Impacts of an M9 Cascadia Subduction Zone Earthquake and Deep Sedimentary Basins on Idealized Structures

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Motivation

No Recordings

ASCE Provisions

Structural Design

M9 Simulations

Structural Response

? 

Duration

Basin Amplifications

Not Considered

Juan de Fuca Plate

North America Plate

M9 Subduction Eq. Possible
M9 CSZ Simulations

Selecting Rupture Parameters

Seismic Wave Velocity Model → Finite-Difference Simulations

Low Frequency Motions (>1s) → Stochastically Generated Motions → High Frequency Motions (<1s) → Generate Broadband Motions

Reference: Frankel, A., Wirth, E., Marafi, N, Vidale, J., Stephenson., W. “Broadband Synthetic Seismograms for Magnitude 9 Earthquakes on the Cascadia Megathrust Based on 3D Simulations and Stochastic Synthetics”, BSSA, 2018
Two Example Realizations

Realization #1: Rupturing **towards** Seattle

Realization #2: Rupturing **away** from Seattle

Reference: Frankel, A., Wirth, E., Marafi, N, Vidale, J., Stephenson., W. “Broadband Synthetic Seismograms for Magnitude 9 Earthquakes on the Cascadia Megathrust Based on 3D Simulations and Stochastic Synthetics”, BSSA, 2018
Time Histories

Realization #1 (towards Seattle)

Realization #2 (away from Seattle)

Variation in Amplitude

Variation in Frequency Content

Seattle
Effect of Basin on $S_a$

Seattle

Realization #1 (towards)

Realization #2 (away)
Time Histories

Seattle

Variation in Amplitude

La Grande
(80 km south of Seattle, similar $R_{rup}$)

Realization #1
(towards Seattle)

Variation in Frequency Content

Realization #2
(away from Seattle)

Regional Variation
Effect of Basin on $S_a$

Seattle

Realization #1 (towards)

Realization #2 (away)

La Grande

$S_a, g$

$T_n, s$

$S_a, g$

$T_n, s$
Deep Sedimentary Basin

[Diagram showing a map with contour lines and markers for Seattle and La Grande, with labels for similar source-to-site distances.]
Effect of Basin on $S_a$

Seattle

La Grande

Larger $S_a$ Variation in Seattle

All 30 Realizations
Effect of Basin on $S_a$

Seattle

20 out 30 exceed $MCE_R$ at 2 s

La Grande

None Exceed $MCE_R$
Regional Variation of $S_a$

Decrease in $S_a$ with Distance

Larger long-period $S_a$ within the basin extent
Period Elongation

> Structure’s period *elongates* under strong shaking.
Spectral Shape

> Frequency content at periods longer than the elastic period matters

Seattle

Variation in Shape

Realization #1 (towards)

Realization #2 (away)

La Grande

(80 km South of Seattle)
Measuring Spectral Shape

> Developed a Spectral Shape Intensity Measure

\[ SS_a(T_1, \alpha) = \frac{\int_{T_1}^{\alpha T_1} S_a(T_n) dT_n}{T_1(\alpha - 1) S_a(T_1)} \]

Reference: Marafi, Berman, and Eberhard (2016) Ductility-dependent intensity measure that accounts for ground-motion spectral shape and duration, Earthquake Engineering Structural Dynamics
Measuring Spectral Shape

> Developed a Spectral Shape Intensity Measure

Reference: Marafi, Berman, and Eberhard (2016) Ductility-dependent intensity measure that accounts for ground-motion spectral shape and duration, Earthquake Engineering Structural Dynamics
Spectral Shape

Note: Integrating from T1 to 3.7T

More **Damaging** Spectral Shapes with Z_{2.5}
Ground Motion Duration

Seattle

Realization #1 (towards Seattle)

Realization #2 (away from Seattle)

~6 minutes long

More Damage

More Cycles

Longer Durations

Reference:
Bommer et al. 2004,
Raghunandan and Liel 2013,
Chandramohan et al. 2015,
Marafi et al. 2016
Summary of M9 Ground Motion Characteristics

*high* spectral accelerations
*damaging* spectral shapes
*long* durations

What about structural *response*?
**SDOF Properties**

> **Stiffness**
> – Periods: 0.1s to 5s

> **Strength**
> – ASCE 7-16 for Seattle

> **Cyclic Degradation**
> – High-Strength Low-Ductility
>   > R = 3, $\mu_{cap} = 3$
> – Low-Strength High-Ductility
>   > R = 8, $\mu_{cap} = 8$
> – Ibarra-Medina-Krawinkler (IMK) Peak-Oriented Material Model
Ductility Demand

More than 50% of Oscillators “Collapsed” at these periods ranges

Seattle has Larger Ductility Demands than La Grande
Ductility Demand

Higher Strength Results in Lower Ductility Demands

More Collapse States

M9 CSZ more damaging than MCE$_R$
Collapse Fragility ($S_a$)

- Computed using an Incremental Dynamic Analysis
- Normalized $S_{a,c}$ with $\eta$ and combined all periods within oscillator type

Variation in Collapse Prediction due to GM Characteristic not capture by $S_a$ alone

$\eta$ is the strength of the oscillator
Effective Spectral Acceleration

> Defining Effective $S_a$

$$S_{a,eff} = S_a \cdot \gamma_{dur} \cdot \gamma_{shape}$$

> Defining Duration Modifier

$$\gamma_{dur} = \left( \frac{D_s}{T_n \cdot 12s} \right)^{c_{dur}}$$

For collapse:

- $c_{dur} = 0.1$
- $c_{shape} = 0.65 \sqrt{\mu_{50} - 1} \leq 1.0$

> Defining Shape Modifier

$$\gamma_{shape} = \left( \frac{SS_a}{SS_{a,0}} \right)^{c_{shape}}$$

where $SS_{a,0} = \frac{\ln \alpha}{\alpha - 1}$

Integral of $1/T_n$

> What do they mean?

- $\gamma > 1$ more damaging & $\gamma < 1$ less damaging than those considered in structural evaluations

REF: Marafi et al. 2018 – Impact of M9 CSZ Ground Motions on Idealized Systems, Earthquake Spectra, in review
Collapse Fragility ($S_{a,\text{eff}}$)

**Similar collapse predictions regardless of GMs used**

- **High-Strength Low-Ductility**
- **Low-Strength High-Ductility**
GM Intensity from Physics-based Simulations

\[ S_a(T_n=0.5s) \]

Spectral Acceleration

\[ SS_a(T_n=0.5s,\mu=8) \]

Spectral Shape

\[ S_{a,eff} = S_a \cdot \gamma_{duration} \cdot \gamma_{shape} \]

REF: Marafi et al. 2018 – Impact of M9 CSZ Ground Motions on Idealized Systems, Earthquake Spectra, in review
GM Intensity from Physics-based Simulations

$S_{a,\text{eff.,col}}$
($T_n = 0.5 \text{ s, Low-Strength High-Ductility}$)

$S_{a,\text{eff.,col.}}$
($T_n = 2.0 \text{ s, Low-Strength High-Ductility}$)
Regional Collapse Predictions in an M9

> Compute Collapse Probability (for each location)

\[
P[\text{col.} \mid M9] = \int \int P[\text{col.} \mid S_{a,eff} / \eta] \cdot f_{S_{a,eff}}(S_{a,eff} \mid M9) \cdot f_{\eta}(1/\eta) \, d1/\eta \, dS_{a,eff}
\]
Regional Variation in Collapse Probability

> Collapse Probability for a Low-Strength High-Ductility System

- \( T_n = 0.5 \text{ s} \)
- \( T_n = 1.0 \text{ s} \)
- \( T_n = 2.0 \text{ s} \)

**Recall**

"Period with most damage"
$S_{a,\text{eff}}$ More Efficient than $S_a$

Using $S_a$

Collapse Prob. ($T_n = 1\text{s}, \text{Low-Strength High-Ductility}$)

Using $S_{a,\text{eff}}$

Collapse Prob. ($T_n = 1\text{s}, \text{Low-Strength High-Ductility}$)

Isolating Highly Damaged Areas
Conclusions

> The simulated M9 CSZ motions in Seattle are damaging
  – Large spectral accelerations
  – Damaging spectral shapes
  – Long durations

> Structural Performance
  – Ductility demands in M9 CSZ exceed MCEₐ CMS
  – Basin Effects result in large ductility demands at periods between 0.5s to 1.5s.
  – Increasing strength and ductility reduced collapse susceptibility

> Effective Spectral Acceleration ($S_{a,eff}$)
  – Accounts for the effects of spectral acceleration, shape, and duration
  – Better isolates areas of high collapse probability than $S_a$
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