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GROUND MOTION CHARACTERISTICS OF SIMULATED M9 CASCADIA SUBDUCTION ZONE EARTHQUAKES IN DEEP BASINS

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Abstract

A United States Geological Survey and University of Washington research team studied the impacts of a large-magnitude, megathrust earthquake on the U.S. Pacific Northwest (PNW) due to the Cascadia Subduction Zone. The team used physics-based simulations of the ground motions resulting from thirty possible magnitude-9 (M9) earthquake scenarios (sampled randomly from a logic tree), on a 1-km grid throughout the Pacific Northwest. The 3-D simulations used a finite-difference approach to generate long-period (T>1s) waves, combined with a stochastic approach to generate short-period waves (T<1s). The long-period components of motion used a seismic-wave velocity model that represents the geological structure of the Cascadia Subduction Zone, including several deep sedimentary basins that underlie urban environments (e.g., Seattle, Portland, and Vancouver). The team examined the spectral accelerations, ground-motion durations and spectral shape of these ground motions.

For ground-motions outside of basins, the simulations were found to be consistent with spectral acceleration predictions from empirical ground-motion models (within 0.5 natural-log) for periods < ~7s. However, for ground-motions inside of basins, the ground-motion models underpredicted the long-period spectral accelerations compared to the 3-D simualtions. In particular, the deep sedimentary basin underlying the city of Seattle was found to amplify long-period (2-5s) spectral accelerations by factors of 4-6 compared to sites outside the basin. The ground-motions generated for Seattle had spectral shapes that were found to be more damaging than those typically observed in other regions. Additionally, the significant duration of strong earthquake shaking was found to be ~110-seconds long in Seattle, significantly longer than observed for crustal and intraslab earthquakes.

Keywords: basin effects, physics-based simulations, ground motion model residuals, spectral shape, long duration

1. Introduction

Geologic evidence indicates that the Cascadia Subduction Zone (CSZ) is capable of producing large-magnitude, megathrust earthquakes at the interface between the Juan de Fuca and North American plates [1,2]. Similar subduction regions in Indonesia, Chile, and Japan have produced devastating earthquakes and tsunamis (e.g., [3,4,5]). The most recent large-magnitude, interface earthquake on the CSZ occurred in 1700 A.D. [1], and according to[6], there is a 10-14% chance that a magnitude-9 earthquake will occur along the Cascadia Subduction Zone within the next 50 years.

There is much uncertainty about the characteristics of the ground motions during an M9 event because of the paucity of seismic recordings from similar events. Based on recordings from other regions, the motions are expected to have long durations. Additionaly, the motions are expected to be modified to have more damaging frequency content because of the deep sedimentary basins underyling the Puget Sound region. The effects of these long durations and the modification of the ground motions by the deep basins are currently not taken into account by current seismic provisions (e.g., AASHTO 2017 [24] and ASCE 7-16 [25]), which reference the 2014 version of the National Seismic Hazard Model [12].

To address the absence of recorded interface earthquake in the Pacific Northwest, Frankel et al. [7] and Wirth et al. [8] simulated the generation and propagation of magnitude 9 CSZ earthquakes for a range of rupture scenarios. In this paper, the motions from these simulations (denoted as the M9 simulations herein) are characterized using three intensity measures (spectral acceleration, ground-motion duration and spectral shape) that are known to correlate with structural response [9], including the ductility demands and collapse performance of structures (e.g., [10], [11]). The following sections summarize the simulations and discuss the corresponding three ground-motion intensity measures.

2. Simulations of M9 Cascadia Subduction Zone Earthquake

Frankel et al. [7] reported the results of thirty physics-based magnitude-9 (M9) CSZ earthquake simulations that were developed as part of a collaboration between the United States Geological Survey and the University of Washington with the support of the National Science Foundation. The thirty realizations represent a variety of magnitude-9 scenarios of a full Cascadia Subduction Zone rupture. The scenarios varied the slip distribution, hypocenter location, inland extent of the rupture, and the location of high stress drop subevents along the fault plane. The extent of the down-dip rupture was varied to be consistent with the logic tree branches for a full-length rupture of the CSZ used in the U.S. National Seismic Hazard Maps [12].

For low frequencies (up to 1 Hz), the motions were generated using a finite-difference code ([13]) that uses a 3D seismic velocity model [14] that reflects the geological structure of the CSZ and the Puget Sound region. The Puget Sound region is founded on glacial deposits that overlay sedimentary rocks between the Olympic and Cascade Mountains and includes several deep sedimentary basins, including the deepest one that underlies the city of Seattle. Each scenario generated approximately 500,000 motions on a 1-by-1 km grid spacing for a region ranging from Northern California to Vancouver Island, and from the offshore Cascadia Trench to as far inland as central Washington and Oregon. For high frequencies (above 1 Hz), the motions were generated with a stochastic procedure [15] assuming a generic rock site profile ([27]) without considering the effects of the basins. These simulations were then used to generate broadband motions by combining the low-frequency and high-frequency components using a matched filter at 1 Hz. These motions can be retrieved from the following reference [27].

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3. Spectral Accelerations

Building and bridge specifications (e.g., ASCE 7-16, AASHTO 2017) in the United States use spectral acceleration (for a damping ratio of 5%) at the fundamental period of a structure to estimate the seismic designs loads. Figure 1a shows the spectral acceleration with respect to period for all 30 realizations for a site in downtown Seattle. For comparison, the design spectrum corresponding to the ASCE 7-16 risk-adjusted maximum considered earthquake (MCE_R) (assuming Site Class C) is shown with a solid red line.

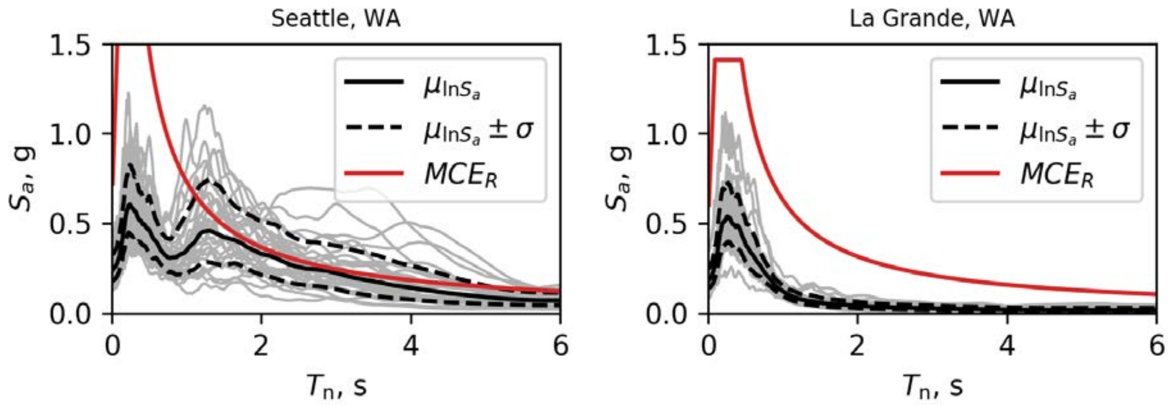

Figure 1. Geometric mean (solid black line) of the spectral acceleration for both horizontal components for all 30 M9 simulations for (a) Seattle and (b) La Grande. Dashed black lines denote one lognormal standard deviation above and below the mean, and the response spectra from individual M9 earthquake scenario are shown in gray. Response spectra corresponding to the risk-targeted maximum considered earthquake for Seattle and La Grande (using the 2014 USGS NSHM) are shown in red.

For Seattle, the spectral acceleration of the M9 simulations are much smaller than the MCE_R design values for periods below 1 second. However, for periods ranging from 1 to 4 s, the geometric mean of the M9 spectral accelerations are only slightly below the MCE_R design values, and the spectral accelerations for many of the simulated motions exceed the MCE_R design values. This exceedance is important, because magnitude-9 interface earthquakes have a return period of about 475 years, and they represent only part of the seismic hazard in Seattle, which has large contribution from the Seattle Fault. For example, at short periods (0.5 s), the CSZ full-rupture earthquake (M8.8 to 9.3) contributes only 20% of the seismic hazard, and at a period of 2.0s, it contributes 43%.

Figure 1b shows the same information as Figure 1a but for a site 73 km south of Seattle (near La Grande, Washington). Ground-motion models predict similar spectral accelerations for the Seattle and La Grande sites for an interface earthquake, because both locations have similar values of closest-distance to the fault-rupture plane (R_{CD}). Indeed, the design spectra (accounting for all sources) for the two locations are within 15% for periods less than 0.5 s. In contrast, for periods greater than 0.5 s, the simulated values of S_a are much lower in La Grande than the motions simulated for Seattle and than the MCE_R values.

The differences between the motions simulated for Seattle and La Grande can be attributed mainly to the effects of the deep sedimentary basin that underlies Seattle. A one-dimensional measure of the basin depth is the depth to very stiff bedrock material with a shear-wave velocity (V_s) of 2.5 km/s, denoted as $Z_{2.5}$. Campbell and Bozorgnia [28] used this measure of basin depth in their ground-motion model (GMM) for crustal earthquakes. Figure 2 shows the variation of $Z_{2.5}$ within the Puget Lowland

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region in which $Z_{2.5}$ reaches values of 4 to 5 km over a wide area. Seattle and many of its surrounding cities are located in the Seattle Basin, a region where $Z_{2.5}$ reaches values up to 7 km. The map shows that there are also shallower basins near Everett (north of Seattle) and Tacoma (southwest of Seattle). In contrast, $Z_{2.5}$ is equal to ~0.5 km for the location near La Grande.

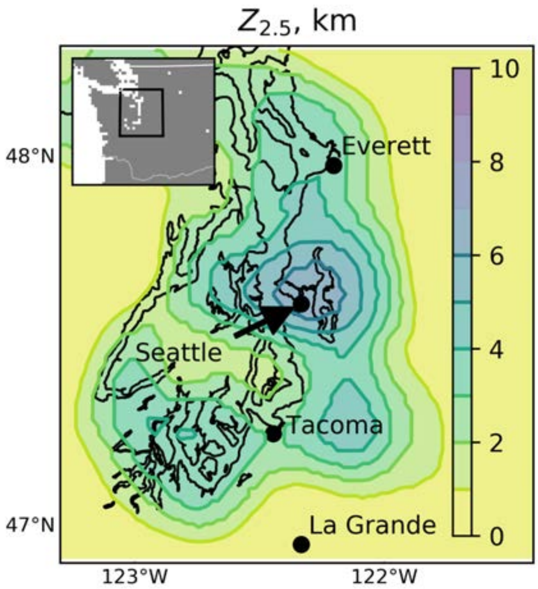

Figure 2. Map of $Z_{2.5}$ for the Puget Lowland region.

The effects of the basin on ground-motion intensity can be visualized by comparing the map of $Z_{2.5}$ (Figure 2) with the regional variation of the geometric mean of the spectral acceleration for the thirty M9 simulations (Figure 3) across the Puget Sound region. Figure 3a shows that, as expected, the short-period (0.5s) spectral accelerations attenuate consistently with distance from the fault rupture plane (smaller spectral accelerations going eastward). In contrast, Figure 3b shows that at longer periods (e.g., 2.0 s) the spectral accelerations increase within the Puget Sound Lowland compared to nearby locations, and the spectral accelerations are particularly high for locations in the deepest part of the Seattle Basin.

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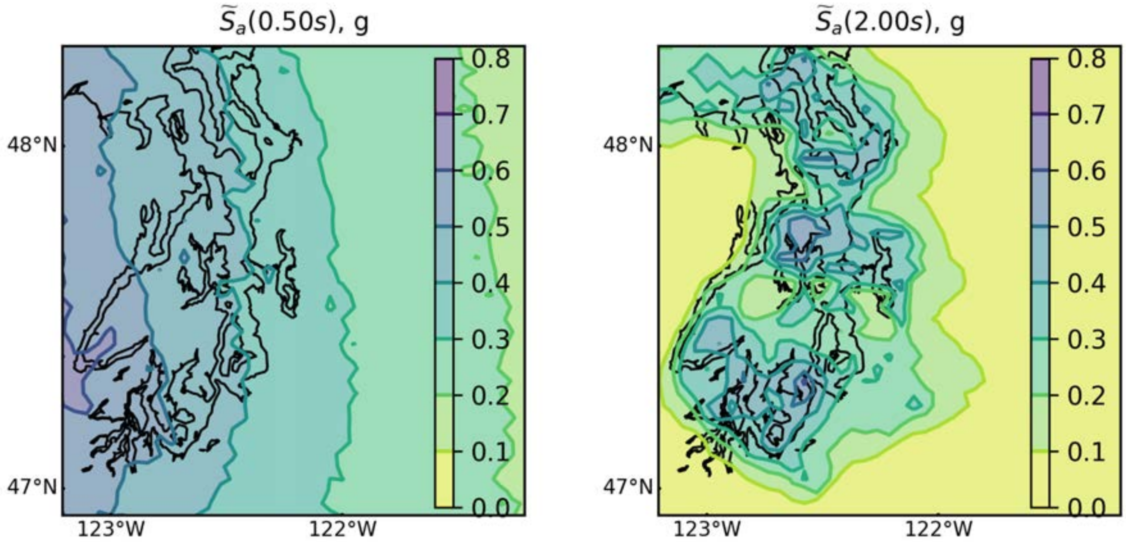

Figure 3. Regional variation of geometric mean of S_a for all M9 realizations of the spectral accelerations at periods of (a) 0.5 seconds and (b) 2.0 seconds.

4. Spectral Shape

The effects of the response spectra shape are not typically considered in conventional design. Nonetheless, numerous researchers have found that the spectral shape at periods near the fundamental period of the structure affect the response of nonlinear systems. Haselton et al. [17] and Eads et al. [18] have shown that spectral shape influences collapse probabilities for structures. Marafi et al. [19] developed a measure of spectral shape, SS_a, that accounts for the differences in period elongation between brittle and ductile structures. This measure correlated well with the collapse performance for recorded crustal and subduction earthquake ground motions. This measure can be used to evaluate the effects of basins on spectral shape by relating SS_a to $Z_{2.5}$.

SS_a is defined using the integral of the ground-motion response spectrum between the fundamental period of the building (T_n) and the nominal elongated period (αT_n). To make SS_a independent of the spectral amplitude at the fundamental period, the integral is normalized by the area of a rectangle with a height of $S_a(T_n)$ and width of $(\alpha\text{-}1)T_n$.

$$SS_a(T_n, \alpha) = \frac{\int_{T_n}^{\alpha T_n} S_a(T)dT}{S_a(T_n)(\alpha - 1)T_n} \tag{2}$$

where αT_n accounts for the period elongation of the structure. Values of SS_a larger than 1.0 indicate that the spectral accelerations increase with increasing period, on average, which is likely to make the ground motion more damaging. Values of SS_a smaller than 1.0 indicate that the spectral accelerations decrease with increasing period.

Figure 4 plots the regional variation of the geometric mean of SS_a (computed with α = 3.7 and is representative of a ductile system, see Marafi et al. [10]) for all thirty realizations for a period of 0.5 s (Figure 4a) and 2.0 s (Figure 4b). The spectral shapes in Seattle are more damaging (SS_a larger) for

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periods in the range of 0.5s to 1.3s than longer periods. This observation is consistent with the response spectra shown in Figure 1a, in which the spectral acceleration in Seattle reaches a maximum at a period of about 1.5s. Periods above that value have lower spectral accelerations, which decreases the spectral shape factor. Therefore, SS_a is more likely to be larger inside the basin at medium periods than at longer periods.

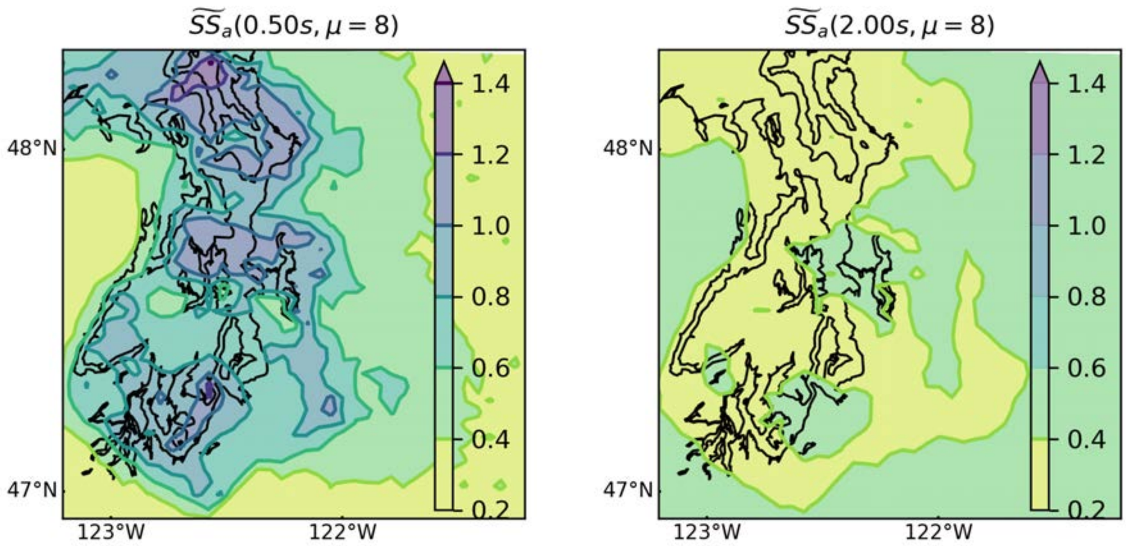

Figure 4. Regional variation of SS_a for a period of (a) 0.5s and (b) 2.0s where α is taken as $\sqrt{13.4}$ and is representative of a ductile system.

5. Duration

Researchers have shown that the duration of the ground motion can affect structural response. For example, Bommer et al. [20] found that the effects of duration are pronounced in structures that are susceptible to low-cycle fatigue, and undergo strength and stiffness degradation with cyclic loading. Hancock and Bommer [21] and Chandramohan et al. [22] found that significant duration, D_s, correlated well with structural collapse and had the advantage of being scale independent. Significant duration is defined as the time between two target values of the integral, $\int_0^{t_{max}} a_g(t)^2 dt$, where a_g is the ground acceleration and t_{max} is the total duration of the record. This paper uses significant duration computed at the 5-95% thresholds, $D_{s,5\text{-}95\%}$.

There are currently no ground motion models for significant duration for subduction interface earthquakes. However, $D_{s,5\text{-}95\%}$ is known to increase with earthquake magnitude, extent of rupture plane and site-to-source distance [23]. Figure 5 shows the regional variation of the geometric mean of $D_{s,5\text{-}95\%}$ for all thirty M9 realizations. As expected, $D_{s,5\text{-}95\%}$ increases with distance from the fault rupture plane (moving eastwards). The duration does not vary consistently with $Z_{2.5}$. For example, both the Seattle and La Grande ground-motion sets had $D_{s,5\text{-}95\%}$ geometric mean values near 110 s.

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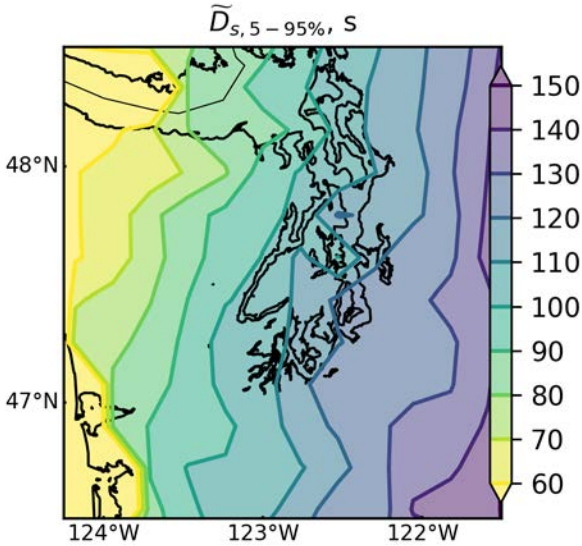

Figure 5. Regional variation of the geometric mean of the $D_{s,5\text{-}95\%}$ for all thirty M9 CSZ realizations.

6. Conclusions

Spectral acceleration and shape, and ground-motion duration were quantified using the suite of thirty physics-based simulations of an M9 earthquake due to the Cascadia Subduction Zone. At period above 1.0s, the spectral acceleration inside the Puget Lowland region were found to be much larger than those outside the region. An example site in Seattle was found to have many ground motion realizations which exceeded the MCE_R spectral acceleration intensity currently considered in the seismic provisions (e.g., ASCE 7-16). These large spectral accelerations were mainly attributed to the effects of sedimentary basins underlying the region.

Additionaly, the observed basin amplification on spectral acceleration was period-dependent, which led to ground motions with damaging spectral shapes for structures for periods below 1.0s. The simulated ground motions had significant duration near 110 s in Seattle which is mainly attributed to the large magnitude of the earthquake. While these durations are long, the basin underlying the Puget Sound region was not found to further increase the significant duration of the simulated motions, using a duration meaure based on the acceleration waveforms. These ground motion intensities are important for assessing the response of structures in the U.S. Pacific Northwest.

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