Presidential Address: Seismic Hazard Analysis, Earthquake Prediction, and the SSA

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In preparing for this address, I realized that time was not sufficient to touch upon all facets of research conducted by Society members. So, with an apology to those members whose specific interests I ignore, and as a testament to the very diversity of our Society, I have chosen to limit myself to a brief discussion concerning the future of seismic hazard analysis and the intimate relationship between earthquake prediction research and seismic hazard analysis. It is perhaps most useful to place these ideas within a historical perspective. In my view, the roots of modern seismic hazard analysis emanate from the study of the great 1906 earthquake (Lawson and others, 1908; Reid, 1910), the same earthquake that served to catapult the SSA into existence. Meeting here as that Society more than 90 years past the earthquake is quite a compliment to the 1906 investigators. The works of Grove Karl Gilbert in the years immediately following the earthquake paved the way to taking an active approach to defining the locus of future earthquakes. He clearly described the distinct morphology produced by active faults, indicated that the unique geomorphology was clear evidence of repeated earthquakes through time, and essentially described what is now often called "neotectonics" or, more aptly, earthquake geology (Gilbert, 1909). From study of that same earthquake, it was Harry Fielding Reid who showed the importance of geodesy to earthquake studies and introduced the concept of elastic rebound. And still today, the concept of elastic rebound remains the cornerstone for estimates of average repeat time and the expected recurrence time of future large earthquakes. Complementing Reid and Gilbert's work bearing on the location and frequency of earthquakes, Harry O. Wood clearly noted that aspects of surface geology correlated strongly with the degree of ground shaking registered during the earthquake and, in effect, introduced the concept of microzonation. Given that seismic hazard analysis is based on understanding the location and frequency of earthquakes and the interaction of the resulting waves with the ground surface, the investigators of 1906 not only defined the principal elements of seismic hazard analysis but also introduced methods to approach the problem, methods which are still largely in practice today.

I think it is reasonable to put forth the thesis that, since 1906, progress in seismic hazard analysis does not reflect first-order advances in the basic concepts and directions outlined in the 1906 report, nor does it necessarily reflect fundamental advances in our understanding of the physics of the earthquake process. That is not to say that major advances have not taken place in seismic hazard analysis. But, rather, the advances are better attributed to the development of tools that now allow us to better characterize and collect the observations necessary for seismic hazard analysis. Equally important, these same tools can be traced to research efforts aimed at better understanding the physics of the earthquake process or, if you will, seismologists' efforts to ultimately predict earthquakes.

Development of regional and global seismic networks has led to a much clearer understanding of earthquake geography and statistics. The seismograms collected from these networks, along with the development of the computer, have provided us the ability to measure in greater detail the source properties of earthquakes and the complex nature of wave propagation. In a like manner, the development and implementation of strong ground motion instruments has provided the basis to examine and characterize the shaking that produces damage. In this regard, so many aspects of seismology that were once research topics have now become standard tools we use to characterize earthquake sources and the ground shaking that results from those earthquakes. But, while the resolution to which we can view the geography of earthquakes and characterize the earthquake source and attendant ground motions has increased, it might be questioned, at least in the context of seismic hazard analysis, whether or not the work has yet led to any first-order change in our understanding of the earthquake process as expressed by investigators in the 1906 report.

Similar statements may be made about geodesy. The ability and resolution with which we can now monitor strain changes through space-based geodetic measurements far surpasses previous capabilities, allowing us to view the spatial and temporal distribution of strain changes in active tectonic areas. However, with respect to our knowledge of when and where future earthquakes will occur, our understanding and application of those data have not progressed significantly beyond what was recognized and recommended in the 1906 report (though the rapid collection of data in this arena certainly holds the potential to soon alter this assertion).

In the realm of earthquake geology, the most significant advances in the geological characterization of earthquakes have been the result of the development of radiometric dating techniques. While not seismology in any sense of the word, that development provided us the means to begin quantifying long-term rates of slip on faults and to unravel the past frequency of earthquakes through the application of stratigraphic and structural principles to exposures excavated across active faults. The years since this latter approach was first applied in the late 1960s have led to an application of those techniques to virtually all active faults in California, an effort which continues in the United States and is being extended around the world today. The information resulting from these studies is now a standard input to seismic hazard analysis and, perhaps, represents the one type of information now commonly being used in seismic hazard analysis that was not directly envisioned by investigators of the great 1906 earthquake.

With all the observations that these tools of research have brought forth, where do we stand today? In short, today's assessments of seismic hazard are the most complete depictions of seismic hazard ever presented in this country. The recent national hazard maps, representing an amalgamation of both geological and seismological data, are perhaps most illustrative of this point (Frankel *et al.*, 1996). And though the best manner in which to ultimately incorporate geodetic data into regional seismic hazard analysis is perhaps undecided, the recent efforts of investigators in the Southern California Earthquake Center tell me we are not far away (Ward, 1994; Working Group, 1995).

It seems prudent that future research in seismic hazard analysis should be driven by what is missing from today's expressions of seismic hazard. In my view, the most immediate of these relates back to an original observation of the 1906 report, that ground conditions play a major role in the character and distribution of the strong ground motions which actually produce damage. In the near future, I think it is research aimed at understanding and ultimately predicting the complex variations in site amplification resulting from variations in geological conditions that holds the potential to elevate seismic hazard analysis to a new level of practical import to the users of such informaton, be it the engineers who design the structures or the insurers who gamble with them. It is certainly not a simple problem. Nonetheless, it is my impression that all the tools of research which have been developed during the years since 1906 are in place to make significant inroads to the problem, and it is in this venue that I am sure that members of our Society can and will play a lead role.

As I've mentioned, Reid also put forth a physical basis to predict or, in current terminology, forecast the occurrence time of future earthquakes. That methodology has in essence formed the underpinnings of the development of seismic gap theory and probabilistic estimates of recurrence time along the San Andreas and plate margins around the world. Although the approaches are perhaps not universally accepted (*e.g.*, Nishenko and Sykes, 1993), they represent a natural step in the evolution of ideas and efforts aimed at ultimately developing short-term earthquake prediction methodologies. The topic of earthquake prediction is particularly important. As said long ago, the successful prediction holds the potential to reduce earthquakes from natural disasters to interesting natural phenomena (Gilbert, 1909). It is also a topic that particularly grabs the attention of the public and the representatives of the public in government. Today, scepticism bearing on the possibility of short term predictions appears to be particularly high and vocal (*e.g.*, Geller, 1997; Geller *et al.*, 1997). That scepticism appears founded in the judgment of some of our community that the earth is in a state of self-organized criticality and, hence, earthquakes are inherently unpredictable in the conventional sense. On the other hand, the reports of physical precursors prior to large earthquakes, in my view, are far too many to ignore (*e.g.*, see review of Scholz, 1990), and the observation that earthquakes are the result of release of slowly accumulated tectonic strains certainly cannot be ignored. Thus, while I am certainly sure that today we cannot consistently and accurately predict earthquakes, I am concerned with statements indicating that we will never be able to predict earthquakes. Such statements imply that we currently have a complete understanding of the physics of the earthqake process, and I am quite sure that is not true. So, though skepticism in science is healthy, we must not undermine our efforts toward understanding the physics of the earthquake process. After all, it is in large part the results of such efforts by members of our Society that have led to the tools we now use to assess seismic hazard. And in that regard, it would be a mistake to allow current skepticism to steer research away from fundamental studies of the earthquake source and consideration of those findings in terms of earthquake prediction.

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