LONG-TERM MRI ALGORITHMS, SHORT-TERM RADON ANOMALIES, AND EARLY WARNING: THE MEXICAN EXPERIENCE

LOMNITZ, C. Institute of Geophysics, UNAM, 04510 Mexico, D.F., Mexico.

Abstract

The Mexican experience in earthquake prediction provides encouraging results in long-term forecasting by the moment-ratio imaging method (MRI). This method is based on the suggestion that an earthquake of magnitude 7+ lowers the seismic moment potential over an epicentral distance on the order of 17 fault lengths, which may either enhance or depress the relative moment potential (MR) in adjacent regions. It was found that an MRI peak appeared 10-15 years before a major earthquake, such as the 1985 Michoacan event. So far all major events have been preceded by MRI peaks, including the 1985 Chile and the 1995 Kobe earthquakes. So far the method is applicable only to regions of high activity; otherwise the MRI records become too noisy.

Short-term prediction using radon and other geo-chemical precursors has shown promising initial results for artesian springs located in the coastal batholith. High radon peaks were detected in soils before large volcanic eruptions. Ground-water measurements appear to be sensitive to near earthquakes in the 3-4 magnitude range. No major shock has yet been recorded in the experimental area.

Finally, an attempt to exploit the unusually large epicentral distances of damaging shocks to Mexico City for early warning purposes has yielded disappointing results. The rate of false alarms to legitimate alarms has been around 50:1 and the record of casualty prevention has been dismal. A moderate effort in earthquake prediction seems more likely to pay off, especially as the presence of the expensive early warning system provides an alibi for laxity in enforcing building regulations. Mexico may represent a natural laboratory for testing new approaches to earthquake prediction.

Is earthquake prediction possible?

The history of earthquake prediction research is unsteady. In the early period of seismology prediction was the central objective of the young science. In the early 1920's seismologists believed that earthquakes could be predicted by extrapolating the rates of plate motion. Later, Richter dismissed prediction as a form of witchcraft. After 1964 the efforts of Japan, China and Russia induced a new sensation of optimism as various precursors began to be tested (Lomnitz, 1994).

The paper by Bak et al. (1988) and subsequent investigations introduceed the idea that earthquakes are a product of self-organized criticality. Subsequently, the critique by Geller of the Japanese earthquake prediction program led to its partial cancellation, and the view that earthquakes cannot be predicted gained a certain amount of acceptance. The idea is that self-organized criticality is extremely dependent on initial conditions: and we know almost nothing about the initial conditions of the earth. Hence earthquakes cannot be predictable.

While this position may seem plausible in theory, the fact is that total unpredictability does not exist in reality because all systems have regularities, such as space-time correlations, attractors and so on. In practice this translates as a finite prediction time. The weather is a part of the same system which generates earthquakes: its prediction time is on the order of days. Even if the prediction time of earthquakes were of the same order the effort of prediction research would be worthwhile.

Weather prediction became increasingly successful after new methods of observation (radar, radiosondes, satellites) became available. But peasants have predicted the weather for ages. In 1992 a spokesman for the U.S. Geological Survey was quoted as saying that "Many of us in the scientific community feel intuitively that the Landers-Big Bear quake sequence has increased the probability of large earthquakes over the next few years." Two years later the destructive Northridge earthquake occurred in Southern California, and in 1999 another shock similar to Landers occurred in the same region. The estimated return period of these earthquakes was on the order of 10,000 years. The events were preceded by foreshocks.

It seems likely that earthquake prediction at the level of present performance of weather prediction is still in the distant future, especially as direct methods of observation comparable to satellites are not available for the earth's interior. But in principle the problems involved in both forms of prediction are similar.

The Mexican experience

The earthquake hazard situation in Mexico is unique in that Mexico City is located at 350 to 450 km inland from an active subduction zone and the vulnerability of Mexico City is vastly larger than that of the intervening region. The subduction zone describes an elliptical arc of more than 500 km length about Mexico City, and almost any large earthquake on this arc can produce severe damage in the metropolitan area. Thus the potential reward of advances in earthquake hazard prediction and control is very great.

The best-known attempt to predict the recurrence of large earthquakes at plate boundaries was the concept of seismic gaps (Fedotov, 1965; Sykes, 1968). In general, identified seismic gaps correlate with the locations of subsequent large earthquakes in Mexico as elsewhere. However, on the whole the efforts to quantify the seismic gap hypothesis have not been very successful.

One approach which has been tried in Mexico with some initial success is the MRI algorithm (Lomnitz, 1993; 1996). This is based on the idea of healing, i.e. that the time needed for a rupture on a plate boundary depends on the location and the seismic moment of all preceding earthquakes. The healing equation is exponential as for the healing of wounds:

$$m_0(t) = M_0 \exp(-0.69315t / \tau) \qquad (1)$$

where τ is the half-life of the moment anomaly m_o produced by an earthquake of moment Mo at time t=0. Thus $m_o(t+\tau)=0.5m_o(t)$. If we assume that the effects of overlapping moment releases are additive, we may compute the local value of m_o as a sum of terms similar to the right-hand side of Eq (1).

It was found that the graphical expression of mapping m_o at a plate boundary was not very useful because it decayed to zero with increasing hazard, and because it depended on the relative seismicity of a given segment of plate boundary. Better results were obtained when we used the reciprocal of the normalized value of m_o, called the "moment ratio":

$$\Re(t) = \overline{M} / m_0(t) \qquad (2)$$

where $\overline{M}$ is the historical cumulative moment release in the epicentral region.

Preliminary results indicate that τ is around 20 years in Mexico. This means roughly that a rupture shrinks to half its size in 20 years. Before the 1985 Mexico earthquake the moment ratio from Eq (2) was about 7 times the mean background value along the plate boundary. Similarly, in Japan the moment ratio in the Kobe area was about twice the background value before the 1995 earthquake. After each major earthquake the moment ratio drops below the mean background value and neighboring regions may become more prominent as a result. The procedure used for producing graphs of moment ratio is called Moment Ratio Imaging, or MRI.

At the present stage we use only earthquakes of magnitude 7 or above, and we define the space window as 17 fault lengths. If this is done, it turns out that MRI peaks begin to appear as early as 15 years before the earthquake. All major events at subduction boundaries which we have imaged so far were preceded by prominent MRI peaks at least 10 years before the event. The cases of the 1985 central Chile and 1995 Kobe events were particularly clear as those events were located in areas of low moment-ratio background.

MRI is not distinct from the seismic gap hypothesis, it is merely a quantitative approach based on the same assumptions. However, if it had been used in Japan the Kobe earthquake could have been anticipated, as the MRI peak for Kobe had grown to be almost the same size as for the Tokai area in 1994. The point is that MRI peaks are relative—they depend on the activity of adjacent regions.

Ground-water anomalies

Chemical anomalies in ground water are among the earliest and most consistently useful earthquake precursors. Radon has been extensively used because it is relatively easy to detect and to quantify. Since 1997 we have begun observing geochemical parameters in natural springs located in the coastal batholith of Guerrero, near the plate boundary and inland from the city of Acapulco. These are thermal springs in granitic intrusives, more than 350 km from the nearest volcanic area. They are not fed by surface sources. Seismic activity in the region is high.

In cooperation with a German group in Freiberg, specially designed online analysis equipment has been installed. The spectrum of alpha radiation is measured and the relative abundances of various chemical species are recorded in real time. The chemical signals are transmitted by satellite. No major seismic events have occurred in the region and it may be premature to report any results; but some correlation between peaks in CO_2 and seismic activity seems to exist. A second station is now being installed on the same plate boundary.

This approach may be appropriate to Mexico because ground-water fluctuations in wells are commonly observed in the epicentral region before and after major Mexican earthquakes.

Early-warning systems

Mexico City is famous for its earthquake early-warning system known as SAS. This system was installed in 1993 by a semi-private group contracted by the city government. A network of 12 local seismic stations was installed along the coast of the state of Guerrero and the data were transmitted to Mexico City. Because of the large epicentral distance a detection of up to 50 seconds in advance of arrival of the P–wave signal can be achieved in theory.

Unfortunately the performance of the system was lower than anticipated. During the first three years of operation there were more than a dozen false alarms for one hit—and even this event caused no damage in Mexico City. More seriously, the major earthquakes which did occur were not detected because they occurred outside the geographical coverage of the network.

It is generally agreed that the geographical location of Mexico City is unusually favorable for an effective early-warning system because of the large distance to the plate boundary. However, the experience with the SAS system suggests that the detection network should surround Mexico City on all sides and especially where most of the earthquakes are likely to occur. This means a much more expensive system. The reliability of detection is also a major problem. Earthquakes of magnitude 4 to 4.5 are often mistaken for events of magnitude greater than 6. Finally the wide dissemination of the alarm over commercial radio and TV channels caused serious problems and a gradual erosion of public confidence in the system. At present the alarm is triggered manually by an operator and the signal is restricted to schools and public buildings. Even so, false alarms continue to be frequent.

In spite of the optimistic appraisals of the group operating the alarm the usefulness of such early-warning syystems has begun to be questioned. Even if it worked at a high level of reliability, a one-minute warning time may not provide a significant safety margin. On the other hand, it was found that responsible city authorities tend to use the early-warning system as an alibi or a substitute for tightening the inspection and retrofitting of unsafe structures. On the whole, experts are not confident that the overall level of earthquake safety in Mexico City has improved significantly over 1985.