ENGINEERING CHARACTERIZATION OF EARTHQUAKE STRONG GROUND MOTIONS IN THE PACIFIC NORTHWEST

By Walter J. Silva,[1] Ivan G. Wong,[2] *and* Robert B. Darragh[3]

ABSTRACT

Strong-motion recordings of earthquakes in the Pacific Northwest are few in number and nonexistent for events along the megathrust fault of the Cascadia subduction zone. The prediction of strong ground shaking from future large earthquakes in the region based on an empirical approach is hampered by this lack of data. In this study, strong ground motions for the 1949 surface-wave magnitude (M_S) 7.1 Olympia and 1965 M_S 6.5 Seattle-Tacoma earthquakes in Washington have been computed in terms of acceleration response spectra based on a numerical modeling technique that incorporates the band-limited-white-noise earthquake source model and random-vibration theory. The estimates compare favorably with the actual records of these earthquakes, as recorded at two soil sites in Seattle and Olympia, although the model underpredicts the motions for the latter. Based on this calibration of the technique, acceleration response spectra for a hypothetical moment magnitude (M_W) 8.5 Cascadia subduction-zone earthquake have also been predicted for the same two soil sites. At source-to-site distances of 101 km and 146 km for Olympia and Seattle, respectively, the estimated peak horizontal ground accelerations are 0.15*g* and 0.14*g* (where *g* is 980 cm/s^2). Because these values strongly depend upon the assumed crustal damping beneath western Washington and the location of the eastern extent of rupture of a potential Cascadia subduction-zone earthquake, they should be viewed as approximations. Based on our analysis, the effects of near-surface soils and the properties of the underlying rock will likely be significant factors controlling strong ground motions in the Puget Sound region and other geologically similar regions in the Pacific Northwest such as the Willamette Valley.

INTRODUCTION

An essential element in the seismic design of engineered structures is a quantitative estimate of the characteristics of strong ground motion. Of particular importance is a specification of the peak levels of ground motion as well as spectral content as typically characterized by response spectra. The spectral content is reasonably well defined for crustal earthquakes of approximate moment magnitude (M_W) 6–7 occurring in western North America (Mohraz, 1976; Seed and others, 1976; Joyner and Boore, 1988). However, recent observations of strong ground motions in other tectonic regimes have revealed significant differences in the spectral content of earthquakes recorded at rock sites. Ground motions recorded in stable tectonic regimes typical of eastern North America may have significantly higher frequency content and larger peak values than corresponding motions typical of active regimes like western North America (Boore and Atkinson, 1987; Toro and McGuire, 1987; Silva and others, 1989; Silva and Darragh, 1995). In the seismotectonic setting of the Pacific Northwest, which includes the Cascadia subduction zone, ground motions may also be unique. However, few strong-motion records exist and the prediction of strong ground shaking must rely on data from other regions, including other subduction zones, if traditional empirical techniques are to be used.

In the past decade, numerical modeling techniques have been developed in an effort to provide alternative approaches to ground-motion prediction. Such techniques have been used in evaluating strong ground motions in the Pacific Northwest including the Puget Sound region (Langston, 1981; Langston and Lee, 1983; Ihnen and Hadley, 1986; Cohee and others, 1991; Wong and Silva, 1994) and the Portland, Oreg., area (Wong and others, 1990, 1993). One such technique incorporates the use of a stochastic earthquake source model called the band-limited-white-noise (BLWN) model and random-vibration theory (RVT). This approach has been remarkably successful in predicting peak ground motion

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[1] Pacific Engineering & Analysis, 311 Pomona Ave., El Cerrito, CA 94530.

[2] Woodward-Clyde Federal Services, 500 12th Street, Oakland, CA 94607.

[3] California Division of Mines and Geology, Sacramento, CA 95816.

values as well as spectral ordinates in different tectonic regimes (Hanks and McGuire, 1981; Boore, 1983; Boore and Atkinson, 1987; Silva and others, 1989; Schneider and others, 1993; Wong and Silva, 1993).

In this study, we have applied the BLWN-RVT methodology to compute 5-percent-damped acceleration response spectra to compare with the 1949 surface-wave magnitude (M_S) 7.1 Olympia and 1965 M_S 6.5 Seattle-Tacoma earthquakes in Washington as recorded by the strong-motion instruments in the Highway Test Office in Olympia and the Federal Office Building in Seattle (1965 earthquake only). Both earthquakes occurred within the subducting Juan de Fuca plate. Site-specific shear-wave velocity and density data for these two sites and the source parameters of the two earthquakes were used in the analysis.

Of particular importance to seismic hazards in the Pacific Northwest is the possibility of a great earthquake (M_W greater than 8) occurring along the megathrust of the Cascadia subduction zone beneath western Washington and Oregon. Based on the calibration of the BLWN-RVT approach using the 1949 and 1965 events, 5-percent-damped acceleration response spectra for a postulated M_W 8.5 megathrust earthquake have also been estimated for the Olympia Highway Test Office and Seattle Federal Office Building sites.

The focus of this study is to incorporate the effects of appropriate source, region-specific path, and site-specific parameters in the evaluation of ground motions. Such effects influence ground motions at periods of greatest engineering significance, between 0.1 and 1.0 s. Large-scale two- and three-dimensional effects on ground motions such as those due to basin geometry, however, have not been incorporated into our analysis. Basin effects, as suggested by Langston (1981) and Ihnen and Hadley (1986), can be significant for long-period ground motions in the Puget Sound.

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APPROACH USED IN THE STUDY

The BLWN-RVT ground-motion methodology has been applied to a worldwide data set of earthquakes in the range of M_W 1.5–8.1 in an analysis of rock motions recorded at distances generally less than 50 km (Silva and Darragh, 1995). This included four earthquakes, among them the September 19, 1985, M_S 8.1 Michoacan mainshock, that occurred in the subduction zone along the coast of western Mexico and were recorded by the Guerrero strong-motion network. The spectral content of these events has been modeled quite well for periods of 0.03–4 s at distances to the rupture surface as close as 16 km (Silva and Darragh, 1995). The technique has also shown that the controlling factors in the specification of strong ground motion at rock sites for engineering design are moment magnitude, source-to-site distance, and the rock properties directly beneath the site. Specifically, the near-surface attenuation modeled through the approximate parameter κ exerts a predominant effect upon spectral composition for frequencies greater than about 3 Hz. Below this frequency, M_W or seismic moment through corner frequency (see equation 3) controls spectral shapes in the BLWN-RVT ground-motion methodology.

An additional advantage of the BLWN-RVT methodology is the ability to easily incorporate site-specific nonlinear soil response directly into the ground-motion analyses using RVT in an equivalent-linear formulation. This is an important consideration in seismic-hazard evaluations in the Pacific Northwest because of widespread alluvial deposits beneath most of the major urban areas in the Puget Sound region and the Willamette Valley of Oregon.

The BLWN ground-motion model first developed by Hanks and McGuire (1981) assumes a point source with energy distributed randomly over the duration of the source. The model assumes an ω^{-2} source model (Brune, 1970, 1971) with a single corner frequency and a constant stress drop (Boore, 1983). The acceleration spectral density, $a(f)$, is given by

$$a(f) = C \frac{f^2}{1+\left(\frac{f}{f_c}\right)^2} \frac{M_o}{R} P(f) A(f) e^{-\frac{\pi f R}{\beta_o Q(f)}} \qquad (1)$$

where f is frequency;
M_o is seismic moment;
R is distance to the equivalent point source;
β_o is shear-wave velocity at the source;
$Q(f)$ is the frequency-dependent quality factor;
$A(f)$ are near-surface amplification factors;
$P(f)$ is the high-frequency truncation filter;
f_c is source corner frequency; and

$$C = \left(\frac{1}{\rho_o \beta_o^3}\right)(2)(0.55)\left(\frac{1}{\sqrt{2}}\right)\pi \qquad (2)$$

where ρ_o is the density at the source (fig. 147). C is a constant that accounts for the free-surface effect (factor of 2), the S-wave source radiation pattern averaged over a sphere (0.55) (Boore, 1986), and the partition of energy into two horizontal components $\left(1/\sqrt{2}\right)$. In order to compute peak-time domain values, that is, peak acceleration and peak oscillator response, RVT is used to relate root-mean-square computations to peak value estimates (Boore, 1983; Boore and Joyner, 1984).

Source scaling is provided by specifying two independent parameters, M_o and the stress drop ($\Delta\sigma$) (fig. 147). The stress drop relates f_c to M_o through the relation

$$f_c = \beta_o \left(\frac{\Delta\sigma}{8.44\, M_o} \right)^{1/3} \tag{3}$$

The spectral shape of the single-corner-frequency ω^{-2} source model is then described by the two free parameters M_o and $\Delta\sigma$ (Silva, 1991). The corner frequency increases with the shear-wave velocity and stress drop, both of which are region dependent.

The $P(f)$ filter models the observation that acceleration spectral density appears to fall off rapidly beyond some region-dependent maximum frequency. This observed phenomenon truncates the high-frequency part of the spectrum and is responsible for the band-limited nature of the model. In the Anderson and Hough (1984) attenuation model, the form of the $P(f)$ filter is

$$P(f) = e^{-\pi f \kappa(r)} \tag{4}$$

The function $\kappa(r)$ is a site- and distance-dependent parameter that represents the effect of intrinsic attenuation on the seismic waves as they propagate through the crust from source to receiver. The parameter κ depends weakly on the epicentral distance (r) and on both the shear-wave velocity (V_s) and quality factor (Q_s) averaged over a depth of H beneath the receiver or site. At zero epicentral distance, κ is given by

$$\kappa(0) = \frac{H}{\bar{V}_S\, \bar{Q}_S} \tag{5}$$

The value of $\kappa(0)$ (herein referred to as kappa) is attributed to attenuation in the very shallow crust directly beneath the site (Hough and Anderson, 1988). Silva and Darragh (1995) suggested that the predominant kappa effects extend from the surface down to several hundred meters and possibly as deep as 1–2 km. The intrinsic attenuation along this part of the path is thought to be frequency independent but site dependent (Hough and others, 1988). For a typical western North America rock site, kappa values are in the range of about 0.02–0.06 s (Boore, 1986; Silva and Darragh, 1995).

The acceleration spectral density, $a(f)$, models direct shear waves in a homogeneous half-space (with effects of a velocity gradient through the $A(f)$ filter). For vertically heterogeneous layered structures, the plane-wave propagators of Silva (1976) are used to propagate S_H or P–SV motion through the layered structure.

In a half-space model, the near-surface amplification factors, $A(f)$, account for the increase in amplitude as the seismic energy travels through lower velocity crustal

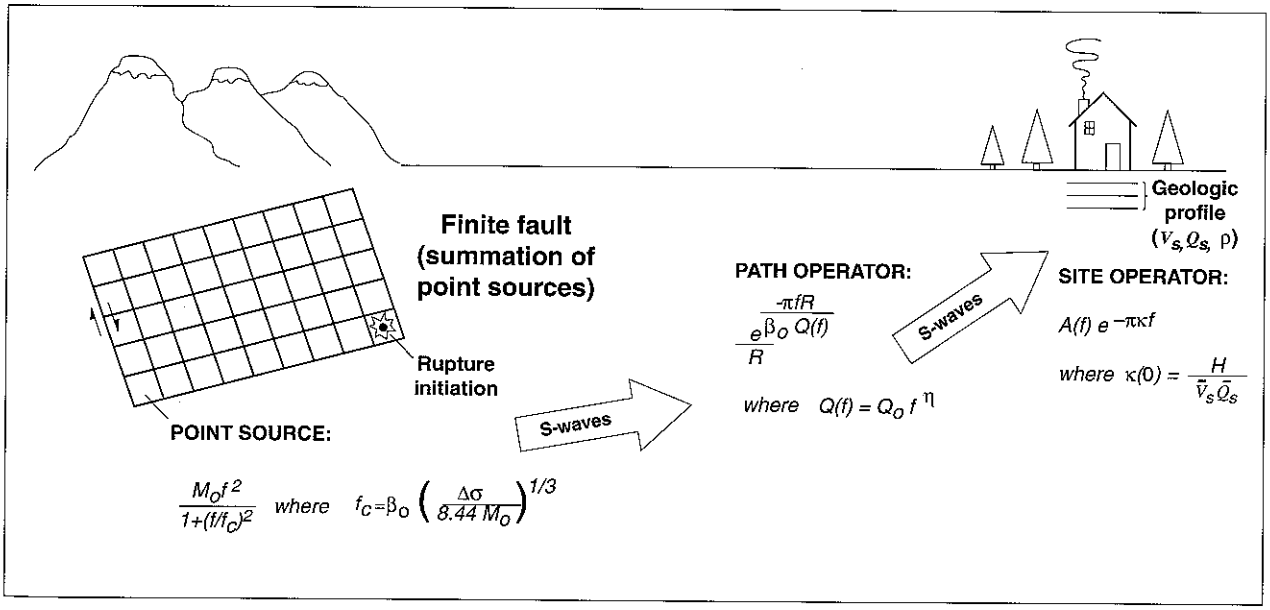

Figure 147. Schematic diagram of the band-limited-white-noise and random-vibration-theory approach used in this study to estimate ground motions due to earthquakes. Small arrows show relative motion across fault surface. M_o, seismic moment; f, frequency; f_c, source corner frequency; β_o, shear-wave velocity at the source; $\Delta\sigma$, stress parameter; R, distance to the equivalent point source; $Q(f)$, frequency-dependent quality factor where Q_o and η are model parameters; $A(f)$, near-surface amplification factors; κ, near-surface seismic-wave attenuation parameter where $\kappa(0)$ is the attenuation directly beneath the site; H, depth; V_s, shear-wave velocity; Q_s, shear-wave damping; and ρ, density in the site geologic profile.

materials near the surface. These factors depend on average crustal and near-surface shear-wave velocity and density. Western United States amplification factors developed by Boore (1986) have typically been used in the past to account for the amplification by near-surface velocity gradients. If detailed shear-wave velocity data are available for a site, it is more desirable to use such information instead of amplification factors.

The anelastic path attenuation from the source to just below the site is modeled with the frequency-dependent quality factor $Q(f)$ where $Q(f)=Q_o f^{\eta}$ and Q_o and η are model parameters. Geometric attenuation is taken as $1/R$ or $\left(1/\sqrt{R}\right)$ for distances greater than 100 km.

In order to accommodate the effects of site-specific soil response, the BLWN power spectrum of the rock outcrop motion is propagated through the one-dimensional soil profile using the plane-wave propagators of Silva (1976). In this formulation, only S_H waves are considered. Arbitrary angles of incidence may be specified, but normal incidence is used throughout the present analyses.

In order to deal with possible material nonlinearities, the equivalent-linear formulation is used. RVT is used to predict peak time-domain values of shear strain based upon the shear-strain power spectrum. In this sense, the procedure is analogous to the computer program SHAKE (Schnabel and others, 1972) except that peak shear strains in SHAKE are measured in the time domain. The purely frequency-domain RVT approach obviates a time-domain control motion and, perhaps just as significantly, eliminates the need for a suite of analyses based on different input motions.

FINITE-FAULT METHODOLOGY

A methodology that combines aspects of finite earthquake source modeling (Hartzell, 1978; Irikura, 1983) with the BLWN point-source model has also been developed to produce response spectra as well as time histories appropriate for engineering design (Silva and others, 1990). The approach is very similar to the empirical Green's-function summation methodology introduced by Hartzell (1978) and Irikura (1983). In this case, however, the BLWN point source is substituted for the empirical Green's function. Peak accelerations, peak velocities, and response spectra (when time histories are not produced) are estimated using RVT. The model can accommodate a region-specific $Q(f)$, Green's-function sources of arbitrary seismic moment or stress drop, and site-specific kappa values. A detailed description of the methodology is contained in Schneider and others (1993) and Wong and Silva (1993).

STRONG-MOTION DATA AND INPUT PARAMETERS

The strongest earthquakes to have shaken the Puget Sound region this century occurred in 1949 and 1965. Fortunately, both events were recorded by at least one strong-motion station (either the Olympia Highway Test Office or the Seattle Federal Office Building), and these records largely constitute the available empirical data for earthquakes in the region. As such, several investigators (for example, Langston, 1981) have used these records to evaluate strong ground motions in the Puget Sound region. It must be noted, however, that neither strong-motion station is in the desired free field. The Olympia instrument is located in a one-story wood-framed building. The Seattle accelerograph is located in the subbasement of an eight-story structure, 4.6 m below grade. Despite these possible complications, we have attempted to model these earthquakes with the intent of calibrating our approach.

INTRAPLATE EARTHQUAKES

The 1949 Olympia earthquake occurred at a depth of 54 km and at an epicentral distance of about 5 km from the Olympia Highway Test Office (Baker and Langston, 1987) (fig. 148). Peak horizontal ground accelerations of 0.16*g* and 0.28*g* were recorded at this site (table 22). The 1965 Seattle-Tacoma earthquake occurred at a depth of 60 km and at epicentral distances of 21 km and 61 km from the Seattle Federal Office Building and Olympia Highway Test Office, respectively (Langston and Blum, 1977) (fig. 148). Peak accelerations of 0.06*g* and 0.08*g* were recorded as horizontal components at the Federal Office Building, whereas horizontal values of 0.14*g* and 0.20*g* were recorded at the Highway Test Office. As also noted by others (for example, Langston, 1981), larger peak horizontal accelerations were recorded at the Highway Test Office than at the Federal Office Building although the earthquake was closer to the latter site.

Ground motions for the 1949 and 1965 earthquakes were calculated using the BLWN-RVT point source approach. Given the relatively long distances to Seattle or Olympia and the estimated source dimensions for either earthquake, a point source for both earthquakes was assumed valid. The input parameters required in the modeling are as follows: (1) earthquake source parameters including M_W and stress drop; (2) distance between the site and a point-source representation of the fault-rupture plane; (3) propagation-path parameters (assuming a half-space) including β_o, ρ_o, Q_o, and η; and (4) site parameters such as V_s and ρ specified as a function of depth, kappa, and appropriate shear-modulus reduction and damping curves for the soil and unconsolidated sediments overlying rock at each site.

Stress drops have not been estimated for either the 1949 or 1965 earthquakes. A stress drop of 100 bars, typical of western North America earthquakes (see Hanks and McGuire, 1981) was assumed in the modeling of the intraplate events.

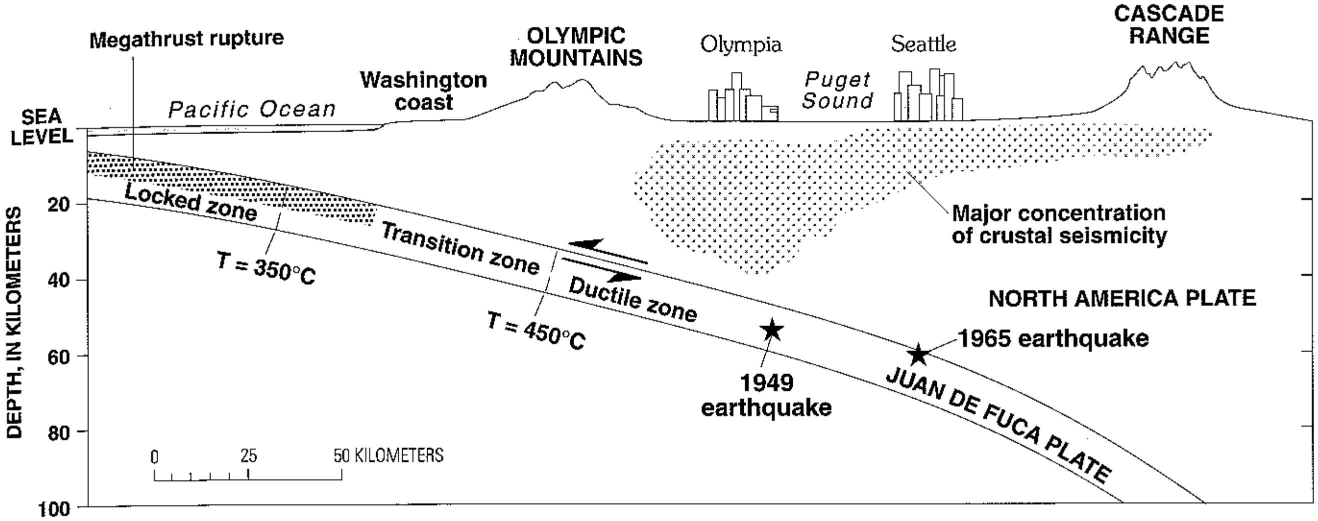

Figure 148. Cross section of the Cascadia subduction zone at latitude of southern Puget Sound in Washington. Divisions of subduction zone are adopted from Hyndman and Wang (1993). The rupture of a great megathrust earthquake is assumed to extend into one-third of the transition zone. Arrows show relative motions of plates. Temperatures (T) represent lower and upper bounds for transition zone in which stable sliding occurs. The zone separates the locked zone, where stick-slip sliding occurs and earthquakes may nucleate, from the ductile zone, where plastic deformation takes place due to high temperatures and where no earthquake rupture can occur.

Table 22. Observed and predicted median peak horizontal ground accelerations for earthquakes in the Puget Sound region.
[OHT, Olympia Highway Test Office; FED, Seattle Federal Office Building; (obs), observed; (pred), predicted; (--), not required]

Recording station	Earthquake	Depth (kilometers)	Horizontal[1] distance (kilometers)	Source-to-site[2] distance (kilometers)	Magnitude	Stress drop (bars)	Peak horizontal acceleration (g)
OHT	April 13, 1949	54	5	54	M_S 7.1	100	0.16, 0.28 (obs) 0.15 (pred)
OHT	April 29, 1965	60	61	85.6	M_S 6.5	100	0.20, 0.14 (obs) 0.07 (pred)
FED	April 29, 1965	60	21	63.6	M_S 6.5	100	0.06, 0.08 (obs) 0.10 (pred)
OHT	Cascadia subduction zone	25	98	101	M_W 8.5	--	0.15 (pred)
FED	Cascadia subduction zone	25	144	146	M_W 8.5	--	0.14 (pred)

[1] For the 1949 and 1965 earthquakes, this distance is equivalent to epicentral distance. For a Cascadia subduction-zone event, this is the shortest horizontal distance to the vertical projection of the rupture plane on the Earth's surface.

[2] For the 1949 and 1965 earthquakes, this distance is equivalent to hypocentral distance. For a Cascadia subduction-zone event, this is the shortest distance to the rupture plane.

The propagation path for the intraplate events was characterized by a β_o of 4.5 km/s and ρ_o of 3.05 g/cm^3 based on the P-wave crustal model for western Washington used in routine earthquake locations (Ludwin and others, 1991). A Poisson's ratio of 0.25 was used to determine S-wave velocities. A Q_o of 380 and η of 0.39 for the Cascadia subduction zone were assumed based on estimates by Atkinson (1995). The hypocentral distances from the 1949 and 1965 earthquakes to the Olympia Highway Test Office and the Seattle Federal Office Building were adopted as the point-source-to-site distances in the BLWN-RVT modeling (table 22).

Geologic profiles for the two recording sites were developed based on downhole data collected by Shannon & Wilson, Inc., and Agbabian Associates (1978) (fig. 149). At Olympia, a 156-m-deep borehole was almost entirely within glacial sediments. Low-strain shear-wave velocities ranged from 165 m/s at the surface to 1,000 m/s at a depth of nearly 152 m (fig. 149). At Seattle, fill material was found to a depth of 7 m. The natural deposits at the site have velocities ranging from 198 to 1,000 m/s to a depth of 122 m (fig. 149). Kappa values of 0.04 s and 0.06 s were assumed appropriate for the rock underlying the soils and unconsolidated sediments at the Olympia and Seattle sites, respectively, based on comparisons with similar rock types where site-specific kappa values have been estimated (Silva and Darragh, 1995). Rock in the geologic profiles was assumed to occur below the depths of 144 m at Olympia and 101 m at Seattle. Shear-modulus reduction and damping curves appropriate for soils comprising sands, gravels, and low-plasticity-index clays were used (Electric Power Research Institute, 1993). The degradation curves accommodate the effects of confining pressure on modulus reduction and damping and are implemented for profiles extending to 305 m (Electric Power Research Institute, 1993).

CASCADIA MEGATHRUST EARTHQUAKE

For the finite-fault modeling of the Cascadia subduction-zone earthquake, the rupture plane was defined as eastward-dipping (average of 7°), 280 km long, and 120 km wide. The rupture width was estimated based on the model of the megathrust proposed by Hyndman and Wang (1993) for offshore northern Washington. We assume the rupture will not only include the locked portion of the megathrust but will also extend downdip about one-third of the width of the transition zone (Wong and others, 1993) (fig. 148). The rupture length was constrained to a value where the rupture area (length times width) would be appropriate for a M_W 8.5

OLYMPIA HIGHWAY TEST OFFICE

DEPTH (m)	GEOLOGY	DESCRIPTION	V_S (m/s)	ρ (g/cm³)
3	Fill	Loose sand	165	1.5
12	Glacio-fluvial (?) deposits	Medium dense fine to medium sand	220	1.5
20	Glacio-lacustrine (?) deposits	Interbedded very stiff to hard fine sandy silt and very dense silty fine to medium sand	270	1.5
41			330	1.5
65	Glacio-fluvial (?) deposits	Very dense fine to medium sand	350	1.5
93			450	1.6
110			500	1.6
126			575	1.6
144			975	2.0
156	Glacio-lacustrine (?) deposits	Interbedded hard silty clay and very dense silty fine sand	1,000	2.0

SEATTLE FEDERAL OFFICE BUILDING

DEPTH (m)	GEOLOGY	DESCRIPTION	V_S (m/s)	ρ (g/cm³)
7	Fill	Loose to medium clayey, silty, fine sand	152	1.5
9	Quaternary glacial drift deposits	Very dense, silty, gravelly fine sand	198	1.5
16			411	1.5
33		Very dense silty clay with gravel	427	1.6
47		Hard silty clay with some gravel	503	1.7
65		Very dense, silty, sandy, fine gravel and silty, gravelly, fine to coarse sand with some cobbles	610	1.8
101			762	1.9
122			1,000	2.0

Figure 149. Geologic profiles for the Olympia Highway Test Office and Seattle Federal Office Building strong-motion recording sites in Washington. V_S is shear-wave velocity, and ρ is density.

earthquake based on the empirical relationship between rupture area and magnitude by Wells and Coppersmith (1994). Both the Seattle Federal Office Building and Olympia Highway Test Office sites were assumed to be located approximately in the middle along the strike of the rupture plane model, given our lack of knowledge on the possible segmentation of the Cascadia subduction zone.

A total of 50 randomized slip models (fig. 150) were used to estimate ground motions, given the absence of information on the actual slip distribution of a future Cascadia megathrust earthquake. The randomized slip models were generated in the spatial domain using a process that preserves the area and number of asperities based on the slip models derived from a number of large earthquakes. Large slips near the edges of the rupture plane were suppressed by applying a cosine taper. Fifteen elements were taken along strike and eight elements along dip, giving a 280 km by 120 km rupture plane. Slip is initiated across the fault using a constant rupture velocity (circular rupture front) of 3.04 km/s. Because we do not know where rupture may nucleate in a future Cascadia megathrust earthquake, points of rupture initiation (foci) were also randomized along a 224-km-long zone (80 percent of the length of the rupture zone) centered in the deeper, east half of the rupture plane.

For the megathrust earthquake, a β_o of 3.9 km/s and ρ_o of 2.8 g/cm^3 were assumed appropriate for the source region based on the western Washington *P*-wave crustal model of Ludwin and others (1991). The Q_o and η values used in modeling the attenuation for the intraplate earthquakes were also assumed appropriate for the megathrust event. The source-to-site distances to Olympia and Seattle were 101 km and 146 km, respectively, although we estimate these values may be uncertain by as much as several tens of kilometers. These distances extend from the sites to the east edge of the megathrust rupture, which is located at a depth of about 25 km (fig. 148).

RESULTS AND DISCUSSION

Based on the above input parameters, acceleration response spectra were computed for (1) the 1949 earthquake at the Olympia Highway Test Office, (2) the 1965 earthquake at both the Olympia Highway Test Office and the Seattle Federal Office Building, and (3) a M_W 8.5 Cascadia megathrust earthquake at both sites. Figure 151 compares the recorded and predicted motions for the 1949 event at the Olympia Highway Test Office in terms of 5-percent-damped spectral acceleration (*Sa*) normalized by the peak horizontal acceleration (a_{max}). The use of this parameter, Sa/a_{max}, allows for a direct comparison of the spectral shapes. The 5-percent-damped recorded spectral shape is the average between the two horizontal components.

The match between the two spectral shapes is relatively good although there is an underprediction at short periods and an overprediction at periods longer than 0.6 s. Strong velocity contrasts in the geologic profiles (fig. 150) are responsible for the peaks in the computed motions. The large overprediction is likely a result of poorly known properties in the deeper part of the profile and points out the need to incorporate uncertainties by randomizing soil properties in modeling ground motions. The predicted peak horizontal acceleration for the 1949 event at the Olympia Highway Test Office is $0.15g$ compared to the average recorded value of $0.22g$ (table 22). A somewhat higher stress drop of about 130 bars, very much within the range of stress drops for western North America earthquakes, would result in matching the observed peak acceleration.

Comparisons between the 5-percent-damped spectral shapes of the recorded 1965 earthquake at both the Olympia Highway Test Office and the Seattle Federal Office Building and as predicted by the BLWN-RVT model are shown in figure 152. As with the 1949 event, the spectral shape of the predicted 1965 motions shows an underprediction at a period of about 0.1 s and an overprediction at periods beyond 0.2 s compared to the actual recorded motions at the Olympia site. The predicted peak horizontal acceleration is $0.07g$ compared to an average value of $0.17g$ for the recorded motions. The reason for this underprediction is unknown although this difference has been noted by other investigators (for example, Langston, 1981). Shakal and Toksoz (1979) suggested that higher values of Q_s are characteristic of the Olympia site as compared with the Seattle site. More detailed borehole and upper crustal information on v_s and Q_s is needed to resolve this inconsistency.

In contrast, the predicted peak horizontal acceleration $0.10g$ for the Seattle site is slightly higher than the actual, average value of $0.07g$ (table 22). In general, the spectral shapes of the recorded 1965 earthquake and the model prediction compare very favorably, with a slight model underprediction at long periods. Whereas these differences are likely due to site effects, the site-specific modeling captures quite well the large overall differences in spectral composition seen in the motions recorded at the two sites.

Based on this calibration of the BLWN-RVT model and path and site parameters, we have computed ground motions for a postulated M_W 8.5 Cascadia megathrust earthquake. Figure 153 shows the absolute 5-percent-damped acceleration response spectra for both the Olympia and Seattle sites. Although lacking the site resonant peaks exhibited by the 1965 earthquake, the differences in the spectral shapes of the Seattle and Olympia sites (fig. 153) again illustrate the significant site response effects of the near-surface geology. At a source-to-site distance of 101 km, the predicted median peak horizontal acceleration is $0.15g$ at Olympia (fig. 153, table 22). For Seattle, the model-predicted median peak horizontal acceleration is $0.14g$. The Seattle site exhibits a greater high-frequency site amplification than the Olympia site, as exemplified by its peak horizontal acceleration, even though it is 45 km farther from the rupture

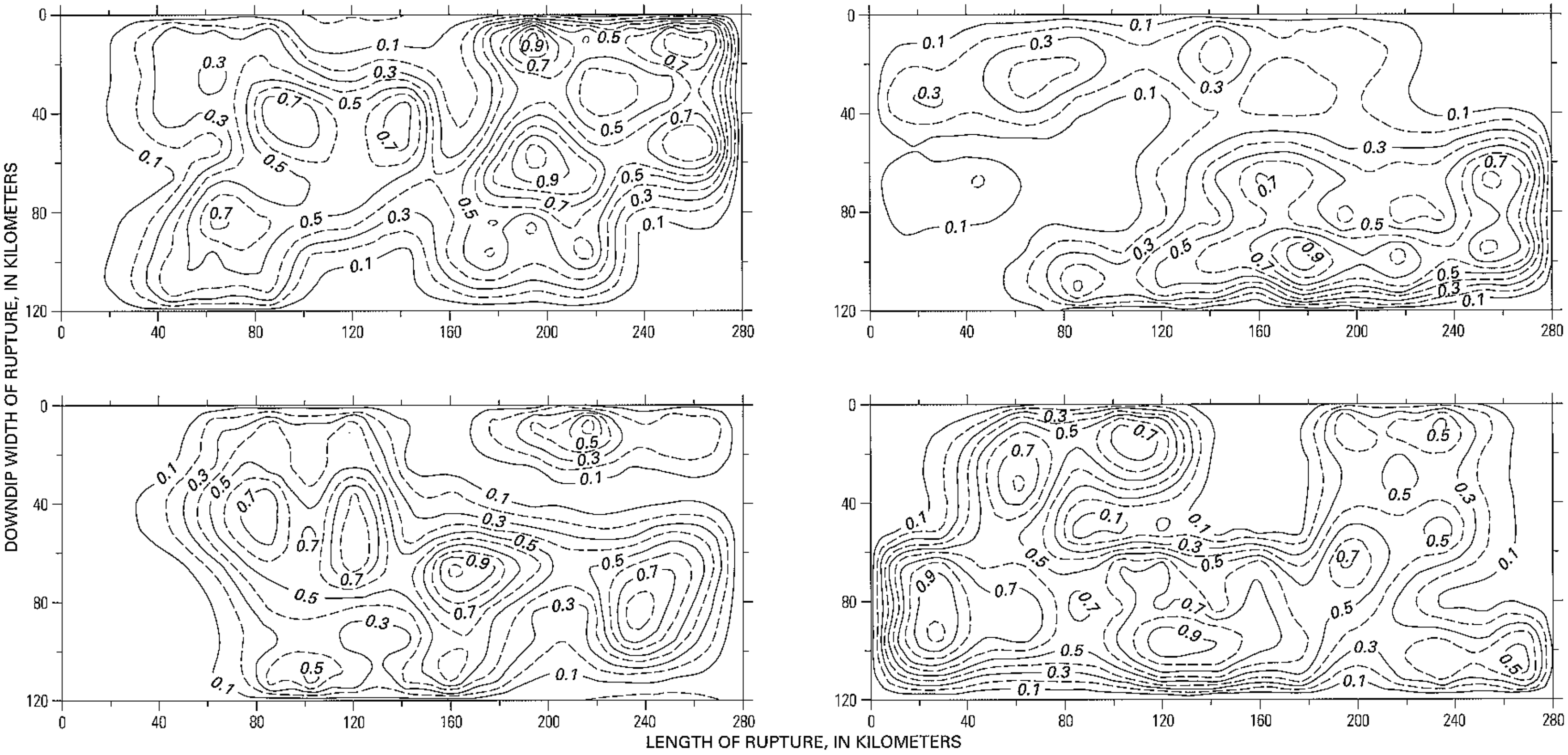

Figure 150. Four of the 50 randomized slip-distribution models used in the estimation of ground motions for the hypothesized M_w 8.5 Cascadia subduction-zone earthquake. Contours represent coseismic slip along the rupture planes, normalized to the maximum slip. Contour interval is 0.2. Areas of large slip are called asperities.

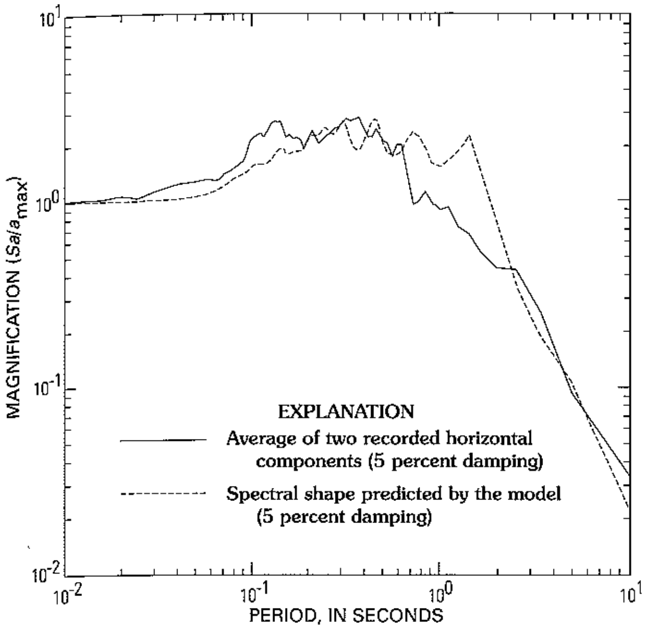

Figure 151. Observed and predicted 5-percent-damped acceleration response spectral shapes of the April 13, 1949, earthquake recorded at the Olympia Highway Test Office site. Spectral shape is defined by the parameter Sa/a_{max}, where Sa is spectral acceleration and a_{max} is peak horizontal acceleration.

zone of the megathrust earthquake. Based on an empirical attenuation relationship for subduction-zone earthquakes and rock-site conditions (Youngs and others, 1988), median peak horizontal accelerations for a M_w 8.5 megathrust event at distances of 101 km and 146 km are estimated to be 0.12g and 0.09g, respectively.

An important aspect of any numerical modeling approach is a proper statistical estimate of uncertainty. Total uncertainty is a combination of modeling and parametric uncertainties. A quantitative assessment of the modeling uncertainty associated with both the BLWN-RVT point source and finite-fault approach has been computed based on analyses of the 1989 M_w 7.0 Loma Prieta, Calif., earthquake (Schneider and others, 1993). The parametric uncertainties permit a rapid and cost-effective means of assessing which source, path, and site parameters are controlling the ground motions for a particular application.

The parametric uncertainties for the predictions of the megathrust earthquake are illustrated in figure 154 and listed in table 23. At all frequencies, the site profiles at both sites dominate the uncertainties in the ground motions, suggesting that a reduction in uncertainty is attainable with detailed site investigations. Source effects (focus and slip) are also large at low frequencies, with slip variation (asperity location) tending to remain constant with frequency (fig. 154). The path damping parameter Q_o is not a major contributor to the uncertainty in the ground-motion predictions because of the low attenuation in the Cascadia subduction zone, as suggested by Atkinson (1995). Because the motions are low, the effects of soil nonlinearity are insignificant, showing a near-zero uncertainty for modulus reduction and damping.

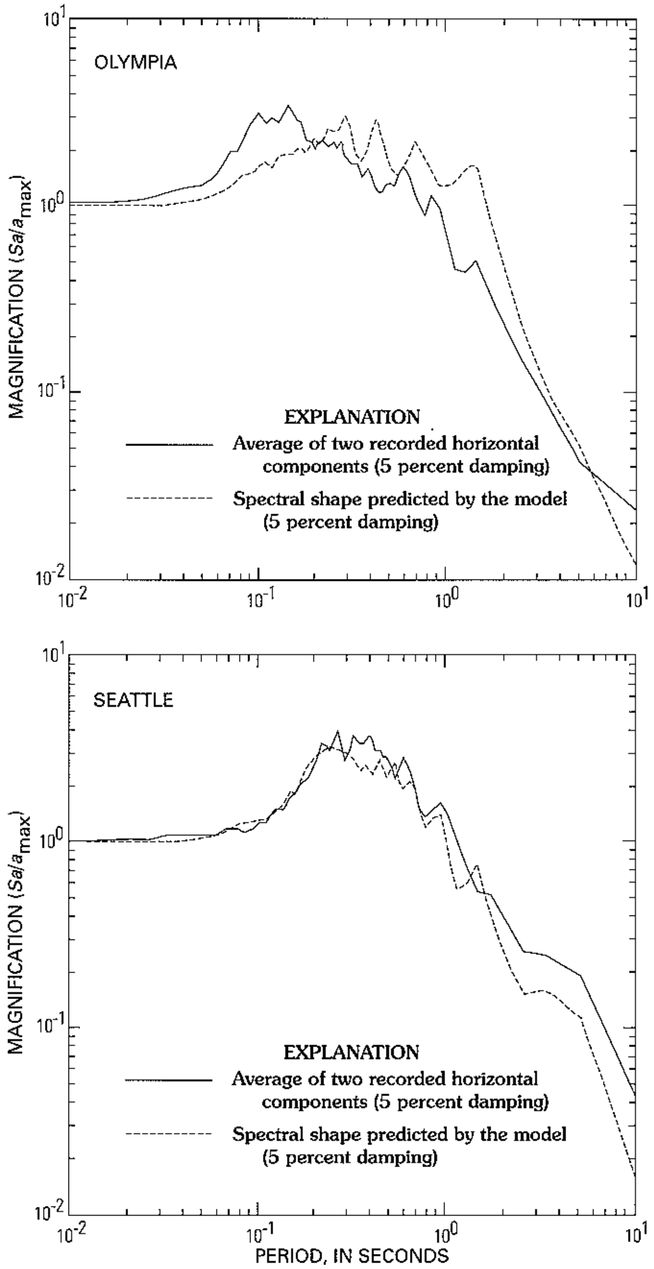

Figure 152. Observed and predicted 5-percent-damped acceleration response spectral shapes of the April 29, 1965, earthquake recorded at the Olympia Highway Test Office and Seattle Federal Office Building sites.

SUMMARY

Predicted peak accelerations and acceleration response spectra for the 1949 and 1965 Puget Sound earthquakes based on the BLWN-RVT ground-motion methodology

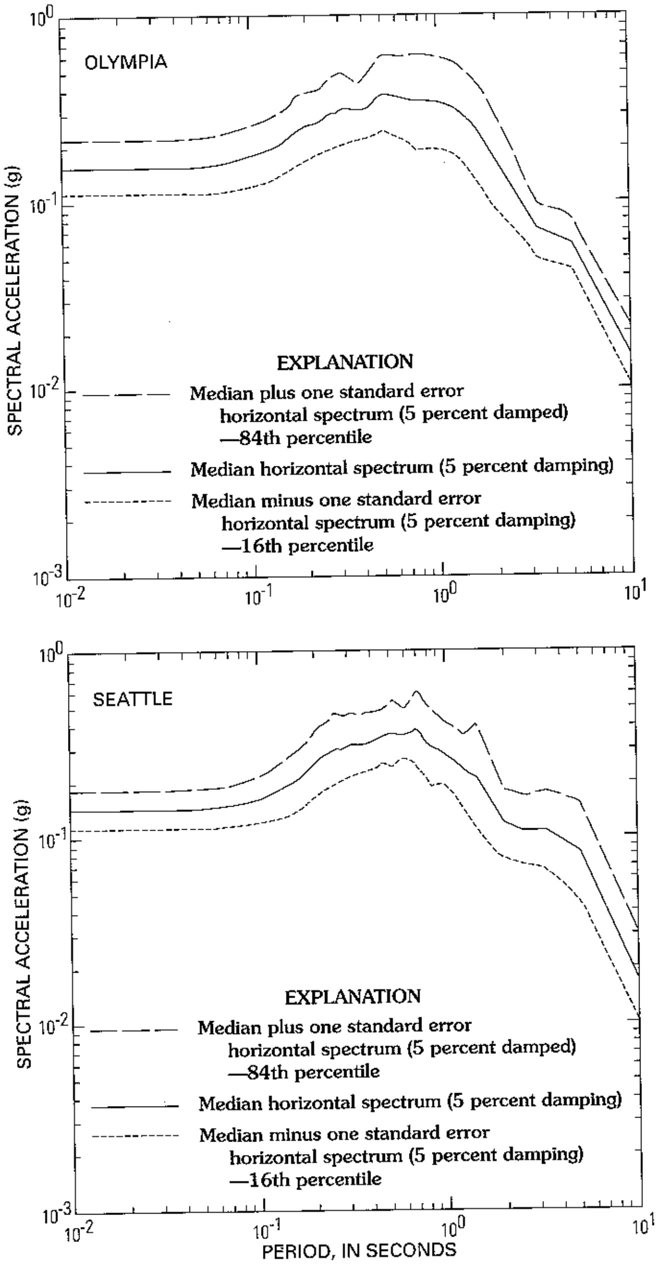

Figure 153. Predicted 5-percent-damped acceleration response spectra of a hypothetical M_w 8.5 Cascadia subduction-zone earthquake at the Olympia Highway Test Office and Seattle Federal Office Building sites.

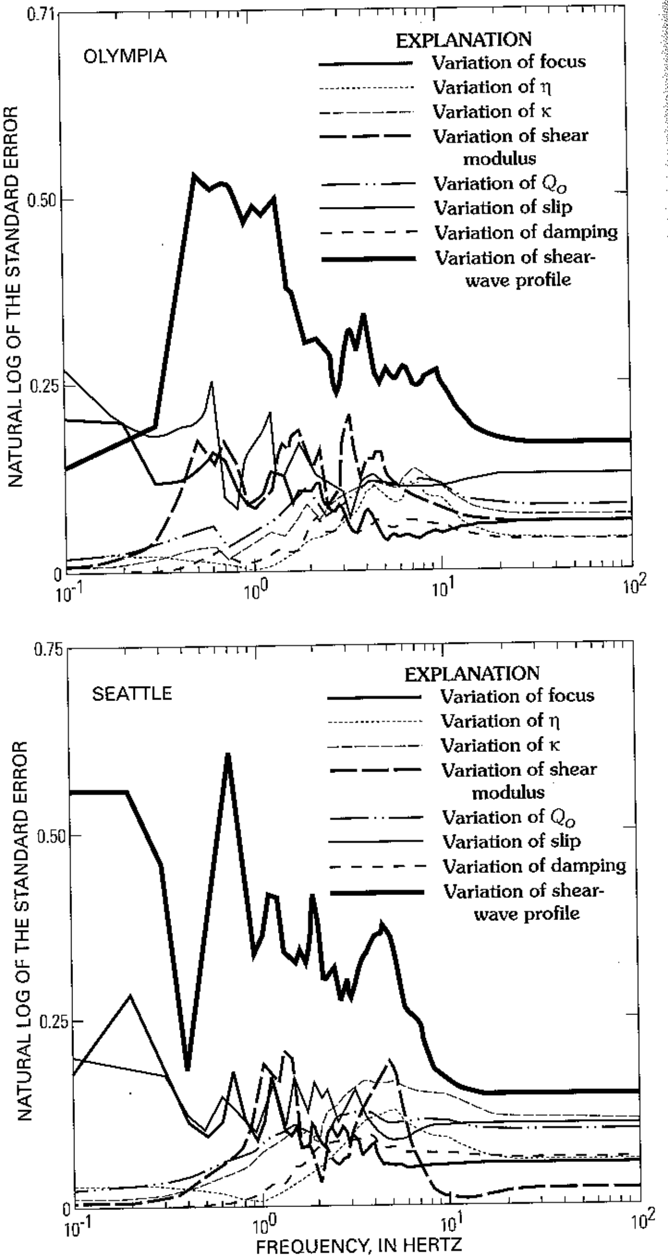

Figure 154. Parametric uncertainties in the band-limited-white-noise and random-vibration-theory computations of ground motions for a hypothetical M_w 8.5 Cascadia subduction-zone earthquake, as predicted for the Olympia Highway Test Office and Seattle Federal Office Building sites. The uncertainties are a result of varying each parameter shown in table 23.

were calibrated against actual recordings made at the Olympia Highway Test Office and Seattle Federal Office Building. An application of the methodology predicts median peak horizontal accelerations of 0.14*g* for the downtown Seattle site and 0.15*g* for the Olympia site from a postulated M_w 8.5 Cascadia subduction-zone earthquake. The uncertainty in these values is large and is driven by uncertainties in the shear-wave velocity profile beneath each site as well as the source-to site distance of the rupture zone of a future megathrust event. The need for more site-specific studies is exemplified by the observation that the site response at the Olympia Highway Test Office differs significantly from the site response at the Seattle Federal Office Building and by our inability to match, in absolute terms, the 1965 ground motions at Olympia. Based on this analysis, the effects of near-surface soils and the properties of the underlying rock likely exert a dominant influence on strong ground motions in the Puget Sound region and probably the Willamette Valley in Oregon.

Table 23. Model input parameters and uncertainties in parametric variations for a hypothetical M_W 8.5 Cascadia subduction-zone earthquake.
[(--), not required]

Parameter	Mean or median value	Distribution	Standard error (σ)[1]
Focus	Randomized in nucleation zone	--	--
Slip	Randomized models	--	--
Attenuation parameter (Q_o)	380	Lognormal	0.18
Attenuation parameter (η)	0.39	Normal	0.05
Near-surface attenuation (κ)	0.04 s (Olympia) 0.06 s (Seattle)	Lognormal	0.30
Shear-wave profile[2]	See figure 149	Lognormal	0.40
Shear-modulus reduction	See Electric Power Research Institute (1993, p. 7–A.41)	Lognormal	0.35
Shear-wave damping	See Electric Power Research Institute (1993, p. 7–A.42)	Lognormal	0.35

[1] For lognormal distributions, σ is actually σ_{ln}.

[2] Approximately lognormal based on a correlation model for velocity and layer thickness.

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