Earthquake early warning for information-based societies

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22 November 2007
Outline

• What is early warning
• Chronology
• Different flavors of early warning
• Virtual Seismologist method
• Implementation efforts
• Conclusions

from http://www.jma.go.jp
Earthquake hazard information at different time scales

Long term seismic hazard maps

10% probability of being exceeded in 50 yrs

Euro-Med Seismic Hazard Map (Giardini et al, 2003)
Earthquake hazard information at different time scales

Decades

Intermediate-term forecasts

Years
Earthquake hazard information at different time scales

short-term forecasts

Forecast for 04/18/2007 11:00 AM PDT through 04/19/2007 11:00 AM PDT

www.pasadena.wr.usgs.gov/step

Gerstenberger et al, 2003
Earthquake hazard information at different time scales

Real-time seismology

- goal: provide timely information to assist in post-earthquake mitigation, response, recovery efforts

- early warning (earthquakes, tsunamis)
- rapid source characterization
- ShakeMaps
- human impact, casualty estimates (PAGER, QuakeLoss)
- economic loss estimates
Early warning

Target warning area

Earthquake source region

Information traveling at ~300,000 km/s

Origin time

Early warning

1st P detection

ShakeMaps

damaging motions at target region

P-wave 6 km/s

S-wave 3.5 km/s
Fig. 1  Concept of the Front Alarm by Dr. J. D. Cooper.
Chronology

• 1868: Cooper proposes setting up seismic detectors near Hayward fault, ring a bell in central San Francisco
• 1960s: Japan Railway starts developing early warning system to slow or stop high-speed trains (currently UrEDAS)
• 1989: Loma Prieta aftershock sequence - temporary seismic deployment provides constructions workers ~20 seconds of warning (Bakun, 1994)
• 1991: Mexico Seismic Alert System provides up to 70 seconds of warning to Mexico City from earthquakes nucleating in the Guerrero region, about 300 km away
• 1991: Taiwan Central Weather Bureau begins widespread deployment of strong motion instruments with goal of providing early warning
• 2006: Implementation of early warning systems are funded in EU and United States (in reaction to 2004 Sumatra earthquake and tsunami)
• 2007: Japanese Meteorological Agency (JMA) starts releasing early warning information in Japan via radio, television

Kanamori, 2005
In tens of seconds, you could (possibly)...

- duck and cover
- save data, stop elevators
- shut down gas valves, secure equipment, hazardous materials
- slow trains, abort airplane landings, direct traffic
- initiate shutdown procedures in manufacturing facilities
- protect emergency response facilities (hospitals, fire stations)
- in general, reduce injuries, prevent secondary hazards, increase effectiveness of emergency response; larger warning times better
- Structural control applications (Grasso, 2005)

- most of the time, “Light shaking in X seconds, just enjoy the ride” messages over mobile phones

JMA website, 2007
Goltz, 2002
Figure 5  The wave forms of the beginning of close-in displacement records of earthquakes with magnitudes from 2.8 to 8. The amplitudes are in arbitrary scale. The first 3 s is indicated by two dash-dot lines.
Are earthquakes deterministic or not?

Olsen and Allen, 2005

Rydelek and Horiuchi, 2006
Different flavors of early warning

• Single station approach
  – Tau-C approach (Wu and Kanamori, 2004)

• “Front detection”
  – known source region (e.g. Mexico City, Bucharest)

• Network-based approach
  – Many possible source regions
  – Elarms (Allen and Kanamori, 2003), Virtual Seismologist (Cua and Heaton, 2006), Nowcast (Japan)
  – Same ingredients as non-real time seismic hazard analysis

Source x Path x Site effects → Predicted ground motions, onset times, uncertainties
Virtual Seismologist (VS) method for seismic early warning

- **Bayesian** approach to seismic early warning designed for regions with distributed seismic hazard/risk

- Modeled on “back of the envelope” methods of human seismologists for examining **waveform data**
  - Shape of envelopes, relative frequency content

- Capacity to assimilate **different types of information**
  - Previously observed seismicity
  - State of health of seismic network
  - Known fault locations
  - Gutenberg-Richter recurrence relationship
Bayes’ Theorem: a review

Given available waveform observations $Y_{obs}$, what are the most probable estimates of magnitude and location, $M$, $R$?

- **Prior** = beliefs regarding $M$, $R$ before considering observations $Y_{obs}$
- **Likelihood** = how observations $Y_{obs}$ modify beliefs about $M$, $R$
- **Posterior** = current state of belief, combination of prior and $Y_{obs}$
  - maxima of posterior = most probable estimates of $M$, $R$ given $Y_{obs}$
  - spread of posterior = variances on estimates of $M$, $R$

\[
prob(M, R|Y_{obs}) \propto prob(Y_{obs}|M, R) \times prob(M, R)
\]
\[ \text{prob}(M, R|Y_{obs}) \propto \text{prob}(Y_{obs}|M, R) \times \text{prob}(M, R) \]

- 1-sec envelopes
- 9 channels (horizontal and vertical acceleration, velocity, and filtered displacement)
- 1 observed envelope => 11 envelope parameters
• 70 events, $2 < M < 7.3$, $R < 200$ km
• Non-linear model estimation (inversion) to characterize waveform envelopes for these events
• ~30,000 time histories

Data set for learning the envelope characteristics
How do peak P- and S-wave amplitudes depend on magnitude, distance, frequency, site?

\[ \log_{10} A = aM + b(R_1 + C(M)) + d \log_{10}(R_1 + C(M)) + e \]

\[ R_1 = \sqrt{R + 9} \]
RMS S-wave horizontal acceleration (NEHRP sites C and below)
Acceleration amplification relative to average rock station
Average Rock and Soil envelopes as functions of M, R

RMS horizontal acceleration

- **M7.5**
  - at 0 km
  - at 30 km
  - at 150 km

- **M5.0**
  - at 0 km
  - at 30 km
  - at 150 km

- **M3.0**
  - at 0 km
  - at 30 km
  - at 150 km

**Graphs**
- **x-axis**: Time (seconds)
- **y-axis**: RMS horizontal acceleration (cm/s/s)
- **Legend**: rock (black), soil (red)
Estimating M from ratios of ground motion

- P-wave frequency content scales with M (Allen and Kanamori, 2003, Nakamura, 1988)

- Find the linear combination of $\log(\text{acc})$ and $\log(\text{disp})$ that minimizes the variance within magnitude-based groups while maximizing separation between groups (eigenvalue problem)

$$Z_{ad} = 0.36\log(\text{acc}) - 0.93\log(\text{disp})$$

$$= \log\left(\frac{\text{acc}^{0.36}}{\text{disp}^{0.93}}\right)$$

- Estimating M from $Z_{ad}$

$$M_P = -1.627Z_{ad} + 8.94, \sigma_{M_P} = 0.45$$

$$M_S = -1.459Z_{ad} + 8.05, \sigma_{M_S} = 0.41$$
Distinguishing between P- and S-waves

\[ PS = 0.431 \log(Z.a) + 0.551 \log(Z.v) - 0.461 \log(EN.a) - 0.551 \log(EN.v) \]

if \( PS > 0 \) P-wave; if \( PS < 0 \) S-wave
Bayes’ Theorem (again)

\[ \text{prob}(M, R|Y_{obs}) \propto \text{prob}(Y_{obs}|M, R) \times \text{prob}(M, R) \]

How are observed quantities (ground motion envelopes) related to magnitude and location?

- shape of envelopes as functions of M, R
- estimating M from ground motion ratio
- distinguishing between P- and S-wave
- station corrections

\[
L(M, \text{lat}, \text{lon}) = \sum_{i=1}^{\text{stations P,S}} \sum_{j=1}^{\text{stations}} L(M, \text{lat}, \text{lon})_{ij}
\]

\[
L(M, \text{lat}, \text{lon})_{ij} = \frac{(ZAD_{ij} - \bar{Z}_j(M))^2}{2\sigma_{ZAD_j}^2} + \sum_{k=1}^{4} \frac{Y_{obs,ijk} - \bar{Y}_{ijk}(M, \text{lat}, \text{lon})}{2\sigma_{ijk}^2}
\]
Bayes’ Theorem (again)

\[ \text{prob}(M, R|Y_{obs}) \propto \text{prob}(Y_{obs}|M, R) \times \text{prob}(M, R) \]

What else do we know about earthquakes? About the network monitoring the region?

- fault locations
- Gutenberg-Richter relationship
  \[ \log N(M) = a - bM \]
- previously observed seismicity
- station locations
Polygons are voronoi cells (nearest neighbor regions)
1st arrival at SRN implies EQ location within SRN voronoi cell
Green circles seismicity in preceding 24 hrs
Evolution of VS magnitude estimates with time

- **CISN M=4.75**

Graph with x-axis labeled "VS update times, in sec after initial P detection" and y-axis labeled "Magnitude". The graph shows different trends for "amplitudes only", "VS w/ G–R", and "VS w/o G–R" with markers indicating specific values and error bars.
16 October 1999 M=7.1 Hector Mine, California, Earthquake

- Previously observed seismicity within HEC’s voronoi cell are related to mainshock
Constraints on location from arrivals and non-arrivals 3 sec after initial P detection at HEC

\[ R_i - R_1 \geq \Delta T \times \alpha \]

\[ \Delta T = 3 \text{ sec} \]

\[ \alpha \approx 6 \text{ km/s} \]
Evolution of single station (HEC) estimates

<table>
<thead>
<tr>
<th>Est. time</th>
<th>M (no GR)</th>
<th>M (GR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>6.2 (0.5)</td>
<td>5.7 (0.52)</td>
</tr>
<tr>
<td>5.5</td>
<td>7.2 (0.42)</td>
<td>6.6 (0.55)</td>
</tr>
<tr>
<td>7</td>
<td>7.1 (0.33)</td>
<td>6.9 (0.41)</td>
</tr>
</tbody>
</table>
Evolution of VS magnitude estimates with time

CISN M=7.1

Magnitude

VS update times, in sec after initial P detection

- amplitudes only
- VS w/ G–R
- VS w/o G–R
Prior information is important for regions with relatively low station density.

Magnitude estimate can be described by Gaussian pdfs; location estimates cannot.

Possibly large errors (~60 km) in assuming the epicenter is at the 1st triggered station.

Marginal pdfs for Hector Mine, 3 sec after initial P detection.

Latitude estimates 3 sec after initial P at HEC.

Graph showing marginal pdfs for Hector Mine, 3 sec after initial P detection at HEC.
Cost-benefit analysis for early warning users

\[ a \] = actual peak ground motion level at user site (we don’t know this)
\[ a_{\text{thresh}} \] = ground motion level above which damage occurs
\[ a_{\text{pred}} \] = predicted ground motion level from EWS
\[ \sigma_{\text{pred}} \] = uncertainty on predicted ground motion level

Assume for now that user initiates actions when \( a_{\text{pred}} > a_{\text{thresh}} \)

when \( a_{\text{pred}} < a_{\text{thresh}} \)
\[ P_{\text{ex}} = \text{probability of missed alarm} \]

when \( a_{\text{pred}} > a_{\text{thresh}} \)
\[ 1 - P_{\text{ex}} = \text{probability of false alarm} \]
$C_{damage} = \text{cost of damage if no action was taken and } a > a_{thresh}$

$C_{act} = \text{cost of initiating action; also the cost of false alarm}$

$C_{ratio} = \frac{C_{damage}}{C_{act}}$

<table>
<thead>
<tr>
<th>state of nature</th>
<th>prob. of state of nature given $a_{pred}$</th>
<th>cost of &quot;Do nothing&quot;</th>
<th>cost of &quot;Act&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a &gt; a_{thresh}$</td>
<td>$P_{ex}$</td>
<td>$C_{damage}$</td>
<td>$C_{act}$</td>
</tr>
<tr>
<td>$a &lt; a_{thresh}$</td>
<td>$1-P_{ex}$</td>
<td>free!</td>
<td>$C_{act}$</td>
</tr>
</tbody>
</table>

It is cost-effective to act when $P_{ex} = P_{crit} = \frac{1}{C_{ratio}} = \frac{C_{act}}{C_{damage}}$

user threshold

$$a_{pred,crit} = a_{thresh} - \sigma_{pred}\sqrt{2} \left[ erf^{-1}\left(1 - \frac{\sqrt{2\pi}\sigma_{pred}}{C_{ratio}}\right) \right]$$

predicted ground motion level at which user should act

uncertainty on predicted ground motion

error function
\[ a_{pred, crit} = a_{thresh} - \sigma_{pred} \sqrt{2} \left[ erf^{-1} \left( 1 - \frac{\sqrt{2\pi} \sigma_{pred}}{C_{ratio}} \right) \right] \]

- Applications with $C_{ratio} < 1$ should not use early warning information
- $C_{ratio} \sim 1$ means false alarms relatively expensive
- $C_{ratio} >> 1$ means missed warnings are relatively expensive; initiate actions even when $a_{pred} < a_{thresh}$, need to accept false alarms
- Simple applications with $C_{ratio} >> 1$ stopping elevators at closest floor, ensuring fire station doors open, saving data

\[ C_{ratio} = \frac{C_{damage}}{C_{act}} \]
From the user’s perspective, it is optimal to wait whenever possible (the real reason we procrastinate)
JMA Implementation

- JMA releasing warning information via TV, radio as of Oct 2007
- Criteria for releasing warning: more than 2 stations recording event, and predicted JMA intensity > 5
- Type of information: regions to experience JMA intensity 5 or greater, epicenter location
- [http://www.eqh.dpri.kyoto-u.ac.jp/~masumi/eq/ews.htm](http://www.eqh.dpri.kyoto-u.ac.jp/~masumi/eq/ews.htm) (Masumi Yamada website)
- [http://www.jma.go.jp](http://www.jma.go.jp)
JMA methodology

\[ Bt \exp(-At) \]

Odaka, 2003

Horiuchi, 2005
CISN early warning implementation

CISN early warning half-yearly progress report Oct 2007
European implementation

- SAFER (Seismic Early wArning for Europe)
- Elarms in INGV Rome
- Virtual Seismologist in Switzerland
- RT-mag, RT-loc in Naples
- All focused on off-line implementation
Conclusions

• Bayesian framework allows integration of many types of information to produce most probable solution and uncertainty estimates

• Robustness of source estimates is proportional to station density. Prior information is useful in regions with low station density, but increases complexity of information

• Need to carry out Bayesian approach from source estimation through user response. Gutenberg-Richter relationship can reduce false alarms at cost of increasing vulnerability to missed alarms

• Need dialogue between seismologists developing warning systems, and potential user community

• Certain level of false alarms must be tolerated if user wants to ensure proper actions are taken during the infrequent, damaging event
Thank you