Local amplification of seismic waves from the Denali Earthquake and damaging seiches in Lake Union, Seattle, Washington

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Received 6 September 2003; revised 3 December 2003; accepted 30 December 2003; published 14 February 2004.

[1] The Mw7.9 Denali, Alaska earthquake of 3 November, 2002, caused minor damage to at least 20 houseboats in Seattle, Washington by initiating water waves in Lake Union. These water waves were likely initiated during the large amplitude seismic surface waves from this earthquake. Maps of spectral amplification recorded during the Denali earthquake on the Pacific Northwest Seismic Network (PNSN) strong-motion instruments show substantially increased shear and surface wave amplitudes coincident with the Seattle sedimentary basin. Because Lake Union is situated on the Seattle basin, the size of the water waves may have been increased by local amplification of the seismic waves by the basin. Complete hazard assessments require understanding the causes of these water waves during future earthquakes. *INDEX TERMS:* 1845 Hydrology: Limnology; 4239 Oceanography: General: Limnology; 4560 Oceanography: Physical: Surface waves and tides (1255); 7223 Seismology: Seismic hazard assessment and prediction; 7299 Seismology: General or miscellaneous. **Citation:** Barberopoulou, A., A. Qamar, T. L. Pratt, K. C. Creager, and W. P. Steele (2004), Local amplification of seismic waves from the Denali Earthquake and damaging seiches in Lake Union, Seattle, Washington, *Geophys. Res. Lett.*, *31*, L03607, doi:10.1029/2003GL018569.

1. Introduction

[2] The recording of the 3 November 2002 Denali, Alaska earthquake by the strong-motion stations of the Pacific Northwest Seismic Network (PNSN) provided a unique opportunity to study the spectral amplification of long period (1 to 100 sec) seismic waves in the Puget Lowland, and the coupling of seismic and water waves. The earthquake ruptured along the Denali fault system, one of the largest strike-slip fault systems in the world [*Eberhart-Phillips et. al.*, 2003]. The Denali earthquake, at an epicentral distance of 2400 km, was notable in Seattle with ground displacements of as much as 20 cm and maximum acceleration of 5 cm/s^2 during the surface wave arrivals. Although this large amplitude was due in part to source directivity, local amplification also played a role.

[3] Sedimentary basins in the Puget Lowland are documented to affect the amplitude of seismic waves at long periods [*Frankel et al.*, 2001; *Pratt et al.*, 2003]. Impedance contrasts and resonance within the basin sediments only partly explain the observed amplification, and basin surface waves likely play a role [*Frankel and Stephenson*, 2000; *Pratt et al.*, 2003]. Although previous studies have used local earthquakes and teleseisms with waves in the 1 to 10 second period range, the response of the basin at longer periods was unknown. Multistory buildings, long period suspension bridges and other long period structures are vulnerable to shaking at 1–100 sec periods.

[4] Large and distant earthquakes have caused seiches and water waves in Washington state in the past. Lake Union in Seattle appears to be especially susceptible to earthquake induced water waves, possibly due to its physical dimensions. Water waves produced by the 2002 Denali earthquake and the 1964 Alaska earthquake caused similar damage to houseboats on Lake Union. Although such damage during teleseisms is ordinarily minor, the local amplification of long period waves could make urban areas above sedimentary basins in the Puget Lowland particularly vulnerable to high amplitude seiches or water waves during large earthquakes on the Seattle fault or the Cascadia subduction zone. Understanding these effects is therefore important to assessing all earthquake hazards in the region.

2. Geologic Setting

[5] The Puget Lowland is a forearc basin above the subducting Juan de Fuca plate. The Seattle basin beneath Seattle is one of 3 large structural basins beneath the Puget Lowland, the others being the Everett and Tacoma basins [*Brocher et. al.*, 2001]. The Seattle basin is a 30 km by 60 km depression in the volcanic and igneous basement rocks filled with up to 9 km of low-density sedimentary rocks and unconsolidated sediments [*Pratt et al.*, 1997; *Brocher et. al.*, 2001]. In particular, Pleistocene deposits have P-wave velocities of 1.5–2.0 km/s. Miocene to Eocene sedimentary rock velocities vary from 2.5–5.2 km/s. The basement rocks, believed to be Crescent Formation volcanics, have P-wave velocities of 6.0–6.8 km/s [*Brocher et al.*, 2001]. The south end of the Seattle basin is formed by the Seattle Fault zone, an east-west trending reverse or thrust fault separating thick sediments to the north from near-surface bedrock and thin sediments to the south [*Johnson et al.*, 1994; *Pratt et al.*, 1997; *ten Brink et al.*, 2002]. The Seattle Basin is bounded on the west by the Olympic Mountains. Its eastern boundary is not well con-

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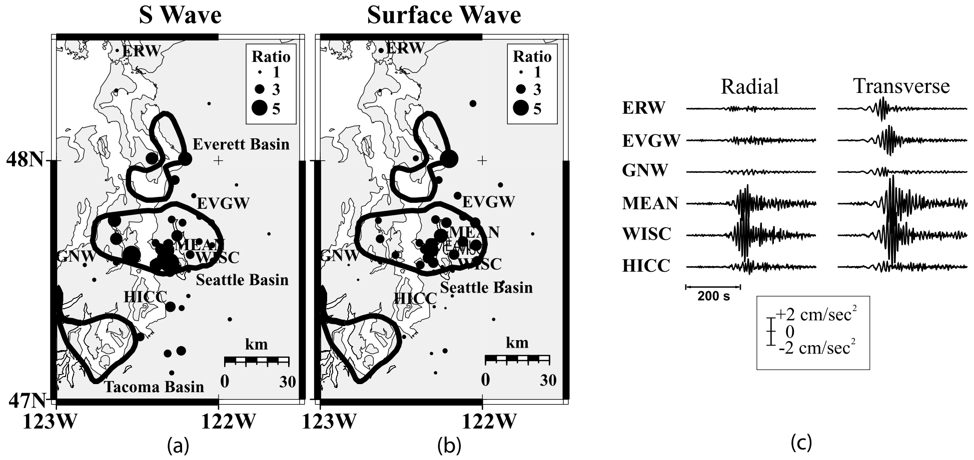

Figure 1. (a) Map showing the relative amplitude of the S-wave spectrum (site spectrum divided by the rock spectrum) for the transverse component of ground acceleration at a wave-period of 8 seconds. The rock spectrum is an average for sites ERW and GNW. Stations enclosed by the heavy contours are defined as basin sites. (b) Same as Figure 1a, but for surface waves (c) Accelerograms for the Denali earthquake showing large surface wave amplitudes. Scale shows 2 cm/sec^2. Amplitudes were much stronger and durations much longer at sites MEAN and WISC over the Seattle basin.

strained, and to the north the basin sediments become thin [*Johnson et al.*, 1994; *Brocher et al.*, 2001].

3. Analysis

[6] A common approach to measuring the effects of site geology on the amplitude of seismic waves is to calculate the spectral ratio between ground motion at a site and at a nearby bedrock site (Standard Spectral Ratio; SSR) [*Hartzell*, 1992]. Ground motion is characteristic of the source, path, station location and the instrument response. For teleseisms, source and path effects can be considered the same for nearby sites. The SSR technique assumes that a hard rock site does not affect the amplitudes of the impinging waves, and the hard rock frequency spectrum is therefore characteristic of the input source spectrum.

[7] To estimate the role of Seattle sedimentary basin on ground motion in the Seattle area, we have computed the spectral ratios of raw acceleration traces, relative to the average of two bedrock sites, of shear and surface waves produced by the Denali earthquake. The data consist of recordings from 46 strong motion stations, distributed around the Puget Lowland both inside and outside of the Seattle basin. The Denali earthquake was also recorded by broadband stations but most of these recordings clipped during the surface wave arrivals and are therefore not used in this analysis. The recorded waves provide a frequency spectrum from 0.01–0.5 Hz (2–100 second period) with a good signal-to-noise ratio ($s > 2n$).

[8] A 70 sec time-window was used to compute the spectra of the shear-wave arrivals, and a 300 second window was used for surface waves. The beginning of the surface wave window was taken to be the arrival of the Love wave. Both horizontal components of the seismograms (vector sum) were used in the calculation of the spectral ratios. Data were tapered with a 5% Hanning taper. The spectral ratios were smoothed with a 0.02 Hz wide running average.

[9] To avoid results that are unduly influenced by a single reference station, we used the average spectra from two bedrock sites (ERW and GNW, see Figure 1) as our reference spectrum. GNW is located on intrusive bedrock, and ERW on volcanic basement rock. Other sites are classified as ''basin'' and ''non-basin'' depending on whether they fall within the contours in Figure 1. Almost all of our basin sites lie on the Seattle basin. Many of the non-basin sites nonetheless are underlain by up to 2 km of sediments and Tertiary sedimentary rock.

[10] Our ratios show large spectral amplifications of shear and surface waves by the Seattle basin. Surface waves were the largest arrivals recorded on the seismograms, with basin sites consistently having the greatest amplitudes and longest duration (Figures 1, 2). Maximum acceleration on strong motion records was 5 cm/s^2, with ground displacement of about 20 cm near Lake Union and at least ten strong cycles of motion (Figure 1c). Average amplification reached factors of 4 or more at periods of 2.5–12.5 seconds (0.08–0.4Hz) (Figure 2). Lack of station coverage does not permit a study of Everett basin effects, but surface waves were amplified by at least 4 at the few sites on or near this basin (Figure 1).

[11] Shear wave arrivals showed similar amplification values, but their absolute amplitudes were much smaller than the surface wave amplitudes. Shear waves were

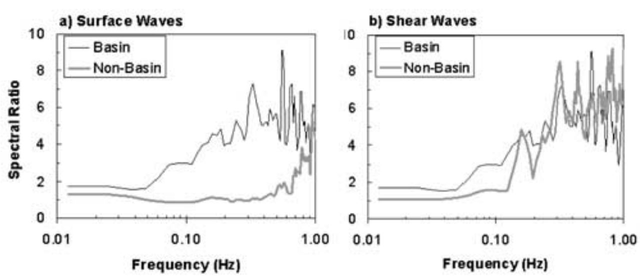

Figure 2. Average of spectral ratios of basin and non-basin sites with respect to bedrock. (a) Surface waves, (b) shear waves. Non-basin sites show significant amplification because they also overlie sediments, although not as thick as the basin sediments.

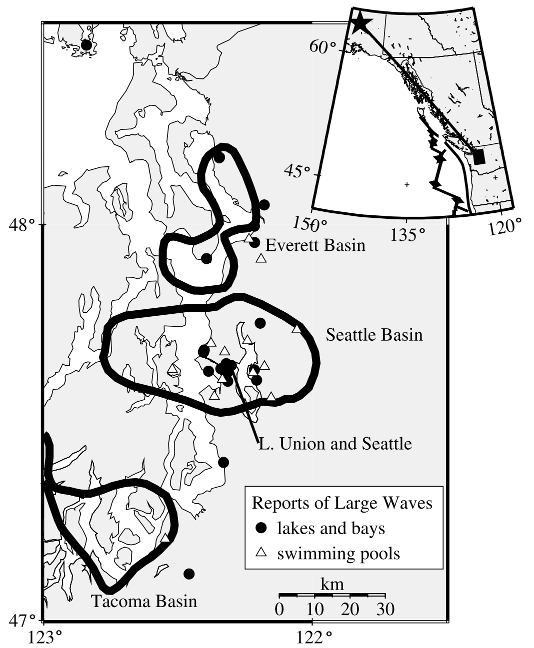

Figure 3. Sites reporting water waves in bays, lakes and swimming pools collected from local sources and USGS Community Internet Intensity reports via the internet. Heavy contours show the approximate outline of the deepest part of the sedimentary basins beneath the Puget Lowland based on P-wave tomography (*VanWagoner et al.*, 2002). Each contour delineates a P-wave velocity of 3.5 km/sec at a depth of 2 km. Lake Union is within the city of Seattle at the dense collection of water wave observations. The inset shows the path of the waves from the epicenter to Seattle.

amplified relative to bedrock at all basin sites by at least 4 at wave periods of 1.5 to 7 seconds (0.15 to 0.7 Hz) (Figure 2). Seismic shear wave amplitudes reached peak amplification of 9 at a period of about 2 seconds. The deepest, central part of the basin is associated with the greatest amplitudes (Figure 1). Amplification of shear waves due to the Seattle basin in the 3–5 second period range has been observed before [*Pratt et al.*, 2003]. Shear waves outside the basin were also amplified by shallow sediments (Figures 1 and 2).

4. Observations of Water Waves

[12] The effects of the Denali earthquake on water bodies were observed in western Canada [*Cassidy et al.*, 2002] and the United States [reports to National Earthquake Information Center]. Water was reported to have surged 5 feet horizontally on the shoreline at Lake Wenatchee, just east of the Cascade Mountains. In western Washington State, reported damage was concentrated around Lake Union and Portage Bay, an arm of Lake Union (Figures 3, 4). Water waves were responsible for several buckled moorings, and many broken sewer and water lines near the east shores of Lake Union. Sloshing action was also reported in indoor and outdoor swimming pools, ponds and lakes in many locations in Washington state (Figure 3).

[13] Unfortunately, water-level records are not available for Lake Union during this earthquake, so we rely on anecdotal reports to the USGS. Several observers reported strong water wave oscillations in Lake Union and other locations in Washington state at times corresponding to the arrival time of the surface waves. Most observers estimated that water wave action lasted 1 to 5 minutes and clearly stated no other forcing mechanism present such as wind. This correlates well with the approximately 300 seconds duration of the largest surface waves as recorded by the PNSN seismographs. Many observers reported water moving back and forth horizontally with little vertical motion by the waves. On large bodies of water people reported horizontal runup on the shore of 0.6–3 m with most observers reporting 1 m. Thus, the water wave motions appear to be considerably larger than the 20cm seismic surface waves that induced them. Vertical amplitudes observed at swimming pools were typically 15 to 30 cm. Reported wave periods were 5, 15, and 20 sec (Table 1). The period of the largest surface wave recorded by seismographs was about 8 sec, much shorter than the natural periods expected for larger bodies of water (Table 1). A few reports contained an estimate of the number of cycles (8–10).

[14] Previous earthquakes producing water waves near Seattle include the M_w 9.2 March 1964 Alaska earthquake (The Seattle Times, March 29th, 1964), the M 7.1 April 13, 1949 Olympia earthquake (The Seattle Times, April 14th, 1949), the M 6.5 April 28, 1965 Seattle-Tacoma earthquake (The Seattle Times, 19 and 30 April 1965) and the 1899 Yakutat Bay Alaska earthquake [*Dow*, 1964]. Damage during the last two major Alaska earthquakes (1964 and 2002) was concentrated around Lake Union and Portage Bay. During the Denali earthquake, reported water waves on swimming pools and lakes overlying the Seattle basin were clustered in areas over the deepest, central part of the basin, coinciding with the greatest surface wave amplitudes (Figures 1, 3). Although the distribution of these reports are obviously biased by population density and demographic factors, the density of reports shows a good correspondence with the largest ground motions. This correlation suggests that basin amplification was a major factor contributing to damaging water waves over the Seattle basin.

5. Discussion

[15] Large, distant earthquakes have been associated in the past with the triggering of seiches in bodies of water [*Kvale*, 1953; *McGarr and Vorhis*, 1968]. According to

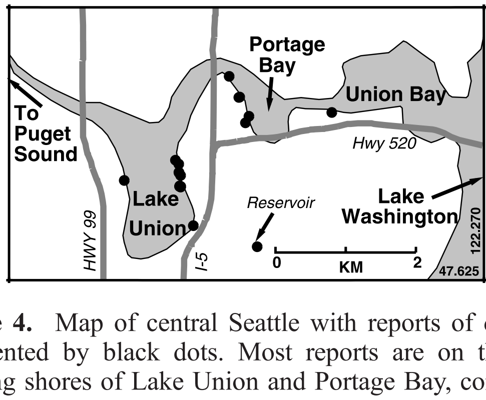

Figure 4. Map of central Seattle with reports of damage represented by black dots. Most reports are on the N-S trending shores of Lake Union and Portage Bay, consistent with large E-W (transverse) motions during the Love wave arrivals (Figure 1c).

Table 1. Comparison of Estimated Periods and Amplitudes of Water Waves With Those Reported[a]

Water Body	L, width m	D, m	Fundamental mode N = 1, sec	Predicted water wave amplitude 2η, m	Reported[b] period of water waves, sec
Lake Union	800	8	180	0.16	5–20
Portage Bay	400	2	180	0.08	5–20
Swimming Pool	10	2	4.5	0.08	5–20

[a]The predicted amplitude of the water waves was calculated using equation (3) and a particle velocity of 0.09 m/sec.
[b]Periods of water waves obtained from the reports do not necessarily correspond to the specific section of Lake Union or Portage Bay.

McGarr and Vorhis [1968] major tectonic features such as basins and thrust faults affect the distribution of seiches, with seiche activity being a direct function of the amplitude distribution of surface waves in the period range from 5 to 15 seconds.

[16] Unusually large amplitude water waves may lead to extensive coastal inundation, erosion and damage to coastal structures [*Korgen*, 1995]. It is evident that Lake Union is prone to earthquake induced water waves. Lake Union is a shallow Y shaped lake with depth varying between 6 and 14 m and maximum horizontal dimensions of approximately 1.5 and 2.5 km (Figure 4). Its relatively small size and its location above the Seattle basin makes it susceptible to seiches or other earthquake generated water waves. The greatest concentration of water wave reports from the Denali earthquake occurred where the amplitude of seismic surface waves was greatest (Figures 1, 3). We suggest it was the surface waves from the Denali earthquake, locally amplified by the Seattle basin, that caused the observed water waves (Figure 3).

[17] As an initial approach to understanding the driving mechanism of these water waves we present the allowable wavelengths λ and periods T of seiches given by Merian's formula for a water-filled basin of simple rectangular shape [*Lamb*, 1932; *Rueda and Schladow*, 2002] of length L and depth D:

$$\lambda = \frac{2L}{N} \qquad N = 1, 2, 3, \ldots \tag{1}$$

$$T = \frac{2L}{N\sqrt{gD}} \qquad N = 1, 2, 3, \ldots \tag{2}$$

where g is the acceleration due to gravity and N is the mode-number. Table 1 summarizes the predicted fundamental (N = 1) period of seiches for sections of Lake Union, Portage Bay and a swimming pool of residential size. Our calculations of the fundamental period of seiches in parts of Lake Union (Table 1) suggest only the higher modes of resonance could match the dominant periods of the surface waves. However, higher modes will be affected more by the geometry of the basin and will be damped faster therefore making them less favoured [*McGarr*, 1965]. The first-order (fundamental period) seiches could have occurred in the smaller, shallower water bodies but the fundamental periods for Lake Union are greater than the periods of amplified surface waves.

[18] The large amplitude water waves observed on Lake Union cannot be explained by simple resonance. The discrepancy between the predominant periods of the high-amplitude seiches and those of Lake Union may be explained by sloshing initiated by the surface waves [*McGarr*, 1965] causing larger amplitude nonlinear runup. A simple estimate of 8–16 cm water wave amplitudes on the shore (2η) [*Lamb*, 1932; *McGarr*, 1965] is provided by:

$$\eta = \sqrt{(D/g)}U \tag{3}$$

where η is the surface elevation of the water above the undisturbed level, and U the water wave velocity the edge of the canal. This estimate is half or less of the reported water wave amplitudes. Resonance initiated by multiple cycles of surface waves, focusing, and near-shore effects (not considered here) must further amplify the water waves. A theoretical approach [*McGarr*, 1965] indicates that the main driving mechanism for earthquake induced water waves is the horizontal motion of the steep sides of the water body. In a narrow body of water, opposite shores generate waves of opposite phase, causing interference at odd modes. This resonance can increase water wave amplitudes by factors of 10 provided a long enough duration of ground motion provides several cycles of seismic forcing.

[19] The damaging water waves observed in Seattle during the Denali earthquake appear to have been caused by a combination of local amplification of seismic waves by the Seattle basin and constructive interference of water waves within Lake Union. The response of water bodies under strong shaking needs to be evaluated to determine the potential magnitudes of the water waves during large local events on crustal faults or during large earthquakes in the Cascadia subduction zone.

[20] **Acknowledgments.** We thank the Advanced National Seismic System (ANSS) for partial financial support of the strong motion network, Ruth Ludwin for the information provided about the 1899 Alaska earthquake, Arthur McGarr, Harold Mofjeld and Tom Brocher for their great suggestions on improving the manuscript.

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