Monte Carlo uncertainty analysis for the hazard from the Cascadia Subduction Zone in the Pacific Northwest of the United States

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Abstract

The Cascadia subduction zone contributes significantly to the hazard along the coastal Pacific Northwest of the United States. We have constructed a logic tree for assessing the uncertainty in the ground motions that includes variability in the location of the bottom of the rupture, the magnitude, the recurrence rate, and the ground motion attenuation relations. Results of this uncertainty analysis indicate an overall coefficient of variation for the Cascadia hazard model with 2% probability of exceedance in 50 years between 0.3 and 0.5. Variability in each of the individual parameters results in coefficient of variations less than 0.3. The logic tree for the Cascadia subduction zone and synthetic seismograms for hazard involve extensive computer calculations that may be facilitated by a supercomputer.

Introduction

The Cascadia subduction zone is a 1000 km long structure that accommodates about 40 mm/yr of convergence between the overriding North American and the subducting Juan de Fuca tectonic plates. Although no great earthquake has been recorded directly in the 200 year historic record, paleoseismic evidence of abrupt subsidence (e.g., Atwater, 1995[2]; Clague, 1997[4], Nelson et al., 1996[9]), continental slope turbidite deposits (Adams, 1990[1]), tree ring analysis (Jacoby et al., 1997[8]), and tsunami records in Japan (Satake, 1996[11]) are evidence of large prehistoric events along the Cascadia margin. The Cascadia subduction zone contributes considerably to the hazard in the Pacific Northwest of the United States, especially along the coastal portion of Washington State.

For a probabilistic seismic hazard assessment it is essential to account for all possible earthquakes. Therefore, it is necessary to assess the various sizes, locations and recurrence rates of events that may occur along the zone and the ground motions that may result from these earthquakes. Because we do not know where or how often future ruptures will occur, we typically develop multiple models and weight them according to their likelihood. This analysis results in a mean hazard estimate and describes the best estimate of hazard that the science community can provide at a particular moment in time.

It is also important to assess the variability in the hazard so that end-users can judge how much they can rely on a particular hazard estimate. To quantify this uncertainty, we construct a logic tree that considers all realistic models that are justified by data and accepted by the scientific community. Each of these individual models results in a mean hazard estimate and the collection of all of these hazard values provides an estimate of the uncertainty in the mean. For this paper we calculate the mean hazard and estimate its uncertainty for the Cascadia subduction zone at 2%

probability of exceedance in 50 years. In addition, this uncertainty analysis quantifies which parameters contribute most to the overall hazard. We describe the variability in the location, recurrence, and size of future ruptures and estimate this uncertainty as a coefficient of variation, the standard deviation divided by the mean.

Logic Tree

The logic tree used in this analysis is a representation of the possible outcomes of hazard obtained using different source or ground shaking models. Each of the branches of the tree represents a parameter that is needed in the hazard analysis. The ends of the branches represent complete models that can be used for computing a mean hazard estimate. The distribution of the outcomes from each of the branches indicates the uncertainty in the hazard. Parameters that contribute most to the uncertainty in the hazard include: location of source, magnitude of source, recurrence rate of sources, and attenuation relations used to calculate the ground motion. The logic tree that we applied is shown in Figure 1.

Logic Tree for Cascadia Subduction Zone

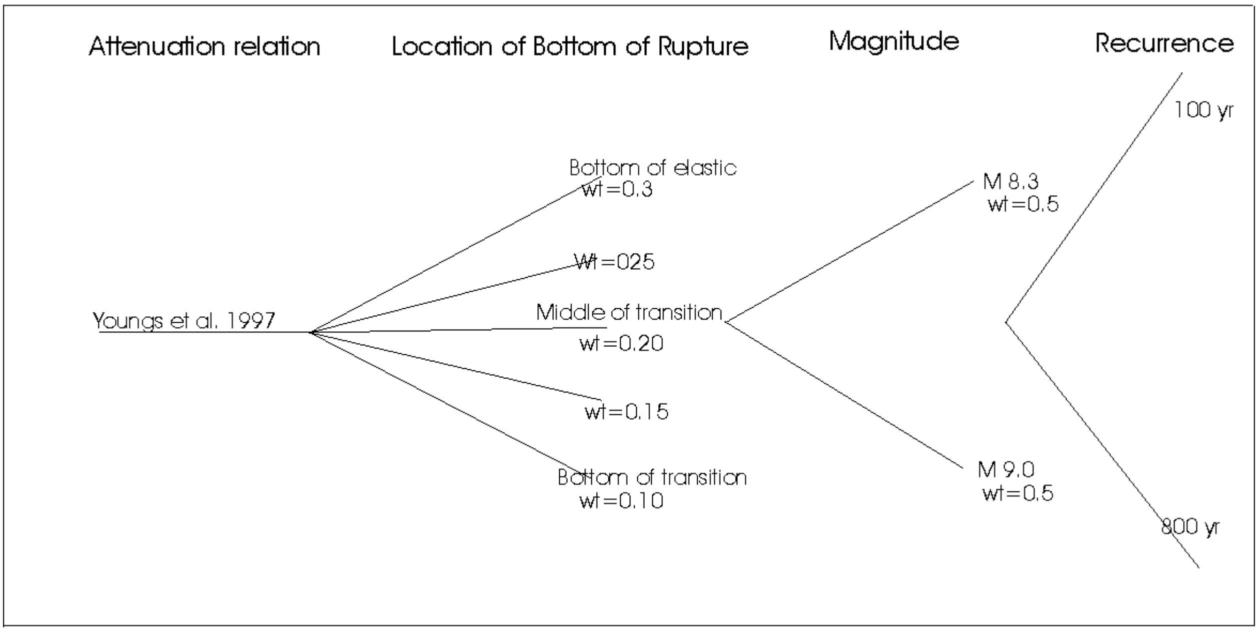

Figure 1: Logic tree for the Monte Carlo simulation used in this uncertainty analysis.

We sample the logic tree using a Monte Carlo simulation (Press et al., 1992[10]) because the number of calculations necessary to run hazard models for all of the branches of the logic tree is often quite large.

Attenuation Relation

We apply the Youngs et al. (1997[12]) attenuation relation for this analysis. Several other attenuation relations are currently being prepared for subduction zone ground motions on rock sites.

However, these relations were not available for this assessment. The alternative attenuation relations will be included in future uncertainty analyses. Typically the uncertainty in the attenuation relationship results in a coefficient of variation of about 0.2 to 0.3.

Depth of the Rupture

Hyndman and Wang (1995[7]) and Flueck et al.(1997[5]) assembled models for the Cascadia subduction zone based on thermal constraints of the downgoing slab (Figure 2). In these models a locked elastic zone, obtained from dislocation modeling of recent deformation data, represents the portion of the slab with temperatures up to 350° C. A transition zone is located downdip and adjacent to the elastic zone and represents the portion of the slab with temperatures between 350° and 450° C. At deeper depths, the slab is thought to be so hot to that deformation occurs viscoelastically. The hazard is very sensitive to the depth of earthquake rupture at sites located above the slab.

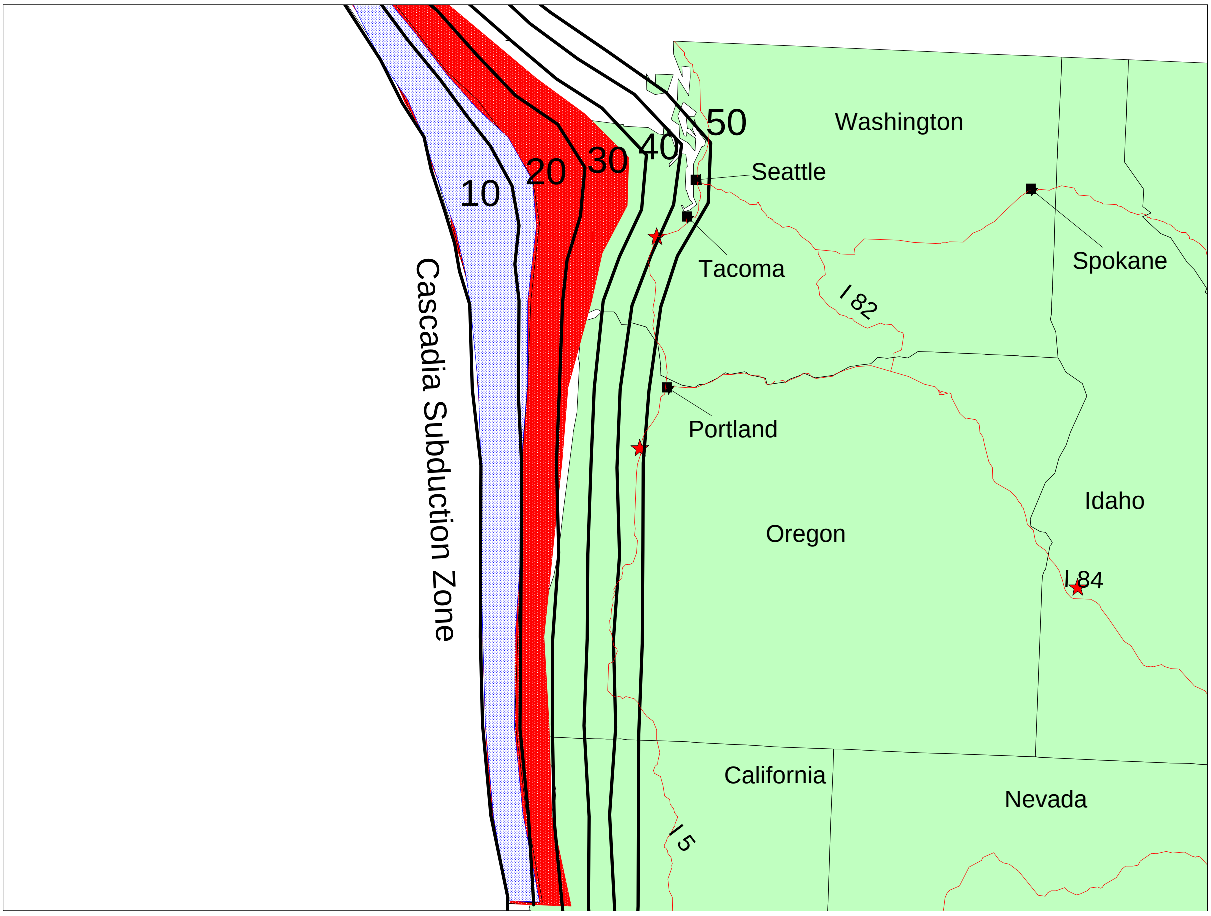

Figure 2: Map showing location of the Cascadia subduction zone in the Pacific Northwestern U.S. The contours represent the depth of the zone in kilometers. Shaded regions represent elastic (shallow) and transition (deep) zones.

We modeled the rupture as beginning at the top of the Flueck et al. (1997[5]) model that is about 4 km below the surface. The rupture continues downdip to a depth that varies from the bottom of the elastic zone (about 10 to 15 km depth) to the bottom of the transition zone (15 to 30 km depth). Because it is more likely that the rupture would occur at the bottom of the elastic zone than at the bottom of the transition zone, we used a ramp function to weight the various models.

The coefficient of variation resulting from the variability in the location of the bottom of the rupture ranges from 0.1 to 0.3. This uncertainty is highest in northern Washington where the fault dip is shallowest.

Magnitude

The magnitude of the earthquake is critical in determining the level of ground shaking. Generally, larger earthquakes produce higher ground motions (up to some threshold) and affect larger areas. The great earthquakes along the trench are thought to range from M 8.3 to 9.0. For example, a M 8.3 rupture would be consistent with a rupture along the 300 km Gorda segment of the Cascadia zone. A M 9.0 earthquake would be consistent with a rupture along the entire 1000 km zone. We applied equal weights to the M 8.3 and the M 9.0 earthquakes and allowed the magnitude to vary by one-tenth of a magnitude unit for one standard deviation and truncated the distribution at 2 standard deviations. The coefficient of variation for the magnitude alone is about 0.2 along the coast of Washington and Oregon.

Recurrence Rate

The recurrence rate of the great Cascadia events is thought to range between about 100 and 800 years, with a best estimate of about 500 years. We estimated the recurrence rate by obtaining earthquake intervals using a Monte Carlo approach that sampled the individual dates with uncertainty from the Atwater and Hemphill-Haley (1997[3]) paleoseismic data. The recurrence intervals were modeled using a normal distribution with the midpoint representing the median and the range representing 2 standard deviations. The resulting median recurrence interval is 440 years with a lognormal standard deviation (intrinsic sigma) of 0.58. This implies a mean recurrence interval of 520 years.

For this analysis we assume that the recurrence rates observed in the trenches are only from M 9.0 or M 8.3 earthquakes. First, we assume that all of the events recorded in the trench are M 9.0 earthquakes and calculate a moment rate for these earthquakes. The M 9 earthquakes recur with the rate obtained from the Monte Carlo analysis. Next, we use the moment rate of the M 9.0 earthquakes to determine an equivalent recurrence rate for M 8.3 earthquakes along the zone. The M 8.3 earthquakes are allowed to float anywhere along the zone. The result of varying the recurrence rate is a coefficient of variation of about 0.2 to 0.3 along the coastal Pacific northwestern United States.

Overall Uncertainty

The overall uncertainty obtained by varying the depth of the rupture, the magnitude, and the recurrence rate is shown in Figure 3. In most areas of the Pacific northwestern United States the total uncertainty has a coefficient of variation of about 0.3 to 0.4. The uncertainty is highest in the Puget Lowlands, where the dip of the Cascadia subduction zone is shallow. The uncertainty is lower in central Oregon where the Cascadia subduction zone is farther away and the hazard from this subduction zone is lower. This overall uncertainty is quite high and could be reduced by additional constraints on the location of the rupture and the recurrence rate for these earthquakes.

Calculations

The calculations necessary for an uncertainty evaluation may be quite extensive depending on the number of sites, and number of parameters that will be varied in the analysis. The number of calculations is quite large when one considers the hundreds of faults, random earthquakes, and 150,000 sites considered in the U.S. National Maps. In addition, these calculations use generic attenuation relations for ground motions. A more accurate procedure would be to use 3-D simulations to produce time histories of strong motions that include basin effects, directivity, and non-linear soil response. These time histories would be input for inelastic models of building response, to produce estimates of probabilistic damage (Frankel and Safak, 1998[6]). Therefore uncertainty analysis for the U.S. National Seismic Hazard maps may benefit from supercomputer applications.

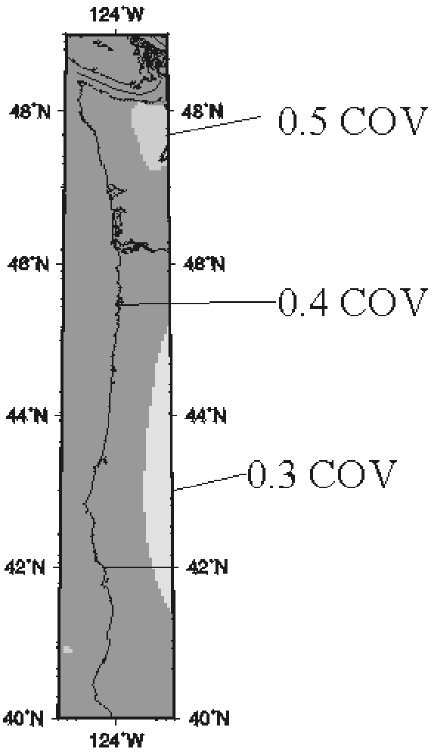

Figure 3: Coefficient of Variation (Ratio of standard deviation to mean) for coastal Pacific Northwest at 2% probability of exceedance in 50 years for peak ground acceleration on a rock site condition.

Conclusions

The 2% probability of exceedance in 50 year hazard from the Cascadia subduction zone has a coefficient of variation of up to 0.5 but is generally about 0.3 to 0.4 along the coastal Pacific northwestern part of the United States. The location of the bottom of the rupture, the magnitude, and the recurrence rate each contribute about the same amount to this uncertainty, ranging from about 0.2 to 0.3 coefficient of variation. Scientific research that constrains these parameters will yield better estimates of the mean hazard and reduce the high uncertainty in the hazard associated with this zone. As more parameters are varied, the number of sites is increased, and synthetic seismograms are generated these analyses will demand more computational resources and may be facilitated by supercomputer applications.

Acknowledgments

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