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The Loma Prieta, California earthquake of October 17, 1989

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The Loma Prieta earthquake, Richter Magnitude 7.1, originated on the San Andreas Fault system approximately 90 km south of the city of San Francisco. This earthquake produced the strongest shaking in the city since the 1906 San Francisco earthquake that was generated by fault slipping from a point approximately 100 miles south of San Francisco and extending to a point approximately 100 miles north of San Francisco, thus passing a few miles west of the city (see Figure 1). The metropolitan area, with approximately 5 million people, is spread around San Francisco Bay. The major portion of the population is on the San Francisco peninsula, the Oakland city region, and the San Jose city region.

The people and the city governments were aware of the earthquake hazard because of the 1906 earthquake and also the knowledge that the metropolitan area lies between two major faults, the San Andreas Fault to the west and the Hayward Fault to the east, both of which are known to have generated large earthquakes in the past. A modern building code is in effect and new buildings are designed and constructed according to the seismic requirements in the code. However, seismic requirements have been in the code only for about 50 years so that many buildings in San Francisco and Oakland were constructed before 1945 and these have less seismic resistance than modern buildings. The early seismic requirements were improved as we learned from each destructive earthquake: 1933 Long Beach M6.2, 1952 Tehachapi M7.5, 1971 San Fernando M6.5, and other smaller earthquakes; thus, structures designed under the early requirements in the code do not have a resistance to earthquakes as great as buildings designed more recently. It is thus clear that California, one of the leaders in seismic research and design, still has weaknesses and efforts are now underway to minimize these weaknesses by a program of retrofitting.

RECORDED GROUND MOTIONS

Many strong-motion accelerographs were in the region affected by strong ground shaking and much was learned from the recorded accelerograms. On firm ground, in the near-field the peak accelerations were in the range of 50–60% g; and in San Francisco, at a distance of 80 km on firm ground, the peak accelerations averaged approximately 10% g but with a considerable spread in values.

The nature of the ground shaking at a site depends upon the source mechanism, the travel path of the seismic waves, and the local soil conditions; and these effects were clearly illustrated by records obtained during the earthquake. In California earthquakes the expected fault slip originates at one point and then progresses along the fault to the other extremity of the slipped area; but in the Loma Prieta earthquake the fault slip started at the hypocenter and then progressed in both directions. This had the effect of reducing the duration of strong shaking and increasing the intensity. At 10 km from the fault the Gilroy No. 1 record had a duration of strong shaking of approximately 4 seconds and the Corralitos record at 5 km from the fault had a duration of strong shaking of approximately 7 seconds; these durations are much less than would have been expected from a magnitude 7.1 earthquake (Figure 3). An effect of travel path is shown in the Santa Cruz record at 20 km from the site. This record has a much higher frequency content than the Corralitos record, for example, and has a longer duration of strong shaking. A pronounced effect of local site conditions on ground shaking is illustrated in Figure 5. Over the years, filled ground was built up around the edge of the Bay and these areas are underlain by soft Bay mud. The ground shaking recorded on these sites was much affected by a reduction in high frequency content and an amplification of longer period content. This is illustrated in Figure 6 which compares the motions recorded on a rock island with the motions recorded on an adjacent man-made island. The peak accelerations were amplified by a factor of approximately 2.5; similar ground motions were recorded on filled ground overlying Bay mud at several other locations around the shore of the Bay.

A disasterous earthquake not only causes deaths, injuries and suffering but also can have a long-

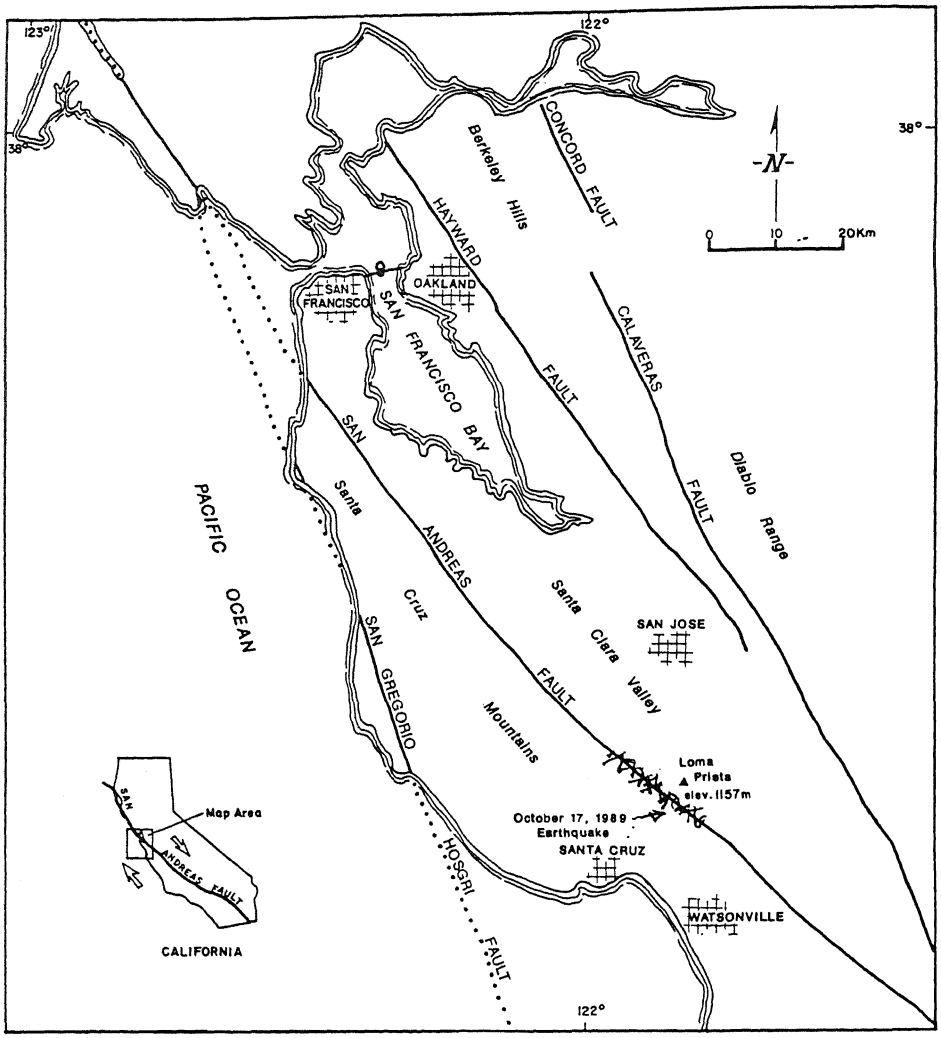

Figure 1. Map of the Loma Prieta–San Francisco region of California. The San Andreas Fault and the Hayward Fault have produced major earthquakes in the last 150 years. The ground motions were amplified and higher frequencies were filtered out at sites near San Francisco and Oakland where filled ground was underlain by Bay mud along the shore of the Bay. The metropolitan area of 5 million inhabitants is flanked by the San Andreas Fault to the west and the Hayward Fault to the east, so it is very likely that one or both faults will generate a large earthquake in the next one hundred years.

lasting economic depression because of the impact on the functioning of the city because industry and commerce have been negatively impacted.

RECORDED BUILDING MOTIONS

The Embarcadero Four building in San Francisco, a 47-story, steel-frame structure, had been well-instrumented prior to the earthquake. The peak recorded acceleration in the base of the building was approximately 10% g and the motion recorded on the 47th floor had a peak acceleration of 46% g (Figure 7). This acceleration came from the motion of the third mode of vibration; the accelerations of the first mode (5 seconds) were relatively small because the duration of strong ground motion was relatively short. The high accelerations in the upper parts of several high-rise buildings were sufficiently strong to cause damage to architectural features. On the roof of a 4-story, shear-wall building in Watsonville, a peak acceleration of 1.25 g was recorded; no significant damage.

FREEWAY STRUCTURE AND BRIDGES

The Golden Gate Suspension Bridge was designed in the 1930's before dynamic analysis was possible. No significant damage was sustained but after the earthquake thorough dynamic analyses were made of the bridge and a retrofit program was initiated to strengthen weak points that had been identified. The San Francisco-Oakland Bridge is composed of two suspension spans going from San Francisco to Yerba Buena Island and a multispan steel-truss structure going from Yerba Buena Island to Oakland. This bridge was also designed in the 1930's for 10% g static force. Some damage was sustained by the truss segment of the bridge and dynamic analyses are being made to ascertain what retrofit is needed.

The Cypress Viaduct was a reinforced concrete, two-story structure in Oakland. That portion that passed over the filled ground underlain by Bay mud was subjected to ground shaking having approximately 25% g peak acceleration. The structure had been designed in 1950 and was relatively weak and brittle so that approximately one mile of the upper deck collapsed onto the lower deck. Following the earthquake, the Governor directed the Department of Transportation to undertake a retrofit program to ensure that no bridge in California would collapse in future earthquakes and that major bridges and important freeway structures should survive an earthquake and remain functional. This program is now underway.

SEISMOLOGICAL FEATURES

The San Andreas Fault, together with its related faults, forms the boundary between the Pacific Ocean crestal plate and the North American crestal plate. The movement of the Pacific plate relative to the Continental plate is at a rate of about 4 cm per year. The strains produced by this movement build up shear stresses which produce a sudden slip on the fault. In 1906 the slip occurred over a length of about 220 miles centered approximately on San Francisco. The maximum relative slip across the fault, just north of San Francisco, was about 6 meters. A large earthquake is expected to occur on the San Andreas Fault and adjacent to San Francisco. Such an earthquake could produce ground shaking in San Francisco three times as intense as during the Loma Prieta earthquake and with three times the duration of strong shaking. Had the Loma Prieta earthquake been this expected event the damage and loss of life would have been much greater.

A large earthquake (estimated magnitude 7.1) occurred on the Hayward Fault in 1868, so a similar earthquake could occur in the future. Such an earthquake would produce strong ground shaking in San Francisco and very strong ground shaking in Oakland.

The Loma Prieta earthquake occurred on a segment of the fault that slipped in 1906. The area of the 1989 slip is well defined by the locations of aftershocks (see Figure 2). The length of slipped fault was approximately 50 km. The fault slip did not reach the surface of the ground so it is inferred that in 1906 the fault slip extended only a few kilometers beneath the ground surface. The area of fault slip is consistent with a magnitude 7.1 earthquake. The Loma Prieta earthquake made the public aware that an earthquake of magnitude 6.5, or greater, can produce a disaster if it is sufficiently

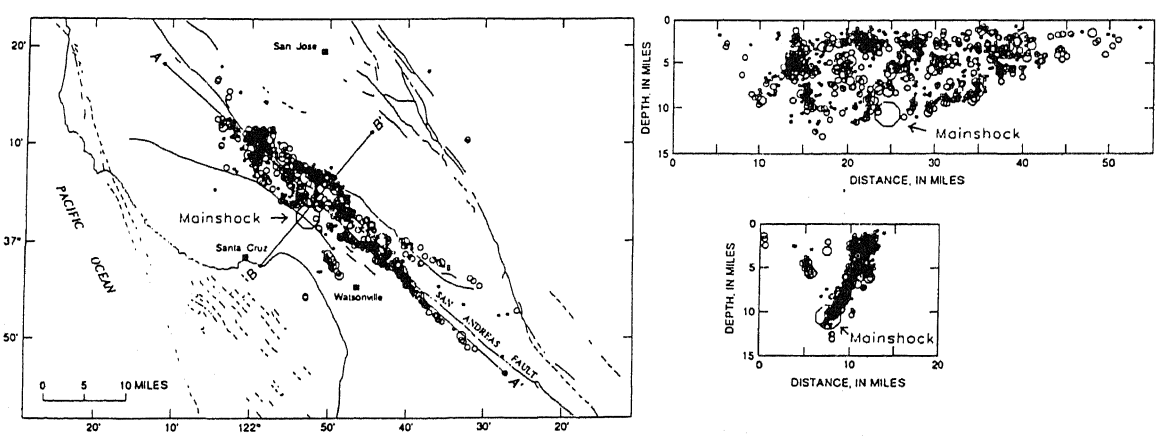

Figure 2. Plot of small aftershocks following the Loma Prieta earthquake. Seismic instruments were installed in the vicinity of the fault and the hypocenters thus determined depict the slipped area of the fault. The slip did not extend to the surface of the ground. During the 1906 earthquake a relatively small slip occurred at this location. This information, provided by seismological research was valuable to engineers by explaining the source mechanism of the quake and helping to assess past and future seismic hazards. (From Plafker 1989)

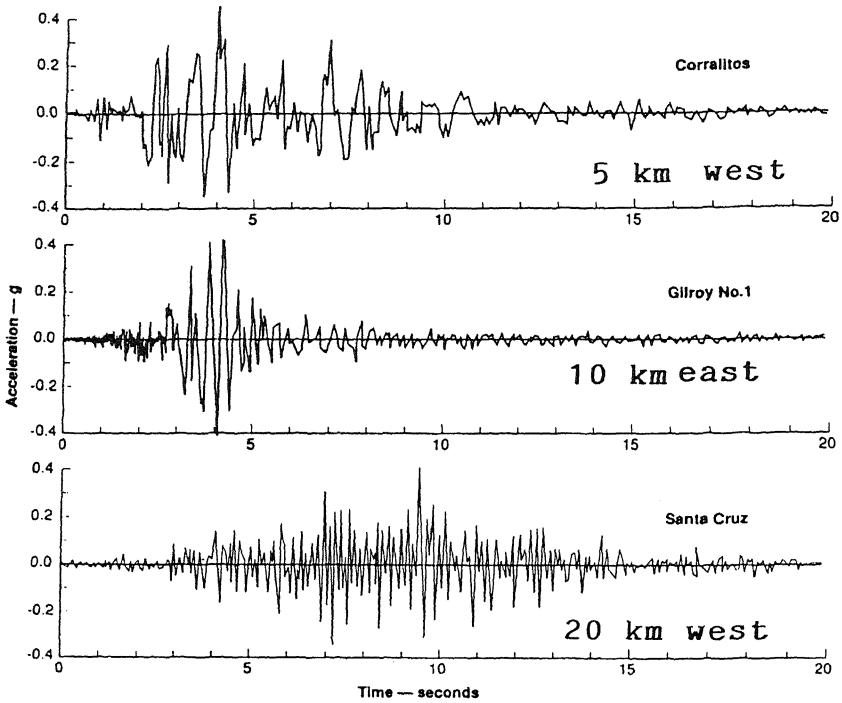

Figure 3. East-west accelerations recorded at sites 5, 10, and 20 km from the fault, recorded on firm ground. The remarkable differences are attributed to travel-paths of the seismic waves. The peak accelerations are the same on the three accelerograms but the frequency characteristics and the duration of strong shaking differ.

close to a city that is not prepared and in California the average return period for such earthquakes is four years, based on twentieth century data.

NON-ENGINEERING IMPACTS

The death toll was relatively small with only 67 casualties, of which 42 were killed in the collapse of the Cypress Viaduct. 3,757 people were injured during the earthquake. These are relatively small numbers for such an earthquake but, on the other hand, the damage to property was estimated to be $6 billion and the total impact of the earthquake was estimated to be as much as $10 billion. Approximately 1.4 million customers temporarily lost electricity after the earthquake. Approximately 1,000 single family residences were destroyed and 23,000 were damaged. Approximately 64,000 people were given temporary shelter by the Red Cross, and one year later 3,000 people were still homeless.

The earthquake had an impact on business activities and on industrial activities (Silicon Valley) but these impacts have not been quantified. Few data of this type have been collected in California earthquakes because of a relectance to provide information.

Before the earthquake, the San Francisco-Oakland Bridge carried 240,000 vehicles on a typical weekday and for the one month that the bridge was closed for repairs traffic was diverted to other crossings. This shift in traffic pattern affected the Bay Area cities and had a noticeable effect on businesses. This made it clear that the functioning of the Bay Area cities was dependent on the six bridges plus the sub-bay rapid transit tube and if several of the major bridges collapsed during an earthquake there would be a very severe impact on the Bay Area cities.

CONCLUSIONS

Important lessons were learned from the Loma Prieta earthquake because of the following features: 1) modern cities were in the shaken area; 2) many strong motion accelerographs recorded the strong shaking; 3) modern seismic requirements were in the building code; 4) numerous pre-code buildings were in the region; 5) many earthquake engineers and researchers were in the region; 6) the Seismological Branch of the U.S. Geological Survey was stationed in the shaken area. Thus, the earthquake generated many data and these were studied by numerous

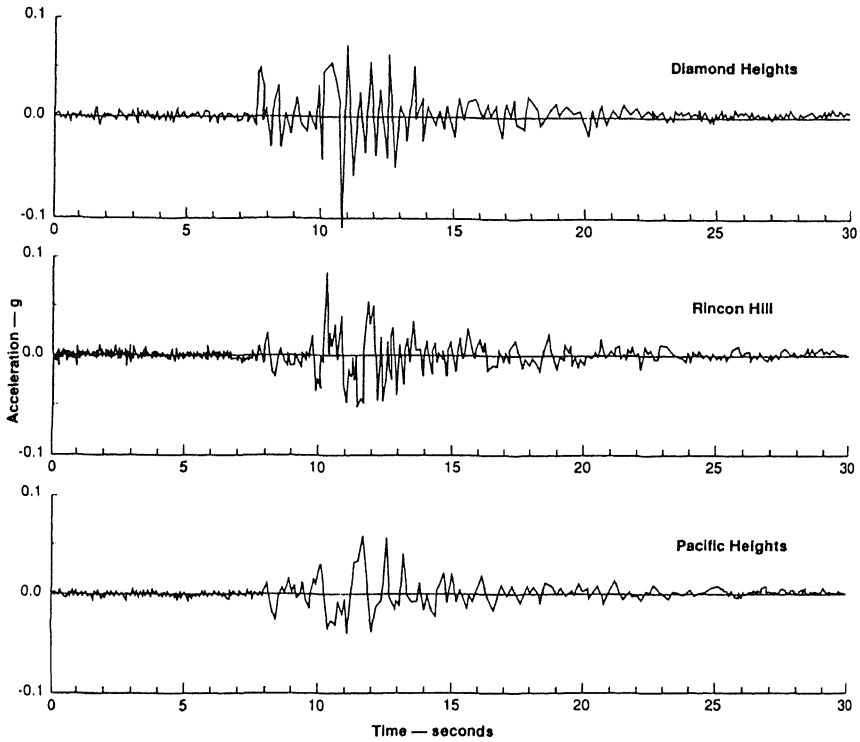

Figure 4. East-west accelerations recorded on three different rock sites in San Francisco. Peak accelerations on firm ground in San Francisco were approximately 10% g. The attenuation of shaking on firm soil was consistent with past experience. (Housner 1990)

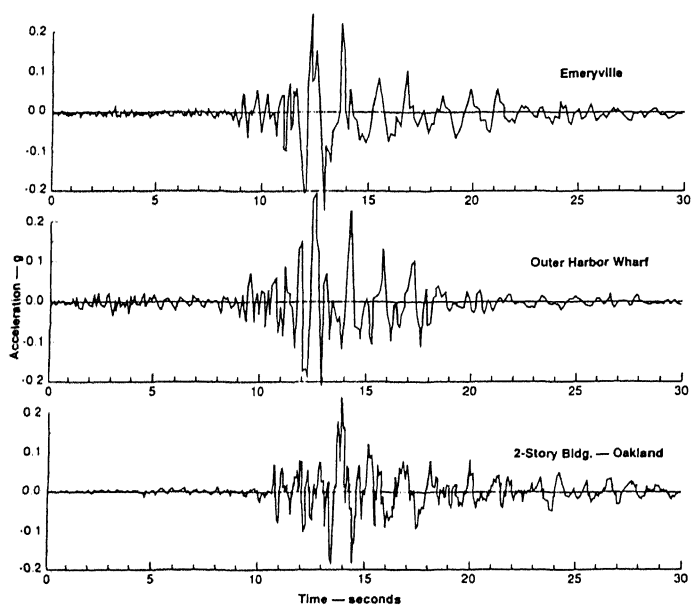

Figure 5. East-west accelerations recorded on three sites in the Oakland area on filled ground underlain by Bay mud.

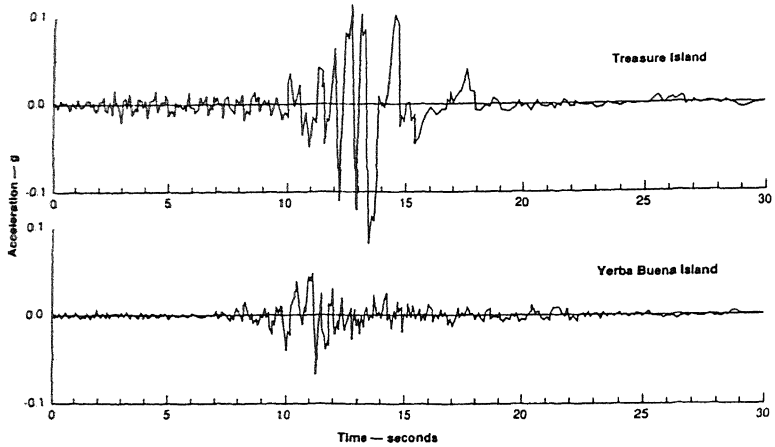

Figure 6. East-west accelerations on Yerba Buena Island (rock) between San Francisco and Oakland, and on Treasure Island (filled ground underlain by Bay mud), which is an extension of Yerba Buena Island. (Housner 1990)

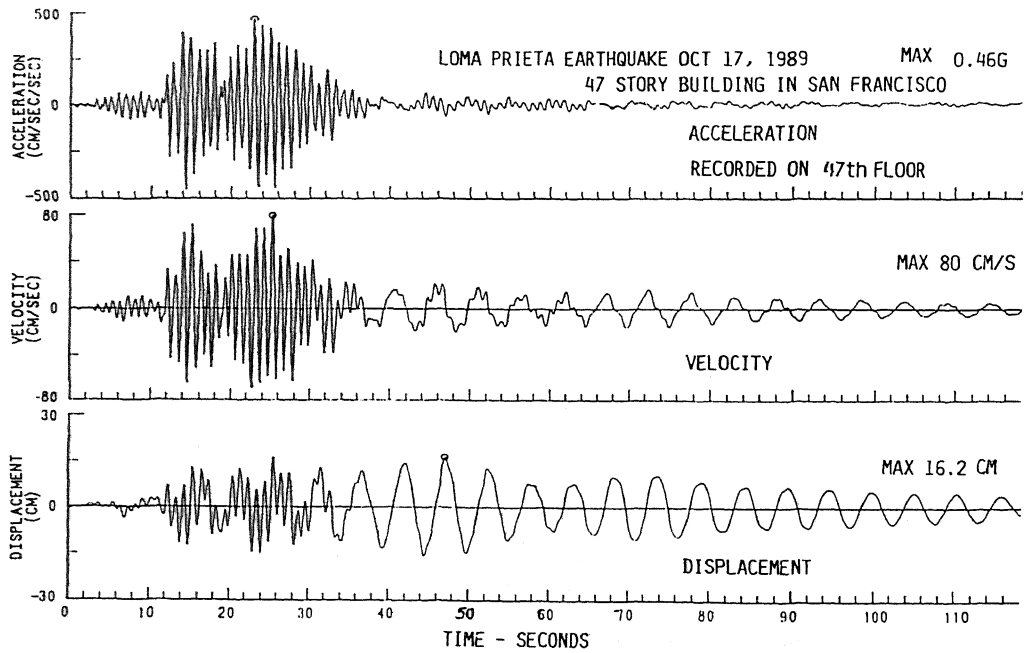

Figure 7. Motion recorded on the top floor of the 47-story Embarcadero Four building in San Francisco. The peak acceleration at the base of the building was 11% g and on the 47th floor 48% g. The acceleration was dominated by the 3rd mode of vibration (1 sec period); the first mode of vibration (5 sec period) is prominant in the displacement.

people, so it can be expected that many new things were learned. Almost every major earthquake teaches us something new and brings to our attention complexities of which we were not aware, so that it often seems — The more we "learn", the less we "know". The principal lessons learned from the Loma Prieta earthquake are:

1. Buildings designed according to the modern code requirements performed well. However, the intensity of ground shaking in the metropolitan area was not exceptionally strong and a few modern buildings did receive damage, so it is necessary to

re-think the seismic requirements of the code.

2. Older buildings not designed according to "modern" code requirements performed less well and buildings constructed before there were requirements in the building code exhibited dangerous weaknesses. When very strong ground shaking occurs in the metropolitan region there will be many collapsed buildings if an appropriate retrofit program is not undertaken.

3. The metropolitan area lies between two major faults each of which has generated a large earthquake (1868 and 1906) in the past and will certainly generate earthquakes in the future. When a large earthquake occurs on either of these faults the intensity of ground shaking will be perhaps three times greater than during the Loma Prieta earthquake and the duration of strong shaking will be three times longer. The damage potential of these earthquakes is much greater than the damage potential of the Loma Prieta earthquake.

4. The populace and the city and state governments must recognize that strong earthquakes will come and that the region should be prepared to respond appropriately.

5. Seismological and geological data greatly improved the understanding of the Loma Prieta earthquake and the seismic hazard faced in the future.

6. The network of strong-motion accelerographs provided data of great value to earthquake engineers. Characteristics of ground shaking that had never been observed before were obtained. However, major bridges, traffic tube, etc., had not been instrumented and, therefore, it is not known what motions and stresses these structures underwent.

7. Accelerograms obtained during the Loma Prieta earthquake showed unusual effects of the source mechanism, the travel path geology, and the local soil conditions. The duration of strong shaking was shorter and the intensity of ground shaking was somewhat greater than would have been expected from an earthquake of magnitude 7.1. Near-field accelerograms showed markedly different characteristics of ground shaking attributable to the travel path geology. Around the border of San Francisco Bay there were locations where filled ground was underlain by bay mud and this amplified the intensity of shaking and filtered out higher frequencies of ground motion.

8. Bridges not designed according to modern seismic codes are susceptible to damage and collapse if subjected to strong ground shaking. This was demonstrated by the collapse of the Cypress Viaduct and by the damage to the San Francisco-Oakland Bridge. Following the earthquake, the Governor of California directed the Department of Transportation to check all bridges in the state and to retrofit them as required to prevent collapse and important bridge and freeway structures were to be retrofitted so as to remain functional. There are about 40 major bridges and major freeway interchange structures and 24,000 other bridges in California. A retrofit program is underway but will require a number of years to complete.

9. Very strong accelerations were experienced in the upper parts of some high-rise buildings from higher modes of vibration (two, three, four). Although such motions do not threaten to collapse the structure, they do cause damage that is objectionable to the tenants.

10. Soil liquefaction occurred in a number of places where filled ground was underlain by bay mud. And also in other locations where there was soft ground with high water table. Liquefaction does not produce life-threatening damage but it can be costly to repair the effects.

11. Some modern buildings did experience structural damage. This indicates that the seismic requirements in the building code and their implementation need some improvements. The improvements to the building code should be made with reference to the fact that much stronger ground shaking in San Francisco will occur in future earthquakes.

12. Retrofit of older buildings is needed. The old pre-code buildings pose a great hazard to life and limb. Also, investigations should be made of the seismic resistance of engineered buildings that were constructed in the early decades of the seismic requirements in the code. These buildings do not meet the modern requirements in the building code and the effect of the deficiencies should be determined and structures should be strengthened as required.

13. The impact of the Loma Prieta earthquake was costly ($6 to $10 billion) but not as costly as if it had been a magnitude 8 earthquake adjacent to San Francisco ($50 billion, or more); and the number of deaths and injuries would have been much greater. The disaster relief activities and the disaster recovery measures performed quite well, with a few exceptions; however, when a large earthquake occurs on a fault close to the metropolitan region a much greater demand will be put on relief and recovery measures. It will be important now to use the Loma Prieta experience as a base from which to estimate the relief and recovery measures needed in the event of a large, close earthquake.

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