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Earthquake prediction: a political problem?

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Abstract Earthquake prediction is an area of research of great scientific and public fascination. The reason for this is not only that earthquakes can cause extremely large numbers of fatalities in a short time, but also because earthquakes can have a large social and economic impact on society. Earthquake prediction in the sense of making deterministic predictions about the place, time, and magnitude of earthquakes may very well be fundamentally impossible. However, based on a variety of data, earth scientists can make statements about the probability that earthquakes with a certain size will occur in a certain region over a specified time period. In this context one speaks of "earthquake forecasting." A number of methods to achieve this are presented. However, it is not obvious how society should respond to these forecasts. It is shown that there is a fundamental dilemma for decision makers that statements of scientists concerning earthquake occurrence either contain very specific information but are very uncertain, or contain very general information but are very certain. Earthquake hazard can to a large extent be reduced by formulating and enforcing appropriate building codes. However, given the fact that the majority of the population that is threatened by earthquakes is living in the third world, it is clear that this cannot easily be realized. For these reasons, earthquake prediction is not only a scientific problem: it also has a complex political dimension.

Key words Earthquakes · Forecasting · Hazard · risk · Decision making

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Introduction

Earthquakes are among the natural disasters that threaten human populations. In contrast to flooding and volcanic eruptions, earthquakes are not dangerous. People may drown in floods or may be covered by volcanic ash during a volcanic eruption, but the shaking due to an earthquake is not dangerous. However, earthquakes can literally frighten people to death. During in 1994 Northridge (USA) earthquake, a dramatic increase in the number of sudden cardiac deaths due to the emotional stress induced by the earthquake has been reported (Leor et al. 1996). Obviously, this is not the reason that earthquakes can be true disasters; earthquake fatalities are generally caused by indirect earthquake effect such as collapse of human-made structures, fires, tsunamis, avalanches, etc. (Fig. 1).

The violence of the ground motion during strong earthquakes should not be underestimated. Recent observations have confirmed that ground acceleration may exceed the acceleration of gravity. In their account of the Northridge earthquake Shakal et al. (1996) show recordings from the Cedar Hill nursery, at 5 km distance from the epicenter, indicating horizontal acceleration exceeding repeatedly the acceleration of gravity (1 g) for a duration of 7–8 s with a peak of 1.9 g. Ground accelerations of this order of magnitude can be a frightening experience and obviously wreak complete havoc on buildings. A vivid description of the chaos during an earthquake is given by Darwin (1839) who during his voyage with the Beagle experienced several earthquakes in South America and who gives an eyewitness report:

> "A bad earthquake at once destroys the oldest associations: the world, the very emblem of all that is solid, has moved beneath our feet like a crust over a fluid; one second of time has conveyed to the mind a strange idea of insecurity, which hours of reflection would never have created. . . Mr. Rous, the English

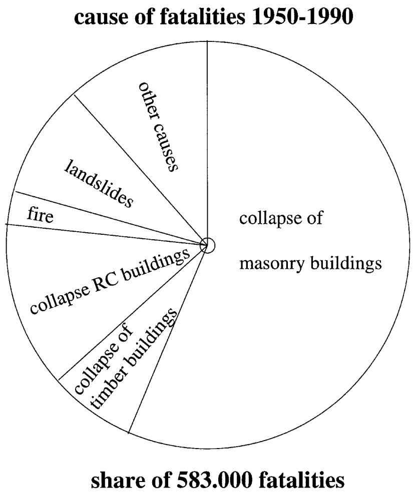

Fig. 1 Cause of fatalities (1950–1990). Total number of fatalities during this period 583 000 (RC stands for Reinforced Concrete). (After Coburn and Spence 1992)

> consul, told us he was at breakfast when the first movement warned him to run out. He had scarcely reached the middle of the courtyard, when one side of his house came thundering down. He retained presence of mind to remember, that it he once got on the top of that part which had already fallen, he should be safe. Not being able, from the motion of the ground, to stand, he crawled up on his hands and knees; and no sooner had he ascended his little eminence, than the other side of the house fell in, the great beams sweeping close in front of his head. With his eyes blinded, and his mouth choked with the cloud of dust which darkened the sky, at last he gained the street. As shock succeeded shock, at the interval of a few minutes, no one dared approach the shattered ruins; and no one knew whether his dearest friends and relations might not be perishing for want of help. The thatched roofs fell over the fires, and flames burst forth in all parts. Hundreds knew themselves to be ruined, and a few had the means of providing food for the day. Can a more miserable and fearful scene be imagine?"

How many people die because of earthquakes? On a yearly basis, there are approximately 14 000–16 000 fatalities due to earthquakes (Fig. 2; Coburn and Spence 1992). This is approximately half the yearly average of fatalities due to traffic accidents in the United States (Kerncijfersverkeersonveiligheid 1994). Seen in this light earthquakes cannot be considered a major threat. However, a single large earthquake may cause, within a short time and within a limited area, more than 100 000 fatalities and inflict material damage amounting to billions of dollars. Such events are obviously major disasters, from a human, social, and economic viewpoint. Its unpredictable character and its impact in such a short time (seconds) and limited area makes earthquake hazards unacceptably high to most people, especially to those living within an earthquake-prone country. However, the notion of disaster remains a relative one. While the area around 1994 Northridge earthquake epicenter was declared a disaster area by the authorities, the number of fatalities, 57, is minor when compared with, for example, the Tangshan (China) earthquake in 1976 (with at least 250 000 fatalities), or the Messina (Italy) earthquake in 1908 with approximately 58 000 fatalities. An eyewitness account of the aftermath of the 1908 Messina earthquake is given by Munthe (1931):

> "I know that I dragged single-handed an old woman from what had been her kitchen but I also know that I abandoned her in the street screaming for help, with her two legs broken. There was indeed nothing else for me to do, until the arrival of the first hospital ship no dressing material and no medicine whatsoever was obtainable. . . The aqueduct having been broken, there was no water except for a few stinking wells, polluted by the thousands of putrefied bodies strewn all over the town. No bread, no meat, hardly any macaroni, no vegetables, no fish, most of the fishing boats having been swamped or smashed to pieces by the tidal wave which swept over the beach, carrying away over a thousand people, huddled there for safety.... That robbery from the living and the dead, assaults, even murders, occurred frequently before the arrival of troops and the declaration of martial law is not to be wondered at. I know of no country where they would not have occurred under similar indescribable circumstances."

This quote summarizes some of the devastating effects of earthquakes on society. In addition to the direct injuries and casualties, the medical facilities are often impaired, the infrastructure is completely disrupted so that the food and water supply can be endangered, and the economic damage can be great. There can be accompanying disasters such as tsunamis or major fires, and even the social structure of society can be affected not only by the countless number of homeless people but also by the occurrence of looting.

A troublesome development is that many rapidly growing population centers are situated within areas of high seismic hazard (see Table 1, adapted from Bilham 1988). The majority of these cities are in developing countries with little resources for adequate earthquake protection measures. It is obvious from this table that in the future major earthquake catastrophes may occur in these megacities.

What are the economic losses inflicted by earthquakes? Table 2 provides a few examples of estimated losses due to earthquakes, whereas Fig. 3 shows an overview and projection of the economic and insured losses due to natural hazards of which earthquakes

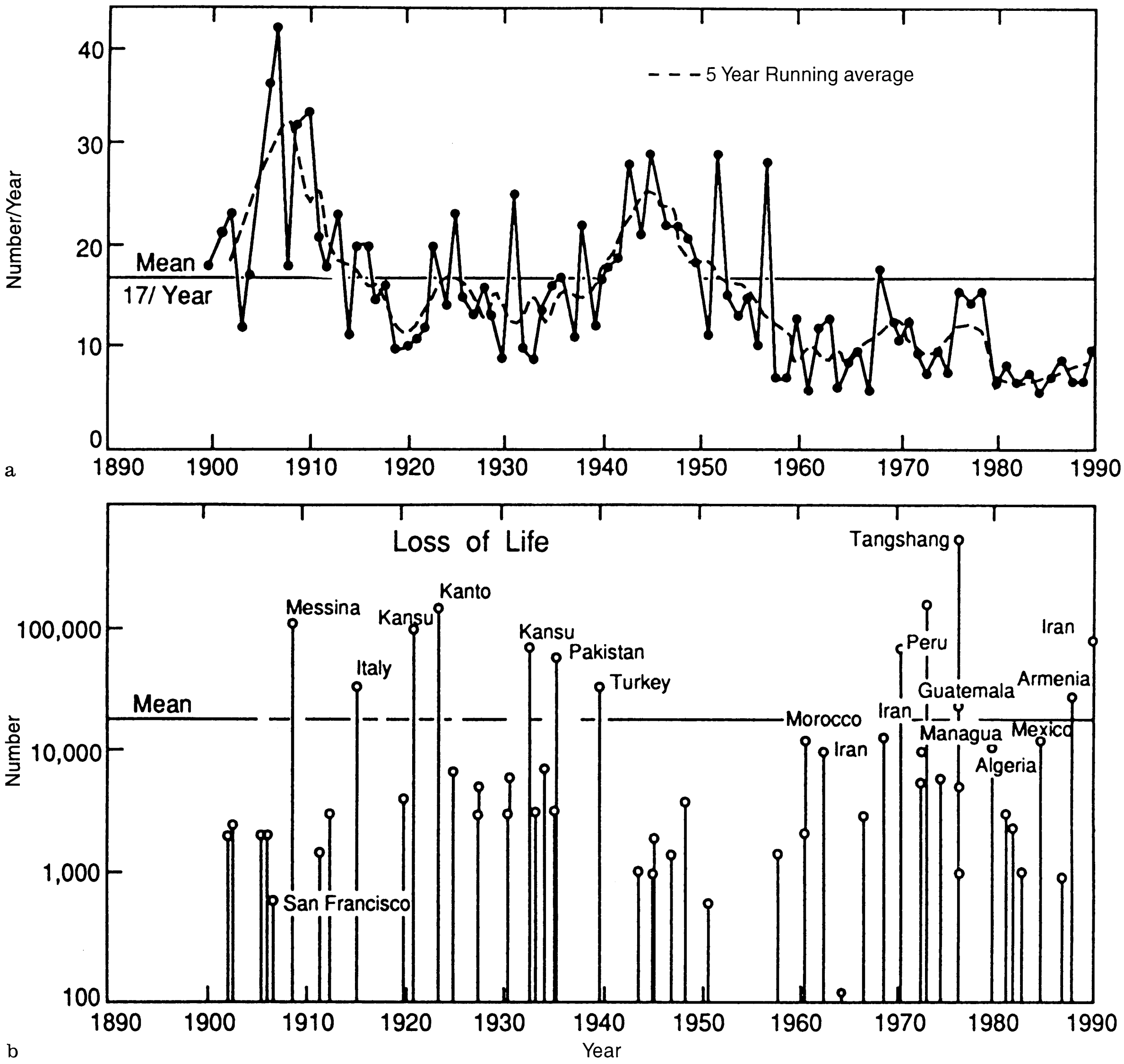

Fig. 2 a Annual number of large ($M_S \geqslant 7.0$) shallow earthquakes around the world. **b** Earthquake-induced fatalities in this century, with the locations of major events being indicated. (After Lay and Wallace 1995)

play a very important role. From Tables 2 and 3, and Fig. 3, three things are clear: Firstly, the vulnerability of society to earthquakes differs greatly among different nations. Secondly, the majority of large earthquake disasters have occurred in third world countries. Thirdly, economic losses seem to increase nearly exponential with time. These are troubling observations that are further enhanced by the observation that many rapidly growing population centers are in earthquake-prone countries (Bilham 1988). Consequently, the stakes in earthquake prediction are rising rapidly.

From the above the significance of a successful earthquake prediction becomes apparent. The term earthquake prediction, however, needs some clarification. In Fig. 4 we sketch a simple scheme showing the relation between earthquake prediction, loss-reducing measures, and decision making including the groups that are involved in these activities. The popular view of an earthquake prediction is an advance warning for a magnitude M earthquake at a specified time and place. Scientists and decision makers consider this type of deterministic earthquake prediction to have little future prospects due to the inherent chaotic nature of earthquakes. Earthquake prediction with a probability connected to it, or earthquake forecasting, is considered to be a more realistic goal. In this approach one makes statements about the (possibly enlarged probability that an earthquake with magnitude M or larger will occur in a specified region during a specific time interval. Seismic hazard analysis, where one estimates the probability of ground motion to exceed a certain value at a specific location, can be considered as a special type of this approach. Our emphasis is

Table 1 Examples of cities that are located within 200 km of a potential mangitude-7 earthquake or a historically damaging earthquake

City	Population in 2000 (million)	Growth rate (%/year)
Mexico City	25.8	2.2
Tokyo, Japan	20.2	0.5
Tehran, Iran	13.6	3.4
Jakarta, Indonesia	13.2	3.2
Beijing, China	11.2	1.8
Manila, Philippines	11.1	2.8
Los Angeles, USA	11.0	0.3
Bangkok, Thailand	10.7	3.6
Osaka, Japan	10.5	0.6
Lima, Peru	9.1	2.8
Baghdad, Iraq	7.4	3.1
Bogota, Colombia	6.5	1.7
Lahore, Pakistan	6.2	3.4
Medan, Indonesia	5.4	5.2
Santiago, Chile	5.3	1.3
Ankara, Turkey	5.2	3.3
Caracas, Venezuela	5.0	1.7
Algiers, Algeria	5.1	3.7
Naples, Italy	4.3	0.4

Table 2 Losses due to large earthquakes in California. (Modified after The Economist 1995; California Seismic Safety Commission)

Location	Date	M	Deaths	Cost ($ million)[a]
1990s				
Northridge	1994	6.7	57	20 000
Big Bear	1992	6.6	0	96
Landers	1992	7.5	1	–
Cape Mendocino	1992	7.1	0	51
Cape Mendocino	1992	6.5	0	–
Joshua Tree	1992	6.1	0	–
Sierra Madre	1991	5.8	1	36
Upland	1990	5.5	0	11
1980s				
Loma Prieta	1989	6.9	63	7 100
Imperial County	1987	6.2	0	–
Imperial County	1987	6.6	0	4
Whittier	1987	5.9	8	467
Chalfont	1986	6.0	0	–
Oceanside	1986	5.3	1	–
Palm Springs	1986	5.9	0	7
Morgan Hill	1984	6.2	0	14
Coalinga	1983	6.4	0	46
Eureka	1980	7.0	0	4
Owens Valley	1980	6.1	–	–
Owens Valley	1980	6.2	0	4
Livemore	1980	5.5	1	22
1970s				
Imperial Valley	1979	6.4	0	61
Gilroy/Hollister	1979	5.9	0	–
Santa Barbara	1978	5.7	0	16
Oroville	1975	5.9	0	–
Point Mugu	1973	5.9	0	3
San Fernando	1971	6.4	58	1 870
1960s none				
1950s				
San Francisco	1957	5.3	0	5
Eureka	1954	6.6	1	11
Bakersfield	1952	5.8	2	56
Kern County	1952	7.7	12	280
1940s				
Santa Barbara	1941	5.9	0	–
El Centro	1940	7.1	9	64

[a] Adjusted by consumer price inflation

on earthquake forecasting and seismic hazard and its relation to decision making in seismic protection strategies.

We have mentioned the most important aspects contained in seismic risk, i.e., the losses due to earthquakes: fatalities and economic loss. Both factors are not only dependent on the earthquake occurrence; they also depend critically on the vulnerability of structures. Consequently, a reduction in these losses can be achieved through better earthquake forecasts, but also by decreasing the vulnerabilities of human-made structures. Both approaches should be applied simultaneously and require a clear strategy from the appropriate decision makers (e.g., politicians or business executives). That this is not an obvious task is reflected in the often heated debates in the literature (e.g., Bolt 1991; Olson et al. 1989; Normille 1996b; Geller 1991).

Short-term or long-term earthquake forecasting?

From the Introduction it is clear that the ability to predict impending earthquakes could reduce significantly our loss in terms of fatalities and economics. What are the prospects for such an ability and why do we seem to have so many problems in obtaining accurate predictions? To answer this, we first try to specify what is expected of a meaningful earthquake prediction and then discuss different methods.

We first define the criteria that any earthquake prediction should satisfy in order to be useful to society:

1. The prediction must be correct. What is meant here is that the statement made in the prediction cannot be false. For example, the statement "all earthquakes occur on the 20th of May" can be shown to be untrue. For deterministic predictions, where place, time, and size are predicted, this criterion leaves us with only two alternatives, true or untrue. On the other hand, for probabilistic predictions this criterion obviously does not imply that the earthquake should indeed occur.
2. The prediction must be verifiable. A method for verifying a prediction is crucial in assessing its reliability. Unfortunately, the usefulness and reliability of existing earthquake prediction schemes is often difficult to assess (Wyss 1991; Kisslinger 1989; Geller 1996). With probabilistic predictions, especially when the probability that the earthquake will occur is small, this becomes even more difficult (e.g., see Rhoades and Evison 1989b).

Table 3 Losses due to some large earthquakes in percentage of GNP. (After Coburn and Spence 1992, and Tucker et al. 1994)

Country	Earthquake	Year	Loss		
			$ billion	%GNP[a]	%GRP[b]
Nicaragua	Managua	1972	2.0	40	
Guatemala	Guatamala City	1976	1.1	18	
China	Tangshan	1976	6.0	1.5	
Italy	Campania	1980	45.0	7	
Mexico	Mexico City	1985	5.0	3	
El Salvador	San Salvador	1986	1.5	31	
USA	Loma Prieta	1989	8.0	0.2	6[c]
Iran	Manjil	1990	7.2	7.2	
Philippines	Luzon	1990	1.5	2.7	
USA	Northridge	1994	30.0	<1.0	8[d]

[a] Gross national product in that year
[b] Gross regional product in that year
[c] GRP San Francisco Bay area
[d] GRP Greater Los Angeles area

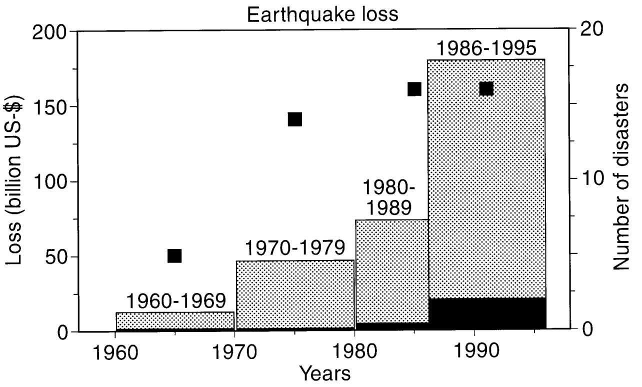

Fig. 3 Economic (total) losses and insured losses due to earthquakes since 1960. *Dark gray* histograms indicate the total economic loss due to earthquake disasters during the 10-year period indicated. *Black histograms* denote the insured losses for the same period and *black squares* the number of disasters during the same period. (Courtesy of G. Berz, Munchener Ruckversicherung, Munich, Germany)

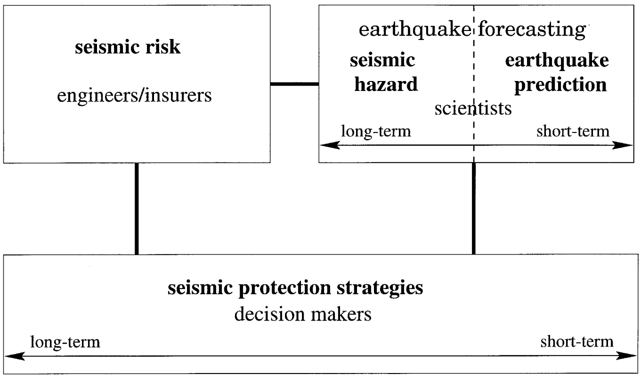

Fig. 4 Relation between earthquake forecasting, seismic risk analysis, and seismic protection strategies. An indication of the main experts involved in each field is given

3. Society must be able to respond with meaningful protection strategies. Earthquake prediction is only useful when it allows us to take loss-reducing measures. (Note that it is assumed that the earthquake occurrence cannot be averted). For example, many prediction schemes are so vague regarding time or place that any meaningful protection strategy is excluded. Alternatively, the economic costs may be in no proportion to the low probability that an earthquake will actually occur.

As we see later, not every earthquake prediction scheme satisfies these criteria. In addition, the last criterion is closely related to the way in which society deals with the dangers that threaten its population. To complicate the issue further, the last criterion cannot be seen independently of political issues.

As mentioned previously, deterministic predictions are presently seen as unrealistic (Geller 1991; Aki 1995). There is ample evidence that earthquakes behave in a chaotic fashion just like the weather. In other words, even if we would know all the physical properties in and around a fault, we would still not be able to predict an earthquake on that fault with absolute certainty. Therefore, we concentrate on probabilistic earthquake prediction schemes, sometimes also called earthquake forecasting. If not specifically indicated otherwise, we use the term earthquake prediction in the remainder of the article in the probabilistic sense.

As shown in Table 4, earthquake prediction can be classified in different categories: long-term (years), intermediate-term (months/weeks), and short-term (days/hours) predictions. To this scheme we also added instantaneous warnings, although strictly speaking these are warnings issued immediately, but automatically, after the occurrence of the earthquake. This

Table 4 Classification of earthquake prediction schemes

	Long term	Intermediate term	Short term	Instantaneous
Time scale	Years	Months/weeks	Days/hours	Seconds
Possible actions of decision makers	Risk mitigation disaster planning	Emergency alert	Evacuation shutdown of vulnerable plants	Emergency turn-off trains, hazardous plants, etc.

straightjacket form of classification organizes different scientific methods with different protection strategies of society.

Long-term predictions, which are made on a timescale of years, cannot lead to immediate and drastic actions, but are crucial in the formulation and enforcement of building codes (Naeim 1989) and in urban planning (Tucker et al. 1994). In long-term earthquake prediction we estimate the probability that an earthquake with magnitude larger than M will occur in a particular region. This is an integral part of seismic hazard analysis, where we estimate the probability that a certain ground motion will be exceeded at a specific site, e.g., a nuclear power plant. The latter formulation is more meaningful for both loss estimation (i.e., seismic risk) and for the formulation of protection strategies.

Intermediate-term predictions are made on a timescale of months or weeks. Abnormal regional crustal deformation, variation in seismicity (smaller earthquakes) patterns and regional time variations in seismic wave propagation belong to this category of geophysical observations. They can lead to a number of actions that lead to raised level of alertness of emergencies. Examples are, informing the public how to act during an earthquake (only 50% of the people in the Greater Vancouver Regional District are aware of the seismic risk in that region (Ventura and Schuster 1994), ensuring that hospitals are prepared and emergency supplies available, and ensuring that adequate supplies of food and drinking water are safely stored. Possibly, one could also close extremely vulnerable structures such as nuclear power plants or bridges with a poor structural integrity.

Short-term predictions are made on a timescale of days or hours and include precursors of different kinds. These short-term predictions could even lead to drastic measures such as evacuating people from dangerous areas, advising the public to remain outdoors, and closing structures and facilities (such as bridges, the subway, chemical plants, or nuclear power plants) that are either sensitive to earthquake hazard or that could create a threat to the population. Obviously, the reliable estimation of the probability of earthquake occurrence is important for decision makers, as higher probabilities warrant costlier (both in economic and social terms) protection measured and vice versa. Also, an integrated model approach, as suggested in Fig. 4, becomes in this case more important. This has been recognized by the National Earthquake Prediction Evaluation Council (NEPEC) in the U.S. and the Earthquake Assessment Committee (EAC) in Japan (Normille 1996b).

What methods are presently available for earthquake prediction or what can earth scientists, preferably in conjunction with related sciences, deliver? A great variety of methods has been proposed to use for earthquake prediction. In general, the methods can be divided in (a) statistical models for seismicity and (b) observations of precursors to large earthquakes.

The statistical models often rely on the spatial and temporal pattern of seismicity for making inferences about the probability of the occurrence of earthquakes in a certain magnitude range. These models may or may not be based on a physical mechanism to support the statistical statements. Long-term predictions and seismic hazard estimates are generally based on such statistical models. However, also for intermediate and short-term predictions statistical seismicity models are used.

When using observations of precursors the idea is that earthquakes may be preceded by observable phenomena. Many of the suggested precursors fall under the short-term earthquake predictors. One should note that it is not strictly necessary to understand the physcial (or chemical or biological) mechanism of the precursor and its relation to the impending earthquake. In order to conform to the above-presented criteria, prediction based on the observation of precursors is often formulated as a probabilistic statement.

Statistical seismicity model

Statistical methods have been formulated at many different levels of sophistication. One of the simplest methods is to analyze for a region the logarithm of the number of events, ln N, occurring in a certain time as a function of magnitude M (Ishimoto and Iida 1939; Gutenberg and Richter 1944), or equivalently as the logarithm of the seismic moment, ln M_0, of the events. It is found empirically that there is a linear relation between $\ln N$ and $\ln M_0$, when observed over a broad area:

$$\ln N = a - b' \ln M_0, \tag{1}$$

where *a* and *b*′ are constants. It is interesting that this empirical law can be explained theoretically when one makes assumptions about the self-similarity of the earthquake source (Bak and Tang 1989). A standard forecasting model is the so-called Poisson model, in which one assumes that in a specified region earthquakes occur randomly at a rate, and with a magnitude distribution, as defined in Eq. (1). An example of this magnitude relation for the Horn of Africa is shown by Fekadu and van Eck (1997) in Fig. 5. The constants *a* and *b*′ in the scaling law (Eq. (1)) differ for different regions on the earth. The idea is that these constants can be determined by observing a relatively large number of small earthquakes. Given these constants one can extrapolate, using Eq. (1), to find the probability that large earthquakes will occur in the same region. This method will only lead to long-term predictions. However, in the absence of observed strong earthquakes in a region it can provide estimates of the recurrence time of large earthquakes and thus provides a first approximation of the seismic hazard and consequently the seismic risk. Presently, an intense debate is being held as to whether this extrapolation to large earthquakes, using a constant *b*, is a correct assumption (e.g. Pacheco et al. 1992). An alternative hypothesis suggests that large earthquakes occur less often than the mentioned extrapolation would indicate.

Another statistical method is based on the theory that large earthquakes with approximately the same size recur more or less regularly on the same fault segment. The idea is that when earthquakes have not occurred in a certain region, the accumulated strain has not been released and the probability of an earthquake will increase. This hypothesis has been presented as those of seismic gaps and led to the publication of maps with the seismic potential (McCann et al. 1979; Nishenko 1991). This statistical method has recently been attacked by others (e.g., Kagan and Jackson 1993), as doing little or no better than the Poisson model, as presented above. In another variation of this model a general statistical model is assumed for large earthquake occurring on (known) fault segments. This hypothesis is usually presented as the characteristic earthquake model (Nishenko and Buland 1987; Wesnousky 1994), referring to the characteristic event (size) for each predefined fault segment. The probability of occurrence increases systematically as time passes since the last big earthquake on this segment. Also this method has been criticized as doing no better than the Poisson model (Kagan 1993; Kagan 1996). However, the recent long-term statistical predictions for large earthquakes in southern California are largely based on improved variations of these models (WGCEP 1995).

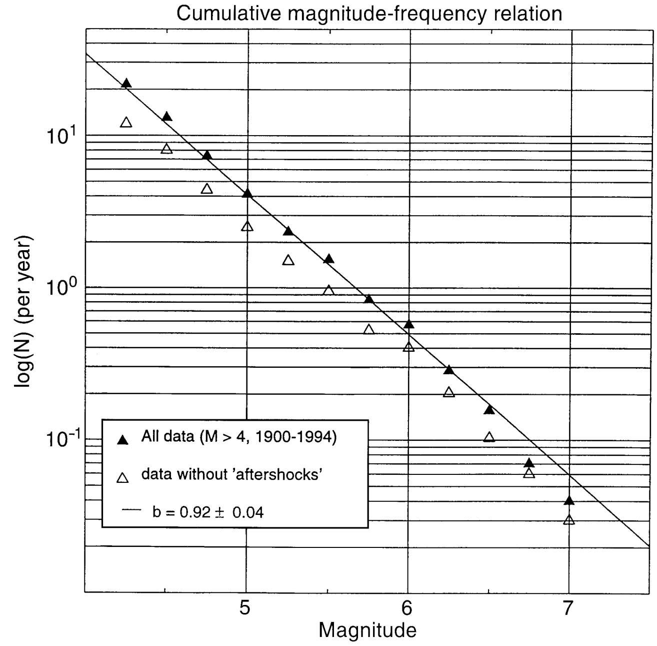

Fig. 5 Frequency magnitude relation for the Horn of Africa, i.e. Ethiopia and its surroundings. (After Fekadu and van Eck 1997)

Numerous other statistical techniques exist that are based on spatial and temporal variations of seismicity. One of them has received a considerable amount of attention and is therefore worth mentioning. Keilis-Borok (1990) and his coworkers presented a pattern-recognition procedure, where a number of subjective weights are tested on past earthquake activity in order to obtain a prediction. Their M8 and CN algorithms developed at the Institute for Mathematical Geophysics and Earthquake Prediction in Moscow are used to determine the time of increased probability (TIP) of earthquakes (Keilis-Borok 1990). According to Keilis-Borok et al. (1990), the Loma Prieta earthquake of 1989 fell within the TIP. However, an evaluation by the National Earthquake Prediction Evaluation Council (NEPEC) in the U.S., where mainly criterion 2 was assessed (see Short-term or long-term earthquake forecasting), judged the procedure inadequate as a practical prediction algorithm (Kisslinger 1989).

It is important to note that despite its obvious simplifications, known fallacies, and clear need to improvements, statistical seismicity models have up to now been the basis for significant seismic risk reduction measures in many countries.

Observation of precursors

It is intuitively appealing that the occurrence of an earthquake is preceded by observable phenomena. The hypothesis is that an earthquake occurs when the accumulated strain leads to stress levels that are close to the failure stress of the material in the earth. If this is the case, some physical properties around the impending earthquake nucleation center can be expected to change and lead to observable precursors to earthquakes. This in its turn may provide us with a prediction that performs better than those made with the statistical models mentioned in the previous section.

A number of physical models with mechanisms for precursory phenomena have been proposed (for a review of these see Scholz 1990). Unfortunately, earth scientists have to live with the complication that they cannot go down in the crust and mantle to carry out in situ measurements in order to support or refute a theory. In the field of earthquake seismology, the closest experiment in this direction is the Parkfield experiment (Roeloffs and Langbein 1994), were many physical parameters are observed along a small section of the San Andreas fault in California. Bakun and Lindh (1988) conjectured that a magnitude-6 earthquake would occur before 1993 on this section of the San Andreas fault with a 95% probability. Their prediction was based on a crude version of the characteristic earthquake model, and was accepted as good argument to fund a large number of instrumentation networks with the objective of capturing precursory phenomena. Although one serious warning was issued in October 1992 after a M 4.7 earthquake, no large earthquake has yet (mid 1997) occurred on the Parkfield segment since the prediction. A critical review of this experiment, as well as many other critical viewpoints on earthquake prediction, can be found in Lomnitz (1994).

Reported earthquake precursors include the following phenomena (e.g., Scholtz 1990; Turcotte 1991; Agnew and Ellsworth 1991; (Lomnitz 1994):

1. Occurrence of foreshocks
2. Changes in seismicity (e.g., quiescence before an impending large quake)
3. b-value variations
4. Variations in Radon outgassing, often observed as changes in Radon content in wells
5. Ground-water anomalies, often observed as water-level fluctuations in wells
6. Variations in seismic wave velocity (e.g., the variation in the ratio of P- and S-wave velocity as well as seismic anisotropy)
7. Variations in the coda of seismic wave trains (as observed in small events that occur near the impending large earthquake)
8. Changes in ground electrical resistivity
9. Electromagnetic anomalies (e.g., the VAN method)
10. Changes in crustal deformation rates
11. Tilt
12. Sky luminescence
13. Anomalous behaviour of animals

Although this list is far from complete, it contains the most widely discussed precursory phenomena. Some of them have a fairly well-understood relation to the occurrence of earthquakes. For example, the first three can be related to the nucleation of large earthquakes near a strong patch on the fault, also called asperities (Lay and Kanamori 1981). In some instances it can be clearly observed that a fault segment is locked and does not move, showing a reduced seismicity (Habermann 1988). Only when its strongest patch (the asperity) along a large fault segment fails, slip (and hence an earthquake) occurs. The failure of this asperity may be accompanied by small earthquakes, i.e., foreshocks. As another example, the precursors 4–7 may be related to the amount and orientation of cracks in the crust (Nur 1972). The stress accumulated in the area of an impending earthquake may alter both the amount and character of the cracks in and around the fault. In fact, laboratory measurements of rock samples have indeed shown a significant dependence of seismic velocity (including anisotropy), electrical resistivity, volume, and microfracturing on the stress (Scholtz 1990). Some precursors are presently not backed by any solid verifiable physical hypothesis (e.g., 9, 12, and 13).

In the remainder of this section we present three examples of observed earthquake precursors to illustrate the complications in verifying them according to the criteria presented in the section Short-term or long-term earthquake forecasting? The first example consists of observations of the Radon concentration (Fig. 6) in a well not far from the epicenter of the 1995 M 6.9 Kobe (Japan) earthquake in which approximately 5500 people lost their lives (Igarashi et al. 1996). It is clear from Fig. 6 that the Radon concentration changes dramatically several weeks before the earthquake. However, this observation was reported after the event. Although a clear signal appears to be visible (in hindsight), this evidence was apparently not considered to be sufficiently convincing to issue an earthquake warning. Additional examples of precursors observed in ground-water wells before a major earthquake are shown by Wakita et al. (1988).

The second example concerns the anomalous behavior of animals and the Haicheng prediction. In a

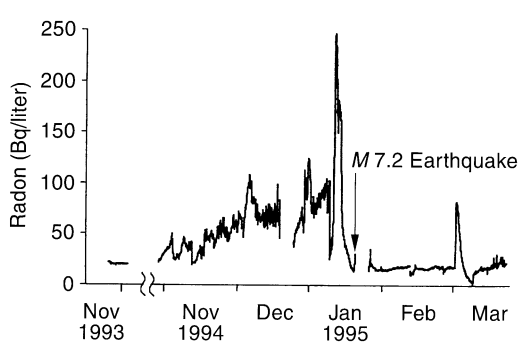

Fig. 6 Radon concentration in groundwater as observed before and after the 1995 Kobe earthquake, measured in a well approximately 30 km northeast from the epicenter of this earthquake. (From Igarashi et al. 1996)

detailed study, Deng et al. (1981) discuss the anomalous behavior of animals and the related prediction of the Haicheng (China) M 7.5 earthquake that occurred at approximately 22:00 hours on 4 February 1975. They state that in the 2 days before the Haicheng earthquakes 421 cases of anomalous behavior of animals in a region of approximately 200 × 200 km have been reported. Their work includes the following examples of anomalous behavior of animals:

> "Two geese flew away from a hillside and flew at an elevation of 50 m for a distance of more than 1 li (0.5 km)."
>
> "In the Anshan city park aviary, there were over 100 birds. Many of them picked up their eggs and flew our of their nests. While they were flying their eggs fell and smashed."
>
> "A four-year-old bull repeatedly bellowed and ran so wildly so that people were not able to get close to him. On the afternoon of 3 February, he was wilder than before."
>
> "Twenty piglets, which were born in October 1974, were found in the pigsty crying wildly. More than half had their tails bitten off and eaten. The manager of the commune's earthquake office investigated this before the earthquake and, considering other anomalies as well, made a prediction to commune. The commune leaders reported this to the appropriate agency and at 08:00 hours, 4 February they called an emergency meeting. They took measures to prepare for an earthquake."

The Liaoning Provincial Seismological Bureau issued an official earthquake warning on 4 February at 10:00 hours (Deng et al., 1981), approximately 12 h before the earthquake. Despite the large number of reports (>1000) of anomalous behavior of animals and of anomalous water-level fluctuations in the days before the earthquake (Deng et al. 1981), it is not clear which precursors prompted the Bureau to issue an earthquake warning. However, one should note that the Haicheng 1975 earthquake was preceded by an extremely large number of foreshocks for approximately 24 h before the main shock many of them with magnitudes 3–4 (see Fig. 19 of Raleigh et al. 1977). These "foreshocks" are large enough to be felt by humans in a fairly large region and may even cause damage. Increased seismicity with events of the size mentioned was observed at least 12 h before the official earthquake warning was issued at 10:00 hours. Indeed, Deng et al. (1981) conclude that:

> "some of the animals may have responded to a shaking of the ground due to foreshocks and other may have sensed changes in the ground water (level, composition, or other properties)."

This example illustrates well the ambiguity of certain precursors and shows some of the problems that decision makers are facing in choosing relevant precursors. In this case the Bureau only issued a warning after exceptionally strong and numerous foreshocks had occurred for more than 12 h. It also should be noted that despite the warning, approximately 1800 people lost their lives because of this earthquake. The "successful prediction" of the Haicheng earthquake should not be interpreted as a sign that earthquake prediction is operational; 1 year later in 1976 a quarter of a million people perished in China in the M 7.8 Tangshan earthquake which was not predicted (Chen et al. 1988), although afterwards several precursors were identified (Ma Zongjin et al. 1989).

The third example consists of observations of electric or electromagnetic phenomena before earthquakes. It has been proposed by Varotsos, Alexopoulis and, and Nomikos that earthquakes can be preceded by measurable fluctuations in the self-potential of the earth (e.g., Varotsos and Lazaridou 1991). This method, which has been named the VAN method after the initials of its inventors, has led to considerable controversy within the scientific community (see Geller 1996). In fact, lawsuits have been filed against the government for ignoring earthquake predictions based on the VAN method (Masood 1995a, b). As an example of the VAN method consider Fig. 7 (adapted from Ralchovsky and Komarov 1988) in which the potential between two electrodes 120 m apart is shown before a M 6.9 earthquake in Vrancea (Rumania). The time of the earthquake is indicated. Note that the timescale of the precursor is only several hours. One can argue whether these electrical signals are reliable indicators of impending earthquakes, as serious disgreement exists about the probabilities indicating its reliability (Geller 1996). A provocative detail is that Meunier (1991) suggests that the electrical signal in Fig. 7 is not generated in the earth, but is due to an ionospheric disturbance that could have triggered the earthquake. In this interpretation the electrical signal would not be a precursor accompanying an increasing stress level in the earth, but it would actually trigger the earthquake though the electrical forces that are associated with this electrical potential.

The above-mentioned examples illustrate the difficulties involved in verifying precursor schemes, i.e., criterion 2 in the section Short-term or long-term earthquake forecasting? Their usefulness and reliability are therefore difficult to assess. To be more specific, in order to be able to verify a precursor and judge its reliability and relevance as a diagnostic tool for impending earthquakes one must specify unambiguously the "rules of the game" for the use of a precursor and test its performance on an independent data set (Rhoades and Evison 1989a). The evaluation should answer the following questions:

1. How often does the precursor occur without being followed by an earthquake?
2. How often does an earthquake occur that is not preceded by the precursor?

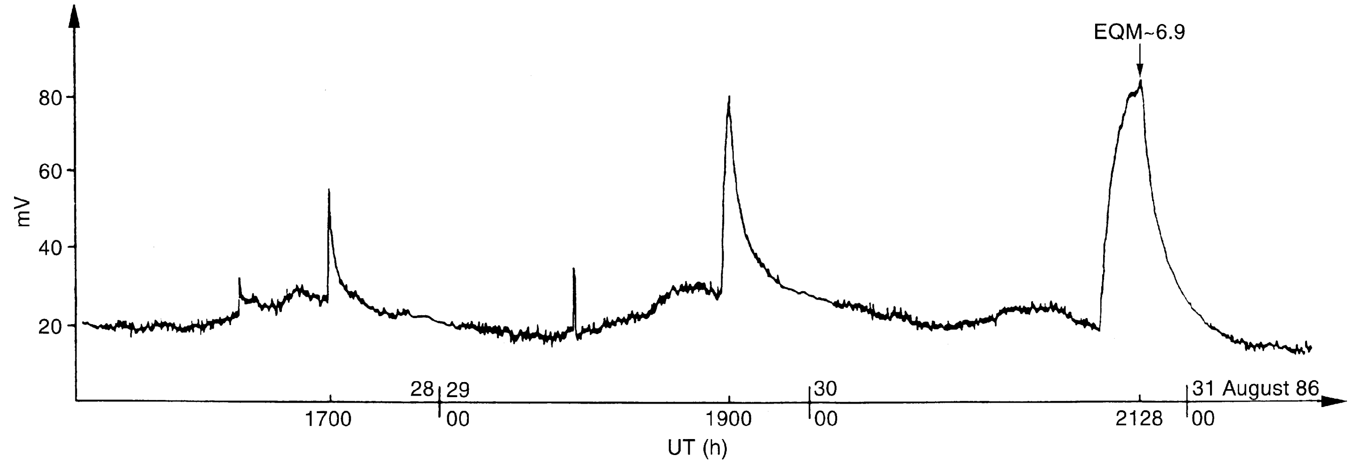

Fig. 7 The self potential between electrodes in the earth 120 m apart during an earthquake in Vrancea. The time of the earthquake is indicated with a *vertical arrow*. (From Ralchovsky and Komarov 1988)

3. Does the precursor predict the earthquake better than a statistical model, where earthquakes occur randomly at a known rate (e.g., the Poisson model).

Unfortunately, it is often difficult to find the answers to these questions in the present literature on earthquake precursors. Although the questions seem simple enough the answer, it is often extremely difficult to formulate the prediction (range of size, location, time of earthquake) and the "rules of the game" into models that can be statistically tested (Rhoades and Evison 1989b, 1996). This does not imply that precursors cannot be used as indicators for impending earthquakes, but it does imply that it is presently extremely difficult to judge the reliability of these precursors for earthquake warning purposes.

Earthquake risks

An assessment of the usefulness of earthquake forecasting requires a short overview of what the actual seismic risks are or what the expected losses from the occurrence of an earthquake are. Discussions on earthquake prediction research are inevitably connected to the priorities put forward by the society and these are obviously connected to seismic risk and much less to seismic hazard. We are much less interested in the impacts of a M 7 earthquake near the Tonga islands in the Pacific than a M 5 earthquake near Tokyo. So what are the risks?

1. Direct risks. As mentioned in the introduction, strong ground acceleration does not constitute a major risk, neither is surface rupturing during an earthquake. Very few fatalities have been reported as due to such direct effects.
2. Indirect short-term risks. These include the largest cause of fatalities. Approximately 75% of the fatalities are due to structural collapse of human-made structures, predominantly buildings (see Fig. 1). Additional indirect causes that make earthquakes a disastrous phenomena are fires, tsunamis, landslides, and liquefaction, but also disruption of lifelines, i.e., roads, railways, power-, gas-, and water lines, phone- and data-communication lines. Most buildings in San Francisco survived the (in)famous 1906 M 8.3 earthquake. Instead, the disastrous effect was due to fire, caused by gas leaking from gas pipes. Once started, the fire could not be extinguished due to the ruptured water supply system. A firefighter's nightmare is a similar scenario for an earthquake that hits Tokyo.
3. Indirect long-term risks. These include health risks due to the outbreak of epidemics as a consequence of lack of clean water, warm shelters, medical aid, etc., but also environmental risks due to the collapse of a nuclear power plant, toxic waste disposals, or storage tanks with toxic material. Of increasing concern are the economic consequences of a large earthquake causing damage to economic centers. For example, a member of the scientific research team of one of the world's leading insurance companies formulated their driving force behind seismic risk assessment research as "ruin probability" to express that a single earthquake could very well render insurance companies bankrupt. More specifically, a large earthquake in Tokyo has been estimated to cost somewhere between US$ 900 billion and US$ 1.4 trillion (The Economist 1995), around 20% of Japan's present gross domestic product (GDP). This could induce a worldwide economic contraction with all its consequences (Hadfield 1991).

This represents a far-from-complete list of risks due to earthquakes, but shows the most important components. A more general review can be found in Ambraseys (1988). To illustrate the importance of the indirect long-term risks, many of the recent advances in seismic hazard research in the western world have been either initialized or sponsored by the nuclear power industry and its regulators (e.g., Reiter 1990).

The question arises as to whether these risks can be eliminated or at least reduced, and what role earthquake forecasting will have in this. Obviously, such an assessment involves the formulation of cost-benefit relations, where costs include human lives and health as well as material property. This brings us back to the relation between scientists, engineers/insurers, and decision makers (Fig. 4).

Reducing the impacts of earthquake

A number of earthquake protection strategies are available (Coburn and Spence 1992). This involves mostly decision makers on a national level, e.g., in long-term budget planning for disasters and emergency management, but also in education, both for professionals and the general public. However as shown again during the 1995 Kobe earthquake, where 89% of the fatalities were due to collapse of houses (Hayashi and Kawata 1995), improved building practices can significantly reduce the number of fatalities. Minimum standards for design and construction are therefore an important step in reducing the impacts of earthquakes. Consequently, many countries have formulated national codes of practice and building regulations for seismic design (IAEE 1988). However, in the formulation of these codes four ingredients are necessary. Firstly, seismologists and geotechnical engineers need to specify the ground acceleration that can reasonably be expected in a certain region, i.e., seismic hazard assessment. A clear expose of the procedures followed can be found in Reiter (1990). In this context it is crucial to note that the ground acceleration may depend critically on very local soil and topographic conditions such as the shape and fill of sedimentary basins (Aki 1993) and ground-water level including complex phenomena such as liquefaction (Lew and Nissen 1989). Secondly, earthquake engineers need to be capable to employ and develop building techniques in order to design earthquake-resistant buildings. The information provided by the seismologist or geotechnical engineer contains a description of the expected ground motion, either as spectral response spectra or, preferably, as time series. Thirdly, the expert recommendations of seismologists and engineers need to be incorporated in appropriate (often regional) building codes. Given the large costs involved, this requires a cost-benefit assessment and consequently becomes a political/economic task. For example, in the U.S. the priorities have generally been clearly stated as “to provide for life safety but not to insure against damage” (Di Julio 1989). Fourthly, once building codes are formulated, it is crucial to ensure that these building codes are being used. Control and enforcement by local and federal government are necessary for this. All of these tasks are crucial, and we see again that this does not only involve the scientist and the engineer, but becomes to a very considerable degree the task of the decision maker/politician. This is particularly the case for underdeveloped regions where making buildings earthquake resistant often cannot receive a high priority.

Many building codes are relatively simple, specifying the static lateral force that a building should withstand (Di Julio 1989). This static approach corresponds very much to similar codes for wind-resistant design and reflects the importance of the mainly horizontal ground motion due to earthquakes. In this formulation it is obviously important to know the peak ground acceleration. In tall buildings, however, not the static force but the dynamic force (i.e., the period and duration of the oscillations) is important. The building acts essentially as an inverted pendulum that will resonate when exposed to the appropriate frequencies. An example of this phenomenon is shown in Fig. 7 from Cara et al. (1988) who placed seismometers in the crypt, the ceiling, and the spire of the cathedral of Strasbourg (Fig. 7a). It can be seen in Fig. 7b that the horizontal motion is dramatically amplified in the spire, largely due to its resonance at a frequency of approximately 1.2 Hz.

As a successful example of one of the earthquake mitigation techniques used, consider Fig. 8 (from Celebi and Brown 1994). The base isolation of a building on the University of California campus in Los Angeles suppressed the ground accelerations during the 1994 Northridge M 6.6 earthquake significantly. In the free field, away from the building the peak, acceleration is 0.49 g. The foundation of the building (below the base isolation) experiences a peak acceleration of 0.37 g. The base of the building (just above the base isolation) experiences a peak acceleration of 0.13 g, which implies that the base isolation has suppressed the acceleration by a factor 3! The roof of the building at the eighth floor accelerates with only 0.21 g, which is less than half the acceleration in the free field. Given the fact that normally the upper levels of building oscillate much stronger then the base levels, this is a remarkable reduction in the acceleration that threatens the structural integrity of buildings.

The dramatic reduction in acceleration that has been achieved in the previous example does not imply that all problems are solved. The uncertainties that are involved in the formulation of building codes are considerable, and the issue can be more complex than it appears at first sight. An example of this is given by Heaton et al. (1995) who carry out finite element simulations of a 20-story steel-framed building during an

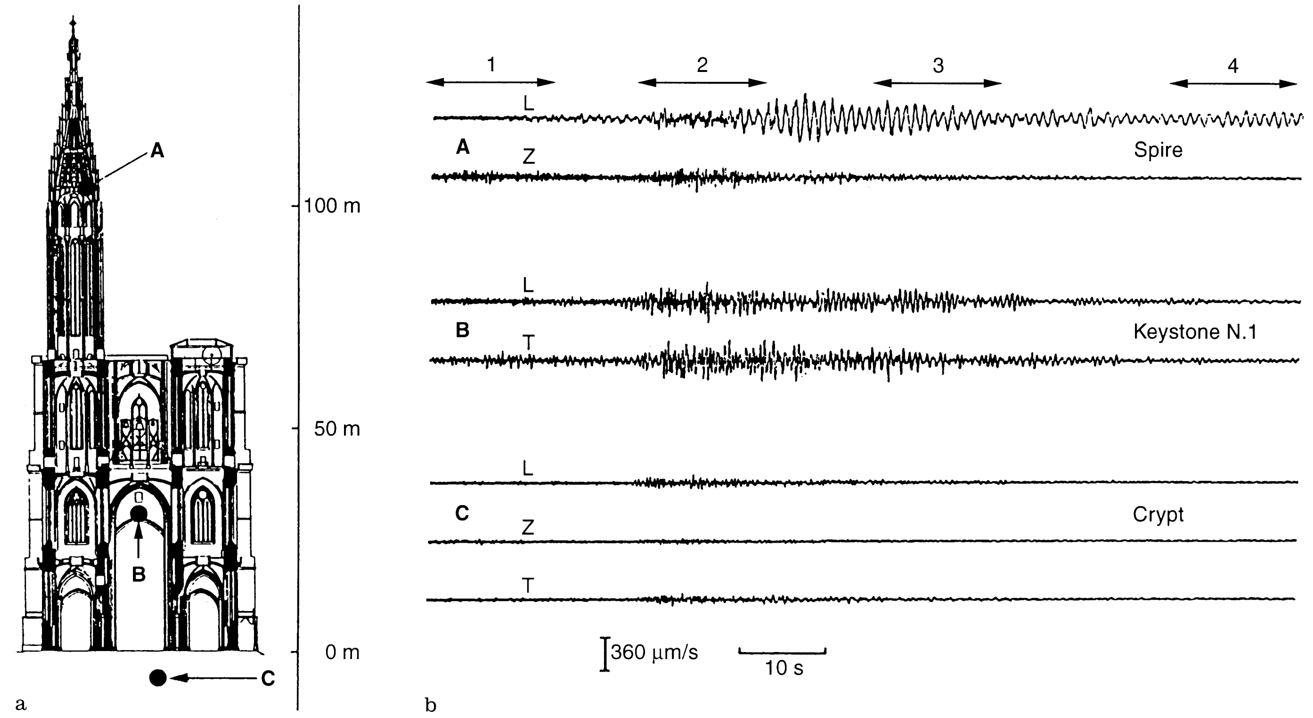

Fig. 8 The response of different elements of the cathedral of Strasbourg as recorded due to an earthquake of M = 3.8 approximately 186 km north of Strasbourg. Accelerometers are placed at the spire (*A*), the ceiling (*B*), and the crypt (*C*). **a** The locations of the accelerometers; **b** the accelerograms as recorded at the three different sites. (From Cara et al. 1988)

earthquake similar to the 1994 Northridge earthquake. (Iornically, this work appeared in *Science* 4 days before the disastrous 1995 Kobe earthquake). The lateral displacement in their model simulation is shown by the solid lines in Fig. 9. Despite the fact that the lateral displacement of the roof is 3 m, the building will not collapse. One of the surprises of the Northridge earthquake was that many steel-framed buildings suffered considerable structural damage. When this kind of structural damage is included in the finite element simulation, the building collapses approximately 4 s after the onset of the ground motion (see the dashed lines in Fig. 9). This requires a reevaluation of the structurally damaged buildings and probably a revision of the building codes, as structural degradation inflicted to buildings by earthquakes is probably larger than anticipated. Given the predominant building style of new buildings in California and the prospect of larger or more frequent earthquakes in the Los Angeles metropolitan region (Dolan et al. 1995), this issue is of more than academic interest.

Much can technically be done in earthquake mitigation and much has been done. For example, many of the structural failures due to the Kobe earthquake occurred to older buildings that had not been built according to the newer codes of 1980. However, even newer structures, built according to the more stringent codes, failed. This, and the example of Fig. 9, shows that scientists, engineers, and decision makers are facing a cost-benefit problem of large proportions, even more so as the majority of the major cities in Table 1 are located in developing countries. In this context both the third world as well as the second world (e.g., the Armenia M 6.9 earthquake of 1988) are of importance. Establishing a practice of earthquake-resistant buildings in these regions will require a Herculean effort with predominantly economic, social, and political aspects.

Information vs certainty: a political dilemma

From the foregoing discussions it should be clear that earthquake forecasting and seismic risk assessment are not only an issue of the expert, either scientists, engineers, or insurers. A successful seismic protection strategy requires a multidisciplinary concerted action, where decision makers spell out the priorities. The lack of such an overall strategy is obvious.

For example, the assessment of Bolt (1991) that "because of indecision between minimizing loss of life and maximizing broader benefits, general agreement on acceptable earthquake risk remains confused" is still actual. This also applies to his statement that "risk reduction is characterized by bursts of activity and

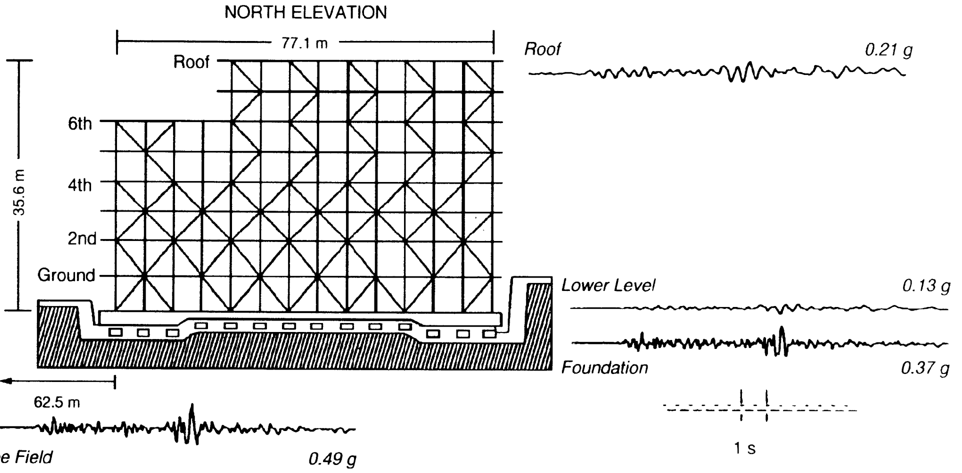

Fig. 9 The response of a base-isolated building on the University of California campus in Los Angeles due to the 1994 Northridge M = 6.6 earthquake. (From Celebi and Brown 1994)

political support after damaging earthquakes, and decay curves that have a half-life of a year or so before public effort recedes." Except for a longer half-life span, the first part of the statement is amply illustrated by recent events in Japan where 1 year after the Kobe earthquake the government announced a 47% increase in public spending on earthquake-related research (Normille 1996a). However, this budget increase has not been preceded by serious discussions on priorities as solicited by, for example, Geller (1991). The book of Lomnitz (1994) offers stimulating reading on the lack of multidisciplinary constructive interaction with regard to earthquake forecasting.

Why is it so difficult for decision makers to spell out priorities and to utilize available forecasting tools and risk estimates? We postulate that earthquake forecasting poses a basic dilemma for the decision maker due to its inherent trade-off between information and certainty (Fig. 10). It should be clear from the preceding text that earthquake predictions are predominantly phrased as probabilistic statements. Unfortunately, such a prediction puts the decision maker in a precarious position. On one hand, he aims at reducing loss of life and property by taking preventive measures, generally based on a cost-benefit analysis. In order to make these, he prefers very specific predictions, i.e., accurate location, size, time, and hazard and risk assessments, in other words, much (specific) information. On the other hand, he also aims at minimizing the risks of making a faulty decision. Especially with regard to earthquake prediction the stakes are high in social, political, and economic terms. As he aims at successful decisions, he prefers predictions with a high degree of reliability. In other words, he prefers information with a high degree of certainty in the sense that the probability that an earthquake will actually occur in a specified time span and region is high.

Unfortunately, the nature of the problem dictates that more information means less certainty. In order to illustrate this problem we present a simple example. Consider the following two end-member statements:

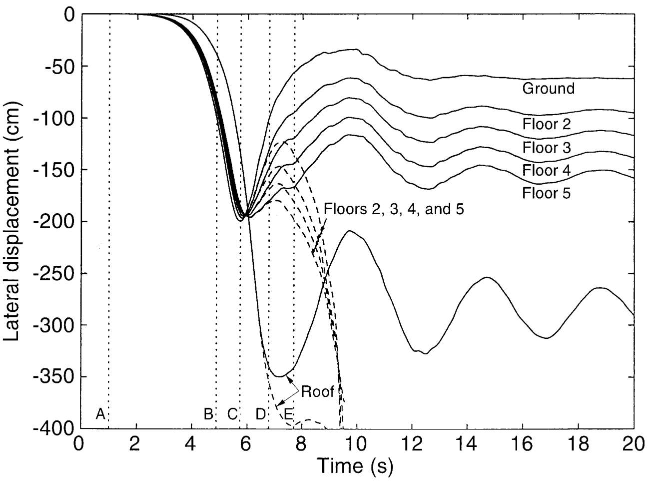

Fig. 10 Lateral displacements in a model simulation of a steel-framed high building exposed to earthquake shaking before and after degradation. The *solid lines* indicate the response of the different floors in a simulation in which no degradation occurs. The *dashed lines* correspond to simulations, e.g., an aftershock, in which degradation, after a major earthquake, has been included. This figure is from Heaton et al. (1995) who point out that the response of a building that has been hit earlier in its lifetime by a strong earthquake has degraded seriously and cannot be considered earthquake resistant anymore

> "Every earthquake takes place within 3 months of an equinox.
> "The probability of an earthquake with magnitude larger than 6 in the XX-basin within a week is 0.4%."

The first statement is adopted from a statement of Charles F. Richter. This statement will be realized with a 100% probability; in this sense the statement is absolutely certain. However, this statement (which proclaims that earthquakes occur somewhere in the year) does not tell us anything that we do not know already. The statement carries no information. This implies that

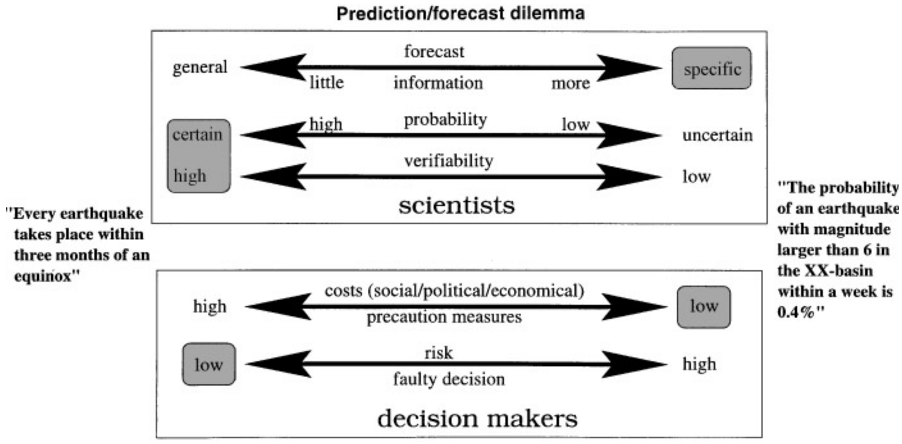

Fig. 11 Presentation of the prediction dilemma. In earthquake forecasting, the scientist is responsible for defining a forecast and its associated probability. The politician or business executive, has to make a decision based on this information and tries to strike a balance between reducing the precaution measures and minimizing his risks of making a faulty decision. The preferred options have been *shaded* to show clearly the basic incompatibility of the requirements

society can attach no consequences to this statement and that this statement does not satisfy criterion 3 of the section Short-term or long-term earthquake forecasting? Now consider the second statement. Let us assume that the probability of such a strong earthquake taking place within a week is significantly higher than the normal probability. In that case this statement carries important information: It tells us that the probability of an earthquake is larger than average. The effects of such an earthquake could be considerable, and society could attach drastic consequences to this statement. Some areas might be evacuated, potentially dangerous structures and facilities could be closed, etc. It should be clear that the economic costs of such a line of action for society can be very high. Note that the probability that the earthquake actually occurs within a week is only 1 in 250. Despite the fact that the statement is very specific and that the consequences of the earthquake could be disastrous, the probability that the event will happen is extremely small. This also implies that it is very difficult, if not impossible, to verify this statement.

To see this, consider the example that somebody claims that the probability of throwing “1” with a die is 1 in 6. Suppose one throws the die once and that the outcome is “1”. One could be tempted to say that the statement was correct since “1” was indeed obtained. However, a skeptic might argue that the statement is wrong, because the probability of throwing something else than “1” is 5 in 6 and therefore 5 times as great as throwing “1”. Both viewpoints are erroneous. Probability is operationally defined as the relative occurrence of the outcome of an experiment when the experiment is often repeated. When one claims that the probability of throwing “1” with the die is 1 in 6, one therefore states that if one throws many times, one will throw “1” in 1 in 6 of the cases. It is impossible to verify this statement after throwing the die only once. This implies that in order to verify whether the statement, “The probability of an earthquake with magnitude larger than 6 in XX-basin within a week is 0.4%,” is correct one needs to consider the outcome of at least approximately 1000 predictions of this kind to assess the truth of the statement. Practically speaking, this means that the statement cannot be verified and that criterion 2 of the section Short-term and long-term earthquake forecasting? is not satisfied by this statement.

Referring to Fig. 10 the above reasoning implies that the decision maker has to act on a situation in which the two end members are a relatively certain but vague prediction (meaning a low-risk/high-cost decision), or an uncertain, but specific, prediction (meaning a high-risk/low-cost decision), Neither are attractive alternatives, but avoiding a decision can be disastrous, too. This is a general dilemma for all types of earthquake forecasts, but it becomes especially acute in short time predictions where those complicated decisions have to be made within a relatively short time.

Note that we have already assumed implicitly that earthquake forecasts can be made with correct probability estimates (criterion 1 of the section Short-term and long-term earthquake forecasting?). However, since these estimates are lacking in most short-term predictors, e.g., in the VAN method (e.g., Geller 1996), the problem for the decision maker is even worse and vivid debates arise (Masood 1995a, b).

The end-member cases of statements regarding the occurrence of earthquakes illustrate a fundamental trade-off in earthquake forecasting (see Fig. 10). The preferred combination of “low” costs and low risks of a faulty decision are for the decision maker inherently incompatible. In order to understand the full impact of this dilemma one should realize that earthquake forecasting is a field with extremely strong social and political consequences.

On one hand, suppose an eart↓hquake occurs that has not been predicted. This may lead to a great loss of life and property which possibly (at least in part) could have been prevented. In addition to this, society has a low

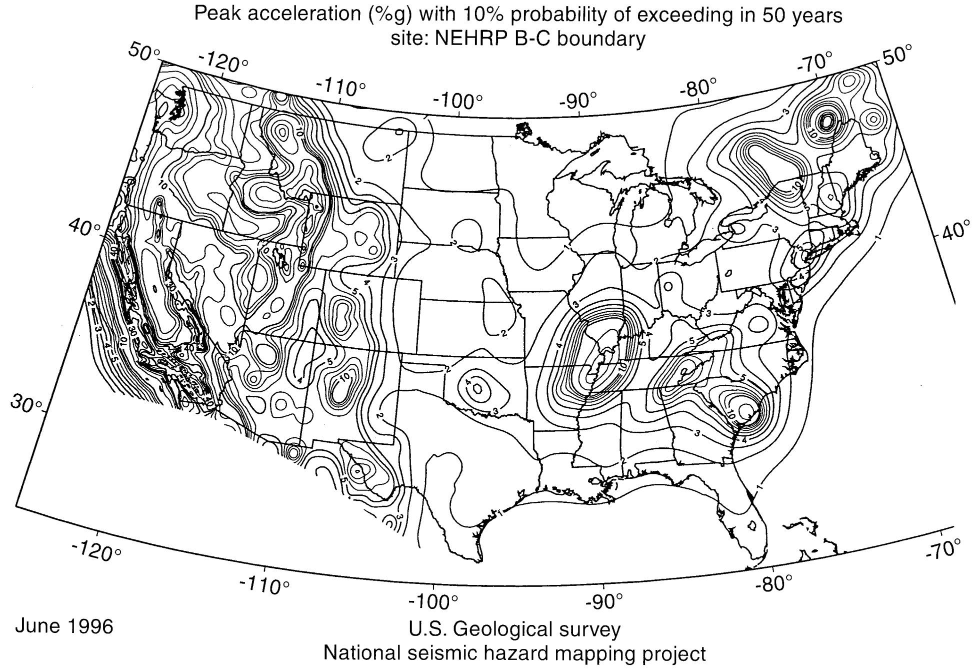

Fig. 12 The new seismic hazard map for the U.S. based on an integrated hazard analysis approach as described in Frankel (1995). The map shows the peak ground acceleration (in %g) that with a 10% probability will be exceeded in 50 years

level of acceptance for risks that involve sudden loss of many lives (see Table 5). In the Netherlands, 1300 people die in traffic accidents every year (Kerncijfersverkeersonveiligheid 1994); apparently, this is considered to be acceptable. However, the 4 October 1992 El-Al (airline of Israeli) jumbo jet crash over a suburb of Amsterdam in the Netherlands left 43 persons dead, but caused a major outcry to determine who was responsible and to determine whether preventive measures could have been taken.

On the other hand, an official earthquake prediction may have serious economic consequences, regardless of whether the earthquake actually occurred or not. Such predictions can lead to a disruption of society from a social point of view, with huge (economic) costs. Imagine, for example, the loss made by closing the Boeing factories near Seattle (Washington) for a single day. Given the occurrence of potential devastating earthquakes with magnitudes larger than 8 in this region (Rogers 1988; Heaton 1990; Satake et al. 1996), this scenario is not unrealistic. Even when an earthquake prediction does not lead to drastic immediate measures, it can have a considerable effect on the price of property. This shows that earthquake prediction is a touchy issue viewed from a political point of view. The inherent trade-off between certainty and information in earthquake forecasts aggravates this issue considerably.

Table 5 Probability of an individual dying in any 1 year from various sources (After Coburn and Spence 1992)

Smoking 10 cigarettes a day	1 in 200
All natural causes (age 40)	1 in 850
Any kind of violence or poisoning	1 in 3300
Influenza	1 in 5000
Accident on the road (Europe)	1 in 8000
Leukemia	1 in 12 500
Earthquake (living in Iran)	1 in 23 000
Playing field sports	1 in 25 000
Accident at home	1 in 26 000
Accident at work	1 in 43 500
Homocide (Europe)	1 in 100 000
Earthquake (living in California)	1 in 2 000 000
Hit by lightning	1 in 10 000 000
Wind storm, northern Europe	1 in 10 000 000

Is earthquake forecasting a feasible tool?

Herein we have illustrated the political dilemma of the decision maker and may have raised the reader's doubts about the feasibility of earthquake forecasting as a way to reduce earthquake loss. We are, however, convinced that earthquake forecasting is and will be a powerful tool in seismic protection strategies. We mention a few examples of promising developments within the earth sciences and the interdisciplinary fields with engineers/insurers and decision makers:

1. Reliability of earthquake forecasting models. Physical and statistical models for earthquake mechanisms are improving:

   Statistical seismological models. Both types of statistical models that are being used (the Poisson and characteristic earthquake model) have evolved from purely statistical models into physical models (e.g., Rundle 1993; Rice 1993; Main 1995). Although the physical models presented may contradict each other in some respects, the questions have become more specific.

Earthquake nucleation models. Multidisciplinary research involving, among others, theoretical geophysics and physics, observational seismology, and fracture mechanics, provide models for the earthquake nucleation process and thus better characterization of possible earthquake precursors (e.g., Vidale 1996; Mikumo et al. 1992; Beroza 1995; Nielsen et al. 1995).

Probability assessments of precursors. General consensus among geophysicists is reached about probability assessment of potential precursors (Agnew and Jones 1991; Aki 1995; Geller 1996).

2. Seismic hazard modeling. Seismic hazard assessments benefit from the improved forecasting models mentioned above, but also from work by, among others, geologists, geodesists, and geotechnical engineers:

   Extended earthquake catalogues and accurate crustal deformation measurements. Paleoseismic data (Yeats and Prentice 1996) and precise geodetic measurements (Hudnut 1995) add to the observational seismological database and consequently improve forecasting models (WGCEP 1995).

   Site response. Recent site response studies (Nakamura 1989; Field and Jacob 1995; Aki 1993) promise to predict better the ground motion estimates due to strong earthquakes.
3. Forwarding earthquake forecasting information. Successful examples of collaboration between decision makers and scientists, engineers/insurers have been reported in education (Coburn and Spence 1992; Gere and Shah 1984), the development of forecasting and alert protocols (Roeloffs and Langbein 1994; Aki 1995), and disaster emergency planning (Coburn and Spence 1992).
4. Instantaneous earthquake warning systems. In some situations the impact of earthquakes on society can be reduced even if a short warning is available. For example, in Mexico large earthquakes occur in the subduction zone along the west coast. These earthquakes may cause considerable damage far inland. In 1985 an earthquake along the west coast of Mexico caused more than 9500 fatalities in Mexico City. Presently, a Seismic Alert System (Espinoza Aranda et al. 1995), consisting of 12 strong motion instruments installed in the epicentral region, enables an early warning in Mexico City. A warning for a strong earthquake can be relayed to Mexico City within a few tens of seconds. This could be sufficient for such a warning to be useful, as it still takes approximately 1 min for the large-amplitude waves to propagate from the source to Mexico City. In Japan similar warning systems have been installed to stop the Shinkansen high-speed trains.
5. Seismic risk reduction. As shown in Earthquake risk improved building techniques are crucial in earthquake mitigation. While advanced techniques are available (Naeim 1989) and still improving (Heaton et al. 1995), much work remains to be done in many countries on improving, implementing and enforcing building codes (Coburn and Spence 1992). This is especially the case for third-and second-world countries. An extensive review of these problems can be found in Coburn and Spence (1992).

Conclusion

It should be clear that earthquake prediction in the sense of predicting the precise time and place of an earthquake is presently not feasible. Given the fact that earthquake dynamics may very well be chaotic, it is likely that this goal will never be achieved. This does not mean that scientists and decision makers cannot take steps to reduce the impact of earthquakes on society. As illustrated above, many earthquake protection tools are presently available to the decision maker. Unfortunately, these tools are accompanied by a fundamental dilemma. This implies that apart from the scientific and technical issues, the social, economic, and political aspects of earthquake protection strategies deserve attention. In addition, an intensive interaction between scientists and decision makers is needed to implement optimal seismic protection strategies. The lines of action shown above indicate that much can presently be done (and much is done) to reduce the impact of earthquakes on human populations.

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