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Uniform Probability Response Spectra for Selecting Site Specific Design Motions

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SYNOPSIS In the majority of the current building codes, the shape of a design spectrum is defined by considering only the local soil conditions. This paper examines the validity of this simplification. In particular, it is shown how effects of "deep soil" or "rock soil" conditions on uniform probability site specific spectra can be simulated by varying the geological site conditions (depth of sediments) and the distance from the fault. On the basis of the results presented in the paper and similar results from earlier papers considering the effects of the choice of the geometry of the model fault and the assumed rupture area, as well as the seismic moment rate, the maximum magnitude, the b-value, and the confidence of the prediction, it is concluded that the shapes of design spectra should not be determined only on the basis of the local soil conditions.

INTRODUCTION

In the development of code provisions, it is important that the shape of design spectra is appropriately defined. There are many factors influencing the shape of spectra of ground motion. For a particular event, the shape of a response or Fourier spectrum at a site depends on: (1) the earthquake magnitude(Trifunac, 1994a,b,c), (2) the distance to the ruptured area, (3) the local geologic and soil conditions, and (4) the propagation path characteristics. Typically, there is more than one potential earthquake source, each with different likelihood of occurrence for events of a particular size (Todorovska, 1994a). It is uncertain which of these sources will contribute during the service time of the structure, and what their magnitude would be. Different events will have different consequences on the structural response. The events with the largest energy release are usually rare, and, moreover, may occur far from the site (the San Andreas fault and downtown Los Angeles, for example). The spectral shape from the possible earthquake with most severe consequences for the structure may be very different from the shape of spectra of also damaging smaller but more likely events. Which of the many contradictory requirements should the design spectra accommodate and how can that be achieved? Should the structure be designed for the event with most severe consequences, even though it is rare, or for the more likely events, or for neither of these two? The concept of uniform risk spectra, introduced in the mid 1970's, may serve as a vehicle in achieving a balance among many of these factors (Anderson and Trifunac, 1977, 1978, 1979). These spectra are such that each of the spectral ordinates has equal probability of being exceeded during the lifetime or service time of the structure. They do not have the shape of any particular earthquake, but contain a balanced contribution of all the contributing sources (Todorovska, 1994a,b; Todorovska et al., 1994; Jordanovski and Todorovska, 1994).

A common oversimplification in choosing the shape for a design spectrum is that only one of the factors influencing the shape is considered. The building codes, for example, typically consider only the local soil conditions. Shapes of site specific spectra are also often determined only by considering the local soil conditions. This paper examines the validity of these procedures, through a study of several factors influencing the shape of uniform probability spectra.

THE MODEL

The model fault is the Whittier-Elsinore fault in southern California, whose surface trace is shown by the dashed line in Fig. 1. This fault is modeled by a vertical surface of length $L = 230$ km and width 15 km. The surface trace of the fault is the segment $\overline{AC}$ of the solid line in Fig. 1. It is assumed that the seismic moment rate for this fault is $\dot{M}_0 = 1.2\times10^{24}$ dyn·cm/year, and that it is released by events with magnitudes $M_{\min} \le M \le M_{\max}$, in increments $\Delta M = 0.5$. The assumed b-value in the linear, incremental Gutenberg-Richter relationship is $b = 0.86$ (Anderson, 1979; Trifunac, 1990a). The rupture length–magnitude relationship used is $L_R = 10^{0.53M-1.47}$ (this implies $L_R = 0.1$, 2, 32 and 126 km for $M = 3$, 5, 7 and 8). If not indicated otherwise, ground motion is evaluated at a point 20 km from the fault along the d-axis bisecting the surface trace of the fault (Fig. 1). It is assumed that this fault is the major contributor to seismic hazard at the site, and that influence of all other sources is negligible.

This same model fault was used in Todorovska (1994b) and Todorovska and Lee (1994) to study the effects of the earthquake source parameters ($\dot{M}_0$, $M_{\max}$ and b) and the choice of the geometry of the model and the assumed rupture size on amplitudes and shape of uniform probability spectra at different probabilities of exceedance. This paper focuses on the influences of the local conditions at the site (geologic site conditions and local soil conditions) and distance. The computer program NEQRISK (the updated 1992 version, Lee and Trifunac, 1985; Trifunac and Lee, 1987; Lee, 1992) is used to evaluate the results.

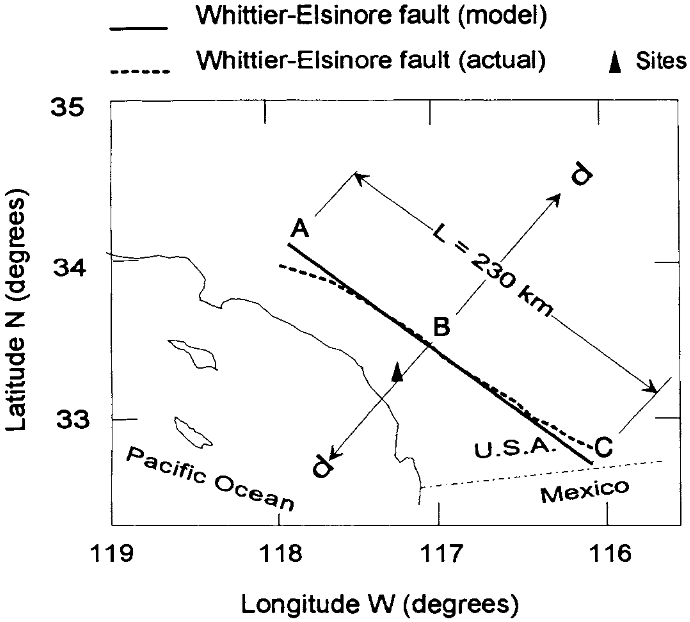

Fig. 1 The model fault: a vertical plane (length $L = 230$ km and width $W = 15$ km, with characteristics similar to those of the Whittier-Elsinore fault in southern California.

RESULTS AND ANALYSIS

Influence of the Geologic and Local Soil Conditions

It has been long recognized that alluvium and soil deposits underneath the site modify the motions on the surface by interference of waves inside these deposits. The modification depends on the elastic properties of the soil and the sediments underneath, on the impedance contrast and on the size (depth of the layers, for example), and it is frequency dependent. In general, due to the larger characteristic size, the sediments tend to affect more the longer periods, while the soil tends to influence more the intermediate and shorter periods. The overall effect also depends on the impedance contrast (between the sediments and the basement rock, and between the soil layer and the sediments). The following also affects the amplification of ground motion in sediments and soils. Soils have lower Q (Trifunac, 1994d), and very short waves will be amplified at first, but then attenuated while bouncing back and forth between the boundaries of the soil layer. The sediments have higher Q and some of the trapped higher frequency energy may also be amplified. Ground motion at sites on basement rock and on "rock" soil are usually considered as reference. According to the geologic site conditions, sites can be either classified into general categories specified by indicator variables (e.g, the site condition variable s), or the depth of the deposits, h, can be specified. Similarly, the local soil conditions can be specified either by an indicator variable (e.g., the local soil parameter s_L), or by the velocity profile (Trifunac, 1990b).

The effects discussed in this paper may be more or less pronounced depending on the particular scaling relationships for ground motion used in the calculations. Therefore, these should be well defined before the results are interpreted. The program NEQRISK, used for the calculations in this paper, has built in scaling equations for California, and for several other countries (south-east Europe). Those for California are described in Trifunac and Lee (1985), Lee (1987) and Trifunac (1987). It is possible to choose one of a variety of models, depending on which variables are available and in what detail. For example, the size of the earthquakes can be described either in terms of magnitude or intensity of shaking, and the local geology can be specified either by the parameter s or by the depth of sediments, h, if known. The geologic site conditions categories are: basement rock ($s = 2$), sediments ($s = 0$), and difficult to classify ($s = 1$). The local soil site condition categories are: "rock" soil ($s_L = 0$), stiff soil ($s_L = 1$), and deep soil ($s_L = 2$). The scaling equations were obtained via multi-variable regression applied to a set of about 550 three-component strong motion recordings in California from 1933 through 1984. For the analysis in this paper, the MAG-SITE-SOIL and the MAG-DEPTH-SOIL models are used, using the earthquake magnitude, and the local soil condition parameter, s_L, and the geologic site condition parameter, s, and the depth of sediments, h, respectively.

The difference in uniform probability PSV spectra arising from differences in local soil conditions only is illustrated in Fig. 2. The two plots are for probability of exceedance $p = 0.5$ and 0.1. The solid lines correspond to "rock soil" ($s_L = 0$) over rock ($s = 2$), and the dashed lines to "deep soil" $s_L = 2$) over rock ($s = 2$). The later parameter refers to geological basement rock. This figure illustrates the current state of the practice which considers how much the local soil change the spectrum that would have been recorded on rock. Taking "rock soil" and rock as reference, it is seen that at low frequencies, "deep soils" amplify the spectral amplitudes (e.g., about 1.7 times at 0.36 Hz), and at higher frequencies attenuate the amplitudes (e.g., about 1.4 times at 25 Hz).

In nature (about 75% of the time), "rock soil" is found over rock and "deep soil" over sediments. Uniform probability spectra for these extreme conditions are shown in Fig. 3. It is seen that at low frequencies the sediments further amplifies the spectral amplitudes so that at 3.6 Hz the spectral amplitudes for "deep soil" over sediments are about 2.4 times relative to the reference ("rock soil" over rock). At higher frequencies (between 3 and 25 Hz) however, the amplitudes are practically the same. The sediments amplify also the higher frequencies of the incident motion, but then attenuate this motion before it reaches the surface.

To illustrate the effects of local geology only, in Fig. 4, response spectra are plotted for sites on "deep soil" over rock (zero depth of sediments) and on "deep soil" over 3 km of sediments. If the spectra for "deep soil" over rock are taken as reference, it follows that the amplification due to the alluvium is about 1.6 times at 3.6 Hz and about 1.5 times at 25 Hz. This example shows that spectra at "deep soil" sites may be very different in shape, In fact, the two spectra look as if one is on "rock soil" and the other on "deep soil."

An unlikely but possible combination of geologic and local soil site conditions (found about 25% of the time) is "deep soil" over rock and "rock soil" over sediments. Fig. 5 illustrates uniform probability response spectra for such cases. The solid line corresponds to "rock soil" over 3 km deep sediments, and the dashed line to "deep soil" over rock. It is seen that, at higher frequencies (between 3 and 25 Hz), the spectral amplitudes for "rock soil" over 3 km of sediments are larger than those for "deep soil" over rock

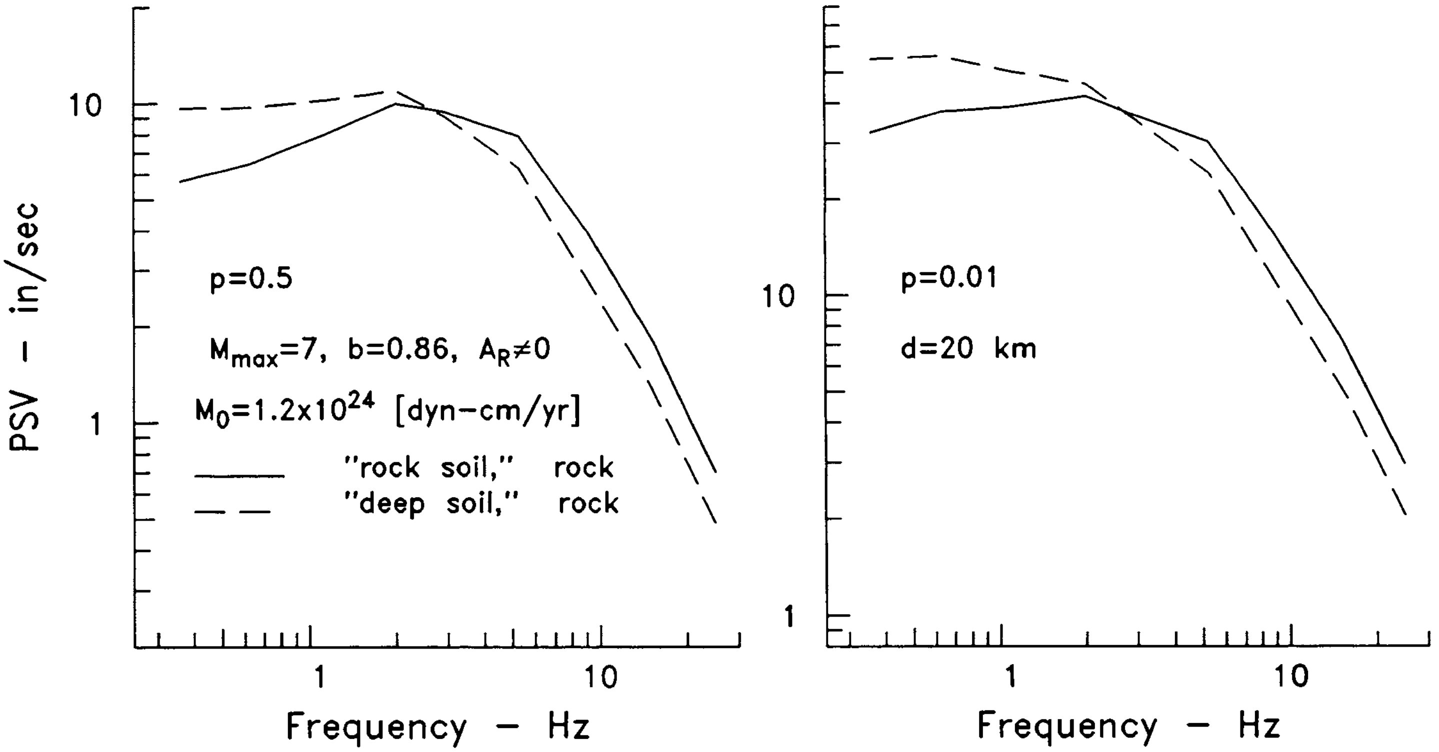

Fig. 2 Uniform probability PSV spectra at distance 20 km from the model fault. Differences between "rock soil" and "deep soil" spectra are illustrated. The geologic site condition for both spectra is rock.

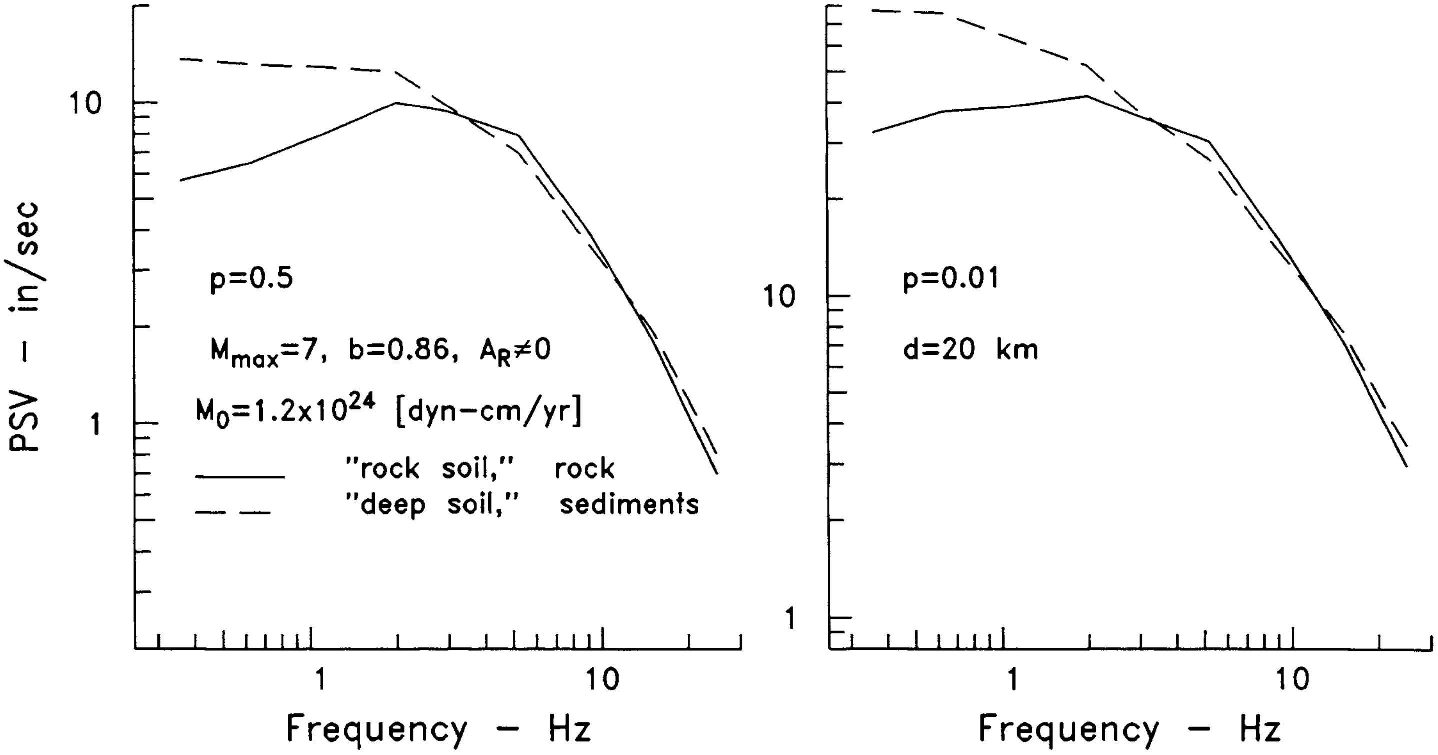

Fig. 3 Uniform probability PSV spectra at distance 20 km from the model fault. Differences between spectra for combinations of "hard" and "soft" geologic and soil conditions are illustrated (a likely combination of geologic and local soil site conditions).

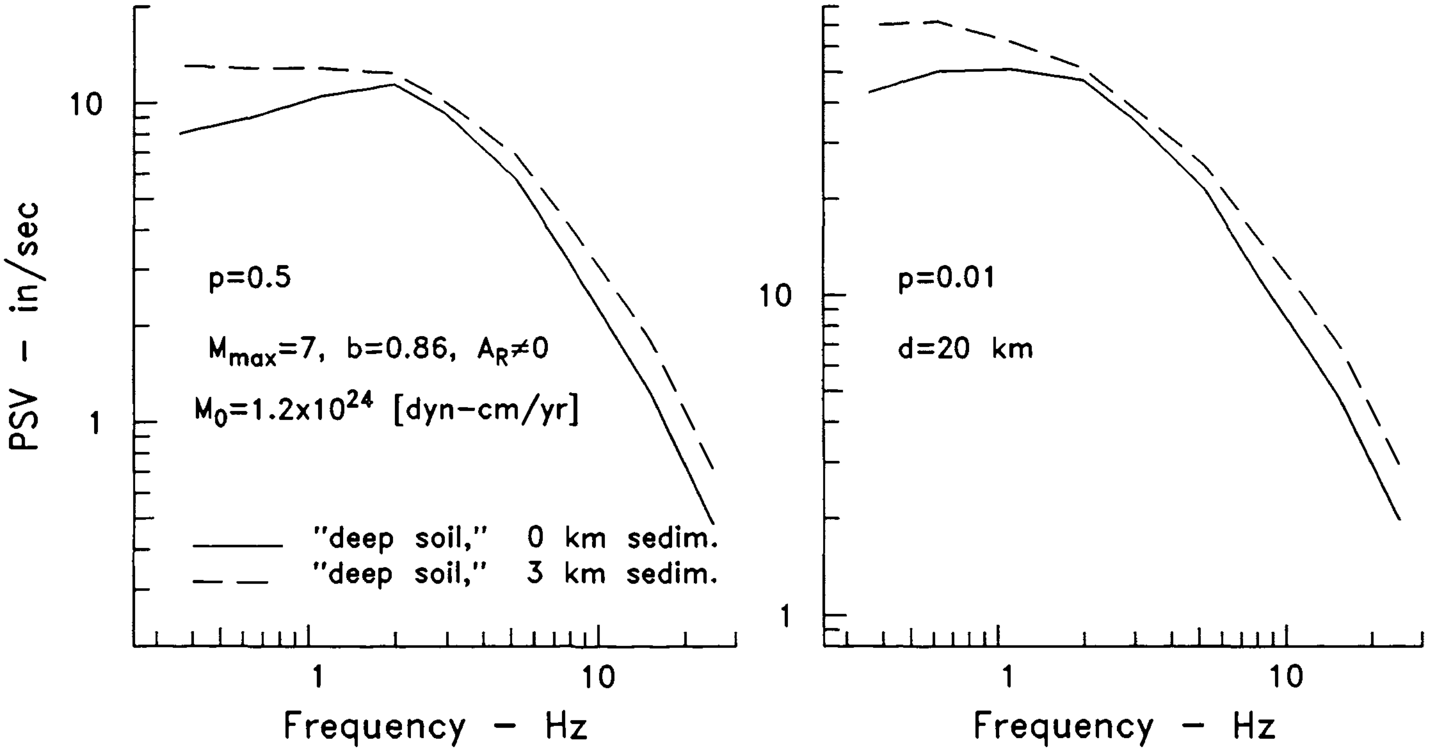

Fig. 4 Uniform probability PSV spectra at distance 20 km from the model fault. Differences between spectra for geologic rock and sediments are illustrated. The local soil condition for both spectra is "deep soil."

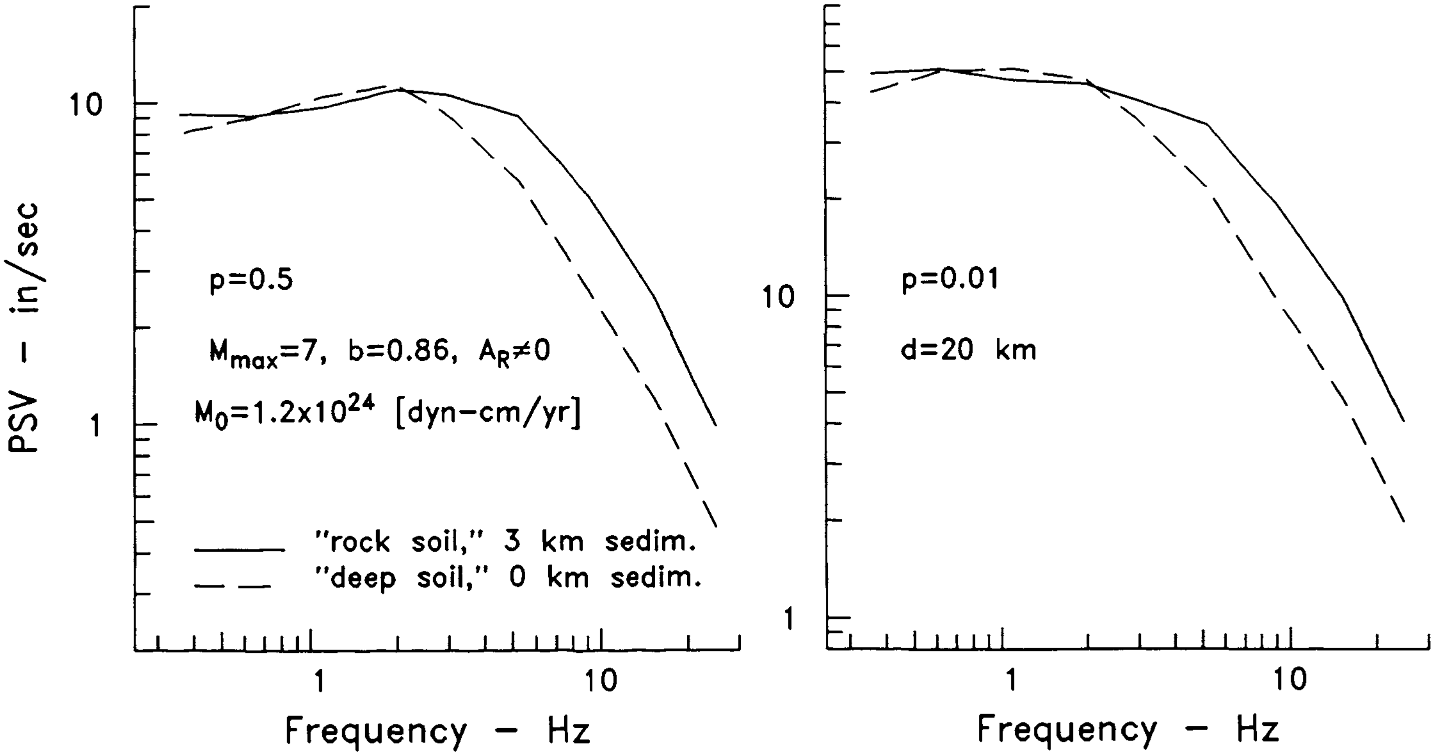

Fig. 5 Uniform probability PSV spectra at distance 20 km from the model fault. Differences between spectra for unlikely combinations of geologic and soil conditions are illustrated ("rock soil" and sediments, and "deep soil" and rock).

by about 2 times. Between 0.7 and 3 Hz, the amplitudes are very similar, and for frequencies lower than 0.7 Hz, it is observed that the amplitudes for "rock soil" over 3 km deep sediments tend to be larger. If this trend continues for frequencies lower than those presented in the figure, then the spectrum at the "rock soil" site would resemble a spectrum on deep soils.

Influence of Distance

The attenuation of strong ground motion with distance is frequency dependent (Trifunac and Lee, 1985, 1990). The higher frequency content of ground motion is attenuated more with distance than the low frequency content, due to more frequent encounter along the path with obstacles whose size is comparable to the wavelengths of these waves. Therefore, the shape of uniform probability spectra changes with distance. This change is illustrated in Fig. 6, where uniform probability spectra are shown at distances d = 20 and 80 km, by the heavier and the lighter lines respectively. The solid lines correspond to "rock soil" over rock and the dashed lines to "deep soil" over rock. The spectra (on a logarithmic scale) are shifted relative to each other, so that shapes of spectra for same local conditions can be emphasized. It is seen that spectra at 80 km distance look like "deep soil" spectra relative to the spectra at 20 km distance from the fault. This change of shape cannot be captured if some peak amplitude of strong motion is chosen and then a fixed spectral shape is scaled by it.

DISCUSSION AND CONCLUSIONS

The building codes consider only the local soil conditions in determining the shape of response spectra for design. The results presented in this paper show that "deep soil" effects on shape of uniform probability spectra can be simulated, among other factors, by the local geology and distance. In Todorovska (1994b), it was shown how the shape of such spectra changes with the moment rate, $\dot{M}_0$, the maximum credible magnitude for a fault, $M_{\max}$, the b-value and the probability of exceedance. ($M_{\max}$ and b control the likelihood of occurrence of large relative to smaller events on the fault.) It was shown that "deep soil" effects on the shape of spectra can be simulated by increasing $\dot{M}_0$, decreasing the probability of exceedance, decreasing the b-value, and varying $M_{\max}$ (the dependence of the shape on $M_{\max}$ is not simple, and depends on other factors). In Todorovska and Lee (1994), it was shown how the shapes of spectra change with spatial distribution of epicenters of possible events, controlled by the choice of fault geometry and the assumptions on the rupture size. It was also shown that these effects may depend on the location of the site relative to the fault, for short distances, and on $M_{\max}$.

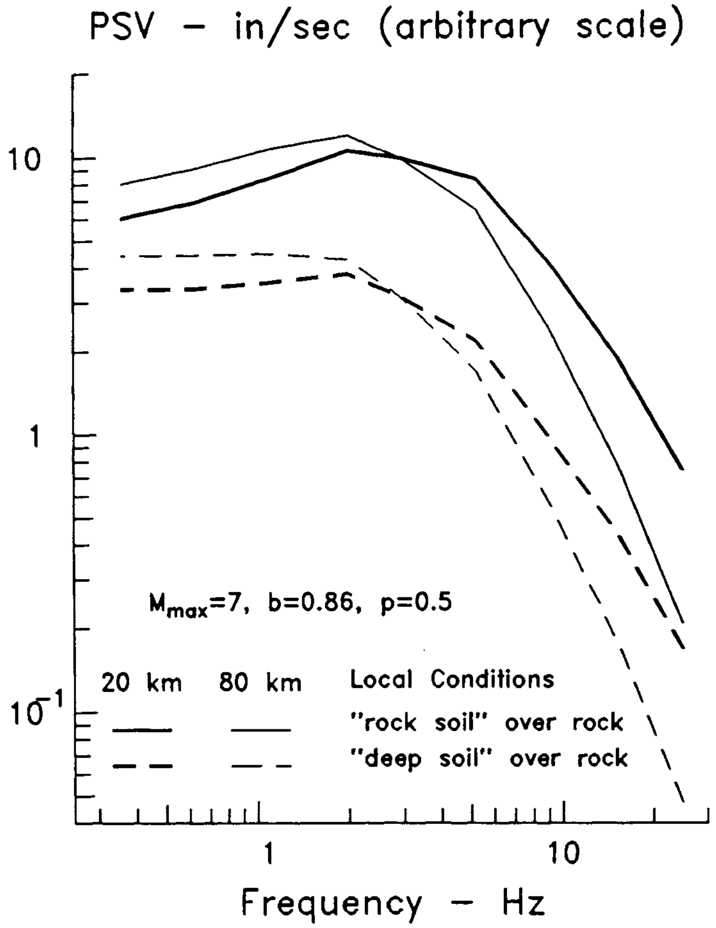

Fig. 6 Shapes of uniform probability PSV spectra at distances 20 km and 80 km from the model fault are compared. The spectra are shifted on a log scale so that difference only in shape of spectra can be observed.

From the above discussion, it can be concluded that there is sufficient evidence to show that it is not correct to consider only the local soil effects in defining the shape of design spectra. Instead, simultaneous influence of all contributing attenuation and amplification factors (some of which were mentioned in this discussion for a single fault), as well as relative contribution to the hazard of ground motion from all the contributing earthquake sources has to be considered. Uniform probability spectra can be used as a guideline to define shape of design spectra with balanced influence of all of the mentioned factors. Using uniform probability spectra, microzonation maps can be first constructed for a specific spectral period, as those for the Los Angeles metropolitan area, presented in Lee and Trifunac (1987) and Trifunac (1989, 1990a). The concept of uniform probability response spectra (based on exceedance at least once during the exposure time) can be extended to similar spectra based on exceedance during at least several earthquakes, and on similar spectra for the higher order peaks in the response of SDOF and MDOF structures (Todorovska, 1994c). The fact that a large earthquake has just occurred on a fault or is overdue may also be considered in defining design loads. However, this may not be easy to carry out in practice, due to other non-engineering considerations, and in other instances may not be significant (Todorovska, 1994a). Finally, one should extend the frequency range of the uniform probability spectra beyond the range limited so far by the recording and processing noise. This will be possible when extended scaling equations for strong ground motion (Trifunac 1993a,b; 1994a) become available for all spectra and site conditions used in the NEQRISK program.

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