New Paradigm for Seismic Networks: Crowd-Sourced Seismic Networks, including Buildings

Tom Heaton, Monica Kohler, Rob Clayton, Mani Chandy, Andreas Kraus, Ming Hei Cheng, Matt Faulkner, Leif Strand, Julian Bunn, Annie Liu, Richard Guy, Elizabeth Cochran, Jesse Lawrence
Long-Term Vision

• Currently individuals are largely ignorant of the strengths/vulnerabilities of the buildings they inhabit.

• In the future, there will be an app for information about each building ... like Google Earth.

• What is the structural type and its strengths/vulnerabilities?

• What are the particular characteristics of the site ... resonance from soils?

• What is the building’s structural “medical history”?
What Helmut Kohl says about people with a vision

“Anybody with a vision should consult a physician”
A LONGER VIEW

- Everyone is instantly connected to everything, and everything will have seismometers
- Smart phones
- Automobiles
- Apple TV’s
- Our task is to harvest and manage information
- This involves close integration between geoscience, engineering, and information science
- We need to break discipline barriers to invent the future
- This talk is a report on our efforts to invent the future
Borrowed from Egill Hauksson
SCSN: what does it encompass?

- ~360 Seismic Stations
- ~60 stations from partners
- Data communications
- Data Acquisition & Processing
- Real-time notification
- Post-processing
- Archiving/ SCEDC

Borrowed from Egill Hauksson
Station: JCS - Julian Camp Stevens
SCSN/SCEDC Caltech Staff

1) Dave Johnson   Coordination/ field work
2) Alberto Devora Field work/ inventory/ Instrum. testing
3) Mike Watkins   Datalogger config/ data communications
4) Rayo Bhadha    Technical Manager
5) Rae Yip       UNIX sys. admin./ Real-time systems
6) Kalpesh Solanki Software development/ EEW
7) Paul Friberg (consultant/ISTI)/ Software maintenance
8) Kate Hutton   Media response/Catalog production
9) Nick Sheckel  CISN Display for ERA/ Timing/ Duty Op
10) Ben Wu       Data quality/ Timing
11) Anthony Guerrino Timing/ Media Center/ Duty Op/Web site
12) Elsa Villate  Accounting/Budgets
13) Sarah Gordon Proposals & Budgets/Reports/Phone bills
14) Egill Hauksson Project Management
15) Ellen Yu      SCSN/SCEDC Products Manager
16) TBD          Oracle DBA
17) Sheng-Lin    Systems Administrator
18) Fariha Chowdhury Part-time programmer/station meta data
SCSN/USGS Pasadena Office

1) Doug Given  Manager and programmer
2) Bob Dollar  Earthworm operator/Duty seismo/
3) Allan Walter  Programmer
4) Brian Flagg  Programmer/ ShakeMap operator
5) Chuck Koesterer  Electronics engineer/Data communications
6) Gary Cone  Manager (Honeywell)
7) Stan Schwartz  Systems Administrator
8) Bill Curtis  Field technician (Honeywell)
9) Scott Lydeen  Field technician in Indio (Honeywell)
10) David Sutton  Field technician in Bakersfield (Honeywell)
11) Sue Hough  Chief scientist/Duty Seismo

SCSN/SCEDC total of ~26 FTE’s
Crowd Sourced Networks

• Current broadband seismic network is an incredible scientific instrument ... BUT
• Difficult to permit, install, and maintain large numbers of new stations in traditional network
• Develop “plug and play” seismometers that can be installed and maintained by affiliated groups (utilities, emergency services, volunteers)
• How to gather data and metadata from many divergent sources and then assemble useful products ... how do you do this? ... and who does it?
• How to integrate with the current networks
• How to deal with privacy
Community Seismic Network (CSN)

- Caltech initiative between Seismology (Clayton), Civil Engineering (Heaton and Kohler), and Computer Sciences (Chandy and Kraus who is currently at ETH)
- 3-year funding from the Gordon and Betty Moore Foundation
- Major emphasis on dense deployment within 10’s of km of Caltech
- Building deployments are special focus ... I consider this as a “game changer”
Quake Catchers Network (QCN)

• The “vision” of UCLA grad students Jesse Lawrence and Elizabeth Cochran
• Originally funded by faculty start-up funds from Stanford (Lawrence) and UCR (Cochran who is currently at USGS-Pasadena)
• Collaboration with UCB computer sciences through the BOINK project
• Currently funded largely by NSF
• Has been deployed widely around the globe
• Some emphasis on buildings
Coordination between CSN and QCN

• Elizabeth Cochran (QCN co-PI) is now with the USGS on the Caltech campus and she attends weekly CSN meetings

• Tom Heaton and Monica Kohler are both co-PI’s on QCN NSF projects

• Natural competition between projects, but all recognize that we are working towards the same end ...

• We would like to see both projects succeed and transform into something that is not managed by individual university faculty
Current cost of a Phidget is About $40
Two sandwiches in Switzerland
Sheeva plug computer and HP 24-bit Mems accelerometer

Clips at 0.1 g

1,000,000 are being manufactured for Shell Oil company
Thanks to Monica Kohler
Ming Hei Cheng
Matt Hopcroft (HP)
John Clinton
Figure is from Georgia Cua at ETH. The different lines are the magnitude and distance at which one expects to see a record having a peak amplitude of 10 digital counts assuming a digitizer designed to clip at 3g. Current state of the art strong motion seismometers consist of force-balance seismometers recorded by 24-bit digitizers. These are typical of the instruments deployed in the Southern California Seismic Network. The highest quality mems devices (solid state accelerometer) have a resolution appropriate for a 20-bit digitizer. Although I have not actually seen them, I have heard “rumors” of 16-bit mems accelerometers.
• CSN Accelerograms from a Phidget
• Prepared by Monica Kohler
• Most stations are near Caltech
• Notice that some stations have timing offsets (NTP problem)
Station Data Delivery

Problem with power saver modes

Wind storm in Nov 2011 cut power
Community Seismic Network (CSN)

CLIENTS: Geocells containing active client(s) are shown on the map.

Show Events (Picks)  Show Active Clients

- All Clients  - Static Clients  - Mobile Clients
CSN status

• Original home-use, plug-into-PC version
  – Over 350 sensors distributed
    • ~225 installed (2/3)
    • ~125 active concurrently (1/3)
  – Requires software download, PC rarely off/asleep

• New standalone “orange box”
  – No PC, no software needed
  – Only power and a network jack
  – Schools, City, large/small commercial settings
Key CSN Partners

• City of Pasadena
  – Water & Power
  – Library (Central + 9 branches)
  – and many other departments
• San Marino Schools
• La Canada Schools
• Altadena Libraries
• Huntington Hospital
• USC (tall buildings)
1.) Early Warning Alert Message

2.) Cloud to Device Alert Message

3.) Report Local Acceleration
CSN-Droid App

Faulkner and Kraus
THE QUAKE CATCHER NETWORK:
INSTALLING SEISMMETERS AROUND EVERY CORNER

Elizabeth S. Cochran
23 May 2012
I. Quake-Catcher Network

- Better understand earthquakes and mitigate seismic risk by increasing the density of seismic observations using:
  - New sensor technology
  - Distributed sensing techniques
  - Community participation
II. Data Collection

MEMS Sensors

Previous Generation
- JW24F8 – 10 bit sensor (4 mg)
- MotionNode – 12 bit sensor (1 mg)
- JW24F14: 14 bit sensor (.24 mg; $50)

Current Generation (2011)
- ON-12: 12 bit sensor (1 mg; $40)
- ON-16: 16 bit sensor (60 µg; $100)

Coming soon
- ON-24: ~20 bit sensor (4 µg; $140)
Low cost seismic network that utilizes:

2. Distributed Computing

Volunteers donate CPU time to monitor sensors attached to their computer.

We use the Berkeley Open Infrastructure for Network Computing (BOINC) open-source distributed computing platform

Advantages:
1) Reduced infrastructure costs (existing networked computers process data and send information to us
2) Easy to modify software and push changes to participants

(Anderson, 2004)
II. Data Collection

Network Time Protocol (NTP):
Since 1985

Multi-tier system grounded to
- GPS Clocks
- Atomic Clocks
- Radio Clocks

Peer-to-peer method often provides better than 0.1 second accuracy, often +/- 20 msec.


Frassetto et al. (SRL, 2003)
Data Transfer Latency

- Initially transfer minimal data:
  - Time
  - Amplitude on each components
  - Significance
  - Station information (location, sensor type)

- Station to server trigger latency:
  - 3.62 seconds within California
  - 4.29 seconds globally
Distribution of Participants

Statistics
- 2000 Seismic stations globally in 67 countries
- Recorded earthquakes between M 2.6 (New Zealand) – M 8.8 (Chile)
New Zealand Aftershock Deployment

Installed 192 sensors in New Zealand in the week following the 3 Sept 2010 M7.2 earthquake

Used for:

a) Rapid earthquake detection
b) Analysis of detailed ground motion
c) Observations of liquefaction
Instrumenting Buildings

- Typically buildings are instrumented by individual research groups in earthquake engineering
- Usually only triggered during strong shaking
- Data is typically not open
- Crowd sourced seismic networks can revolutionize how buildings are recorded
Problem: Installing traditional, wired, structural health monitoring networks has severe physical, hardware, cost, and time limitations.

- 100s-1000s of m cable.
- Physically invasive installation.
- Expensive.
- One centralized digitizer and archive.
- No computing at sensors.
- Single, one-way, fixed-path communications.
- Cannot relocate hardware.
- Months to years to install;

Permission
Connected through “USC Wireless.” All 5 boxes connected to server machine in CS through openVPN with static IP assignment.
Caltech’s Robert A. Millikan Library

9-story reinforced concrete building with subbasement; constructed in 1966
A synchronized vibration generator ("shaker") is installed on the roof of Millikan Library for forced vibration tests.
Wigner-Ville
Time/frequency
From Casey Bradford
Imperial County Services building after the 1979 M 6.5 Imperial Valley Earthquake
Building stiffness vs. time

Wigner-Ville
Time/frequency
From Casey Bradford

PhD dissertation of Casey Bradford
1994 M 6.7 Northridge Earthquake
GoogleEarth view of downtown Los Angeles with 3D Buildings layer

Monica Kohler is leading this development
Google *SketchUp* to construct building model

43.3 m
Paraview to convert model to mesh nodal points
March 16, 2010 $M_L=4.4$ Pico Rivera Earthquake
recorded at Millikan Library
March 16, 2010, $M_L=4.4$ Pico Rivera Earthquake
recorded at Millikan Library
Peak Acceleration
• Working on ways to derive mode shapes from modal Frequencies

• From just a few stations we can simulate the 3-d motions of the entire building
What’s Next?

- Widespread use of digital cellular communications … no firewalls
- Android tablet systems (cheap, cell communications, battery)
- Need to develop a structure for a database to describe station attributes
- Need to develop an interface to merge data with traditional network data
- Need to develop tools so users can see/interpret their data
- Need to publish standards so manufacturers can produce “plug and play” equipment for different applications
- Extension to other types of environmental data, e.g. weather, air quality
Conclusions

• Helmut Kohl thinks we need a doctor
• There are no other conclusions … we are just at the beginning of the climb
• attach accelerometer to desktop computer at USB port.
• residential structures and high rises.
• San Gabriel Valley, to begin with, for residential.
Characteristic of Different Instruments

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Clipping Level</th>
<th>Digitizer</th>
<th>Noise Level*</th>
<th>Dynamic Range</th>
<th>Sampling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Android Phone</td>
<td>8g</td>
<td>14bits</td>
<td>0.0061g</td>
<td>62.1dB (1.3x10³)</td>
<td>~90Hz</td>
</tr>
<tr>
<td>Phidgets</td>
<td>2.5g</td>
<td>16bits</td>
<td>2.8x10⁻²g</td>
<td>78.7dB (8.9x10³)</td>
<td>250Hz (constant)</td>
</tr>
<tr>
<td>Episensor</td>
<td>2g</td>
<td>24bits</td>
<td>3.9x10⁻⁷g</td>
<td>133.7dB (5.1x10⁶)</td>
<td>200Hz (constant)</td>
</tr>
</tbody>
</table>

*Noise level defined by standard deviation (rms) of noise

Ambient Noise Test of Sensitivity of Phidgets Sensors

Millikan Library, Caltech

Average spectrum of 10 1-hour ambient noise samples
UCLA Factor Building

- Steel moment-frame; 17 stories
- School of Nursing, Jonsson Cancer Center, biomedical labs, lecture halls
- Constructed 1978-1979 (UBC 1973)
**Characteristic of Different Instruments**

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<td>Episensor</td>
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<td>24bits</td>
<td>3.9x10^{-7}g</td>
<td>133.7dB (5.1x10^6)</td>
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*Noise level defined by standard deviation (rms) of noise

**Ambient Noise Test of Sensitivity of Phidgets Sensors**

Millikan Library, Caltech

Average spectrum of 10 1-hour ambient noise samples
Caltech’s Robert A. Millikan Library

9-story reinforced concrete building with subbasement; constructed in 1966
Sept. 1, 2011 M4.2 Newhall earthquake
Google *SketchUp* to construct building model

*Paraview* to convert model to mesh nodal points
September 1, 2011 M=4.2 Newhall Earthquake recorded at Millikan Library
CSN status

• Original home-use, plug-into-PC version
  – over 300 home nodes distributed
    • ~200 installed
    • >100 active at any time
  – Requires software download, PC rarely off
• New standalone “orange box” for businesses
  – No PC, no software needed
  – Only power and a network jack
  – Schools, City, large/small commercial settings
Quake-Catcher Network

- **Low-cost strong-motion (M>3) network:**
  - MEMS sensors connected to desktop computers or internal to laptops
  - Distributed sensing techniques that uses unused CPUs
  - Sensors are installed in homes, businesses, and schools

- **Objectives:**
  - Rapid earthquake detection and characterization
  - Earthquake source imaging
  - Wave propagation and seismic hazard
  - Community understanding of earthquake risk
Background: UCLA Factor Building

- UCLA Factor Building
  - 17-story, moment-resisting steel-frame structure
  - Embedded 72-channel accelerometer array
  - N-S modal frequencies: 0.59 Hz, 1.8 Hz, 3.1 Hz
  - E-W modal frequencies: 0.55 Hz, 1.6 Hz, 2.8 Hz

- Experimental data and numerical model (ETABS)

Kohler, M. Heaton, T., Bradford, C. 2007. BSSA.
Background: UCLA Factor Building

• **Impulse Response Function**
  – Deconvolution is used to extract the transfer function
  – Bandpass filtered between 0.5 Hz and 10 Hz
  – Stack over small EQs to stay in linear response

• **Shear beam**: waves travel nondispersively throughout the lower floors of the building ($v \approx 160$ m/sec)

• For bending beams, the waves would disperse with the wave velocity increasing as the square root of the frequency

**Impulse Response Functions**

Kohler, M., Heaton, T., Bradford, C. 2007. BSSA.

**Experimental Hammer Test**
March 5, 2012 M4.0 El Cerrito Earthquake

M3.4 foreshock (at ~48 sec) and M4.0 mainshock (~55 sec) recorded by new QCN sensors

Left: Shaking intensity map generated 9 seconds after the mainshock started (estimated mag 3.7).
Right: Final interpolated shaking map (estimated mag. 4.3)

Automatically generated record section of the M4.0 mainshock
The Community Seismic Network

Monica Kohler
Dept. of Mechanical and Civil Engineering, Caltech

The Community Seismic Network Group
Richard Guy, Project Manager
Tom Heaton, Monica Kohler (Civil Engineering and Seismology)
Rob Clayton (Geophysics, Seismology)
Mani Chandy, Julian Bunn (Computer Sciences)

(Ramesh Govindan, USC Dept. of Computer Sciences)

www.communityseismicnetwork.org
July 29, 2008 M=5.4 Chino Hills earthquake
Sept. 1, 2011 M4.2 Newhall earthquake
Phidget Demo
THE QUAKE CATCHER NETWORK:
INSTALLING SEISMMETERS AROUND EVERY CORNER

USGS
science for a changing world
I. Introduction to QCN
II. Data collection
III. Recent Deployments
   A. GeoNet versus QCN Data
   B. Rapid Earthquake Characterization
   C. 2012 El Cerrito, CA detection
IV. Future Work
I. Introduction to QCN
Low-cost seismic network that utilizes:

1. MEMS Sensors

Microelectromechanical systems (MEMS) accelerometers utilize interdigitized fingerlike structures that measure a change in capacitance due to an applied acceleration.

Widely used in cars for airbag deployment, phones for screen orientation, and laptops for harddrive protection.

From O’Reilly et al., 2009
Shake Table Tests  [with I. Stubilo, UCLA]

- Single harmonic
  - Frequencies range 0.2 – 10 Hz
  - Acceleration range 0.03g – 2g
- Earthquake ground motion
  - Scaled Northridge (0.5g and 1g)

Additional sensor testing conducted at ASL
II. Data Collection

Location

Initial location based on IP address

More accurate location from participant input into a Google Map interface
Examined several possible triggering algorithms to:

- Maximize true (earthquake) triggers, minimize false triggers
- Use efficient triggering algorithm for rapid reporting

Time domain triggers based on STA/LTA are simple and fast to implement

Example 1: M 3.2 Earthquake in San Francisco Region
Examined several possible triggering algorithms to:

- Maximize true (earthquake) triggers, minimize false triggers
- Use efficient triggering algorithm for rapid reporting

Time domain triggers based on STA/LTA are simple and fast to implement

Example 2: M 5.0 Earthquake in Los Angeles Region
III. Recent Aftershock Deployments

Rapidly deploy dense sensor networks in urban areas after significant earthquakes

Approach:

• Maintain a pool of sensors (200+)

• Collaborate with local universities and research centers

• Recruit volunteers through social media
Installed 192 sensors in New Zealand in the week following the 3 Sept 2010 M7.2 earthquake

Collaboration between GNS Science and QCN
Darfield earthquake continues to have a vigorous aftershock sequence and is being recorded by the QCN array.
Temporary installation with greatest station density between September 15 – December 15.

Overview:

- QCN stations provide reliable measurements of peak ground motion
- Data can be used to provide rapid and reliable earthquake detections

![Christchurch M4.6 earthquake on Oct 15, 2010 (envelopes; 2-8 Hz)](image-url)
A. Comparison between GeoNet and QCN Data
We compare peak ground motions (acceleration, velocity) recorded at existing GeoNet strong motion sites and QCN temporary stations.

**GeoNet Strong Motion Sensors:**
Kinemetrics Etna and CSI CUSP-3, CUSP-M
Peak Ground Acceleration vs. Distance

- Similar PGA values seen for GeoNet and QCN data
- RMS scatter in PGA is 0.521 for GeoNet and 0.475 for QCN
Peak Ground Velocity vs. Distance

- Similar PGV values seen for GeoNet and QCN data
- RMS scatter in PGV is 0.698 for GeoNet and 0.532 for QCN
Small-Scale Array Comparison

Zoom area
Small-Scale Array Comparison

GeoNet: SHLC, located in Shirley Library

QCN: 6 stations located mostly in residences
Spectra are similar for closely located station pairs

Some deviation at higher frequency response likely due to different noise levels of the QCN sensors.
B. Real-Time Event Detection

1. Trigger message sent from client station

2. Server correlates triggers within:
   - 100 seconds
   - 200 km radius

3. Issue a detection if the # of triggers > regional threshold

4. Check moveout
   - Is wave traveling at seismic velocities:
     \[ \Delta T_{ij} \leq \Delta D_{ij} / V_{\text{min}} + \epsilon \]
Real-Time Detection

After a detection is issued we estimate:

1. Location:
   - Triggers may be P or S arrivals
   - Starting location is set to the location of the first trigger
   - Grid search of possible locations
   - Iterate to find best location

2. Magnitude:
   • Vector sum of PGA: \(|PGA|\)
   • Updated amplitude every 1, 2, and 4 seconds
   • Use empirical distance-magnitude relationship (e.g. Campbell, 1981; 1989; Wu et al., 2003; Cua and Heaton, 2007):

\[
|PGA| = \frac{1}{b} \exp \left( \frac{1}{a} \left( M_L - c \ln(R) - d \right) \right)
\]
Example: M4.6 Earthquake

**Initial event characterization:**
5 seconds after the origin time
11 triggers

**Final event characterization:**
194 total triggers from 104 stations

QCN Earthquake – M4.3 Lon=172.48 Lat=−43.57
Depth=1.8 Oct 15 2010 09:31:41

Detected: Oct 15 2010 09:31:47

QCN Earthquake – M4.6 Lon=172.46 Lat=−43.72
Depth=5.0 Oct 15 2010 09:31:40

Detected: Oct 15 2010 09:35:58
**Detections to date:**

- Real-time detection between mid-September 2010 and June 2011
- Most detections in New Zealand – few locations currently have both:
  - Dense network of QCN stations
  - Earthquakes
• Most initial detections are within 8-12 seconds after the *earthquake origin time*.

• Detection time includes:
  • Source-receiver propagation time
  • Trigger transfer from station to server
  • Trigger correlation
  • Event characterization

• As additional triggers are reported the magnitude and location of the earthquake is modified
**Comparison to GNS Catalog**

- Final QCN estimate of earthquake origin time versus GNS Science
- QCN is biased ~1.5 seconds early
- Mean error in earthquake location is ~7 km

**Earthquake Origin: GNS vs. QCN**

**Earthquake Location: GNS vs. QCN**
**Comparison to GNS Catalog**

- Magnitude increases between iteration 1-4, then stabilizes

- QCN magnitude estimates are biased larger than GNS catalog

- Need to improve attenuation relationship used

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**Magnitude vs. Iteration**

![Magnitude vs. Iteration graph]

**Magnitude: GNS vs. QCN**

![Magnitude: GNS vs. QCN graph]
M4.0 El Cerrito, CA Earthquake
March 5, 2012

M3.4 foreshock (at ~48 sec) and M4.0 mainshock (~55 sec) recorded by new QCN sensors

Automatically generated record section of the M4.0 mainshock
Rapid Detection

Left: Shaking intensity map generated 9 seconds after the mainshock started (estimated mag 3.7).

Right: Final interpolated shaking map (estimated mag. 4.3)
V. What Can We Learn From Dense Networks?

1. Extremely dense ground motion records for seismic hazard analysis and emergency response

2. Large number of records to invert for source characteristics including rupture velocity and
Ground motion observations provide information about:
- Velocity of material
- Depth of basin
- Complex structures (basin edges, faults, etc.)
- Large ground accelerations (trampoline effect)

Models of wave propagation are now much higher resolution than seismic observations.
Dense Networks: Site Effects

- Very dense network in Christchurch and Concepcion recorded many M3.5+ earthquakes

- Estimate site effects using S-wave spectral ratio inversion (e.g. Borcherdt, 1970; Bonilla et al., 1997) and/or Kappa method (e.g. Hough et al., 1988)

Considerations:
1. Measurements are not free field, e.g. convolve building response into record
2. Need to test a suite of MEMS to ensure instrument response is stable
Preliminary Site Response Comparison

• Comparison of spectra ratios computed for nearby GNS and QCN stations

• Early results suggest QCN stations give similar estimates of site response

With A. Kaiser, GNS Science
<table>
<thead>
<tr>
<th>Simple Procedure</th>
<th>Complex Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Warning broadcast</td>
<td>1. Emergency agent stand-by</td>
</tr>
<tr>
<td>2. Elevator control[^4]</td>
<td>2. Auto-saving for important data or running simulations</td>
</tr>
<tr>
<td>3. Open fire station garage doors</td>
<td>3. Air-bearing for small structures[^1]</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Stop traffic (traffic light/highway entrance control)</td>
<td>1. Active/Semi-active structural control (base-isolator/active damper[^5])</td>
</tr>
<tr>
<td>2. Stop trains/metro (Japan Shinkansen – UrEDAS[^6,^7])</td>
<td>2. Theme parks shut down</td>
</tr>
<tr>
<td>3. Stop surgery in hospitals</td>
<td>3. Terminate chemical processes (industrial)</td>
</tr>
<tr>
<td>4. Stop airplane landing</td>
<td>4. Terminate nuclear plant activities</td>
</tr>
<tr>
<td>5. Life-line control (water, gas, electricity, internet)</td>
<td></td>
</tr>
</tbody>
</table>
Problem setup:
- Decide mitigation action
- Choose DV
- Expected-DV calc.:
  - PBEE
  - Surrogate model (RVM)
Simulation of 20-story steel frame building drifts assuming a repeat of the 1906 earthquake (Olsen, Aagaard, and Heaton)

Buildings in the yellow or red areas are damaged beyond repair
Buildings with drift > 0.04 are in danger of collapse
Earthquake Early Warning for Large Earthquakes (Finite Faults)

Seismic
- High-quality broadband & strong-motion data from dense arrays & Community Seismic Network (CISN) (CSN)
- Acceleration data from the California Integrated Community Seismic Networks (CISN) (CSN)

Geodetic
- Total displacement data from real-time Global Positioning Systems (GPS), e.g., Earthscope Plate Boundary Observatory (PBO)

Data

Complex fault ruptures
- Probabilistic fault recognition
  - Slip detector for San Andreas Fault, San Jacinto

Complex earthquake sequences fore- & aftershocks, multiple events...
- Probabilistic ground motion prediction

Seismology

Engineering
- Site-specific prediction of building shaking
- Engineering information & decision-making

Algorithms

Off-line Tests
- Archived waveforms
- Synthetic waveforms

Real-time Tests
- USGS funded project “CISN ShakeAlert System”
Southern San Andreas Fault Buildout

Map by Doug Given

Green: New seismic stations
Red: Upgraded seismic stations
Yellow: Awaiting permits

Note: GPS will not necessarily be co-located at all seismic stations.

New GPS stations shown in red

Photo by Ken Hudnut

Co-located seismic and GPS sensors at Snow Peak
Earthquake Early Warning – getting ahead of strong ground shaking

USGS/CISN

- Phase I (2007-2009)
  Algorithm testing
- Phase II (2010-2012)
  Prototype end-2-end system
  Work with test users
- Phase II+1/2 (2010-2011)
  ARRA funding to reduce datalogger delays
Seismic Interferometry

Seismic Interferometry – Impact Test – Time-Reversed Reciprocal
QCN & Building Response:

- 10s to 100s of sensors can be deployed in buildings

- Analyze building response from local earthquakes

- Use ambient noise techniques to produce impulse response functions for each floor

Deployed 5 16-bit sensors in the UCLA Factor building. Use to compare with existing building array.

[Prieto et al., 2009]
Dense Networks: Building Response

• Deployed 5 QCN stations at Factor Building, UCLA one month ago
• 16-bit O-Navi sensors recording continuously
• Recent M4.2 earthquake (40 km away):
SUMMARY

- Low-cost MEMS and distributed sensing techniques provide valuable strong motion data for real-time event detection and characterization

- Future work:
  - Dense observations for earth structure and seismic hazard
  - High resolution source imaging
  - Large-scale building response studies

- Partnering with Chile, Mexico, Columbia, New Zealand, and SE Asia to expand the network
Thank you to all of the QCN participants

QCN is funded by:

Project website: qcn.stanford.edu

Any Questions?
Real-time GPS integration for prototype earthquake early warning and near-field imaging of the earthquake rupture process


United States Geological Survey; Earthquake & Volcano Program Offices

Earthquake Early Warning Research Group Meeting at Caltech
April 25, 2012
Southern San Andreas Fault Buildout

Photo by Ken Hudnut

Co-located seismic and GPS sensors at Snow Peak

Map by Doug Given

USGS: science for a changing world
Sample accelerometer deployments
(accelerometer is the palm-size black box on floor with white label on top)

Connected to CPU tower via USB using ethernet
Connected to silver linux box via USB using wifi