Use of 3D Ground-Motion Simulations for Seismic Hazard Mapping in the Pacific Northwest

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Why Do We Need 3D Simulations?

- Sedimentary basin effects: more than just S-wave amplification from shallow soils; Vs30 isn’t sufficient to account for basin effects.
- Edges of sedimentary basins produce basin surface waves and S-wave focusing. This has been observed for Nisqually, Kobe, Northridge, and Christchurch earthquakes, and affected the damage patterns.
- Incoming surface waves are amplified by basin structure differently than near-vertical S-waves.
- 3D simulations also account for rupture directivity effects and complex path effects between source and site.
Earthquakes used to quantify amplification of Seattle basin.

We validated 3D model for Seattle basin by comparing observed basin amplification with 3D finite-difference simulations for 4 earthquakes and by modeling waveforms of a M4.8 event and the M6.8 Nisqually earthquake

(Frankel et al., 2009)
3D Simulation of M6.5 Earthquake on the Seattle Fault

From Frankel and Stephenson (2000)
M6.8 Nisqually Earthquake (depth= 52 km) seismograms; 0.67- 1.33 Hz

Filtered Transverse Velocity

Filtered Radial Velocity

3.7 cm/sec

6.6 cm/sec

Epicentral distance (km)

Time after origin time (sec)

south

southern edge of Seattle Basin

basin surface waves

Time after origin time (sec)

north
Observed amplification of spectral response values for stiff soil sites (C-class) in the Seattle basin

Referenced to site with thin soil over firm-rock outside of basin

The basin sites and reference site have comparable Vs30 values; ref site Vs30 = 350 m/s

Illustrates the need to include basin amplification terms
1 Hz Amplification at stiff-soil sites in Seattle basin wrt rock site Amplification depends on direction to earthquake
Seattle Urban Seismic Hazard Maps
Released in 2007

• Based on 541 3D simulations. 1 Hz spectral accelerations with 10%, 5%, and 2% probabilities of exceedance


• SA values on 280m grid available at: earthquake.usgs.gov/hazards/urban/seattle.php
541 3D finite-difference simulations used in Seattle seismic hazard maps

- 458 simulations for earthquakes in Seattle fault zone (M6.6-M7.2)
- 9 simulations for earthquakes on Southern Whidbey Island fault
- 10 simulations for point sources on Cascadia subduction zone
- 48 simulations for shallow earthquakes: 8 azimuths, 3 distances and two depths (10 and 15 km)
- 16 simulations for deep earthquakes (50 km depth): 8 azimuths and 2 distances
- Calculated synthetics at 7236 sites, with 280m spacing
- Used about 7.8 million synthetic seismograms
- 3D finite difference code written by Pengcheng Liu, U.S. Bureau of Reclamation
Procedure to Make Seattle Urban Seismic Hazard Maps

PSHA= Probabilistic Seismic Hazard Assessment

3D simulations for various earthquake scenarios

Amplification maps with basin effects (and directivity for SF and SWIF)

Nonlinear amplification for soft soils

Earthquake recurrence parameters

PSHA calculation of hazard curves

Ground motion maps for specified probability
Probabilistic seismic hazard with site and source dependent amplification and rupture directivity

Annual probability of having ground motion exceeding $u_0$ at site $i$:

$$P(u \geq u_0) \approx \sum_{M} \sum_{\text{source}_j} \text{rate}(M, \text{source}_j) P(u \geq u_0 | \text{site}_i, \text{source}_j, M)$$

$$u = u_{\text{rock}}(M, D) \text{amp}(\text{PGA}_{\text{rock}}, \text{site}_i, \text{source}_j)$$

Amp factor contains 3D basin effects and rupture directivity determined by 3D simulations for various scenarios and nonlinear site response for fill/alluvium sites determined from Choi and Stewart (2005) factors.
Float rupture zones along Seattle fault traces, do nine 3D simulations for each rupture zone (3 slip distributions, 3 hypocenters)

37 rupture zones M6.6-M7.2 on each of three fault traces, two dips.
Two scenarios for Seattle fault earthquakes M6.6

Ground-motion Maps (1 Hz)  

slip on fault surface  

Used kinematic description of rupture on fault surface
Epicenters of shallow (black circles) and deep (red circles) used in simulations to capture azimuthally dependent amplification.
one of 2002 national seismic hazard maps; rock site condition

Using 3D simulations with basin effects and directivity

Using 3D simulations and nonlinear ampl. for fill/alluvium

1 Hz Spectral Acceleration (%g) with 2% chance of being exceeded in 50 years
Unreinforced Masonry Building locations in Seattle plotted on USGS urban seismic hazard map showing spectral accelerations with 2% probability of exceedance in 50 years.

Urban seismic hazard maps useful for screening purposes and as check for site-specific studies;
City of Seattle has recommended that basin amplification terms be used for design of tall Buildings since 2013.

Map from City of Seattle
*Unreinforced Masonry Building Seismic Hazards Study, 2007*
3D Simulations of M9 Earthquakes on the Cascadia Subduction Zone

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The M9 Project: University of Washington funded for 4 years by NSF
USGS/UW has produced a large set of broadband (0-10 Hz) synthetic seismograms for M9 Cascadia earthquakes; considering a range of rupture scenarios

**Ground Motions and Tsunami inundation**

- Synthetic seismograms produced from 3D simulations of M9 Cascadia earthquakes (Frankel, Wirth, Marafi)
- Tsunami simulations for M9 Cascadia earthquakes (Gonzalez, LeVeque)

Supercomputer time provided by Pacific Northwest National Laboratory and the Texas Advanced Computing Center

**Impact**

- Evaluation of tall building response and damage from long-duration, long-period ground shaking (Berman, Eberhard, Marafi)
- Evaluation of landslides and liquefaction from ground shaking (Duvall, Wartman, Kramer, Grant)
- Evaluation of tsunami effects on structures near coast (Motley, LeVeque, Gonzalez)
- Assessment of effectiveness of multiple scenarios for emergency preparedness, community resilience (Bostrum, Abramson)
- Testing of Earthquake Early Warning
Bill Stephenson developed the 3D velocity model for Cascadia. Used seismic refraction/refraction data and tomography for Seattle basin, Moschetti et al. (2010) crustal tomography, used smoothed version of McCrory et al. (2012) plate interface.

We use 3D finite difference code written by Pengcheng Liu (U.S. Bureau of Reclamation). 4th order in space, 2nd order in time. Grid spacing varies with depth:

- 100 m grid spacing in top 5 km
- 300 m horizontal spacing 5-60 km depth
- Minimum Vs = 600 m/s, similar to surficial glacial sediments

Simulations run up to 1 Hz.
Background slip

M8.0 Sub-events ("strong-motion generation areas")

Run 21

Compound rupture model informed by observations and modeling of M9.0 Tohoku and M8.8 Maule earthquakes (see, e.g., Frankel, 2013, 2017)

About 600,000 source points (500m spacing); total Mw = 9.0

Used McCrory et al. (2012) plate interface (smoothed)

500 x 200 km corr. distance

50 km correlation distance

Slip velocity = 0.65 m/s

Slip velocity = 5.4 m/s

Max. rise time = 35 s

Max. rise time = 2 s

stochastic, stress drop = 200 bars

Used Von Karman correlation functions for constant stress drop scaling ($k^{-2}$ falloff)
Hypocenters

0.5 wt
1 cm/yr
locking
from GPS and uplift

0.3 wt
top of
tremor
zone

30 rupture
Scenarios;
20 sensitivity
runs

Sub-event rupture zones

0.2 wt
Midpoints
of thermal
model
locked zone
and GPS
1 cm/yr

Also
Varied slip
distributions

Figures from Erin Wirth
Example from Run 21

Sub-event slip
Contours are depth to Vs of 2.5 km/s; Seattle basin outline from R. Blakely
3.0 sec S.A. for run 21; errors bars are intra-event standard deviation

Sites in Puget Lowland With Z2.5 > 1.0 km

Used 3D synthetics at about 10,000 onland sites
Amplification of Seattle basin sites relative to rock site outside of basin
M9 synthetics averaged over 30 runs and observations from M5.0 Satsop EQ
Note that Vs30 values are similar between basin and rock sites

Basin amplification from Seattle basin data and M9 synthetics much larger
than that predicted by GMPE's for crustal earthquakes
S to Rayleigh wave conversion at southern edge of Seattle basin

Quaternary sediments

SFZ = Seattle fault zone

M9 Synthetics

NS component

S-wave

S-wave

SFZ

1 km

QAW, in the Seattle basin

fundamental mode surface waves

Sp2, outside of Seattle basin
Summary

• Seattle seismic hazard maps were the first probabilistic seismic hazard maps based on 3D simulations (Frankel et al., 2007). The maps incorporated 3D basin effects, nonlinear response of soft soils, and rupture directivity. 7236 sites at 280 m spacing.

• Our recent 3D simulations of M9 Cascadia earthquakes (Frankel et al. and Wirth et al., in press BSSA) quantify the effects of rupture directivity, basin amplification, and the sensitivity of ground motions to sub-event locations. Broadband synthetics (0-10 Hz) and response spectra for about 32,000 sites for each of the 50 M9 scenarios are posted on DesignSafe Website https://doi.org/10.17603/DS2WM3W

• We plan to use M9 simulations as part of new Seattle and Portland seismic hazard maps
Constructing M9 Broadband Synthetics

- Stochastic P-wave (1-10 Hz)
- Stochastic S-wave (1-10 Hz)
- Finite-difference synthetic (0-1 Hz)
- Broadband (0-10 Hz)

20% g
3 sec SA with respect to closest rupture distance for 30 runs; onland, non-basin sites
Green lines from BC Hydro Ground Motion Prediction Equations (extrapolated from M5-8.4 strong-motion data from subduction zones; Abrahamson et al. 2016)
blue symbols Maule data. Black error bars: total variability; Red error bars inter-event
Take-Home Points

We have produced a large set of broadband synthetic seismograms of Cascadia M9 earthquakes that are being used to evaluate building response and ground failure

• For non-basin sites, 0.1-6.0 s spectral accelerations are similar, on average, to BC Hydro GMPE’s, but exceed them at > 6 s.

• Synthetic response spectra have large variability from proximity to sub-events and, at long periods, from rupture directivity that combines with basin response

• Synthetics have amplification factors of 2-5 at 1-10 s for the Seattle basin; much larger than that found for crustal earthquakes in NGA West 2 GMPE’s

• Synthetics show long durations of shaking (100 s at distance of 100 km)

• Synthetics are posted on DesignSafe Website https://doi.org/10.17603/DS2WM3W

• ShakeMaps will be posted on USGS Scenario ShakeMap site
Epicenters of point sources used to estimate amplification for CSZ great earthquakes.
Log averaged SA values from 30 scenarios

Seattle basin
Tacoma basin
For the stochastic part we assume, for now, a uniform stiff-soil site condition; $V_{s30} = 600$ m/s
Log averaged SA values from 30 scenarios

For periods less than 1 second, we made stochastic synthetics for $V_{s30} = 600 \text{ m/s}$

We combined 3D synthetics with stochastic synthetics using matched filters with 1 second crossover period
“logic tree” used for 30 rupture scenarios, Mw= 9.0

Also completed 20 3D simulations for sensitivity tests of rupture parameters
(Wirth et al., in press)

Figure by E. Wirth