
Red Jacket Quadrangle, Buffalo, NY 14261

PREFACE

This report was developed from information gathered during earthquake reconnaissance investigations in October, November, and December, 1989. Part of the information contained herein, as well as several of the figures and photos, were used in technical briefings in Washington, D.C. and Boston, MA, which were organized and sponsored by the Earthquake Engineering Research Institute (EERI), the National Center for Earthquake Engineering Research (NCEER) and the National Research Council (NRC). In addition, portions of the text and several figures and photos presented herein were selected for the EERI reconnaissance report on the Loma Prieta earthquake, and appear in the chapters of that report dealing with the geotechnical aspects of the earthquake.

ABSTRACT

Soil liquefaction in San Francisco caused by the 1989 Loma Prieta earthquake occurred at the same locations that liquefaction was observed after the 1906 earthquake. The four main areas of San Francisco affected by soil liquefaction in 1989 and 1906 are the Marina, Foot of Market, South of Market, and Mission Creek districts. Liquefaction effects involved subsidence and loss of bearing of shallow foundations, with differential settlement, racking, and tilting of two to four-story timber structures. In the Marina, deformation was evident on virtually all streets. The pattern of cracking and surface ruptures in the streets did not show a coherent sense of displacement or lateral movement in a preferred direction. Strong ground shaking in the Marina was the principal cause of building damage. The most severe structural damage was concentrated at apartment buildings with multiple garages at ground level. Lateral spreading was observed in the northwestern corner of the Marina Green and docks area, with 0.6 m of horizontal movement toward the bay.

One of the most distinctive features of the earthquake was the concentration of permanent ground movements, sand boils, pipeline and surface structure damage at specific locations of the city underlain by Recent Bay Mud. Amplification of bedrock motions through the deposits of soft clay and silt contributed to strong shaking and damage at the surface.

Preliminary reconnaissance indicates that the underground infrastructure influenced the pattern of soil and street displacement and may have affected the potential for soil liquefaction in certain locations. Severe differential settlements occurred in the Marina and South of Market areas, where liquefaction and consolidation of loose sands occurred next to pile-supported storm drain and sewage facilities. In the Mission Creek district, the presence of the Bay Area Rapid Transit (BART) system seems to have influenced the pattern of soil liquefaction.

Damage in water distribution piping was located primarily in areas of strong ground shaking, liquefaction, and permanent soil displacements. The heavy concentration of MWSS damage in the Marina underscores the importance of site response in the performance of pipeline networks. The recognition that pipeline

damage tends to be concentrated in areas which are especially vulnerable to earthquake damage implies that remedial and protective measures would be best focused in zones where the goetechnical site characteristics tend to promote strong ground shaking and liquefaction.

The 1989 Loma Prieta earthquake has shown how quickly water can be lost from broken mains and how rapidly the reservoir supply can be depleted. Strategies for future improvements, therefore, should be based on rapid isolation of damaged pipelines. Remote electric and radio-controlled gate valves at key locations will promote swift isolation of damage and preservation of the remaining sections of the system.

The flexibility provided by the Portable Water Supply System (PWSS) was of critical importance in controlling and suppressing the fire which erupted in the Marina. The ability to operate with portable hosing and draft from a variety of water sources, including underground cisterns and fireboats, provides a valuable extra dimension in the city's emergency response.

ACKNOWLEDGMENTS

The authors wish to thank several people who assisted in the earthquake reconnaissance and acquisition of information. Special thanks are extended to Dr. C. H. Trautmann and Mr. B. Roth, both of Cornell University, who participated in the on-site post-earthquake investigations during October 19-21, 1989. In addition, Mr. Roth helped in reducing data and developing several of the plots and soil profiles which appear in this report. Mr. R. D. Darragh of Dames and Moore provided valuable assistance in gathering information and helping in site investigations. Dr. T. L. Holzer and Mr. M. J. Bennett of the U.S. Geological Survey assisted in the initial earthquake reconnaissance visits. Thanks also are extended to Mr. H. L. Taylor of Harding Lawson Associates, Dr. C. R. Scawthorn of EQE, Inc., and Dr. J. Isenberg of Wiedlinger Associates. Messrs. W. C. Olinger and S. Champeau of the San Francisco Water Department helped during site visits and in obtaining data, respectively. Mr. W. D. Meyersohn of Cornell University helped in the analysis of pipeline repair data. Mrs. K. J. Stewart prepared the manuscript and Mr. A. Avcisoy drafted the figures.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SECTION 1

INTRODUCTION

1.1 BACKGROUND

The magnitude 7.1 Loma Prieta earthquake, which occurred at 5:04 p.m. PDT on October 17, 1989, was felt over an area of approximately 1,000,000 km^2 [Plafker and Galloway, 1989]. Strong ground shaking and ground failures caused damage to buildings and lifeline facilities throughout the San Francisco Bay region and environs. Although the influence of the earthquake was extensive and many areas afford comparable opportunities for investigation, there is perhaps no area more important than the City of San Francisco. The city offers a unique chance to compare and contrast the effects of earthquakes in 1989 and 1906.

Several areas of the city were affected by locally strong ground shaking, which was caused by amplification of bedrock motions transmitted through deposits of soft clays and silts. In many locations, the ground shaking resulted in the liquefaction of sandy fills. By studying different locations within the city, it is possible to evaluate how variations in fill thickness and density, thickness and consolidation state of underlying soft clay, subsurface water, and depth to bedrock affect ground surface response and the development of soil liquefaction for similar levels of bedrock motion. Moreover, the evaluation of ground response coupled with the performance of buried lifeline systems provides an additional chance to quantify how soil-structure interaction affects complex networks critical for emergency operations.

To evaluate geotechnical and selected lifeline aspects of the earthquake in San Francisco, reconnaissance was performed by a research team from Cornell University, with support from the National Center for Earthquake Engineering Research, Buffalo, NY. Initial field work was conducted on October 19-21, 1989, with follow-up communication, correspondence, and coordination with various engineering, geological, and public utility organizations. Additional field investigations were performed over a period of approximately 10 weeks after the earthquake at select locations in San Francisco to clarify and refine information gathered in the initial field work. The investigations were performed in coordination with the San Francisco Fire and Water Departments, USGS, Dames and Moore, EQE, Inc., and Harding Lawson Associates.

One of the goals of the reconnaissance was to investigate areas of soil liquefaction and large ground deformation. It is known from previous studies [e.g., Youd and Hoose, 1975; Lawson, et al., 1908; O'Rourke and Lane, 1989] that several well defined areas of San Francisco had been subjected to locally severe ground shaking, soil liquefaction, and large permanent ground deformations during the 1906 earthquake. The 1989 earthquake permitted the investigation of areas of previous liquefaction and make assessments regarding reliquefaction, permanent ground movements, soil-structure interaction, and the influence of subsurface soil conditions and groundwater on site response. Such information provides a valuable data base to benchmark site response and surface structural effects for two earthquakes, each with different intensities and duration of strong shaking. The variation in soil conditions, including depth and in-situ density of granular fills, groundwater levels, and thickness and stiffness of underlying clay deposits allows for comparisons among the different areas so that site characteristics of principal importance can be identified by comparative study and used to refine and improve analytical models for predicting earthquake effects.

Another goal of the reconnaissance was to assess the damage to buried lifelines and its consequences on emergency response. Of principal interest was the water distribution system. Because fire following earthquake is one of the most serious threats to the city, the state of repair and functioning of the water supply is a continuing and critical concern. It should be recognized that approximately 85% of the total damage in the City of San Francisco after the 1906 earthquake was caused by fire [Gilbert, et al., 1907]. More than 10.6 km^2 were burned, destroying 490 city blocks and causing partial destruction of 32 additional blocks. The extensive fire damage was due in large measure to ruptures in water trunk and distribution pipelines.

SECTION 2

GEOTECHNICAL ASPECTS OF THE EARTHQUAKE

2.1 CITY OF SAN FRANCISCO

Figure 2-1 shows four areas within San Francisco for which there is historical evidence of soil liquefaction and large ground deformations during the 1906 earthquake. These areas, which are bounded by dashed lines, include the Mission Creek, South of Market, Foot of Market, and Marina districts. Each of these areas was investigated after the 1989 earthquake within the approximate boundaries shown by the solid lines.

2.1.1 Mission Creek

East of Mission and Capp Sts., soil liquefaction occurred in the same places it had been observed after the 1906 earthquake. The most prominent damage caused by soil liquefaction occurred as differential settlement, racking, and tilting of Victorian two to four-story timber frame buildings on South Van Ness, Shotwell, and Folsom Sts. between 17th and 18th Sts. Sand boils were observed at all these locations. The most severe damage was observed at the middle west side of Shotwell St., where maximum building settlements on the order of 0.2 to 0.4 m occurred. Figure 2-2 shows differential settlement and tilting of timber structures in 1906 on the east side of South Van Ness between 17th and 18th Sts. Figure 2-3 shows differential settlement and tilting of similar structures in 1989 on the west side of Shotwell St. between 17th and 18th Sts.

In contrast to this damage, the area west of Mission St. apparently was unaffected by soil liquefaction, even though lateral spreading and subsidence of 1.5 to 2.0 m were observed at Valencia and Guerrero Sts. in 1906. It is not known what influence the construction of BART, along Mission St., may have had on the subsurface conditions and potential for liquefaction in this vicinity.

Elsewhere in the Mission Creek district, differential settlement and prominent street cracks were observed along 14th St. between Folsom and Harrison. Differential settlements at two to four-story Victorian timber frame buildings were observed on the north side of 15th St. about 30 m west of Folsom in an area where

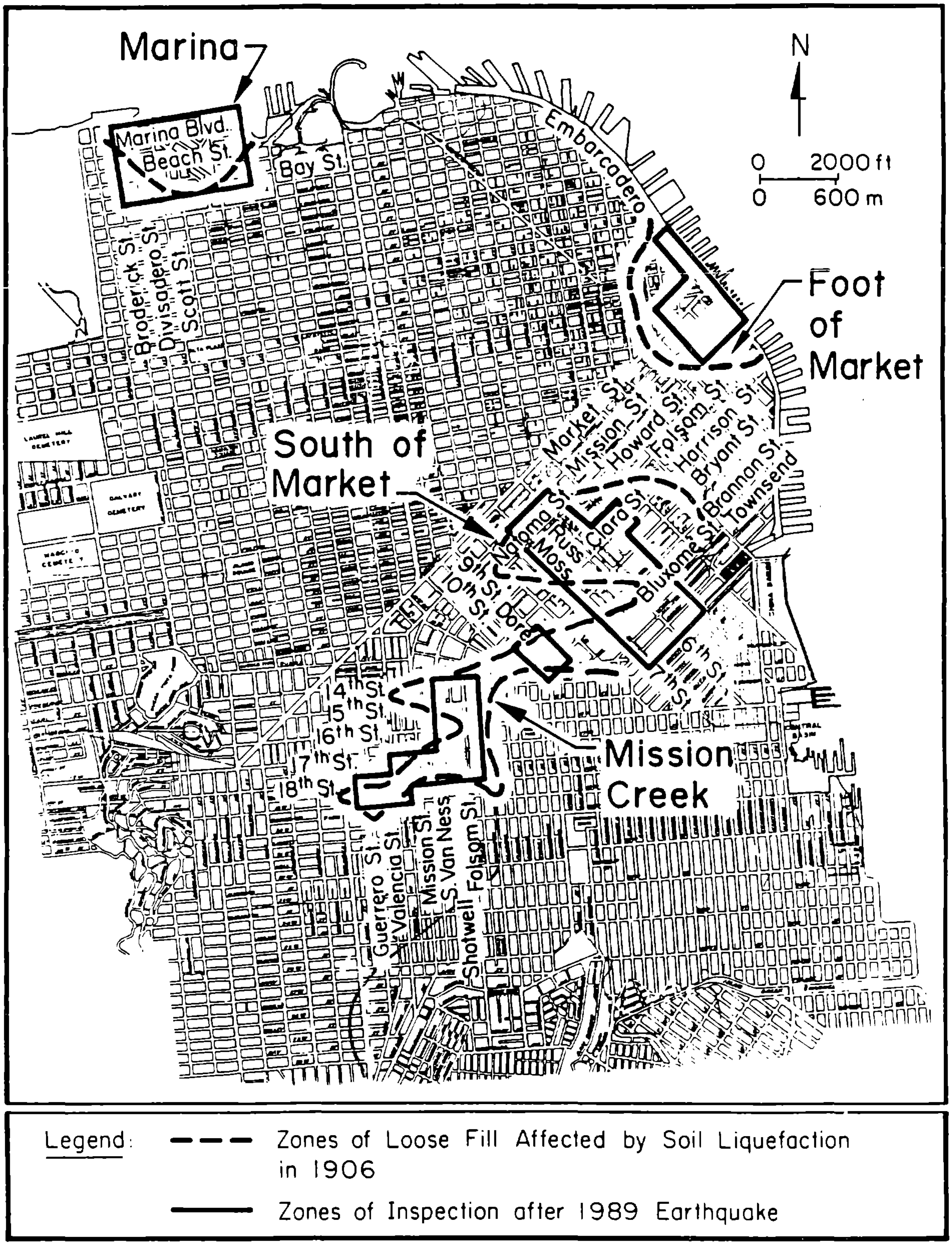

FIGURE 2-1. Plan View of San Francisco Showing Zones of 1906 Soil Liquefaction and Inspection after the 1989 Earthquake

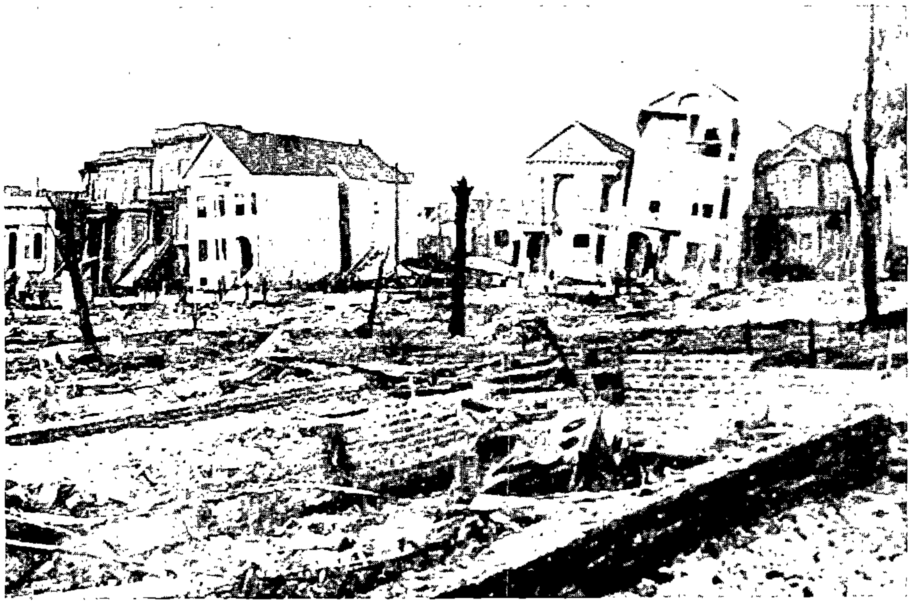

FIGURE 2-2. Racking and Settlement of Houses on South Van Ness Between 17th and 18th Sts. in 1906 [after Lawson, et al., 1908]

FIGURE 2-3. Racking and Settlement of Houses on Shotwell St. Between 17th and 18th Sts. in 1989. These Houses are Directly Behind the Location of Houses in Figure 2-2 (photograph by T. D. O'Rourke)

sand boils were apparent along the curb line. The occupants of these structures claimed that settlement had continued for as long as four days after the earthquake.

About 0.3 m of subsidence was observed in a parking lot off Dore St. approximately 30 m north of its intersection with Bryant St. This was a location of substantial settlement and lateral spreading in 1906. There was about 100 mm of settlement of the sidewalk adjacent to the building on the northeast corner of Dore and Bryant Sts. and differential settlement of the structure. The sidewalk along Bryant St. adjacent to the building was buckled and a water service had been ruptured. Figure 2-4 shows differential settlement of 1.5 m on Dore St. in 1906 compared with approximately 0.3 m of differential settlement on Dore St. in 1989, as shown in Figure 2-5.

2.1.2 South of Market

South of Mission St., sand boils were observed along curb and building lines at various locations on 7th, 6th, Natoma, Russ, Moss, Clara, Bluxome, and Townsend Sts. From Mission to Folsom St., 10 to 30-mm-wide cracks were observed down the centerline of 7th St., with differential settlement to the east and west of the cracks. As shown in Figure 2-6, differential settlement of roughly 0.3 m was observed at the southeast corner of Natoma and 7th Sts., with settlement and severe deformation of the two and three-story timber frame buildings at this location. Sand flowed into the basement of a building at the corner of Howard and 7th Sts., filling it with approximately 0.6 m of material. Differential settlements and cracks were apparent on 6th St. between Folsom and Harrison Sts. Approximately 0.3 m of differential settlement and sand boils were observed beneath the Rt. 280 elevated highway near the intersection of 6th, Bluxome, and Townsend Sts. Compression ridges in the form of buckled street pavements and sidewalks were observed along Russ St., approximately 30 to 60 m north of Folsom St.

At the intersection of 6th St. with Bluxome and Townsend Sts., there was substantial differential settlement. Beneath the western curb line of 6th St. at this location, there is a 2-m-diameter concrete sewer supported on piles. The ground settled sharply adjacent to each side of the sewer, with settlements of roughly 0.4 to 0.5 m at the northeast corner of 6th and Townsend Sts. relative to the

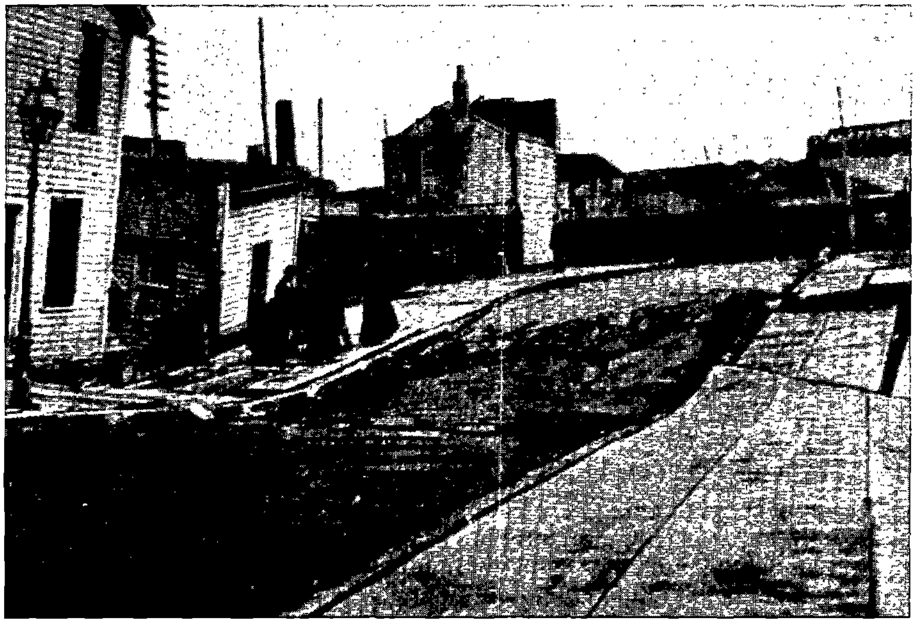

FIGURE 2-4. Large Differential Settlement on Dore St. Between Bryant and Brannon Sts. in 1906 [after Lawson, et al., 1908]

FIGURE 2-5. Differential Settlement Along Dore St. Just North of Bryant St. in 1989 (photograph by T. D. O'Rourke)

FIGURE 2-6. Differential Settlement of 0.1 to 0.3 m Adjacent to Building at Corner of 7th St. and Natoma St. (photograph by T. D. O'Rourke)

FIGURE 2-7. Differential Settlement at Corner of 6th St. and Townsend St. (photograph by T. D. O'Rourke)

sewer centerline. Figure 2-7 shows local differential settlement of roughly 150 mm adjacent to the building at the northeast corner of 6th and Townsend Sts. Differential settlements of 150 to 250 mm were observed adjacent to pile-supported columns of the Rt. 280 highway ramp at this location. Abrupt settlement with a maximum vertical offset of 200 mm was measured to the west of the pile-supported sewer beneath the Rt. 280 ramp. Recent differential settlements were apparent along the north side of Townsend St. for a distance of about one block to the east and west of its intersection with 6th St. Sand boils were observed beneath the Rt. 280 highway ramp. No sand boils or differential settlements were observed in the vicinity of the rail yard immediately south of Townsend St.

A 300-mm-diameter cast iron water main of the Auxiliary Water Supply System, which is operated by the Fire Department, ruptured on 7th St. between Mission and Howard in an area of soil liquefaction and differential movements. This, in combination with pipeline breaks at hydrants elsewhere in the South of Market area, caused a sudden and severe loss of water from the Jones Street Tank. As a consequence, the supply of water to the Marina area was reduced substantially where pipelines of the Municipal Water Supply System also had been damaged. The resulting loss of water and pressure in the Marina required that portable hosing be deployed, with water pumped from the fireboat to fight the fire which had erupted there.

2.1.3 Foot of Market

Differential settlements and lateral displacements were observed along the Embarcadero from Howard St. to just north of the Ferry Building. Subsidence of approximately 0.3 m was observed immediately north of the intersection of Market St. and the Embarcadero. Sand boils were observed along the Embarcadero between the Ferry Building and Pier 1.

Figure 2-8 shows fissures after the 1906 earthquake in the pavement along East St. (now the Embarcadero) about two to three blocks south of Market St. These fissures are evidence of vertical and lateral movements of approximately 1 m toward the bay. In comparison, Figure 2-9 shows a prominent crack with as much as 100 mm of vertical offset which occurred in 1989 immediately north of the intersection of Market St. and Embarcadero. The crack extended roughly 60 m in a northeasterly direction from the intersection.

FIGURE 2-8. Large Differential Ground Movements and Fissures on East St. (Embarcadero) in 1906 [after Himmelwright, 1906]

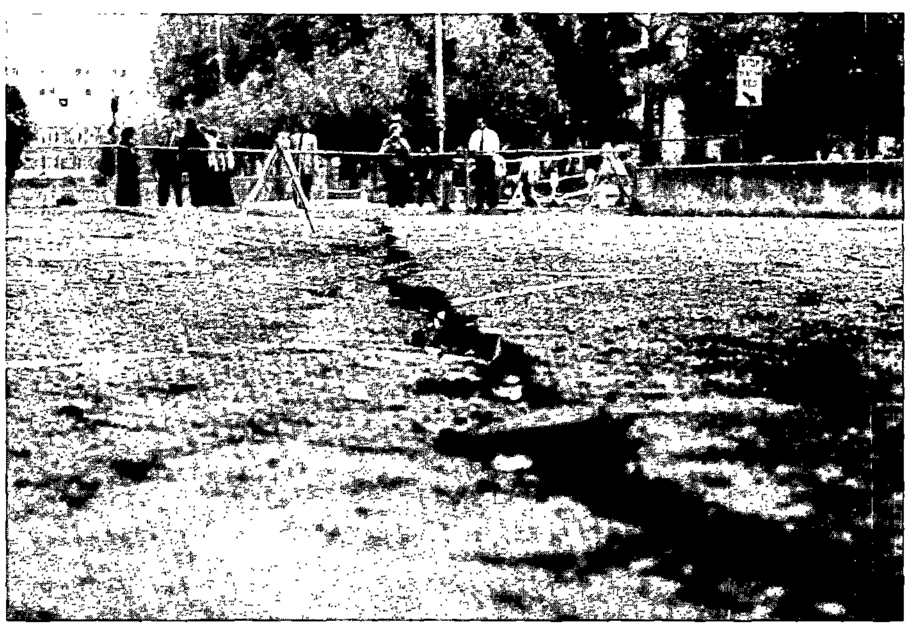

FIGURE 2-9. Differential Settlement on the Embarcadero Near the Intersection of Market St. in 1989 (photograph by T. D. O'Rourke)

Figure 2-10 shows a prominent 25-mm-wide crack which opened beneath the Embarcadero Skyway, running parallel to the seawall for the full distance between Howard and Mission Sts. The crack indicates lateral movement toward the bay at a distance of about 20 m behind the seawall. Differential settlements of 25 to 100 mm were observed adjacent to the pile-supported columns of the Embarcadero Skyway, as shown in Figure 2-11.

2.1.4 **Marina**

The Marina was the site of some of the most devastating and well publicized damage caused by the earthquake. The damage occurred in two to four-story timber frame structures with concrete and masonry bearing wall foundations. The worst damage was concentrated at apartment buildings with multiple garages at ground level. These structures lacked sufficient strength and stiffness to resist shear distortion caused by seismic shaking. Where buildings with soft bottom stories were located at street corners or adjacent to open spaces, the absence of support from neighboring structures resulted in severe racking and, occasionally, structural collapse.

Although ground shaking was the principal cause of building damage, permanent ground movements also contributed to structural distortion. Permanent ground deformation was evident on virtually all streets. Buckled and fractured sidewalks and street pavements were apparent throughout the Marina district. Most buckled streets had compressive ridges oriented in a north-south direction, which appears to be perpendicular to the direction of strongest seismic shaking. The pattern of cracking and surface ruptures in the streets did not show a coherent sense of displacement or lateral movement in a preferred direction. Conspicuous permanent settlements and lateral displacements were confined to relatively small areas. For example, local differential settlements and lateral movements of 50 to 100 mm were observed at the northwest corner of Beach and Divisadero, southwestern corner of Divisadero and Jefferson, and on North Point St. approximately 60 m west of Webster. Lateral displacement of 175 mm northward over 30 m was measured in the Winfield Scott School playground, roughly 40 m east of the intersection of Beach and Divisadero.

Throughout the Marina, there was direct evidence of soil liquefaction in the form of sand boils. Sand boils were observed on virtually every street where there

FIGURE 2-10. Open 25-mm Crack Beneath the Embarcadero Skyway Between Howard and Mission Sts. Showing Movement Toward the Bay (photograph by T. D. O'Rourke)

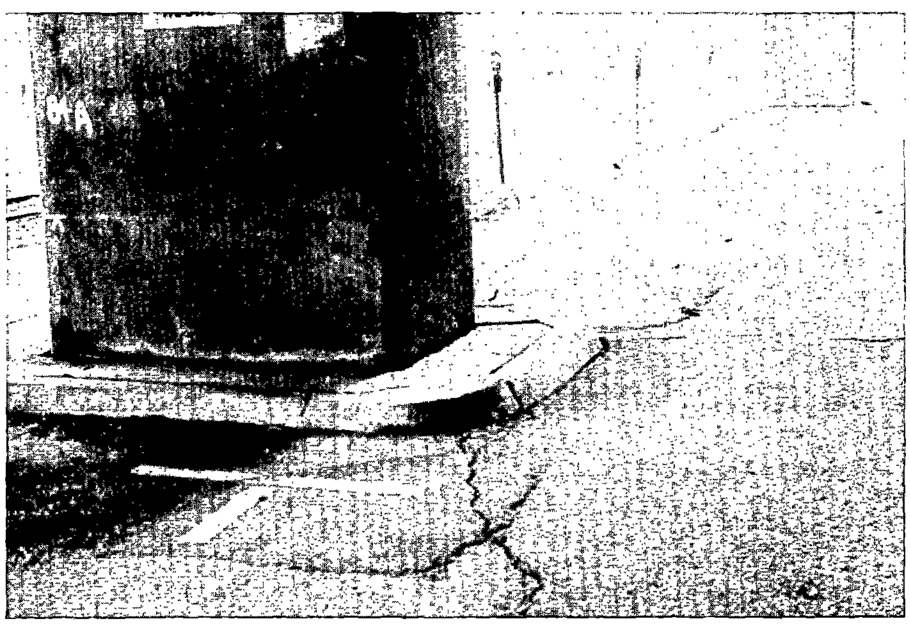

FIGURE 2-11. Differential Settlement Adjacent to Pile-Supported Column of Embarcadero Skyway Near Mission St. (photograph by T. D. O'Rourke)

was damage to buildings. Sand boils were observed along curb lines, sidewalks, and foundation bearing walls. In many instances, sand erupted into garages, forming deposits 0.3 to 0.6 m thick. Sand boils also were observed in the front gardens and back yards of houses and at several locations on Marina Green.

Figure 2-12 shows sand which had been ejected in the garage of a building on Scott St. and had flowed into the driveway in front of the structure. Figure 2-13 shows the intersection of Divisadero and Jefferson Sts. Differential settlement and the buckled pavements of roadways and sidewalks are evident in the photo.

Along the northern boundary of Marina Green, a prominent 50-mm-wide crack was observed roughly 12 m behind and parallel to the seawall. Sand had been ejected along this fissure. Differential settlements as large as 200 mm were observed adjacent to portions of the seawall, although no lateral deformation or settlement of the seawall was apparent. Cracks and fissures approximately 25 mm wide were observed in the road entering Marina Green, directly north of the intersection of Scott St. and Marina Blvd. Differential settlements of approximately 50 to 100 mm were observed in Marina Green adjacent to a buried 2.4-m-diameter concrete sewer and surrounding a circular underground sewage pump station.

Of special interest are ground movements and structural response at the St. Francis Yacht Club, located adjacent to the bay in the northwestern corner of the Marina Green area. The northwestern portion of the two-story clubhouse is supported on 400-mm-square prestressed concrete piles driven to depths of approximately 18 m. Differential settlement as large as 200 mm was observed between this part of the structure and the southern wing of the building, which was supported on spread footings. There was severe structural distortion in the southern wing of the building, whereas the pile-supported section of the building was functional, with little visible damage.

Prominent ground fissures were observed parallel to the retaining wall immediately north of the yacht club at distances of 12 to 50 m from the wall. The cumulative crack widths suggest that northward lateral displacements exceeding 0.6 m occurred in this area. Along the north side of the clubhouse is a deck supported on timber piles. Lateral spreading resulted in approximately 0.6 m of horizontal movement toward the bay, which displaced the deck and timber piles

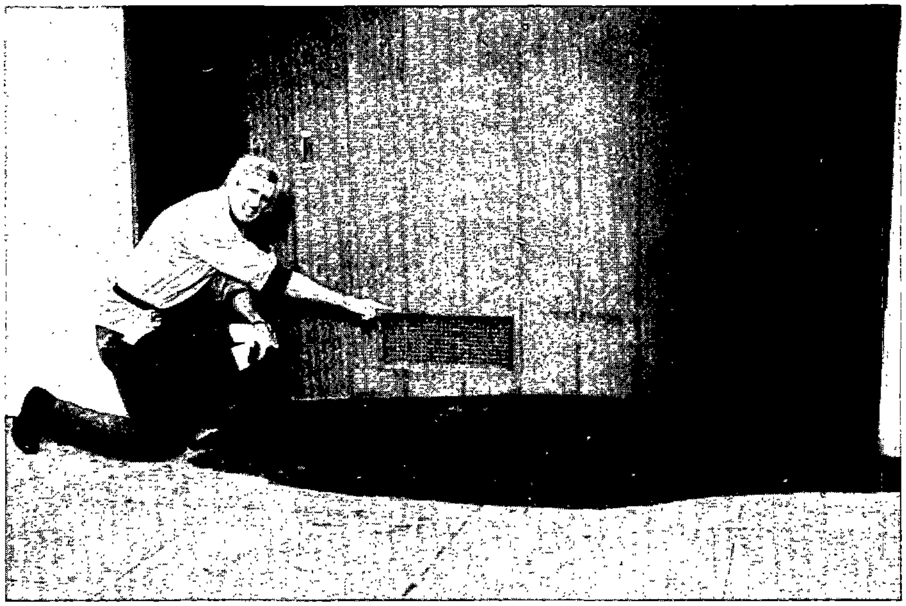

FIGURE 2-12. Sand Ejected from Garage of Building on Scott St. (photograph by H. E. Stewart)

FIGURE 2-13. Buckled Pavements and Ground Deformations at Corner of Divisadero St. and Jefferson St. (photograph by T. D. O'Rourke)

away from the main clubhouse. Some deformation could be seen in the 400-mm concrete piles supporting the main building. There was a distinct inclination of each pile beneath the northern building line, indicating that underlying sections of the piles had rotated outward relative to the pile caps.

2.2 GEOTECHNICAL CHARACTERISTICS OF THE MARINA

It is important to evaluate the geotechnical characteristics of the Marina to understand what role the subsurface soils played in concentrating damage on such a local basis. Like several other sites in the Bay Area, the Marina had been developed by placing sandy fills on soft clays and silts. By investigating the nature of the fill and characterizing the underlying soils, it is likely that general features can be identified which affected other sites as well.

Figure 2-14 shows a plan view of the Marina on which is superimposed the 1857 shoreline, as mapped by the U.S. Coast Survey [1857]. Along its western boundary, there was a prominent sand bar known as Strawberry Island, with adjacent salt water marshes. Sand dunes, 6 to 12 m high, were located south of the shoreline and marshy ground.

To aid in the construction of industrial facilities, a seawall was built in the 1890's [Olmsted, et al., 1977]. The seawall was constructed by dumping rock, which had been hauled to the site on barges, and backfilling behind the rock embankment with sand taken primarily from the dunes. Similar construction was performed by the San Francisco Gas Light Company to establish an earthen mole. Figure 2-15 shows the 1899 seawall and earthen mole [Sanborn and Ferris, 1899]. This configuration of seawall, embankment, and artificial fill remained essentially unchanged until approximately 1913, when construction on site was started for the 1915 Panama Pacific International Exposition.

The lagoon enclosed by the seawall was filled with dredged soil pumped from depths of 10 to 15 m at distances of 180 to 600 m offshore. Relatively strict control of the fill material was exercised. The opening along the northern line of the seawall was used to sluice out fine grained and organic materials during hydraulic filling. It was estimated that 70% of the fill placed in this way was sand [Olmsted, et al., 1977].

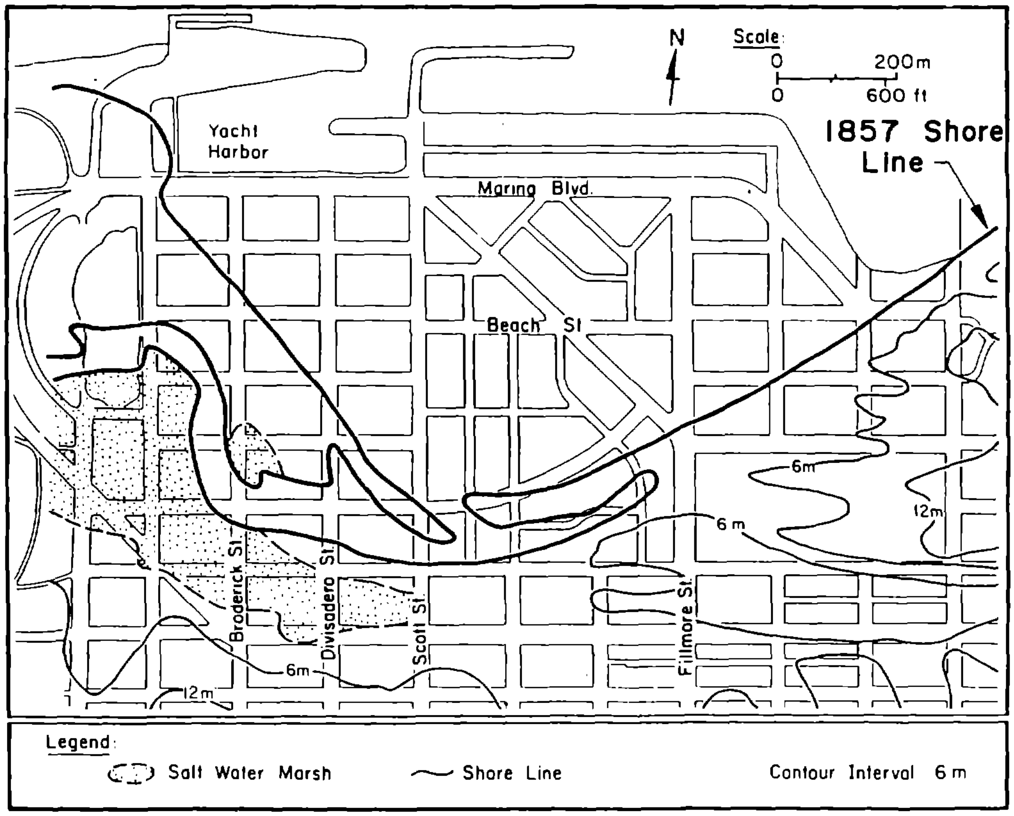

FIGURE 2-14. Marina District Showing 1857 Shoreline

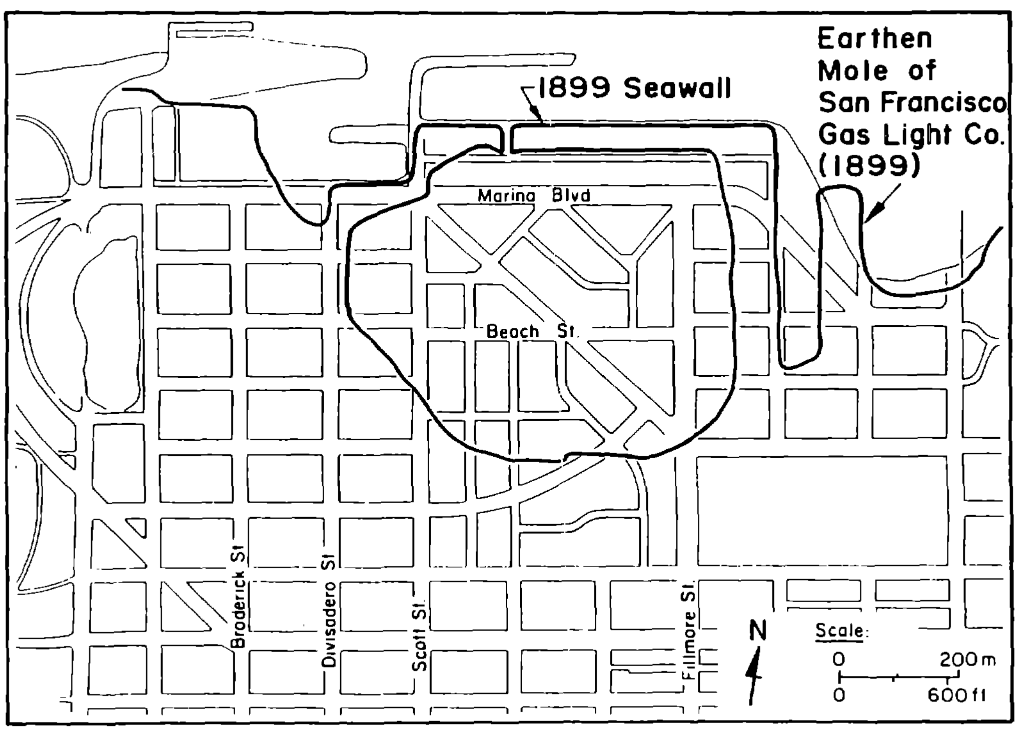

FIGURE 2-15. Marina District Showing 1899 Shoreline

To ascertain how site response during the 1989 earthquake was related to the two principal stages of filling, data were collected on water distribution pipeline repairs. It was felt that building damage would be a heavily biased indicator of ground movement because of the variable nature of building design and construction. In contrast, the Municipal Water Supply System (MWSS) pipelines in the Marina are predominantly 100 to 200-mm-diameter cast iron conduits buried at a nominal depth of 0.9 m. Because of the relatively small size and full embedment, their movement was coupled to that of the ground. Locations of repair, therefore, become a direct reflection of the intensity of combined transient and permanent ground deformations.

Figure 2-16 shows a plan view of MWSS pipeline repairs relative to the current street system, 1899 shoreline, and approximate 1857 shoreline. Most repairs were concentrated in the area of hydraulic fill within the lagoon bounded by the 1899 seawall or along the eastern margins of the seawall and 1857 shoreline. There were about 120 repairs in the Marina, more than three times the number of repairs in the entire MWSS outside the Marina. Repairs were made at locations of sheared or disengaged service connections with mains, flexural round cracks in mains, and leaking joints. The predominant mode of damage was associated with the first two categories.

To represent the distribution of damage, the Marina was divided into a grid of approximately 40 cells, and the number of repairs per length of pipeline in each cell was counted. Each repair rate then was normalized with respect to a reference length of 300 m to provide a consistent basis for evaluation. Contours of equal repairs per 300 m of pipeline were drawn and superimposed on the street system and previous shorelines, as illustrated in Figure 2-17. The contours of pipeline repair rates are related closely to the 1857 shoreline, with virtually all pipeline damage falling within this boundary. Higher concentrations of pipeline repair fall within the area of hydraulic fill, with the heaviest repair concentration at the junction of the hydraulic fill, 1899 seawall embankment, and 1857 shoreline.

Figure 2-18 shows the locations of two subsurface cross-sections, A-A' and B-B'. Cross-section A-A' in Figure 2-19 is along Marina Blvd. from Lyon to Laguna Sts., and was developed primarily from borings performed for the North Shore and Channel Outfalls Consolidation Project [Dames and Moore, 1977]. Cross-section

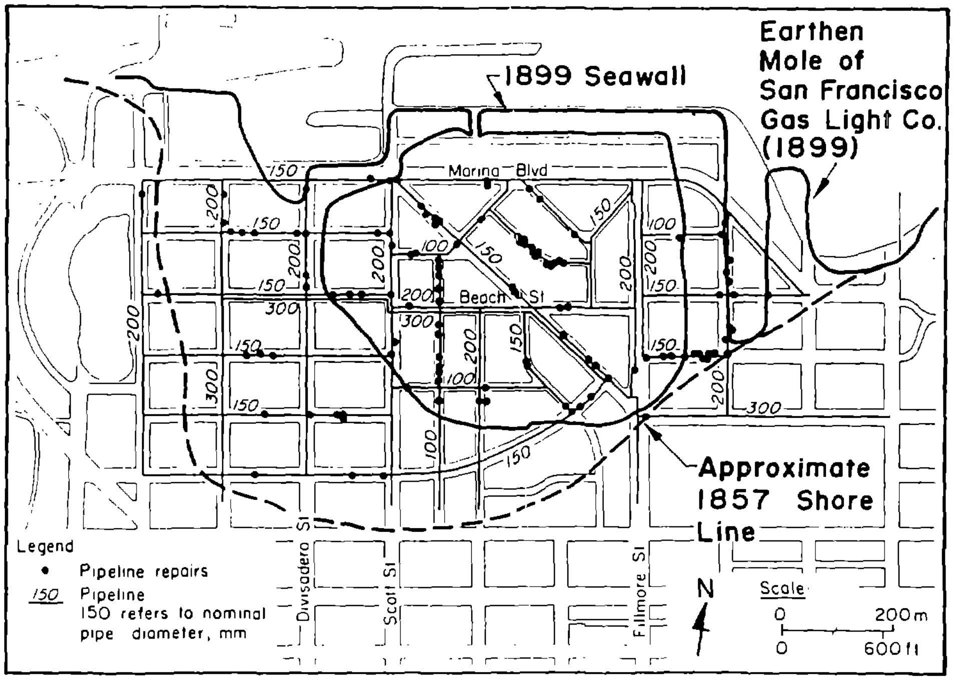

FIGURE 2-16. Pipeline Repairs in Municipal Water Supply System (MWSS) in the Marina District

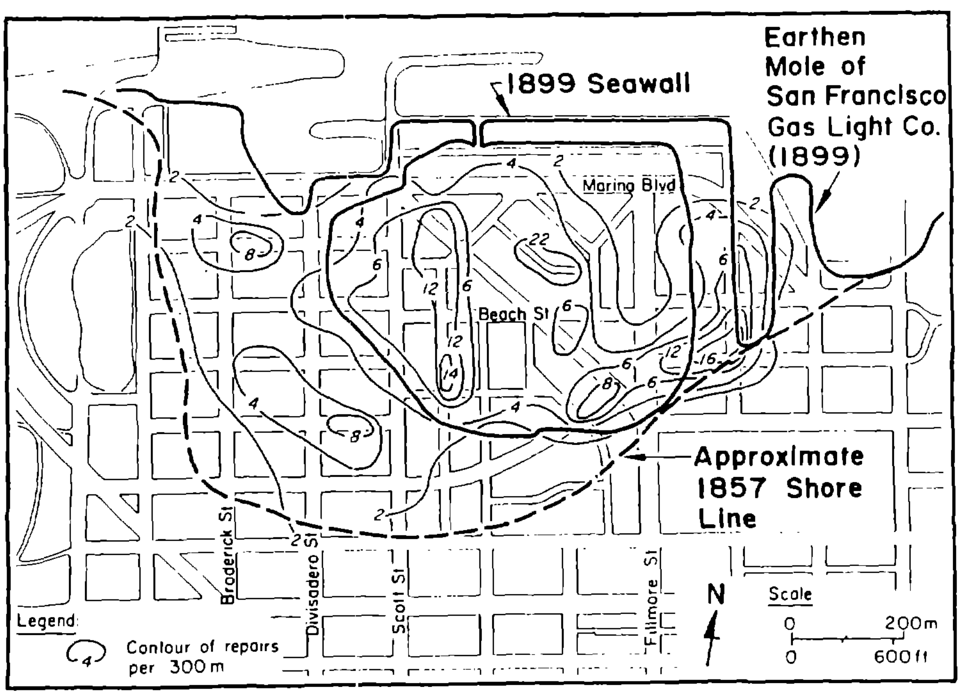

FIGURE 2-17. Contours of Pipeline Repairs per 300 m for MWSS in the Marina District

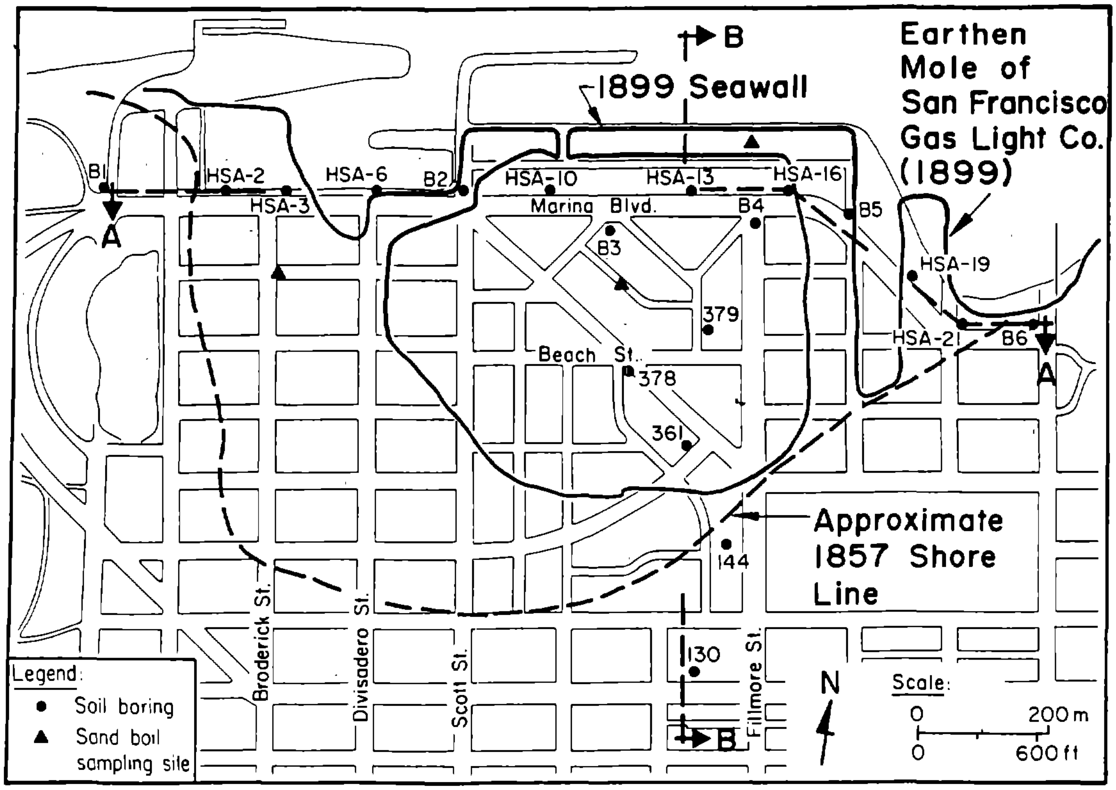

FIGURE 2-18. Plan View of Soil Profile Locations for the Marina District

B-B′ in Figure 2-20 is from Marina Blvd. to approximately Lombard St., and was developed primarily from borings performed for the aforementioned project as well as data summarized by the Institute of Transportation and Traffic Engineering [1950]. Data for each borehole are summarized in the form of uncorrected Standard Penetration Test (SPT) values, equivalent SPT, and Torvane undrained shear strengths, as explained by the borehole legend in Figure 2-19. Symbols and descriptions of the soils and rock encountered are summarized in the legend of Figure 2-20. All uncorrected SPT measurements were consistent with ASTM specifications [ASTM, 1989]. Equivalent SPT readings were estimated from blow count measurements performed with nonstandard equipment according to the recommendations of Roth and Kavazanjian [1984].

Figure 2-19 shows loose fill with a maximum depth of about 9 m extending along Marina Blvd. from approximately Baker to Buchanan Sts. This distance correlates well with the distance between locations of the 1857 shoreline shown in Figure

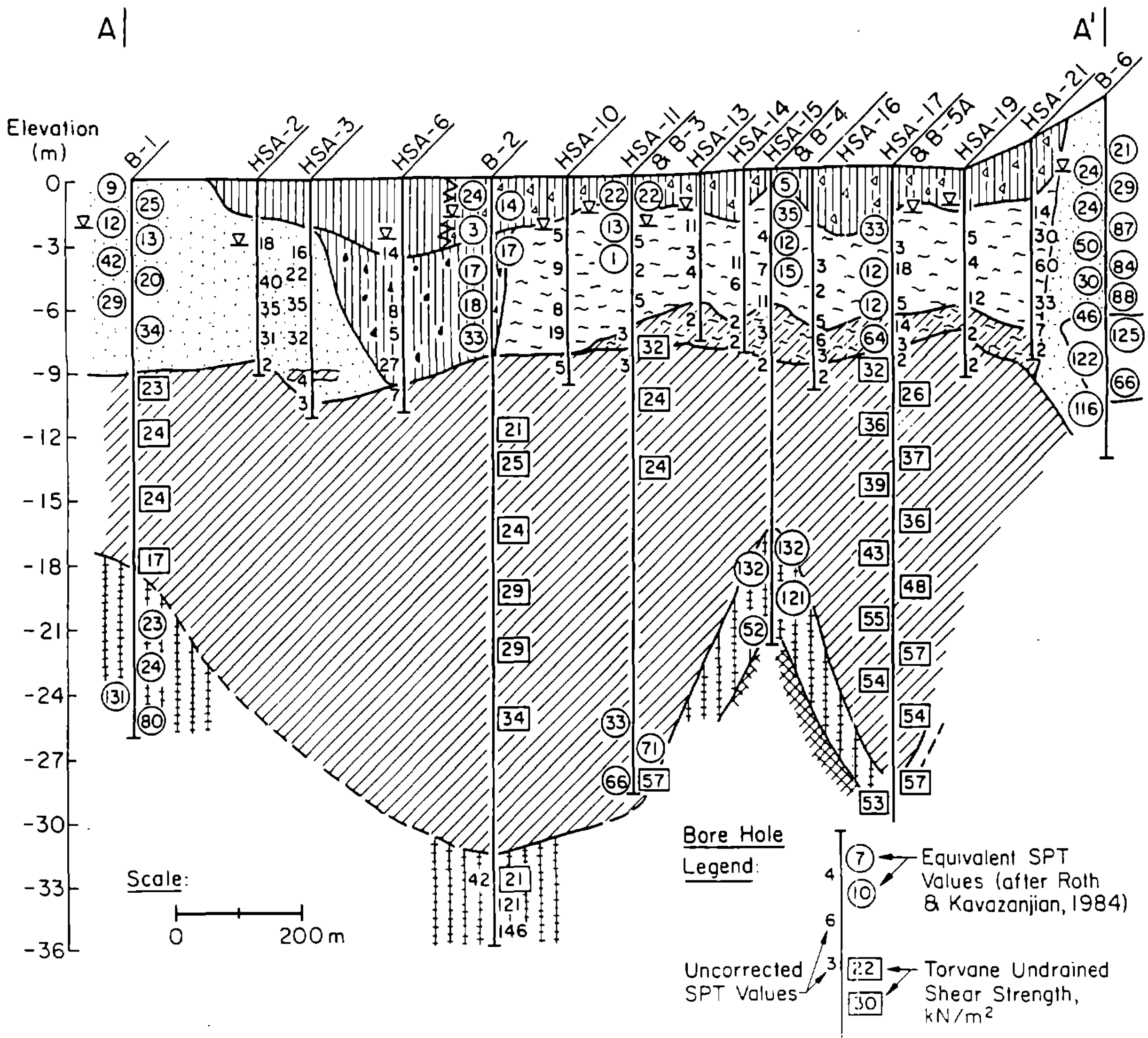

FIGURE 2-19. Soil Profile A-A' Along Marine Boulevard

2-14. The depth to water table is between 1.5 and 2 m in the Marina. Underlying the loose fills and natural sand deposits is a stratum of Recent Bay Mud, which varies in thickness along Marina Blvd. from 9 to 23 m and extends to a maximum depth of 32 m. Underlying the Recent Bay Mud are dense sands and stiff to hard clays. Figure 2-20 shows that weathered bedrock at a location near Lombard and Filmore Sts. was encountered at a depth of roughly 45 m below zero San Francisco datum.

Undrained shear strengths obtained with a Torvane device indicate that the clay is soft to medium in consistency. Figure 2-21 shows a soil profile in which the

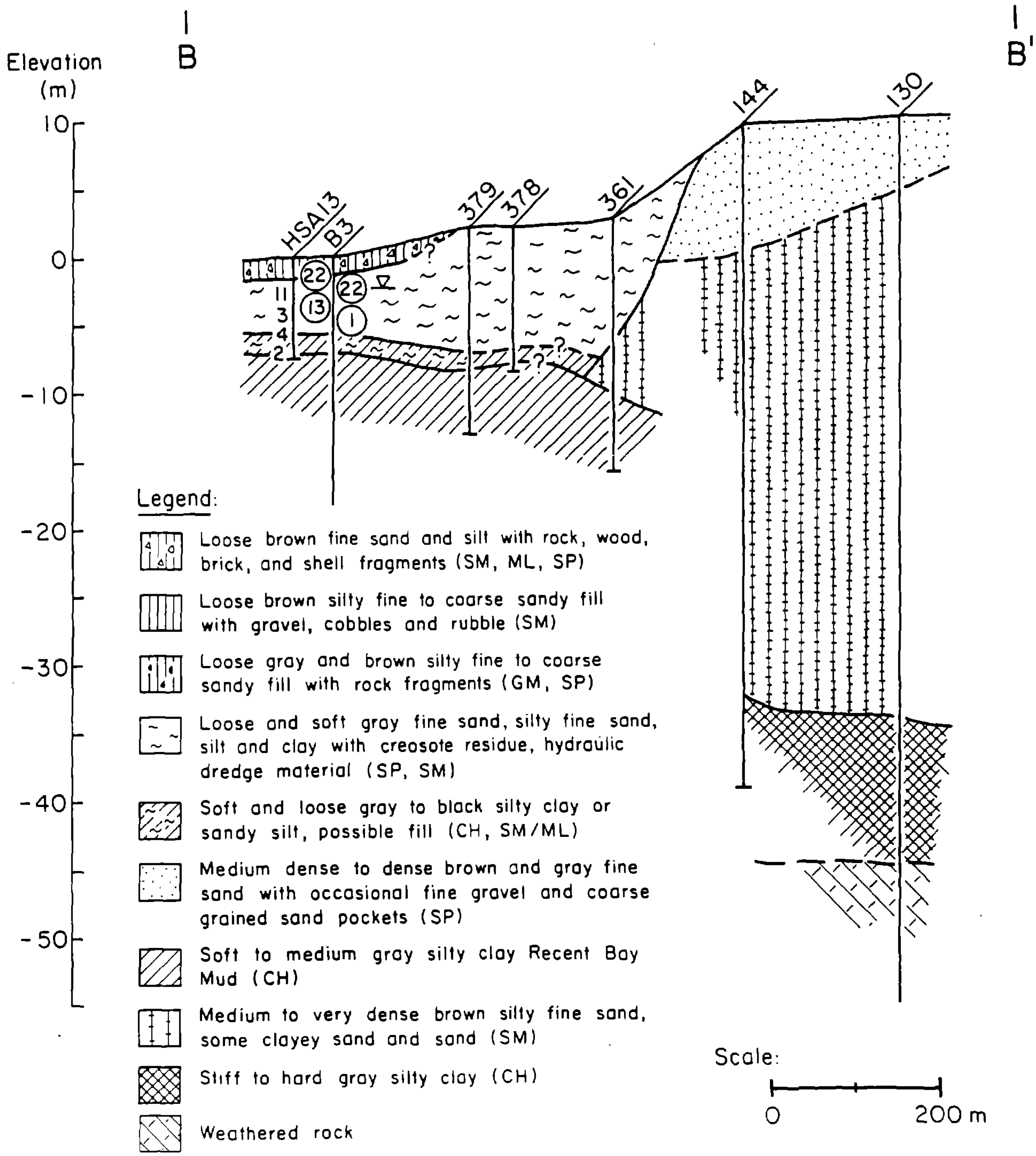

FIGURE 2-20. Soil Profile B-B' in Marina District

Torvane undrained shear strengths are plotted as a function of depth. For comparison, the ratios of undrained shear strength to effective vertical stress for triaxial compression ($s_{u_{TC}}/\sigma_{vo}'$) and direct simple shear ($s_{u_{DSS}}/\sigma_{vo}'$) also

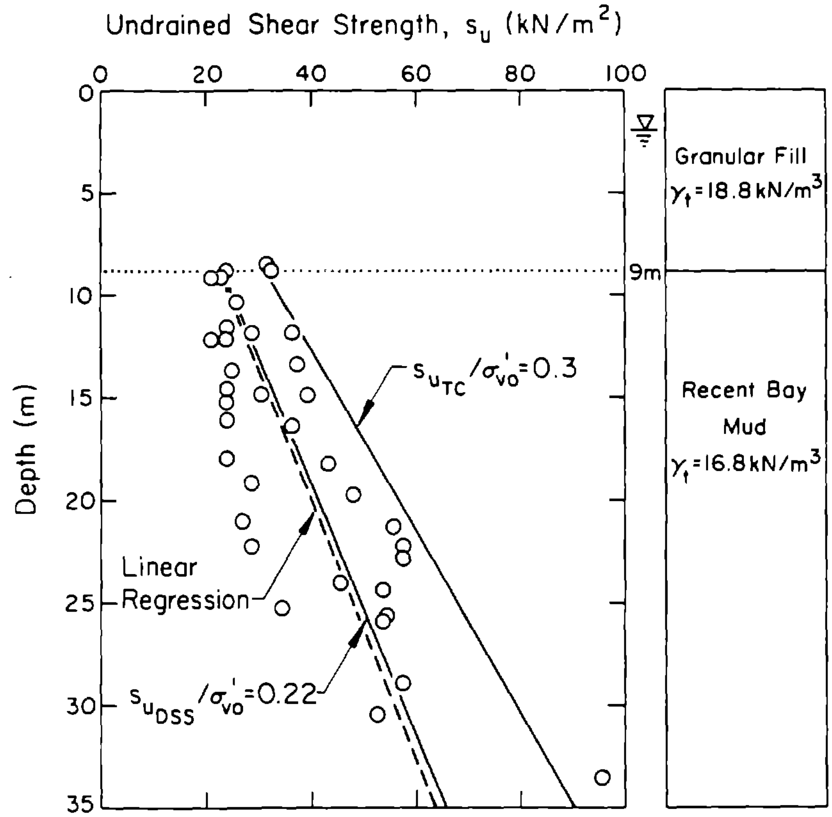

FIGURE 2-21. Soil Profile and Torvane Shear Strength Characteristics of Recent Bay Mud at the Marina

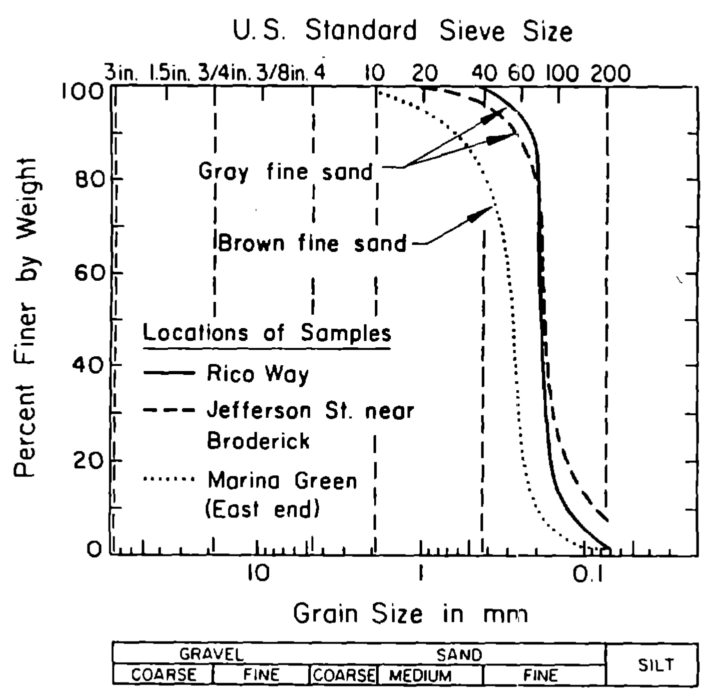

FIGURE 2-22. Grain Size Distribution Plots for Soil Collected in the Marina at Sand Boils and Vents

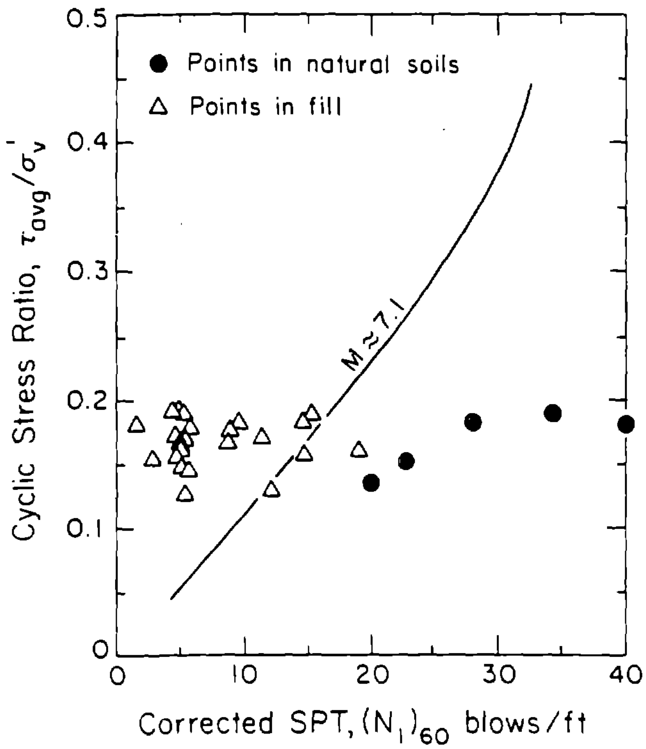

FIGURE 2-23. Chart for Evaluation of Liquefaction Potential with Points Representing Granular Fill and Native Materials in the Marina

are plotted. The $s_{u_{DSS}}/\sigma_{vo}'$ profile is consistent with trends recommended for a normally consolidated clay [e.g., Mesri, 1989]. Both the $s_{u_{DSS}}/\sigma_{vo}'$ and $s_{u_{TC}}/\sigma_{vo}'$ profiles are consistent with trends established for Recent Bay Mud [Dames and Moore, 1989]. The linear regression of the Torvane strengths plots close to the $s_{u_{DSS}}/\sigma_{vo}'$ line, and implies that the clay is normally consolidated. It should be recognized, however, that Torvane tests involve substantial sample disturbance and thus are useful only as an index of shear strength.

Figure 2-22 presents grain size distribution plots of material ejected from sand boils and vents at three different locations in the Marina, which are shown in Figure 2-18. All materials are fine uniform sand with very low to negligible fines content. The gray fine sand was subrounded to subangular in shape, composed of quartz and ferromagnium minerals. The fine brown sand contained the highest percentage by weight of quartz and also some shell fragments.

A liquefaction potential analysis was performed using the empirical relationship between cyclic stress ratio and the corrected SPT values developed by Seed, et al. [1983]. As plotted in Figure 2-23, SPT values were corrected from field measurements according to the recommendations of Seed, et al. [1983]. The cyclic stress ratios for various depths were calculated assuming a maximum acceleration of 0.2 g, which is consistent with the peak horizontal component of acceleration measured at the nearby Presidio. The curve shown in Figure 2-21 is the empirical dividing line between liquefiable and nonliquefiable soils for a magnitude 7.1 earthquake. It is clear that the fill, shown as open triangles, plot within the liquefiable zone. The natural soils, shown as solid circles, fall into the nonliquefiable zone. The natural soils are predominantly sand bar and beach sand deposits. No correction in Figure 2-21 was made for silt content.

SECTION 3

EARTHQUAKE EFFECTS ON WATER SUPPLY LIFELINES

3.1 SAN FRANCISCO WATER DISTRIBUTION SYSTEM

The City of San Francisco receives its water from two systems of reservoirs and pipelines: the Municipal Water Supply System (MWSS) and the Auxiliary Water Supply System (AWSS). The MWSS supplies potable water for domestic and commercial uses, as well as for fire fighting via hydrant and sprinkler systems. The AWSS supplies water exclusively for fire fighting purposes. A discussion of the MWSS, its special characteristics, and earthquake preparedness measures is provided in Appendix A.

The MWSS provides water from 18 different reservoirs and a number of smaller storage tanks. The water is stored at different levels creating zones, or districts, where water is distributed within a certain range of pressure. There are 23 different pressure districts, of which the Sunset and University Mound Reservoir Systems are the largest. Figure 3-1 shows a plan view of the Sunset Reservoir System in which the trunk, or feeder, mains are indicated. The pipelines in this portion of the feeder main network range in diameter from 250 to 1500 mm, and vary in composition from riveted and welded steel to cast iron. There are approximately 483 km of feeder pipelines in the MWSS.

Figure 3-2 shows a plan view of part of the distribution system which is typical of the makeup and configuration of this type of piping throughout the city. Distribution pipelines are principally 100, 150, and 200 mm in diameter. They receive water from the feeder main network for delivery to hydrants and buildings.. There are approximately 1350 km of distribution piping in the AWSS.

After the earthquake and fire of 1906, the AWSS was constructed to provide emergency fire protection [Manson, 1908]. This system, shown in Figure 3-3, was intended to augment the city's existing fire fighting capacity by providing a supplementary network that would work independently of, but in parallel with, the MWSS. It is separated into an upper and lower zone. Each zone operates nominally at a pressure of about 1 MPa, which is approximately 2.5 times the pressure in the domestic municipal system. The system is supplied by the Twin

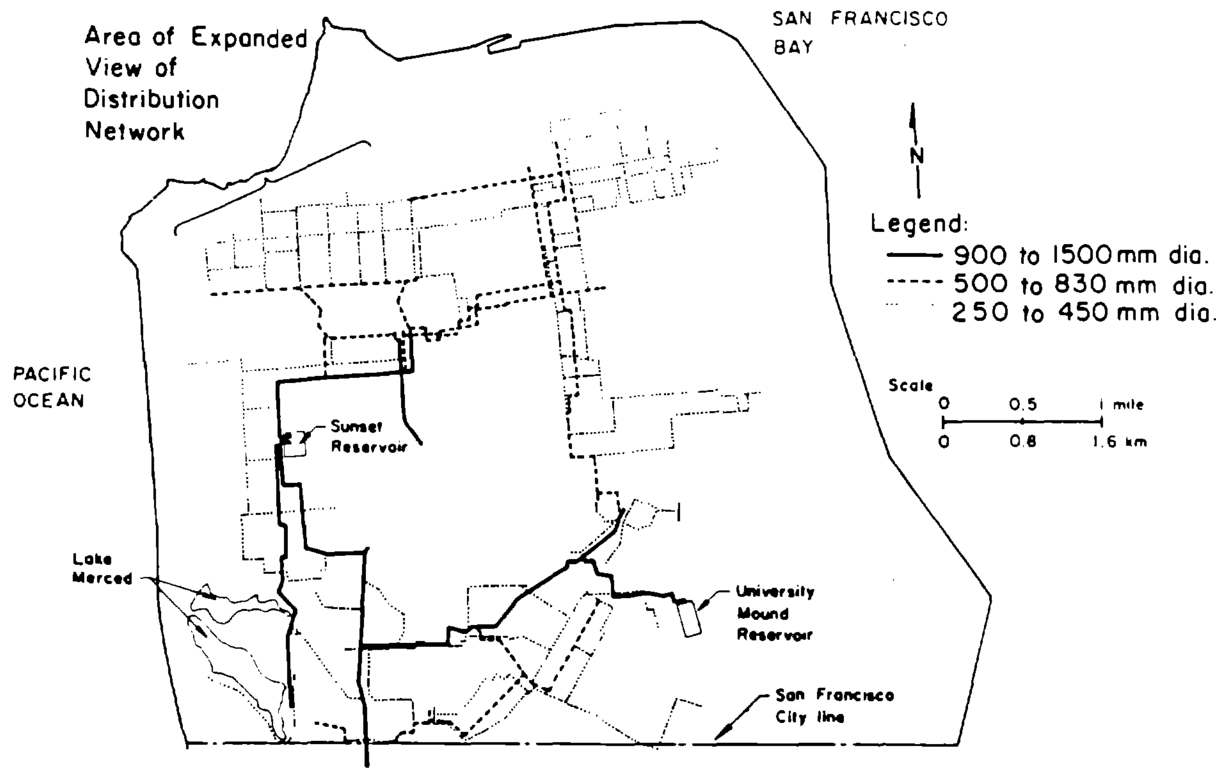

FIGURE 3-1. Sunset Reservoir System of the MWSS

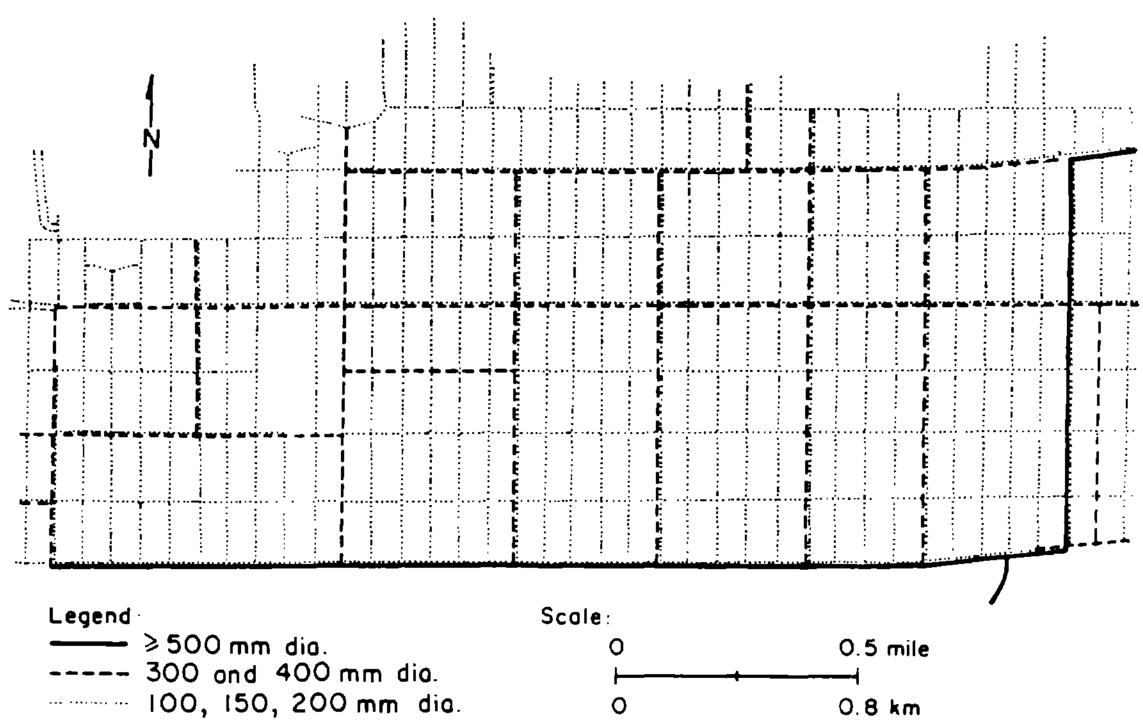

FIGURE 3-2. Typical Portion of the Distribution System of the MWSS

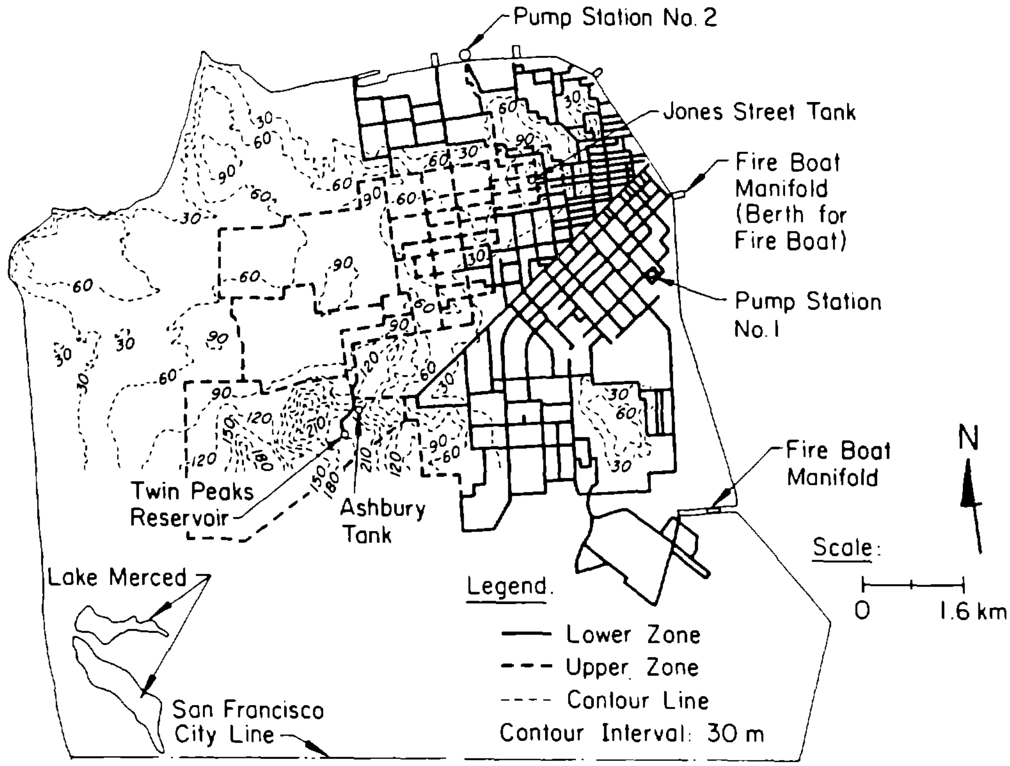

FIGURE 3-3. San Francisco AWSS

Peaks Reservoir, the Ashbury Tank, and the Jones St. Tank, which hold 38, 1.9, and 2.8 million liters, respectively. Two pump stations can pump salt water from San Francisco Bay into the system to augment the water supply. The stations have four diesel pumps, each of which can pump 9500 liters/min. at 2 MPa into the lower zone. The city's fireboat, "Phoenix," can be connected to each of five manifolds to inject an additional 38,000 liters/min. at 1 MPa into the lower zone. Additional water for fire fighting is stored in a series of underground cisterns, each of which holds an average of about 284,000 liters.

The AWSS is the only high pressure system of its type in the U.S. It comprises approximately 200 km of buried pipe, with nominal diameters ranging from 250-500 mm. Nearly 160 km of the system is cast iron, to which about 40 km of ductile iron pipe have been added during the past several decades. The AWSS has no building connections or service lines; only fire hydrants can draw from the system.

3.2 PERFORMANCE OF MWSS

Damage was relatively low throughout the MWSS in areas outside the Marina. As discussed previously, there were approximately 120 repairs in the Marina. In the Foot of Market and South of Market zones (see Figure 2-1), there were 21 repairs. About five pipeline repairs were performed in the area around Islais Creek, and nine repairs were undertaken in other portions of the system. Damage was manifested in the piping network as broken service connections, round cracks in mains, and leaking joints. The majority of the damage was concentrated in the distribution pipelines of 100 to 200-mm diameter. Reservoirs, pumps, and valves generally performed in a satisfactory manner.

3.3 PERFORMANCE OF AWSS

Table 3-I summarizes the damage in the AWSS with respect to approximate street location and characteristics of the damage. The damaged pipelines were composed of cast iron. Hydrants were the most vulnerable parts of the system, with damage being concentrated at elbows. Typical construction involves a 200-mm-diameter cast iron elbow affixed to a concrete thrust pad beneath the street surface hydrant. Damage at hydrant elbows occurred as 45° fractures centered on the elbows.

Even though substantial damage was sustained by the MWSS in the Marina, there was only one instance of AWSS repair in this area. This occurred at a leaking joint at Scott and Beach Sts. Pipelines of the AWSS are equipped with sleeved joints, which are restrained against pullout by longitudinal bolts. Cast iron pipelines of 300-mm diameter are used in the Marina with joint-to-joint lengths of 3.7 m. The relatively large diameter-to-length ratio, in conjunction with joints which are able to rotate and are axially restrained, allows the pipelines to accommodate differential ground movement.

The most serious damage was the break of a 300-mm-diameter cast iron main on 7th St. between Mission and Howard Sts. Water flow through this break, supplemented by losses at broken hydrants, emptied the Jones St. Tank (see Figure 3-3) of its entire storage of 2.8 million liters in approximately 20 to 30 minutes. Loss of this reservoir supply led to the loss of water and pressure throughout the lower zone of the AWSS. This resulted in an especially sensitive condition in

TABLE 3-I. Summary of Damage to Auxiliary Water Supply System

Location	Description
Mission and Fremont Sts.	Hydrant elbow break
5th St. between Harrison and Bryant Sts.	Hydrant elbow break
6th St. between Howard and Folsom Sts.	Pipe to hydrant broken at 45° elbow where it passes over sewer
6th and Bluxome Sts.	Broken hydrant; hit by falling brick work
7th St. between Howard and Mission Sts.	300-mm-diameter main broken where it passes beneath a sewer
Folsom and 18th Sts.	Joint leak[1] at a hydrant tee on hydrant side of tee
Scott and Beach Sts.	Joint leak[1] at a 300-mm-diameter pipeline tee

[1]Leaks were relatively small

the Marina, where damage in the MWSS had cut off alternative sources of pipeline water.

When fire broke out at the corner of Divisadero and Beach Sts., water to fight the fire was drafted and relayed from the lagoon in front of the Palace of Fine Arts, approximately three blocks away. The fireboat, "Phoenix," and special hose tenders were dispatched to the site. Approximately one and a half hours after the main shock, water was being pumped from the fireboat and conveyed by means of 125-mm-diameter hosing, which had been brought to site by the hose tenders. Eventually, the supply of water to the fire was about 23,000 liters/min. The fire was brought under control within about three hours after the earthquake.

The special hose tenders and large-diameter hoses belong to the Fire Department's Potable Water Supply System (PWSS), which can move throughout the city and connect with the fireboat, underground cisterns, the underground pipeline network, and other sources of water to provide an additional measure of flexibility under emergency circumstances. The system had been implemented only two years before the earthquake.

The Twin Peaks Reservoir can be opened remotely by an electrically-controlled valve. However, because of electricity loss after the earthquake, this valve only could be operated manually. About three hours after the earthquake, the Twin Peaks Reservoir was opened into the upper zone, which in the meantime had received its pressure from the Ashbury Tank. It was decided to keep the valves connecting the upper and lower zones closed so that a substantial supply of water and sufficient pressure would be available in the higher elevations.

As described earlier, the AWSS is designed to receive water from two pump stations. Because the Jones St. Tank had emptied and part of the system had gone dry, significant time was required to pump water from the stations back into the lower zone. Approximately three to four hours of careful pumping and venting were needed to avoid water hammer effects.

3.4 PIPELINE DAMAGE IN RELATION TO SUBSURFACE CONDITIONS

As was shown for the Marina, pipeline damage in the South of Market area occurred in locations where loose sandy fills had been placed over deposits of soft to medium clay. Figures 3-4 and 3-5 show pipeline repairs in the South of Market area for the MWSS and AWSS, respectively. The pipeline repairs, pipeline network, and current street system are shown relative to salt marshes and the shoreline of Mission Bay which once were located at this site. The marshes and shoreline were established by reference to topographical maps prepared by the U.S. Coast Survey [1853; 1857]. The area was filled during the years between 1850 and 1865, primarily with material excavated from nearby sand dunes [Dow, 1973; Kavazanjian and Roth, 1984].

The highest concentration of pipeline repairs was in the area bounded by 8th, Mission, 5th, and Harrison Sts. As described in the preceding section, differential settlements and fractured pavements (indicating lateral movement) were observed throughout this area. Although the level of damage was much more severe in 1906, it is interesting to note that some of the pipeline damage in 1989 occurred in the same general area as in 1906. For example, Reynolds [1906], in

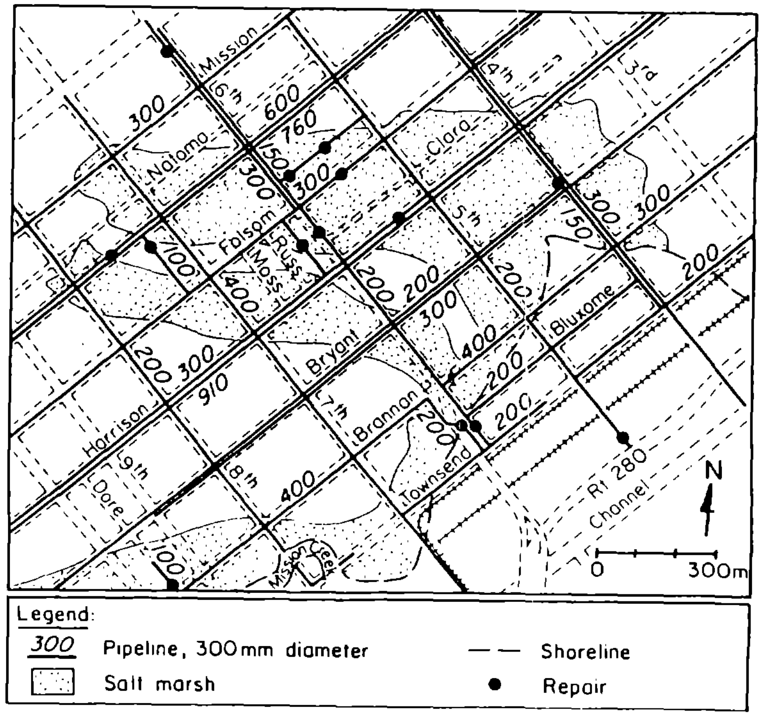

FIGURE 3-4. MWSS Pipeline Repairs in South of Market Area

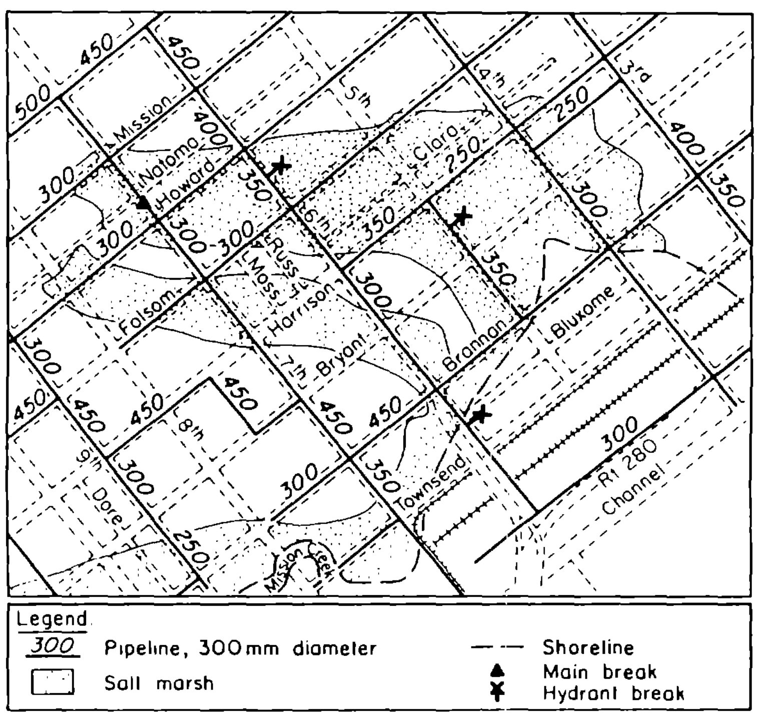

FIGURE 3-5. AWSS Pipeline and Hydrant Repairs in South of Market Area

reporting on the condition of buried electrical conduits, stated: "Along 7th St. from Mission to Howard, the earth was displaced from 5 to 8 ft (1.5 to 2.4 m) in a direction lengthwise to conduit. This caused some of the manholes to crush... The conduit was pulled apart at other places, and cables were wrenched and torn apart from their boxes..." Numerous additional descriptions of buried lifeline damage in the South of Market and other locations of 1906 San Francisco have been compiled and the reader is referred to these sources for additional information [e.g., Youd and Hoose, 1978; O'Rourke and Lane, 1989].

It should be recognized that time-dependent settlement has occurred in the South of Market area because of consolidation of underlying clay in response to the weight of fill and buildings. During field investigations along parts of Clara St., for example, it was apparent that some buildings had experienced differential settlement well before the earthquake. Such differential settlement tends to reduce the capacity of buried pipelines to resist transient and permanent ground displacements, and may have contributed to the earthquake damage in this general area.

SECTION 4

LESSONS LEARNED

4.1 GEOTECHNICAL ASPECTS

Soil liquefaction in San Francisco caused by the 1989 Loma Prieta earthquake occurred at the same locations that liquefaction was observed after the 1906 earthquake. The four main areas of San Francisco affected by soil liquefaction in 1989 and 1906 are the Marina, Foot of Market, South of Market, and Mission Creek districts. Liquefaction effects involved subsidence and loss of bearing of shallow foundations, with differential settlement, racking, and tilting of two to four-story timber structures.

In the Marina, deformation was evident on virtually all streets. There were many buckled and fractured sidewalks and street pavements. The pattern of cracking and surface ruptures in the streets did not show a coherent sense of displacement or lateral movement in a preferred direction.

Strong ground shaking in the Marina was the principal cause of building damage. The most severe structural damage was concentrated at apartment buildings with multiple garages at ground level. These structures lacked sufficient strength and stiffness to resist shear distortion caused by seismic shaking. Where buildings with soft bottom stories were located at street corners or adjacent to open spaces, the absence of support from neighboring structures resulted in severe racking and, occasionally, structural collapse.

Lateral spreading was observed at the St. Francis Yacht Club, adjacent to the bay in the northwestern corner of the Marina Green and docks area. Along the north side of the clubhouse is a deck supported on timber piles. Lateral spreading resulted in approximately 0.6 m of horizontal movement toward the bay, which displaced the deck and timber piles away from the main clubhouse. There was a distinct inclination of each pile beneath the northern building line, indicating that underlying sections of the piles had rotated outward relative to the pile caps.

One of the most distinctive features of the earthquake was the concentration of permanent ground movements, sand boils, pipeline and surface structure damage at specific locations of the city underlain by Recent Bay Mud. Amplification of bedrock motions through the deposits of soft clay and silt contributed to strong shaking and damage at the surface. In the Marina, Foot of Market, and South of Market areas, the thickness of Recent Bay Mud is as much as 20 to 30 m. There are, however, substantial variations in thickness in all three districts. Maximum depths of Recent Bay Mud in the three locations varies from 30 to 40 m. Each site has been filled with loose granular material, typically 6 to 9 m thick, with the water table at depths of 1 to 3 m below ground surface.

Preliminary reconnaissance indicates that the underground infrastructure influenced the pattern of soil and street displacement and may have affected the potential for soil liquefaction in certain locations. Severe differential settlements occurred in the Marina and South of Market areas, where liquefaction and consolidation of loose sands occurred next to pile-supported storm drain and sewage facilities. For example, abrupt offsets of 150 to 250 mm were observed near 6th and Townsend Sts. as a result of differential settlement adjacent to a 2-m-diameter concrete sewer supported on piles.

In the Mission Creek district, the presence of the Bay Area Rapid Transit (BART) system may have influenced the pattern of soil liquefaction. Ground deformation and other liquefaction affects were absent within the filled areas of Mission Creek west of BART, even though lateral spreading and subsidence of 1.5 to 2.0 m were observed in this location in 1906. Two blocks east of BART on South Van Ness, Shotwell, and Folsom Sts., liquefaction occurred in the same locations in 1989 as it did in 1906.

4.2 LIFELINES FOR WATER SUPPLY

Damage in water distribution piping was located primarily in areas where geotechnical factors contributed to strong ground shaking, liquefaction, and permanent soil displacements. The heavy concentration of MWSS damage in the Marina underscores the importance of site response in the performance of pipeline networks. Outside the Marina, there were 35 repairs over a total pipeline length of approximately 1800 km, or 0.02 repairs/km. Within the Marina, there were 120 repairs over roughly 15 km of pipeline for an average of approximately 8 repairs/km.

Clearly, the intensity of pipeline damage was highly dependent on location.

The recognition that pipeline damage tends to be concentrated in areas which are especially vulnerable to earthquake damage implies that remedial and protective measures would be best focused in zones where the goetechnical site characteristics tend to promote strong ground shaking and liquefaction. The fact that pipeline damage tends to concentrate locally also has important implications for network computer modeling. Simulation of earthquake damage should account for a general rate of repair based on the widespread and somewhat randomly distributed damage from traveling ground waves, and also should account for local concentrations of damage based on a geotechnical assessment of site response.

Rapid loss of water in the lower zone of the AWSS because of one main rupture and a limited number of hydrant breaks emphasizes the importance of reservoir capacity and the need to isolate quickly sections of broken line. The AWSS was planned with a special configuration of closed valves to control water into zones known as "infirm areas," where there was heavy concentration of pipeline damage in 1906. The AWSS is operated such that each infirm area is fed by a single pipe. In this way, a single gate valve can be closed either remotely or manually to isolate breaks in the infirm area, thus isolating the undesirable hydraulic effects from the rest of the system. The 1989 Loma Prieta earthquake has shown how quickly water can be lost from broken mains and how rapidly the reservoir supply can be depleted. Strategies for future improvements, therefore, should be based on rapid isolation of damaged pipelines. Remote electric and radio-controlled gate valves at key locations will promote swift isolation of damage and preservation of the remaining sections of the system.

The flexibility provided by the Portable Water Supply System (PWSS) was of critical importance in controlling and suppressing the fire which erupted in the Marina. The ability to operate with portable hosing and draft from a variety of water sources, including underground cisterns and fireboats, provides a valuable extra dimension in the city's emergency response.

SECTION 5

REFERENCES

American Society for Testing and Materials, "Standard Method for Penetration Test and Split-Barrel Sampling of Soils," Annual Book of Standards (D-1586-84), Vol. 4.08, ASTM, Philadelphia, PA, 1989, pp. 221-225.

Dames and Moore, "Final Report: Subsurface Investigation, North Shore Outfalls Consolidation Project, Contracts N1, N2, and N4, San Francisco, California, for the City and County of San Francisco," Dames and Moore, San Francisco, CA, Nov. 1977.

Dow, G. R., "Bay Fill in San Francisco: A History of Change," M.A. Thesis, California State University, San Francisco, July 1973.

Grigoriu, M. D., Ed., "Workshop on Serviceability Analysis of Water Delivery Systems," Technical Report NCEER-89-0023, National Center for Earthquake Engineering Research, Buffalo, NY, 1989.

Himmelwright, A. L. A., The San Francisco Earthquake and Fire: A Brief History of the Disaster, The Roebling Construction Company, New York, NY, 1906.

Institute of Transportation and Traffic Engineering, "Selected Logs of Borings in the City and County of San Francisco, CA," Information Circular No. 11, ITTE, University of California and USGS, Dec. 1950.

Lawson, A. C., et al., The California Earthquake of April 18, 1906: Report of the California State Earthquake Investigation Commission, Pub. No. 87, Carnegie Institute, Washington, D.C., 1908, Two Volumes and Atlas.

Mesri, G., "A Reevaluation of $s_{u(mob)} = 0.22\,\sigma_p'$ Using Laboratory Shear Tests," Canadian Geotechnical Journal, Vol. 26, No. 1, Feb. 1989, pp. 162-164.

Olmsted, R., N. Olmsted, and A. Pastron, "San Francisco Waterfront: Report on Historical Cultural Resources for the North Shore and Channel Outfalls Consolidation Projects," San Francisco Wastewater Management Program, City of San Francisco, CA, Dec. 1977.

O'Rourke, T. D. and P. A. Lane, "Liquefaction Hazards and Their Effects on Buried Pipelines," Technical Report No. NCEER-89-0007, National Center for Earthquake Engineering Research, Buffalo, NY, 1989.

Plafker, G. and J. P. Galloway, Eds., "Lessons Learned from the Loma Prieta, California Earthquake of October 17, 1989," U.S. Geological Survey Circular 1045, U.S. Geological Survey, Denver, CO, 1989.

Reynolds, L. E., "How Electricity Was Served to Consumers and Street Car Lines by the San Francisco Gas and Electric Co. After the Fire," Proceedings, 14th Annual Meeting of the Pacific Coast Gas Association, San Francisco, CA, Sept. 1906, pp. 365-373.

Roth, R. A. and E. Kavazanjian, Jr., "Liquefaction Susceptibility Mapping for San Francisco, California," Bulletin of the Association of Engineering Geologists, Vol. 21, No. 4, Nov. 1984, pp. 459-478.

Sanborn Ferris Map Co., "Insurance Maps, San Francisco, California," Volume 4, New York, NY, 1899.

Seed, H. B., I. M. Idriss, and I. Arango, "Evaluation of Liquefaction Potential Using Field Performance Data," Journal of Geotechnical Engineering, ASCE, Vol. 109, No. 3, Mar. 1983, pp. 458-482.

U.S. Coast Survey, Topographic Map of "City of San Francisco and Its Vicinity, California," surveyed by R. D. Cutts, 1853.

U.S. Coast Survey, Topographic Map of "City of San Francisco and Its Vicinity, California," surveyed by A. F. Rodgers, 1857.

Youd, T. L. and S. N. Hoose, "Historic Ground Failures in Northern California Triggered by Earthquakes," Geologic Survey Professional Paper 993, U.S. Government Printing Office, Washington, D.C., 1978, 177 p.

APPENDIX A

On December 4 and 5, 1988, a workshop on serviceability of water delivery systems was held at Cornell University [Grigoriu, 1989] to which various water industry participants, engineering consultants, and academics were invited, including representatives of the San Francisco Water and Fire Departments. In this appendix, the comments prepared for the workshop by T. S. Dickerman, now Assistant Manager of the City Distribution Division of the San Francisco Water Department, are presented. This work provides an overview of the MWSS and helps to focus on issues related to lifeline earthquake preparedness.

"It is important for the San Francisco Fire and Water Departments to discuss mutual interests in providing water for fire protection following the next major earthquake in the San Francisco Bay Region. At this time, it is not clear how effectively our water distribution systems complement one another. If one system were out of service following a major earthquake, how quickly could the system be restored to service? How reliably are we protecting our high-value districts? How can we best improve the reliability of our systems?

Perhaps a good starting point would be to make a specific statement of our goals. I would suggest the following goal statement: 'How can we, within available technology and funding, best improve our water systems and operations, so as to minimize losses following a major earthquake?'

This statement suggests the need to address the problem from a holistic perspective. It is important that the survivability of the physical system, in all its components, and the response of operations to an emergency, be taken as a total approach in meeting this goal. Material selection, operations preparedness, system controls, data acquisition, and communications all are vital in addressing this issue. Let me touch on the operations issues briefly.

No system can be made earthquake-proof. Our efforts in hardening our physical plants will be more effective if related operations issues also are addressed. Leading operations personnel need to develop detailed operational and repair plans to be carried out after the quake. These plans should include: 1) family preparedness programs, so personnel can quickly take care of their families and then get back to work, 2) supplies and equipment, including repair clamps, food, water, medical supplies, blankets and cots, fuel, and so on, 3) a detailed operations emergency handbook, 4) earthquake drills and drill evaluations, and 5) clear agreements with labor unions, retired personnel, and contractors.

Operations preparedness should include specialized training for all personnel. It should include water system data acquisition, so that the status of the systems can be readily known at a central console. Perhaps it even should include key system controls from a central command center. Operating personnel should have a hardened (radio or microwave) communication system which does not use vulnerable ground lines, and which has a highly reliable backup source of power. Communications with the Fire Department and the Civil Defense Center should be included in order to provide for coordination during an emergency.

Now let us focus on the long-term planning, construction, and reconstruction of the water system physical plant. This also is a vital issue, the opposite hand of operations preparedness. Large water departments spend millions of dollars annually in improving their physical plant. It is important that this money be spent wisely, so as to maximize the benefit from limited funds. Generally, outlays are used to renew the aging system, to upgrade water delivery and storage, and to improve water quality. The work may or may not address the issue of the system survivability vis-a-vis an earthquake. However, the last issue we here can clearly understand is one of a water department's important tasks. As we will see, it often is handled as a by-product of addressing other issues.

Historically, the largest part of the capital improvement program has been directed to replacement of the oldest distribution mains. Priorities for main replacements now include 1) priorities based on age of main, 2) priorities based on records of repair of mains, 3) priorities for replacement of small mains (1-in. through 4-in.), and 4) priorities for replacement of asbestos cement mains. The SFWD has developed a computer file of its priorities in each of these categories, block by block, throughout the city system. From these lists, we have tentatively selected contract work for the next five years.

Currently, most mains being replaced are unlined cast iron mains over 100 years old. The rate of replacement of small mains is 9,000 m per year. We also are replacing feeder mains and adding new feeder mains at a rate of 2,500 m per year. The primary argument for replacing the oldest mains is that they have restricted carrying capacity, due to internal corrosion. From a seismic perspective, there is an important gain, because the new mains are ductile iron, whereas the existing mains are more brittle cast iron.

Ductile iron mains, as you know, are capable of withstanding much higher tensile stresses and impact loads than cast iron. The old joints in the pipe generally are lead-caulked. The new joints have Tyton-type gaskets. Except on straight runs, joints on new pipes have been restrained with externally mounted steel tie rods across the joint anchoring between steel restraints (back of the bell) and steel lugs (lag-bolted into the spigot end of the pipe).

Beginning this year, this restrainer assembly has been discontinued (except for 400-mm pipe), and Field-Lok gaskets are being used instead. Field-Lok gaskets have stainless steel inserts in them which bite into the barrel of the spigot end, and bear against the inside of the bell to form a slightly flexible but strong anchorage between the lengths of pipe. Field-Lok gaskets have been tested in Water Department shops. A test of 300-mm Field-Lok gaskets last month held without leakage at 4.8 MPa. At that pressure, the gaskets did not fail. Failure occurred in lag bolts holding a tie rod at a capped end.

Ductile iron pipe with tie rods provide excellent characteristics for seismic loads. With Field-Lok gaskets, the installation is even better, and has a longer service life.

Most of our system will consist of cast iron pipe with lead joints for many years to come, since 1900 km of main in the city distribution system is being replaced at only 11,600 m per year.

With an eye toward earthquake safety, we will now hopefully establish as a priority the replacing of mains in former bay estuaries which have underlying Bay Mud and random fills. These areas are subject to liquefaction and settlement of the random fills, both of which may cause damage to the old cast iron mains or cause separation at the joints. There is a history of main failures in these areas, especially in the 1906 earthquake.

There are three major reservoir systems which provide water for fire protection to perhaps three-fourths of the city's high-value districts. These are the

Auxiliary Water Supply System of the Fire Department, the University Mound System, and the Sunset System. The College Hill and Lombard Systems also serve the high-value districts to a lesser extent.

In reviewing these systems regarding the effects of a major earthquake, let's begin at the source of supply and track the water as it makes its way to the city. During the first few days following an earthquake, the city conceivably could be cut off from the Hetch Hetchy Reservoir. The city also could be cut off from the reservoirs in Alameda County. Of the four transmission mains from Sunol to the Peninsula, two cross the Bay at the Dumbarton Bridge and are quite vulnerable there. Two go around the south end of the Bay, and may be less vulnerable.

These supplies, in any case, will not be critical during the first few days after the earthquake. Peninsula reservoirs hold about a month's supply, based on average demand. A network of Peninsula transmission mains from these reservoirs to the city apparently provides a high degree of redundancy, and therefore a reliable supply. Even if supply from the Peninsula were interrupted, reservoirs in the city typically hold four or five days of average system demand.

In the southeastern part of the city, the University Mound reservoir has 140 million gallons of storage in firm ground, with much of the storage below grade. Two large steel mains carry the water north from University Mound toward the downtown area, about five miles away. These mains cross the old Mission Bay estuary and the South of Market area, where they are vulnerable to underlying liquefaction and the settlement of random fills.

The Sunset System provides water to another large section of the city's high-value district. The Sunset Reservoir, in the westerly part of the city, is in good sandy earth. Two mains supply the Sunset Reservoir from two different sources: The San Andreas Reservoir on the Peninsula, and the Hetch Hetchy System, thus providing fully redundant water transmission. One of these supply mains is boosted at the Lake Merced Pump Station. This station now has backup diesel power. The Sunset Reservoir holds 670 million liters. The reservoir not only supplies the large Sunset distribution system, but also supplies the AWSS's Twin Peaks Reservoir, which has very small storage of its own. North of the Sunset Reservoir, a single 1500-mm transmission main provides the only large water-carrying capacity to the north and east parts of this system, and to the Twin Peaks Reservoir feeding the High Pressure System. The Water Department is planning to add a 900-mm main in the eastern part of the Sunset System, so that we have a way to feed the northeast part of the Sunset System in the event that the 1500-mm main is out of service.

The larger feeder mains in the major reservoir systems, which take water from reservoirs and deliver it to the local distribution networks, generally are steel and have usually been mortar-lined in place. The joints in the older steel feeder mains usually are riveted. The newer mains have welded joints. Although riveted joints may leak if movement occurs, the steel mains are ductile and usually in firm ground. Most of these mains should be expected to survive an earthquake in relatively good shape.

The intermediate-sized mains, also termed "feeder mains," sizes 300-mm through 750-mm, often are cast iron. These mains may pose the greatest seismic risk, since they are not ductile like the steel mains, but are important transmitters of water to the local distribution areas. Breaks in these mains will be the most difficult to repair, I believe. They cannot be welded, and repair clamps or replacement pipe in these sizes are insufficiently warehoused by the City Distribution Division to handle a major earthquake. In the University Mound System, many of these mains are in Bay Mud and/or random fill areas.

The vast bulk of mileage of mains in the city systems is composed of small mains, usually 150 and 200-mm, which distribute water within the local grid. These mains, though important, are considered less critical for fire suppression. If a break occurs here, the loss of water will be far less, and the main usually can be isolated by closing three or four valves. It is felt that, if necessary during an emergency, these mains can be left out of service while feeder mains are repaired. Fire suppression in the immediate area can be handled effectively by pulling hoses from mains left in service, since the mains which would be shut down generally are only 150 to 250 m long between gate valves.

Service pipes also can fail during an emergency. The city currently is installing about 7,000 new services a year, primarily replacing lead and galvanized steel. New services' sizes and materials have been standardized as follows: a) 25-mm polybutylene, b) 50-mm copper, heavy wall, and 3) 100, 150, and 200-mm ductile iron with locking gaskets. Probably all of these materials have a long life, and excellent characteristics for earthquake survivability.

The safety of reservoir storage also should be investigated for seismic risk. Currently, the city monitors groundwater leakage from all of its reservoirs on a regular basis, as mandated by the State Division of Safety of Dams. Generally, this water storage is fairly secure. It usually is below grade and constructed of concrete-lined earth embankments. The Stanford Heights Reservoir currently is being evaluated for seismic stability.

The distribution system's pump stations also are critical to the districts they serve. Fortunately, the bulk of the city is gravity-fed from large reservoirs. All pump stations in the San Francisco Water Department system will be reviewed for earthquake anchorage as part of a facility inspection process at the City Distribution Division. Additional seismic anchorage will be proposed as warranted, and other improvements also will be recommended. All pump stations need to have backup power facilities installed, similar to that just completed at the Lake Merced Pump Station. The primary power for pump stations is electric, and probably would be out of service following a major earthquake. Diesel power at the site probably is the best secondary power source."

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH
LIST OF PUBLISHED TECHNICAL REPORTS

The National Center for Earthquake Engineering Research (NCEER) publishes technical reports on a variety of subjects related to earthquake engineering written by authors funded through NCEER. These reports are available from both NCEER's Publications Department and the National Technical Information Service (NTIS). Requests for reports should be directed to the Publications Department, National Center for Earthquake Engineering Research, State University of New York at Buffalo, Red Jacket Quadrangle, Buffalo, New York 14261. Reports can also be requested through NTIS, 5285 Port Royal Road, Springfield, Virginia 22161. NTIS accession numbers are shown in parenthesis, if available.

NCEER-87-0001 "First-Year Program in Research, Education and Technology Transfer," 3/5/87, (PB88-134275/AS).

NCEER-87-0002 "Experimental Evaluation of Instantaneous Optimal Algorithms for Structural Control," by R.C. Lin, T.T. Soong and A.M. Reinhorn, 4/20/87, (PB88-134341/AS).

NCEER-87-0003 "Experimentation Using the Earthquake Simulation Facilities at University at Buffalo," by A.M. Reinhorn and R.L. Ketter, to be published.

NCEER-87-0004 "The System Characteristics and Performance of a Shaking Table," by J.S. Hwang, K.C. Chang and G.C. Lee, 6/1/87, (PB88-134259/AS). This report is available only through NTIS (see address given above).

NCEER-87-0005 "A Finite Element Formulation for Nonlinear Viscoplastic Material Using a Q Model," by O. Gyebi and G. Dasgupta, 11/2/87, (PB88-213764/AS).

NCEER-87-0006 "Symbolic Manipulation Program (SMP) - Algebraic Codes for Two and Three Dimensional Finite Element Formulations," by X. Lee and G. Dasgupta, 11/9/87, (PB88-219522/AS).

NCEER-87-0007 "Instantaneous Optimal Control Laws for Tall Buildings Under Seismic Excitations," by J.N. Yang, A. Akbarpour and P. Ghaemmaghami, 6/10/87, (PB88-134333/AS).

NCEER-87-0008 "IDARC: Inelastic Damage Analysis of Reinforced Concrete Frame - Shear-Wall Structures," by Y.J. Park, A.M. Reinhorn and S.K. Kunnath, 7/20/87, (PB88-134325/AS).

NCEER-87-0009 "Liquefaction Potential for New York State: A Preliminary Report on Sites in Manhattan and Buffalo," by M. Budhu, V. Vijayakumar, R.F. Giese and L. Baumgras, 8/31/87, (PB88-163704/AS). This report is available only through NTIS (see address given above).

NCEER-87-0010 "Vertical and Torsional Vibration of Foundations in Inhomogeneous Media," by A.S. Veletsos and K.W. Dotson, 6/1/87, (PB88-134291/AS).

NCEER-87-0011 "Seismic Probabilistic Risk Assessment and Seismic Margins Studies for Nuclear Power Plants," by Howard H.M. Hwang, 6/15/87, (PB88-134267/AS). This report is available only through NTIS (see address given above).

NCEER-87-0012 "Parametric Studies of Frequency Response of Secondary Systems Under Ground-Acceleration Excitations," by Y. Yong and Y.K. Lin, 6/10/87, (PB88-134309/AS).

NCEER-87-0013 "Frequency Response of Secondary Systems Under Seismic Excitation," by J.A. HoLung, J. Cai and Y.K. Lin, 7/31/87, (PB88-134317/AS).

NCEER-87-0014 "Modelling Earthquake Ground Motions in Seismically Active Regions Using Parametric Time Series Methods," by G.W. Ellis and A.S. Cakmak, 8/25/87, (PB88-134283/AS).

NCEER-87-0015 "Detection and Assessment of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 8/25/87, (PB88-163712/AS).

NCEER-87-0016 "Pipeline Experiment at Parkfield, California," by J. Isenberg and E. Richardson, 9/15/87, (PB88-163720/AS).

NCEER-87-0017 "Digital Simulation of Seismic Ground Motion," by M. Shinozuka, G. Deodatis and T. Harada, 8/31/87, (PB88-155197/AS). This report is available only through NTIS (see address given above).

NCEER-87-0018 "Practical Considerations for Structural Control: System Uncertainty, System Time Delay and Truncation of Small Control Forces," J.N. Yang and A. Akbarpour, 8/10/87, (PB88-163738/AS).

NCEER-87-0019 "Modal Analysis of Nonclassically Damped Structural Systems Using Canonical Transformation," by J.N. Yang, S. Sarkani and F.X. Long, 9/27/87, (PB88-187851/AS).

NCEER-87-0020 "A Nonstationary Solution in Random Vibration Theory," by J.R. Red-Horse and P.D. Spanos, 11/3/87, (PB88-163746/AS).

NCEER-87-0021 "Horizontal Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by A.S. Veletsos and K.W. Dotson, 10/15/87, (PB88-150859/AS).

NCEER-87-0022 "Seismic Damage Assessment of Reinforced Concrete Members," by Y.S. Chung, C. Meyer and M. Shinozuka, 10/9/87, (PB88-150867/AS). This report is available only through NTIS (see address given above).

NCEER-87-0023 "Active Structural Control in Civil Engineering," by T.T. Soong, 11/11/87, (PB88-187778/AS).

NCEER-87-0024 Vertical and Torsional Impedances for Radially Inhomogeneous Viscoelastic Soil Layers," by K.W. Dotson and A.S. Veletsos, 12/87, (PB88-187786/AS).

NCEER-87-0025 "Proceedings from the Symposium on Seismic Hazards, Ground Motions, Soil-Liquefaction and Engineering Practice in Eastern North America," October 20-22, 1987, edited by K.H. Jacob, 12/87, (PB88-188115/AS).

NCEER-87-0026 "Report on the Whittier-Narrows, California, Earthquake of October 1, 1987," by J. Pantelic and A. Reinhorn, 11/87, (PB88-187752/AS). This report is available only through NTIS (see address given above).

NCEER-87-0027 "Design of a Modular Program for Transient Nonlinear Analysis of Large 3-D Building Structures," by S. Srivastav and J.F. Abel, 12/30/87, (PB88-187950/AS).

NCEER-87-0028 "Second-Year Program in Research, Education and Technology Transfer," 3/8/88, (PB88-219480/AS).

NCEER-88-0001 "Workshop on Seismic Computer Analysis and Design of Buildings With Interactive Graphics," by W. McGuire, J.F. Abel and C.H. Conley, 1/18/88, (PB88-187760/AS).

NCEER-88-0002 "Optimal Control of Nonlinear Flexible Structures," by J.N. Yang, F.X. Long and D. Wong, 1/22/88, (PB88-213772/AS).

NCEER-88-0003 "Substructuring Techniques in the Time Domain for Primary-Secondary Structural Systems," by G.D. Manolis and G. Juhn, 2/10/88, (PB88-213780/AS).

NCEER-88-0004 "Iterative Seismic Analysis of Primary-Secondary Systems," by A. Singhal, L.D. Lutes and P.D. Spanos, 2/23/88, (PB88-213798/AS).

NCEER-88-0005 "Stochastic Finite Element Expansion for Random Media," by P.D. Spanos and R. Ghanem, 3/14/88, (PB88-213806/AS).

NCEER-88-0006 "Combining Structural Optimization and Structural Control," by F.Y. Cheng and C.P. Pantelides, 1/10/88, (PB88-213814/AS).

NCEER-88-0007 "Seismic Performance Assessment of Code-Designed Structures," by H.H-M. Hwang, J-W. Jaw and H-J. Shau, 3/20/88, (PB88-219423/AS).

NCEER-88-0008 "Reliability Analysis of Code-Designed Structures Under Natural Hazards," by H.H-M. Hwang, H. Ushiba and M. Shinozuka, 2/29/88, (PB88-229471/AS).

NCEER-88-0009 "Seismic Fragility Analysis of Shear Wall Structures," by J-W Jaw and H.H-M. Hwang, 4/30/88, (PB89-102867/AS).

NCEER-88-0010 "Base Isolation of a Multi-Story Building Under a Harmonic Ground Motion - A Comparison of Performances of Various Systems," by F-G Fan, G. Ahmadi and I.G. Tadjbakhsh, 5/18/88, (PB89-122238/AS).

NCEER-88-0011 "Seismic Floor Response Spectra for a Combined System by Green's Functions," by F.M. Lavelle, L.A. Bergman and P.D. Spanos, 5/1/88, (PB89-102875/AS).

NCEER-88-0012 "A New Solution Technique for Randomly Excited Hysteretic Structures," by G.Q. Cai and Y.K. Lin, 5/16/88, (PB89-102883/AS).

NCEER-88-0013 "A Study of Radiation Damping and Soil-Structure Interaction Effects in the Centrifuge," by K. Weissman, supervised by J.H. Prevost, 5/24/88, (PB89-144703/AS).

NCEER-88-0014 "Parameter Identification and Implementation of a Kinematic Plasticity Model for Frictional Soils," by J.H. Prevost and D.V. Griffiths, to be published.

NCEER-88-0015 "Two- and Three- Dimensional Dynamic Finite Element Analyses of the Long Valley Dam," by D.V. Griffiths and J.H. Prevost, 6/17/88, (PB89-144711/AS).

NCEER-88-0016 "Damage Assessment of Reinforced Concrete Structures in Eastern United States," by A.M. Reinhorn, M.J. Seidel, S.K. Kunnath and Y.J. Park, 6/15/88, (PB89-122220/AS).

NCEER-88-0017 "Dynamic Compliance of Vertically Loaded Strip Foundations in Multilayered Viscoelastic Soils," by S. Ahmad and A.S.M. Israil, 6/17/88, (PB89-102891/AS).

NCEER-88-0018 "An Experimental Study of Seismic Structural Response With Added Viscoelastic Dampers," by R.C. Lin, Z. Liang, T.T. Soong and R.H. Zhang, 6/30/88, (PB89-122212/AS).

NCEER-88-0019 "Experimental Investigation of Primary - Secondary System Interaction," by G.D. Manolis, G. Juhn and A.M. Reinhorn, 5/27/88, (PB89-122204/AS).

NCEER-88-0020 "A Response Spectrum Approach For Analysis of Nonclassically Damped Structures," by J.N. Yang, S. Sarkani and F.X. Long, 4/22/88, (PB89-102909/AS).

NCEER-88-0021 "Seismic Interaction of Structures and Soils: Stochastic Approach," by A.S. Veletsos and A.M. Prasad, 7/21/88, (PB89-122196/AS).

NCEER-88-0022 "Identification of the Serviceability Limit State and Detection of Seismic Structural Damage," by E. DiPasquale and A.S. Cakmak, 6/15/88, (PB89-122188/AS).

NCEER-88-0023 "Multi-Hazard Risk Analysis: Case of a Simple Offshore Structure," by B.K. Bhartia and E.H. Vanmarcke, 7/21/88, (PB89-145213/AS).

NCEER-88-0024 "Automated Seismic Design of Reinforced Concrete Buildings," by Y.S. Chung, C. Meyer and M. Shinozuka, 7/5/88, (PB89-122170/AS).

NCEER-88-0025 "Experimental Study of Active Control of MDOF Structures Under Seismic Excitations," by L.L. Chung, R.C. Lin, T.T. Soong and A.M. Reinhorn, 7/10/88, (PB89-122600/AS).

NCEER-88-0026 "Earthquake Simulation Tests of a Low-Rise Metal Structure," by J.S. Hwang, K.C. Chang, G.C. Lee and R.L. Ketter, 8/1/88, (PB89-102917/AS).

NCEER-88-0027 "Systems Study of Urban Response and Reconstruction Due to Catastrophic Earthquakes," by F. Kozin and H.K. Zhou, 9/22/88.

NCEER-88-0028 "Seismic Fragility Analysis of Plane Frame Structures," by H.H-M. Hwang and Y.K. Low, 7/31/88, (PB89-131445/AS).

NCEER-88-0029 "Response Analysis of Stochastic Structures," by A. Kardara, C. Bucher and M. Shinozuka, 9/22/88, (PB89-174429/AS).

NCEER-88-0030 "Nonnormal Accelerations Due to Yielding in a Primary Structure," by D.C.K. Chen and L.D. Lutes, 9/19/88, (PB89-131437/AS).

NCEER-88-0031 "Design Approaches for Soil-Structure Interaction," by A.S. Veletsos, A.M. Prasad and Y. Tang, 12/30/88, (PB89-174437/AS).

NCEER-88-0032 "A Re-evaluation of Design Spectra for Seismic Damage Control," by C.J. Turkstra and A.G. Tallin, 11/7/88, (PB89-145221/AS).

NCEER-88-0033 "The Behavior and Design of Noncontact Lap Splices Subjected to Repeated Inelastic Tensile Loading," by V.E. Sagan, P. Gergely and R.N. White, 12/8/88, (PB89-163737/AS).

NCEER-88-0034 "Seismic Response of Pile Foundations," by S.M. Mamoon, P.K. Banerjee and S. Ahmad, 11/1/88, (PB89-145239/AS).

NCEER-88-0035 "Modeling of R/C Building Structures With Flexible Floor Diaphragms (IDARC2)," by A.M. Reinhorn, S.K. Kunnath and N. Panahshahi, 9/7/88, (PB89-207153/AS).

NCEER-88-0036 "Solution of the Dam-Reservoir Interaction Problem Using a Combination of FEM, BEM with Particular Integrals, Modal Analysis, and Substructuring," by C-S. Tsai, G.C. Lee and R.L. Ketter, 12/31/88, (PB89-207146/AS).

NCEER-88-0037 "Optimal Placement of Actuators for Structural Control," by F.Y. Cheng and C.P. Pantelides, 8/15/88, (PB89-162846/AS).

NCEER-88-0038 "Teflon Bearings in Aseismic Base Isolation: Experimental Studies and Mathematical Modeling," by A. Mokha, M.C. Constantinou and A.M. Reinhorn, 12/5/88, (PB89-218457/AS).

NCEER-88-0039 "Seismic Behavior of Flat Slab High-Rise Buildings in the New York City Area," by P. Weidlinger and M. Ettouney, 10/15/88, (PB90-145681/AS).

NCEER-88-0040 "Evaluation of the Earthquake Resistance of Existing Buildings in New York City," by P. Weidlinger and M. Ettouney, 10/15/88, to be published.

NCEER-88-0041 "Small-Scale Modeling Techniques for Reinforced Concrete Structures Subjected to Seismic Loads," by W. Kim, A. El-Attar and R.N. White, 11/22/88, (PB89-189625/AS).

NCEER-88-0042 "Modeling Strong Ground Motion from Multiple Event Earthquakes," by G.W. Ellis and A.S. Cakmak, 10/15/88, (PB89-174445/AS).

NCEER-88-0043 "Nonstationary Models of Seismic Ground Acceleration," by M. Grigoriu, S.E. Ruiz and E. Rosenblueth, 7/15/88, (PB89-189617/AS).

NCEER-88-0044 "SARCF User's Guide: Seismic Analysis of Reinforced Concrete Frames," by Y.S. Chung, C. Meyer and M. Shinozuka, 11/9/88, (PB89-174452/AS).

NCEER-88-0045 "First Expert Panel Meeting on Disaster Research and Planning," edited by J. Pantelic and J. Stoyle, 9/15/88, (PB89-174460/AS).

NCEER-88-0046 "Preliminary Studies of the Effect of Degrading Infill Walls on the Nonlinear Seismic Response of Steel Frames," by C.Z. Chrysostomou, P. Gergely and J.F. Abel, 12/19/88, (PB89-208383/AS).

NCEER-88-0047 "Reinforced Concrete Frame Component Testing Facility - Design, Construction, Instrumentation and Operation," by S.P. Pessiki, C. Conley, T. Bond, P. Gergely and R.N. White, 12/16/88, (PB89-174478/AS).

NCEER-89-0001 "Effects of Protective Cushion and Soil Compliancy on the Response of Equipment Within a Seismically Excited Building," by J.A. HoLung, 2/16/89, (PB89-207179/AS).

NCEER-89-0002 "Statistical Evaluation of Response Modification Factors for Reinforced Concrete Structures," by H.H-M. Hwang and J-W. Jaw, 2/17/89, (PB89-207187/AS).

NCEER-89-0003 "Hysteretic Columns Under Random Excitation," by G-Q. Cai and Y.K. Lin, 1/9/89, (PB89-196513/AS).

NCEER-89-0004 "Experimental Study of 'Elephant Foot Bulge' Instability of Thin-Walled Metal Tanks," by Z-H. Jia and R.L. Ketter, 2/22/89, (PB89-207195/AS).

NCEER-89-0005 "Experiment on Performance of Buried Pipelines Across San Andreas Fault," by J. Isenberg, E. Richardson and T.D. O'Rourke, 3/10/89, (PB89-218440/AS).

NCEER-89-0006 "A Knowledge-Based Approach to Structural Design of Earthquake-Resistant Buildings," by M. Subramani, P. Gergely, C.H. Conley, J.F. Abel and A.H. Zaghw, 1/15/89, (PB89-218465/AS).

NCEER-89-0007 "Liquefaction Hazards and Their Effects on Buried Pipelines," by T.D. O'Rourke and P.A. Lane, 2/1/89, (PB89-218481).

NCEER-89-0008 "Fundamentals of System Identification in Structural Dynamics," by H. Imai, C-B. Yun, O. Maruyama and M. Shinozuka, 1/26/89, (PB89-207211/AS).

NCEER-89-0009 "Effects of the 1985 Michoacan Earthquake on Water Systems and Other Buried Lifelines in Mexico," by A.G. Ayala and M.J. O'Rourke, 3/8/89, (PB89-207229/AS).

NCEER-89-R010 "NCEER Bibliography of Earthquake Education Materials," by K.E.K. Ross, Second Revision, 9/1/89, (PB90-125352/AS).

NCEER-89-0011 "Inelastic Three-Dimensional Response Analysis of Reinforced Concrete Building Structures (IDARC-3D), Part I - Modeling," by S.K. Kunnath and A.M. Reinhorn, 4/17/89, (PB90-114612/AS).

NCEER-89-0012 "Recommended Modifications to ATC-14," by C.D. Poland and J.O. Malley, 4/12/89.

NCEER-89-0013 "Repair and Strengthening of Beam-to-Column Connections Subjected to Earthquake Loading," by M. Corazao and A.J. Durrani, 2/28/89, (PB90-109885/AS).

NCEER-89-0014 "Program EXKAL2 for Identification of Structural Dynamic Systems," by O. Maruyama, C-B. Yun, M. Hoshiya and M. Shinozuka, 5/19/89, (PB90-109877/AS).

NCEER-89-0015 "Response of Frames With Bolted Semi-Rigid Connections, Part I - Experimental Study and Analytical Predictions," by P.J. DiCorso, A.M. Reinhorn, J.R. Dickerson, J.B. Radziminski and W.L. Harper, 6/1/89, to be published.

NCEER-89-0016 "ARMA Monte Carlo Simulation in Probabilistic Structural Analysis," by P.D. Spanos and M.P. Mignolet, 7/10/89, (PB90-109893/AS).

NCEER-89-0017 "Preliminary Proceedings of the Conference on Disaster Preparedness - The Place of Earthquake Education in Our Schools, July 9-11, 1989," 6/23/89, (PB90-108606/AS).

NCEER-89-0018 "Multidimensional Models of Hysteretic Material Behavior for Vibration Analysis of Shape Memory Energy Absorbing Devices, by E.J. Graesser and F.A. Cozzarelli, 6/7/89.

NCEER-89-0019	"Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures (3D-BASIS)," by S. Nagarajaiah, A.M. Reinhorn and M.C. Constantinou, 8/3/89.
NCEER-89-0020	"Structural Control Considering Time-Rate of Control Forces and Control Rate Constraints," by F.Y. Cheng and C.P. Pantelides, 8/3/89, (PB90-120445/AS).
NCEER-89-0021	"Subsurface Conditions of Memphis and Shelby County," by K.W. Ng, T-S. Chang and H-H.M. Hwang, 7/26/89, (PB90-120437/AS).
NCEER-89-0022	"Seismic Wave Propagation Effects on Straight Jointed Buried Pipelines," by K. Elhmadi and M.J. O'Rourke, 8/24/89.
NCEER-89-0023	"Workshop on Serviceability Analysis of Water Delivery Systems," edited by M. Grigoriu, 3/6/89, (PB90-127424/AS).
NCEER-89-0024	"Shaking Table Study of a 1/5 Scale Steel Frame Composed of Tapered Members," by K.C. Chang, J.S. Hwang and G.C. Lee, 9/18/89.
NCEER-89-0025	"DYNA1D: A Computer Program for Nonlinear Seismic Site Response Analysis - Technical Documentation," by Jean H. Prevost, 9/14/89.
NCEER-89-0026	"1:4 Scale Model Studies of Active Tendon Systems and Active Mass Dampers for Aseismic Protection," by A.M. Reinhorn, T.T. Soong, R.C. Lin, Y.P. Yang, Y. Fukao, H. Abe and M. Nakai, 9/15/89.
NCEER-89-0027	"Scattering of Waves by Inclusions in a Nonhomogeneous Elastic Half Space Solved by Boundary Element Methods," by P.K. Hadley, A. Askar and A.S. Cakmak, 6/15/89, (PB90-145699/AS).
NCEER-89-0028	"Statistical Evaluation of Deflection Amplification Factors for Reinforced Concrete Structures," by H.H.M. Hwang, J-W. Jaw and A.L. Ch'ng, 8/31/89.
NCEER-89-0029	"Bedrock Accelerations in Memphis Area Due to Large New Madrid Earthquakes," by H.H.M. Hawng, C.H.S. Chen and G. Yu, 11/7/89.
NCEER-89-0030	"Seismic Behavior and Response Sensitivity of Secondary Structural Systems," by Y.Q. Chen and T.T. Soong, 10/23/89.
NCEER-89-0031	"Random Vibration and Reliability Analysis of Primary-Secondary Structural Systems," by Y. Ibrahim, M. Grigoriu and T.T. Soong, 11/10/89.
NCEER-89-0032	"Proceedings from the Second U.S. - Japan Workshop on Liquefaction, Large Ground Deformation and Their Effects on Lifelines, September 26-29, 1989," Edited by T.D. O'Rourke and M. Hamada, 12/1/89.
NCEER-89-0033	"Deterministic Model for Seismic Damage Evaluation of Reinforced Concrete Structures," by J.M. Bracci, A.M. Reinhorn, J.B. Mander and S.K. Kunnath, 9/27/89, to be published.
NCEER-89-0034	"On the Relation Between Local and Global Damage Indices," by E. DiPasquale and A.S. Cakmak, 8/15/89.
NCEER-89-0035	"Cyclic Undrained Behavior of Nonplastic and Low Plasticity Silts," by A.J. Walker and H.E. Stewart, 7/26/89.
NCEER-89-0036	"Liquefaction Potential of Surficial Deposits in the City of Buffalo, New York," by M. Budhu, R. Giese and C. Baumgrass, 1/17/89, to be published.
NCEER-89-0037	"A Deterministic Assessment of Effects of Ground Motion Incoherence," by A.S. Veletsos and Y. Tang, 7/15/89.
NCEER-89-0038	"Workshop on Ground Motion Parameters for Seismic Hazard Mapping," July 17-18, 1989, edited by R.V. Whitman, 12/1/89.

NCEER-89-0039 "Seismic Effects on Elevated Transit Lines of the New York City Transit Authority," by C.J. Costantino, C.A. Miller and E. Heymsfield, 12/26/89, to be published.

NCEER-89-0040 "Centrifugal Modeling of Dynamic Soil-Structure Interaction," by K. Weissman, Supervised by J.H. Prevost, 5/10/89.

NCEER-90-0001 "Geotechnical and Lifeline Aspects of the October 17, 1989 Loma Prieta Earthquake in San Francisco," by T.D. O'Rourke, H.E. Stewart, F.T. Blackburn and T.S. Dickerman, 1/90.