State-of-the-art in earthquake early warning and implications of real-time OBS deployments

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contributions from

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Outline

- What is Earthquake Early Warning (EEW)
- JMA system & performance during M9.0 Tokohu earthquake
- EEW efforts in California
- EEW in Europe
- Conclusions and Outlook

“Kinkyu Jishin Sokohu”

緊急地震速報
来る前に知る

Namazu = in Japanese mythology, a giant catfish who causes earthquakes
EEW is not a new idea...

**Fig. 1** Concept of the Front Alarm by Dr. J. D. Cooper.

From J. D. Cooper, 1868 courtesy of H. Negishi, NIED
Accelerating early warning development

Number of early warning publications per year

Development projects

California: CISN ShakeAlert
Europe: SAFER / REAKT
Japan: Implementation of public warning

2011: EEW Summit, UC Berkeley

2011 Soil Dyn Earthquake Eng
EEW around the world

Allen, 2011
Regional and single-station EEW

Satriano, 2011

Advanced users and general public
EEW in Japan

- Japan Meteorological Agency (JMA)
- Meteorological Service Law (2007.12.1) states that only JMA can release EEW information to public
- Combination of single station and regional approaches
- HomeSeismometer
Seismometers distribution used for EEW

- **JMA stations**
  - HH and HG channels
  - 100 sps, 24 bit
  - on-site processing

- **Hi-net stations**
  - short period stations

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From Keiji Doi, JMA

<table>
<thead>
<tr>
<th>Land Area (km²)</th>
<th>Stations</th>
<th>Ave. interstation spacing (km)</th>
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<tbody>
<tr>
<td>Japan</td>
<td>378,000</td>
<td>1000</td>
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<tr>
<td>California</td>
<td>404,000</td>
<td>383</td>
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<tr>
<td>Switzerland</td>
<td>39,769</td>
<td>46</td>
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Dissemination of EEW

- Intensity 5L or greater
- Intensity 3 or $M \geq 3.5$

from Keiji Doi, JMA
Possible EEW applications...

Extensive public education campaign

Earthquake Early Warning: Dos & Don’ts

At Home
- Protect your head and shelter under a table
- Don't rush outside
- Don't worry about turning off the gas in the kitchen

In Public Buildings
- Follow the attendant's instructions
- Remain calm
- Don't rush to the exit

When Driving
- Don't slow down suddenly
- Turn on your hazard lights to alert other drivers, then slow down smoothly
- If you are still moving when you feel the earthquake, pull safely over to the left and stop

Remain calm, and secure your personal safety based on your surroundings!

Outdoors
- Look out for collapsing concrete-block walls
- Be careful of falling signs and broken glass
- Take shelter in a sturdy building if there is one close enough

On Buses or Trains
Hold on tight to a strap or a handrail

In Elevators
Stop the elevator at the nearest floor and get off immediately

Near Mountains/Cliffs
Watch out for rockfalls and landslides

For more information about the Earthquake Early Warning system, please contact the following department or visit the agency's website. Administration Division, Seismological and Volcanological Department, Japan Meteorological Agency
Address: 1-3-1 Otemachi, Chiyoda-ku, Tokyo 100-8122
Phone: 03-3212-8141

The Earthquake Early Warning system has been made possible through joint technological development by the Japan Meteorological Agency and the Railway Technical Research Institute, as well as through achievements in technological development by the National Research Institute for Earth Science and Disaster Prevention.
**JMA detection rate**

First 3 years: 2007-2010
- 21 warnings
- 9 warnings for M>6.0 earthquakes

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<td>58.3</td>
<td>4.5</td>
<td>13.9</td>
<td>20.8</td>
<td>9.7</td>
<td>3.8</td>
<td>26.8</td>
<td>4.1</td>
<td>3.6</td>
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Warning threshold: JMA intensity 5- (equivalent to MMI 8-9)

- one false, zero missed

Kamigaichi et al 2009, Doi et al 2011 and Jim Mori
Earthquake Warning

M9.0 Pacific coast of Tohoku

Origin time: 14:46:18.1
First detection: +22.1 s (M4.3)
EEW Warning issued: +30 s (M7.2)
Tsunami warning issued: +3 min

Sendai had 15-20 sec warning before the strong motion, and 15 minutes warning before tsunami

Richard Allen
Warning information:
http://www.seisvol.kishou.go.jp/eq/EEW/kaisetsu/joho/20110311144640/content/content_out.html
Cellphone, TV and radio warnings

- 52 million people received warning over cellphones
- Shinkansen trains stopped without derailment
- Warning info used effectively at schools
- Control rods inserted at nuclear plants

courtesy of Masumi Yamada, Richard Allen
No warning in Tokyo?

Yamada, 2011
Summary of M9.0 Tokohu event (future challenges for EEW)

- First of all, EEW was in general successful
- Need to develop methods to estimate fault finiteness in real-time
- Need to improve robustness of system in aftershock sequences (concurrent events)
- Improved integration of all data, better ocean-floor observation
Warning time in sec for the next Tonankai Earthquake

Issue information that the Tonankai Earthquake occurs when small part of its fault area is ruptured. Its brings long warning time.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Deaths</th>
<th>Damage (Yen)</th>
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<tbody>
<tr>
<td>Tokai</td>
<td>9,200</td>
<td>37 trillion</td>
</tr>
<tr>
<td>Tonanai-Nankai</td>
<td>17,600</td>
<td>57 trillion</td>
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Meguro (2004) pointed out that the installation of EEW decreases death tolls by the next Tokai EQ by 82%.
Dense Ocean Floor Network Systems for Earthquakes and Tsunamis (DONET)

DONET stations could provide 5-10 sec additional warning time.
CISN ShakeAlert

Currently testing components of a warning system in California

• 400 seismic stations
• warning received on computer desktops
• warnings to small test user group this year

3 algorithms
• On-site (Caltech/U. Taiwan)
• Virtual Seismologist (ETH/Caltech)
• Elarms (UC Berkeley)

Implementation of a Japan-type public statewide system (starting from current network):
• will take 5 years
• cost $80 million
Current output from the DM:

- Weighted averages and uncertainties of magnitude, location, O.T., and probability of false alert event cancelation.

To do:

Bayesian framework

Include a priori probabilities.
Predominant period as estimator for $M$

**Single station approach**

OnSite (Caltech) algorithm predicts PGM at same site

**Network approach**

ElarmS (UCB) predicts PGM throughout region

Allen and Kanamori 2003
Virtual Seismologist EEW algorithm

- Regional, network-based Bayesian approach
- Shape and frequency content of envelopes / “background” information
- Implemented by ETH via SAFER
- Real-time testing via CISN EEW project
- Real-time in Switzerland since August 2010

Bayes’ Theorem in EEW

\[
\text{prob}(M, \text{lat, lon} \mid \text{obs}) \propto \text{prob}(\text{obs} \mid M, \text{lat, lon}) \cdot \text{prob}(M, \text{lat, lon})
\]

Posterior (“answer”) \hspace{1cm} Likelihood (“data”) \hspace{1cm} Prior (“other” information)
Current "operational" version in ShakeAlert requires minimum of 4 stations for first estimate (available ~20 sec after OT)

Correctly detected more than 3000 events in real-time in CA in 2010, 469 with M≥3.0 (including M7.2 Sierra El Mayor)

Real-time testing of VS-MTED

% of VS location estimates within 10 km of catalogue

2010: 75%
2009: 93%
Current Status

- Current “operational” version in ShakeAlert requires minimum of 4 stations for first estimate (available ~20 sec after OT)

- Correctly detected more than 3000 events in real-time in CA in 2010, 469 with M≥3.0 (including M7.2 Sierra El Mayor)

- Real-time testing of VS-MTED

2010: mean 22s, std=7s
2009: mean=20, std=6s
VS-MTED (Multiple Threshold Event Detection)

- Single station event declaration if amplitudes are high enough
- Evolves to “standard” VS as additional data available
- Requires estimates of probabilities of false alarms
VS coming soon to Europe

- Real-time testing in Switzerland since Aug 2010
- Integration into SeisComP3 and earthworm through NERA JRA2
- Additional real-time installations in Naples, Istanbul, Iceland, Patras through REAKT WP4 & WP7
Community Seismic Network (CSN)

Detect and monitor earthquakes using smart phones, USB sensors, and cloud computing.

from Andreas Krause
Community Sensors

Android phones and tablets

Phidgets, Inc. 16-bit USB accelerometer

from Andreas Krause
CSN Network Overview

Google App Engine

Event Detection

Network Management

from Andreas Krause
CSN Applications

Earthquake early warning  tens of seconds of warning

Rapid, detailed ShakeMaps  block-by-block maps of acceleration guide emergency teams after quake

Detailed subsurface maps
Determine subsurface structures and soil conditions that enhance ground shaking.

Images of Fault Rupture

Building/Structure Monitoring

from Andreas Krause

Didyoufeelit.com
REAKT Strategies and Tools for Real-Time Earthquake Risk Reduction

WP2: Earthquake transients

WP3: Towards operational earthquake forecasting

WP4: Early warning and rapid alerts

WP5: Time-dependent risk assessment

WP6: Strategies and tools for decision making and risk mitigation

WP7: Strategic applications and capacity building

WP8: Dissemination
Important Features of the Project

- Relates earthquake early warning to real-time risk reduction („end to end“ EWS: from data to risk reduction)!
- Includes concept development for real-time risk reduction related to a few specific and strategic structures (railway system, large school, port authority, …...) or applications (civil protection,..) in a few areas in partnership with end users (from the beginning on)
- End users should not only be “civil protection“, but also others (director of a large school, security officer of a high rise building, security officer of a railway system,…..)
WP7: Strategic applications and partnerships

- SwissNuclear (ETHZ)
- SINES Industrial Complex, Portugal (IST)
- Circumvesuviana Railways (AMRA)
- EEW in schools (AMRA, GFZ)
- Department of Civil Protection Italy (AMRA, DPC)
- IGDAS Natural Gas Network, Istanbul (KOERI)
- Thessaloniki Port (AUTH, GFZ)
- AHEPA Hospital, Thessaloniki (AUTH, GFZ)
- Iceland (IMO, ETHZ)
- Regional EEW for eastern Carribbean (EUCENTRE, UWI)
- Patras EEW, Rion Antirion bridge (UPAT, ETHZ)
- Fatih Sultan Mehmet Bridge (KOERI)
Closing thoughts…

- EEW systems are slowly but steadily becoming a reality
- Still some methodology developments required
  - Real-time finite fault characterization
  - Robust performance during aftershock sequences
  - Faster warning times (methodology, decreasing data latencies)
  - Optimal use of different types of data (possibly OBS, GPS, strainmeters, cell phones, low cost but dense deployments, mobile aftershock deployments, etc.)
- Let’s learn from each other’s efforts!
Thank You
EEW in California

Goal: evaluate real-time performance of early warning methods

Three algorithms:

1. Onsite warning (Caltech/U. Taiwan)
2. Virtual Seismologist (Caltech/ETH)
3. ElarmS (UC Berkeley)

Algorithm Evaluation:
Alert information and summaries (SCEC/USC)