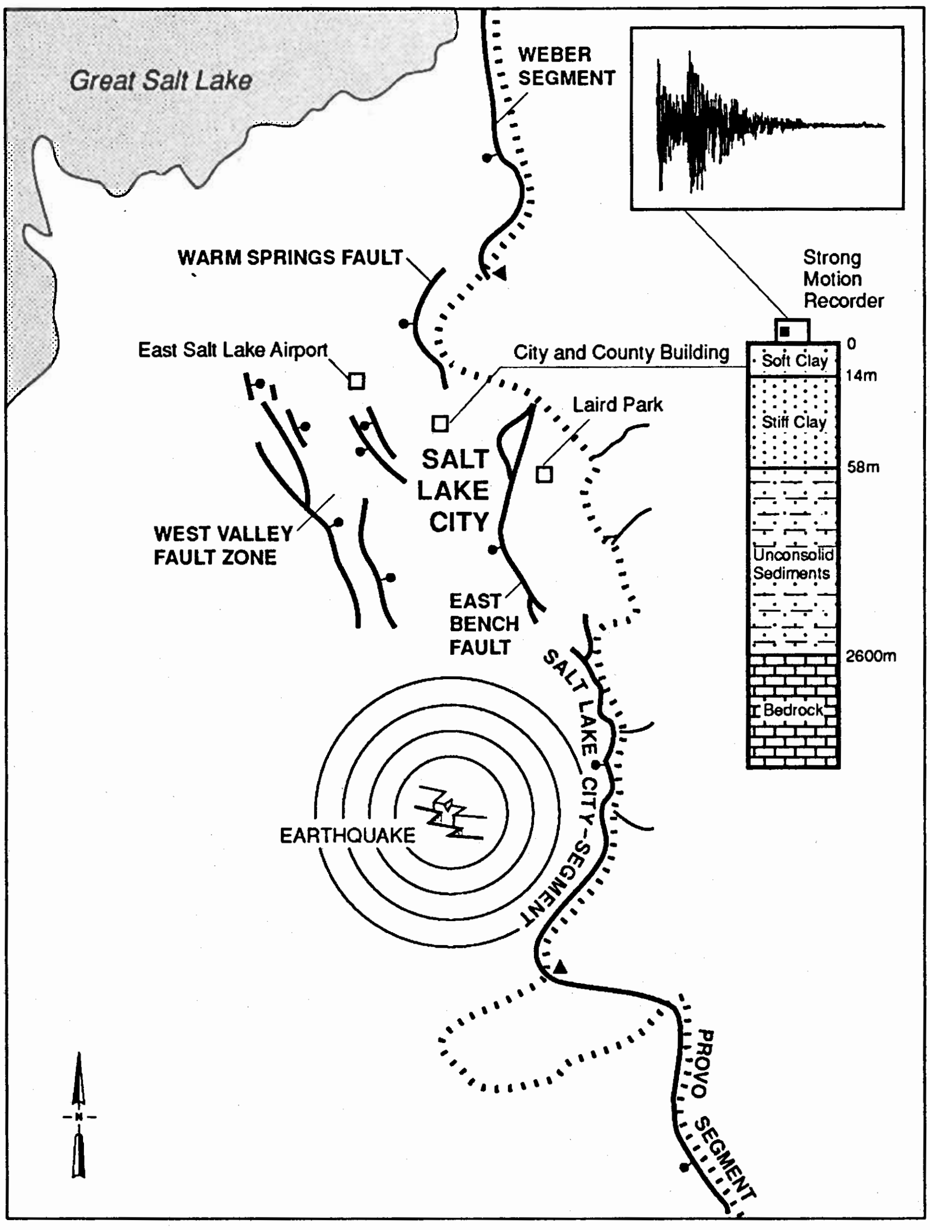
SITE-SPECIFIC STRONG GROUND MOTION ESTIMATES FOR THE SALT LAKE VALLEY, UTAH

by

Ivan G. Wong and Walter J. Silva



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ABSTRACT

The high level of seismic hazard in Salt Lake Valley from potential large earthquakes (surface wave magnitude [M_s] $\geq$ 7) on the Wasatch fault zone has long been recognized. Of obvious importance to hazard mitigation is the prediction of the near-field strong ground shaking that will be generated by such earthquakes. Estimates of strong ground motions in Salt Lake Valley that incorporate the site-specific effects of the shallow subsurface geology and details of the earthquake rupture process, however, have not been available to date. Such estimates are especially important because of the potentially significant effects on ground motions from the alluvial deposits which underlie most of Salt Lake Valley.

In this study, we have performed such a site-specific characterization of potential strong ground motions in the Salt Lake Valley based upon a methodology that combines aspects of finite earthquake source modeling with the Band-Limited-White-Noise ground motion model, random vibration theory and an equivalent-linear soil response approach. The objective was to assess the strong ground motions that could be generated assuming a moment magnitude (M_w) 7.0 earthquake occurring on the Salt Lake City segment of the Wasatch fault.

Strong ground motions were estimated for three sites located within the Salt Lake Valley. These sites were selected to represent the range of near-surface conditions in the valley based on the Uniform Building Code (UBC) soil classifications S_1, S_3 and S_4. Geologic and shear-wave velocity profiles were developed for each site based on borehole logs and shear-wave velocity measurements and other subsurface information. For the source, randomized slip models based on a modified version of the M_w 6.8 1983 Borah Peak, Idaho earthquake slip distribution were used in the finite fault modeling.

The site-specific acceleration response spectra were compared with and, in all cases, exceeded UBC seismic zone 3 and 4 spectra for each site. The peak horizontal accelerations were also generally higher than typical empirical median values. The effects of being located on the hanging wall versus the footwall of the fault, in the near-field of large slip areas (asperities) along the rupture plane, site amplification and possibly rupture directivity appear to be factors which will enhance strong ground shaking. For deep soft soil sites, soil damping is a controlling factor at high frequencies resulting in reduced but still very significant ground motions for locations near the Great Salt Lake.

ACKNOWLEDGMENTS

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INTRODUCTION

The 340-km-long north-trending Wasatch fault in northern and central Utah has been recognized since the late-1800's as the source of repeated large surface-faulting earthquakes. The location of the heavily populated Salt Lake Valley adjacent to the fault results in a high level of seismic hazard. The potential rupture of the Salt Lake City segment of the Wasatch fault immediately adjacent to the greatest concentration of population along the Wasatch Front could result in a significant loss of life and severe structural damage (Rogers et al., 1976).

Of obvious importance to Salt Lake Valley is the prediction of strong ground motions generated by a surface wave magnitude (M_s) ≥ 7 earthquake on the Salt Lake City segment of the Wasatch fault. In the past, empirical approaches based on recordings from outside Utah have been required to characterize strong ground shaking due to the absence of strong motion data for Salt Lake Valley (e.g., Campbell, 1987). Consequently, estimates of strong ground motions which incorporate the site-specific effects of the shallow subsurface geology in the Salt Lake Valley have not been available. Such information is important for seismic safety and design because of the heterogeneous nature of soils and sedimentary deposits beneath Salt Lake Valley and their long-recognized effect of influencing earthquake ground motions. Of additional concern are observations that in the near-field of moderate to large earthquakes, anomalously strong ground motions can result from the processes of coseismic rupture along the associated faults. Aspects of the earthquake source are thus also investigated in this study.

Objectives and Scope of Work

In this report, we describe and summarize the results of a site-specific engineering characterization of potential strong ground motions in the Salt Lake Valley. The purpose of this study was to assess the strong ground motions that could be generated assuming the occurrence of a moment magnitude (M_w) 7.0 earthquake on the Salt Lake City segment of the Wasatch fault. Our analysis is based on a methodology that combines aspects of finite earthquake source modeling with the Band-Limited-White-Noise (BLWN) ground motion model and random vibration theory (RVT). An equivalent-linear site response technique is also employed to accommodate nonlinear soil behavior.

Peak horizontal accelerations and acceleration response spectra have been computed for three sites located in the valley. These sites include: (1) a deep soft soil site located just east of the Salt Lake City airport (EAP); (2) the City and County Building site (CCH) in downtown Salt Lake City which is underlain by deep, fairly stiff soils; and (3) a relatively thin stiff soil site at Laird Park (LAI) (near 1800 E., 12th S.) on the east side of the city near the Wasatch Front. The three sites correspond to Uniform Building Code (UBC) soil types of S_4, S_3 and S_1, respectively. They are also located within a few kilometers of the Salt Lake City segment of the Wasatch fault as is much of Salt Lake City.

The specific tasks of this study were to:

- Develop slip distribution models for a potential M_w 7.0 earthquake occurring on the Salt Lake City segment of the Wasatch fault. The M_w 6.8 (M_s 7.3) 1983 Borah Peak, Idaho slip distribution model was assumed to be a reasonable analogue and was modified to provide a basis for developing the randomized slip distributions. These models, which statistically may be more meaningful, were used in the ground motion predictions.

- Develop geologic and shear-wave velocity profiles for each site based on available subsurface data including geotechnical borehole and geophysical data.

- Calculate peak horizontal accelerations and acceleration response spectra for each site employing the BLWN-RVT finite fault methodology and an equivalent-linear soil response approach.

- Compare the estimated site-specific ground motions with UBC seismic zone 3 and 4 response spectra.

The ground motions estimated in this study should be considered in the context of the uncertainties inherent in such efforts particularly given our significantly less than perfect knowledge of earthquake source, path, and geologic site parameters. Thus our estimates should not be used directly for any site-specific seismic design.

Previous Studies

The earliest studies of earthquake ground motions in the Salt Lake Valley involved the evaluations of site amplification due to near-surface sediments based on spectral ratios from records of distant explosions (Wong, 1979; Hays and King, 1984; King et al., 1987). Recent studies have concentrated on analyzing two- and three-dimensional basin effects using finite-element or finite-difference approaches (Benz and Smith, 1988; Murphy, 1989; Hill et al., 1990; Olsen and Schuster, 1992). Such effects will predominant at long-periods (greater than about 1.0 sec) which will be critical for tall or long structures. A probabilistic analysis of earthquake ground shaking along the Wasatch Front has also been performed (Youngs et al., 1987).

Two additional studies, although not directly applicable to the Salt Lake Valley, are relevant to strong ground motion assessments along the Wasatch Front. Wong et al. (1990) estimated site-specific strong ground motions at ten sites within 27 km of a M_w 6.8 Borah Peak-type earthquake occurring along the Howe segment of the Lemhi fault in southeastern Idaho. Finite fault modeling and the BLWN-RVT methodology were also used to compute acceleration response spectra for the same event (Silva et al., 1990). Computations were made at source-to-site distances of less than 10 km for three points of rupture initiation. These studies form the basis for the approach used in this study.

APPROACH

In the near-source region of large earthquakes, the effects of a finite source including rupture propagation, directivity, and source-site geometry can be quite significant and thus should be incorporated into strong ground motion predictions. We have utilized an approach which combines the modeling of a finite source rupture with the BLWN-RVT methodology.

The following is a detailed description of the Band-Limited-White-Noise ground motion methodology employed in this study. The relatively new earthquake source model, called the BLWN model, which is extremely simple in concept, combined with RVT is appropriate for an engineering characterization of ground motion since it captures the general features of strong ground motion with a minimum of free parameters. In applications to strong ground motion, the methodology has been especially effective in the frequency range of engineering interest, 1 to 35 Hz.

Band-Limited-White-Noise Point Source Model

The BLWN ground motion model first developed by Hanks and McGuire (1981) (sometimes referred to as the stochastic model), assumes a point source with energy distributed randomly over the duration of the source. The model has proven remarkably effective in modeling a wide range of ground motion observations. Time-domain measures such as peak accelerations and peak velocities, Wood-Anderson magnitudes, and short-period P- and S-wave amplitudes, as well as frequency domain measures such as relative velocity response and Fourier amplitude spectra, have been predicted with reasonable accuracy using the BLWN ground motion model (Hanks and McGuire, 1981; Boore, 1983, 1986; Boore and Atkinson, 1987; Silva and Lee, 1987; Toro and McGuire, 1987; Wong et al., 1991a; Silva et al., 1993). The ground motion model employed here uses a ω^{-2} Brune source model (Brune, 1970; 1971) with a single corner frequency and a constant-stress parameter (Boore, 1983; Atkinson, 1984) (Figure 1).

The acceleration spectral density a(f), where f is frequency, is given by

$$a(f) = C \frac{f^2}{1+(f/f_c)^2} \frac{M_0}{R} P(f)\ A(f)\ e^{-\frac{\pi f R}{\beta_0 Q(f)}} \tag{1}$$

where:

M_o = seismic moment
R = distance to the equivalent point source
β_o = shear-wave velocity at the source
Q(f) = $Q_0 f^{\eta}$, frequency dependent quality factor model where Q_0 and η are model parameters

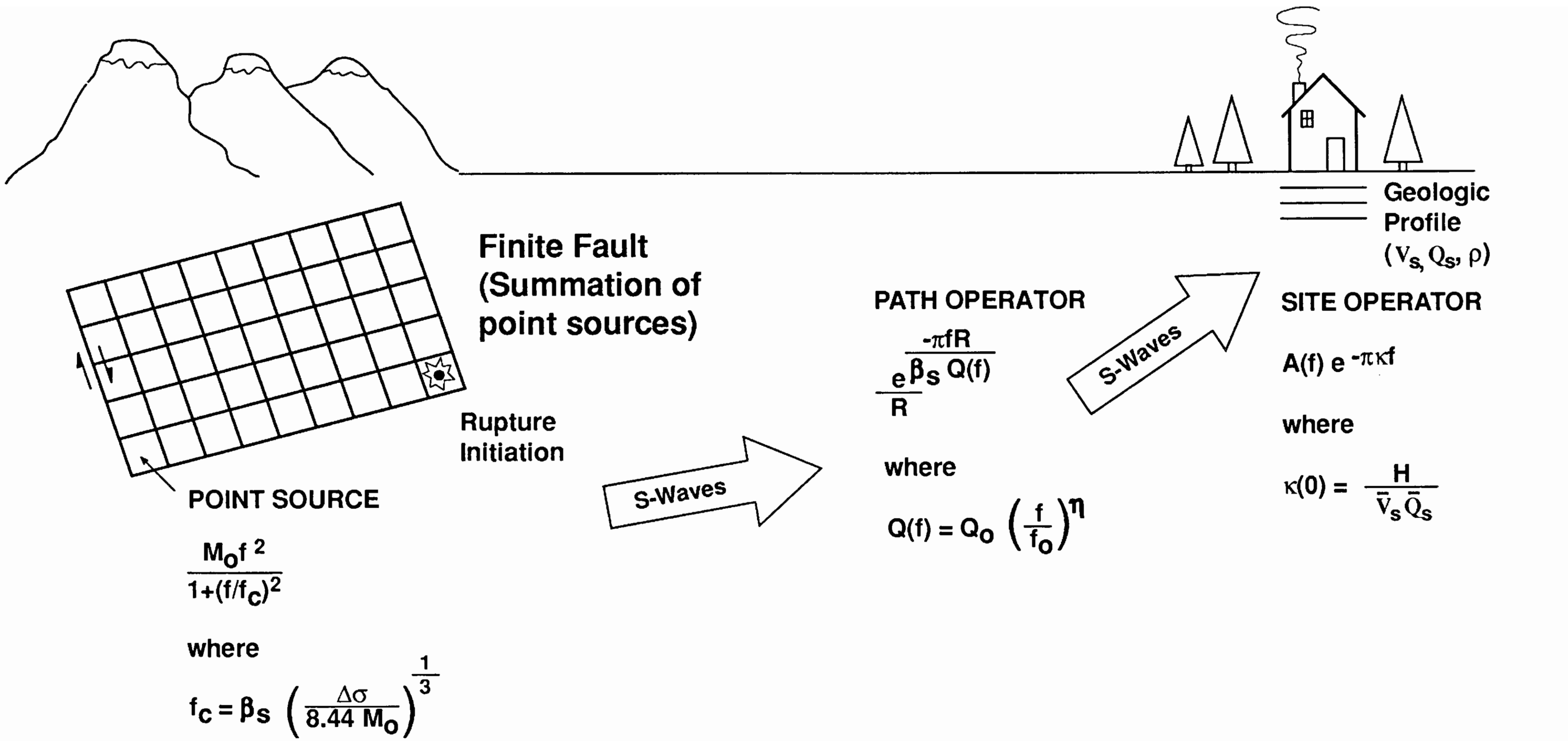

Figure 1. STOCHASTIC FINITE FAULT GROUND MOTION METHODOLOGY

$A(f)$	=	near-surface amplification factors
$P(f)$	=	high-frequency truncation filter
f_c	=	source corner frequency and
C	=	$(1/\rho_o\beta_o^3) \times (2) \times (0.55) \times (1/\sqrt{2}) \times \pi$.

C is a constant which contains source region density ρ_o and shear-wave velocity terms and accounts for the free-surface effect (factor of 2), the S-wave source radiation pattern averaged over a sphere (0.55) (Boore and Boatwright, 1984), and the partition of energy into two horizontal components ($1/\sqrt{2}$).

Source scaling is provided by specifying two independent parameters, M_o and the high-frequency stress parameter ($\Delta\sigma$). M_o is related to M_w through the relation

$$\log M_0 = 1.5\ M_w + 16.1 \qquad \text{(Hanks and Kanamori, 1979)} \qquad (2)$$

The stress parameter relates the corner frequency f_c to M_0 through the relation

$$f_c = \beta_o\ (\Delta\sigma/8.44\ M_o)^{1/3} \qquad \text{(Brune, 1970; 1971)} \qquad (3)$$

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

Random Vibration Theory

In order to compute peak time-domain values, i.e., peak acceleration, peak particle velocity, and peak oscillator response, RVT is used to relate rms calculations to peak value estimates (Boore, 1983; Boore and Joyner, 1984). The procedure, in general, involves computing the rms value by integrating the power spectrum from zero frequency to the Nyquist frequency and applying Parseval's relation. Extreme value theory is then used to estimate the expected ratio of the peak value to the rms value of a specified duration of the BLWN time history. The duration is generally taken as the inverse of the corner frequency (Boore, 1983).

Stress Drop

The stress parameter, for earthquakes which have a source spectrum consistent with a single-corner-frequency-ω^{-2} model, is the stress drop of the earthquake. In this case, the stress drop may be computed by determining M_0 and f_c and inverting Equation (3) and is generally referred to as the Brune stress drop. A convenient way of assessing the appropriateness of the BLWN source model used here is to compare stress drops using Equation (3), with the root-mean-square (rms) stress drops, both computed from data recorded in the region of interest (Stark et al., 1992).

The rms stress drop was introduced by Hanks (1979) and is defined as the stress drop required in the single-corner-frequency ω^{-2} Brune model to predict observed rms accelerations. If both the rms stress drops and the Brune stress drops are equivalent, then the observed source spectra are consistent with Equation (1).

Near-Surface Crustal Amplification and Damping

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 materials near the surface (Figure 1). These factors depend on average crustal and near-surface shear-wave velocity and density. In this study, amplification by near-surface velocity gradients is accounted for in the detailed velocity models.

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 portion of the spectrum and is responsible for the band-limited nature of the stochastic model. This spectral fall-off has been attributed to near-site attenuation (Hanks, 1982; Anderson and Hough, 1984) or to source processes (Papageorgiou and Aki, 1983) or perhaps to both effects. Hanks (1982) termed the phrase f_{max} to describe this site-dependent corner frequency. In the Anderson and Hough (1984) attenuation model, which is adopted in this study, the form of the P(f) filter is taken as

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

$\kappa(r)$ 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 (Figure 1). κ depends on 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

$$\kappa(0) = \frac{H}{V_s Q_s} \tag{5}$$

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) (Figure 1). Silva and Darragh (1990) suggest that the predominant kappa effects extend from the surface down to several hundred meters and possibly as deep as 1 to 2 km. The intrinsic attenuation along this part of the path is thought to be frequency-independent, but site-dependent (Hough et al., 1988). Kappa has been determined for several rock and soil sites representative of western North America (Anderson and Hough, 1984; Anderson, 1986). For an average western North American rock site, a value between 0.02 and 0.06 sec is appropriate (Boore, 1986; Silva and Darragh, 1990). The path attenuation from the source to just below the site is modeled with the frequency-dependent quality factor Q(f) (Figure 1).

The Fourier amplitude spectrum, a(f), models direct shear waves in a homogeneous half-space (with effects of a velocity gradient treated separately through the A(f) filter). For vertically inhomogeneous layered structures, the plane-wave propagators of Silva (1976) are used to propagate S_H motion through the layered structure.

Finite Source Model

A methodology that combines aspects of finite earthquake source modeling techniques (Hartzell, 1978; Irikura, 1983) with the BLWN-RVT ground motion model has been developed to produce response spectra as well as time histories appropriate for engineering design (Silva et al., 1990). This methodology has been used in this study (Figure 1).

The approach is very similar to the empirical Green's functions methodology introduced by Hartzell (1978) and Irikura (1983). In this case, however, the stochastic point source is substituted for the empirical Green's function and peak amplitudes. Peak accelerations, peak velocities, and response spectra (when time histories are not produced) are estimated using RVT. Use of the stochastic point source as a Green's function is motivated by its demonstrated success in modeling ground motions in general and particularly strong ground motions (Boore, 1983, 1986; Silva and Stark, 1992) and the desire to have a model that is truly site- and region-specific. The model can accommodate a region-specific Q(f), Green's function sources of arbitrary moment or stress drop, and site-specific kappa values. The necessity of regional and site-specific recordings or the modification of possibly inappropriate empirical Green's functions is eliminated.

For the finite-source characterization, a rectangular fault is discretized into NS subfaults where NS is the number of subfaults of moment M_0^s. The empirical relationship

$$M_w = 4.02 + \log A \quad \text{(Wells and Coppersmith, 1993)} \qquad (6)$$

where A is the rupture area in km^2 is used to assign areas to both the target earthquake (if its rupture surface is not fixed) as well as to the subfaults. The sub-event magnitude M^s is generally taken in the range of M_w 5.0 to 6.5 depending upon the size of the target event. The value of NS is determined as the ratio of the target event area to the subfault area. To constrain the proper seismic moment, the total number of events summed (N) is given by the ratio of the target event moment to the sub-event moment. The sub-event rise time is determined by the equation

$$\log \tau_s = 0.33 \log M_0^s - 8.62 \qquad (7)$$

which results from a fit to the M_0 - rise time data given in Heaton (1990). Slip on each subfault continues for a time τ_s multiplied by N/NS which is the modeled or target event rise time. Heterogeneity of the earthquake source process is modeled by randomizing the location of the sub-events within each subfault (Hartzell, 1978) as well as the sub-event rise time. The stress drop of the stochastic point-source Green's function is taken as

$$\Delta\sigma = \frac{7}{16}\left(\frac{M_e}{R_e^3}\right) \qquad (8)$$

where R_e is the equivalent circular radius of the rectangular sub-event.

Different values of slip are assigned to each subfault as relative weights so that asperities or non-uniform slip can be incorporated into the methodology. The rupture velocity is taken as depth independent at a value of 0.8 times the shear-wave velocity generally at the half-depth of the slip surface. The rupture velocity is randomized within the range of $\pm$ 20%. The radiation pattern is computed for each subfault, a random component added, and the RMS of the radiation pattern is applied to the motions computed at the site.

The ground motion time history at the receiver is computed by summing the contributions from each subfault associated with the closest Green's function, transforming to the frequency domain, and convolving with the Green's function spectrum (Equation 1). The locations of the Green's functions are generally taken at the center of each subfault for small subfaults or at a maximum separation of about 5 to 10 km for large subfaults. As a final step, the individual contributions associated with each Green's function are summed in the frequency domain multiplied by the RMS radiation pattern, and the resultant power spectrum at the site is computed. The appropriate duration used in the RVT computations for peak acceleration and oscillator response is computed by transforming the summed Fourier spectrum into the time domain and computing the 5 to 75%s Arias intensity (Ou and Herrmann, 1990).

As with the point-source model, crustal response effects are accommodated through the amplification factor (A[f]) or by using vertically propagating shear waves through a vertically heterogenous crustal structure. Propagation path damping, through the Q(f) model, is incorporated from each fault element to the site. Near-surface crustal damping is incorporated through the kappa operator (Equation 1). To model crustal propagation path effects, the method of Ou and Herrmann (1990) can be applied from each subfault to the site.

For fixed fault size, mechanism, and moment, the specific source parameters for the finite fault are slip distribution, location of nucleation point, and site azimuth. Variability in these parameters may be thought of as replacing the variability in stress drop associated with the point source model. The propagation path and site parameters remain identical for both source models.

Equivalent-Linear Approach for Soil Response

It is well known from laboratory testing that soils exhibit pronounced nonlinear behavior under shear loading conditions. Shear modulus decreases with increasing strain with an accompanying increase in material damping (Seed and Idriss, 1970). If this observation is applicable to in-situ soil properties subject to earthquake loading, then site-response calculations must accommodate these strain dependencies as material nonlinearities.

In general, strain dependence of moduli and damping would result in a nonlinear wave equation with the full finite-strain terms. In this case, superposition is invalid, the wave equation does not separate into P, SV, and SH fields, and Fourier analysis cannot be applied. The approach generally adopted is to assume infinitesimal displacements, utilize a linear wave equation, and confine the nonlinearity to the constitutive relation.

If a nonlinear constitutive relation is utilized, then velocities and damping become strain dependent. This can result in a wavefield and site response that depart significantly from linear one-dimensional theory. For high levels of ground motion, strain-dependent velocities would generally result in longer characteristic site periods. Strain-dependent damping would generally reduce overall response at high strain levels. Depending upon site structure and input motion, these effects could be very large.

Departures of soil response from a linear constitutive relation may be treated in an approximate manner through the use of the equivalent linear approach introduced by Seed and Idriss (1970). Basically, the approach is to approximate a second-order nonlinear equation, over a limited range of its variables, by a linear equation. Formally this is done in such a way that an average of the difference between the two systems is minimized. This is done in an ad hoc manner for ground response modeling by defining an effective strain which is assumed to exist for the duration of the excitation. This value is usually taken as 65 percent of the peak time-domain strain calculated at the midpoint of each layer, using a linear analysis. Moduli and damping curves are then used to define new parameters for each layer. The linear response calculation is repeated, new effective strains evaluated, and iterations performed until the changes in parameters are below some tolerance level. Generally, a few iterations are sufficient to achieve a strain-compatible linear solution. This stepwise analysis procedure was formalized into a one-dimensional, vertically propagating shear-wave code called SHAKE (Schnabel et al., 1972). Subsequently, this code has become the most widely used analysis package for one-dimensional site response calculations. While the assumptions of vertically propagating shear-waves and equivalent-linear soil response certainly represent approximations to actual conditions, their combination has achieved demonstrated success in modeling observations of site effects (Schnabel et al., 1972; Silva et al., 1987).

The computational scheme incorporated in the BLWN-RVT code to estimate the site response uses the BLWN model to generate the power spectral density and spectral acceleration of the rock or input motion. This motion or power spectrum is then propagated through the one-dimensional soil profile using the plane-wave propagators of Silva (1976). In order to treat possible material nonlinearities, the equivalent-linear formulation is employed. 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 program SHAKE except that peak shear strains in SHAKE are measured in the time domain. The purely frequency-domain approach obviates a time-domain control motion and, perhaps just as significant, eliminates the need for a suite of analyses based on different input motions. This arises because each time domain analysis may be viewed as a simulation of a random process. Therefore, several simulations of the random process must be sampled to have a statistically stable estimate of site response. The simulations are usually performed by employing different control motions with approximately the same level of peak acceleration.

In the case of the frequency-domain approach, the estimates of peak shear strain as well as oscillator response are, as a result of the RVT, fundamentally probabilistic in nature. The procedure of generating the BLWN power spectrum, computing the equivalent-linear layered-soil response, and estimating peak time domain values has been validated by comparison with SHAKE (Toro et al., 1988).

INPUT PARAMETERS

The strongest ground motions which will occur in the Salt Lake Valley will probably be generated by a future large earthquake rupturing the Salt Lake City segment of the Wasatch fault. The following describes the source, propagation path, and site parameters used in this study (Table 1).

Earthquake Sources

The 35-km-long Salt Lake City segment is a moderately westward-dipping normal fault (Figure 2) that exhibits abundant geologic evidence for repeated episodes of surface-faulting throughout late-Quaternary and Holocene times (Swan et al., 1980; Schwartz and Coppersmith, 1984; Lund, 1988; Machette et al., 1991). Based on empirical relationships between magnitude and potential rupture length or rupture area, the Salt Lake City segment appears to be capable of generating an earthquake of M_s 7.0 to 7.7 (Arabasz et al., 1987; Youngs et al., 1987; Machette et al., 1991).

Bruhn et al. (1987) have suggested that the 1983 Borah Peak earthquake represents a reasonable analogue for a future event on the Salt Lake City segment; hence, in this analyses we used a variation of the Borah Peak slip distribution developed by Mendoza and Hartzell (1988). It is important to note that we are approximating this segment of the Wasatch fault, which exhibits a curvilinear fault trace, with a planar rupture model. Whether the resulting deviations are significant in terms of ground motions, we cannot answer at this time.

The Mendoza and Hartzell rupture model was reduced in length from 52 km to 35 km by removing the northern 17 km (Figure 3) to be generally consistent with the length of the Salt Lake City segment (Figure 2). Although estimates of fault dip range from 45° to 72° at the surface for the Salt Lake City segment (Bruhn et al., 1987), an average dip of 50° was assumed. The width was 22.6 km. The resulting rupture area (791 km^2) is consistent with a M_w 7 earthquake based on the relationship for rupture area (Wells and Coppersmith, 1993).

TABLE 1

INPUT PARAMETERS

Source Parameters	
Magnitude	M_w 7.0
Rupture Plane	35 km x 22.6 km
Slip Distribution	Randomized Models
Propagation Path Parameters	
Shear-Wave Velocity	3.5 km/sec
Density	2.75 g/cm^3
Q(f)	500f$^{0.2}$
Site Parameters	
Shear-Wave Velocities	Tinsley et al. (1991)
Kappa	0.04 sec
Modulus reduction and Damping	See Figure 6

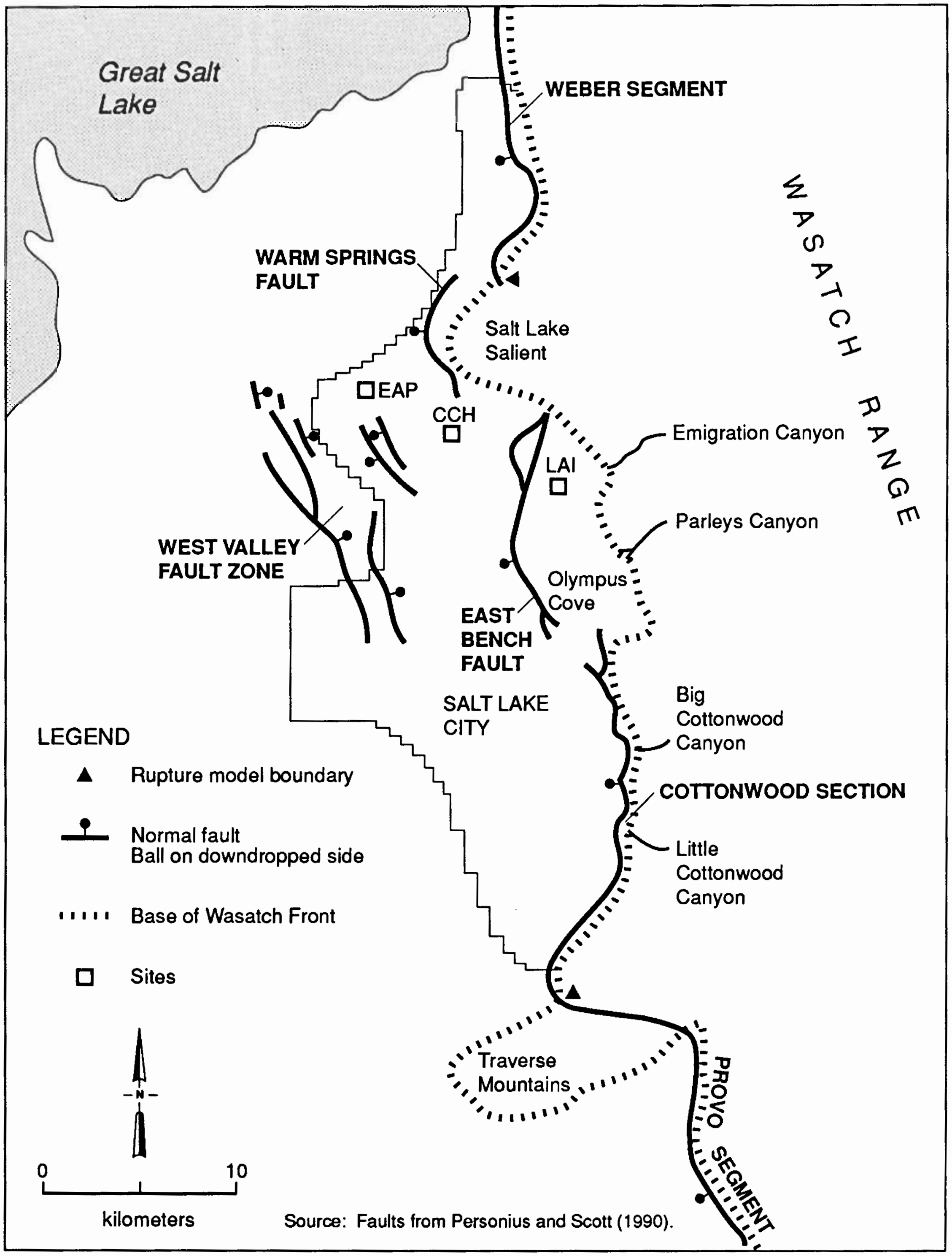

Figure 2. SALT LAKE CITY SEGMENT OF THE WASATCH FAULT AND SITES EVALUATED IN THIS STUDY

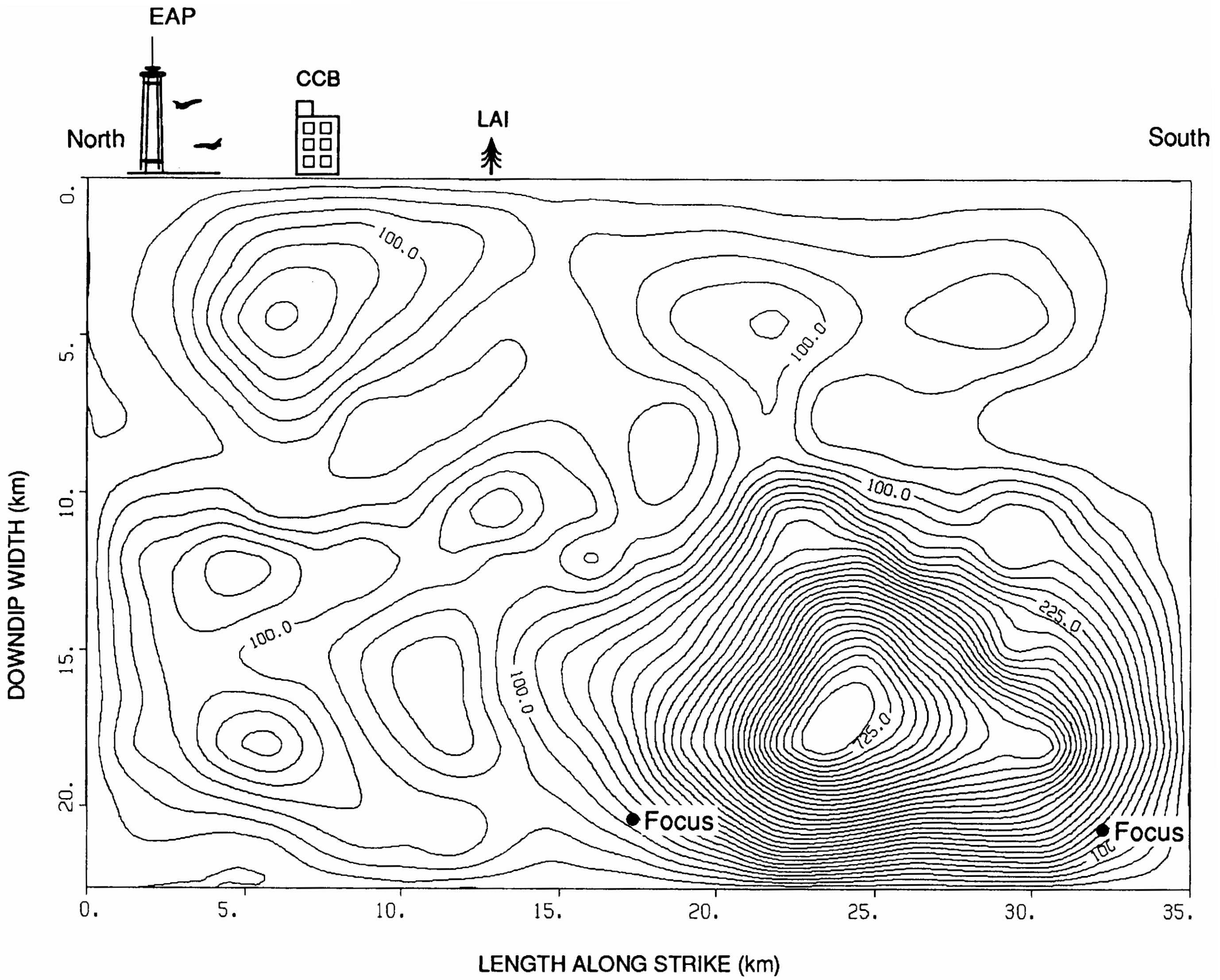

Figure 3. SLIP DISTRIBUTION (IN CM) USED IN THIS STUDY MODIFIED FROM THE 1983 M_W 6.8 BORAH PEAK EARTHQUAKE

Based on this rupture area and the seismic moment for a M_w 7.0 event (4×10^{26} dyne-cm), the static stress drop was computed to be 19 bars using Starr's formula consistent with the 12 and 17 bars estimated by Doser and Smith (1985) and the 25 bars calculated by Mendoza and Hartzell (1988) for the Borah Peak earthquake. The amount of slip for the reduced rupture area was scaled upwards to an equivalent M_w 7.0 earthquake. Consistent with Mendoza and Hartzell (1988), the top of the slip model was placed at a depth of 1 km. This placement is consistent with the assumption that negligible fault slip occurs in the near-surface.

We realize that deviations, possibly significant ones, will exist between the modified Borah Peak model and the actual distribution of slip on the potential rupture plane of the Salt Lake City segment. Also in practical terms, an *a priori* detailed knowledge of the actual slip distribution of an impending fault rupture will probably not be available for strong motion predictions. Thus randomized slip distribution models were used in the finite fault modeling. Figure 4 shows a sample of randomized models which have been normalized to their maximum slip value. To generate these randomized slip models, the two-dimensional wavenumber spectrum of the modified Borah Peak slip model was computed and its phase randomized. Large slips near the edges of the rupture plane were suppressed by applying a cosine taper. The randomized slip distributions appear to be physically reasonable based on the limited number of slip models derived from actual earthquakes (Figure 4).

Points of rupture initiation were varied for each site. Foci were randomized within a rectangular area between the depths of 14 to 17 km and for an along strike distance of 5 km centered in the middle and at the southern end of the rupture plane (Figure 3). Foci were also randomized along a zone between the depths of 14 to 17 km extending the full length of the rupture plane. In the Borah Peak earthquake, the hypocenter was located at a depth of 16 km in the southern corner of the fault and the rupture appears to have proceeded unilaterally to the northwest (Doser and Smith, 1985; Richins et al., 1987). Based on structural analysis, Bruhn et al. (1987) have suggested that past earthquakes along the Salt Lake City segment also initiated at the southern end of the rupture at or adjacent to the Traverse Mountains segment boundary (Figure 2) with rupture propagating unilaterally to the north. An alternative possibility is that rupture may begin in the central portion of the Salt Lake City segment, possibly near the southern end of Olympus Cove where the fault bifurcates (Bruhn et al., 1987) (Figure 2). Such a scenario would result in a bilateral rupture.

Propagation Paths

For the propagation path, a half-space model characterized by a shear wave velocity (β_s) of 3.5 km/sec and a density (ρ) of 2.75 g/cm^3 was assumed based on Hill et al. (1990). Based on an analysis of Lg waves, Singh and Herrmann (1983) determined a crustal coda Q_o of 500 and a η of 0.2 for the Utah region to describe the frequency-dependent attenuation Q(f) (Figure 1). The effects of seismic attenuation on ground motions are, however, not expected to be significant for an earthquake on the Salt Lake City segment because the sites and most of Salt Lake Valley are at near-field distances.

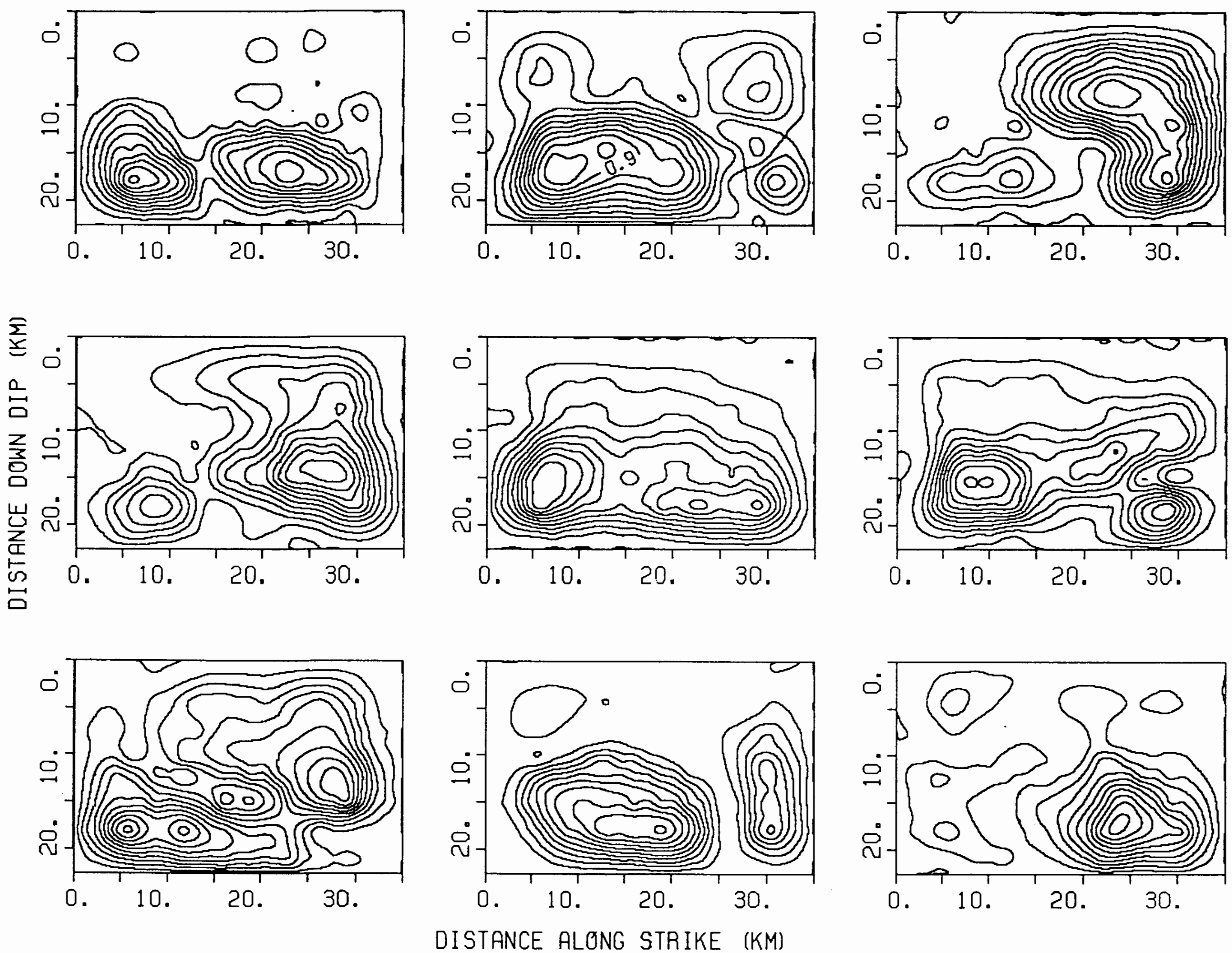

Figure 4. SAMPLE OF NORMALIZED RANDOMIZED SLIP MODELS

Sites

Salt Lake City is located in the alluvial-filled basin which forms the Salt Lake Valley. Based on borehole logs and *in situ* shear-wave velocities collected by the USGS (Tinsley et al., 1991) and generalized velocity models of the valley proposed by Murphy (1989) and Hill et al. (1990), first-order geologic profiles were developed for each of the sites (Figure 5). Two site parameters need to be specified as a function of depth in the BLWN-RVT approach: the shear wave velocity (V_s) and density (ρ). A κ of 0.04 sec, typical of western U.S. rock sites (Silva and Darragh, 1990), was assumed for the rock beneath all sites.

Shear modulus reduction and damping curves appropriate for cohesive soils were used to characterize the response of the soils as a function of strain in the geologic profiles. Specifically, the curves of Vucetic and Dobry (1991) were used for the clays, Seed and Idriss (1982) for gravels, and recently developed Electric Power Research Institute (EPRI) curves for the sands and sediments. We consider these curves, which are shown in Figure 6, to be the most up-to-date and best available relationships for these types of materials.

Based on the 1988 UBC classification, EAP is characterized as an S_4 (more than 40 feet [12 m] of soft clay) or a marginal S_3 site. CCH, also a deep soil site like EAP, is classified as a S_3 site because the underlying clays are relatively stiff with less than 40 feet (12 m) of them soft. LAI, with about 8 m of sand and gravel over a "rock-like" sedimentary layer, is classified as a S_1 site. Note, however, the stiff albeit unconsolidated layer at a depth of 18 to 24 m (Figure 5) which effectively is a low-velocity layer within the shear-wave velocity profile. Such site-specific characteristics can be very significant in influencing ground shaking at a site. Both EAP and CCH are west of the fault on the downthrown block and LAI is located to the east on the upthrown block (Figure 2). The source-to-site distances for the three sites, EAP, CCH, and LAI are 3.3 km, 1.5 km, and 2.8 km, respectively. For LAI, the source-to-site distance extends not to the surface trace of the fault but to a depth of 1 km consistent with the placement of the rupture model.

RESULTS AND DISCUSSION

Based on the approach previously described, site-specific 5% damped acceleration response spectra were computed for each site at the ground surface and at the base of the soil and unconsolidated sediments (top of rock where it is defined as having a $V_s > 750$ m/sec) (Figures 7 to 9). Figure 7 shows the spectra based upon 50 randomized slip distribution models for each focus. Site-specific spectra computed from a single slip model similar to the modified Borah Peak model and assuming rupture initiations at the middle and southern foci are shown in Figure 8. Figure 9 shows the median spectra assuming randomized foci and randomized slip models compared to the UBC seismic zone 3 and 4 spectra according to the soil classification for each site. (The UBC does not specify a spectrum for S_4 sites). Table 2 lists the computed median peak horizontal accelerations for the randomized slip models and Table 3 for the single slip model. Listed in Table 4 are peak horizontal accelerations computed from several widely used empirical attenuation relationships appropriate for soil.

TABLE 2

STOCHASTIC SITE-SPECIFIC PEAK HORIZONTAL ACCELERATIONS USING RANDOMIZED SLIP DISTRIBUTIONS

		Horizontal Distance (km)	Along Strike Distance (km)	Rupture Distance (km)	Southern Focus (g)	Middle Focus (g)	Randomized Foci (g)
CCH	Rock	1.9	9	1.5	1.00	1.05	1.00
	Soil				0.60	0.62	0.61
EAP	Rock	4.3	4	3.3	1.01	1.00	0.99
	Soil				0.69	0.71	0.73
LAI	Rock	1.8	11	2.8	0.70	0.75	0.71
	Soil				1.07	1.11	1.07

TABLE 3

STOCHASTIC SITE-SPECIFIC PEAK HORIZONTAL ACCELERATIONS USING SINGLE SLIP MODEL

		Horizontal Distance (km)	Along Strike Distance (km)	Rupture Distance (km)	Southern Focus (g)	Middle Focus (g)
CCH	Rock	1.9	9	1.5	1.27	1.14
	Soil				0.70	0.70
EAP	Rock	4.3	4	3.3	1.24	1.02
	Soil				0.70	0.67
LAI	Rock	1.8	11	2.8	1.03	0.98
	Soil				1.34	1.35

TABLE 4

ESTIMATED MEDIAN EMPIRICAL PEAK HORIZONTAL ACCELERATIONS ON SOIL

Fault	Fault Type	Magnitude (M_w)	Horizontal Distance[3] (km)	Seismogenic Distance[4] (km)	Rupture Distance[5] (km)	Joyner & Boore (1988) (g)	Campbell (1990) (g)	Tsai et al. (1990) (g)	Idriss (1991) (g)	Average (g)
CCH[1]	N[6]	7.0	0.0	2.0	1.5	0.54	0.61	0.50	0.51	0.54
EAP[1]	N	7.0	0.0	2.0	3.3	0.54	0.61	0.45	0.46	0.52
LAI[2]	N	7.0	1.8	4.0	1.8	0.53	0.52	0.49	0.63	0.54

[1]Deep Soil Relationships Used
[2]Stiff Soil Relationships Used
[3]Used in Joyner and Boore (1988)
[4]Used in Campbell (1990). Assumed the top of seismogenic rupture is at depth of 2 km.
[5]Used in Tsai et al. (1990) and Idriss (1991)
[6]Normal fault

Salt Lake City Airport East (EAP)

DEPTH (m)	LITHOLOGY	Vs (m/sec)	ρ (g/cm^3)
→	Soft Clay	129	1.78
8.0	Soft Clay	175	1.78
14.0	Stiff Clay	223	2.00
22.0	Stiff Clay	223	2.00
34.0	Stiff Clay	304	2.00
52.0	Stiff Clay	571	2.00
58.0*	Unconsolidated Sediments	620	2.10
200	Unconsolidated Sediments	668	2.10
400	Unconsolidated Sediments	820	2.15
590	Semi-Consolidated Sediments	1310	2.20
1050	Consolidated Sediments	2890	2.65
2600	Bedrock	3460	2.75

Laird Park (LAI)

DEPTH (m)	LITHOLOGY	Vs (m/sec)	ρ (g/cm^3)
	Interbedded Sand and Gravel	336	2.00
8	Tufa - Cemented Gravel	944	2.15
18	Stiff Clay, Sand or Gravel	536	2.00
24	Semi-Consolidated Sediments	992	2.15
28	Semi-Consolidated Sediments	1634	2.30
56	Semi-Consolidated Sediments	1750	2.30
59*	Weathered Limestone	2600	2.50
70	Limestone	3000	2.75

City and County Building (CCH)

DEPTH (m)	LITHOLOGY	Vs (m/sec)	ρ (g/cm^3)
	Clay	242	2.00
28	Clay with some Gravel	384	2.00
68*	Stiff Clay	820	2.15
83	Semi-Consolidated Sediments	1310	2.20
270	Shale	3000	2.75

* Bottom of borehole
--- Proposed layer boundaries
→ Top of water table

Figure 5. GEOLOGIC AND SHEAR-WAVE VELOCITY PROFILES

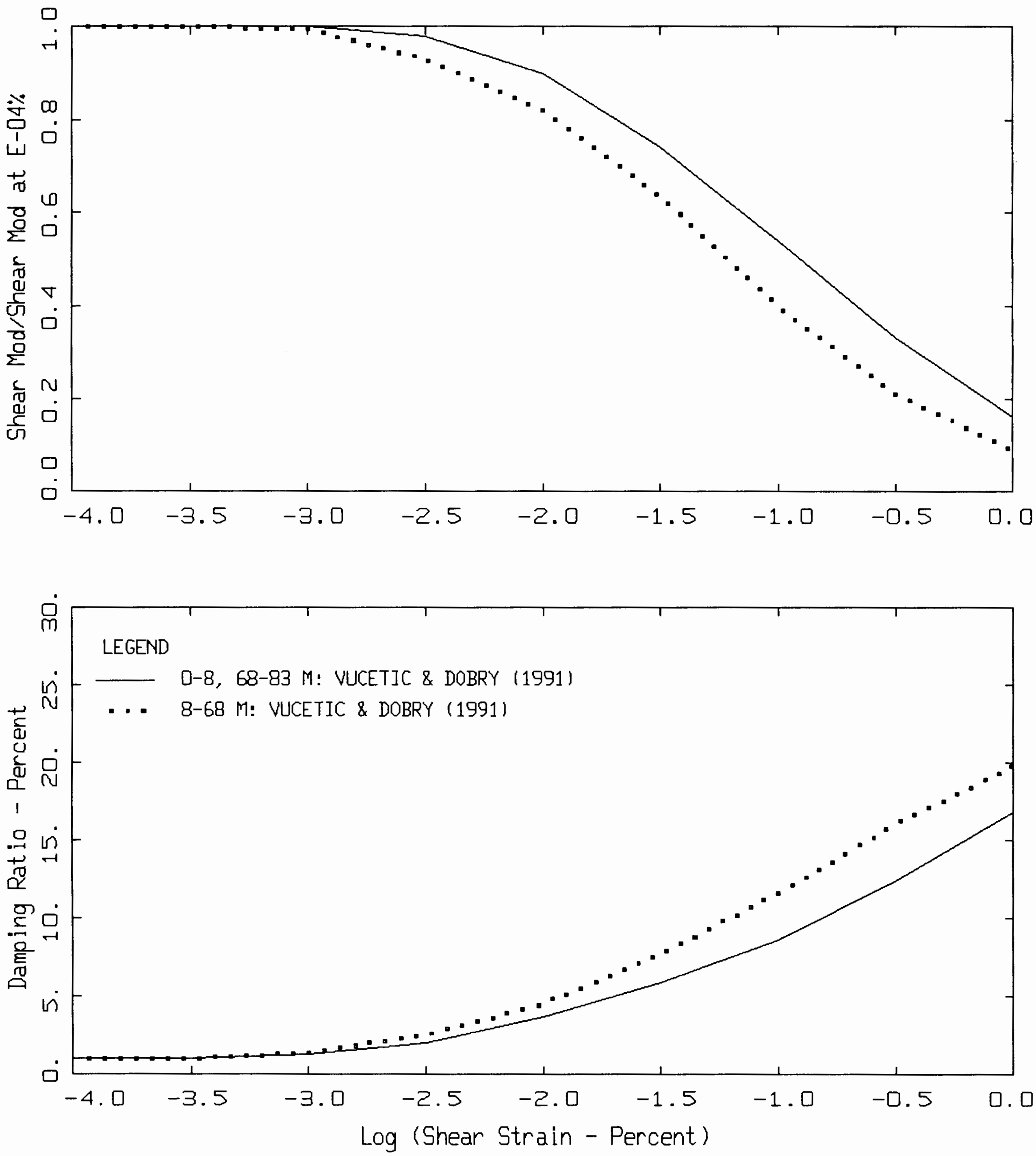

Figure 6a. SHEAR MODULUS REDUCTION AND DAMPING CURVES FOR CCH

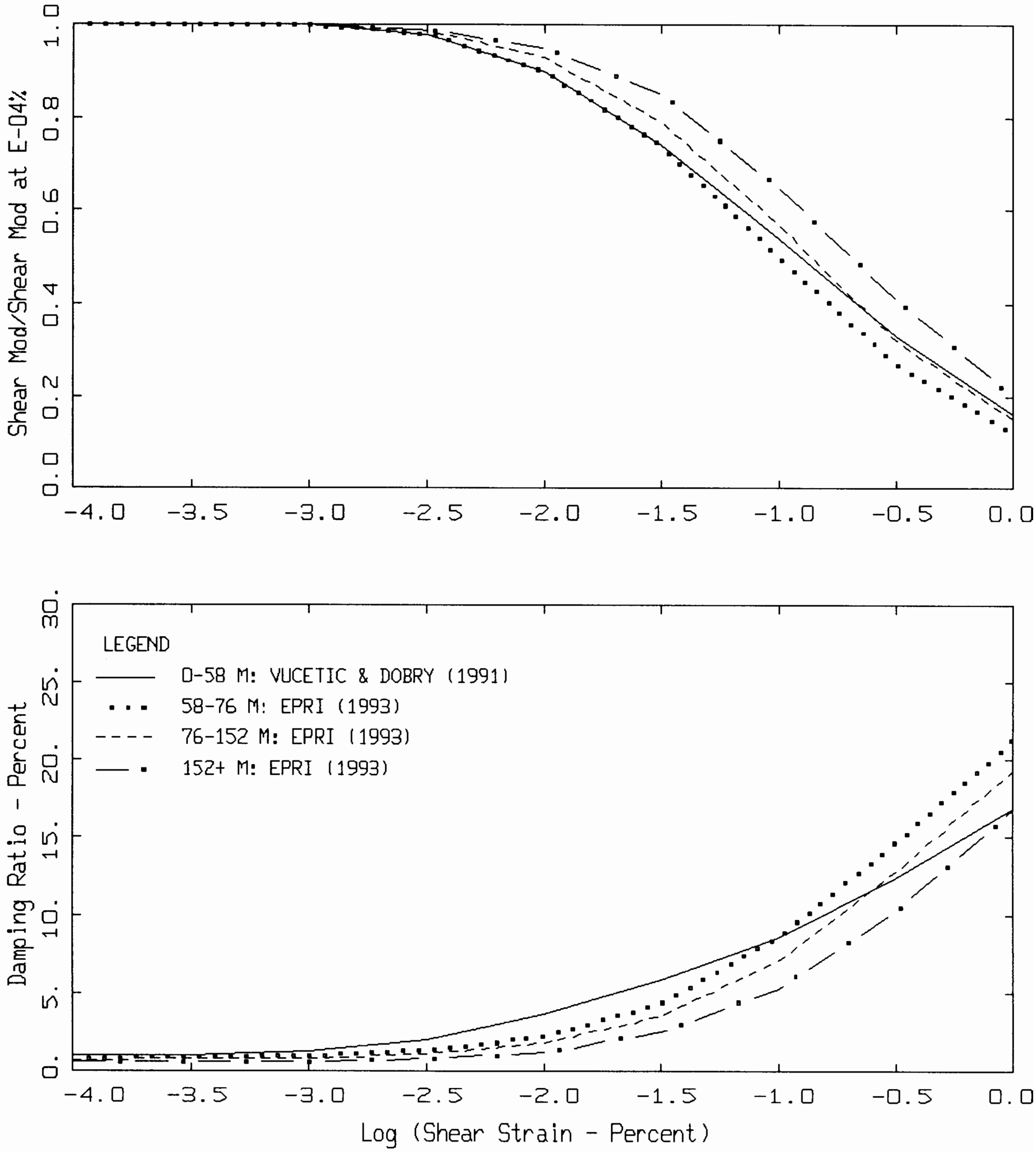

Figure 6b. SHEAR MODULUS REDUCTION AND DAMPING CURVES FOR EAP

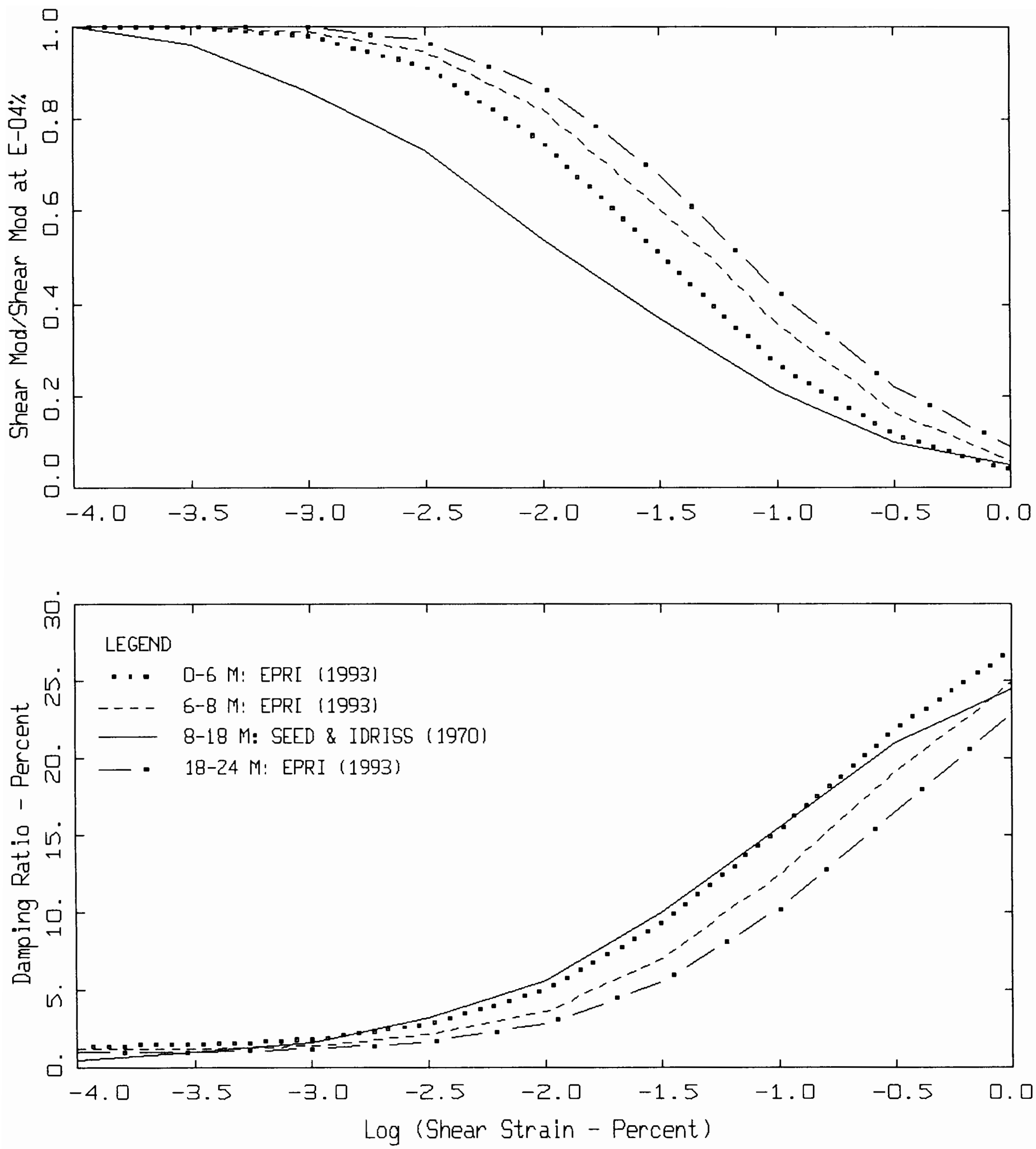

Figure 6c. SHEAR MODULUS REDUCTION AND DAMPING CURVES FOR LAI

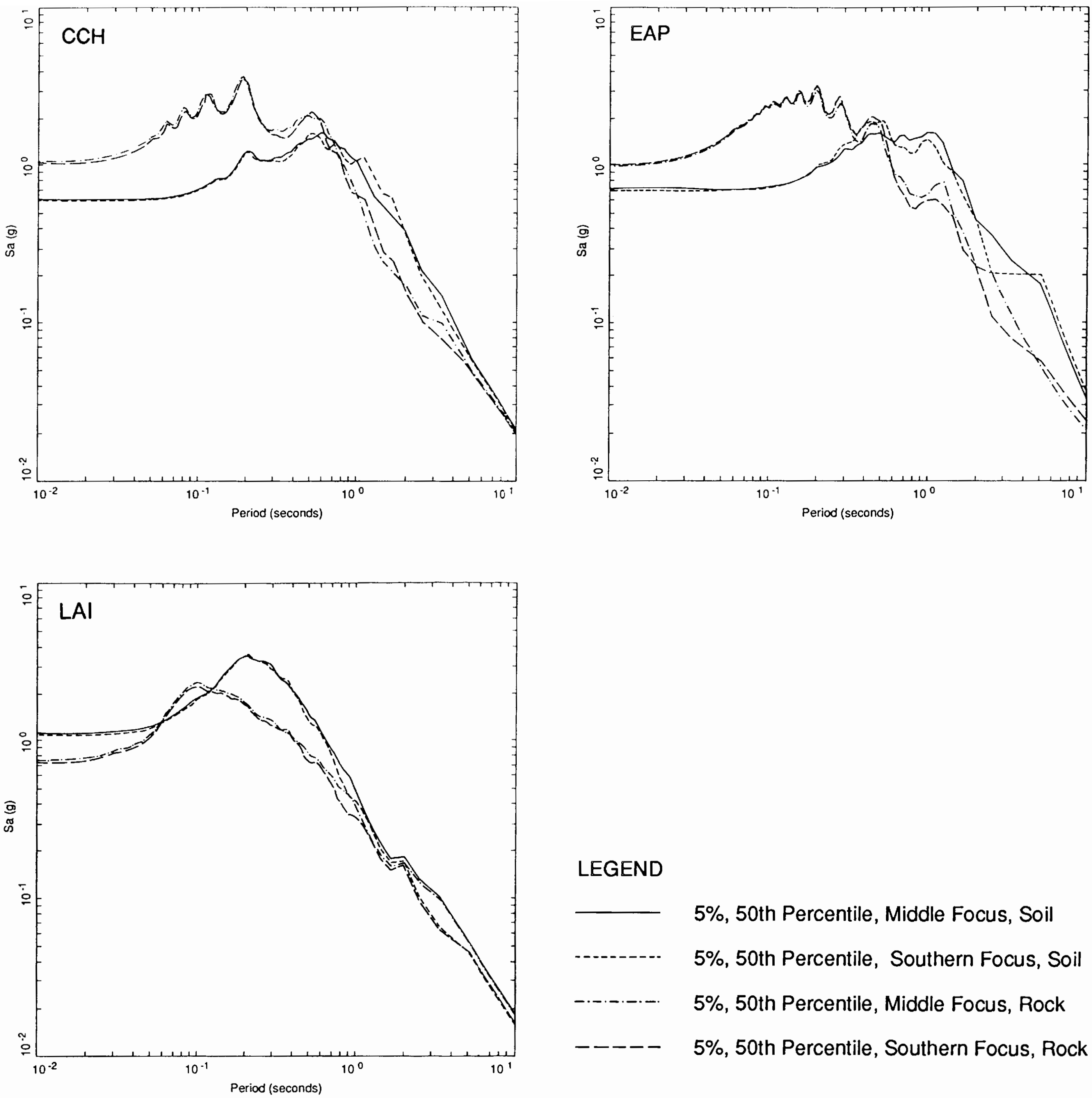

Figure 7. SOIL AND ROCK ACCELERATION RESPONSE SPECTRA USING RANDOMIZED SLIP MODELS, MIDDLE AND SOUTHERN FOCI

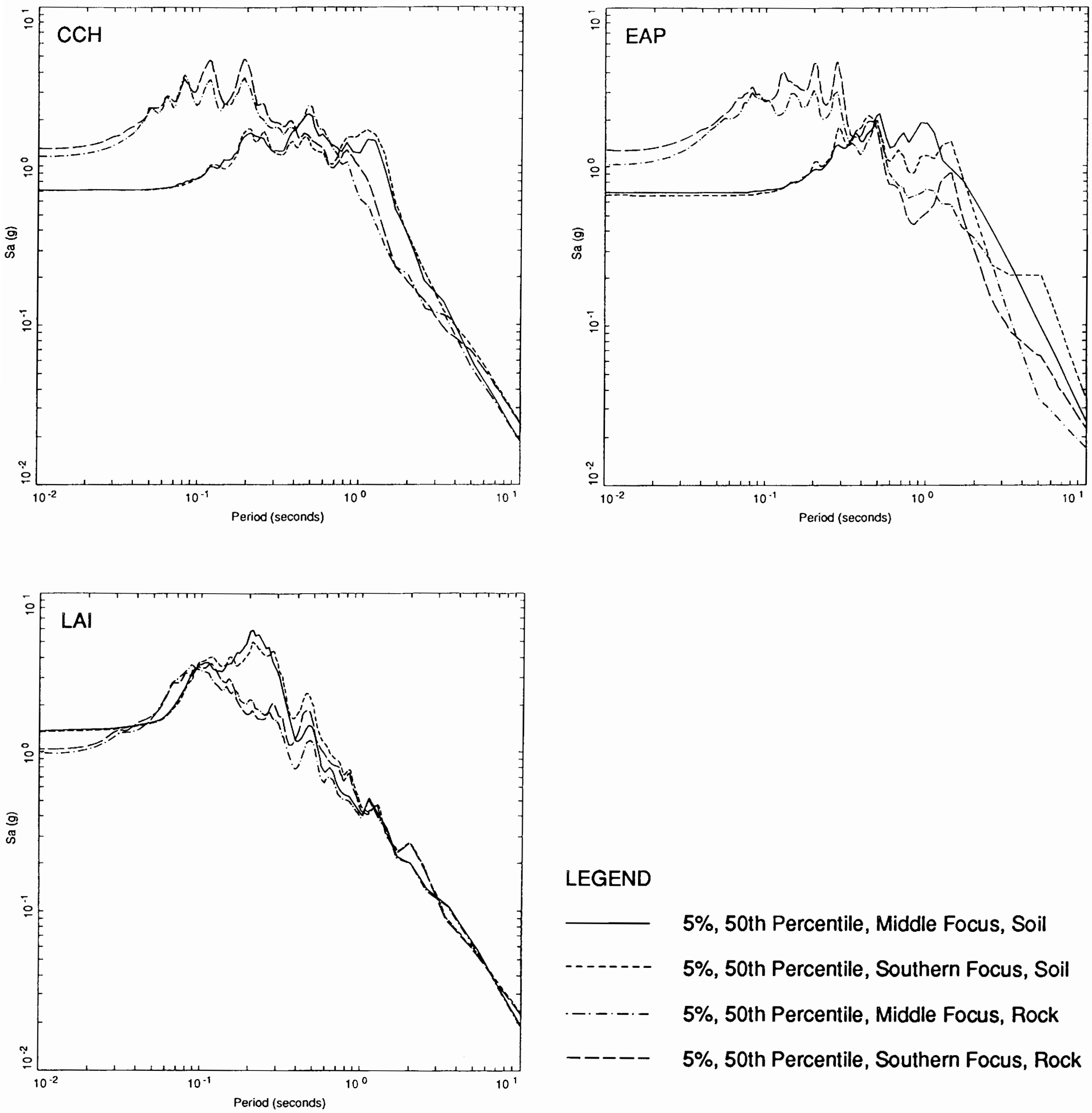

Figure 8. SOIL AND ROCK ACCELERATION RESPONSE SPECTRA USING A SINGLE SLIP DISTRIBUTION, MIDDLE AND SOUTHERN FOCI

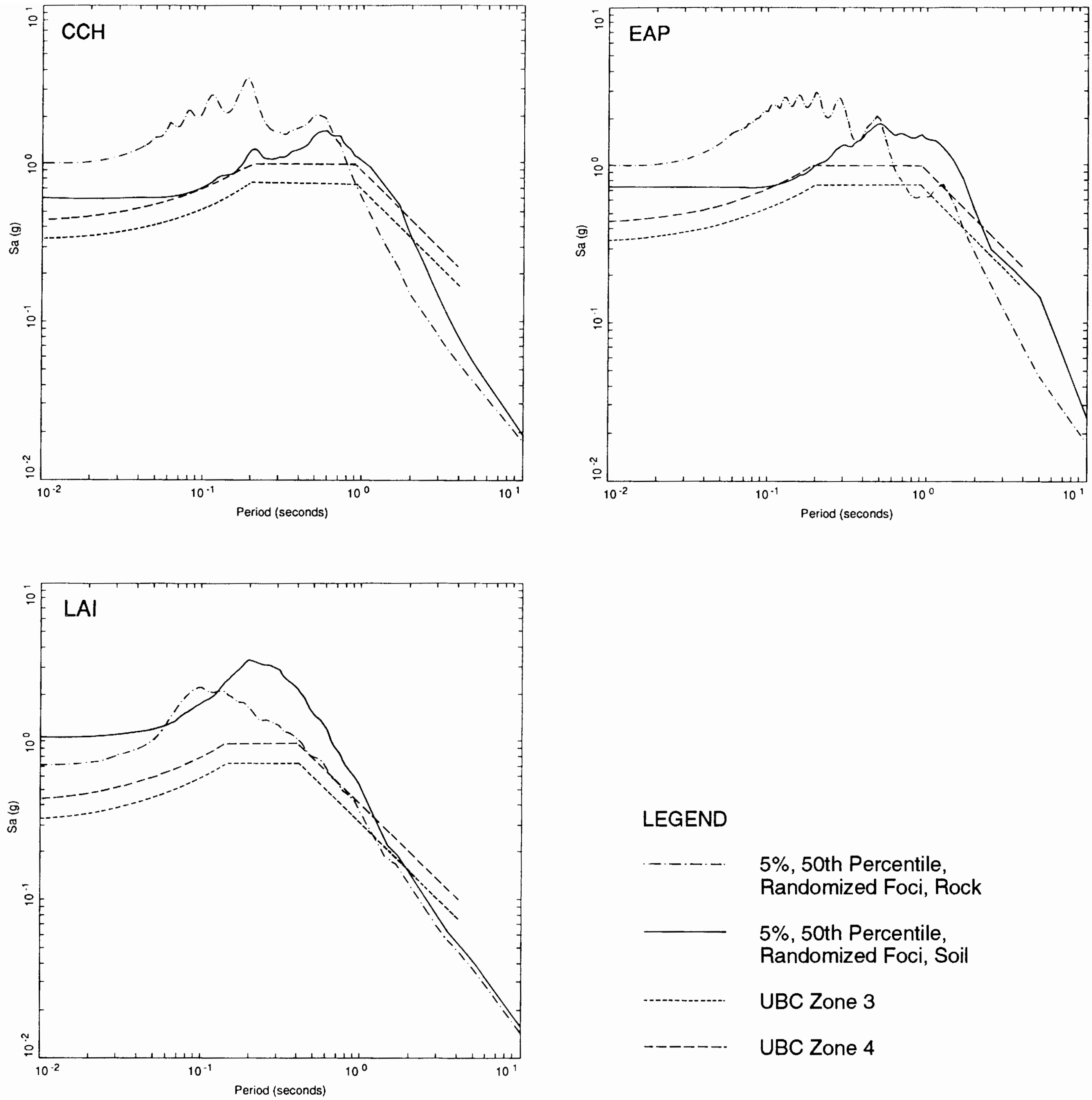

Figure 9. SOIL AND ROCK ACCELERATION RESPONSE SPECTRA USING RANDOMIZED SLIP MODELS, RANDOMIZED FOCI VERSUS UBC SPECTRA

These values will be used in comparison with the site-specific stochastic estimates determined in this study.

City and County Building

Examination of the acceleration response spectra employing the randomized slip models shows similar peak horizontal accelerations and spectral shapes for both foci (Figure 7). Directivity effects due to the location of rupture initiation are not apparent in the ground motions. The striking aspect of the response spectra is the significant damping of the surface motions at high frequencies (periods less than 0.8 sec) due to the 68 m thick soil column (Figure 5). The peak horizontal accelerations at the ground surface for any foci show a 40% reduction compared to the values at the top of rock (Figures 7 and 9; Table 2). Any site amplification, such as due to the velocity contrast between the clay layers at a depth of 68 m, (Figure 5) appears to be offset by the soil damping except at longer periods.

If a slip distribution similar to that observed in the 1983 Borah Peak earthquake is assumed for the Salt Lake City segment, the peak horizontal ground acceleration at CCH for a southern focus is 0.70 g (Figure 8; Table 3). For a middle focus and bilateral rupture, the peak horizontal ground acceleration is also 0.70 g. No effects due to directivity between the middle and southern foci are evident (Figure 8). However, for the rock motions for all sites including CCH, the southern focus gives the higher peak horizontal acceleration (Table 3). Any directivity effects may be masked by the soil at least at high frequencies.

Comparison of the median CCH soil response spectrum based on randomized slip models and randomized foci with the UBC spectrum for an S_3 site shows exceedance of the former at nearly all periods of general engineering interest, up to 2.0 sec for both seismic zones 3 and 4 (Figure 9). The CCH site-specific peak horizontal acceleration of 0.61 g is comparable to the 0.54 g based on the empirical relationships (Table 4). The rock and soil spectra (Figure 9) illustrate quite well the frequency dependence of site amplification and material damping.

East Salt Lake City Airport

For the randomized slip models, the amplitudes and shapes of both the soil and rock EAP spectra for the two foci are very similar (Figure 7). For this very deep soil site (more than 200 m thick), significant damping of surface motions is occurring at high frequencies (periods less than 0.5 sec) as at CCH. Peak accelerations are reduced by approximately 30%. Directivity effects are not apparent. Although the peak accelerations on rock are comparable between EAP and CCH (Table 2), the surface motions at EAP are slightly higher possibly due to the strong velocity gradient and some amplification created by the numerous layers in the profile (Figure 5).

As observed at CCH for the single slip model, the peak horizontal accelerations for the two foci are about 0.70 g (Table 3). The UBC spectra for a S_3 site (no shape available for S_4 sites) for both seismic zones 3 and 4 are generally exceeded by the site-specific EAP soil spectra (Figure 9). The median peak horizontal acceleration of 0.73 g (Table 2) exceeds the average empirical value of 0.52 g (Table 4). At periods greater than 0.6 sec, the ground motions on soil exceed the rock motions due to amplification in contrast to shorter periods (high frequency) where soil damping effects predominate (Figure 9).

Laird Park

The randomized slip models for LAI give very high ground motions regardless of the location of rupture initiation (Figures 7 and 9). The peak accelerations exceed 1.0 g for all foci (Table 2). Significant thin soil site amplification is the cause of these high motions due to the strong velocity contrast at the base of the soil column at a depth of 24 m. Damping, unlike at EAP and CCH, is not significant because the soil at LAI is thin. The peak horizontal acceleration at LAI shows a 50% increase compared to the value at the base of the soil column (Table 2). Similarly, based on empirical data, Campbell (1987) suggests that for a thin soil site, the peak horizontal acceleration could be, in general, 50% higher due to site amplification. The lower rock motions at LAI compared to the sites EAP and CCH probably reflect the difference in radiation patterns for sites located on the footwall as compared to the hanging wall sides of the fault (Figure 2). The shift of the maximum spectral peaks to longer periods for all sites is typical of the effects of soils on ground motions (Figure 7).

High peak ground accelerations are controversial although values of 1.0 g and greater have been observed in the near-field of moderate to large earthquakes worldwide. As an example, the recent 1992 M_s 7.0 Cape Mendocino earthquake generated peak vertical and horizontal accelerations greater than 1.8 g at a site situated over the rupture. Recently developed empirical peak acceleration-attenuation relationships indicate median values can approach 0.9 g (N. Abrahamson, personal communication, 1993).

For the single slip model, the ground motions at LAI are even higher with peak horizontal accelerations at about 1.35 g (Figure 8). This difference is probably due to the contribution of the large asperity at the southern end of the rupture model (Figure 3). The dominant resonant peak centered at 0.3 sec is typical of spectra influenced by thin soil site amplification. Directivity effects appear to be minimal in the LAI spectra possibly because of the location of the site on the footwall of the fault.

The UBC spectra for a S_1 site obviously does not account for thin-soil site amplification (Figure 9). Neither do the empirical peak horizontal accelerations which give an average value of only 0.54 g. As previously stated, Campbell (1987) has observed that thin-soil site amplification can result in 50% higher peak accelerations. Comparison of LAI with EAP or CCH, however, shows higher spectral accelerations at periods greater than 1.0 sec due to amplification by the deeper soil deposits (Figure 9).

SUMMARY AND RECOMMENDATIONS

Based on the BLWN-RVT finite fault methodology, we have attempted to characterize, on a site-specific basis, the near-field strong ground motions that might be generated by a future M_w 7.0 earthquake rupturing the Salt Lake City segment of the Wasatch fault. The resulting peak horizontal accelerations and acceleration response spectra for the randomized slip models exceed typical empirical values. This is not surprising given the fact that empirical peak acceleration-attenuation relationships are based on very few near-field strong motion records for large earthquakes. Recent observations attest to the possibility of very high peak accelerations in the near-field of M 6 to 7 earthquakes. The site-specific ground motions at these three sites in Salt Lake Valley exceed UBC spectra for both seismic zones 3 and 4.

Further assessments of site-specific strong ground shaking in the Salt Lake Valley should be made in an effort to characterize the full range of potential effects on ground motions of the earthquake source and geologic site effects. Based on our limited modeling to date, the site location with respect to the rupture plane (footwall versus hanging wall) and the locations of asperities are critical factors that can greatly influence strong ground shaking. The effects of directivity on ground motions at long periods (>1 to 2 sec) for normal faults may be significant although our general use of randomized slip models probably obscures any such effects in our results. Site geology, as observed in previous studies, is also extremely important influencing strong ground motions in the Salt Lake Valley, not only in terms of site amplification, but also in soil damping. The latter is particularly important for deep soil sites, as observed for sites CCH and EAP, where damping probably reduces ground motions by about 30% to 40% at high frequencies for what would be otherwise extremely strong near-field ground shaking. It is hoped that further site-specific strong ground motion estimates will result in a sufficiently large number of characterized sites such that an eventual microzonation of the Salt Lake Valley will be developed in preparation for the impending rupture of the Wasatch fault.

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