The Prediction Problems of Earthquake System Science

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Earthquakes are an emergent behavior of active fault systems.
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Earthquake System Science

• Earthquake systems
  – Models of active fault systems that predict earthquake behaviors

• Earthquake behaviors of societal interest
  – Fault rupture
  – **Ground shaking** ← focus of this presentation
  – Tsunami
  – Liquefaction, landsliding, and other secondary effects

• Fundamental prediction problem of earthquake system science
  – Provide *prospective* information about these behaviors useful in reducing earthquake risks and preparing for earthquake disasters
Fundamental Prediction Problem

Provide information about future ground motions useful in reducing earthquake risks and preparing for earthquake disasters

- Two main approaches:
  1. **Deterministic short-term prediction**: “Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA during the next month.”
  2. **Probabilistic long-term forecasting**: “Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA with a 2% probability in the next 50 years.”
Two Approaches to Earthquake Prediction

Deterministic Earthquake Prediction

“Silver-Bullet Approach”

- Search for diagnostic precursory signals that can predict the location, time, and magnitude of an impending event with high probability and low error rates (false alarms and failures-to-predict)

x Has not yet produced a reliable method for short-term deterministic prediction

Probabilistic Earthquake Forecasting

“Brick-by-Brick Approach”

- Build system-specific models of earthquake recurrence, stress evolution, and triggering within the framework of probabilistic seismic hazard analysis (PSHA)

✓ Has produced reliable methods for long-term and short-term probabilistic forecasting
Fundamental Prediction Problem

Provide information about future ground motions useful in reducing earthquake risks and preparing for earthquake disasters

1. Deterministic short-term prediction: “Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA during the next month.”

2. Probabilistic long-term forecasting: “Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA with a 2% probability in the next 50 years.”

- Replace the first with:

3. Probabilistic short-term forecasting: “Earthquake shaking having a peak ground acceleration of 1 g or greater will occur in downtown LA with a 2% probability in the next month.”

- In this example, the short-term probability gain is the ratio

\[ \frac{50 \text{ yrs}}{1 \text{ month}} = 600 \]

- Should short-term forecasts with high-gain but low-probability be disseminated to the public?
Outline

• Probabilistic Seismic Hazard Analysis
  – Concepts of aleatory variability and epistemic uncertainty

• Long-term earthquake rupture forecasting
  – Uniform California Earthquake Rupture Forecast (UCERF3)

• Ground motion prediction
  – CyberShake physics-based hazard model

• Short-term earthquake forecasting
  – Operational earthquake forecasting

• Future of physics-based earthquake forecasting
  – Earthquake rupture simulators
Probabilistic Seismic Hazard Model

Working Group on California Earthquake Probabilities (2007)
Uniform California Earthquake Rupture Forecast (UCERF2)

Earthquake Rupture Forecast
Ground Motion Model
Intensity Measures

\[ P(S_k) \quad P(Y_n \mid S_k) \quad P(Y_n) \]
Probabilistic Seismic Hazard Model

Boore et al. (1997)
Empirical Ground Motion Prediction Equations (GMPEs)

Earthquake Rupture Forecast

Ground Motion Model

Intensity Measures

\[ P(S_k) \quad P(Y_n \mid S_k) \quad P(Y_n) \]
**Probabilistic Seismic Hazard Model**

**Hazard Curve:**
- **Shaking intensity:** Peak Ground Acceleration (PGA)
- **Interval:** 50 years
- **Site:** Downtown LA

![Diagram](image)

- **Probability of Exceedance in 50 yr**
  - 2% in 50 yr
  - 10% in 50 yr

**Mathematical Expressions:**
- $P(S_k)$
- $P(Y_n \mid S_k)$
- $P(Y_n)$
Probabilistic Seismic Hazard Model

National Seismic Hazard Map
PGA (%g) with 2% Probability of Exceedance in 50 years

Earthquake Rupture Forecast

Ground Motion Model

Intensity Measures

\[ P(S_k) \quad P(Y_n | S_k) \quad P(Y_n) \]
Scales of Seismic Hazard Change

- Faults accumulate stress over centuries during quasi-static tectonic loading
  - stress cycle represented by Reid renewal models
- Faults redistribute stress in seconds during dynamic ruptures
  - earthquake sequences represented by Omori-Utsu clustering models
- These two types of models are statistically opposed
  - “medium-term forecasting gap”

Earthquake origin time

- long-term renewal models
- “medium-term gap”
- short-term clustering models

century decade year month week day

Anticipation time
**Long-Term Forecasting Models**

Uniform California Earthquake Rupture Forecast (UCERF3) by the Working Group on California Earthquake Probabilities (Field et al., 2014)

- **Fault Models**
  - Specifies the spatial geometry of larger, more active faults.

- **Deformation Models**
  - Provides fault slip rates used to calculate seismic moment release.

- **Earthquake-Rate Models**
  - Gives the long-term rate of all possible damaging earthquakes throughout a region.

- **Probability Models**
  - Gives the probability that each earthquake in the given Earthquake Rate Model will occur during a specified time span.
**Long-Term Forecasting Models**

**Reid model:** Characteristic earthquakes occur according to a renewal distribution set by time since last event $T_L$, the mean recurrence interval $\mu$, and an aperiodicity $\alpha$.

**Example:** Brownian Passage Time (BPT) renewal model
Long-Term Forecasting Models

SC/EC

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- Time-independent forecast incorporated into NSHMP
- Long-term forecast has been finalized (BSSA, in press)
- Short-term component is still under development

Uniform California Earthquake Rupture Forecast (UCERF3) by the Working Group on California Earthquake Probabilities (Field et al., 2014)

UCERF2
UCERF3
Uncertainties in Earthquake Rupture Forecasts

1440 branches express the epistemic uncertainties in the UCERF3 time-independent forecast
Uncertainties in Ground Motion Prediction Equations

Few data epistemic uncertainty
High scatter aleatory variability

Boore et al. (1997)
Empirical Ground Motion Prediction Equations (GMPEs)

Earthquake Rupture Forecast
Ground Motion Model
Intensity Measures

\[ P(S_k) \quad P(Y_n | S_k) \quad P(Y_n) \]
Much of the aleatory variability in the GMPEs comes from 3D heterogeneity in crustal structure.
ShakeOut Scenario
M7.8 Earthquake on Southern San Andreas Fault
Full-3D Waveform Tomography

(Lee, Chen, Jordan, Maechling, Denolle & Beroza, JGR, 2014)
Test of CVM-S4.26 synthetics against data from the 03/28/14 La Habra Earthquake (M5.1)

data in black
synthetics in red
CyberShake Model: Physics-Based PSHA

KFR = kinematic fault rupture model
AWP = anelastic wave propagation model
NSR = nonlinear site response

Graves et al. (2011)
CyberShake Model: Physics-Based PSHA

- **Sites:**
  - 283 sites in the greater Los Angeles region

- **Ruptures:**
  - All UCERF2 ruptures within 200 km of site (~14,900)

- **Rupture variations:**
  - 415,000 per site using Graves-Pitarka pseudo-dynamic rupture model

- **Seismograms:**
  - 235 million per model
Comparison of 1D and 3D CyberShake Models for the Los Angeles Region

1. lower near-fault intensities due to 3D scattering
2. much higher intensities in near-fault basins
3. higher intensities in the Los Angeles basins
4. lower intensities in hard-rock areas
Importance of Reducing Aleatory Variability

\[ \ln Y(r, k, x, m; \varepsilon) = \ln \bar{Y}(r, k, x, m) + \sigma_T \varepsilon \]

The exceedance probabilities at high hazard levels depend strongly on the total aleatory variability \( \sigma_T \) encoded by the GMPEs.

At long periods, accurate simulations can reduce \( \sigma_T \) by one-third, leading to large PoE reductions at high hazards.
NGA(2014)-CyberShake Hazard Curve Comparisons

Site LADT
(Los Angeles)
The ability to predict rupture directivity would further reduce the aleatory variability of ground motion predictions.

TeraShake simulations of M7.7 earthquake on Southernmost San Andreas
Scales of Seismic Hazard Change

• Faults accumulate stress over centuries during quasi-static tectonic loading
  – stress cycle represented by Reid renewal models

• Faults redistribute stress in seconds during dynamic ruptures
  – earthquake sequences represented by Omori-Utsu clustering models

• These two types of models are statistically opposed
  – “medium-term forecasting gap”
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Canterbury Earthquake Sequence

What is the current seismic hazard in Christchurch?

Epicentral dots scaled by magnitude; M ≥ 5 in red

New Zealand

Christchurch

M7.1 Sept 4
M6.0, M5.8 Dec 23
M5.5, M6.3 Jun 13
M6.3 Feb 22

Canterbury Earthquake Sequence

M6.3 Feb 22
Short-term Forecasting Models

Canterbury sequence, $M \geq 3.0$ (GNS Science, 2012)

Epidemic-type aftershock sequence (ETAS) model (Ogata 1988)

- Every earthquake is a mainshock that generates its own aftershocks

Gutenberg-Richter scaling

$$\log N \approx b M$$

Omori scaling

$$\log n \approx -p \log t$$

Utsu scaling

$$\log N_m \approx \alpha M$$
Short-term Forecasting Models

- **California**
  - 29 July 2008
  - (Gerstenberger et al., 2005)

- **Italy**
  - 7 April 2009
  - (Marzocchi & Lombardi, 2009)

- **New Zealand**
  - 28 June 2011
  - (Gerstenberger, 2011)
Collaboratory for the Study of Earthquake Predictability

Infrastructure for automated, blind, prospective testing of forecasting models in a variety of tectonic environments and on a global scale

CSEP Testing Regions & Testing Centers
429 models under test in Sept, 2014
CSEP Testing in New Zealand
(Gerstenberger & Rhoades, 2012)

Testing region: New Zealand (Canterbury sequence)
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

Short-term forecasts provide probability gains > 1000 relative to long-term forecasts
Scales of Seismic Hazard Change

- Poisson
- 100-yr recurrence interval

- High-probability environment
- Low-probability environment

Anticipation time:
- Century
- Decade
- Year
- Month
- Week
- Day

Probability scale:
- 0.2
- 0.4
- 0.6
- 0.8
- 1.0
Scales of Seismic Hazard Change

- High-probability environment
- Low-probability environment

- Poisson
- 100-yr recurrence interval

Anticipation time:
- Century
- Decade
- Year
- Month
- Week
- Day

Probability scale:
- $10^{-4}$
- $10^{-3}$
- $10^{-2}$
- $10^{-1}$
Scales of Seismic Hazard Change

Brownian passage time model
100-yr recurrence interval
$T_0 = 100 \text{ yr}, \; \alpha = 0.3$

G = 2
Reid

Poisson

Anticipation time

← century decade year month week day →

Probability

$10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$
Scales of Seismic Hazard Change

- Reid
- Poisson
- Omori-Utsu
- STEP model (low M)

Probability

- $10^{-1}$
- $10^{-2}$
- $10^{-3}$
- $10^{-4}$

- century
- decade
- year
- month
- week
- day

Anticipation time

$G = 100$
Scales of Seismic Hazard Change

Forecasting on time scales of less than a decade is currently confined to a low-probability environment.
Operational Earthquake Forecasting

Timely dissemination of authoritative information about the future occurrence of potentially damaging earthquakes to reduce risk and enhance earthquake preparedness in threatened communities

Problems that confront the deployment of OEF systems:

• While the probability gains of short-term, seismicity-based forecasts can be high (> 1000 relative to long-term forecasts), the probabilities of large earthquakes typically remain low (< 1% per day)
  – Preparedness actions appropriate in such high-gain, low-probability situations have not been systematically developed

• Standardization of OEF methods and protocols is in a nascent stage
  – Incremental benefits of OEF for civil protection (e.g., relative to long-term seismic hazard analysis) have not been convincingly demonstrated

• Under these circumstances, the responsible governmental agencies have been cautious in deploying OEF capabilities
  – Progress has been made in New Zealand (on-going Canterbury sequence) and Italy (in response to the 2009 L’Aquila earthquake)
Operational Earthquake Forecasting System

- **Transparency Principle**: Short-term forecasting information must be delivered to the public quickly, transparently, authoritatively, and on a continuing basis.

- **Separation Principle**: The OEF realm of hazard assessment should be kept distinct from the risk-analysis & mitigation realm of OEF users.

Provisioning of probabilistic forecasts and their epistemic uncertainties.
Conditioning of forecasting information for a multiplicity of users.
Allowance for many types of users, each with their own risk framework and thresholds for action.
Coupling CyberShake and UCERF3 to Forecast Time-Dependent Ground Motion Probabilities

- Pre-computed CyberShake ground motion models are easily coupled to short-term forecasting models, such UCERF3-ETAS
  - Output is a time-dependent seismic hazard estimate

\[
P(S_k, T) \quad P(Y_n | S_k) \quad P(Y_k, T) \quad T = \text{forecast time}
\]

- Short-term forecasting localizes epicenter probabilities
  - Coupled model achieves significant gains in ground motion probabilities through the forecasting of source directivity and directivity-basin coupling
UCERF3-CyberShake Aftershock Forecast for M6 Scenarios

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  - Based on average of 100,000 UCERF3 simulations of aftershock sequences
  - UCERF3 supra-seismogenic fault ruptures mapped onto UCERF2 ruptures in the CyberShake 14.2b model
**UCERF3-CyberShake Aftershock Forecast for M6 Scenarios**

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California Earthquake Forecasting Models

Reid renewal

UCERF3 long-term

UCERF2

NSHM

Omori-Utsu clustering

UCERF3 short-term

STEP/ETAS

“medium-term gap”

long-term renewal models

short-term clustering models

century decade year month week day

Anticipation time
California Earthquake Forecasting Models

Simulator-based UCERF

UCERF3 long-term          UCERF3 short-term

UCERF2                      STEP/ETAS

NSHM

long-term renewal models   “medium-term gap”   short-term clustering models

century decade year month week day

Anticipation time
RSQSim Earthquake Simulator

(Dieterich, 1995; Dieterich & Richards-Dinger, 2010; Richards-Dinger & Dieterich, 2012)

- Tectonic loading of faults by backslip approximation
- Rupture nucleation by rate- and state-dependent friction
- Radiation damping and dynamic overshoot
- Slip-mediated stress transfer in homogeneous elastic halfspace
- Very efficient 3-state computational algorithm
RSQSim Earthquake Simulator

(Dieterich, 1995; Dieterich & Richards-Dinger, 2010; Richards-Dinger & Dieterich, 2012)

Magnitude dependence of inter-event times on the Carrizo-Cholame sections of the San Andreas fault from a million-year catalog

- **M ≥ 6.0**: Omori-Utsu clustering (~1/t decay)
- **M ≥ 6.5**: Near-uniform distribution
- **M ≥ 7.0**: Reid renewal (μ ≈ 200 yr)
- **M ≥ 7.5**: Reid renewal (μ ≈ 200 yr)
**Earthquake Supercycles in Rupture Simulators**

100-yr Moving Average of Seismic Moment Release

**RSQsim (Dieterich & Richards-Dinger, 2010)**

**ALLCAL (Ward, 2008)**

Owing to supercycles, our long-term forecasts may be less reliable than our short-term forecasts.

Might we be here?
Development of Physics-Based Earthquake Forecasting

RSQsim
Earthquake Rupture Simulator

CyberShake
Ground Motion Simulator

Ground Motions

extended ERF

Earthquake Rupture Forecast

Ground Motion Prediction Eqn

Intensity Measures

UCERF3

NGA-W2

Physics-based simulations

Empirical models
Conclusions

• Progress is being made in solving the “fundamental problem of earthquake prediction”
  – Brick-by-brick using the probabilistic, rather than deterministic, approach

• Current methods can provide useful information for operational earthquake forecasting across a range of temporal scales
  – Statistical models of earthquake interactions can capture many of the short-term temporal and spatial features of natural seismicity

• Much of the aleatory variability in the conditional forecasting ground motions is due to 3D crustal structure
  – Accurate earthquake simulations could reduce the residual variance of the ground motion predictions by a factor of ~2

• Physics-based forecasting methods are replacing empirical methods
  – A key issue for long-term forecasting in California is the degree of rupture synchronization within the San Andreas fault system
Thank you!