Cascadia Megathrust Earthquakes: Reducing Risk through Science, Engineering and Planning

Jeffrey Berman, Associate Professor

NSF Hazards SEES
EAR-1331412
Unsteady slow slip underneath, which is locked, creaking, and bizarre.
Last 10,000 years of M8+ earthquakes (from Offshore Geology)

> 10-20% probability of a Cascadia M9 in the next 50 years

> 25-40% probability of a Southern Cascadia M8-9 in the next 50 years
By the time the shaking has ceased and the tsunami has receded, the region will be unrecognizable. [a top authority] says, “Our operating assumption is that everything west of Interstate 5 [7 million people] will be toast.”
M 9 Project

2 Post Docs, 8 Ph.D. Students, 2 MS Students, 3 Undergraduates

Broadband Ground Motions and Fault Rupture Models

Frankel (USGS), Vidale

Landslides

Wartman, Duvall

Liquefaction

Kramer

Berman, Eberhard

Interactive integrated risk analysis maps

All, Guttorp

Buildings and Infrastructure

Buildings and Infrastructure

Tsunamis

LeVeque, Gonzales, Motley

Early Warnings – perceptions decisions & behaviors

Tsunamis

Vidale, Bostrom

Community Planning and Enhanced Resilience

Abramson, Bostrom

Education and Outreach

All
Long Term Goals and Impacts

> Advance fundamental knowledge about extreme seismic events and their related hazards:
  – Tsunami, landslides, liquefaction
  – Structural response

> Updated building codes and changes in engineering practice

> Effectively designed early warnings

> Land use and planning changes that lead to increased resilience

> Integrated into emergency response and decision-making process
Ground Motions – Overall Scheme

- 3D ground motion simulation
- ~50 rupture scenarios
  - Each with its own probability, which includes the weight on the relative likelihood of having that scenario
  - About 1 week to run a single scenario using 1024 cores at PNNL
  - Providing maps of intensity measures and time histories
- Consistent fault rupture models for tsunamis
- Validation:
  - Comparison with simulations for Maule and Tohoku
  - Comparison with GMPEs
  - Comparison with Nisqually and other PNW data
- Status:
  - Preliminary runs complete
  - Establishing rupture scenarios (with input from outside groups)
3D Velocity Model (USGS, Frankel)

(From seismic refraction/refraction data, Delorey and Vidale (2011) noise correlation model for Seattle basin, Moschetti et al. (2010) regional Vs, McCrory et al. plate interface.)
Sedimentary Basins: A Deeper Look

Portland, OR

McPhee et al. (2014)

Seattle, WA

Blakely et al. (2000)
Seattle Basin

$z_{2.5}, \text{ m}$

Seattle

Snoqualmie
M 9: 3 – M in.
Simulation

East-West Velocity (m/sec)
Synthetic Accelerograms

Synthetic acceleration records for M9.0 Cascadia Earthquake assumes Vs30 = 500 m/s

Queen Anne, Seattle

Forks

Seaside, OR

black = Vert, red = NS, green = EW
Rupture coming or going variability

Velocity synthetics, station on Queen Anne hill, in Seattle basin

deep slip, rupture more towards Seattle

black: vert.
red: NS
green: EW

shallow slip, rupture away from Seattle

Time after OT (s)
Comparing Realizations

Realization #1
(Rupture Towards Seattle)

Realization #2
(Rupture Away From Seattle)
Accelerogram Comparison

- Crustal (Northridge)
- M9 – Subduction (In Seattle)

- Long durations
- Smaller PGA
Minimum Design Base Shear:
\[ V = \frac{S_a(T)w}{R} \geq 0.044S_{DSIEW} \]
NL SDOF Response
IDA

Realization #1

Realization #2

FEMA
Seattle
Snoqualmie

ASCE Design
NL SDOF Response
IDA - IM_{comb}

Realization #1

Realization #2
Tsunami Inundation and Forces on Structures

Michael Motley, Assistant Professor
Randy LeVeque, Professor
Frank Gonzalez, Affiliate Professor
Multi-Scale Modeling

Large-Scale Inundation
Multi-Scale Modeling

Large-Scale Inundation

Community-Scale Inundation and Force
Multi-Scale Modeling

Large-Scale Inundation

Community-Scale Inundation

Structure-Scale Force Prediction
Multi-Scale Modeling

Large-Scale Inundation

Community-Scale Inundation

Structure-Scale Force

Component-Scale Structural Response
Probabilistic Tsunami Hazard Assessment (PTHA)

Traditional Inundation Map:

Probabilistic Map:
Shows annual probability of any flooding
Probabilistic Tsunami Hazard Assessment (PTHA)

Two random realizations

Realization 2: $dz$ at Crescent City = -0.88 m

Realization 03: $dz$ at Crescent City = 0.46 m

Seafloor deformation

Crescent City Inundation
Community-Scale Models

Seaside, OR
Community-Scale Models

Full-scale, the inland section of Seaside, OR is approximately 0.5 km by 0.625 km, and the solitary wave is initiated by a wave maker approximately 1.7 km offshore.
Experimental data was provided for wave height, fluid velocity, and momentum flux at a series of locations.
Community-Scale Models

Both GeoClaw, the shallow-water equation model and OpenFOAM CFD model were used to predict wave height, velocity, and momentum flux.
Probabilistic Communication in Hazard Planning

Leads: Dan Abramson, Ann Bostrom, Peter Dunn
Tsunami Modelers: Randy LeVeque, Loyce Adams, and Frank Gonzalez
Workshop facilitators: Ashley Bennis, Adnya Sarasita and URBDP 508
Mapping support: Mike Greenfield and alex grant
Aberdeen Washington Tsunami Hazard Maps
(top map deterministic, bottom map probabilistic)
Aberdeen Coastal Resilience Workshop Febr 11, 2016: Multi-disciplinary M9 team effort to convey the current science in a community (public) forum

12 participants representing:
- City council
- City engineer
- Fire, police, emergency management
- Community organizations
- WA SeaGrant
Aberdeen Workshop Initial Results

- Attendees aware of multiple hazards
- Port identified as a major economic driver for their community and key to community resilience
- Probabilistic versus Deterministic Map
  - Nature of the community is a low-lying area that floods frequently. Large inundation regions were not a surprise
  - The edge of the probabilistic map was essentially treated as the deterministic map.
  - Some interest in the lower likelihood of inundation at the port
- Asset-framed discussion groups
  - Focused on ties with community more than hazards-framed discussion groups
  - More open to positive aspects of community
  - More open to relocation and cooperation with other communities
- Will return to initiate the multi-hazard discussion: shaking, tsunami, and landsliding
Conclusions

> Convincing evidence for basin amplification

> Simulations suggest ground motions in Seattle would have:
  – Large response spectra at long periods
  – Long durations
  – Response spectra with “humps” at basin frequencies

> For M9 Eq., collapse margin ratios would likely be:
  – Large for short periods
  – Large for structures outside of basin (and far from source)
  – Smaller for long periods

> Tsunami work is ongoing
  – Multi-scale simulation being used to tie PTHA to damage estimates

> Early outreach to coastal communities that face multiple hazards from M9 indicates value in asset-based and probabilistic approach to planning.
Thank You

Questions?
Observed Deep Basin Amplification

Yufutsu Basin

$R_{\text{median}} = 222 \text{ km}$

M8 Tokachi-Oki Eq. (2003)
Observed Deep Basin Amplification

(Yufutsu Basin, M8 Tokachi-Oki Eq.)
## Collapse Ratios (Tn = 0.2 s)

Ductile, SDOF Oscillator with $S_{ay} = 0.34$ g

### FEMA Ground Motion Set

<table>
<thead>
<tr>
<th></th>
<th>$S_{a,MC}$</th>
<th>$S_{a,collapse}$</th>
<th>Ratio</th>
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<tbody>
<tr>
<td><strong>FEMA Ground Motion Set</strong></td>
<td>1.37</td>
<td>1.26</td>
<td>0.9</td>
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### Location

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<tr>
<th>Location</th>
<th>M9 Realization</th>
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<th>$S_{a,collapse}$</th>
<th>Ratio</th>
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<tbody>
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<td>0.14</td>
<td>0.76</td>
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### Collapse Ratios ($T_n = 1.5 \text{ s}$)

Ductile, SDOF Oscillator with $S_{ay} = 0.10 \text{ g}$

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<th>$S_{a,record}$</th>
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<th>Ratio</th>
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<tr>
<td></td>
<td>2</td>
<td>0.09</td>
<td>0.28</td>
<td>3.2</td>
</tr>
</tbody>
</table>

**FEMA Ground Motion Set**

- $S_{a,MCE}$: 0.46
- $S_{a,collapse}$: 0.68
- Ratio: 1.5
New Intensity Measure

\[ IM_{comb} = S_a * IM_{dur}^{C_{dur}} * IM_{shape}^{C_{shape}} \]

> \( C_{dur} \) and \( C_{shape} \) account for the structures sensitivity
  - \( C_{dur} = 0.11 \)
  - \( C_{shape} = 0.72 \)

> \( IM_{dur} \) – Significant Duration
  - Correlates to Collapse Analysis Results \((Chandramohan et al. 2015)\)

> \( IM_{shape} \) – \( SS_a \)
  - Demonstrated to correlate to collapse better than other measures
Aberdeen Workshop Initial Results

> All groups: Identified frequently-occurring hazards in Aberdeen and the Port as a major economic driver for their community and key to community resilience

> Probabilistic versus Deterministic Map
  – Community members were well educated on existing DNR tsunami maps
  – Nature of the community is a low-lying area that floods frequently. Large inundation regions were not a surprise
  – The edge of the probabilistic map was essentially treated as the deterministic map.
  – Some interest in the lower likelihood of inundation at the port

> Asset-framed discussion groups
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Comparison of Puget Sound Shaking with GMPEs

Sites in Seattle and Tacoma basins

Graph showing 3.0 sec Spectral Acceleration (g) vs Closest Distance to Rupture (km) with different models and data points.
Collapse Margin Ratio

> Computing CMR

\[
CMR_{set} = \frac{\tilde{S}_{a,\text{col},\text{set}}}{S_{a,MCE}}
\]

> Consistent CMRs between locations

\[
CMR_{\text{inside}} \approx CMR_{\text{outside}}
\]
> What should I amplify the design spectral acceleration by to ensure consistent CMRs?

\[
\frac{\tilde{S}_{a,c,\text{inside}}}{S_{a,MCE}} \times \frac{1}{BAF_{S_a}} \times \text{DF} = \frac{\tilde{S}_{a,c,\text{outside}}}{S_{a,MCE}}
\]

Accounts for \( S_a \) Basin Amplifications
Consistency in CMR

> What should I amplify the design spectral acceleration by to ensure consistent CMRs?

\[ DF = BAF_{S_a} \times \frac{\tilde{S}_{a,c,\text{outside}}}{\tilde{S}_{a,c,\text{inside}}} \]

Basin Amplification due to:
- Frequency content
- Duration
- Other?
Design Factor vs. Period

Tokachi-Oki
Yufutsu

Tokachi-Oki
Konsen

Tohoku
Kanto

DF within-event = $B A F_{S_a} \times \frac{\bar{S}_{a,c,\text{outside}}}{\bar{S}_{a,c,\text{inside}}}$
Design Factor vs. Period

Tokachi-Oki
Yufutsu

Tokachi-Oki
Konsen

Tohoku
Kanto

DF

DF

DF

DF_{FEMA} = BAF_s \times \frac{\tilde{S}_{a,c,FEMA}}{\tilde{S}_{a,c,inside}}