Forecasting Earthquakes: The RELM Test

Earthquakes don't have precursors that can be reliably used for earthquake prediction. However, distributions of earthquakes (seismicity) can be used to forecast an earthquake hazard. These distributions in space, time, and magnitude can be studied in a variety of ways. The Regional Earthquake Likelihood Models (RELM) test compares the different approaches.

Recent earthquakes have demonstrated the extent of seismic hazards. The magnitude $m_w = 9.2 \pm 0.1$ Sumatra-Andaman earthquake from 2004 resulted in more than 230,000 deaths, primarily because of the resulting tsunami. A major problem was the lack of a tsunami warning system for the Indian Ocean. The magnitude $m_w = 9.1 \pm 0.1$ Tohuko, Japan earthquake in 2011 resulted in more than 15,867 deaths, and the estimated US$235-billion cost made it the most expensive natural disaster on record. The resulting tsunami had a runup of as much as 40 meters above sea level. The tsunami caused both a large percentage of the deaths and the meltdown and radioactive gas emissions at the Fukushima nuclear power plant.

Because earthquakes can be so disastrous, it's important that we use the tools we have to forecast future earthquake hazards to the best of our abilities. Here, we use the Regional Earthquake Likelihood Models (RELM) test to compare the effectiveness of various tools and approaches that measure earthquake distributions (seismicity) in space, time, and magnitude. Before we discuss the test's implications and future directions in earthquake forecasting (or prediction), let's consider some basic information about earthquake measurements and occurrences.

Earthquake Measurements and Occurrences

Earthquakes occur on preexisting faults. The standard measure of an earthquake's intensity is the seismic moment

$$M = GA_r\bar{\delta},$$

where A_r is the fault's rupture area, $\bar{\delta}$ is the mean displacement across the fault during the earthquake, and G is the shear modulus.[1] However, because of the historical use of seismographs to measure earthquake intensity, standard practice is to convert the seismic moment to the moment magnitude

$$m_w = \frac{2}{3}\log M - 6.1,$$

with M in joules.[1] For large earthquakes ($m_w > 5$), we can obtain the seismic moment directly from digital seismograph records. For small earthquakes, we use various empirical methods to obtain magnitudes.

For $m_w > 5$, the global seismic networks obtain a complete catalog of earthquakes. Because of

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the established validity of Equation 1 (shown in the following paragraph) over a wide range of magnitudes, catalog completeness is defined by a significant deviation from the scaling given in Equation 1. The annual number of $m_w > 5$ earthquakes is about 2,000 per year. Regional networks have variable sensitivities. In southern California, catalog completeness is available for $m > 1.8$, and the annual number is about 5,000 earthquakes per year.

A major contributor to the fear of earthquakes is the total absence of precursors. Possible precursory phenomena include changes in seismicity, changes in seismic velocities, tilt and strain precursors, electromagnetic signals, hydrologic phenomena, and chemical emissions. A few successes have been reported, but to date no precursors to large earthquakes have been detected that would provide reliable predictions. This was confirmed by the failure to observe any precursory phenomena prior to the 2004 Parkfield earthquake.[2] A series of $m \simeq 6$ earthquakes occurred on the San Andreas fault's Parkfield segment at intervals of about 25 years. In anticipation of the next event, the US Geological Survey began placing a large array of instruments adjacent to the fault segment in 1985. When the anticipated earthquake occurred in 2004, no precursory phenomena were observed. However, earthquakes don't occur randomly in space and time. Large earthquakes occur preferentially in regions where small earthquakes occur. Earthquakes are complex phenomena, but they do obey several scaling laws. One example is Guttenberg-Richter frequency-magnitude scaling. The cumulative number of earthquakes N_c with magnitudes greater than m in a region over a specified time period are well approximated by the relation

$$\log N_c = a - bm, \tag{1}$$

where most estimates of b are about 1.0 and a is a measure of the seismicity level.[1] We can use small earthquakes to determine a and extrapolate Equation 1 to determine the probability of large earthquake occurrence.

A question that many groups have studied is whether there are temporal variations in seismicity that we can use to forecast the occurrence of future earthquakes. About 10 percent of all earthquakes have one or more foreshocks.[3] These foreshocks have magnitudes close in magnitude to the succeeding main shock. In fact, the main shock is an aftershock of the foreshock that happens to be larger than the original main shock. The relatively small fraction of earthquakes that have foreshocks makes their use of little value in prediction.

Earthquakes on major faults (such as California's San Andreas) occur quasiperiodically. A reasonable hypothesis would be that the rate of regional seismicity would accelerate during the period between major earthquakes. There's no evidence that this occurs systematically. Background seismicity in California appears to be stationary. With the exception of years with large aftershock sequences, seismic activity in Southern California in the magnitude range $1.5 < m < 4$ for the period of 1983 to 2010 is well represented on a yearly basis by Equation 1, taking $a = 5.4$ and $b = 1.0$. Nevertheless, for the same area and time period, there's evidence for seismic activation (accelerated moment release) at moderate magnitudes prior to the Landers (1992) and Northridge (1994) earthquakes.[4] However, Jeanne Hardebeck and her colleagues have argued that it isn't possible to use an accelerated moment release to forecast an earthquake without knowing the subsequent earthquake's location—thus it can't be used for prospective forecasting.[5]

Basically retrospective forecasts—that is, a forecast of an earthquake that already has occurred—can't be trusted. This problem led to our decision to use the RELM test. RELM was the first open, competitive test of prospective earthquake forecasts.

RELM Test

To test methods for forecasting future earthquakes, the Southern California Earthquake Center formed the RELM working group in 2000.[6] For the first time, a competitive test of prospective earthquake forecasts was carried out. Research groups were encouraged to submit forecasts of future earthquakes in California. At the end of the test period, the forecasts would be compared with the actual earthquakes that occurred.

There were three ground rules for the RELM test. First, the test region to be studied was the state of California. However, the selected region extended somewhat beyond the state's boundaries (see Figure 1).

Second, a five-year time period for the test was selected extending from 1 January 2006 to 31 December 2010. Earthquakes with $m \geq 5$ were to be forecast. This magnitude cutoff was chosen because at least 20 $m \geq 5$ earthquakes could be expected in this period. The applicable magnitudes were taken from the Advanced National Seismic System online catalog (see www.ncedc.org/anss/anss-detail.html).

Third, participants were required to submit the number of earthquakes expected to occur in specified spatial cells during the test period. To do this, the test region was subdivided into N_c = 7,682 spatial cells with dimensions 0.1 × 0.1°.

In discussing the RELM test, we'll consider the forecast probability λ_i that a test earthquake would occur in cell i. The summation of λ_i over all cells is unity (where $m > 5$ will occur somewhere in the test region during the test period). The best forecast has the highest value of λ_i for the test earthquake considered.

The 14 forecasts submitted by eight groups are available on the RELM website (http://relm.cseptesting.org). To illustrate how seismicity is used to forecast earthquakes, we'll use the pattern informatics (PI) forecast submitted by James Holliday and his colleagues.[7]

In forecasting $m \geq 5$ earthquakes in a region divided into 0.1 × 0.1° cells, the rates of seismicity in the cells are studied to quantify anomalous behavior. Precursory changes that include either increases or decreases in seismicity are identified during a prescribed time interval. If changes exceed a prescribed threshold, hot spots are defined. The forecast is that future $m \geq 5$ earthquakes will occur in the hot spots. In the PI-based RELM forecast, all hot spot cells are given equal probabilities for an earthquake. This probability for an earthquake with $m > 5$ to occur in a test cell was $\lambda_i = 1.51 \times 10^{-3}$. Instead of being alarm-based, the RELM test was based on probabilities of earthquake occurrence in each cell in the test region. This required a continuous hazard assessment rather than a binary, alarm-based assessment. To do this, the Holliday forecast introduced a uniform probability of occurrence for hot spot cells and added smaller probabilities for non-hot spot cells, based on the relative intensity of the cell's seismicity.

During the test period of 1 January 2006 to 31 December 2010, there were $N_e = 31$ earthquakes in the test region with $m \geq 4.95$. Figure 1 shows the locations of the test earthquakes. Earthquakes occurred in 22 of the 7,682 test cells. The major earthquake that occurred during the test period was the $m_w = 7.2$ El Mayor-Cucapah earthquake on 4 April 2010. This earthquake was on the plate boundary between the North American and Pacific plates. The epicenter was about 50 km south of the Mexico-US border, but occurred within the test region. Eight test earthquakes were well-defined aftershocks of the El Mayor-Cucapah earthquake. A precursory swarm of eight test earthquakes also occurred in this region. This swarm of earthquakes can't be considered foreshocks, due to their relatively small magnitudes and early occurrence, but they might represent a seismic activation.

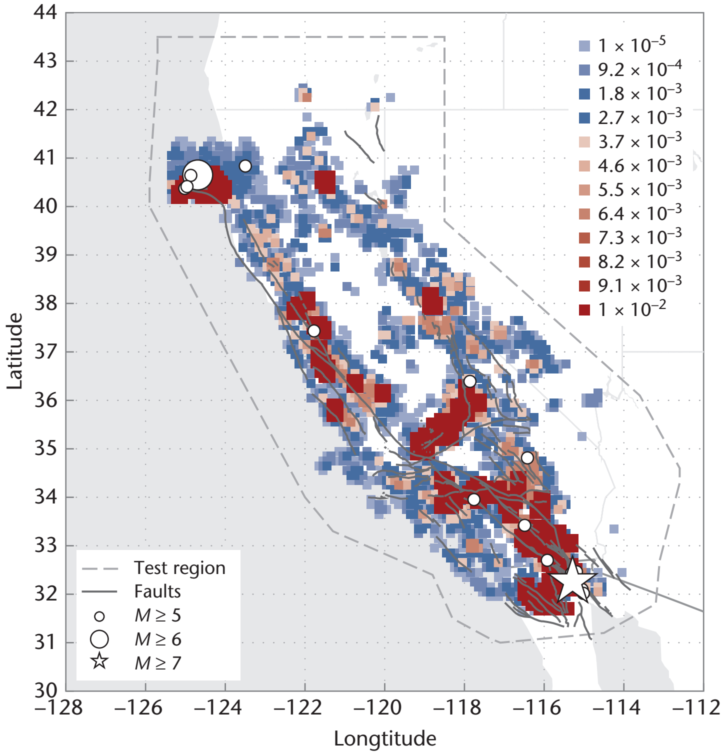


Figure 1. Map of the earthquake probabilities λ_i given for the test region by James Holliday and his colleagues using their pattern informatics (PI)-based forecast.[7] The "hot spots" are shown in red. The 31 test earthquakes are also shown.

Researchers have conducted several comprehensive evaluations of the RELM test.[8,9] Here, we'll restrict our discussion to the alarm-based (hot spot) aspects of Holliday's forecast.[7] As we've discussed, the hot spot forecast probability that an $m > 5$ earthquake would occur in a test cell during the test period was $\lambda_i = 1.51 \times 10^{-3}$. A perfect forecast—in which only the 22 cells where earthquakes occurred were forecast to have earthquakes—would have had $\lambda_i = 1/22 = 4.5 \times 10^{-2}$ in each of those 22 cells, and $\lambda_i = 0$ in the remaining 7,660 cells. A random forecast in which all 7,682 cells were given equal probabilities would have the probability

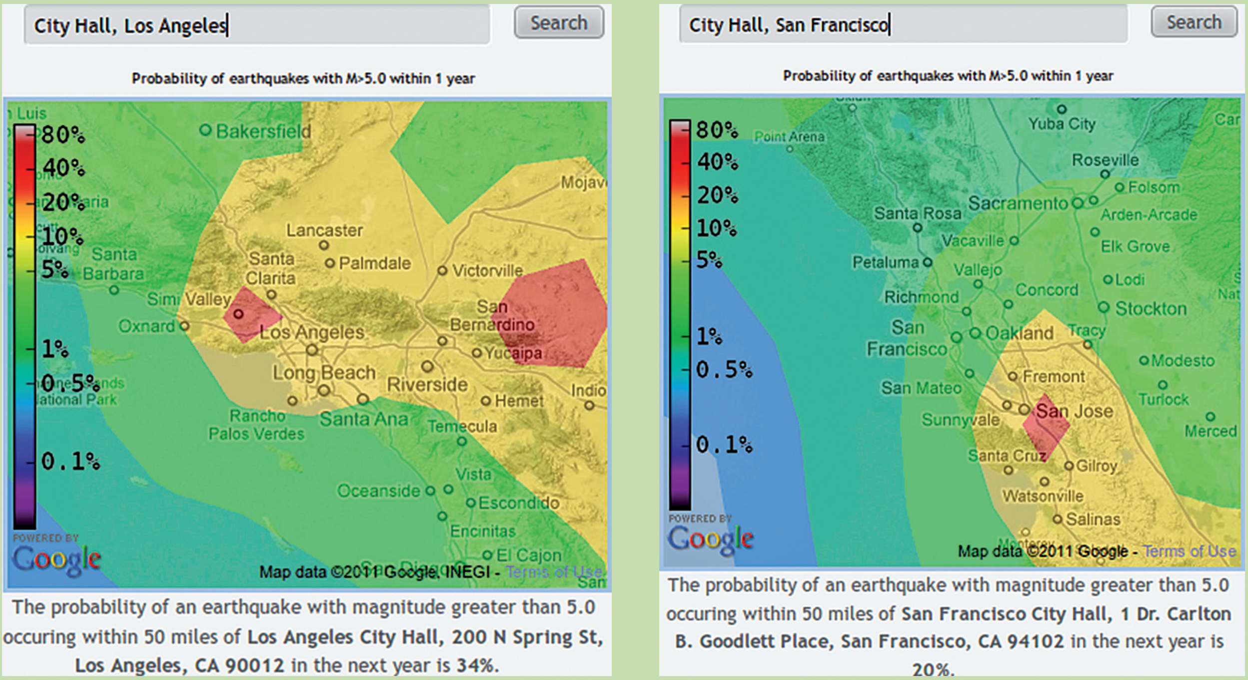
$$\lambda_{\text{random}} = 1/7{,}682 = 1.30 \times 10^{-4}$$

for all 7,682 test cells.[7] The hot spot forecast was a factor of 10 better than a random forecast, but a factor of 30 worse than a perfect forecast.

Another example of alarm-based forecasting is the alarms issued for tornado occurrence. An extensive methodology has been developed for evaluating tornado forecasts.[10] We now apply this

Do-It-Yourself Earthquake Forecasts

A widely accepted measure of the earthquake hazard at a specific location is the probability of a magnitude greater than 5.0 earthquake occurring within a specified distance from the location in a specified time interval (for example, occurring within 50 miles in the next year). This type of hazard analysis can be accessed on a worldwide basis at the OpenHazards website. Using their "Personal Earthquake Forecast" tool (see www.openhazards.com/my-forecast), you can enter the location or address and obtain a quantitative hazard assessment. We give two examples in Figure A.



(a) **(b)**

Figure A. Screenshots from the OpenHazards website (see www.openhazards.com/my-forecast). The maps show the color-coded probabilities of an $m > 5$ earthquake within 50 miles of (a) the city hall in Los Angeles and (b) the city hall in San Francisco in the next year. The contour maps give the probabilities of occurrence in the regions covered.

Table 1. Contingency table for the hot spot forecast's success for the Regional Earthquake Likelihood Models (RELM) test.

	Observed		Total
Forecast	Yes	No	Total
Yes	$a = 17$	$b = 620$	637
No	$c = 5$	$d = 7{,}042$	7,047
Total	22	7,662	7,684

methodology to Holliday's alarm-based forecast of RELM test earthquakes.[7]

The basis of this evaluation is a contingency table (see Table 1). There were 22 cells in which earthquakes occurred out of 7,684 cells. The contingency table entries are

- $a = 17$ (forecast yes, observed yes);
- $b = 620$ (forecast yes, observed no);
- $c = 5$ (forecast no, observed yes); and
- $d = 7{,}042$ (forecast no, observed no).

The hit rate $H = a/(a + c) = 0.77$ is the fraction of cells in which earthquakes occurred as forecasted. An alarm had been issued for 17 of the 22 cells in which earthquakes occurred. The false alarm rate $F = b/(b + d) = 0.08$ is the fraction of cells in which earthquakes didn't occur as forecasted. Alarms were issued for 637 cells, and 620 of these were false alarms. For a random forecast, we have $F = H$. Thus, to obtain the hit rate $H = F = 0.77$, the number of false alarm cells would have been 5,900.

Discussion

Although we've focused on the Holliday forecast,[7] it's interesting to compare it with other submitted forecasts. One way to compare forecasts is to consider the mean values of λ_i for the 22 cells in which earthquakes occurred. For the Holliday forecast, $(\lambda_i)_{mean} = 1.13 \times 10^{-3}$. The mean forecast values submitted by the other five contestants[11] were $(\lambda_i)_{mean} = 1.44 \times 10^{-3}$, 1.38×10^{-3}, 7.51×10^{-4}, 6.99×10^{-4}, and 5.95×10^{-4}. Thus, the forecasts varied by about a factor of two.

A perfect forecast (a forecast that predicted earthquakes in only the 22 cells in which they actually occurred) would have a value $(\lambda_i)_{mean} = 4.5 \times 10^{-2}$. A no-skill forecast (a forecast with equal probabilities for all 7,682 cells) would have a value $(\lambda_i)_{mean} = 1.3 \times 10^{-4}$. The conclusion is that the spatial hazard of earthquakes can be evaluated with moderate uncertainty. However, the times of occurrence of specific earthquakes remain undetermined.

Earthquake forecasting is of value for a variety of reasons. It can

- inform the general public about the earthquake hazards where they live, so that they can prepare their homes (by, for example, bolting book cases to walls) and plan what to do when an earthquake occurs (such as get under a table);
- implement strict building codes in regions with high hazard rates;
- prepare evacuation and other contingency plans in the event of a severe earthquake; and
- establish fair rates for earthquake insurance premiums.

Although the RELM test's results indicate that the present status of earthquake forecasting provides a valuable service, it's still not possible to forecast individual earthquakes.

Because current studies on earthquake hazards are primarily based on earthquake occurrence, accurate catalogs of such occurrences are important to earthquake hazard assessment. At present, data storage requirements are relatively modest. This could change as new data streams become available.

One example of current data streams is continuous GPS measurements. Some 1,000 stations are now being continuously monitored in California. The stations provide benchmark positions with millimeter accuracy and generate maps of surface strain. Another example is satellite-based interferometry synthetic aperture radar (INSAR) observations, which can map surface displacement on the subcentimeter scale with a spatial resolution approaching one meter.

From a scientific point of view, it's surprising that precursory phenomena prior to an earthquake can't be observed. It's certainly possible that, in the future, measurements of new phenomena, more accurate measurements of currently studied phenomena, or new methods of processing currently available data will provide reliable precursors.

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