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Hazard Assessment Based on Geology: History, Principles, and Examples

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Introduction

Geology now plays a fundamental role in estimating the location, size, and rate of future earthquakes and, hence, seismic hazard in the United States. The use of geology in development of the most recent United States National Seismic Hazard maps underscores that point. Here I provide a brief historical perspective of that development and examples of the success of the approach. The observations may have bearing on efforts to establish a national program to study earthquake hazards in India.

History

Although it was early recognized that the geologically recent history of earthquakes is often well manifested in the geomorphic peculiarities associated with active fault displacements (e.g., Gilbert, 1883; Lawson, 1908; Lensen 1964; Wellman, 1952), seismic hazard analysis was primarily the domain of seismologists and historians until the last couple of decades. A change in that mindset began in the late 1960's with the occurrence of the moderate M6.6 Borrego Mountain earthquake in southern California. A trench was excavated by Clark *et al.* (1972) across the resulting fault trace. Application of structural and stratigraphic principles and radiometric dating techniques to offset beds in the exposure provided evidence of the recurrence of earthquakes along that fault on average about each 150 years. The same approach was applied by Sieh (1978a) to the San Andreas fault adjacent to the densely populated Los Angeles region of southern California. He showed that the geology recorded the recurrence record of surface rupturing earthquakes extending back through the Holocene. In essence, these studies introduced the science of *Paleoseismology* or *Earthquake Geology*, whereby the geologic record is used to assess the past history of earthquakes in regions of active tectonics. The impact of the studies was great, serving to focus the interests and energy of many geologists toward refining and developing geologic methods to interpret the prehistoric record of earthquakes in both inter-and intraplate regions. It was not long before efforts were placed toward using both trench exposures and geomorphology to define the amount of displacement and, hence, size of past earthquakes on faults (e.g., Sieh , 1978b). Similarly, geologic and geomorphic methods begin being employed with radiometric techniques to determine the Holocene slip rate of active faults (e.g., Sieh and Wallace, 1987; Weldon & Sieh, 1985). Reid (1910) had earlier demonstrated that earthquakes were the result of a sudden release of slowly accumulating elastic stress. In this regard, geological estimates of falt slip rate are a direct measure of that long-term rate of strain accumulation along active faults. By dividing the measures of coseismic offset expected along faults by estimates of fault slip rate along the respective fault, geologists were able to begin estimating the long-term recurrence rate of major earthquakes along active faults. In sum, geological methods were allowing investigators to take an active aproach to defining the location, size, and expected recurrence time of earthquakes (e.g., Wesnousky *et al.*, 1984), rather than relying solely of generally short and incomplete historical records of earthquake phenomena.

Examples

Examination of the geologic record quickly began to show the deficiencies that accompany the analysis of seismic hazard based solely on earthquake statistics. For example, whereas geologic and geomorphic study shows the San Andreas fault to be clearly active along the entire 1000 km extent of exposure through California, the fault is virtually devoid of seismic activity down to the microearthquake level along major sections of the fault (Allen *et al.*, 1965), an observation that might well be mimicked by the Himalayan frontal thrust system of India. Observations like these along the San Andreas provided the impetus to incorporate geological observations of fault slip rate and recurrence time into seismic hazard analysis. By the 1980's, the wealth of geological observations bearing on the past history of earthquakes in the western United States and Japan was becoming sufficient to begin developing seismic hazard maps with geological observation as the underpinning (Wesnousky *et al.*, 1984; Wesnousky, 1986). The methodology was in principle simple. Faults observed to displace late Quaternary deposits were considered to be active seismic sources. The expected sizes of earthquakes on these faults were estimated from geologic measures of the past size of earthquakes on faults or measures of the mapped fault length. The return time of earthquakes on those faults was determined by either direct paleoseismic interpretation of trench exposures or a division of the expected earthquake displacement by the geologically determined fault slip rate. Maps depicting seismic hazard were then constructed by combining the estimates of earthquake size and recurrence time with empirical relationships between earthquake size, source-to-site distance, and the expected strong ground motion. Such maps have now been in existence for 10 years or more in California and Japan and are shown in Figures 1 and 2, respectively. A comparison of the moderate to large earthquakes that have occurred since that time to the predictions of those maps serves to illustrate the value of incorporating geologic data into seismic hazard analysis. In California, the M=7.5 1992 Landers, the M=7.0 1989 Loma prieta, and M=6.6 1994 Northridge as well as numerous other moderate sized earthquakes have each occurred in regions marked by elevated levels of seismic hazard. Similarly, the recent M=6.9 Kobe (Hanshin-Awaji) earthquake of 1995 in Japan occurred in a region marked by elevated seismic hazard.

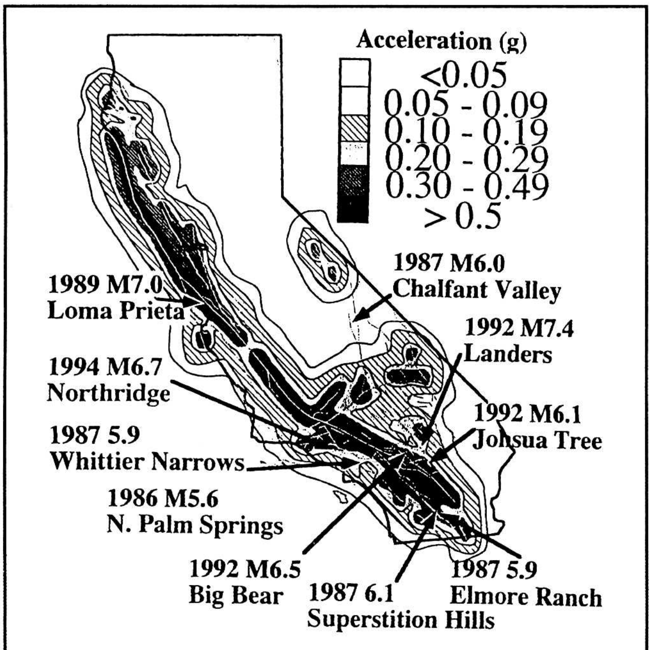

Fig. 1. Map shows the peak ground acceleration expected in California over a period of 50 years at a 10% level of probability. Map was constructed by Wesnousky *et al.* in 1986 based primarily on the geologic record of earthquakes. Moderate and large earthquakes that have occurred since that time have generally occurred within the regions of higher expected ground motions.

Discussion

The observations shown in Figures 1 and 2 are strong argument that geological observations can provide the basis for a confident picture of the relative levels of seismic hazard in a region. The confidence in the United States is manifest in the integration of geological data such as those discussed here into the United States Geological Survey national seismic hazard maps (Frankel et al., 1996; Fig. 3). Today, these maps are a principal input into national decisions related to seismic hazard mitigation and to the Uniform Building Code which guides the design of earthquake resistance to engineered structures across the United States.

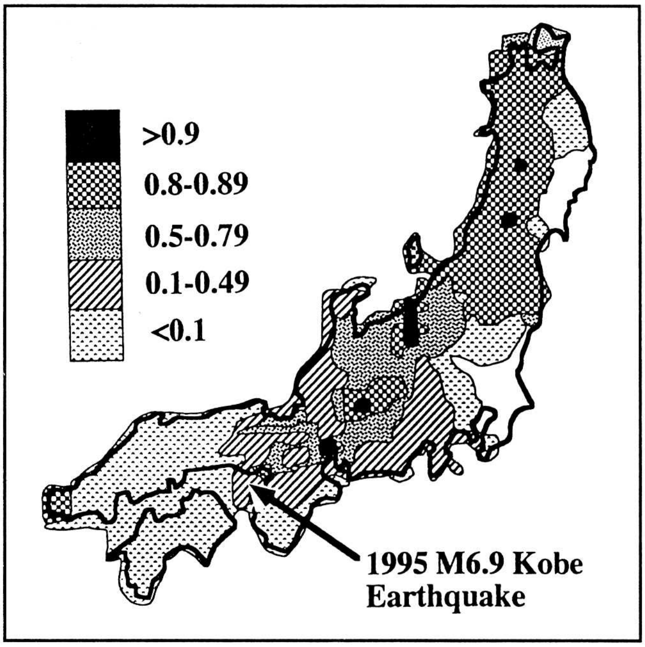

Fig. 2. Map shows the probability of Japanese meteorological Agency (JMA) Intensity VS haking resulting from intraplate earthquakes over a 50 year period. Map was constructed by Wesnousky *et al.* in 1984 based primarily on the geologic record of earthquakes. The only large earthquake occurring since that time occurred in a region marked by elevated hazard.

From the evidence collected thus far, it seems clear to the author that geological study of active faults should be an integral part of any national program of seismic hazard analysis. But, it should not be misconstrued from this discussion that seismic hazard analysis is solely the domain of the geologist. The most complete estimates of seismic hazard, such as the National Seismic Hazard map shown in Figure 3, will only result from an integration of historical, seismological, geological, and geodetic observations.

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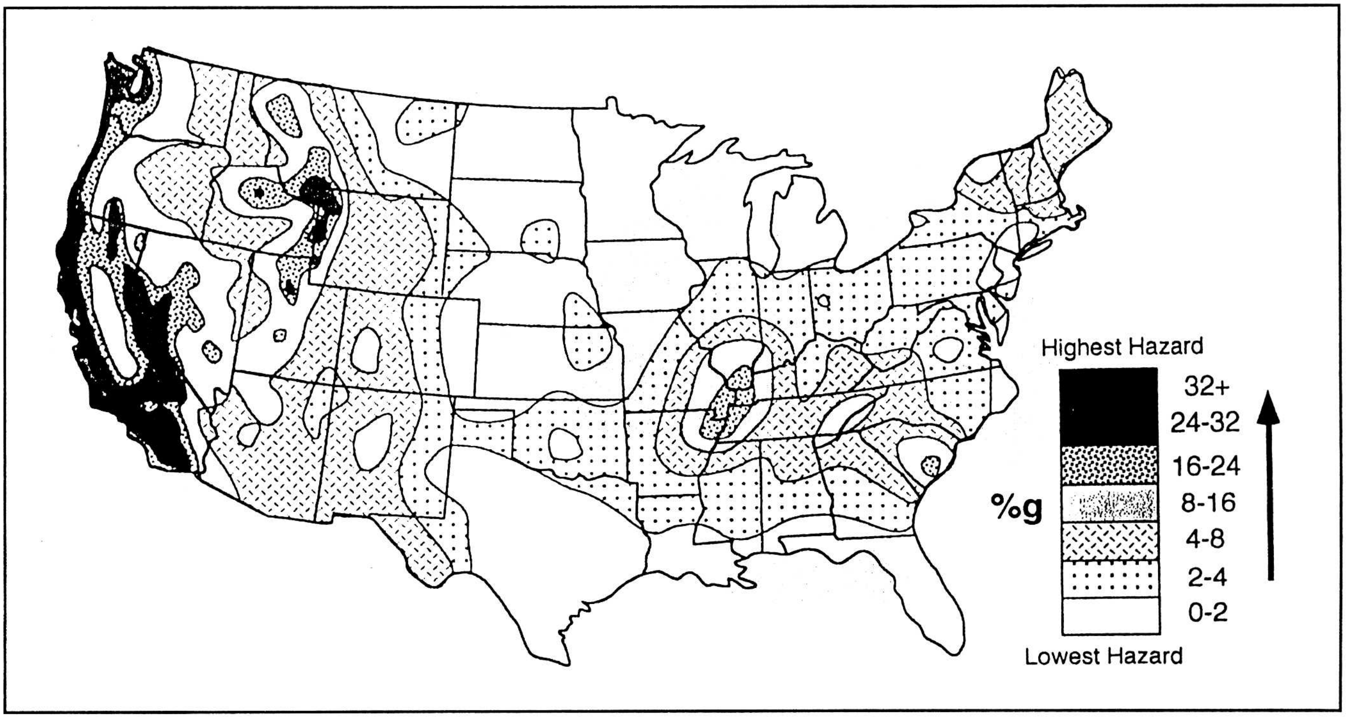

Fig. 3. United States Geological Survey National Seismic hazard map showing peak horizontal ground acceleration having 10% probability of being exceeded in a 50 year period of time. (Adapted from Frankel and others (1996) and redrawn from Website: http:geohazards.cr.usgs.gov/eq/).

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