3-D SIMULATIONS OF M9 EARTHQUAKES ON THE CASCADIA MEGATHRUST: KEY PARAMETERS AND UNCERTAINTY

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ABSTRACT

We examine the range and variability of ground motions from potential magnitude 9 Cascadia subduction zone earthquakes using 3-D numerical simulations of 50 M9.0 earthquake scenarios. We vary key rupture parameters, including the down-dip limit of the rupture zone, the spatial distribution of slip, the hypocenter location, and the along-strike distribution of strong motion-generating subevents. We observe up to a factor of ~10 variation in the response spectra (1-10 s) across the earthquake scenarios. For the down-dip limit of slip, we test the three different down-dip rupture extents from the 2014 National Seismic Hazard Maps. We find that ruptures that terminate offshore tend to produce lower ground motions for inland sites near major cities at periods < 5 s compared to ruptures that extend to the coastline or beyond the coastline. Rupture scenarios with slip extending to the 1 cm/yr locking contour (i.e., based on modeling GPS and uplift data) provide the best match to coastal geologic evidence for co-seismic offset during previous Cascadia earthquakes. We also find that rupture directivity, which depends on the hypocenter location, as well as the slip distribution, strongly impacts the resulting ground motions. Rupture directivity effects are strongest when high slip patches or strong-motion generating subevents are located along the rupture path in the direction from hypocenter-to-site. Overall, our results provide a basis for probabilistically evaluating building response, liquefaction, and the generation of landslides due to M9.0 Cascadia earthquakes.

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ABSTRACT

We examine the range and variability of ground motions from potential magnitude 9 Cascadia earthquakes using 3-D numerical simulations of 50 M9.0 earthquake scenarios. We vary key rupture parameters, including the down-dip limit of the rupture zone, the spatial distribution of slip, the hypocenter location, and the along-strike distribution of strong motion-generating subevents. We observe up to a factor of \(\sim 10\) variation in the response spectra (1-10 s) across the earthquake scenarios. For the down-dip limit of slip, we test the three different down-dip rupture extents from the 2014 National Seismic Hazard Maps. We find that ruptures that terminate offshore tend to produce lower ground motions for inland sites near major cities at periods < \(\sim 5\) s compared to ruptures that extend to the coastline or beyond the coastline. Rupture scenarios with slip extending to the 1 cm/yr locking contour (i.e., based on modeling GPS and uplift data) provide the best match to coastal geologic evidence for co-seismic offset during previous Cascadia earthquakes. We also find that rupture directivity, which depends on the hypocenter location, as well as the slip distribution, strongly impacts the resulting ground motions. This effect will be strongest when high slip patches or strong-motion generating subevents are located along the rupture path in the direction from hypocenter-to-site. Overall, our results and sensitivity analyses provide a basis for probabilistically evaluating building response, liquefaction, and the generation of landslides due to M9.0 Cascadia earthquakes.

Introduction

Geologic and historical records indicate that the Cascadia subduction zone is capable of generating large, megathrust earthquakes up to \(\sim\)M9.0. However, since the last great Cascadia earthquake occurred in 1700, there is no direct measure on the intensity of ground shaking or specific rupture parameters from seismic recordings. Obtaining reasonable estimates of expected ground shaking due to a Cascadia megathrust earthquake is critical to improving seismic hazard assessment in the Pacific Northwest.

We use 3-D numerical simulations to evaluate a range of possible ground motions due to M9.0 earthquakes on the Cascadia megathrust. We test reasonable choices of critical rupture

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parameters (e.g., hypocenter location, the down-dip rupture extent, and the proximity to high-stress drop subevents), and demonstrate their effects on strong ground motions.

**Methods**

The generation of broadband synthetic seismograms includes deterministic 3-D finite difference simulations for ground motions < 1 Hz, combined with 1-D stochastic synthetics for frequencies > 1 Hz. For the 3-D deterministic simulations, we use a compound rupture model (Fig. 1): slip on the fault consists of multiple high-stress drop subevents with short rise times in the deeper portion of the rupture, superimposed on a background slip distribution with longer rise times. The slip distributions are randomly generated for each scenario using a Von Karman autocorrelation function and specified correlation distances. We assume that high-frequency energy (i.e., the stochastic synthetics) is generated exclusively by the subevents. Similar compound source models have accurately reproduced response spectral accelerations from the 2010 M8.8 Maule, Chile and 2011 M9.0 Tohoku, Japan earthquakes [1,2]. In total, we simulate 50 different Cascadia subduction zone earthquake scenarios.

![Figure 1](image.png)

Figure 1. The earthquake source is characterized by a compound rupture model, in which slip on the fault consists of (left) background slip and (right) high-stress drop subevents. The stars indicate the hypocenter locations for the synthetic data shown in Fig. 2.

**Results**

We measure the effects of varying earthquake rupture parameters on 5% damped spectral acceleration ($S_A$) for periods of 1 – 10 s. Plots of $S_A$ as a function of distance from the rupture demonstrate the extent to which variations in specific rupture parameters affect the intensity of ground motions.
**Hypocenter Location**

We evaluate the resulting ground motions for two scenarios in which all rupture parameters are equivalent except for the hypocenter location. Due to rupture directivity, the hypocenter that is located farther offshore (Fig. 1, filled star) produces median $SA$ values that are ~2x higher than the inland hypocenter for sites up to ~200 km away from the rupture at periods of $1 – 10\ s$ (Fig. 2). For certain individual sites, the estimated $SA$ varies by a factor of 10 between the two scenarios. In addition, numerous locations have predicted spectral accelerations that exceed the estimates of the BC Hydro ground motion prediction equations [3]. We also note a coupling between rupture directivity and basin effects, in which amplification of ground motions by sedimentary basins increases when rupture directivity effects are stronger.

![Figure 2](image-url)

**Figure 2.** (top) Spectral acceleration as a function of closest distance to the rupture for various periods. Estimates from simulated ground motions at individual sites are shown as colored circles; black edges indicate sites within the Puget Lowland sedimentary basins. The median spectral accelerations are shown as colored lines. (bottom) Ratio of median spectral acceleration for the offshore hypocenter (Fig. 1, filled star) to the onshore hypocenter (Fig. 1, open star), as a function of closest distance to the rupture.

**Down-Dip Rupture Extent**

In Cascadia, the down-dip rupture extent controls an earthquake’s closest approach to major inland cities such as Seattle, WA; Portland, OR; and Vancouver, BC. We predict stronger ground motion intensities for inland locations when the rupture extent is farther down-dip, primarily due to the deeper (i.e., landward) location of the high-stress drop subevents. Variations in the down-dip limit result in a significant but lesser change in $SA$ (roughly up to a factor of 5) at individual locations.
Proximity to High-Stress Drop Subevents

To assess the importance of a site’s location relative to high-stress drop subevents, we evaluate $S_A$ as a function of distance for sites located within two transects: a transect directly landward of a subevent (Fig. 3, orange points) and a transect landward of a gap between subevents (i.e., a low stress drop region; Fig. 3, blue points). A site’s proximity to subevents on the megathrust results in a >10x increase in the median $S_A$ for stations close to the rupture (i.e., ~ 20 km).

![Figure 3. Spectral acceleration as a function of closest distance to the rupture for various periods. Sites located directly landward of a subevent are shown in orange (“subevent transect”) and sites located in a gap between subevents are shown in blue (“gap transect”).](image)

Conclusions

We produce broadband synthetic seismograms for various $M_{9.0}$ Cascadia earthquake rupture scenarios, highlighting the effects of varying key rupture parameters on strong ground motions. Changes in the hypocenter location, down-dip rupture extent, and proximity to high-stress drop subevents can cause estimates of response spectral accelerations ($1 – 10$ s) to vary by up to a factor of ~10 at individual sites. The synthetic ground motions produced by this study are being used to evaluate building response, and to assess the potential for liquefaction and landslides.

Acknowledgments

This work was supported by National Science Foundation grant EAR-1331412. The authors acknowledge the Texas Advanced Computing Center at The University of Austin, Pacific Northwest National Laboratory, and the University of Washington for providing high performance computing resources that contributed to the results reported within this paper.

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