Effects of Long-Duration M9 Motions on Buildings in Deep Sedimentary Basins

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EERI Annual Meeting, 9 March 2017
Acknowledgments

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> **Structural Modeling:** Curt Haselton, Dawn Lehman, Laura Lowes, Josh Pugh

> **Sponsors:**

- NSF
- EERI

EAR-1331412

EERI/FEMA NEHRP Graduate Fellow
Outline

> PNW Seismicity
> Simulated Ground Motions
  – Spectral Accelerations
  – Duration
  – Spectral Shapes
  – Combined Intensity Measure
> Effect of Motions
  – Frame Buildings
  – Wall Buildings
> Conclusions
Pacific Northwest Seismicity

(From USGS)
Motivation – M9 Subduction Eq.

Long Durations

Basin Amplification

No recordings;
Effects not reflected in codes.
M9 Project

M9 Cascadia Subduction Zone Simulation

Tsunami
Buildings & Infrastructure
Liquefaction
Landslides

Early Warning
Community Planning & Enhanced Resilience
Integrated Risk Maps
Community Engagement

Pl. John Vidale,
Univ. of Washington
Simulations

Selecting Rupture Parameters

Seismic Wave Velocity Model

Finite-difference Simulations

Generate Broadband Motions

Puget Lowland Basin

Tualatin Basin
Sedimentary Basins

Portland, OR

Seattle, WA

McPhee et al. (2014)

Blakely et al. (2000)
Simulation Results

Playback Speed: x12
Spectral Accelerations
Regional Variation of $S_a$

Realization #1

$S_a(0.5\text{s}), \%g$
Regional Variation of $S_a$

Realization #1

$S_a(1.0s)$, %g
Z_{2.5} Basin Proxy

> Depth to Sediment Layer where V_s = 2500 m/s
Geographical Distribution of $Z_{2.5}$

Velocity Model from Delorey and Vidale (2011)
Acceleration Response Spectra

- MCE - Site Class C
- Snoqualmie - Real. 1
- Snoqualmie - Real. 2

$S_a, g$ vs $T_n, s$
Acceleration Response Spectra

- MCE - Site Class C
- Snoqualmie - Real. 1
- Snoqualmie - Real. 2
- Seattle - Real. 1
- Seattle - Real. 2

Realization #1
- Larger $S_a$

Realization #2
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 various data points and curves for different models.
Deep Basins in Japan

Velocity Profile from Koketsu et al. 2009
Deep Basins in Japan

Yufutsu Basin

2003 $M_w$ 8.3
Tokachi-Oki

Velocity Profile from Koketsu et al. 2009
Spectral Acceleration

Yufutsu Basin - Tokachi-Oki Eq.

- $Z_{2.5} < 1.5$
- $1.5 \leq Z_{2.5} < 3.0$
- $3.0 < Z_{2.5} < 4.5$
- $4.5 \leq Z_{2.5}$

Increasing $Z_{2.5}$
**Basin Amplification Factor (BAF_{Sa})**

- Uses GMPE Residual that accounts for:
  - Local-soil effects
  - Attenuation with distance
- Computes Basin Amplification on $S_a$

$$B A F_{S_a} = \frac{S_{a,inside}}{S_{a,outside}}$$

For $Z_{2.5} > 3$ km:
- Inside Basin
- Outside Basin

For $Z_{2.5} < 1.5$ km:
- Inside Basin
- Outside Basin
Comparison of BAFs

Maximum $\text{BAF}_{Sa} \approx 3$ at $T_n=4-6 \text{ sec}$
Comparison of BAFs

Maximum $B_{AF_{sa}} \approx 4-5$ at $T_n=3-5$ sec.

$B_{AF_{sa}}$ similar for $T_n > 0.5$ sec.
But it is more than Spectral Value at Tn
Ground-Motion Duration
Duration

Simulated M9 CSZ

$D_s \approx 80-120 \text{s}$

Typical FEMA Ground Motion (Northridge)

$D_s \approx 5-10 \text{s}$

Longer Durations
More Cycles
More Damage

(Bommer et al. 2004, Raghunandan and Liel 2013, Chandramohan et al. 2015)
**Significant Durations**

The graph illustrates the probability distribution of significant durations, with the following key features:

- **Three Curves**:
  - Far-Field FEMA
  - Sim. M9
  - Median

- **x10 Longer** indicator highlights a duration that is ten times longer than the median value, emphasized by a purple arrow pointing to the right.

- **Axes**:
  - **Y-axis**: Probability
  - **X-axis**: $D_{s, 5-95}$, s

The graph visually compares the simulated and FEMA data, indicating significant differences in the distribution of durations.
Basin Effect on Significant Duration

Yufutsu Basin - Tokachi-Oki Eq.

$R^2 = 0.11$

p-value = 0.01

$D_{S,5-95}, S$

$Z_{2.5}, KM$

Positive Slope

High Variability
Spectral Shape
Spectral Shape

- MCE - Site Class C
- Snoqualmie - Real. 1
- Snoqualmie - Real. 2
- Seattle - Real. 1
- Seattle - Real. 2

Realization #1

Realization #2

More Damaging Record

$S_a$ vs $T_n$

Softening Structures (i.e., Structures with Damage)
### Measuring Spectral Shape

- **Spectral Shape Intensity Measure** (Marafi et al. 2016)

\[ SS_{\alpha}(T_1, \alpha) = \frac{\int_{T_1}^{\alpha T_1} S_{\alpha}(T_n) dT_n}{T_1(\alpha - 1) S_{\alpha}(T_1)} \]
Measuring Spectral Shape

- Spectral Shape Intensity Measure (Marafi et al. 2016)

\[ SS_a < 1 \]

\[ SS_a > 1 \]
Effects of Basin on Spectral Shape

Spectral Shape is more damaging than FEMA motions.

Spectral Shape increases with basin depth.
Regional Variation of $SS_a$

Realization # 3

$SS_a(T=1.0, \mu=8)$
Combined Intensity Measure ($IM_{comb}$)
Duration and Shape Parameters

\[ T_n = 1.00 \]

\( D_{S,5-95, S} \)

\( SS_a \)
Duration and Shape Parameters

$T_n = 1.00$

![Plot showing $D_{S, 5-95, S}$ vs $SS_a$ with data points and labels FEMA and Outside]
Duration and Shape Parameters

\[ T_n = 1.00 \]

- 150
- 100
- 50
- 20
- 10
- 5
- 3

\[ S S_{a} \]

\[ S_{5-95}, S \]

- Realization #1
- Inside Basin
- Outside Basin
- Realization #2
- Inside Basin
- Outside Basin

FEMA
- Outside
- Inside
Combined Intensity Measure

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

> \( IM_{dur.} = \) Significant Duration, \( D_{s,5-95} \)

> \( IM_{shape} = SS_a \)

(Marafi, Berman and Eberhard, “Ductility dependent intensity measure that accounts for duration and spectral shape”, EESD, 2016.)
GM Intensity from Physics-based Simulations

\[ IM_{comb} = S_a(T_n) \times D_s^{C_{dur.}} \times SS_a^{C_{shape}} \]
GM Intensity from Physics-based Simulations

$IM_{comb}(T_n = 1s, \mu = 8)$
Effects on Frame Buildings
Example Frame Building Response

> 4-Story RC Moment Frame
  - \( T_n = 1.1 \text{s} \)
> Realization 2 Cascadia motion
Incremental Dynamic Analysis

\[ \mu = \frac{\delta}{\delta_c} \]

\[ S_a(T_n) \]

Collapse
IDA with Simulated Motions

> Archetypes from Haselton et al. 2011
> RC-SMF
> 4-Story Frame
  - $T_n = 1.1$ s

![Graph showing Max. Interstory Drift Ratio vs. $S_{0,g}$](image)
IDA with Simulated Motions

The graph illustrates the relationship between $S_{\alpha, g}$ and the maximum interstory drift ratio, expressed as a percentage. Different lines represent various scenarios, including FEMA and real-world data from Seattle and Snoqualmie, for both realizations. The graph helps in understanding how different factors affect structural performance during simulated motions.
Collapse under M9 CSZ?
Collapse Fragility

- Lumped Plasticity
- P-Delta Column

8-Story

Archetype ID: 1022 - Tokachi-Oki $M_w 8.3$

- Inside Yufutsu
- Outside Yufutsu
- FEMA
- $S_{MT}$

Concrete Frame by Haselton et al. 2008
Combined Intensity Measure

Differences in $S_{a,c}$ due to spectral shape and duration.

$IM_{comb} = S_a(T_n) \times D_{S,5-95\%}^{0.11} \times SS_{a}^{0.54}$
**Basin Design Factor**

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

Amplifications in \( S_a \) alone

Decreased Capacity due to Duration and Spectral Shape

\[ = 1.87 \times \frac{0.95}{0.77} = 2.3 \]
Basin Design Factor for 30 RC-SMF Archetypes

Yufutsu Basin - Tokachi-Oki Eq.

$D_F \approx 1.9$

$D_F \approx 2.3$
**Basin + Subduction Design Factor**

Amplifications in $S_a$ alone

Decreased Capacity due to Duration and Spectral Shape

$$DF_{basin+sub} = BAF_{S_a} \times \frac{{\tilde{S}}_{a,c,FEMA}}{{\tilde{S}}_{a,c,inside}}$$

$$= 1.87 \times \frac{1.11}{0.77} = 3.0$$
**Basin + Subduction Design Factor**

Yufutsu Basin - Tokachi-Oki Eq.

- $\approx 2.5$
- $\approx 2.7$

- $DF$
- $T_n, s$

- • basin
- ▲ basin+sub.
Effects on Wall Buildings
Concrete Shear Walls

Boundary Elements

P-Delta Column

12-Stories

Designed for Seattle (Pugh 2013)

Force-based Elements with 5-Integration Points

Fiber Section

Regularized material model based on crushing/fracture energy (Pugh, Lowes, Lehman 2015)

Fiber Section

Crushing Energy

Fracture Energy

Modelling Methodology
Calibrated to Experimental Data

Experiment
Collapse Fragilities

ArchetypeT73S12R60 - Yufutsu

Collapse Capacity

Probability of Collapse

0.0 0.2 0.4 0.6 0.8 1.0

0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

FEMA
Outside
Inside

1.51
0.66
1.07

Col G
**Basin Design Factor**

Amplification in $S_a$ alone

Decreased Capacity due to Duration and Spectral Shape

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

\[ = 1.35 \times \frac{1.07}{0.66} = 2.2 \]

Recall 8-Story Moment Frame

\[ DF = 2.3 \]
Basin + Subduction Design Factor

\[ DF_{basin+sub} = BAF_{S_a} \times \frac{\tilde{S}_{a,c,FEMA}}{\tilde{S}_{a,c,inside}} \]

Amplifications in \( S_a \) alone

Decreased Capacity due to Duration and Spectral Shape

\[ = 1.35 \times \frac{1.51}{0.66} = 3.1 \]

Recall 8-Story Moment Frame

DF = 3.0
Conclusions

> Combination of Basin + M9 Eq. Leads to:
  - Higher spectral accelerations at long periods
  - Longer ground motions
  - More damaging shapes

> Are These Results Plausible?
  - Simulations consistent with GMPEs
  - BAFs, duration and spectral shapes consistent with Japanese motions
  - BAFs consistent with Nisqually Earthquake

> Duration and Shape Decrease Collapse Capacity of Frame and Wall Buildings

> To Account for All Three Effects, Need Factor of 2-3 on Spectral Acceleration
Thank You!