Earthquake Hazard Studies in the U.S. Pacific Northwest: From Crustal Models to Shallow Geophysics

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Summary
Earthquake hazard assessments in the U. S. Pacific Northwest have improved dramatically over the past two decades as we have developed a better understanding of the seismic sources and the distribution of ground shaking. A number of geological and geophysical experiments have been carried out to delineate the major faults in the region, to characterize these faults and determine their earthquake history, and to measure the influence of shallow sediments and deep sedimentary basins on ground shaking. These results are fueling new models for the style of faulting in the region, the ages of earthquakes, and the influence geologic features have on ground shaking during earthquakes.

1. Introduction
The Cascadia region of the U. S. Pacific Northwest (Figure 1) is an area of active subduction in which the Juan de Fuca oceanic plate is subducted beneath the North American continent. Two major expressions of this subduction zone setting are the Cascade Range volcanic arc and the Puget-Willamette forearc basin. The major urban areas of the U. S. Pacific northwest lie within the Puget-Willamette valley, including the cities of Seattle, Tacoma, Olympia and Vancouver, Washington State, and the cities of Portland and Salem in Oregon State.

The major cities of the U. S. Pacific northwest are at risk from three major earthquake source zones: 1) the subduction zone plate interface, 2) Benioff zone earthquakes within the subducted Juan de Fuca Plate, and 3) shallow faults within the North American crust. Of these source zones, the most dangerous are believed to be the great subduction zone earthquakes because of the potentially large magnitude (9), and the shallow North American faults because of their location directly beneath the largest cities in the region. Of particular concern is the Seattle fault because it hosted an earthquake about 1100 years ago directly beneath the region’s largest cities (Bucknam et al., 1992).

Assessments of the earthquake hazard in the U. S. Pacific Northwest have seen major improvements in the past two decades because of technological advances and the application of geological, paleoseismological and geophysical methods. These studies have included the acquisition of complementary sets of geologic and geophysical data to locate and characterize crustal faults.

2. Delineation of Active Faults
Active faults in the Puget Lowland were first identified from abrupt changes in Bouguer gravity values (Gower et al., 1985). Since that initial study, further compilations of gravity measurements (Finn et al., 1991), and an aeromagnetic survey undertaken specifically for earthquake hazards research, have delineated the Seattle, Southern Whidbey Island, Devils Mountain and Tacoma faults, plus a possible fault beneath the city of Olympia (Figure 2).

To further locate and characterize major faults,
U.S. Geological Survey scientists, university researchers, and local government agencies worked together to obtain Light Detection and Ranging (LIDAR) data. LIDAR data, acquired from an airplane, provide an unprecedented digital elevation model of the ground surface beneath the canopy of dense vegetation. These LIDAR data have allowed us to identify fault scarps cutting the shallow layers of late Pleistocene and Holocene sediments, giving us targets for paleoseismic studies.

To obtain subsurface images of potential faults, and to provide constraints on computer modeling of earthquakes, U.S. Geological Survey and university scientists undertook the series of Seismic Hazard Investigations of Puget Sound (SHIPS) to obtain a tomographic image of the crust in the region (Figure 2; Brocher et al., 2001; Van Wagoner et al., 2002). These tomographic studies utilized earthquakes and active sources (airguns and blasts) recorded on the Pacific Northwest Seismic Network (PNSN) and temporary seismometer installations. The results have given us a low-resolution image of the deeper parts of the faults and some 3-dimensional control on the geometry of the sedimentary basins in the region (Fig. 2).

The crustal faults beneath Puget Sound were interpreted by Pratt et al. (1997) as an interconnected thrust system, based on analysis of a network of marine seismic reflection profiles acquired for energy exploration. Seismic reflection profiling during the 1998 SHIPS experiment provided data to refine the thrust interpretation for the Seattle fault (tenBrink et al., 2000). Reinterpretation of these seismic profiles led Brocher et al. (in press) to a more controversial roof thrust model for faults in the region.

High-resolution seismic reflection profiles have played a key role in documenting recent motion on faults beneath Puget Sound. High-resolution marine seismic surveys, carried out using small airguns or uniboom sources, have been acquired across all of the major faults. Recent motion has been documented

Figure 2. Map of the Puget Sound region of Washington State showing the speed of sound at 2.5 km depth from a tomographic study (Van Wagoner et al., 2002) and the major crustal faults. Labeled faults are the Devil’s Mountain (DF), Southern Whidbey Island (SWIF), Seattle (SF), Tacoma (TF) and the hypothesized Olympia fault (OF).

Figure 3. East-west profiles across the Seattle basin showing spectral amplitudes relative to bedrock sites (a, b), and a profile showing the P-wave velocity structure of the Seattle basin derived from tomographic analysis of the SHIPS 99 data (bottom). The numbers in parentheses in the legend on the top graph are the wave periods in sec. Red contour on the velocity model (4.5 km/s) is near the top of basement rocks. Note the large amplification of 1.0 to 0.2 Hz waves (1 sec to 5 sec periods) over the basin (a). Seismic stations contributing to the upper plots are listed.
major faults. Recent motion has been documented on the Devil’s Mountain, Southern Whidbey Island, Seattle, and Tacoma faults (Johnson et al., 1996, 2004). Most recently, seismic reflection profiles acquired in the spring of 2004 appear to show vertical displacement of shallow strata in the Olympia, Washington area (unpublished data).

The high-resolution seismic reflection profiling has been carried out in close cooperation with geologists using sea-level changes and trenching to document Holocene motion on shallow faults (Sherrod, 2001; Sherrod et al., 2003, 2004). These geologic studies are now being driven by the LIDAR images, which are especially effective at highlighting fault scarps that are otherwise hidden beneath the dense vegetation. Trenches across these scarps reveal the faults and allow for dating of organic material to determine the ages of the most recent activity (e.g., Sherrod et al., 2003, Nelson et al., 2003). Holocene motion has now been documented on the Seattle and Tacoma faults (Sherrod et al., 2004; Nelson et al., 2003), and Quaternary motion has been documented on the Southern Whidbey Island fault (Johnson et al., 1996).

4. Ground motion during earthquakes

A number of recent studies document the amplification effects caused by shallow deposits and depth sedimentary basins in the Puget Sound region. The amplification of seismic waves by shallow deposits (site response) has been observed in the region since the 1965 earthquake (Inhen and Hadley, 1986). Recent analyses of recordings of local earthquakes and airgun shots have shown marked amplification in the Holocene river valleys, particularly the Duwamish River valley in south Seattle (Frankel et al., 1999; Hartzell et al., 2000). The shallow, Holocene deposits filling the river valleys can cause significant amplification compared with nearby bedrock sites.

The 2001 Nisqually earthquake provided evidence for non-linear behaviour in the soft sediments of the Duwamish River valley (Frankel et al., 2003). Amplification factors for the mainshock are much smaller in some areas than the amplification at the same sites during a small aftershock. The implication is that non-linear soil behavior reduces the amplification during the mainshock. This non-linear behavior occurred at moderate peak ground accelerations, but many areas did not show non-linearity at these same accelerations. Shallow S-wave velocity measurements are being made at an increasing number of sites in the Seattle area to better understand the amplification effects from the shallow strata (e.g., Williams et al., 1999)

On a larger scale, Pratt et al. (2003a, 2003b) have carried out a series of studies to examine the influence of the Seattle sedimentary basin on ground shaking in the region. They used recordings of seismograms and local earthquakes to document substantial amplification of 0.2 to 0.8 Hz seismic waves by the Seattle basin (Fig. 3). In contrast, seismic waves at frequencies above about 7 Hz show a net attenuation within the basin sediments.

The low-frequency amplification documented by Pratt et al. (2003a) was also confirmed by Barberopoulou et al. (2004). They analyzed shear-wave and surface-wave arrivals from the 2002 Denali, Alaska, earthquake recorded by the PNSN strong-motion instruments to study the amplification by the Seattle basin in the 0.01 to 1 Hz frequency range. Results confirmed the peak amplification at about 0.3 Hz, but also showed significant amplification at lower frequencies. Interestingly, this low-frequency amplification contributed to the generation of large water waves in lakes overlying the Seattle basin. These water waves were large enough during the Denali earthquake to cause minor damage to at least 20 houseboats along the waterfront areas of Seattle, despite an epicentral distance of about 2400 km for the earthquake. These results highlight the need for better understanding the local amplification of seismic waves before accurate earthquake hazard assessments can be made.

References


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