Earthquake Science and Seismic Risk Reduction

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Preface

What is the first thing that ordinary people, for whom journalists are the proxy, ask when they meet a seismologist? It is certainly nothing technical like “What was the stress drop of the last earthquake in the Imperial Valley?” It is a simple question, which nevertheless summarizes the real demands that society has for seismology. This question is “Can you predict earthquakes?” Regrettably, notwithstanding the feeling of omnipotence induced by modern technology, the answer at present is the very opposite of “Yes, of course”.

The primary motivation for the question “Can you predict earthquakes?” is practical. No other natural phenomenon has the tremendous destructive power of a large earthquake, a power which is rivaled only by a large scale war. An earthquake in a highly industrialized region is capable of adversely affecting the economy of the whole world for several years. But another motivation is cognitive. The aim of science is ‘understanding’ nature, and one of the best ways to show that we understand a phenomenon is the ability to make accurate predictions.

While it is unquestionable that our present understanding of earthquake physics is poor, leaving deterministic prediction of individual large earthquakes well beyond our reach at present and for the foreseeable future, it would be incorrect to state that earthquakes are totally unpredictable phenomena that are equally likely to strike anywhere and at any time. In fact, it is well known that seismogenesis is not completely random and that earthquakes tend to be more localized in space, primarily on plate boundaries, and more clustered in time and space than would be expected for a completely random process.

The scale-invariant nature of fault morphology, the frequency-magnitude distribution of earthquakes, the spatio-temporal clustering of earthquakes, their relatively constant dynamic stress drop, and the apparent ease with which they can be triggered by small perturbations in stress are all clues that can be used to achieve a semiempirical predictive power even without the capability to physically model the earthquake source process. However, our present predictive power falls far short of that envisioned by journalists and the public. Whether or not there are prospects for future improvements, and, if so, to what extent, is a topic of intense scientific discussion; some of the arguments will be introduced in this volume.

Notwithstanding the less than satisfactory state of our present scientific knowledge, earthquakes do occur, and recent earthquakes have caused substantial human casualties and economic losses in many countries. It is extremely rare for earthquakes to be the direct cause of casualties; almost all casualties are due to the failure of buildings or other structures, or to secondary effects such as fires. It is necessary to take all feasible steps to reduce seismic risk. The main arena for practical steps to reduce seismic risk is that of earthquake engineering. However, the measures taken by engineers must be soundly based on the best state of present scientific knowledge (including its uncertainties). Our goal for this volume is to provide a concise summary of the present state of earthquake science and to discuss how this can be reflected in practical measures for seismic risk reduction.

This volume is based on the lively discussions at the NATO Advanced Research Workshop (ARW) on “State of scientific knowledge regarding earthquake occurrence and implications for public policy” held in Arbus, Sardinia, from October 14 to October 19, 2000, under the Co-Direction of Stathis Stiros and M. Nafi Toksöz. The program and list of participants may be found at `http://ibogeo.df.unibo.it/arw2000/index.html`.

It is traditional for symposia and workshops to publish a proceedings volume, but in many cases these are just a collection of papers that have been stapled together. The participants in this ARW decided that it would be worth the extra effort to produce a work in which the various contributions would be more tightly integrated. To this end, an initial outline was agreed on, and authors were commissioned to write particular sections or chapters. The authors of each section or chapter are identified at its beginning. The contributions were then edited extensively to produce a more uniform and coherent work. Much time and effort on the part of the Associate Editors, Silvia Castellaro and Matteo Ciccotti, was required to perform this integration. The editors thank them for the great job they have done. They also thank Kenji Kawaii for his help in checking the references.

The contributors to this volume are listed on the inside cover page. Principal contributors are first authors or co-authors who also attended the ARW; co-contributors are co-authors who did not attend the ARW.

Why is the earthquake problem so difficult?

Our goal in this volume is to provide a coherent ‘snapshot’ of the state of the art in earthquake science and seismic risk reduction, summarizing both what is known and what is still the subject of research and controversy. Why is there still so much that we don’t yet know?

The Earth is comprised of a core composed primarily of iron (with some nickel, and traces of other elements). The inner core is solid, while the outer core is liquid. Above the core, with a thickness of about 3000 km, is the mantle, composed mostly of silicate rocks. The mantle is viscoelastic, behaving as a solid on time scales of minutes or hours, but deforming viscously on a time scale of tens of thousands or millions of years. Above the mantle is the crust, with thickness ranging from a few km to about 100 km. The crust and the uppermost few tens of km of the mantle compose the lithosphere, which tends to release stress by by brittle failure (earthquakes) rather than by viscous deformation. Lithospheric slabs that subduct at oceanic trenches sink into the mantle and in some cases are still sufficiently cool to allow earthquakes at depths of up to about 700 km. However, with the exception of slabs, almost all earthquakes occur at shallow depth (< 30 km).

Excepting the brittle lithosphere, the mantle as a whole is thermally convecting. It acts as a giant engine, carrying thermal energy from the core-mantle boundary to the Earth's surface. Strain energy builds up in the lithosphere as it is dragged along by the convection in the mantle. Some of this strain energy is released from time to time by earthquakes. The lithosphere can be modeled as consisting of a small number (approximately ten) of rigid plates that move a constant velocity relative to one another. This model, plate tectonics, can explain the large scale geology of the Earth's surface, but it breaks down in several ways. For example, the plates are not perfectly rigid—earthquakes sometimes occur in the interior of plates, not just at plate boundaries. Also, in some regions around plate boundaries the deformation takes places over zones with a width of several hundred km or more, rather than just at a single sharp boundary. Some of the strain that is built up in the lithosphere is released by slow slip rather than by earthquakes. Over 90 per cent of the total energy of earthquakes is released at plate boundaries. Most of the earthquake energy release at plate boundaries occurs at subduction zones or at boundaries where two continents converge.

The mismatch of geological and human time scales is a fundamental barrier to our understanding of earthquakes. The characteristic time scale for mantle convection is about 10^8 yr, but we have only about 100 yr of instrumental seismic data. Basically weather runs on an annual cycle, so in 100 yr we would see 100 cycles. On the other hand, we have seen only about one millionth of one cycle of mantle convection in our 100 years of instrumental recording of earthquakes. By analogy to weather, this is like seeing one millionth of a year, i.e. less than one minute, of weather data and trying to extrapolate from that. This places a fundamental limitation on what earthquake scientists can accomplish by a brute force inductive approach.

How can we cope? First, both earthquake scientists and the users of our research (i.e., engineers, government officials, the public) must accept that even when we have done our best, estimates of future seismicity will inevitably be quite uncertain. Second, we can try to get more data in several ways. We can go backwards in time, using geological studies to gain information on earthquakes over the past, say, ten thousand years. We can use space-based observing techniques to study the ongoing deformation of the plates. We can also use laboratory studies and theoretical modeling to try to improve our understanding of the earthquake process. But while all of these can help, none can make an order of magnitude difference in eliminating the uncertainties we must live with. This may not be what people want to hear, but to do the best job possible of reducing seismic risk we must start with the way things are, not the way we would like them to be.

Many earthquake scientists, including some of the authors in this book, use the term ‘earthquake cycle’. If this is understood as being a kind of characteristic time there is no problem, but if this term is mistakenly interpreted as implying periodicity in a rigorous sense—the same earthquake repeating on the same fault at regular intervals—this is a highly unfortunate misunderstanding. Almost every significant earthquake that has occurred in the past hundred years has had one or more aspects that differed markedly from what was expected. This pattern is so consistent that the only thing that should really surprise us is an earthquake that is not a surprise in any way. We must, as the noted seismologist Hiroo Kanamori[1] admonishes us, prepare for the unexpected.

Guide to this book

The first three chapters synthesize what is known—and what is not known—about earthquakes. Chapter 1 emphasizes methodological issues. The empirical approach is the starting point of any scientific research, but if we sift through large volumes of data until we find what we want we can get into trouble, as an apparently meaningful pattern might be merely a random fluctuation in a sea of noise. Proper use of statistical methods can save us from many pitfalls.

Chapter 2 is a summary of the classical approaches to studying earthquakes. Geological and seismological data are presented, and the basic earthquake source parameters are defined. This leads into a discussion of the classical elastic rebound model of earthquakes, and a discussion of whether earthquakes have a well-defined nucleation process which begins a long time before the event. Finally, we consider laboratory experiments and field data on slip and fracture, and their applicability to earthquakes. The material in this chapter is based on a classical continuum-mechanics based view of earthquakes. While this approach is intuitively appealing, it fails in many ways to satisfactorily explain observations associated with earthquakes. This suggests that a new paradigm is needed.

The most important developments in physics in the first half of the $20th$ century were in quantum electrodynamics, nuclear physics, and high energy particle physics. However, some of the most important developments in the second half of the $20th$ century came in the field of the physics of complex non-linear systems. It appears that in many cases such systems have common properties independent of the particular physical system being considered. Chapter 3 discusses this ‘new physics’ and its applicability to earthquakes.

We now shift gears and consider more applied topics. Chapter 4 presents a discussion of time-independent hazard estimation. Standard techniques and also some of their uncertainties are discussed. Chapter 5 discusses time-dependent hazard estimation and forecasting. If we use information on past earthquakes

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[1] *Seism. Res. Lett.*, **66**(1), 7–8, 1995.

together with a model then we can perhaps obtain better estimates of hazards than by time-independent estimates. The first section of chapter 5 presents some approaches to this issue. The second section of chapter 5 presents a data-based approach to estimating earthquake occurrence probabilities based on the history of past seismic activity. The third section of chapter 5 looks at hazard estimation from a statistical point of view and strongly questions the significance of some of the approaches now being used. These disparate points of view reflect an ongoing controversy within the scientific community; the presentations in chapter 5 make it clear what the issues are. Note that all three sections of chapter 5 were written independently, and that none of the authors saw the other sections in the course of writing or editing their own contributions.

Chapter 6 presents discussions of two important sources of new data. One is space-based techniques for observing the ongoing deformation of the Earth's surface, and the second is paleo-seismology, which allows us to extend the instrumental catalogue of earthquake data (about 100 yr) by using geological data in coastal areas to study earthquakes which occurred in, say, the past 10,000 yr.

The last two chapters turn to issues that directly affect society. Chapter 7 discusses risk mitigation, based on recent earthquakes in Greece and Turkey. The conclusions drawn from the experiences in these two countries are remarkably similar. The main cause of loss of life was the collapse of substandard construction. Unfortunately once substandard structures exist, it is expensive to reinforce them, and this usually cannot be justified in purely economic terms. Government intervention is therefore required, but, because of the high costs, it is impossible to reinforce all unsafe structures. The best way to reduce risk is therefore to ensure that all new construction satisfies modern codes for earthquake resistance. The experience in both countries shows that it is essential to carry out strict checks to ensure that the code requirements are actually being rigorously followed.

Finally, in chapter 8, public policy issues are discussed. A review of research in social science and actual experience shows that short-term earthquake prediction could be useful to society only if it is highly accurate and reliable, but there are no scientific prospects for this at present. Many instances of social disruption caused by false earthquake predictions are discussed, and methods for dealing with such problems are suggested.

Following the NATO format, this book includes only black and white illustrations. However, in many cases the original illustrations were in color, and this is essential to fully understanding the information. You will find the original artwork in the CD which accompanies this book.

Francesco Mulargia, Bologna
Robert J. Geller, Tokyo
July 2003

Recommendations adopted by the ARW

At the conclusion of the NATO Advanced Research Workshop (ARW) ‘State of scientific knowledge regarding earthquake occurrence and implications for public policy”, held in Le Dune, Piscinas - Arbus, Sardinia, Italy, from October 15 to October 19, 2000, the participants adopted the following recommendations.

1. *Reduce seismic risk*. Measures should be taken to reduce seismic risk, with particular emphasis on urban areas. Since the costs of such measures can be high, it is necessary to identify critical facilities and buildings for immediate action, and also to give incentives to owners to strengthen their buildings. Governments should develop retrofitting guidelines. At least a minimum level of seismic resistance should be incorporated into building codes for zones of low seismic activity within seismically active regions; the resulting increase in construction costs will be relatively modest. All risk-reduction actions should take local site conditions into account.

2. *Encourage broad cooperation and public awareness*. Reducing earthquake risk requires the cooperation of scientists, engineers, statisticians, social scientists, government authorities, the news media, non-governmental organizations, and the general public. Communication and cooperation among these groups, efforts to educate the public about earthquake risks, and international cooperation should be strongly encouraged.

3. *Improve scientific understanding of earthquakes*. As our present scientific understanding of earthquakes is far from satisfactory, further theoretical, observational, experimental, computational and historical basic research should be strongly encouraged. The establishment of common standards, and the continuous and stable operation of networks of observational instruments, data centers, and systems for international data distribution are essential.

4. *Improve methods for making seismic hazard estimates*. It is not possible at present to make reliable and accurate warnings of imminent individual large earthquakes. Even if such warnings were possible, they would not be a substitute for efforts to reduce seismic risk, in which seismic hazard estimates are a key parameter. The limitations of the data should be accounted for by incorporating appropriate conservatism in estimates of seismic hazard. To reduce these uncertainties, research to identify faults and to measure their slip rates and earthquake histories and the deformation of the surrounding earth should be encouraged. Data from such studies and from other modern techniques, including satellite geodesy and advanced geological methods, should be incorporated into studies on hazard estimation.

5. *Enforce high scientific standards*. Research on making quantitative and

objectively testable statements regarding future seismic hazards should be encouraged. Such work must meet the highest standards of scientific and statistical rigor. Methodology in this area should be systematically validated and upgraded by comparison of forecasts to actual seismicity. Scientists and engineers should accurately represent the current state of the art when seeking funding for work in earthquake science. Funding agencies should evaluate proposals on the basis of well-established and rigorous rules of peer review.

6. *Establish policies for evaluating earthquake warnings*. Governments should establish policies and systems for evaluating earthquake warnings and deciding what actions, if any, should be taken. All persons are strongly encouraged to comply with these policies. The evaluators should work with the news media to discourage the dissemination of warnings that have not been approved and should inform the media on the scientific issues involved in making such warnings.

Addendum

The above recommendation are reproduced exactly as they were adopted by the Workshop. However, the editors would now propose that the following recommendation should also have been adopted:

7. *Enforcement*. Building codes and other regulations for seismic safety must be strictly enforced. Corruption and administrative laxity greatly increase the risk to the public.