Forecasting Earthquakes: The RELM Test

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Abstract—Earthquakes do not have precursors that can be reliably used for earthquake prediction. However, distributions of earthquakes (seismicity) can be used to forecast the earthquake hazard. These distributions in space, time, and magnitude can be studied in a wide variety of ways. In order to compare alternative approaches, the Regional Earthquake Likelihood Models (RELM) test was carried out. Five year forecasts of $m \geq 5$ earthquakes in California were solicited prior to the 2006-2010 test period. Thirty one test earthquakes occurred and we discuss the performance of the forecasts. We currently provide quantitative constraints only on where earthquakes are expected to occur. A prediction of when a specific earthquake will occur has not been reliably demonstrated.

Index Terms—Earthquakes, forecast testing, hazard assessment.

1 Introduction

RECENT earthquakes have demonstrated the extent of the seismic hazard. The magnitude $m_w = 9.2 \pm 0.1$ Sumatra-Andaman earthquake on Dec. 26, 2004 resulted in more than 230,000 deaths, dominated by 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 resulted in more than 20,000 deaths and the estimated $300 billion cost made it the most expensive natural disaster on record. The resulting tsunami had a run up of as much as 40 meters above sea level. The tsunami caused a large fraction of deaths and the meltdown and radioactive gas emissions at the Fukushima nuclear power plant.

Earthquakes occur on preexisting faults. The standard measure of the intensity of an earthquake is the seismic moment [1]

$$M = GA_r\bar{\delta} \tag{1}$$

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

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

with M in joules. For large earthquakes ($m_w > 5$) the seismic moment can be obtained directly from digital seismograph records. For small earthquakes various empirical methods are used to obtain magnitudes.

For $m_w > 5$ the global seismic networks obtain a complete catalog of earthquakes. Because of the established validity of Eq. (3) over a wide range of magnitudes, catalog completeness is defined by a significant deviation from the scaling given by Eq. (3). The annual number is about 2,000 per year. Regional networks have variable sensitivities. In southern California catalog completeness is available for $m > 1.8$, 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 Parkfield segment of the San Andreas fault at intervals of about 25 years. In anticipation of the next event the U.S. Geological Survey beginning in 1985, placed a large array of instruments adjacent to the fault segment. When the anticipated earthquake occurred in 2004 no precursory phenomena were observed. However, earthquakes do not 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 period of time are well approximated by the relation [1]

$$\log N_c = a - bm \tag{3}$$

where most estimates of b are about 1.0 and a is a measure of the level of seismicity. Small earthquakes can be used to determine a and Eq. 3 can be extrapolated to determine the probability of occurrence of large earthquakes.

A question that has been studied by many groups is whether there are temporal variations in seismicity that can be used to forecast the occurrence of future earthquakes. About 10% 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 (say the San Andreas in California) occur quasi periodically. A reasonable hypothesis would be that the rate of regional seismicity would accelerate during the period between the major earthquakes. There is 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 1983 to 2010 is well represented on a yearly basis by Eq. (3) taking $a = 5.4$ and $b = 1.0$. Nevertheless, for the same area and time period there is evidence for seismic activation (accelerated moment release) at moderate magnitudes prior to the Landers (1992) and Northridge (1994) earthquakes [4]. However, Hardebeck et al. [5] have argued that it is not possible to use accelerated moment release to forecast an earthquake without knowing the location of the subsequent earthquake, thus it cannot be used for prospective forecasting.

Basically retrospective forecasts, that is a forecast of an earthquake that already has occurred, cannot be trusted. This problem led to the Reginal Earthquake Likelihood Models (RELM) test. This was the first open, competitive test of prospective earthquake forecasts. We will give a brief overview of the RELM test and summarize the implications of the test. We will then give a discussion of future directions in earthquake forecasting (prediction).

2 RELM TEST

In order to test methods for forecasting future earthquakes, the Southern California Earthquake Center (SCEC) formed the working group for Regional Earthquake Likelihood Models (RELM) in 2000 [6]. For the first time a competitive test of prospective earthquake forecasts was to be 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.

The ground rules for the RELM test were as follows:

1) The test region to be studied was the state of California, however the selected region extended somewhat beyond the boundaries of the state as shown in Figure 1.
2) 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 (ANSS) on-line catalog http://www.ncedc.org/anss/anss-detail.html.
3) Participants were required to submit the number of earthquakes expected to occur in specified spatial cells during the test period. In order to do this, the test region was subdivided into $N_c = 7682$ spatial cells with dimensions $0.1^\circ \times 0.1^\circ$.

In discussing the RELM test we will 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. The best forecast has the highest value of λ_i for the test earthquake considered.

The fourteen forecasts submitted by eight groups are available on the RELM website (http://relm.cseptesting.org/). In order to illustrate how seismicity is used to forecast earthquakes we will utilize the pattern informatics (PI) forecast submitted by Holliday et al. [7].

In forecasting $m \geq 5$ earthquakes in a region divided into $0.1^\circ \times 0.1^\circ$ 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 hotspot cells are given equal probabilities of 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 occurrence of an earthquake in each cell in the test region. This required a continuous assessment of hazard rather than a binary, alarm based assessment. To do this, the Holliday et al. [7] forecast introduced a uniform probability of occurrence for hotspot cells and added smaller probabilities for non-hotspot cells based on the relative intensity of seismicity in the cell. A map of the Holliday et al. [7] forecast is given in Figure 1.

During the test period 1 January 2006 to 31 December 2010, there were $N_e = 31$ earthquakes in the test region with $m \geq 4.95$. The locations of the test earthquakes are shown in Figure 1. Earthquakes occurred in 22 of the 7682 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-United States border, but occurred within the test region as shown in Figure 1. 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 cannot be considered foreshocks, due to their relatively small magnitudes and early occurrence, but may represent a seismic activation.

Comprehensive evaluations of RELM test results have been given by Lee at al. [8] and by Sachs et al. [9], [10]. We will restrict our discussion to the alarm based (hot spot) aspects of the Holliday et al. [7] forecast. As discussed above the hot spot forecast probability that a $m > 5$ earthquake would occur in a test cell

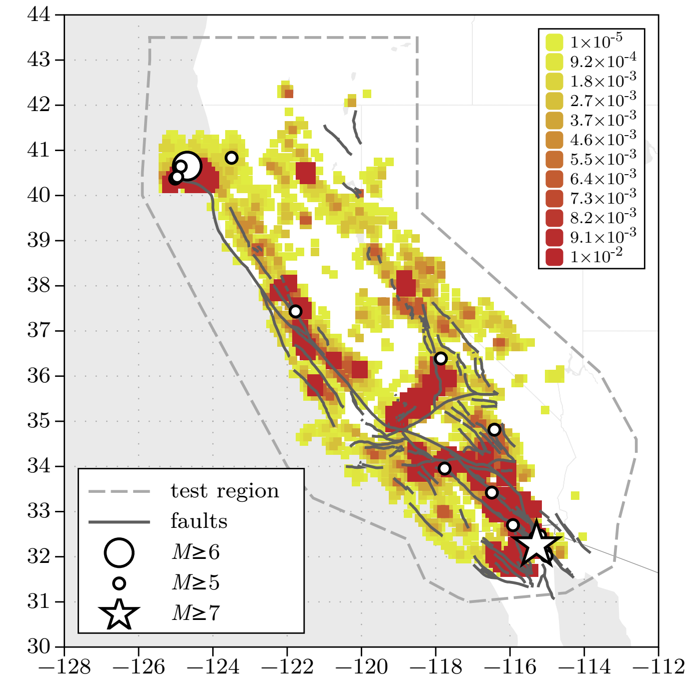

Fig. 1. Map of the earthquake probabilities λ_i given for the test region by Holliday et al. [7] using their PI based forecast. The "hot spots" are shown in red. The 31 test earthquakes are also shown.

during the test period was $\lambda_i = 1.51 \times 10^{-3}$. A perfect forecast in which only the 22 cells in which earthquakes 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 7660 cells. A random forecast in which all 7682 cells were given equal probabilities would have the probability [7]

$$\lambda_{random} = \frac{1}{7682} = 1.30 \times 10^{-4} \tag{4}$$

for all 7682 test cells. 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 are the alarms issued for the occurrence of tornadoes. An extensive methodology has been developed for the evaluation of tornado forecasts [11]. We now apply this methodology to the Holliday et al. [7] alarm based forecast of RELM test earthquakes.

The basis of this evaluation is the contingency table (see Table 1). There were 22 cells in which earthquakes occurred out of 7684 cells. The contingency table entries are:

1) $a = 17$ (forecast yes, observed yes)
2) $b = 620$ (forecast yes, observed no)
3) $c = 5$ (forecast no, observed yes)
4) $d = 7042$ (forecast no, observed no)

The hit rate $H = a/(a + c) = 0.77$ is the fraction of the cells in which earthquakes occurred that had been forecast. 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 the cells in which earthquakes did not occur that were forecast to have earthquakes. Alarms were issued for 637 cells, 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.

TABLE 1
Contingency table for the success of the hot spot forecast [7] for the RELM test.

	Observed		Total
Forecast	yes	no	total
yes	a = 17	b = 620	637
no	c = 5	d = 7042	7047
total	22	7662	7684

3 Discussion

Although our discussion focused on the Holliday et al. [7] forecast it is of interest to compare this forecast with the other submitted forecasts. One way to compare forecasts is to consider the mean values of the λ_i for the 22 cells in which earthquakes occurred. For the Holliday et al. [7] forecast $(\lambda_i)_{mean} = 1.13 \times 10^{-3}$. The mean forecast values submitted by the other five contestants were [10] $(\lambda_i)_{mean} = 1.44 \times 10^{-3}$, 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 7682 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:

1) Inform the general public as to the earthquake hazard where they live. The public can make preparations in their houses (e.g. bolt book cases to walls) and plan what to do when an earthquake occurs (i.e. get under a table).
2) Implement strict building codes in regions with high hazard.
3) Prepare evacuation and other contingency plans in the event of a severe earthquake.
4) Establish fair rates for earthquake insurance premiums.

The results of the RELM test indicate that the present status of earthquake forecasting provides a valuable service. However, it is not possible to forecast individual earthquakes.

Current studies of the earthquake hazard are primarily based on the occurrence of earthquakes. Accurate catalogs of earthquake occurrence play an important role in earthquake hazard assessment. At the present time, data storage requirements are relatively modest. This may change as new data streams become available. One example is continuous GPS measurements. Some 1000 stations are now being continuously monitored in California. The stations provide bench mark positions with millimeter accuracy. Maps of surface strain are now being generated. Another example is satellite based synthetic aperture radar interferometry (INSAR) observations. These observations can map surface displacement on the sub-centimeter scale with a spatial resolution approaching one meter. From a scientific point of view, it is surprising that precursory phenomena prior to an earthquake cannot be observed. It is certainly possible that measurements of new phenomena, more accurate measurements of currently studied phenomena, or new methods of processing currently available data will provide reliable precursors.

Inset: 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 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 web site. Using their "Personal Earthquake Forecast" tool [12], you can enter the location or address and obtain a quantitative hazard assessment. We give two examples in Fig. 2 below.

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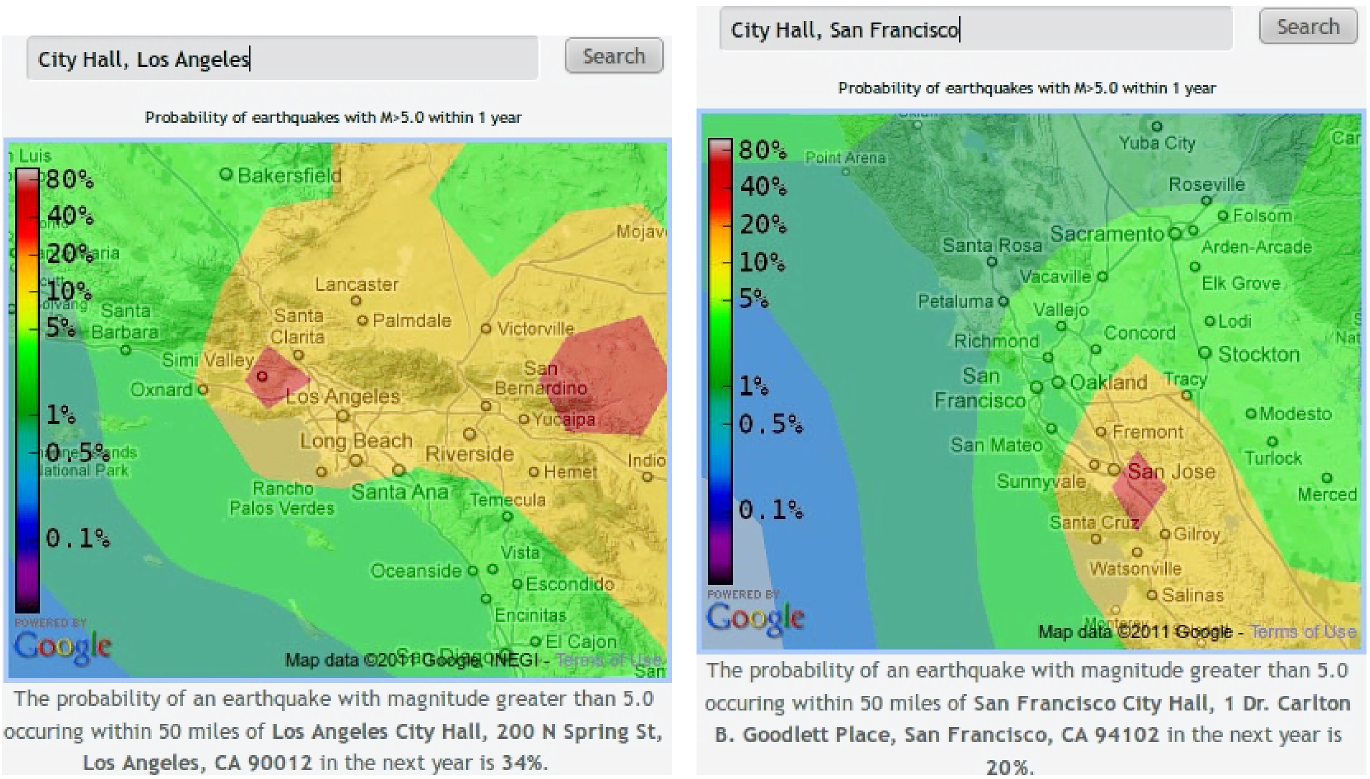

(a) (b)

Fig. 2. On the left is the hazard at city hall, Los Angeles and on the right is the hazard at city hall, San Francisco. The maps show the color coded probabilities of an $m > 5$ earthquake in the region in the next year. The contour maps give the probabilities of occurrence in the regions covered.