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Earthquake Prediction: An Overview

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1. Introduction

Because earthquakes occur suddenly, often with devastating consequences, earthquake prediction is a matter of great interest among the public and emergency service officials. However, the term "earthquake prediction" is often used to mean two different things. In the common usage, especially among the public, "earthquake prediction" means a highly reliable, publicly announced, short-term (within hours to weeks) prediction that will prompt some emergency measures (e.g., alert, evacuation, etc.). Exactly how reliable this type of prediction should be depends on the social and economic situations of the region involved. The issue is whether the quality of prediction is good enough to benefit the society in question. Allen (1976) lists six attributes required for this type of prediction: (1) It must specify a time window. (2) It must specify a space window. (3) It must specify a magnitude window. (4) It must give some sort of indication of the author's confidence in the reliability of the prediction. (5) It must give some sort of indication of the chances of the earthquake occurring anyway, as a random event. (6) It must be written and presented in some accessible form so that data on failures are as easily obtained as data on success.

In the second usage, "earthquake prediction" means a statement regarding the future seismic activity in a region, and the requirement for high reliability is somewhat relaxed in this usage. In a way, this is a more general scientific prediction of a physical system, and as such it is nothing but a study of "physics of earthquakes." The reliability of a specific prediction depends on the level of our understanding of the process, and the amount and quality of data we have. Because the basic physical process of earthquakes is now reasonably well understood, and high-quality geophysical data are being collected, it should be possible to make some predictions regarding the future seismic activity in a region on the basis of whatever geophysical parameters are observed and their interpretations. This type of prediction or forecast also has important social implications on time scales of months and years. However, it is best to distinguish it from the short-term prediction previously described. In either case, a good scientific understanding of the process is a prerequisite to useful practical prediction.

The subject of earthquake prediction has been a matter of intense debate (e.g., Nature Debate, *http://helix.nature.com/debates/earthquake/equake-frameset.html*), and there does not seem to be a general consensus. Recent papers by Geller *et al.* (1997a; 1997b), Scholz (1997), Wyss (1997b), Aceves and Park (1997), and Geller (1997) demonstrate the diversity of opinion on this subject.

In this article, we review the current thinking on the scientific aspect of earthquake prediction research (i.e., with the emphasis on earthquake prediction in the second usage), and discuss its social implications. In this article, no distinction is made in the use of terms "prediction" and "forecast." We note, however, that "prediction" is often used for a statement on a specific earthquake, and "forecast" is more commonly used for a statement on the general seismic behavior of a region in the future.

Many books and review papers are available on this subject (to mention a few, Rikitake, 1976, 1982; Wyss, 1979, 1991; Vogel, 1979; Isikara and Vogel, 1982; Unesco, 1984; Mogi, 1985; Gupta and Patwardhan, 1988; Olson *et al.*, 1989; Lomnitz, 1994; Gokhberg *et al.*, 1995; Sobolev, 1995; Knopoff, 1996; Sykes *et al.*, 1999; and Rikitake and Hamada, (2001), so we do not discuss the details of the individual cases of earthquake prediction, or the specifics of methodology. Also, some national reports (e.g., Sobolev and Zavyalov, 1999; Kuznetsov, 1999; Zhang and Liu, 1999; and Zhu and Wu, 1999) have recently summarized activities in their respective countries.

2. The Earthquake Process

In a narrow sense, an earthquake is a sudden fracture in the Earth's interior, together with the resulting ground shaking; in a broad sense, it is a long-term complex stress accumulation and release process occurring in a highly heterogeneous medium.

INTERNATIONAL HANDBOOK OF EARTHQUAKE AND ENGINEERING SEISMOLOGY, VOLUME 81B *ISBN: 0-12-440658-0*

Advances have been made in understanding crustal deformation and stress accumulation processes, rupture dynamics, rupture patterns, friction and constitutive relations, interaction between faults, fault-zone structures, and nonlinear dynamics. Thus, it should be possible to predict to some extent the seismic behavior of the crust in the future from various measurements taken in the past and at present. However, the incompleteness of our understanding of the physics of earthquakes in conjunction with the obvious difficulty in making detailed measurements of various field variables (structure, strain, etc.) in the Earth makes accurate deterministic short-term predictions difficult.

Earthquakes occur, moreover, in a complex crust–mantle system. This system includes some distinct structures such as the seismogenic zone and faults, as well as highly heterogeneous structures with all length scales. The distinct structures are responsible for the deterministic behavior of earthquakes, but the interactions between different parts of the complex system result in the chaotic behavior of earthquake sequences. Many studies have demonstrated that even a simple mechanical model of earthquakes exhibits a very complex behavior, suggesting that earthquakes have the characteristics of a chaotic process (Burridge and Knopoff, 1967; Otsuka, 1972; Turcotte, 1992). Because of this chaotic component of the process, it would be difficult to predict earthquakes in a deterministic way; predictions can be made only in a statistical sense and only with considerable uncertainty (Turcotte, 1992).

Several processes are especially responsible for the uncertainties. If we assume that plate motion is statistically stationary, then the stress changes due to plate motion can be estimated with relatively small uncertainties. However, the stress in the crust also changes with time on a local scale. For example, the stress on a fault can be affected by nearby earthquakes. Because earthquakes occur on a complex array of faults, the crustal stress field is irregular on a local scale and determination of future earthquake locations would inevitably be uncertain.

The strength of the crust may change as a function of time, too. For example, migration of fluids in the crust could change the local strength of the crust and affect the occurrence of earthquakes (e.g., Raleigh *et al.*, 1976; Ingebritsen and Sanford, 1998). Our knowledge of hydrological processes in the crust is limited, and the temporal variation of the strength of the crust is difficult to predict, so again we have large uncertainties in the timing of the occurrence of earthquakes.

Prediction of the size (magnitude) of an earthquake is also uncertain, because a small earthquake may trigger another event in the adjacent area, cascading to a much larger event (e.g., Brune, 1979). Although the extent of a "stressed" area (e.g., a seismic gap) may ultimately determine the maximum size of the earthquake, the growth of rupture is likely to have some stochastic elements. Any small earthquake may grow into the maximum earthquake determined by the size of the gap, or may stop halfway, depending on small variations in the mechanical properties of rocks in the fault zone. For example, along the Nankai trough, southwest Japan, two adjacent segments broke in two separate $M \approx 8$ earthquakes in 1944 and 1946. However, in 1854 these segments broke in two $M = 8+$ earthquakes 32 hours apart, and in 1707, they broke simultaneously (Ando, 1975). Physically or geologically, each one of these sequences can be considered a single earthquake, but whether it occurs in two distinct events in a single sequence, 32 hours apart, or 2 years apart would have very different social consequences, and it's difficult to determine why these segments broke in these three different sequences.

Another important process is triggering by external effects. Hill *et al.* (1993) observed significant seismic activities in many geothermal areas soon after the 1992 Landers, California, earthquake. Although the detailed mechanism is still unknown, it appears that the interaction between fluid in the crust and strain changes caused by seismic waves from the Landers earthquake was responsible for sudden weakening of the crust. If sudden weakening of the crust resulting from dynamic loading plays an important role in triggering earthquakes, deterministic predictions of the initiation time of an earthquake will be difficult.

In the following, we discuss some issues of long-term forecast and short-term prediction separately, because they have very different social implications. Sometimes forecasts on intermediate time scales are treated separately from long-term forecasts, but here we treat them together as long-term forecasts. There is no generally used definition of "short-term," "intermediate-term," and "long-term" predictions, and we generally follow the definition given by Sykes *et al.* (1999) as a useful guideline: Immediate alert (0 to 20 sec), Short-term prediction (hours to weeks), Intermediate-term prediction (1 month to 10 years), Long-term prediction (10 to 30 years), Long-term potential (>30 years). The actual usage, however, may vary depending on the specific circumstances.

3. Long-Term Forecast

The basis of long-term forecast is the elastic rebound theory (Reid, 1910). If the stress accumulates at a constant rate, and the strength of the crust is constant, one would expect a relatively regular recurrence of earthquakes on a given segment of fault. However, due to previously mentioned fault interactions, weakening of crust due to increase in pore pressures, or some nonlinear processes, the actual occurrence can be more irregular than would be expected from the simple elastic rebound theory. Even with this difficulty, long-term forecasts are useful because considerably large uncertainties can be tolerated for long-term applications. In general, such forecasts are easier for the places where stress accumulation rate is faster (e.g., plate boundaries with fast plate motion) than for the places with slower stress accumulation rates.

3.1 Seismic Gap Method

The seismic gap method is most frequently used for long-term forecasts. The basic premise is that large earthquakes occur more or less regularly in space and time as a result of gradual stress buildup and sudden stress release by failure. Imamura (1928) documented historical earthquakes in the Nankai trough, southwest Japan, and on the basis of regularity of the occurrence of large earthquakes, he forecast large earthquakes in this area. In fact, two large earthquakes with $M \approx 8$ occurred in this area in 1944 and 1946. A similar idea was used by Fedotov (1965) for the Kamchatka and Kurile Is. regions, and by Mogi (1968) for all of Japan.

Kelleher (1970), Kelleher *et al.* (1973), and others used this method more formally in the framework of plate tectonics. A portion of a plate boundary that has historically experienced large earthquakes, but not recently (e.g., 30 years), is more likely to produce a large earthquake in the next few decades than those places that have recently experienced large events—this portion of a plate boundary is called a seismic gap. This method has been used to forecast earthquakes on subduction zones and some strike-slip plate boundaries such as the San Andreas fault. Long-term forecasts made with the gap method are generally considered to have been successful for several large ($M > 7.5$) earthquakes (e.g., the 1972 Sitka, Alaska, earthquake (Kelleher, 1970), the 1973 Nemuro-Oki, Japan, earthquake (Utsu, 1970), the 1978 Oaxaca, Mexico, earthquake (Kelleher *et al.*, 1973), the 1985 Valparaiso, Chile, earthquake (Kelleher, 1972; Nishenko, 1985)), but the method is subject to all the uncertainties previously mentioned, and is not meant to be used for definitive forecasts. In fact, there were several cases in which the forecast with this method caused confusing results. Wyss and Wiemer (1999) describe the case for the 1986 Andreanof Is. earthquake, and emphasize that oversimplified models can lead to a confusing result, and slip history and tectonic difference of fault segments need to be considered in assessing the seismic potential of gaps.

The application of the gap method to smaller earthquakes is subject to even larger uncertainties and its usefulness is somewhat questionable. For smaller events, the uncertainty in the earthquake locations is often comparable to the size of the gap so that the location of the gap becomes ambiguous. Also implicit in this method is the assumption that approximately the same segment along subduction zones fails repeatedly in approximately the same fashion, but many examples have demonstrated that this is not always the case. The rupture patterns vary significantly from sequence to sequence (e.g., the 1906 Colombia earthquake (Kelleher, 1972; Kanamori and McNally, 1982)). This spatial variability is probably a result of complex interactions between different parts of plate boundaries.

Also, large earthquakes occur not only on the main plate boundary but also in the areas adjacent to it, thereby adding complexity to the spatial and temporal pattern of seismicity. Examples are the 1933 Sanriku earthquake ($M_w = 8.4$) and the 1994 Shikotan earthquake ($M_w = 8.3$), both of which occurred within the subducting oceanic plate, but not directly related to the stress accumulation process on the subduction boundary. Because of these difficulties, there have been controversies on the usefulness of the gap method, especially for events with $M < 7.5$ (Jackson and Kagan, 1991, 1993; Nishenko and Sykes, 1993).

Despite these difficulties, the long-term forecast of large earthquakes using the gap method is useful for understanding the long-term behavior of seismic zones, as long as the forecast is interpreted with caution. Given the complex earthquake rupture process, use of oversimplified models—whether in favor of or against the gap hypothesis—should be avoided.

Following are three examples of long-term forecasts that illustrate the use of this method.

3.1.1 Parkfield Earthquake Prediction Experiment

Moderate earthquakes with $M \approx 6$ have occurred on the San Andreas fault near Parkfield, California, in 1922, 1934, and 1966. Further studies revealed that similar-size earthquakes occurred earlier in 1857, 1881, and 1901 in approximately the same area. Several seismologists noted that these events seem to have occurred relatively regularly, with an average interval of about 22 years (Bakun and McEvilly, 1984). Also, the pattern of foreshocks of the 1966 event is strikingly similar to that of the 1934 event. This regularity and similarity led some seismologists to believe that these Parkfield earthquakes are "characteristic" earthquakes occurring repeatedly at approximately the same location on the San Andreas fault. If that regularity had continued into the future, the next event would have been expected to occur sometime around 1988. It is to be noted, however, that (1) the locations of these events are not accurately known, (2) the record before 1900 is uncertain, (3) the 1857 event is an immediate foreshock of the $M \approx 8$ Fort Tejon earthquake and is not an isolated event like the other events, and (4) the range of inter-event intervals is actually fairly large, 12 to 32 years.

Despite these complexities, according to one estimate, the probability of the next characteristic Parkfield earthquake occurring before 1993 was 0.95. A focused earthquake prediction experiment (Parkfield Earthquake Prediction Experiment) began in 1985 (Bakun and McEvilly, 1984; Bakun and Lindh, 1985), and many instruments (seismometers, creep-meters, strainmeters, laser ranging devices, etc.) were installed to monitor various seismological and geophysical parameters with the hope of capturing precursory phenomena before the next Parkfield earthquake. Although many interesting results on seismicity, velocity structures, wave propagation characteristics, and fault slip patterns have been obtained from the data recorded with these instruments, the predicted earthquake has not occurred yet. This result demonstrates that the earthquake process in the Earth's crust is complex, involving many parameters, and predictions on the basis of a simple model with a small number of parameters are inevitably uncertain. In retrospect, many reasons can be given to explain why the predicted earthquake did not occur. For example, (1) the past Parkfield earthquakes may not have occurred on exactly the same segment of the San Andreas fault (Segall and Harris, 1987) and the characteristic earthquake model cannot be used, (2) earthquake activities in the adjacent areas (e.g., Coalinga) may have significantly decreased the stress loading rate on the San Andreas fault near Parkfield, thereby delaying the occurrence of the predicted event (e.g., Miller, 1996), (3) the earthquake process is more random than is usually assumed in the characteristic earthquake model.

Aside from the scientific issues, this type of experiment has merit in allowing the local governments to develop a useful protocol for informing state and local officials about time-dependent hazard levels (NEPECWG, 1994). However, this should not be confused with the scientific issues associated with the Parkfield experiment.

Other issues on the Parkfield prediction are discussed in Savage (1993) and Michael and Langbein (1993).

3.1.2 The 1989 Loma Prieta Earthquake

The 1989 Loma Prieta earthquake ($M_w = 6.9$) occurred in an area where long-term or intermediate-term forecasts of a large earthquake had been made by several seismologists. Most of these forecasts were based on the elastic rebound theory: The next earthquake is likely to occur when the strain released in the previous one has been restored.

The Loma Prieta earthquake occurred near the southeastern end of the rupture zone of the 1906 San Francisco earthquake. The amount of surface break associated with the 1906 San Francisco earthquake suggested that the slip during the 1906 San Francisco earthquake was not large enough to completely release the accumulated strain (i.e., slip deficit) along the Santa Cruz Mountain segment of the San Andreas fault. Also, this segment exhibited a distinct absence of small earthquakes over a distance of some 40 km, a pattern often thought to appear before large earthquakes. On the basis of these observations, as well as the fault geometry, several forecasts had been made for the rupture length, magnitude, and approximate timing, expressed in probabilistic terms. What actually occurred came very close to these forecasts. For example, Sykes and Nishenko (1984) forecast an $M = 7.0$ earthquake with a probability of 0.19 to 0.95 in 20 years. Likewise, Lindh (1983) made a forecast for an $M = 6.5$ earthquake with a probability of 0.30 in 20 years. Scholz (1985) estimated that a rupture of the 75-km-long slip-deficient segment could occur in 60 to 110 years, resulting in an $M = 6.9$ earthquake. By the usual standard for intermediate-term predictions, these forecasts are considered very accurate.

However, one puzzling aspect of these forecasts is that the Loma Prieta earthquake did not seem to have occurred on the San Andreas fault in a strict sense. The fault plane of the Loma Prieta earthquake inferred from the earthquake mechanism and the aftershock distribution is dipping about 70°SW, and does not coincide with that of the San Andreas fault. The fault slip motion had a large vertical component, and is different from what is expected of the San Andreas fault. Because the very basis of the forecast was the slip deficit on the San Andreas fault, the forecast would lose its logical basis if the Loma Prieta earthquake did not occur on the San Andreas fault. Furthermore, the strain data suggest significant amounts of slip at depth on the San Andreas fault during the 1906 earthquake (Thatcher and Losowski, 1987). If this is the case, there was no slip deficit on the San Andreas fault to begin with. Another argument on the basis of the crustal deformation pattern suggests that the repeat time of the Loma Prieta type earthquakes could be several thousand years, rather than several hundred years (Valensise and Ward, 1991). If these arguments are valid, the 1989 Loma Prieta earthquake was not the predicted earthquake, but was a relatively rare event on a structure different from the San Andreas fault that happened to have occurred at about the predicted time.

It would be fair to say that the situation is more complex than either of these simple arguments indicates. The overall regional strain deficit could have existed and the preearthquake seismicity in the area may have justified some forecast, but considering the complexity in the fault structure in the area, one would not expect a very simple scenario as presented to work all the time. For more details, see Harris (1998a).

3.1.3 Tokai, Japan, Earthquake Prediction

Large earthquakes have repeatedly occurred along the Nankai Trough along the southwestern coast of Japan. The sequence during the past 500 years includes large ($M \approx 8$) earthquakes in 1498, 1605, 1707, 1854, and 1944–1946, with an average interval of about 120 years (Ando, 1975). In the early 1970s, several Japanese seismologists noticed that the 1944–1946 sequence was somewhat smaller than the two previous events, and suggested that the rupture during the 1944–1946 sequence did not reach the northeastern part of the Nankai trough (called the Suruga trough), thereby leaving this portion as a mature seismic gap (this argument is similar to that for the forecast of the Loma Prieta earthquake) (Ishibashi, 1977). There is some evidence that the rupture of both the 1854 and 1707 earthquakes extended all the way to the Suruga trough.

With this argument, this portion of the Nankai trough became known as the Tokai gap, with a potential of causing an $M \approx 8$ earthquake in the near future. In 1978, the Japanese government introduced the Large-Scale Earthquake Countermeasures Act, and embarked on an extensive project to monitor the Tokai gap. Many institutions deployed all kinds of instruments for monitoring geophysical activities, and detailed plans for emergency relief efforts were made.

It is more than 20 years since the project began, but the predicted Tokai earthquake has not occurred yet. It is possible that the predicted earthquake is yet to occur, or the deformation pattern near the corner of the plate boundary is so complex that a simple recurrence model cannot be used. In the latter case, the predicted event may not occur in the near future. Because the Tokai earthquake prediction did not have any specific prediction time window, it is hard to assess the significance of this prediction effort at this time. However, many seismologists now seem to agree that accurate forecasts are difficult even for this plate boundary with a seemingly regular historical earthquake sequence.

The complex geometry of the plate boundary (e.g., segmentation) and the effects of large earthquakes in the adjacent areas may have affected the state of stress on the plate boundary.

3.2 Stress Transfer

A question is often raised regarding whether the stress on a particular fault is changing in the direction to promote failure or not. In addition to secular loading by plate motion, the stress on a fault is affected by past earthquakes in adjacent areas. If the size and mechanism of earthquakes in the adjacent areas are known, we can compute the stress changes on the fault on a time scale of a few decades. This concept has been tested by Smith and Van de Lindt (1969), Rybicki (1973), Yamashina (1979), and Das and Scholz (1981). For the 1968 Borrego Mountain, California, earthquake, a significant aftershock cluster occurred in the area where shear stress was increased by the mainshock. This concept was more rigorously applied to several recent earthquakes (the 1992 Landers earthquake (Stein *et al.*, 1992; Harris and Simpson, 1992; Jaume and Sykes, 1992), the 1994 Northridge earthquake (Stein *et al.*, 1994), and the 1995 Kobe earthquake (Toda *et al.*, 1998)). In some cases (e.g., the 1992 Big Bear earthquake ($M = 6.4$) which occurred soon after the Landers earthquake; some aftershocks of the Landers, Northridge, and Kobe earthquakes), the hypothesis of triggering by stress transfer is well demonstrated. In other cases, the situation is not that obvious (Hardebeck *et al.*, 1998). The method has also been used to understand long-term seismicity in California as a result of loading and unloading of faults caused by large earthquakes in the area (Deng and Sykes, 1997; Harris and Simpson, 1996).

In general, if the geometry of the fault system, the loading mechanism, and the structure and properties of the crust are known in an area, it should be possible to compute the regional stress changes and infer the seismic behavior of the entire area (Rybicki *et al.*, 1985). Stress transfer between different faults is an important mechanism controlling regional seismicity on decadal time scales (see Harris, 1998b; Stein, 1999; Chapter 73 by Harris), but the lack of detailed knowledge of the initial stress condition and the model parameters makes it difficult to make definitive forecasts of future seismicity.

3.3 Seismicity Patterns

The change in the stress or strength of the crust may manifest itself as spatial and temporal changes in seismicity patterns such as quiescence, increase, and doughnut patterns (Mogi, 1969; Utsu, 1970; Wyss and Habermann, 1979; Habermann, 1981). For some earthquakes, seismic quiescence had been identified before the occurrence (e.g., 1973 Nemuro-Oki earthquake (Utsu, 1970); the 1978 Oaxaca, Mexico, earthquake, (Ohtake *et al.*, 1977); Bear Valley, California (Wyss and Burford, 1987), 1986 Andreanof Islands earthquake (Kisslinger, 1988)). In some retrospective studies, seismicity patterns were related to the occurrence of several large earthquakes (e.g., the 1906 San Francisco earthquake (Ellsworth *et al.*, 1981), the 1868, 1906, and 1989 earthquakes in the San Francisco Bay Area (Sykes and Jaume, 1990)), but the type of pattern may depend on the regional tectonic structure, fault geometries, and the loading system; it is unclear at present how to quantitatively relate seismicity patterns to an impending earthquake. In some cases, the completeness of seismicity catalogs used for identifying seismicity patterns was questioned (e.g., Whiteside and Habermann, 1989).

Another general approach along this line is a formal assessment of earthquake potential primarily using earthquake catalogs (e.g., Gelfand *et al.*, 1976; Keilis-Borok *et al.*, 1988; Keilis-Borok, 1996). This approach is based on systematic examinations of earthquake catalogs to identify relations between some seismicity patterns (such as clustering, quiescence, and sudden increase in activity) and past large earthquakes, and using these relations to forecast future seismic activities on intermediate time scales. The method is being tested (e.g., Kossobokov *et al.*, 1999; Rotwain and Novikova, 1999), but its usefulness for practical purposes is yet to be determined.

Another use of seismicity data is to relate the temporal variation of cumulative seismic moment of earthquakes in a region to a behavior of a system that evolves toward a critical point. Summaries of the method are found in Jaume and Sykes (1999), and a review of accelerating seismic energy release prior to large earthquakes, and its relation to cellular automata models, is in Sammis and Smith (1999).

4. Short-Term Prediction

For the average citizen and the public, "Earthquake Prediction" means a short-term prediction of a specific earthquake on a relatively short time scale, e.g., a few weeks. Such prediction must specify the time, place, and magnitude of the earthquake in question with sufficiently high reliability and probability (Allen, 1976). However, for the reasons mentioned previously, any such short-term prediction, if made, is bound to be very uncertain. Even uncertain predictions may be useful for those places where the social and economical environments are relatively simple and false alarms can be socially tolerated. However, in modern highly industrialized cities with complex lifelines, communication systems, and financial networks, such uncertain predictions could inadvertently damage local and global economies, so they are generally not useful unless the society involved is willing to accept the potential loss that could be inflicted by false alarms.

Despite this difficulty, many attempts to observe precursory phenomena for the purpose of short-term earthquake prediction have been made.

4.1 Precursors and Anomalous Phenomena

The term "precursor" means two different things. In a restricted usage, "precursor" implies some anomalous phenomenon that always occurs before an earthquake in a consistent manner. This is the type of precursor one would wish to find for short-term earthquake prediction. As far as we know, universally accepted precursors that occur consistently before every major earthquake have not yet been found.

In contrast, "precursor" is often used in a second sense to mean some anomalous phenomena that may occur before large earthquakes. Because an earthquake may involve nonlinear preparatory processes before failure, it is reasonable to expect a precursor of this type. However, it may not always occur before every earthquake, or even if it occurs, it may not always be followed by a large earthquake. Thus, in this case, the precursor cannot be used for a definitive earthquake prediction. Nevertheless, it is an interesting physical phenomenon worthy of scientific study. Foreshocks are a good example of a precursor of this type. Some large earthquakes were preceded by distinct foreshock activity, but many earthquakes do not have foreshocks. Also, a group of small earthquakes can occur without any major earthquake following it.

These precursors may be identified in retrospective studies, but it would be very difficult to identify some anomalous observations as a precursor of a large earthquake before its occurrence. Even if an anomaly were detected, it would be difficult to use it for accurate predictions of the size and timing of the impending earthquake, considering the stochastic nature of earthquakes.

Many anecdotal or qualitative reports on earthquake precursors can be found in the literature (Rikitake, 1986). Systematic efforts to detect precursors began in the 1960s. These efforts included measurements of seismicity, strain, seismic velocities, electric resistivity and potential, radio-frequency emission, ground water level, and ground water chemistry.

Encouraging reports of large (about 10%) precursory changes in the ratio of seismic P velocity to S velocity were made for several earthquakes (Aggarwal *et al.*, 1973; Whitcomb *et al.*, 1973). Similar changes had been reported earlier in the former Soviet Union (Semenov, 1969; Nersesov, 1970) and China. These changes were interpreted as manifestations of rock-dilatancy and fluid diffusion in micro-cracks just before failure (Scholz *et al.*, 1973). However, many precise measurements using not only earthquakes but also controlled sources, performed following the initial reports, failed to verify the large changes in the velocity reported by earlier studies (e.g., McEvilly and Johnson, 1973, 1974). In most cases, the velocity changes, if detected at all, were less than 1% or below the experimental noise level.

Similarly, large changes in ground-water chemistry, especially the concentration of radon, were reported before several large earthquakes in the former Soviet Union and China. Some results in Japan, especially the change before the 1978 Izu-Oshima earthquake, are considered significant by some (Wakita *et al.*, 1980). Tsunogai and Wakita (1995) and Igarashi *et al.* (1995) reported intriguing changes in the chloride ion and radon concentrations in ground water before the 1995 Kobe, Japan, earthquake. However, the results in the United States were generally not encouraging, and most geochemical monitoring efforts have been discontinued. It is probably fair to say that the negative results from seismic velocity ratio and radon monitoring in the United States may not be entirely definitive because of the lack of instruments very close to the epicenters of large earthquakes, but most seismologists would agree that these precursors, if they exist, are not easily detectable.

Several intriguing hydrological precursors have been reported (Roeloffs, 1988), but more complete documentation of the data needs to be made before they can be used for a definitive interpretation of crustal processes leading to seismic failure.

An intriguing observation of very low-frequency (0.1 to 10 Hz) radio (RF) emission was reported for the 1989 Loma Prieta, California, earthquake (Fraser-Smith *et al.*, 1990). The level of RF emission detected by an antenna located at about 7 km from the epicenter increased far above the background level about 3 hours before the earthquake. The emission also increased 12 days and 1 day before the earthquake. Although the exact cause of this emission is not established, this observation is probably one of the clearest anomalous signals detected before a large earthquake.

Crampin *et al.* (1999) recently made an interesting observation of shear-wave splitting. They used temporal variations of shear-wave splitting to correctly forecast the time and magnitude of an $M = 5$ earthquake in Iceland.

Efforts to detect slow strain precursors have been extensive in California, but no obvious strain precursors have been detected (e.g., Johnston *et al.*, 1990, 1994). It is important to note that a slow strain change was observed in 1993 near San Juan Bautista, California (Linde *et al.*, 1996), but no large earthquake followed it. For some subduction-zone earthquakes (e.g., the 1960 Chilean earthquake, Kanamori and Cipar (1974); Cifuentes and Silver (1989), the 1983 Akita-Oki, Japan, earthquake (Linde *et al.*, 1988), and the 1944 Tonankai, Japan, earthquake (Mogi, 1984)), slow deformations prior to the mainshock have been reported, but the instrumental data are not complete enough to make definitive cases.

A prediction method using changes in electric potential has been extensively used for prediction of earthquakes in Greece (e.g., Varotsos and Lazaridou, 1991), but its validity is presently vigorously debated (Lighthill, 1996; Geller, 1996).

Although many precursors have been reported, the study made by a committee under the International Association of Seismology and the Earth's Interior (IASPEI) (Wyss, 1991) concluded that only 3 out of 31 precursors subjected to review qualified as such. Although this type of evaluation depends on the criteria used, it is reasonable to say that reliable predictions using this type of precursor seem to be difficult at present (see also Wyss, 1997a).

Despite the limited value of "precursors" for short-term earthquake prediction, studies of such preparatory processes are important for a better understanding of the physics leading up to seismic failure in the Earth's crust, and careful, systematic, and quantitative investigations may be warranted.

One intriguing example of a short-term prediction is that of the 1975 Haicheng, China, earthquake. A destructive earthquake ($M = 7.3$) occurred near Haicheng, China, on February 4, 1975. More than 1 million people lived near the epicenter. It has been widely reported that this earthquake was successfully predicted. Unfortunately, the Cultural Revolution was still taking place in 1975, and detailed information did not emerge in peer-reviewed scientific literature. Thus, it is not possible to assess this prediction with complete objectivity.

Judging from the various reports on the Haicheng earthquake, it appears that very extensive foreshock activity, including a few hundred instrumentally recorded events, played the most important role in motivating mass evacuation, which saved many thousands of lives. However, it is unclear (1) how many false alarms had been issued before the final evacuation, (2) whether the evacuation was done under the direction of the local government or by more spontaneous decision by the local units or residents, and (3) what the total number of casualties was (the estimate ranges from 0 to 1300). Without knowing these details, it is unclear whether the methodology used in this prediction would work consistently for earthquake prediction purposes in other places, especially other countries with different economic and social environments.

Another example in which somewhat uncertain short-term predictions were actually used for practical purposes is the 1997 earthquakes in Jiashi, Xinjiang, China (Zhang *et al.*, 1999). Anomalous changes in several geophysical parameters were used to predict some events in an active swarm sequence. Again, it is unclear whether similar methods are practical in other countries with different economic and social environments.

5. Strategy for Seismic Hazard Mitigation

Given the uncertainty and indeterminacy described thus far, the important question becomes how can we effectively utilize the physics-based forecasts to reduce the threat of earthquakes? The usefulness of such forecasts depends on the time scale involved for such assessments. To effectively mitigate the impact of future earthquakes, seismic hazards need to be addressed on several different time scales. On the time scale of decades, land use regulations and building codes need to be improved. On the time scale of a few years, earthquake preparedness measures should be encouraged at personal and community levels. On shorter time scales, months to days, accurate earthquake predictions of size, location, and time would be required.

In the following we discuss the mitigation strategies with different time scales.

5.1 Regional Seismic Hazard Assessment

The seismic gap method can be extended to a general methodology for assessing regional seismic hazards. The strain rate in a region can be computed from the rate of plate motion. If we assume that a certain fraction, η, of the strain is relieved by earthquakes, one can estimate the overall rate of earthquake occurrence in the area. Then, if we assume that the size distribution is governed by the conventional magnitude–frequency relation (this relation is often called the Gutenberg-Richter relation, or Ishimoto-Iida relation), or one of its variants, we can estimate the average return period of earthquakes with a given magnitude. If we assume that $\eta = 1$, then the method gives the upper bound of the regional seismic hazard. Although it is in general difficult to determine the value of η, the regional seismicity and geological data can be used to place some constraints on the model and improve the estimate. Because seismological, geodetic, and geological data contain information on different time scales, we can make a more comprehensive estimate of regional seismic hazard by combining all of these data. However, it is not easy to determine the real uncertainty of the estimate because the database is limited and many assumptions are implicitly or explicitly made.

The long-term seismic hazard is usually expressed in maps portraying the likelihood of earthquake occurrence or of specific parameters such as the probability of exceedance of given levels of ground shaking over a certain period (e.g., 30 years). In some cases the hazard value is time-dependent in the sense that it depends on the time since the last large earthquake in the region (e.g., Working Group on California Earthquake Probabilities, 1988). In other cases, the hazard value is estimated on the basis of integrated geological and seismological data for a region, and is time-independent in the sense that it does not change with time from some specific earthquakes in the region (e.g., Working Group on California Earthquake Probabilities, 1995, 1999; Frankel *et al.*, 1996). This type of long-term hazard estimate is important for various seismic hazard reduction measures such as the development of realistic building codes, retrofitting existing structures, and land-use planning. The US building codes are based on time-independent hazard maps.

As already mentioned, earthquake hazard assessment is fundamentally a predictive effort, and is subject to all the uncertainties caused by the limited amount of data and the models used. Also, when it is used for practical purposes, its limitations and uncertainties need to be carefully communicated to the practitioners and public so that the scientific information is properly interpreted and used. The distinction between hazard (the physical phenomenon such as ground shaking, magnitude of expected earthquake, etc) and risk (the likelihood of human and property loss that can result from the hazard) needs to be clearly made, and the hazard information should be judiciously used in conjunction with the concept of acceptable risk (i.e., how safe is safe enough?) appropriate for the question being addressed. More details on this topic are discussed in Chapter 65 by Somerville and Moriwaki.

5.2 Intermediate-Term Strategy

Although short-term prediction with high probability of success is not possible at present, nor in the foreseeable future, there is a possibility that improved physical measurements of various parameters of the crust can be used to identify the areas where the state of the crust is close to failure. For example, continuous monitoring of strain changes in the Earth's crust with GPS will provide us with critical information on where strain is accumulating rapidly, and where aseismic deformation is taking place (Heki, 1997; Kato *et al.*, 1998; Ozawa *et al.*, 1999).

Although the physics is still not well understood, some seismicity patterns, changes in electromagnetic properties, changes in discharge rate and chemistry of ground water, and episodic changes in strain could provide important information on future earthquake activity in the area. A probabilistic use of these precursory changes could provide a useful means for forecasting the likelihood of earthquakes in a region (Aki, 1981). However, it is important to note that the investigations of these phenomena should be considered exploratory at present, and overly optimistic statements on the usefulness of these studies for operational earthquake prediction should be avoided.

5.3 Short-Term Strategy

A short-term prediction, if any is made, is bound to be very uncertain. For certain purposes (e.g., deployment of strong-motion instruments, Yamaoka *et al.*, (1999)), short-term predictions with large uncertainties can be useful. However, even if such short-term predictions should become possible, large earthquakes in densely populated urban areas are likely to cause extensive damage and disruption to society.

5.4 Real-Time Strategy

To minimize the immediate impact of large earthquakes, a mitigation strategy using real-time technology has been implemented. Despite the fact that engineering designs of individual structures have improved significantly, modern urban and suburban regions as a whole are more vulnerable to earthquakes than ever. Effective seismic hazard reduction depends on taking full advantage of the recent technical advances in seismological methodology and instrumentation, computer, and telemetry technology. In highly industrialized communities, rapid earthquake information is critically important for emergency services agencies, utilities, communications, financial companies, and media to make quick reports and damage estimates, and to determine where emergency response is most needed. The recent earthquakes in Northridge, California, and Kobe, Japan, clearly demonstrated the need for such information. Several systems equipped to deal with these needs have been already implemented. With the improvement of seismic sensors and communication systems, a significant increase in the speed and reliability of such a system is possible, so that it will eventually have the capability of estimating the spatial distribution of strong ground motion within seconds after an earthquake. Some facilities could receive this information before ground shaking begins. This would allow for clean emergency shutdown or other protection of systems susceptible to damage, such as power stations, computer systems, and telecommunication networks.

The idea of using rapid earthquake information for emergency operations is not new, and several systems have been developed in Japan, Mexico, Taiwan, and the United States. The following are some examples.

5.4.1 Japan

In the late 1950s, simple seismometers were installed for a railway alarm system. Since the operation of the Bullet Train system started in 1964, an automatic system to stop or slow trains during strong earthquakes has been developed (Nakamura and Tucker, 1988). The most recent system, UrEDAS, utilizes a sophisticated seismic detection/location algorithm, and is currently used by the Japanese railway system. Also, some utility companies have developed real-time ground-motion detection systems for emergency services for their own facilities. Recently, the City of Yokohama embarked on a project to deploy a real-time 150-station strong-motion network.

5.4.2 Mexico

In 1985, a $M = 8.1$ earthquake in the Michoacan seismic gap, about 320 km west of Mexico City, caused very heavy damage in Mexico City. Because a similar large earthquake is expected within the next few decades in the Guerrero seismic gap, about 300 km southwest of Mexico City, a seismic alert system, SAS (Seismic Alert System), was developed as a public early warning system in 1991. This system has a specific objective: to detect $M > 6$ earthquakes in the Guerrero gap with a seismic network deployed in the gap area, and issue an early warning of strong ground motion to the residents and authorities in Mexico City. Because it takes about 100 sec for seismic waves to travel from the Guerrero area to Mexico City, this system could provide an early warning with up to 60 sec lead time. A $M = 7.3$ earthquake occurred on September 14, 1995, in the Guerrero gap, and this system successfully broadcast an alarm on commercial radio stations in Mexico City about 72 sec prior to the arrival of strong ground motion (Espinosa-Aranda *et al.*, 1995; Chapter 76 by Espinosa-Aranda).

5.4.3 Taiwan

Two prototype earthquake early warning systems have been implemented in Taiwan, one for a local area near Hualien, and another for the entire island (Lee *et al.*, 1996; Teng *et al.*, 1997; Chapter 64 by Shin *et al.*). These systems use a state-of-the-art seismic network technology, and are designed to provide critical information on earthquakes and resulting ground motions for various emergency and recovery operations (Wu *et al.*, 1999). During the recent Chi-Chi, Taiwan, earthquake ($M_w = 7.6$), these systems rapidly distributed critical information on the earthquake and ground motions to various emergency services groups in Taiwan to help minimize the impact of the earthquake (Tsai, 2000; Wu *et al.*, 2000).

5.4.4 United States

In 1990, the California Institute of Technology (Caltech) and the US Geological Survey (USGS) Pasadena Office initiated the CUBE (Caltech/USGS Broadcast of Earthquakes) project in southern California (Kanamori *et al.*, 1991). It was realized that closely coordinated efforts between academia, governments, and private companies are essential for effective earthquake mitigation in modern metropolitan areas such as Los Angeles. One of the important objectives of the CUBE project is to promote closely coordinated efforts between various organizations with a rapid and reliable earthquake information system during major earthquake sequences. In 1993, the University of California at Berkeley and the US Geological Survey Office in Menlo Park developed the REDI (Rapid Earthquake Data Integration Project) system to broadcast earthquake data in central California (Gee *et al.*, 1996; Chapter 77 by Gee *et al.*). In 1997, the US Geological Survey, the California Institute of Technology, and the California Division of Mines and Geology cooperated to create TriNet, the next-generation seismic information system for southern California (Chapter 78 by Hauksson *et al.*).

6. Conclusion

Despite the progress made in understanding the physics of earthquakes, the predictions of earthquake activity we can make today are inevitably very uncertain, mainly because of the highly complex nature of earthquake process. The question becomes whether such uncertain predictions are useful for society—Are such uncertain predictions societally acceptable and beneficial? Long-term forecast is important for various seismic hazard reduction measures, such as the development of realistic building codes, retrofitting existing structures, and land-use planning. Short-term predictions with the current level of uncertainty may not be beneficial for a highly industrialized and economically sophisticated society. However, such predictions could be useful for those places where the social and economical environments are such that false alarms can be socially tolerated. Whether short-term predictions with uncertainty are useful or not for a given society should be investigated not only by seismologists, but also by engineers, social scientists, government officials, and industry representatives of the society in question.

The next question, given this uncertainty, is, Can we use our present knowledge of earthquakes effectively for mitigation of seismic risk? There are many ways in which we can improve our ability to minimize the impact of earthquakes. One such approach is "real-time seismology," which includes not only technical development, but also promotion of coordinated efforts between scientists, engineers, government officials, and the general public through the use of real-time systems.

In order to make such efforts more effective, it is important to understand the basic physics of earthquakes, and solid basic research should be promoted. However, it is also important to be aware that more knowledge may not necessarily lead to better prediction capability. We may only understand better why it is so difficult to accurately predict short-term earthquake behavior. Because earthquake prediction is a matter of serious concern among the public and emergency services officials, it is the important responsibility of scientists to communicate to them what is possible and what is not possible at present.

Acknowledgments

I thank Paul Spudich, Evelyn Roeloffs, Max Wyss, and an anonymous reviewer for helpful comments.

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