SCEC/USGS Working Group on Regional Earthquake Likelihood Models (RELM)

5-year forecasting experiments in the California Natural Laboratory

Papers describing 19 RELMs were published in a special issue of *Seismol. Res. Lett.*, February, 2007

Half-time evaluation published by Schorlemmer et al. in *Pure Appl. Geophys.*, 2010

Full 5-year evaluation in production by Zechar et al., 2011
Collaboratory for the Study of Earthquake Predictability

• CSEP goal is rigorous testing of predictability hypotheses and forecasting models
  – Automate blind, prospective testing in a standardized, controlled environment
    N.B. current testing is only “quasi-prospective” owing to catalog latencies
  – Establish experiments in a variety of tectonic environments and on a global scale

• CSEP components:
  – *Natural laboratories* comprising active fault systems with adequate, authorized data sources for conducting forecasting experiments
  – *Testing centers* with validated procedures for registering and evaluating prediction experiments
  – *Model classes* with common target events, forecasting regions, and forecast updating intervals
CSEP Testing Regions & Testing Centers

224 models under test in June, 2011

- SCEC Testing Center
  - Global Testing Region
    - Los Angeles
    - California
      - 46 models
  - Upcoming

- EU Testing Center
  - Italy
    - 48 models
  - Upcoming

- China Testing Center
  - North-South Seismic Belt
    - Beijing
  - Japan
    - 91 models
  - Upcoming

- Western Pacific Testing Center
  - Western Pacific
    - 16 models

- ERI Testing Center
  - New Zealand
    - 15 models

- Testing Center
  - Testing Region
    - Upcoming
CSEP Models Under Test
## CSEP Components

### Example models

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELM</td>
<td>Regional Earthquake Likelihood Models</td>
</tr>
<tr>
<td>PPE</td>
<td>Proximity to Past Earthquakes</td>
</tr>
<tr>
<td>TripleS</td>
<td>Simple Smoothed Seismicity</td>
</tr>
<tr>
<td>EEPAS</td>
<td>Every Earthquake a Precursor According to Scale</td>
</tr>
<tr>
<td>STEP</td>
<td>Short Term Earthquake Probability</td>
</tr>
<tr>
<td>ETAS</td>
<td>Epidemic Type Aftershock Sequence</td>
</tr>
<tr>
<td>ETES</td>
<td>Epidemic Type Earthquake Sequence</td>
</tr>
<tr>
<td>DBM</td>
<td>Double Branching Model</td>
</tr>
<tr>
<td>Coulomb</td>
<td>Coulomb stress + rate/state friction</td>
</tr>
</tbody>
</table>

DBM model of Lombardi & Marzocchi (2011) for $M \geq 8$ earthquakes in All-Japan testing region.
## CSEP Components

<table>
<thead>
<tr>
<th>Example models</th>
<th>Example tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELM Regional Earthquake Likelihood Models</td>
<td>L-test likelihood</td>
</tr>
<tr>
<td>PPE Proximity to Past Earthquakes</td>
<td>N-test number</td>
</tr>
<tr>
<td>TripleS Simple Smoothed Seismicity</td>
<td>M-test magnitude</td>
</tr>
<tr>
<td>EEPAS Every Earthquake a Precursor According to Scale</td>
<td>S-test space</td>
</tr>
<tr>
<td>STEP Short Term Earthquake Probability</td>
<td>R-test likelihood ratio</td>
</tr>
<tr>
<td>ETAS Epidemic Type Aftershock Sequence</td>
<td>T-test paired student $t$</td>
</tr>
<tr>
<td>ETES Epidemic Type Earthquake Sequence</td>
<td>W-test Wilcoxon signed rank</td>
</tr>
<tr>
<td>DBM Double Branching Model</td>
<td></td>
</tr>
<tr>
<td>Coulomb Coulomb stress + rate/state friction</td>
<td></td>
</tr>
</tbody>
</table>
Examples of Forecasting Models Currently Under CSEP Testing in California

RELM 5-Year Models

Mainshock Models

Mainshock/Aftershock Models

1-Day Models

3-Month Models

1-Year Models
Examples of Forecasting Models Currently Under CSEP Testing in California

Testing region: California
Forecast model: TripleS

Testing period: 2008-2010
Target events: $M \geq 3.95$ (301)
Short-Term Earthquake Probability (STEP) Model

Map Archive
What Is This Map?
How Do We Make This Map?
How Can I Use This Map?
What Are Aftershocks, Foresheocks and Earthquake Clusters?

These maps are made with contributions from ETH-Zurich, Switzerland, and the Southern California Earthquake Center.

Gerstenberger et al. (2005)

Probability of Exceeding MMI VI


2004 Parkfield Earthquake
Triggering Models vs. Smoothed Seismicity

Testing region: California
Target events: \( M \geq 3.95 \)
Testing period: 2008-2010
Testing method: T-test

\[ PG = \text{probability gain} = \frac{P}{P_0} \]

\[ IG = \text{information gain} = \log_e(PG) \]

STEP model

Reference forecast

\[ PG = 1.35/\text{eqk} \]

\[ PG = 10/\text{eqk} \]
### Japan and NZ Testing Regions

<table>
<thead>
<tr>
<th>Testing region</th>
<th>Model class</th>
<th>1 day</th>
<th>3 month</th>
<th>1 year</th>
<th>3 year</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Japan</td>
<td></td>
<td>5</td>
<td>9</td>
<td>12</td>
<td>9</td>
<td>35</td>
</tr>
<tr>
<td>Mainland</td>
<td></td>
<td>2</td>
<td>9</td>
<td>11</td>
<td>7</td>
<td>29</td>
</tr>
<tr>
<td>Kanto</td>
<td></td>
<td>4</td>
<td>7</td>
<td>8</td>
<td>8</td>
<td>27</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>11</td>
<td>25</td>
<td>31</td>
<td>24</td>
<td>91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Testing region</th>
<th>1 day</th>
<th>3 month</th>
<th>6 month</th>
<th>5 year</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Zealand</td>
<td>2</td>
<td>8</td>
<td>1</td>
<td>4</td>
<td>15</td>
</tr>
</tbody>
</table>
Darfield Aftershock Forecasting
(Gerstenberger & Rhoades)

Testing region: New Zealand
Target events: $M \geq 4$ (PPE-1d), $M \geq 5$ (PPE-3m, PPE-5y)
Testing period: 4 Sept 2010 - 8 Mar 2011
Testing method: T-test

ETAS model

$PG = 99/eqk$
$PG = 544/eqk$
$PG = 1480/eqk$
### Summary of Probability Gains

<table>
<thead>
<tr>
<th>Method</th>
<th>Gain Factor</th>
<th>$P_{\text{max}}(3 \text{ day})$ SAF-Coachella</th>
<th>Prospectively validated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term renewal</td>
<td>1-2</td>
<td>$1 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Medium-term seismicity patterns</td>
<td>2-4</td>
<td>$2 \times 10^{-4}$</td>
<td>✔</td>
</tr>
<tr>
<td>Short-term STEP/ETAS</td>
<td>10-100</td>
<td>$3 \times 10^{-3}$</td>
<td>✔</td>
</tr>
<tr>
<td>Short-term empirical foreshock probability</td>
<td>100-1000</td>
<td>$3 \times 10^{-2}$</td>
<td></td>
</tr>
</tbody>
</table>

**ICEF Finding:** The probability gains of short-term, seismicity-based forecasts can be high (> 100 relative to long-term forecasts), but the absolute probabilities of large, potentially destructive earthquakes typically remain low (< 1% per day).
End
Pathway Towards Practical Utility

• Exploratory research on earthquake precursors
  – Physics-based concepts regarding physical principles and statistical properties of earthquake predictability

• Hypothesis formulation
  – Casting of testable precursory hypotheses

• Hypothesis testing
  – Retrospective and prospective testing of forecasting methods to assess reliability, skill, and information gain

• Implementation
  – Incorporation of significant precursory information into operational earthquake forecasting
What Is Validation?

• Criteria for asserting model is credible representation of the real system, usable for forecasting behaviors (not that “model is true”)
  – Consistent with knowledge of the system (includes verification)
  – Not too sensitive to initial conditions or unknown forcings
  – Aleatory and epistemic uncertainties are properly characterized
  – Consistent with relevant observations

• Substantiation that a model is sufficiently accurate in predicting system behaviors
  – within its domain of applicability
  – consistent with its intended purposes

• Techniques
  – Testing against observations (surviving invalidation)
  – Competition among models
  – Validation of model components
  – Improvement by data assimilation (inversion)
Problems in Assessing the Quality of Earthquake Forecasts & Predictions

- Scientists are over-optimistic about their own results
- Scientific publications provide insufficient information for independent evaluation
- Active researchers are constantly tweaking their procedures, which become moving targets
- Standards are lacking for testing predictions against reference forecasts
- Data to evaluate prediction experiments are often improperly specified
- Infrastructure for conducting and evaluating long-term prediction experiments has not existed
Validation of Forecasting Methods

Criteria for operational fitness:

• Quality validated by retrospective and prospective testing
• Consistency across temporal and spatial scales
• Value to users

ICEF Recommendations:

• To be qualified for operational use, forecasting methods should be scientifically tested against the available data for reliability and skill, both retrospectively and prospectively.
• All operational models should be under continuous prospective testing.