“Extreme Events Workshop: Developing a Research Agenda for the 21st Century”
June 7-9, 2000

Earthquakes as Extreme Events: Some Perspectives on Improving Understanding of the Phenomena and Communicating Beyond the Scientific Community

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Large earthquakes, even in the most seismically active regions of the earth, are relatively rare events on the time scale of a human lifetime. Earthquake scientists and engineers have relatively few modern, close-in observations to characterize these large events. Some aspects of earthquake processes, such as seismic wave propagation and the outlines of plate tectonics are relatively well understood. Other aspects of the processes are poorly understood, and the limited observations are interpreted through the lens of almost embarrassingly simplistic models. Statistical concepts are extremely useful in thinking about many aspects of the earthquake process. From this point of view most of the action is in the “tails” of skewed distributions, presenting significant challenges to the scientist and engineer, both in striving to improve understanding of the phenomena, and in trying to communicate what is known to the those outside the scientific community. Earthquakes present fascinating intellectual challenges, but they also present real threats to human life and property

Earthquakes as Extreme Events

It is easy to say that extreme events are, by definition, in the tails of distributions. Commonly the distributions that we prefer to use in describing earthquake phenomena are also skewed. The annual number of earthquakes as a function of magnitude follows an exponential distribution. The parameters of ground motion (peak ground acceleration, for example) for a given magnitude and distance is commonly assumed to follow a lognormal distribution. It has been suggested recently that the insured losses from the 1994 Northridge, California, earthquake in each zip code follow a gamma distribution. All these distributions are skewed. And the events of most interest to scientists and engineers, and of greatest importance to society, are those in the tails, and the most difficult to characterize. This fact presents terrific challenges to scientists and engineers in characterizing or predicting these events, and perhaps even greater challenges in communicating what we think we know beyond the scientific community.

The Curse of Few Observations

In earthquake science and engineering we are particularly cursed (or challenged) by the paucity of observations of our extreme events. For example, even though we are called upon to make a probabilistic seismic map of the Central and Eastern United States (to support building codes regulating billions of dollars of construction annually), we have shockingly few observations to guide us. We have almost no meaningful instrumental records of strong ground shaking from earthquakes in the region. We know that seismic waves are propagated much more efficiently in the Earth's crust and mantle beneath the eastern United States. But the attenuation relationships used in the seismic hazard map for the region are based on extrapolations to strong motion from the weak motions of small or distant earthquakes, on assumptions and theories about source processes, and on random vibration theory. A single magnitude 6 earthquake in the east tomorrow would obviously dramatically increase the data. (For better or worse, it would also undoubtedly become the new paradigm for understanding and characterizing future earthquakes in the east without due regard to the limited sample that observations from it would present.)

The largest earthquakes we know about in the eastern United States occurred in 1811 and 1812 near New Madrid, Missouri. The largest of these caused damage widely and were felt throughout much of the eastern United States. The 1996 edition of the seismic hazard map, representing the consensus view at the time, considered recurrence of a magnitude 8 earthquake in the region about 1000 years. This constitutes a rather significant hazard to Memphis and other cities in the region. Recently a research group at Northwestern has interpreted geodetic measurements from Global Positioning System data over a period of about six years to indicate that insufficient strain is accumulating in the region to produce anywhere near magnitude 8 earthquakes with that frequency, and calling the map into question. A scientific and public debate has erupted. Proponents of the original consensus cite paleoliquifaction evidence for large pre-historic earthquakes in the region, and argue about the appropriateness of the model used in the interpretation by the Northwestern group. For our purpose this episode underscores the extreme fragility of our conclusions, when they are based on so little real data, and the consequences in public confusion as the scientific issues are debated.

Even in California, where we have the best understanding of earthquakes of anywhere in the United States, the observations are woefully limited. The largest earthquakes for which we have instrumental observations are significantly smaller that the very large earthquakes along the southern San Andreas fault in1857 and along the northern San Andreas fault in1906. The only reach of the San Andreas fault for which we have reasonably reliable information about successive earthquakes in the same location is the somewhat infamous Parkfield region for which a predicted earthquake is now more than a decade "overdue." We still have relatively few observations of strong ground motion close to very large earthquakes.

Strategies for Overcoming the Curse

How do earthquake scientists and engineers attempt to overcome these limited observations to make predictions about future events? There are several strategies. Obviously we need to get more observations any way we can. This means not only increasing instrumentation in areas of concern and interest within the U.S., but also though collaboration with international partners. Second, we need to intensify our attempts to extend the available time period of observations through geology. We use geologic observations to estimate the slip rates of faults, that is the long-term rates at which faults are moving. We also use geologic observations, paleoseismology, to try to determine the times and characteristics of prehistoric earthquakes. Third, we use observations from earthquakes around the world to develop statistical relationships among earthquake parameters, such as regressions of earthquake fault displacement and area on magnitude, and strong ground motions on magnitude and distance from the event. Finally, we use available physical models, such as the idea of a "slip budget" on a fault (that is, the average recurrence time of large earthquakes is equal to the average displacement in a single earthquake divided by the fault slip rate.) These ideas are combined to estimate future probabilities of earthquakes. Perhaps the best example of the application of these techniques is in the estimation of probabilities for very large subduction zone earthquakes off the coast of the Pacific Northwest where we have no local historic record of such events. These techniques underlie the national probabilistic seismic hazard map, estimates of fault specific probabilities such as that recently produced for the San Francisco Bay region, and estimates for many special construction projects. Physical models shown to be relevant are highly desired.

While our current estimates represent a tremendous amount of work, intellectual insight, and indeed, significant advances over the last few decades, it is far too easy to be seduced by the comfort of now familiar arguments. A critic could argue (and some do) that the more elaborate of our estimates are no more than houses of cards, built with overly simplistic models on weak foundations anchored by relatively few observations. Clearly humility is in order.

Facing (or Ignoring) Uncertainty

From a statistical point of view, it is frequently useful to consider the uncertainties of earthquake processes and of our predictions about them in terms of the inherent randomness of the phenomena (giving rise to the aleatory uncertainty) and our uncertainty about the appropriateness of the model itself or the parameters within it (termed the epistemic uncertainty). Given the limited number of observations and the simplicity of some of our models, we commonly underestimate both these uncertainties. My personal perception is that many earthquake scientists and engineers are uneasy or in some cases unwilling to accept a conclusion that a particular earthquake process is characterized by a high degree of inherent randomness. Perhaps it is a defect in the way we are socialized and trained as scientists to always look for patterns in observations. The model uncertainties are typically poorly known and, in my opinion, almost always underestimated.

The Environment for Communication

My perception is that early twenty-first century man has internalized the concept of the "mean." The concepts of the normal daily high for June 8 in Boulder, Colorado, the normal annual precipitation for eastern Colorado, the normal snow pack in the Central Rocky Mountains are all ideas that one encounters daily in the media. I do not believe that the concept of variance has been internalized to anywhere near the same degree. As scientists and engineers, we take for granted an intrinsic variability in natural events that we characterize by distributions with not just a mean, but also with a variance. We have to learn how to put statements about unusual events into a context that includes an expression of just how unusual or "extreme" the event is.

A second perception is that what intuition we do possess as a society about variance is based on something like the normal distribution. Discussions about distributions other than normal are almost unknown outside circles of specialists. Even the concept that earthquake magnitude is based on a logarithmic scale, is frequently poorly understood, even by well-educated people. Improving the quality of the discussion with non-specialists about the natural variability of earthquake processes, the shape and variance of the relevant distributions, and all the resulting uncertainties must be a long-term goal.

The Role of the Earthquake Scientist and Engineer

The “extremeness” of large earthquakes is a fundamental characteristic of the intellectual and social challenges that they present. While large earthquakes and their effects are rare in the experience of individuals, perhaps even in the experience of individual societies, it seems to be the role of the scientist and engineer to be the “keeper” and “interpreter” of the aggregate experience, thereby reducing the impact of the rarity or “extremeness” of the events. Scientists and engineers seem to be charged with archiving and interpreting the observations from the past, even from prehistoric time, and with translating the experience from one society to another, to make estimates of future earthquake activity and effects. We are aided in this task by statistics and by our sometimes simplistic models. More robust models and more observations are needed to give us more confidence in our estimates. We need to find increasingly clever ways to try to overcome the curse of few observations. Technological society is increasingly vulnerable to the impacts of “extreme” events. Our challenge is both to improve our characterizations of future events, and to communicate that understanding more effectively.