TESTING COMMON ASSUMPTIONS IN EARTHQUAKE FORECASTING

D. Jackson

ABSTRACT

Earthquake forecasts are typically built upon various assumptions, including some of those listed below. Most are reasonable under some conditions but difficult to test rigorously. Testing requires precise definitions of the assumptions and the conditions for which they should apply. Common assumptions are

1. Seismic moment rate equals tectonic moment rate.
2. Big quakes occur only on big faults.
3. Earthquake and strain rates are effectively constant in time.
4. Magnitudes are limited by fault length.
5. Fault segments exert control over large earthquake ruptures.
6. Quakes repeat, with some variability, on a quasi-periodic schedule.
7. “Characteristic” repeating quakes dominate moment rate and hazard.
8. Sediment offsets in paleo-seismic trenches are caused only by quakes.
9. Important faults are known and mapped.
10. Lithosphere is elastic.
11. Quakes are caused by stress.
12. Big and small quakes come from different populations.

Prospective tests are required, but retrospective tests may be helpful. Assumptions 5 and 6 guide many earthquake forecasts but previously published global tests, and new tests of previous forecasts by the Working Group on California Earthquake Probabilities, conflict with them.

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Introduction

Assumptions like those above often form a necessary bridge from scientific observations to conclusions. Many such assumptions have been used so often they seem obvious. But they often come from generalizations based on selected data, or simply from lack of practical alternatives. Most are quite reasonable, and perhaps demonstrably valid for some circumstances but not necessarily for all. Because they can determine the ultimate conclusions of scientific and engineering studies, it’s important to identify them, recognize the circumstances in which they may have been validated, and ask what would it mean if they fail.

Assumption 4 above is especially common in seismic hazard studies. Weiser et al. in this volume raise serious questions about its validity.

Below I discuss assumptions 5 and 6, often combined to imply quasi-periodic recurrence of large earthquakes on fault segments. In fact a discussion of repetition (or “recurrence”) requires a definition of what is repeated. In a few places, small “repeaters” are defined in terms of their similar hypocenters, magnitudes, and recorded seismograms, without reference to segments [1]. To apply the assumptions to larger damaging earthquakes, one generally separates all earthquakes into two classes: large earthquakes on faults, and all others including small quakes and aftershocks. The property of repetition with some required delay is presumed for the large earthquakes on faults, but not for the others. To give the assumptions testable meaning, one then needs to specify which faults, when is an earthquake actually on one of those faults, how large is large, etc. Furthermore, the segment assumption is now commonly generalized to include “multi-segment” earthquakes, and the recurrence is thought to apply to segment rupture.

The “Seismic Gap” Model

Nishenko [2] published a monumental, comprehensive 10-year forecast of large earthquakes around the Pacific rim based on assumptions 5 and 6. He used the term “seismic gap” to indicate a segment with high estimated probability of rupture because the time since the last such rupture exceeded the average interval between events. Nishenko was the first to articulate the widely held concept in a testable form with enough data that a definitive test was possible in a decade. He adopted simple, applicable versions of the segment and quasi-periodic assumptions, and he included information on magnitude thresholds, geographic descriptions of plate-tectonic boundary segments, and time dependent rupture probabilities for 125 segments.

Rong et al. [3] tested that seismic gap model prospectively after its 10-year time window, finding that it over-predicted significantly the total number of earthquakes in the 125 zones. They also found that the locations of earthquakes matching the segment specifications were better fit by a Poisson model using just the past earthquake rate in each segment, rather than the quasi-periodic recurrence model.

Many informal arguments followed. Some suggested that the test period was too short, but in fact the Nishenko model was specified for a decade, and the relevant probabilities were high enough to allow conclusive tests. Others suggested that the basic seismic gap theory was fine but the published parameters, particularly the magnitudes of recurring earthquakes, were
poorly chosen. Unfortunately those discussions did not make it into print, and there has been no updated comprehensive forecast based on the seismic gap model since 2003. The gap hypothesis, is still applied in individual cases, e.g. [4,5,6], but no definitive test is possible in a decade or two because each forecast involves different methods for setting parameters and most are stated only in vague terms. Murru et al. [7] examined segment recurrence retrospectively around the Marmara Sea region in Turkey, and Roth et al. [8] evaluated retrospectively the temporal behavior of large earthquakes along the plate boundaries of South America. Both found that interval times were generally consistent with Poisson recurrence.

There are alternate models of large earthquake occurrence, involving Poissonian temporal behavior, Gutenberg-Richter magnitude distribution, and geographically varying spatial rate density, e.g., the long term smoothed seismicity model of Jackson and Kagan [9]. These models require no assumption of segments or quasi-periodic temporal rates. They can be adapted to include short-term clustering (antithetical to quasi-periodic recurrence) as in the short-term forecasts of Jackson and Kagan [9]. The recent Global Earthquake Activity Rate (GEAR1) forecast [10] combines smoothed seismicity with geodetically and geologically determined surface strain rate on a 0.1 by 0.1 degree grid. All of the forecasts in this paragraph cover large regions and use few parameters. Thus they are easy to test, as they are being tested, in a short time and they generally perform as well as segmented quasi-periodic versions where those have been postulated.

My considered opinion is that quasi-periodic recurrence on fault segments seems convincing only on retrospectively selected data in limited regions, but there is no evidence of any criterion for more general applicability in the future. The seismological community would be well served by a comprehensive testable time-dependent segment model like Nishenko’s, [2] adapted for more recent data and test results. Alternative models like GEAR1 would then be ready for definitive multiple-hypothesis tests.

**WGCEP 1995**

An early flagship project of the Southern California Earthquake Center was the 1995 forecast for southern California [11] by the Working Group on California Earthquake Probabilities (WGCEP). That forecast adopted virtually all of the assumptions in the abstract. However, it presented two forecast versions in the same format, differing only in that one (the “TD” version) assumed time-dependent quasi-periodic recurrence (assumption 5 above), while the other (“TI” version) assumed time-independent (Poissonian) recurrence. Both versions included contributions from characteristic earthquakes on segmented faults as well as distributed earthquake epicenters. While the forecasts were specified to mature in 2024, the earthquake probability calculations can be evaluated at any time.

Looking backwards in time, I calculated first the number of expected and observed earthquakes since 1932, about the start of the period when earthquakes in southern California above magnitude 6 were routinely recorded by instrumental seismic networks. Because most of those quakes were observed before the 1995 report was published, the forecast earthquake rate should be reasonably consistent with the observed rate. However, the forecast was also designed to fit historical (non-instrumental) quake rates, geologically observed fault slip rates, and geodetically measured regional strain rates. Thus compromises were necessary, and none of the data types
were fit as closely as possible. Table 1 shows the total earthquake numbers estimated and observed for the two versions and two different magnitude thresholds. Both the time dependent and time independent models are fairly consistent for magnitude 7 and larger, mainly because the sample sizes (numbers of earthquakes) are small. At magnitude 6 and larger, the time dependent model, which adopts assumption 6 for many of its faults, over-predicts the earthquake rate by almost a factor of 2 and fails a statistical test at 95% confidence as indicated by the red font in the right-hand column.

Table 1. Retrospective performance of the Time Dependent and Time Independent versions of the 1995 WGCEP forecast on earthquakes since 1932. “Total rate” is annual, “lamda” is rate projected to total for 86 years, “Events,N” is total observed number since 1932 and “Prob(0 – N)” is the corresponding probability of the observed number or fewer. Red highlight indicates statistically significant discrepancy.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mag</th>
<th>Total rate</th>
<th>lamda</th>
<th>Events, N</th>
<th>Prob (0 - N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD Total</td>
<td>6+</td>
<td>0.605</td>
<td>52.05</td>
<td>28</td>
<td>0.000</td>
</tr>
<tr>
<td>Ti Total</td>
<td>6+</td>
<td>0.406</td>
<td>34.92</td>
<td>28</td>
<td>0.137</td>
</tr>
<tr>
<td>TD Total</td>
<td>7+</td>
<td>0.067</td>
<td>5.76</td>
<td>3</td>
<td>0.174</td>
</tr>
<tr>
<td>Ti Total</td>
<td>7+</td>
<td>0.064</td>
<td>5.50</td>
<td>3</td>
<td>0.201</td>
</tr>
</tbody>
</table>

Looking forwards from 1994 when the forecast interval started, the elapsed 24 years are sufficient to allow some meaningful tests. In that interval, only three relevant earthquakes occurred in the southern California study area: 1999 Hector Mine m7.1, 2003 San Simeon m6.5, and 2004 Parkfield m6.0. The 2010 El Mayor – Cucapah m7.2 came close, but its epicenter and most of its aftershocks were south of the study zone.

Table 2. Retrospective performance of the Time Dependent and Time Independent versions of the 1995 WGCEP forecast on earthquakes since 1932. Column headings are as in Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Mag</th>
<th>Total rate</th>
<th>lamda</th>
<th>Events, N</th>
<th>Prob (0 - N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD Total</td>
<td>6+</td>
<td>0.605</td>
<td>13.62</td>
<td>3</td>
<td>0.001</td>
</tr>
<tr>
<td>Ti Total</td>
<td>6+</td>
<td>0.406</td>
<td>9.12</td>
<td>3</td>
<td>0.019</td>
</tr>
<tr>
<td>TD Total</td>
<td>7+</td>
<td>0.067</td>
<td>1.51</td>
<td>1</td>
<td>0.555</td>
</tr>
<tr>
<td>Ti Total</td>
<td>7+</td>
<td>0.064</td>
<td>1.44</td>
<td>1</td>
<td>0.578</td>
</tr>
<tr>
<td>TD Char</td>
<td>Char</td>
<td>0.149</td>
<td>3.36</td>
<td>0</td>
<td>0.035</td>
</tr>
<tr>
<td>Ti Char</td>
<td>Char</td>
<td>0.065</td>
<td>1.45</td>
<td>0</td>
<td>0.234</td>
</tr>
</tbody>
</table>

Table 2 shows expected and observed earthquake numbers for the period 1994 – 2018 for two versions of the forecast, and two magnitude thresholds. I’ve also added two rows to show the results for “characteristic” earthquakes, those which rupture one or more contiguous segments for which data allow recurrence calculations. Their magnitudes range from 6.55 to 7.90. However, no such characteristic events occurred, as defined in the forecast report, since 1995. Again red font color indicates statistically significant over-predictions by the forecast model.

For every magnitude threshold and both time intervals, both the time dependent and time
Earthquake forecasts are rife with assumptions, many reasonable but hard to prove, almost all important in the conclusions. The common assumptions that large earthquakes are controlled by segment boundaries and that rupture is quasi-periodic is contradicted for earthquakes around the Pacific Rim since 1989 [2,3] and for magnitude 6 and larger earthquakes in southern California since 1994. No prospective test has shown those assumptions to be valid so far. A straightforward application of those assumptions on a large scale could be evaluated alongside global models formulated as gridded epicenter rates, providing a much needed opportunity to test the validity of those assumptions.

Conclusions

References


