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SYNOPSIS: The Loma Prieta Earthquake of October 17, 1989 was the most costly single natural disaster in U.S. history, resulting in losses of $7 to $9 billion, and claiming 63 lives. These damages were concentrated mainly at a number of distinct sites comprising a relatively small fraction of the affected region, as local site conditions and related geotechnical factors exerted a major influence on damage patterns and loss of life in this catastrophic event. This paper discusses one of these geotechnical factors, the widespread occurrence of soil liquefaction during the earthquake, as well as the associated damages and the resulting lessons learned. Additional significant geotechnical factors which exerted a strong influence on damage patterns during this event, including site-dependent dynamic response and seismically-induced slope instability, are discussed in companion papers in these proceedings.

INTRODUCTION

Soil liquefaction affected a widespread area during the Loma Prieta Earthquake, as shown in Figure 1. In addition to the well-publicized liquefaction-induced damage which occurred in the Marina District in northern San Francisco, considerable damage associated with liquefaction also occurred in areas of eastern San Francisco, on Treasure Island at the center of San Francisco Bay, and along the east San Francisco Bay shore in Oakland, Emeryville, and Alameda, as well as farther south along the Pacific coast in the Santa Cruz and central Monterey Bay regions. The two most northern sites found to show evidence of liquefaction were: (a) a sand boil adjacent to a pile supporting a pier on the south shore of Suisun Bay at Martinez, and (b) a series of sand boils observed and photographed in a lagoon at Bolinas, on the Marin Peninsula, with associated lateral spreading of the adjacent beach.

This paper will provide a brief overview of liquefaction-related phenomena associated with this earthquake, and will also provide some historical context for these observations, as well as a brief discussion of their importance. A more detailed overview of liquefaction-related features of the Loma Prieta Earthquake is presented by Seed, et al. (1990).

SAN FRANCISCO'S MARINA DISTRICT

Widespread liquefaction caused extensive damage to the Marina District, centrally located on the Northern coast of the City of San Francisco. Loose, fine sandy fill liquefied and this resulted in sand boils, lateral spreading, settlement, partial bearing failures, structural distress, pavement damage, and damage to pipes and other buried utilities. This region also suffered considerable damage to structures as a result of strong ground shaking. A number of buildings were destroyed or badly damaged; much of the area was evacuated and public access was restricted immediately following the earthquake. An excellent summary of damages and compilation of geotechnical data for this District is presented by Holzer and O'Rourke (1990).

Much of the liquefaction-related damage in the Marina District is an indirect legacy of the 1906 San Francisco earthquake, as much of the liquefaction occurred in hydraulic fill which was placed to create new land in order to provide a site upon which to host a World Fair: the 1915 Panama Pacific Exposition. Major factors in San Francisco's decision to host this World Fair were a desire to celebrate the successful rebuilding of the city in the wake of the catastrophic 1906 earthquake and fire, which had destroyed major portions of the city, and a desire to demonstrate to the world that the city had been successfully resurrected.

Figure 3 is a map of the Marina District as it existed at the time of the Loma Prieta Earthquake of October 17, 1989. Super-imposed on this is the old 1869 shoreline and the associated marshy deposits occurring at the south-west limit of the small embayment which existed at that time. Much of the existing Marina District consists of landfill placed since 1869, both to reclaim the marshes and to infill the small baylet. This fill, which was placed in two general stages or periods, is composed primarily of uncompacted fine sands and silty sands. It was primarily within these loose, saturated cohesionless soils that widespread liquefaction occurred.

The first stage of fill placement occurred between about 1870 and the end of the 19th century, and consisted primarily of placement of loosely dumped fill around the perimeter of the small Marina bay and in the perimeter marshes. Most of this fill was dune sand taken from onshore dune deposits occurring adjacent to the southeast edge of the Marina District. A seawall was also constructed to provide a protected harbor. The heavy dashed line in Figure 3 shows the resulting coastline and seawall as they existed at the end of the 19th century.

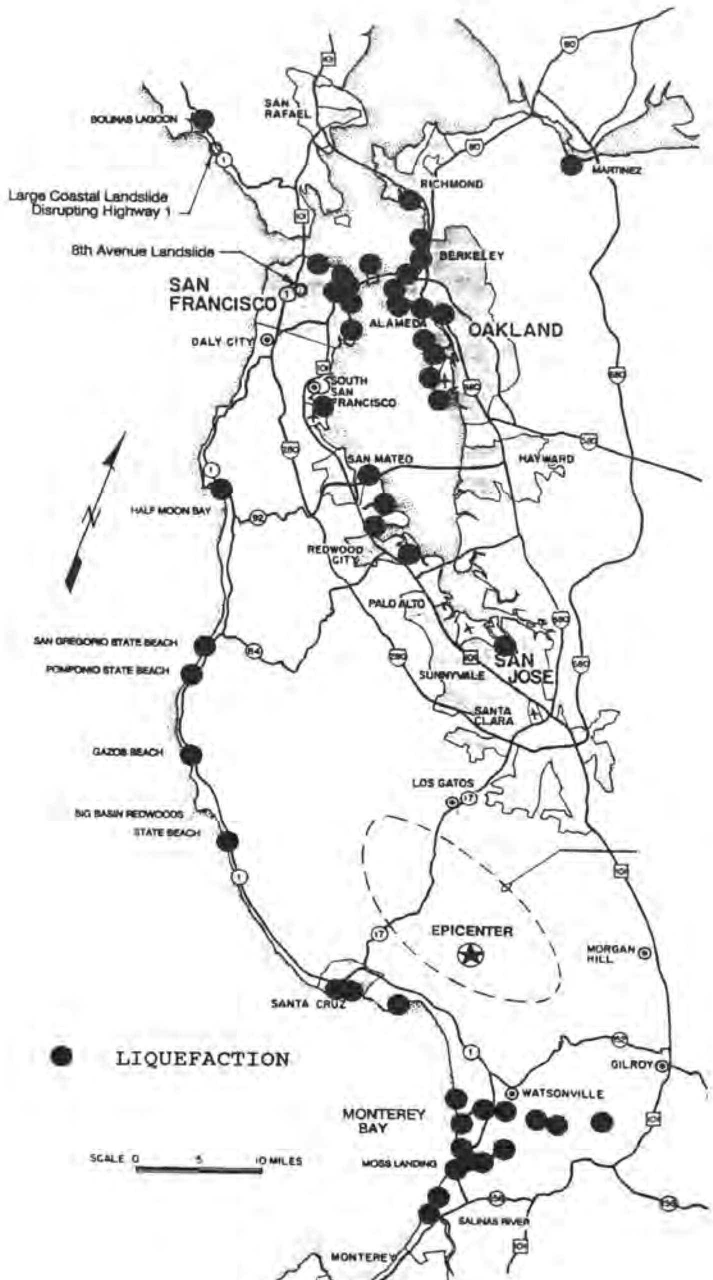

Fig. 1 Map of Affected Region Showing Sites of Soil Liquefaction

After the 1906 San Francisco Earthquake and fire, the Marina District was selected as the site for the 1915 Panama Pacific Exposition (and World's Fair). To create sufficient land, the harbor area enclosed by the 1899 seawall was infilled with hydraulic fill. Dredged material, consisting primarily of fine, silty sand, was pumped in hydraulic suspension into the enclosed harbor and allowed to settle. This hydraulic fill process typically results in a loose saturated fill which is vulnerable to potential soil liquefaction during earthquake shaking, and the Marina fill was no exception to this. Figure 2 is a photograph of the Marina District viewed from Fort Mason, immediately to the east. Taken in January of 1910, this photograph shows conditions as they existed at an early stage of the hydraulic fill placement. Note the seawall at the right of the photograph, and the small barge and floating pipeline in the bay depositing hydraulic fill.

Soil liquefaction during the Loma Prieta Earthquake of October 17, 1989 occurred in both the hydraulically placed fill and the earlier, uncompacted fills around the perimeter of the District, but was significantly more severe and pervasive in the hydraulic fill zones. Numerous sand boils occurred throughout the hydraulic fill zone, both on open ground and along cracks and joints in pavements, gutters, and around the edges of structures. Sand intrusions also occurred in basements and ground floors of buildings. Changes in both color and gradation of the extruded boil materials were readily apparent at various locations across the District, and these could be readily correlated with the origins of the fill materials and their placement history.

Figure 6 illustrates conditions near the center of the Marina District immediately after the earthquake. In addition to the collapsed structure, this figure clearly shows buckling of the sidewalk at two locations. This buckling is not the result of settlement, but rather of lateral compression of the pavement due to lateral spreading associated with liquefaction of the underlying fill in this area. Similar evidence of lateral spreading, including extension and/or compression of pavements, as well as massive and widespread damage to critical buried utilities, occurred throughout much of the District.

Figure 4 shows the locations of breaks in water pipes greater than 4-inches in diameter, as well as breaks in main sewer lines. Considerable damage to buried utilities occurred

Fig. 2 View of the Marina District Looking West from Fort Mason in January of 1910. [Photo courtesy of the San Francisco Maritime Nat'l. Historic Park]

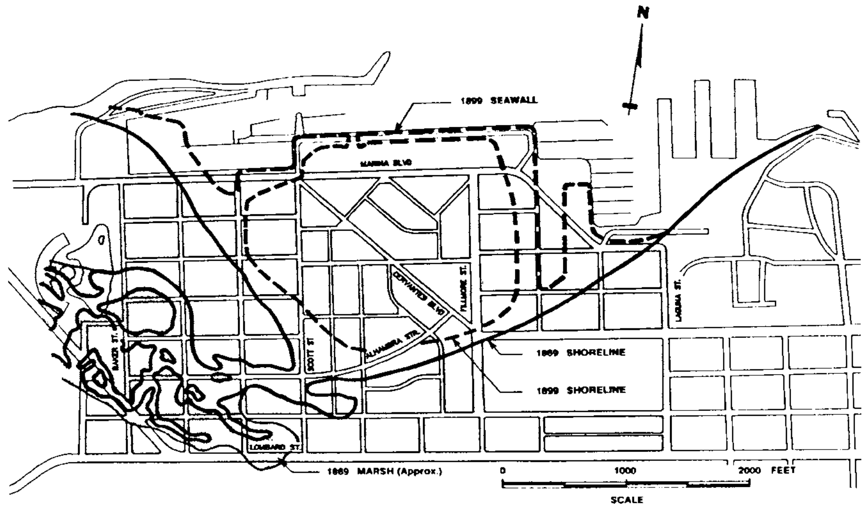

Fig. 3 Map of the Marina District in San Francisco Showing the Approximate Locations of the Earlier Coastlines and Marshes

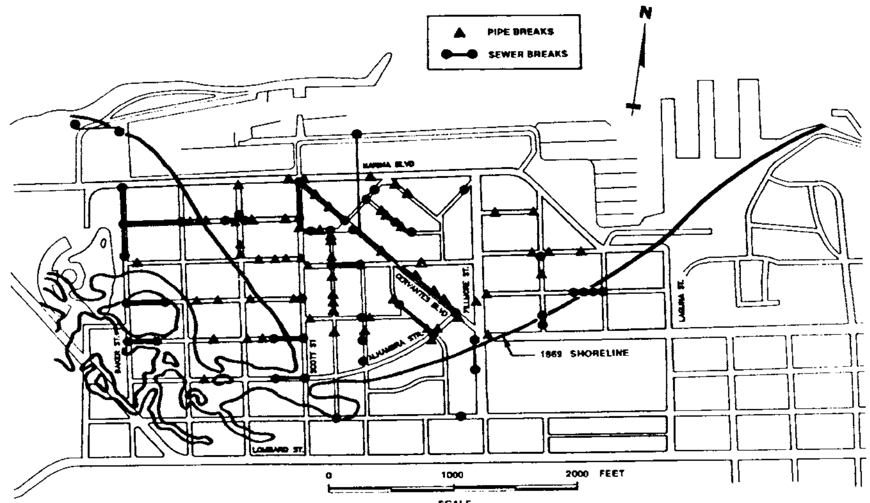

Fig. 4 Location of Major Water Pipe and Sewer Breaks; Marina District, San Francisco

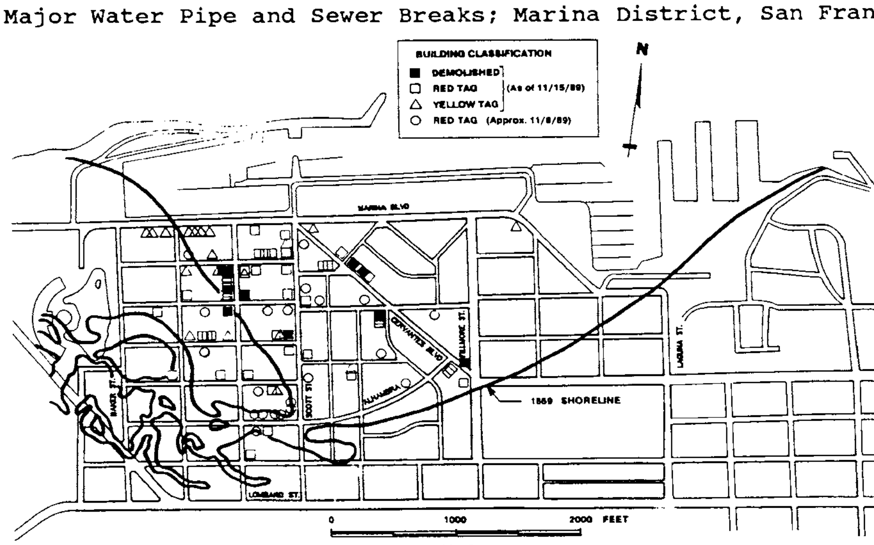

Fig. 5 Locations of Demolished Structures, and Structures Marked with Red and Yellow Post-Earthquake Inspection Tags as of Mid-November, 1989: Marina District, San Francisco

Fig. 6 Pavement Buckling Indicative of Lateral Compression; Marina District, San Francisco

as a result of soil liquefaction in the Marina District during the earthquake. In addition to water and sewer breaks, numerous breaks in natural gas pipelines also occurred. It was, however, the water main outages which were most nearly catastrophic. Several fires occurred in the Marina District immediately after the earthquake, and water outages prevented rapid extinguishing of these.

The largest fire, which occurred at the corner of Beach Street and Divisadero Street, was only contained when the City's fireboat was brought to the edge of the Marina Harbor and hoses were run from the fireboat to the fire. The massive pumping capacity of the fireboat was then used to pump water from the Bay, supplementing the capacity of other portable pumps already on the scene, to contain the fire. It is also interesting to note that shortages of equipment forced the Fire Department to remove two fire trucks from San Francisco's Fire Museum to assist in fighting fires during this earthquake. Apparent shortages of equipment, and widespread loss of water pressure in the main water system, as well as in two auxiliary systems specifically intended to provide water for fighting post-earthquake fires, in Districts throughout much of the City following this relatively moderate earthquake centered more than 40 miles to the south, appear to raise some question as to San Francisco's ability to deal adequately with a larger number of fires and similar losses of emergency water supplies and pressure in hydrants in the wake of a larger or more near-field seismic event which might occur on either the San Andreas or Hayward Faults. Recognition of the resulting potential for catastrophic post-earthquake fires not unlike those which levelled much of the City in 1906 is one of the vitally important lessons to be learned from the Loma Prieta event.

Figure 5 shows the locations of heavily damaged structures, as indicated by post-earthquake inspection "tags", roughly one month after the earthquake. As illustrated in Figure 5, a majority of the structural damage occurred near the heart of the Marina District. Much of this ground is underlain by the loose hydraulic fill placed in 1910-1912, and much of the rest is underlain either by fill placed to reclaim the perimeter marshes or by naturally deposited loose to medium dense beach and dune sands whic occur at the edges of the region. This does nc mean, however, that this concentration c structural damages is due primarily to soi liquefaction. Instead, a majority of the damac to structures in the Marina District on Octobe 17, 1989 was caused by strong shaking, as th fill in much of the region of heavies structural damage is underlain by relativel soft and compressible recent clayey estuarin deposits which served to amplify the levels o shaking in this area. Although strong shakin was the primary cause of structural damage i this region, soil liquefaction also damage structures, as a number of structures wer wracked by differential settlements, latera spreading, or partial bearing failures. Many o these structures were found to have san intrusions in their garages and basements, an in some cases this sand spilled out so as to b visible from external inspection.

SAN FRANCISCO'S EMBARCADERO AND OLD MISSION BA REGIONS

Additional loose, sandy fills underlain b soft cohesive deposits underlie much of th eastern edges of San Francisco, extending wel inland in a number of locations. Though les well-publicized than the liquefaction in th Marina District, the liquefaction of thes eastern fill zones affected a considerabl larger area, and represents significantl greater aggregate risk to life and property i future seismic events than does the now well-documented liquefaction hazard in the Marin District.

Figure 7 presents a map of eastern Sar Francisco, showing the old historic shoreline (the heavy solid line) and the bay marshes (dark zones) which extended well inland prior tc extensive fill placement during the latter half of the last century. Superimposed on this map are three zones outlined with dashed lines anc shaded with cross-hatching; these were the regions of heaviest (pre-fire) damage intensity during the 1906 San Francisco Earthquake. This heavy damage intensity in 1906 was the result of both: (a) site effects on strong shaking, as a result of the soft clays underlying the surface fills, and (b) massive and widespread soil liquefaction inducing bearing failures, differential settlements and lateral spreading.

Despite the relatively moderate levels and short duration of shaking produced in these regions by the Loma Prieta Earthquake of October 17, 1989, soil liquefaction occurred again throughout much of these same areas, as shown in Figure 8. Much of this liquefaction was of moderate severity, representing ground softening and minor settlements producing cracking of pavements and utility breaks, but a number of buildings were also destroyed or damaged beyond repair as a direct result of liquefaction in these areas. In one 15-block area surrounding 6th and Folsom Streets, more than 50% of the structures were either significantly damaged or condemned, representing an overall level of damage not unlike that of the central Marina Distrist.

More typical than this type of widespread structural damage, however, were characteristic

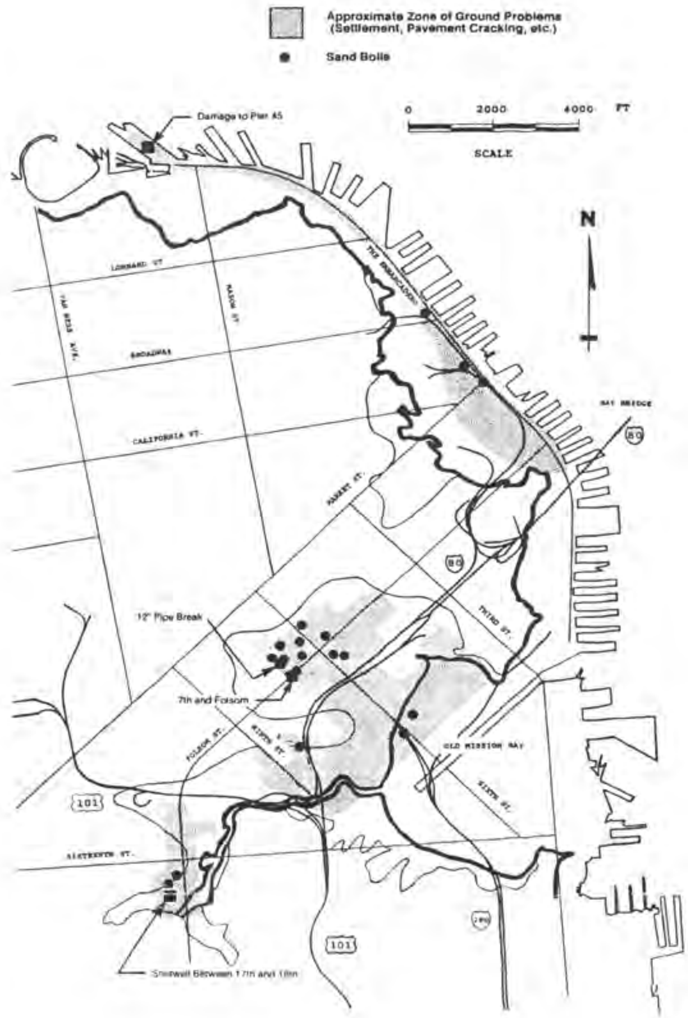

Fig. 7 Map of Eastern San Francisco Showing the Region Most Intensively Damaged During the 1906 Earthquake (Before the Post-Earthquake Fire), and the Historic Coastline and Marshes of 1852

Fig. 8 Apparent Extent of Soil Liquefaction in San Francisco's Embarcadero and Old Mission Bay Regions on October 17, 1989

Fig. 9 Conditions on Dore Street Near Brannan After the 1906 San Francisco Earthquake [Lawson et al., 1908]

centerline cracks in roadways throughout these areas as a result of minor settlements of the ground relative to the large and centrally located buried sewer lines, and minor structural settlements and distress. This must be contrasted with the massive liquefaction-induced ground movements which occurred in these zones in 1906, as illustrated in Figure 9 which shows many feet of heaving and lateral displacement of what had been level ground in this region prior to the 1906 earthquake. Figure 10 shows several houses in this area condemned due to liquefaction-induced damages (settlements and wracking) during the Loma Prieta Earthquake, and Figure 11 shows the devastation wrought by the 1906 Earthquake at precisely the same location. The clear potential for widespread and severe liquefaction in these zones in larger, future earthquakes, and the high population density and poor structural types and conditions south of Market Street (most structures in this region

Fig. 10 Four Buildings on Shotwell near 18th Street Damaged by Liquefaction-Induced Foundation Displacements in the Loma Prieta Earthquake

Fig. 11 Conditions at 18th and Shotwell Streets After the 1906 San Francisco Earthquake [Lawson et al., 1908]

are old, two and three story masonry or concrete structures founded at grade and in generally poor condition), render these zones highly dangerous with regard to future liquefaction hazard.

CENTRAL EASTERN SAN FRANCISCO BAY AREA

The central and east San Francisco Bayshore areas also suffered considerable damage due to liquefaction, as shown in Figure 12. Widespread liquefaction occurred over most of Treasure Island, a man-made island constructed by placing sandy hydraulic fill within rock containment dikes at the center of San Francisco Bay. In addition to producing numerous sand boils and large ponds, and damaging both structures and utilities, this liquefaction caused lateral movements and settlements of many of the levees surrounding this island. Among the most potentially ominous liquefaction-related features observed in the Loma Prieta Earthquake, these movements were indicative of the onset of liquefaction around most of the island perimeter. Studies are currently underway to evaluate the depths to which this liquefaction occurred, and the likelihood of more extensive liquefaction in stronger or more near-field future events producing full failure of the perimeter containment dikes.

On the east bayshore, soil liquefaction caused minor damage at Richmond Harbor and caused cracks and damage to the East Bayshore Highway (Interstate Hwy 80) and the parallel coastal frontage road from Berkeley south to the Bay Bridge approach. From Emeryville south to the bridge, sand boils were observed off to the side of the road and some of the road fissures exuded sands. The fill (mole) approaching the bridge was extensively damaged by both settlement and lateral spreading, with open fissures as much as 300 feet long, numerous fissures and boils exuding sand, and appreciable settlements creating a badly cracked and uneven pavement surface. This was not a major problem during the Loma Prieta event, as the bridge itself was closed due to structural failure of one section, but this type of damage would temporarily disrupt a key transportation artery in any future seismic event.

Immediately south of the Bay Bridge, extensive damage due to liquefaction occurred at the main Port of Oakland container cargo docks at the 7th Street, Matson, APL and Howard Terminals. Settlements and lateral spreading (accompanied by sand boils) damaged pavements and rendered many of these facilities at least temporarily inoperational as a number of massive cranes were unable to traverse railroad tracks rendered uneven by ground displacements. Figure 13 shows a cross section through the edge of a typical wharf at the 7th Street Terminal. The liquefaction-damaged harbor terminals in Oakland all consisted of hydraulic sand fill, placed behind containment dikes, and underlain by deep bay alluvium deposits. The section shown in Figure 13 is fairly typical of these.

Most of the concrete wharves at the edges of the terminal fills were supported primarily on vertical concrete piles, but the inboard two rows of piles at the 7th Street terminal were battered to provide lateral load resistance as shown in Figure 13. These battered piles were massively damaged at their tips, as shown for example in Figure 14, illustrating the problems inherent in the use of battered piles to withstand seismic forces in an otherwise compliant soil system. Most of the terminal wharves at the affected Port facilities had at least one row of battered piles, and these consistently behaved poorly. The damaged piles (both battered and vertical) from the wharves supported on a combination of battered and vertical piles are currently being replaced by vertical piles only.

Several of the newer wharves are supported by vertical piles only (with no battered piles). This provides a more ductile and compliant system, and these wharves do not appear to have been damaged. As wharves combining battered and vertical pile support represent a common design, both on the west U.S. coast and world-wide, there is an important lesson here.

Farther south along the Alameda and Oakland shoreline, runways at both the Alameda Naval Air

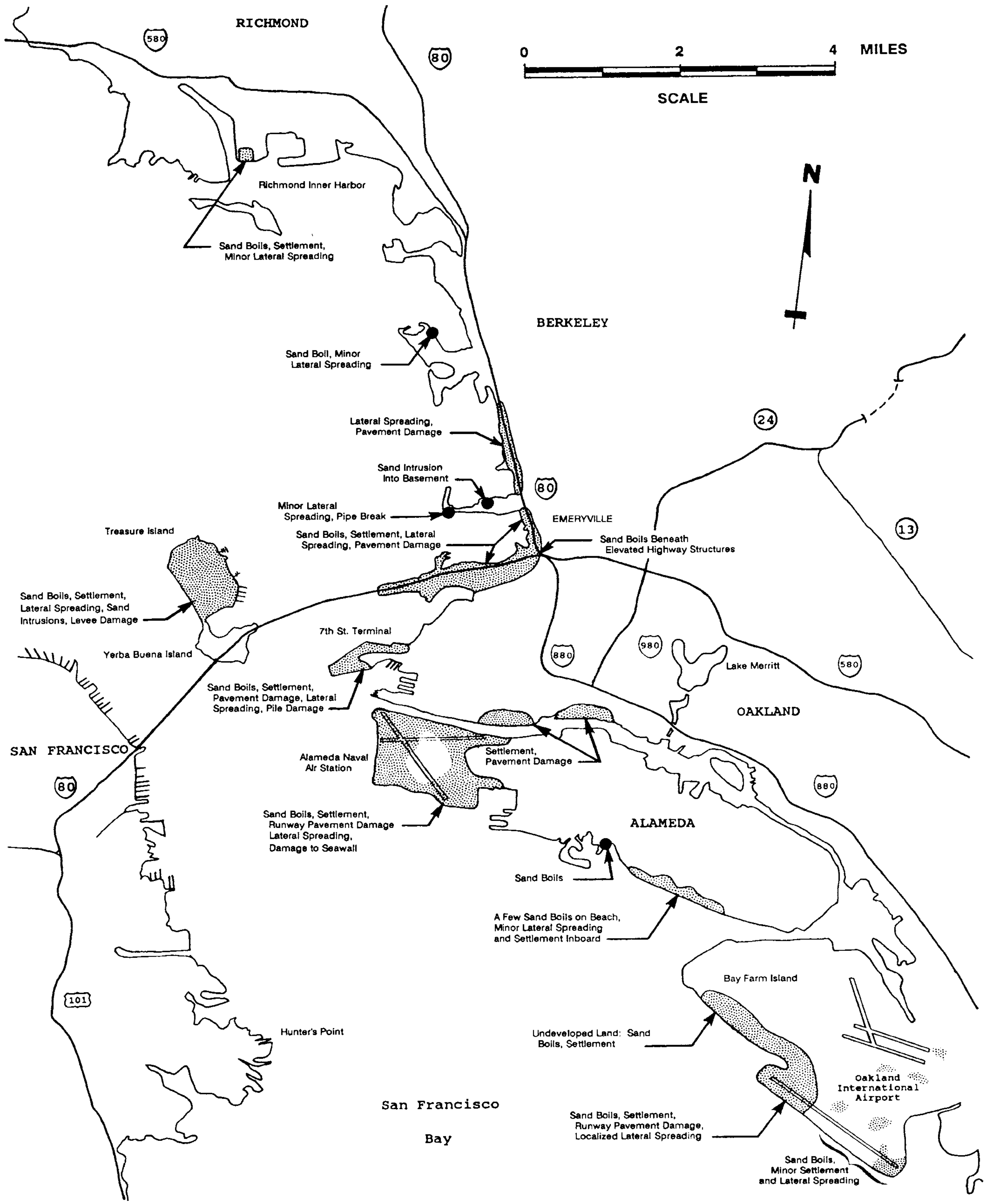

Fig. 12 Map of Eastern and Central San Francisco Bay Area Showing Sites Damaged by Soil Liquefaction

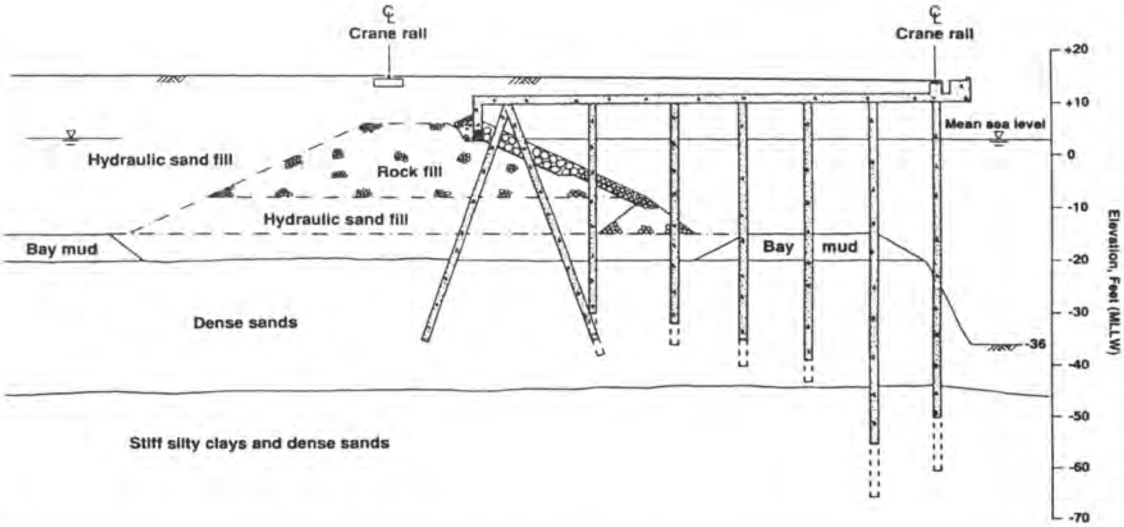

Fig. 13 Cross-Section Through the Edge of the Fill, Dike and Wharf at the North Side of the 7th Street Terminal, Port of Oakland [Benuska et al., 1990]

Station (NAS) and the Oakland International Airport were damaged by liquefaction of hydraulic fills. Figure 15 shows a sand boil adjacent to a runway at Alameda NAS. Lateral spreading, settlement, sand boils and pavement damage occurred at and near the runways at the northern end of Alameda NAS, though farther south in areas containing structures liquefaction was limited and damage to structures was relatively minor.

Soil liquefaction caused significant damage to the northwest end of the main runway at Oakland International Airport, as shown in Figure 16, and also damaged levees surrounding the edges of the airport's hydraulic fill. In addition to the damage to the main runway, sand boils and fissures resulting from lateral spreading occurred over significant portions of the airport fill, and a significant sand intrusion occurred in an annex to one of the two main terminal buildings.

The extensive liquefaction-induced damages to both the Oakland International Airport and Alameda Naval Air Station runways are among the most serious lessons for local policy-makers. As this relatively short-duration earthquake centered more than 40 miles to the south damaged both airports severely, it is clear that a stronger or more near-field event would disrupt service at both airports, and at a time when emergency air transport would be vital.

No significant liquefaction-related phenomena have been observed on the east bay shore south of Oakland International Airport, and none have been observed at the southern end of San Francisco Bay or along or near the sloughs and river channels extending south from the bay into the San Jose area. The few minor

Fig. 14 Tensile Failures at Top of Battered Piles at the 7th Street Terminal [Photo courtesy of the U.S. Army Corps of Engineers, South Pacific Division]

Fig. 15 Large Sand Boil and Sinkhole Adjacent to Runway at Alameda Naval Air Station

Fig. 16 Fissures and Exuded Boil Materials, Main Runway, Oakland International Airport

evidences of liquefaction in these areas were of nominal extent and caused no serious damage. These areas were the subject of both aerial and ground post-earthquake reconnaissance, as they did suffer considerable liquefaction in the 1906 San Francisco Earthquake.

THE PACIFIC COAST

Liquefaction, as evinced by sand boils and lateral spreading, occurred at a number of beaches along the Pacific coast between Half Moon Bay and Santa Cruz. This liquefaction, which typically occurred in dune sands at the edges of lagoons inboard of the surf zone of the beaches, was of little consequence as no major structures or facilities were affected.

Considerable liquefaction (sand boils, settlement, cracking and buckling of pavements, lateral spreading, etc.) occurred in the City of Santa Cruz over an area roughly one kilometer wide and extending at least 1.5 kilometers inland at the mouth of the San Lorenzo River as shown in Figure 17. Considerable structural damage also occurred in this area, including the collapse of a major shopping mall. Additional lateral spreading and sand boils occurred, but caused little damage, immediately south at the edge of the Santa Cruz small craft harbor. The heavy solid line in Figure 17 outlines the zone predicted to be susceptible to soil liquefaction during moderate to strong levels of seismic shaking, based on studies (City of Santa Cruz, 1976) performed using SPT-based procedures (Seed and Idriss, 1971) to evaluate in-situ liquefaction resistance. As shown in Figure 17, these procedures well-defined the zone of liquefaction hazard.

A second and much smaller region, several hundred yards to the southeast of the zone shown in Figure 17, was also identified in the 1976 studies as vulnerable to liquefaction. This region, adjacent to the central yacht harbor, also suffered liquefaction during the Loma Prieta event.

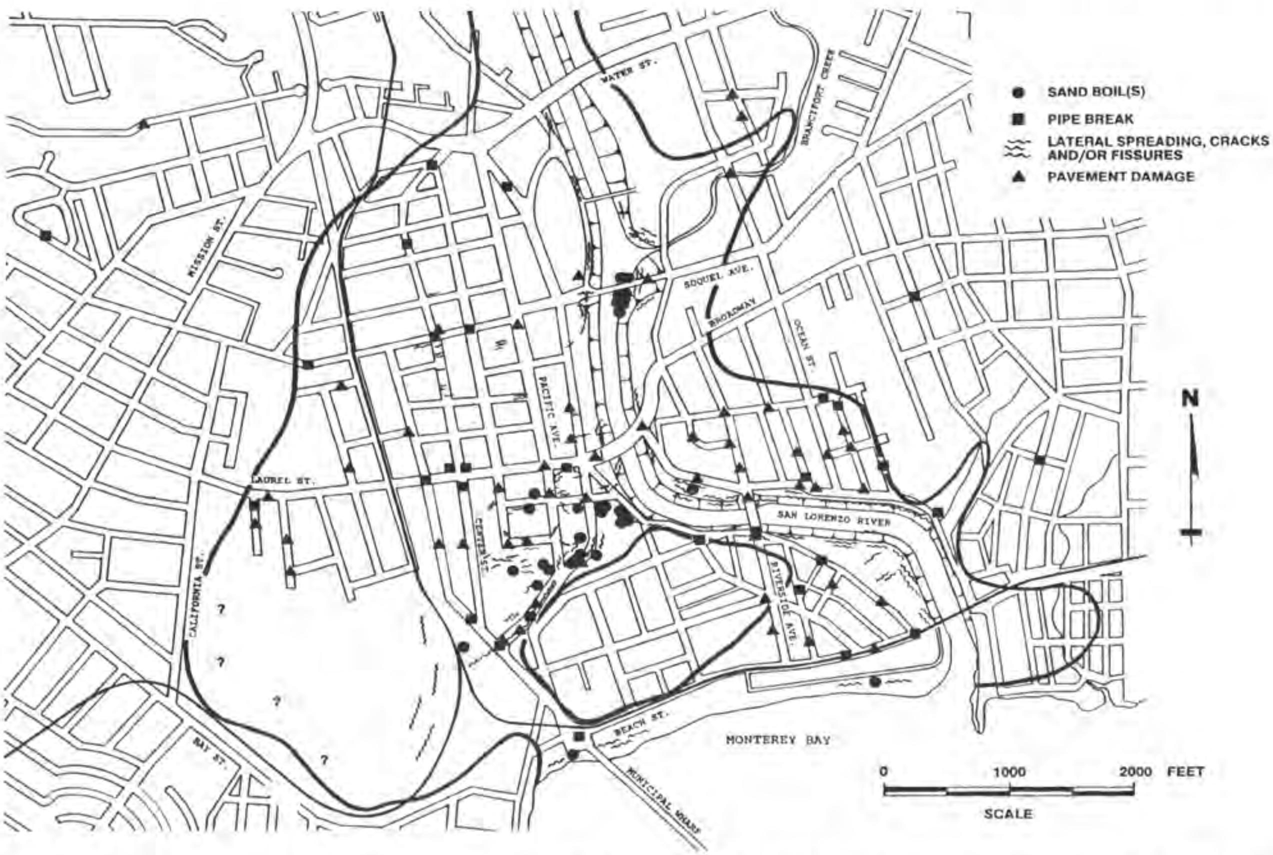

Fig. 17 Map of Central Santa Cruz Showing Major Liquefaction-Related Features After the Loma Prieta Earthquake of October 17, 1989

South of Santa Cruz, widespread liquefaction (lateral spreading and sand boils) occurred along the coast at Moss Landing and at the mouths of Watsonville Slough and the Pajaro River. Figure 18 shows an approach road damaged by liquefaction near Moss Landing State Beach. This was, again, no great surprise as illustrated by Figure 19 which shows a similar failure in this same area in the wake of the 1906 San Francisco Earthquake. Liquefaction extended well inland (more than six miles) along both the Watsonville Slough and the Pajaro River, and resulted in lateral spreading which damaged thousands of feet of levees along these two channels. Numerous sand boils were also observed in cultivated fields in this area, generally following the courses of known ancient stream channel deposits. Structural damages occurred as a direct result of liquefaction on the coast at Moss Landing, including considerable damage to the Marine Research Facility at Moss Landing. No evidence of liquefaction has been found (to date) in the Monterey area or farther south.

One of the clearest examples of the structural damage that can result from soil liquefaction was the destruction of the Marine Research Facility at Moss Landing. This facility was a group of low, modern 1- and 2-story structures founded on concrete slabs. The structures were grouped together to provide a series of classrooms and laboratories surrounding a central courtyard. The buildings do not appear to have been significantly damaged by shaking during the Loma Prieta Earthquake. This facility was, however, destroyed beyond repair by foundation displacements (settlement and lateral spreading) as a result of liquefaction of the foundation soils. The inboard roadway adjacent to this structure settled several feet, and lateral spreading deformations of the foundation soils stretched the facility by 6 feet, literally pulling it apart. Figure 20 presents an exterior view of this facility, clearly showing the massive damage caused by these foundation movements. Figure 21 shows a large warehouse which was destroyed at essentially this same site by similar lateral spreading in the great 1906 San Francisco Earthquake.

LESSONS LEARNED

There were relatively few surprises with respect to the occurrence of soil liquefaction during the Loma Prieta Earthquake: most of the sites which experienced liquefaction had previously been identified as likely to liquefy, and many had been documented as having liquefied in the earlier 1906 San Francisco Earthquake. In general terms, the liquefaction which occurred on October 17, 1989 can be categorized on a regional basis as follows:

1. In the central San Francisco Bay Region: Extensive liquefaction occurred in uncompacted hydraulic sand fills underlain by soft clay deposits known locally as "San Francisco Bay Mud". SPT blowcounts in these fills ranged from $N_1 \approx 2$ to 20 blows/ft, with "representative" values of $N_1 \approx 7$ to 12 blows/ft in most of these fills. Peak horizontal ground surface accelerations, amplified by the underlying clays, were on the order of $a_{max} \approx 0.16$ g to 0.33 g at these sites. Loosely dumped sandy fills, also underlain by soft clays, exhibited modest softening and/or scattered liquefaction at several locations, with representative blowcounts of $N_1 \approx$ 10 to 20 blows/ft being typical for these deposits. Natural alluvial deposits, with representative blowcounts on the order of 15 to 25 blows/ft and higher did not liquefy in this region. All of this is in good conformance with currently widely used SPT-based liquefaction resistance correlations.

2. In the southern San Francisco Bay Area and at San Jose: There are no major uncompacted hydraulic fills in this region. The failure of natural alluvial soils in this region to liquefy to any significant extent in the Loma Prieta Earthquake contrasts with the widespread occurrence of liquefaction in these soils under the stronger levels and longer duration of shaking produced by

Fig. 18 Flow Failure of the Moss Landing Approach Road Embankment

Fig. 19 Apparent Massive Lateral Spreading and Settlement at the Edge of the Salinas River, Near Spreckels, After the 1906 San Francisco Earthquake [Lawson et al., 1908]

Fig. 20 Damage to the Moss Landing Marine Research Facility as a Result of Settlement and Lateral Spreading

Fig. 21 Warehouse at Moss Landing Destroyed by Lateral Spreading in the 1906 San Francisco Earthquake [Lawson et al., 1908]

the 1906 San Francisco Earthquake. This dual behavior provides an important upper and lower bound on the levels of excitation required to cause liquefaction of these soils. Based on limited data from investigations performed to date, the observed behavior appears again to be in good agreement with current SPT-based liquefaction resistance correlations.

3. In the Santa Cruz/East Monterey Bay Region: The strong levels of shaking throughout much of this region produced widespread liquefaction in alluvial channel deposits. Although post-earthquake investigations are somewhat less advanced (to date) in this region than in the San Francisco Bay Area, data available at this time indicates that the behavior of alluvial and dune deposits in this region again conforms well with widely used SPT-based liquefaction resistance correlations. Especially noteworthy in this regard was the successful use of relatively early SPT-based liquefaction correlations to assess liquefaction hazard in the City of Santa Cruz.

In addition to providing excellent support for current SPT-based procedures for liquefaction resistance evaluation, the unusually well-documented liquefaction behavior, coupled with well-defined regional behavior patterns and the large number of instrumental ground motion recordings obtained during the Loma Prieta Earthquake, provides excellent opportunities for research involving development and/or validation of alternate empirical and analytical techniques for evaluation of liquefaction susceptibility. Considerable research efforts are currently underway involving the use of cone penetration testing (CPT), shear wave velocity measurements, and other geophysical and in-situ tests for evaluation of liquefaction risk.

Although the widespread occurrence of liquefaction was no surprise to the geotechnical community, the Loma Prieta Earthquake did demonstrate a significantly higher level of liquefaction vulnerability than had been generally appreciated by local planners and decision makers. Particularly troubling in this regard are:

(1) The high levels of public exposure in San Francisco's Marina District and South of Market regions, as well as on Treasure Island.

(2) The clear likelihood of loss of service of Oakland International Airport, Alameda Naval Air Station and San Francisco International Airport in future, more damaging earthquakes at a time when post-earthquake emergency response renders these facilities vital.

(3) The likely damage to harbor facilities in both San Francisco and Oakland in such future events, again at a time when such facilities would be urgently needed.

(4) The likelihood widespread damage to utilities and the associated post-earthquake fire hazard in both San Francisco and West Oakland in future seismic events. This tremendous potential fire hazard represents one of the gravest ongoing hazards revealed by the Loma Prieta event.

These represent tremendous aggregate risk with regard to the safety of the homes, businesses and infrastructure of this region, as well as to the lives of its inhabitants. Far from representing having survived "the Big One" with minimal damage, the Loma Prieta Earthquake experience represents a litmus test of seismic exposure in this region. The extensive and strongly geotechnically-patterned damages wrought by this relatively moderate quake, with an unusually short duration of shaking, must be seen as precursors for significantly more severe devastation likely to occur in the same areas in stronger future events; events with epicenters likely to occur more directly within the densely populated greater San Francisco Bay Area.

On the positive side, post-earthquake investigations to date provide good support for the ability of current engineering methodologies to correctly and reliably assess hazard potential, and to successfully mitigate the associated dangers.

It should be noted, for example, that in addition to numerous bay shore fills which liquefied on October 17, 1989, a number of initially loose sandy fills, including hydraulic fills, that had been compacted using techniques such as dynamic consolidation, vibroflotation, Terraprobe, compaction piles, gravel columns, and vibratory rollers all performed well and showed no signs of liquefaction even though adjacent, undensified fill zones liquefied at many of these sites. Sites where ground improvement appears to have successfully mitigated liquefaction risk included areas at or within: Treasure Island, Alameda, Bay Farm Island, Emeryville, and Foster City.

As the risks or hazard associated with liquefaction can be identified, as they have now been highlighted by historic precedent in two significant seismic events (1906 and 1989), and as engineering techniques (e.g., densification of liquefiable materials and/or the use of foundations properly engineered to mitigate liquefaction problems) have been proven to represent reliable mitigation techniques, it appears that such risks can and should be quickly remediated.

This, unfortunately, leads to two additional lessons to be derived from the Loma Prieta experience. The first of these is the great difficulty involved in persuading politicians to mandate the costly and consequently politically unpopular programs necessary to accomplish this. There is an urgent need for the engineering community to both educate and persuade both the public and its elected leaders regarding the importance of such programs.

The second lesson has to do with the generally poor level of our current ability to mitigate seismic exposure to existing structures and facilities. This is as true of structural seismic "retrofit" as it is of our relative dearth of feasible and cost-effective methodologies for remediation of liquefaction hazard beneath existing buildings and communities. As a profession we have devoted unfortunately little of our earthquake engineering research efforts (to date) to issues associated with seismic retrofit of existing structures and facilities, and the sites upon which they are founded. The importance of improving our ability to perform efficient and reliable seismic re-evaluation and retrofit, and the need for policy makers to mandate the often financially and politically difficult programs necessary to implement such retrofit, are among the most important lessons to be learned from the Loma Prieta Earthquake.

In addition to having been a major tragedy, the Loma Prieta Earthquake also represents a major opportunity for future improvement of the level of seismic safety provided for society and for its infrastructure. This must be resolutely pursued at all levels, both professional and political, as such improved safety is too precious a goal to command less than our utmost efforts.

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