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Applications of the Band-Limited-White Noise Source Model for Predicting Site-Specific Strong Ground Motions

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SYNOPSIS: Since the Band-Limited-White-Noise (BLWN) source model coupled with random vibration theory (RVT) was first developed in the early 1980's, it has been used successfully to predict strong ground motions at rock sites in different tectonic regimes. The BLWN-RVT methodology is appropriate for an engineering characterization of strong ground motions at a site since the method captures the important features of these motions in terms of peak acceleration and spectral composition and requires a minimum of input parameters. Recently, the capability to estimate strong ground motions at soil sites has been incorporated into the methodology by using RVT and plane-wave propagators in an equivalent-linear formulation. Thus, non-linear soil response that may occur at high strain levels can now be directly estimated and analyzed. Four cases in which the BLWN-RVT methodology has been applied to predict strong ground motions will be discussed: (1) a moment magnitude (M) 7.9 New Madrid earthquake located 10 km beneath a rock site and a deep soil site; (2) a M 6.9 event similar to the 1983 Borah Peak, Idaho earthquake at several rock and thin soil sites at source-to-site distances of 10 to 27 km; (3) a M 8.0 Cascadia subduction zone earthquake at both a deep alluvial and hypothetical hard rock site in Seattle, Washington at a source-to-site distance of 70 km; and (4) a M 7.0 earthquake occurring along the Hayward fault in the eastern San Francisco Bay region at an 18-m-thick soil site, 15 km from the fault. The effects of soil amplification or deamplification (possibly due to either non-linear soil response or soil damping) will be emphasized in these case histories.

INTRODUCTION

The occurrences of the 1985 M 8.1 Michoacan, Mexico, the 1988 M 6.8 Armenia, and the 1989 M 7.0 Loma Prieta, California, earthquakes are recent testimony to the destructive power of such events and how the properties of the local site geology can strongly influence ground shaking. The deep lacustrine clays beneath Mexico City, 350 km from the epicenter, the alluvial soils beneath Leninakan, Armenia, 30 km away, and the deep soft clays and Bay Muds beneath Oakland, at an epicentral distance of 90 km, were significant in amplifying strong ground motions to destructive levels even at large distances. Thus, one of the most significant challenges that faces us in seismic hazards mitigation today is the site-specific prediction of strong ground motions. Historically, a heavy dependence has been placed on empirical techniques that are strongly influenced by the relatively large California strong motion data base. The primary weaknesses of these techniques are that they are non-site-specific and, in particular, they do not adequately address the influence of the local geologic conditions on strong motions. As observed in many past earthquakes, local conditions, particularly at sites underlain by sedimentary deposits, can control the characteristics of strong ground motions.

In this paper, we describe a relatively new methodology which involves the Band-Limited-White-Noise (BLWN) source model (Hanks and McGuire, 1981) combined with random vibration theory (RVT) and an equivalent-linear approach for soil response. Such a stochastic model allows, for the first time, realistic predictions of strong motions (Joyner and Boore, 1988) because it can incorporate the specific characteristics of the earthquake source and wave propagation as well as region- and site-specific propagation path and near-surface geological effects. In a recent analysis of a world-wide data set of earthquakes ranging from moment magnitude (M) 1.5 to 8.1 at distances of less than approximately 50 km, we have shown that the controlling factors in the specification of strong ground motions for engineering design are, in addition to magnitude and source-to-site distance, the properties beneath the site. This is applicable to both rock and soil sites, extending to depths of several hundred meters to approximately 2 km (Silva and Darragh, 1990). Four case histories will be discussed to illustrate our current efforts to predict site-specific strong ground shaking. They include earthquakes located in a variety of tectonic regimes with varied styles of faulting and source-to-site distances: (1) a M 7.9 New Madrid earthquake at 0 epicentral distance and at a focal depth of 10 km beneath both a rock and a deep soil site; (2) a M 6.9 event similar to the 1983 Borah Peak, Idaho earthquake at several rock and thin soil sites at source-to-site distances of 10 to 27 km; (3) a M 8.0 Cascadia subduction zone earthquake at both a deep alluvial and a hypothetical hard rock site in Seattle, Washington at a distance of 70 km; and (4) a M 7.0 earthquake along the Hayward fault in the eastern San Francisco Bay region at an 18-m-thick soil site, 15 km from the fault.

METHODOLOGY

The BLWN-RVT acceleration spectral density a(f) (Figure 1) is defined as

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

where

M_o	seismic moment
R	distance to the equivalent point source
β_o	shear wave velocity at the source
ρ_o	density at the source
$Q(f)$	frequency-dependent quality factor
$A(f)$	near-surface amplification factors
$P(f)$	high-frequency truncation filter
f_c	source corner frequency and
$C =$	$(1/\rho_o\beta_o^{\,3}) \bullet (2) \bullet (0.63) \bullet (1/\sqrt{2})\bullet\pi$

C is a constant which contains ρ_o and β_o terms and accounts for the free-surface effect (factor of 2), the source radiation pattern averaged over a sphere (0.63) (Boore, 1983), and the partition of energy into two horizontal components ($1/\sqrt{2}$).

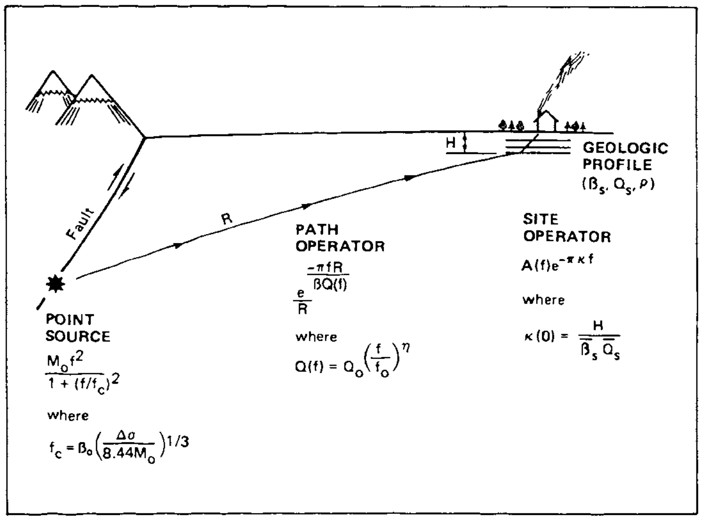

Figure 1. Schematic illustrating the Band-Limited-White-Noise ground motion model showing the source, path, and site operators

Source scaling is provided by specifying two independent parameters, M_o and the high-frequency stress parameter ($\Delta\sigma$) (Figure 1). The stress parameter is taken to be independent of magnitude (Atkinson, 1984; Boore and Atkinson, 1987; Toro and McGuire, 1987) and relates the corner frequency f_c to M_o through the relation

$$f_c = \beta_o(\Delta\sigma/8.44\, M_o)^{1/3} \qquad (2)$$

The spectral shape of the single-corner-frequency, ω-square source model is then described by the two free parameters, M_o and $\Delta\sigma$. The source corner frequency increases with the shear-wave velocity and stress parameter, both of which are region dependent. The increase in amplitude as the seismic energy travels through lower velocity crustal rocks near the surface is accounted for by the use of Boore's (1986) amplification factors or a site-specific geologic profile that is representative of the near-surface geology, down to approximately 2 km.

The P(f) filter is an attempt to model the observation that acceleration spectral density appears to fall off rapidly beyond some region-dependent maximum frequency. This observed phenomenon truncates the high frequency portion of the spectrum and is responsible for the band-limited nature of the model. This spectral fall-off has been attributed to near-site attenuation (Hanks, 1982; Anderson and Hough, 1984), to source processes (Papageorgiou and Aki, 1983) or to both effects, perhaps. In the Anderson and Hough (1984) attenuation model which we have adopted here, the form of the P(f) filter is taken as

$$P(f) = e^{-\pi\kappa f} \qquad (3)$$

In the framework of the BLWN-RVT ground motion model, the attenuation model of Anderson and Hough (1984) exerts a predominant effect upon spectral composition for frequencies beyond approximately 5 Hz in the range of engineering interest at rock sites (Darragh et al., 1990).

At zero epicentral distance

$$\kappa(0) = \frac{H}{\bar{\beta}_s \bar{Q}_s} \qquad (4)$$

The bars in Equation 4 represent an average of these quantities over a depth H beneath the recording site. The value of κ(0) is attributed to attenuation in the very shallow crust directly below the site (Hough et al., 1988). The intrinsic attenuation along this part of the path is not thought to be frequency dependent and is modeled as a frequency independent, but site-dependent constant κ (Hough et al., 1988).

κ has been determined for several rock and soil sites representative of western North America (WNA) and eastern North America (ENA). For a competent WNA rock site, a value in the range of 0.02 to 0.04 sec is appropriate and for an ENA rock site, 0.004 to 0.008 sec (Silva et al., 1989a; Silva and Darragh, 1990). The attenuation along the path from the source to just below the site is modeled with the frequency-dependent quality factor Q(f).

he Fourier amplitude spectrum given by Equa- ion 1 represents the BLWN source model employing a Brune spectrum that is characterized by a ingle corner frequency. It is appropriate for point source and models direct shear-waves in homogeneous half-space (with effects of a velocity gradient through the A(f) filter). ffects due to source finiteness as well as wo-dimensional propagation path complexities do not appear to significantly affect spectral shapes for subduction earthquakes up to M 8.1 nd for epicentral distances ranging from 20 to 66 km (Silva and Darragh, 1990). (Also see igure 2 in Silva et al. [1990]).

n order to compute peak time domain values, hat is peak acceleration and peak oscillator esponse, RVT is used to relate root-mean-quare (rms) computations to peak value esti- ates (Boore, 1983; Boore and Joyner, 1984). xtreme value theory is then used to estimate he expected ratio of the peak value to the rms alue of a specified duration of the BLWN time istory. The duration is generally taken as he inverse of the corner frequency (Boore, 983).

Soil Response

n 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 SH plane-wave propagators. Arbitrary angles of ncidence may be specified but normal incidence s most often used in our analyses. In order to treat possible material non-linearities, an equivalent-linear formulation is employed. RVT s 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 program SHAKE (Schnabel et al., 1972) except that peak shear strains in SHAKE are measured in the time domain. The pure frequency domain 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. (See Silva et al. [1990] for detailed discussion.)

CASE HISTORIES

New Madrid

During the winter of 1811-1812, a sequence of major earthquakes occurred near the town of New Madrid, Missouri in the central Mississippi Valley. The first event occurred on 16 December 1811 at 2:15 a.m. local time and was followed by earthquakes on 23 January and 7 February 1812. Nuttli (1983) has estimated the size of these events to have been surface wave magnitudes (M_s) 8.5, 8.4 and 8.8. Each earthquake appears to have ruptured portions of or all of the three principal segments which comprise the New Madrid seismic zone.

The purpose of a recent study by Silva et al. (1989b) was to estimate the strong ground motion on competent rock and a generic 152-m-thick sandy soil site from the largest New Madrid earthquake, M 7.9. Competent rock was defined for purposes of this study as rock with a shear wave velocity (β_s) of at least 3.5 km/sec. Values for peak ground acceleration, response spectral shape (5% damped response spectral acceleration divided by peak acceleration) and an acceleration time history were calculated.

The epicentral distance was assumed to be 0 km and a focal depth of 10 km was selected consistent with the 5 to 15 km depths of recorded microearthquakes. The acceleration spectral density fall-off was modeled by a κ of 0.006 sec. Frequency-dependent attenuation was assumed along the raypath as $Q(f) = Q_o f^\eta$ where Q_o was 500 and η was 0.65 (Toro, 1985). For the hard rock site at a distance of 10 km, the peak acceleration and velocity were 1.60 g and 124 cm/sec, respectively (Silva et al., 1989b).

Figure 2 shows the acceleration time history computed for the New Madrid event on competent rock scaled to the predicted value of 1.60 g. The accelerogram was produced by combining the BLWN amplitude spectrum with a phase spectrum from an observed strong ground motion recording; in this case, the La Villita record of the 1985 Michoacan earthquake using the technique described by Silva and Lee (1987). The time history appears realistic with reasonable durations, peak values, distribution of energy in time, and it displays typical non-stationarity. The time history is also rich in high-frequency energy, consistent with an eastern North American propagation path length of 10 km in competent rock.

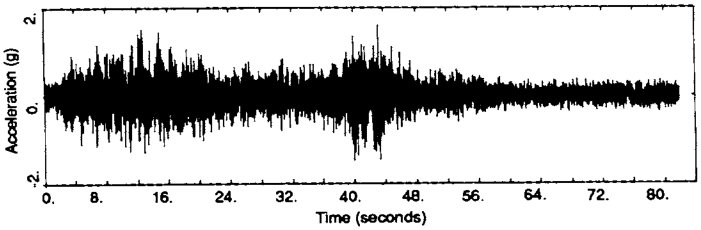

Figure 2. Synthetic acceleration time history for a rock site of a M 7.9 New Madrid earthquake at a focal depth of 10 km and an epicentral distance of 0 km.

Since there are few strong ground motion records in the near-field of large magnitude intraplate earthquakes, the peak values predicted for the New Madrid event cannot be compared with empirical data. Comparisons with estimates based on published attenuation relationships are similarly limited because of the lack of data available for use in the regression analyses. Nevertheless, we have compared the peak accelerations predicted by the BLWN-RVT methodology with extrapolations of published relationships for ground motions in the central and eastern U.S.

Campbell (1981) developed peak acceleration-attenuation relationships for both epicentral and fault distance for the central U.S. For a body-wave magnitude (m_b) 7.4 earthquake at 10 km depth, the relationships predict a value of 0.68 g using fault distance and 3.36 g using epicentral distance. The BLWN-RVT estimate of 1.60 g falls somewhat below the average of these two values. Extrapolation of the Nuttli and Herrmann (1978) relationship for the central U.S. results in an estimate of peak acceleration of 3.13 g at the epicenter of a m_b 7.4 earthquake. Nuttli and Herrmann (1978) point out, however, that large accelerations result when the equation is extrapolated to the New Madrid earthquakes of 1811-1812, and that "there are no existing data which can be used to verify the extrapolations to such large magnitude earthquakes." Toro and McGuire (1987) and Boore and Atkinson (1987) used the BLWN approach to estimate peak accelerations for rock sites in eastern North America. For a Nuttli magnitude (m_{Lg}) 7.4 event, the Toro and McGuire (1987) relationship results in a peak acceleration of 1.56 g at a distance of 10 km. For a M 7.9 earthquake, the Boore and Atkinson (1987) relationship results in a peak acceleration of 1.98 g at a distance of 10 km.

To illustrate the effects of a deep soil profile upon the computed outcrop motion, time histories (Figure 3) as well as response spectra were computed at the surface of a generic sand-like profile. The profile was developed by Toro et al. (1988) as appropriate for deep sand-like sites in the central U.S. The density for the profile was assumed to be 2.1 g/cm^3 with small strain damping taken as $Q_s = 30\ \beta_s^{1.25}$ (Apsel et al., 1982) and a Q_s lower bound of 16.

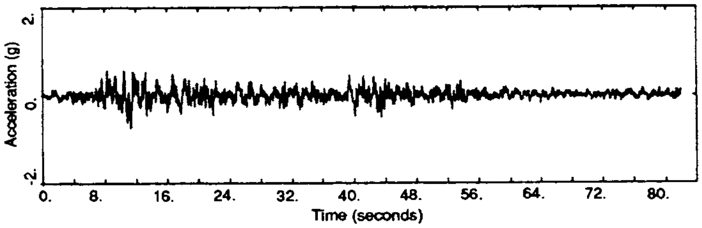

Figure 3. Synthetic acceleration time history of a M 7.9 New Madrid earthquake for a deep soil profile resulting from an equivalent-linear analysis.

For levels of ground motion expected in the near-source region of the largest New Madrid earthquake, traditional dynamic soil models would predict significant non-linear soil response for saturated sands. In fact, evidence of soil failure such as sand boils, which occurred during the 1811-1812 earthquakes, indicates that non-linear soil response should be accommodated in computation of the motion expected at the surface of the profile.

Results of these analyses indicate that for reasonable assumptions regarding the shear-wave damping, peak accelerations at the surface of deep soil sites will be lower than those associated with a corresponding hard outcrop motion (Silva et al., 1989b). The analyses predict a peak acceleration of 0.78 g at a deep soil site due to a New Madrid-type earthquake. This value resulted from an equivalent-linear soil response analysis using the Seed-Idriss (1970) sand curves. Specifically, the upper range modulus reduction curve was used along with the lower-range damping curve.

In summary, the estimated peak values, response spectra, and time history of the New Madrid event appear to be internally consistent (Silva et al., 1989b) because the ratios of the response spectra acceleration values and the peak velocity to the peak acceleration are within the range of expected values. The amplitudes of the estimated values are high; some greater than the largest values recorded. Since no data exist for sites close to a large intraplate earthquake rupture, the accuracy of the estimated values is difficult to assess. Given the possible shortcoming of assuming a point source for the earthquake at a distance less than the source dimensions, the estimates for the outcrop motion are probably conservative. The degree of conservatism cannot be evaluated without additional data from actual events.

Southeastern Idaho

On 28 October 1983, a M_S 7.3 (M 6.9) earthquake occurred near Borah Peak along the Lost River Range, approximately 90 km northwest of the Idaho National Engineering Laboratory (INEL) which is located within the eastern Snake River Plain. Previous geologic studies of the Arco and Howe scarps along the southern segments of the northwest-trending Lost River and Lemhi faults respectively (both Basin and Range normal faults), have uncovered evidence of multiple earthquakes. These data suggest that there exists a potential for future earthquakes, similar to the 1983 Borah Peak event which may occur at close distances to facilities at the INEL.

In a study by Wong et al. (1990), strong ground motion parameters were estimated for a Borah Peak-like event occurring along the southern segment of the Lemhi fault (Figure 4). The

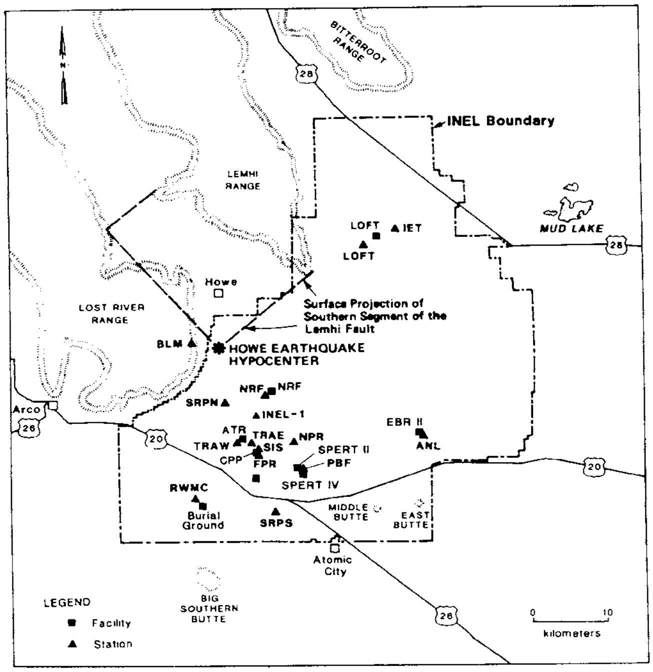

Figure 4. Seismic survey stations and major facilities at the INEL. Also shown is the rupture plane of the postulated Howe earthquake.

arthquake was assumed to be a M 6.9 and to ave a stress parameter of 50 bars. The rupure plane for the earthquake was assumed to be 45° southwest-dipping normal fault with an nitial point of rupture at 16 km depth at the outhwestern bottom corner of the rupture lane, identical to the geometry of the 1983 orah Peak event (Figure 4). The distances etween the plane of rupture and the various NEL facilities ranged from 11 to 27 km.

or the propagation path, a half-space model haracterized by a β of 3.55 km/sec and a ρ of .7 g/cm^3 was assumed. Based on Singh and Ierrmann (1983), a regional crustal coda Q_o of .50 and an η of 0.2 for Q(f) were also asumed. Geologic profiles, 3 km deep, were leveloped from well data for each of the indiidual sites. The upper approximate 750 m of he geologic profiles consists of basaltic lava lows with interbedded sediments of alluvial, acustrine and volcanic origin. The lower ection consists primarily of rhyolitic welded ash-flow tuffs interbedded with devitrified hyolites. At a depth below approximately 2500 n, a rhyodacite porphyry composition was assumed.

ite-specific κ values were estimated by matchng BLWN-RVT generated templates of various ombinations of M, distance, stress parameter and κ to the horizontal response spectral hapes of several regional earthquakes recorded at each of the sites during the operation of a emporary microearthquake network (Wong et al., 990). The κ values ranged from 0.005 sec for a station located in the Lost River Range to .037 sec for several stations within the Snake iver Plain. One station in the plain had an nusually low κ, suggesting the near-absence of interbeds in the basalts, consistent with the ear-surface well data. Evaluation of response pectra of the 1983 Borah Peak accelerograms as ecorded at the INEL yielded an average κ of .03 sec. These site-specific κ values were sed to constrain the Q_s structure in the geologic profiles.

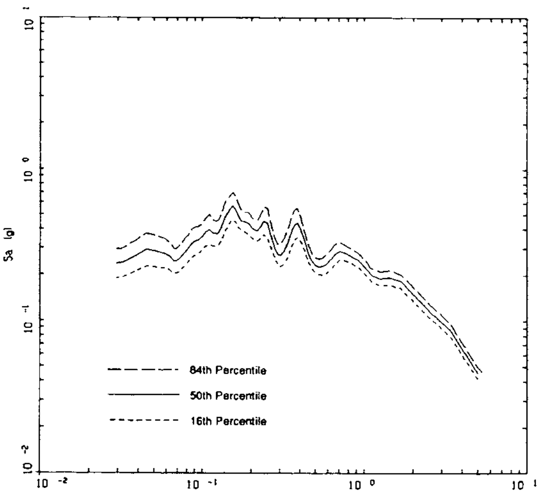

Figure 5. 16th, 50th, and 84th percentile acceleration response spectra on a typical rock site at the INEL.

Shown in Figure 5 are the median, 16th and 84th percentile 5% damped response spectra for one of the rock sites. These estimates are the result of parameter variations which provide weighted values that incorporate the uncertainties of the model input parameters. The site-specific nature of the spectra is reflected in their lack of smoothness. Peak accelerations for the various sites at the INEL ranged from approximately 0.09 to 0.40 g at distances of 27 to 11 km. The differences in peak values were strongly dependent on the distance to the rupture plane and the average κ of the geologic profiles.

A sensitivity analysis was performed to assess the attenuating properties of the basalt interbeds. As the number of thicker interbeds (>30 m) increased, hence increasing kappa, the peak horizontal accelerations decreased (Wong et al., 1990). Thinner interbeds did not appreciably affect the peak accelerations in terms of increasing damping, although some additional attenuation occurred from scattering. Thus the presence of the sedimentary interbeds in the basalts beneath the Snake River Plain appears to attenuate high frequency ground motions to a greater degree than for sites with very few interbeds or for those sites located off the plain.

Puget Sound, Washington

Of particular importance in the assessment of seismic hazards in the Pacific Northwest is the possibility of a great Cascadia subduction zone earthquake ($M \geq 8$) occurring beneath western Washington and Oregon. While the source processes of such earthquakes may, in detail, be different from intraplate and non-subduction interplate events, our analyses suggest that the simple BLWN-RVT model can accurately predict the spectral content of such events for engineering design.

In our effort to calibrate the BLWN-RVT approach and the geologic profiles used in this study (Silva et al., 1990), response spectral shapes were calculated and compared with the 1949 M 7.1 Olympia earthquake and the 1965 M 6.5 Seattle-Tacoma earthquake. The 1949 earthquake occurred at a depth of 49 km and at an epicentral distance of approximately 5 km from the Olympia Highway Test Laboratory (OHT). Peak horizontal ground accelerations of 0.16 and 0.28 g were recorded at OHT. The 1965 Seattle-Tacoma earthquake occurred at a depth of 60 km and at epicentral distances of 21 and 69 km from the Seattle Federal Office Building (FED) and OHT, respectively. Peak horizontal accelerations of 0.067 and 0.068 g were recorded at FED, and 0.14 and 0.20 g at OHT.

In the BLWN-RVT estimates for these events, the stress parameter was assumed to be 100 bars. Although Boore (1986) determined that a value of 50 bars matched the peak accelerations and velocities of 19 earthquakes ranging from M 6.5 to 9.5 (of which the majority were subduction zone earthquakes), the use of 100 bars is within the reasonable range of dynamic stress drops and appears to fit the observed Washington data well (see following discussion).

The propagation path was characterized by a β of 3.2 km/sec, Q_o of 150, η of 0.6, and ρ of 2.7 g/cm^3, based on standard values for western North America (Silva and Darragh, 1990). Beneath OHT, based on borehole data, low-strain shear-wave velocities for the glacial sediments ranged from 142 m/sec at the surface to 685 m/sec at a depth of 131 m. At FED, fill material was encountered to a depth of 7 m. The natural soils at the site have velocities ranging from 198 to 1006 m/sec to a depth of 122 m. Geologic profiles were developed from these data and used in the strong motion estimates.

Response spectral shapes were computed from the recorded data and compared with the BLWN-RVT model shapes (e.g., Figure 6). The BLWN-RVT predictions match the general features of the spectral shapes calculated from the data between 0.2 to 33 Hz quite well. The overall shape, frequency, and level of the maximum spectral amplification and peak ground acceleration compare favorably with the recorded values at these two sites (Silva et al., 1990). The model, however, underpredicts by a factor of approximately two the peak acceleration at OHT for the 1965 earthquake. This discrepancy has also been observed by Langston (1981) and Shakal and Toksoz (1980) who suggest that higher values of Q are characteristic of the OHT site compared to the FED site. More detailed borehole and upper crustal information on β_s and Q are needed to resolve this inconsistency.

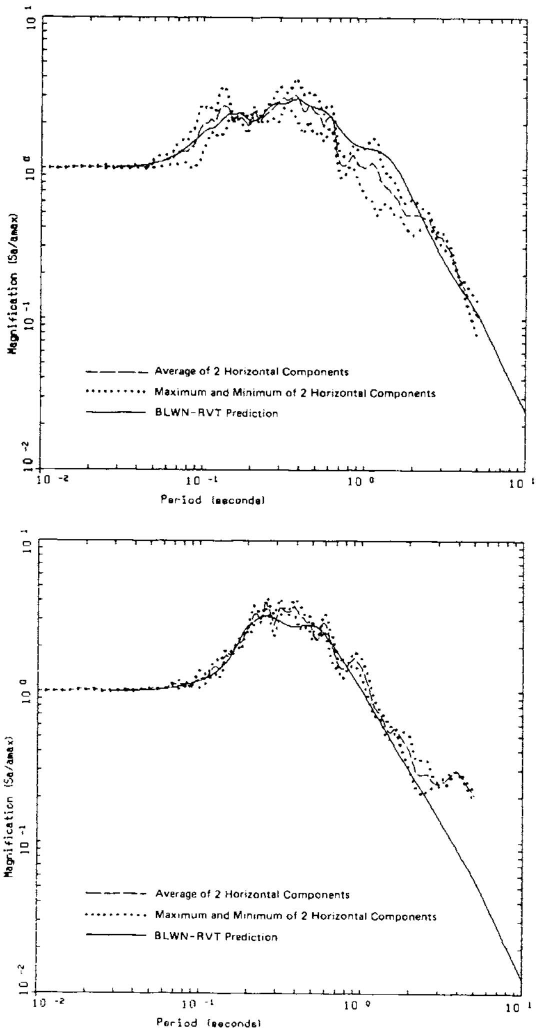

Figure 6. Comparisons of the calculated 5% damped response spectral shapes using the BLWN-RVT ground motion model and the observed data for the 1949 M 7.1 Olympia earthquake at the OHT site in Olympia and the FED site in Seattle.

Ground motions were also computed for the FED site from a postulated M 8.0 Cascadia earthquake at a rupture distance of 70 km. The median peak ground acceleration estimated by the BLWN-RVT model is 0.17 g. For comparison, the ground motions were estimated for a hypothetical hard rock site (the FED geologic profile without the soil) for the M 8.0 event at the same rupture distance. The peak acceleration in this case is 0.11 g. Figure 7 shows the 5% damped absolute acceleration response spectra for these two cases. The dramatic effect of the soil site is apparent. The FED site has an increased response compared to the rock response for periods between 0.2 and 3 sec. This is also evident in the synthetic accelerograms which exhibit higher levels of ground motion and a lower frequency content for the FED site (Silva et al., 1990). The high frequency ground motions from 0.05 to 0.2 sec at the FED site are, however, actually lower than the rock site due to deamplification resulting from either damping in the soil or non-linear soil response (Figure 7).

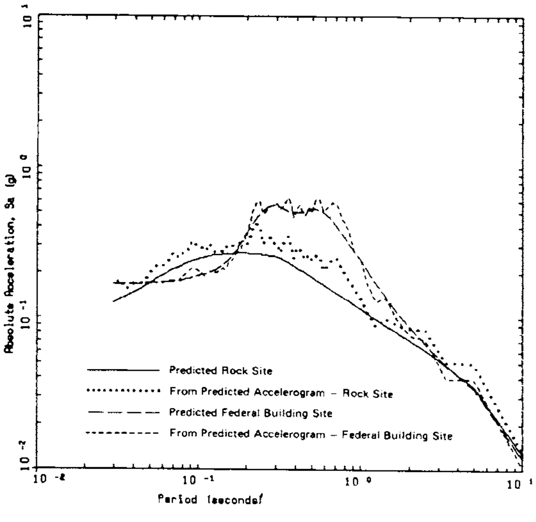

Figure 7. Predicted 5% damped acceleration response spectra of a hypothetical M 8 Cascadia earthquake at a hypothetical hard rock site and at the FED site.

Eastern San Francisco Bay Area

The U.S. Geological Survey recently forecasted that a M 7.0 or larger earthquake had a 28% probability of occurring on the northern egment of the Hayward fault in the next 30 ears. Strong ground motions from such an vent were predicted for a soil site in the own of Walnut Creek in Contra Costa County, 5 km east of the Hayward fault. A stress parameter of 50 bars was assumed appropriate or the Hayward earthquake. A Q_o of 150 and η f 0.55 from Singh and Herrmann (1983) were sed to characterize the crustal attenuation along the raypath. The geologic profile of the ite consists of 18 m of assorted sandy, clayey ediments overlying sandstone and shale bedock. The seven layers of sediments varied considerably in their shear-wave velocities without a monotonic increase in velocity with depth.

In contrast with the other studies, ground motion parameters were calculated not at the ground surface but at a depth of 6 m. The ntent was to provide an acceleration response spectrum (Figure 8) that could be considered for the design of a hospital proposed to be built on base isolation. The computed peak horizontal acceleration was 0.21 g compared to empirical values of 0.24 g and 0.22 g based on the peak acceleration-attenuation relationships of Joyner and Boore (1988) and Campbell (1990), respectively. These latter values are appropriate for rock sites. Despite the presence of low-velocity sediments overlying bedrock at the Walnut Creek site, the absence of a strong velocity gradient combined with soil damping appears to partially offset any significant amplification, particularly at the sediment-bedrock interface.

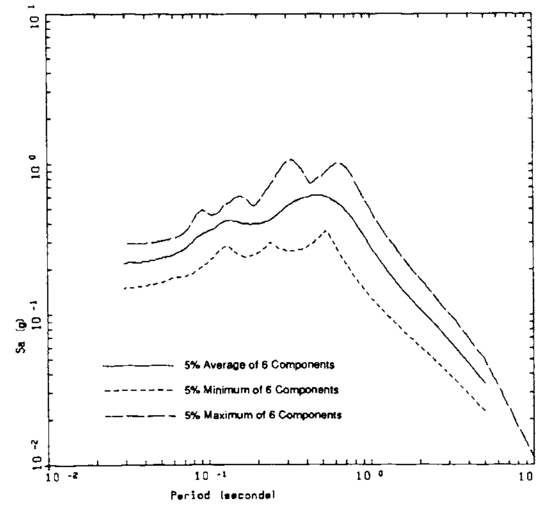

Figure 8. Acceleration response spectra of a M 7.0 earthquake on the Hayward fault 6 m below the ground surface at a soil site in Walnut Creek.

CONCLUSIONS

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 characterized by response spectra or power spectral density. The relatively new BLWN earthquake source model, which is extremely simple in concept, combined with RVT, has been remarkably successful in predicting peak ground motion values as well as spectral ordinates in different tectonic regimes at rock sites.

As demonstrated in the case histories just described, the BLWN-RVT methodology also exhibits considerable potential in the prediction of strong site-specific ground motions at soil sites. Future advancements in the applicability of this approach to both rock and soil sites will require incorporations of the modeling of the earthquake rupture process (Silva et al., 1990) and of more realistic crustal structure. An improved knowledge of (1) κ on a regional basis, (2) the shear modulus reduction and damping behavior of soils, (3) the Q_s of different rock types and (4) more detailed estimates of Q_o and η on a regional or preferably smaller scale will be required if improvements are to be made in the predictions of strong ground motions on a site-specific basis.

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REFERENCES

Anderson, J. G. and Hough, S. E., "A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies," Bulletin of the Seismological Society of America, 1984, v. 74, 1969-1993.

Apsel, R.J., Singh, S.K., Fried, J. and Brune, J.N., "Spectral attenuation of SH waves along the Imperial fault," Bulletin of the Seismological Society of America, 1982, v. 72, 2003-2016.

Atkinson, G. M., "Attenuation of strong ground motion in Canada," Bulletin of the Seismological Society of America, 1984, v. 74, 2629-2653.

Boore, D. M., "Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra," Bulletin of the Seismological Society of America, 1983, v. 73, 1865-1884.

Boore, D. M., "Short-period P- and S-wave radiation from large earthquakes: Implications for spectral scaling relations," Bulletin of the Seismological Society of America, 1986, v. 76, 43-64.

Boore, D. M. and Atkinson, G. M., "Prediction of ground motion and spectral response parameters at hard-rock sites in eastern North America," Bulletin of the Seismological Society of America, 1987, v. 77, 440-467.

Boore, D. M. and Joyner, W. B., "A note on the use of random vibration theory to predict peak amplitudes of transient signals," Bulletin of the Seismological Society of America, 1984, v. 74, 2035-2039.

Campbell, K. W., "A ground motion model for the central United States based on near-source acceleration data," Proceedings, Conference on Earthquakes and Earthquake Engineering - Eastern United States, Beavers, J. E., ed., 1981, v. 1, 213-222.

Campbell, K. W., "Predicting strong ground motion in Utah," Evaluation of Regional and Urban Earthquake Hazards and Risk in Utah, Hay, W. W., and Gori, P. L., eds., U. S. Geological Survey Professional Paper, 1990 (in press).

Darragh, R.B., Silva, W.J., Stepp, J.C. and Schneider, J.F., "Maximum spectral amplification and high-frequency truncation filters in the Band-Limited-White-Noise ground motion model at rock sites," Proceedings of the Fourth U.S. Conference on Earthquake Engineering, 1990, v. 1, 437-446.

Hanks, T. C., "fmax," Bulletin of the Seismological Society of America, 1982, v. 72, 1867-1879.

Hanks, T. C. and McGuire, R. K., "The character of high-frequency strong ground motion," Bulletin of the Seismological Society of America, 1981, v. 71, 2071-2095.

Hough, S. E., Anderson, J. G., Brune, J., Vernon III, F., Berger, J., Fletcher, J., Haar, L., Hanks, T. and Baker, L., "Attenuation near Anza, California," Bulletin of the Seismological Society of America, 1988, v. 78, 672-691.

Joyner, W. and Boore, D.M., "Measurement, characterization, and prediction of strong ground motion," Proceedings of Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground Motions Evaluation, Von Thun, J.L., ed., American Society of Civil Engineering, Geotechnical Special Publication No. 20, 1988, 43-103.

Langston, C. A., "A study of Puget Sound strong ground motion," Bulletin of the Seismological Society of America, 1981, v. 71, 883-903.

Nuttli, O. W., "Average seismic source parameter relations for mid-plate earthquakes," Bulletin of the Seismological Society of America, 1983, v. 73, 519-535.

Nuttli, O. W. and Herrmann, R. B., "Credible earthquakes for the central United States," State-of-the-Art for Assessing Earthquake Hazards in the United States, Report 12, U.S. Army Engineer Waterways Experiment Station, Miscellaneous Paper S-72-1, 1978, 103 p.

Papageorgiou, A. S. and Aki, K., "A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion, Part II: Applications of the model," Bulletin of the Seismological Society of America, 1983, v. 73, 953-978.

Schnabel, P.B., Lysmer, J. and Seed, H.B., "SHAKE-A computer program for earthquake analysis of horizontally layered sites," Earthquake Engineering Research Center, University of California, Report No. EERC 72-12, 1972.

Seed, H. B. and Idriss, I. M., "Soil moduli and damping factors for dynamic response analysis," Earthquake Engineering Research Center, University of California, Berkeley, Report No. EERC 70-10, 1970.

Shakal, A. F. and Toksoz, M. N., "Amplification and attenuation of site structure: Puget Sound strong motion," Earthquake Notes, 1980, v. 50, 20.

Silva, W. J. and Darragh, R. B., "Engineering characterization of strong ground motion recorded at rock sites," Electric Power Research Institute Final Report, 1990 (in press).

Silva, W. J., Darragh, R. B., Green, R., and Turcotte, F. T., "Spectral characteristics of small magnitude earthquakes with applications to western and eastern North American environments: Surface motions and depth effects," U.S. Army Engineers Waterways Experiment Station Miscellaneous Paper GL-89-16, 1989a, 84 p.

Silva, W. J., Darragh, R. B., Green, R., and Turcotte, F. T., "Estimated ground motions for a New Madrid event," U.S. Army Engineers Waterways Experiment Station Miscellaneous Paper GL-89-17, 1989b, 86 p.

Silva, W. J., Darragh, R. B., Stark, C., Wong, I. G., Schneider, J. and Chiou, S., "A methodology to estimate design response spectra in the near-surface region of large earthquakes using the Band-Limited-White-Noise ground motion model," Proceedings of the Fourth U.S. Conference on Earthquake Engineering, 1990, v. 1, 487-494.

Silva, W. J. and Lee, K., "WES RASCAL Code for synthesizing earthquake ground motions," State-of-the-Art for Assessing Earthquake Hazards in the United States, Report 24, U.S. Army Corps of Engineers Waterways Experiment Station, Miscellaneous Paper S-73-1, 1987, 120 p.

Silva, W. J., Wong, I. G., and Darragh, R. B., "Engineering characterization of earthquake strong ground motions with applications to the Pacific Northwest," Assessing and Reducing Earthquake Hazards in the Pacific Northwest, U.S. Geological Survey Professional Paper, 1990 (in press).

Singh, S., and Herrmann, R. B., "Regionalization of crustal coda Q in the continental U.S.," Journal of Geophysical Research, 1983, v. 88, 527-538.

Toro, G. R., "Stochastic model estimates of strong ground motion," Seismic Hazard Methodology for Nuclear Facilities in the Eastern United States, McGuire, R.K., ed., Electric Power Research Institute Report, 1985, v. 3, Appendix B, B77-B116.

Toro, G. R. and McGuire, R. K., "An investigation into earthquake ground motion characteristics in eastern North America," Bulletin of the Seismological Society of America, 1987, v. 77, 468-489.

Toro, G. R., McGuire, R. K., and Silva, W. J., "Engineering model of earthquake ground motion for eastern North America," Electric Power Research Institute Final Report NP-6074, 1988.

Wong, I. G., Silva, W. J., Darragh, R., Stark, C., Wright, D., Jackson, S., Carpenter, G. and Smith, R., "Site-specific strong ground motion predictions of a M 7 Basin and Range normal faulting earthquake in southeastern Idaho," Proceedings of the Fourth U.S. Conference on Earthquake Engineering, 1990, v. 1, 617-626.