Predicting Earthquake Effects—Learning from Northridge and Loma Prieta

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The continental United States has been rocked by two particularly damaging earthquakes in the last 4.5 years, Loma Prieta in northern California in 1989 and Northridge in southern California in 1994. Combined losses from these two earthquakes approached $30 billion. Approximately half these losses were reimbursed by the federal government. Because large earthquakes typically overwhelm state resources and place unplanned burdens on the federal government, it is important to learn from these earthquakes how to reduce future losses. My purpose here is to explore a potential implication of the Northridge and Loma Prieta earthquakes for hazard-mitigation strategies: earth scientists should increase their efforts to map hazardous areas within urban regions.

Earth science contributes to earthquake hazard mitigation primarily by conducting two activities: (i) assessing or characterizing earthquake sources and (ii) predicting earthquake effects. The Northridge and Loma Prieta earthquakes raise a question about how completely earthquake source zones must be characterized for earthquake hazard mitigation. Could adequate mitigation be undertaken if source zones were only generally known but hazardous areas were comprehensively mapped? In economics terms, does the marginal rate of return on the investment in source-zone characterization diminish as identified seismic sources increase?

Although the specific locations of both the Northridge and Loma Prieta earthquakes were surprises in that they initiated on unidentified faults, their general locations were not. Both earthquakes occurred in structurally complex and seismically active areas. The 1987 Whittier Narrows earthquake already had alerted scientists to the earthquake potential of reverse faults that do not offset the land surface in the Los Angeles basin. Thus, only the specific location of the Northridge earthquake came as a surprise. The Loma Prieta earthquake was similar in this respect. It too occurred on a deep, unknown, reverse fault but within a region that was known to have many faults and high earthquake potential. The adjacent segment of the San Andreas fault had been recognized in an earlier government study in 1988 as having a 30% probability of producing a significant earthquake in the next 30 years (*1*).

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Perhaps the most significant finding of either earthquake was the high level of ground shaking that was recorded in the Northridge epicentral area. Peak horizontal ground accelerations were approximately 1.7 times values predicted by data from earlier earthquakes (Fig. 1). Once the new data are incorporated into the ground motion database, near-source ground motion predicted by empirical methods will increase.

In contrast to the Northridge observations, ground motion during the Loma Prieta earthquake was more distinctive for its high value at unusually long distances from the epicenter. Approximately 70% of the property losses caused by the earthquake occurred in localized areas 100 km away from the epicenter (*2*). This is twice the distance at which significant damage normally is observed. The localization of damage was not a surprise, however. Much of the area with damage is underlain by soft clayey soils that amplify ground shaking. On maps published in 1975, these areas were identified as areas subject to elevated levels of shaking (*3*). Forebodingly, some of these areas suffered damage in 1865 from an earthquake that may also have been on the Loma Prieta fault plane. In addition, these areas suffered heavy damage in 1868 and 1906 from nearby earthquakes.

A mitigation strategy that emphasizes delineating hazardous areas in urban regions would encourage society to focus more directly on the effects of earthquakes and the severity of the hazard. For example, mapping soils with potential to amplify seismic waves identifies areas that will be more frequently exposed to damaging ground motions. This approach should have priority because the region is large that contains seismic sources with potential to cause damage. This point is illustrated by a fault map of the greater San Francisco Bay area (Fig. 2). Based on the Loma Prieta earthquake, any magnitude >7 earthquake within approximately 100 km of San Francisco may cause damage in the areas underlain by soft soils. An important aspect to Fig. 2 is that the earthquake potential of many mapped faults is poorly known. In addition, some seismogenic faults may be either buried or not yet recognized at the surface.

By emphasizing hazardous areas in a mitigation strategy, uncertainties in locating specific seismic sources become less critical. San Francisco has implicitly adopted such a strategy in its retrofit program for unreinforced masonry buildings. Priority for low-interest loans in this program is given to nonconforming structures underlain by soft soils. The state of California adopted a similar philosophy following the Loma Prieta earthquake when it enacted the Seismic Hazards Mapping Act of 1990. By this legislation, cities and counties require land developers to address earthquake hazards in areas delineated by the state as subject to high levels of ground shaking, liquefaction, or seismic landslides.

This emphasis might be particularly applicable to the eastern United States where seismic source zones are poorly characterized. Despite intensive investigations in the epicentral regions of the two largest historic earthquakes in the east, the earthquake potential of these regions as well as the remainder of the eastern United States remains unknown (*4*). This uncertainty deters earthquake hazard mitigation in this region.

In conclusion, the Northridge and Loma Prieta earthquakes suggest the merit of increasing efforts to identify and map those parts of urban areas where shaking hazards are greatest. By delineating and evaluating these hazardous areas, we could at least focus on areas where the impact from earth-

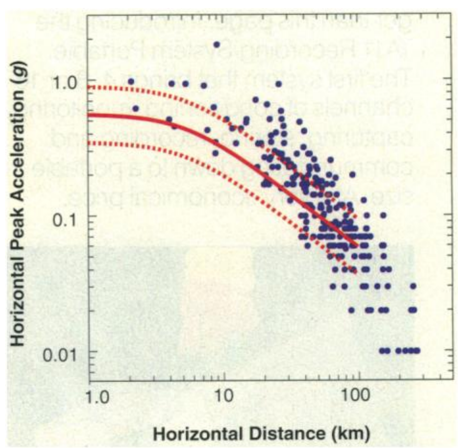

Fig. 1. Observed horizontal peak acceleration versus shortest horizontal distance to map view of the seismic rupture surface for the 1994 Northridge, California, earthquake (blue dots). Solid curve (in red) is empirical attenuation relation for ground motion recorded at very stiff soil or soft rock sites for reverse-slip earthquakes before the Northridge earthquake. Dashed curves (in red) are one standard deviation (*5*).

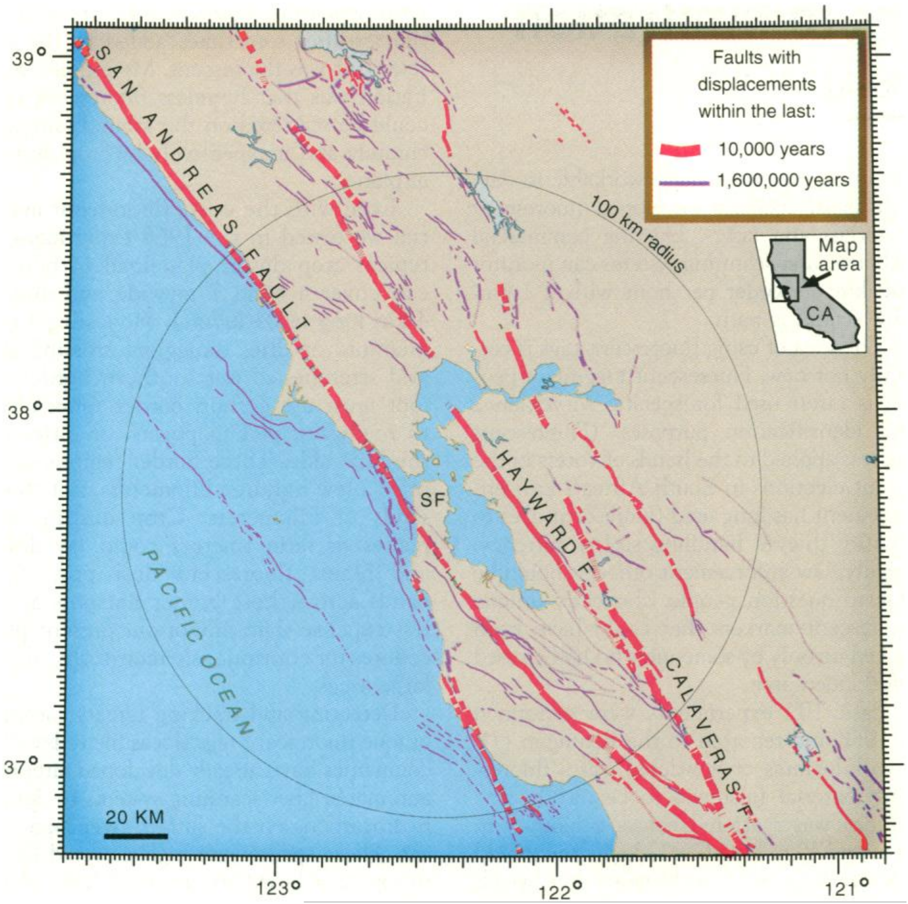

Fig. 2. Map of surface faults in the San Francisco Bay area, California, that have displaced sediments in the last 1,600,000 years (*6*). Faults with displacements in the last 10,000 years are shown in red. The 100-km-radius circle, centered on San Francisco City Hall, encompasses the region in which magnitude >7 earthquakes may damage parts of the City and County of San Francisco (SF) underlain by soft soils that amplify ground shaking.

quakes is likely to be greatest. These efforts would include mapping areas susceptible to local soil amplification and areas susceptible to near-source ground motion where source information is adequate. In addition, liquefaction or landsliding potential could be mapped where appropriate. Clearly, source characterization remains an essential part of earthquake hazard mitigation strategies. In addition, it is necessary to identify the parts of urban areas with potential for near-source ground motion. While we continue to pursue specific seismogenic faults, however, we could begin a systematic national effort to identify the parts of urban areas with the greatest potential hazard.

The Federal Flood Insurance Program provides a precedent for mapping hazardous areas. This program delineates areas subject to flooding with an average recurrence interval of 100 years. It requires parties in those areas who seek mortgages from federally insured institutions to purchase flood insurance. This is not to say that parties outside the mapped flood zone will not be flooded. As midwesterners painfully learned in the summer of 1993, flooding occurs outside the 100-year flood boundary. Government, however, has elected to concentrate its mitigation efforts, here an insurance program, on areas where the hazard is greatest. Similarly, maps of hazardous areas within seismically active regions would allow society to concentrate its mitigation efforts on areas at greatest peril.

REFERENCES AND NOTES

1. The working group on California earthquake probabilities, *U.S. Geol. Surv. Open-File Rep. 88-398* (1988).
2. T. L. Holzer, *Eos* **75**, 299 (1994).
3. R. D. Borcherdt, Ed., *U.S. Geol. Surv. Prof. Pap. 941-A* (1975).
4. Evidence regarding recurrence intervals is conflicting for large earthquakes in the New Madrid, Missouri, seismic zone of the Central United States, the location of three large earthquakes in 1811–1812. Some studies suggest that there were multiple large earthquakes [E. S. Schweig and M. A. Ellis, *Science* **264**, 1308 (1994)], whereas others suggest that nothing comparable to the 1811–1812 earthquakes has occurred in the last 5000 to 10,000 years [S. G. Wesnousky and L. M. Leffler, *Seismol. Res. Lett.* **63**, 343 (1992)]. Field studies near Charleston, South Carolina, site of a large earthquake in 1886, have not been able to identify the geologic structure responsible for the earthquake. Although relics of sand boils that document prehistoric strong ground shaking have been found [S. Obermeier, R. Weems, R. Jacobson, G. Gohn, *Ann. N.Y. Acad. Sci.* **558**, 183 (1989)], the likelihood of recurrence of a Charleston-type earthquake is unknown.
5. Figure prepared by D. M. Boore based on interpretations of strong motion recordings of the Northridge earthquake. Plotted acceleration value is the larger of the two orthogonal components recorded at each recording site. Attenuation curve is from D. M. Boore, W. B. Joyner, and T. E. Fumal [*U.S. Geol. Surv. Open-File Rep. 93-509* (1993)].
6. Modified by J. L. Lienkaemper from C. W. Jennings, *Calif. Div. Mines Geol. Open-File Rep. 92-03* (1992).

7. I thank R. D. Brown Jr. and R. E. Wallace for critical reviews of early drafts. D. M. Boore and J. L. Lienkaemper provided Figs. 1 and 2, respectively.