# GROUND MOTIONS AND RESPONSE SPECTRA AT SOIL SITES FROM SEISMOLOGICAL MODELS OF RADIATED SPECTRA

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## SUMMARY

A simple, yet powerful, method for synthesizing ground motions and response spectra at the surface of soil sites underlain by sediments has been developed. The method uses, as input to a sediment column, stochastic simulations of time series whose amplitude spectra and duration are controlled by seismological considerations.

## INTRODUCTION

It is straightforward to compute site response in the form of Fourier spectral ratios between the surface motion and the equivalent motion recorded in the absence of soil layers, at least for cases where nonlinear response is not expected. As we will show in this paper, however, the Fourier spectral ratios can give a misleading impression of the effect of the site response on structures. More useful for seismic design is the computation of response spectra at the surface of a soil column. This requires specification of the input time series. To do this, we use a recently developed technique based on seismological source models for generating a suite of accelerograms for arbitrary magnitudes and distances (Ref. 1); using these as input motions with any of the available methods for computing soil response enables us to compute ground motions and response spectra at soil sites.

## METHOD

### Input Motion

The specification of the input motion lies at the heart of the method. Discussed in detail by Boore (Ref. 1), only a brief description is given here. The essence of the method is to filter windowed, Gaussian white noise so that the amplitude spectrum is equal, on the average, to a target spectrum obtained from seismological considerations. An $\omega$-squared spectrum with a magnitude-independent high-frequency cutoff and a constant stress parameter has been used for the target or model spectrum. At a given distance, the change of spectral shape and level with earthquake size is controlled by only one parameter: moment magnitude. The target spectrum for a magnitude 5 event and the actual spectrum from one realization of the stochastic process are shown in the upper part of Figure 1. The lower part is similar, except the average spectrum from 20 time series is shown. As emphasized by this example, the target spectrum is met only on the average;

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we think this is a more realistic procedure than demanding that one time series reproduce the target spectrum exactly.

Some of the justification for this simple procedure for generating strong motion is shown in Figure 2, in which peak acceleration and peak velocity are compared with the regression results of Joyner and Boore (Ref. 2; Ref. 3). As shown in more detail in Boore (Ref. 1), the model agrees with predictions of most important measures of strong ground motion, predictions based on the analysis of hundreds of recordings from earthquakes in western North America.

Soil Response

For illustration, all soil responses in this paper were computed by Haskell's method for propagating SH-waves through a stack of constant velocity layers (Ref. 4). The method allows for anelastic attenuation by using complex rigidities in each layer (Ref. 5), but assumes linearity. We don't believe that the assumption of linearity is a severe restriction, but the justification for this statement is beyond the scope of this paper (see, e.g., Ref. 6). Because an input time series is derived, nonlinear soil response calculations could be made if necessary.

## APPLICATIONS

The first application is to two models, both consisting of a single layer over a halfspace. The soil thickness and velocity were chosen to give a 1-Hz and 10-Hz resonant peak in the two cases. The time series for one realization of the process are shown in Figure 3. In this and in all subsequent examples the motions are for a magnitude 6.5 earthquake at 30 km from the source. The bottom trace is the surface motion that would have been recorded in the absence of the soil layer (hereafter called the rock motion). The other two traces are the motions on the surface of the soil layer for the two models. The change in frequency content and increase in peak motions is clear. On the average, the increase in peak motions is less than would have been predicted either from the height of the resonant peak or from considerations of conservation of energy flux (Ref. 7).

The soil transfer functions, defined as the ratio between the Fourier spectra of surface motions with and without the soil layer, are shown in Figure 4. The anelasticity of the soil (Q=16) accounts for both the gradual decay of the spectra at high frequencies and the restricted amplitude of the first resonant peak (which would have reached a value of 5 if no anelastic attenuation had been present). Comparisons of the average ratio of the response spectra and the soil transfer functions are shown in Figure 4. The response spectral ratios tend to lower the peaks and fill in the troughs predicted from the Fourier-spectral soil transfer functions. At the higher frequencies, where the Fourier spectra of the input motion and surface response are much reduced, the oscillators must reach back to ground-motions at lower frequencies for their response. On the average the soil motion at these lower frequencies is enhanced over the rock motions, and therefore the ratio of response spectra increases with frequency at high frequencies, eventually reaching the average ratio of the peak accelerations.

The final example is for a more realistic soil column than the previous examples. In this case the model corresponds to the sediments underlying a portion of the margin of San Francisco Bay. The velocity-depth profile, taken from Joyner and others (Ref. 8), is shown in Figure 5. A thin layer of bay mud is underlain by alluvium. Sixty-seven layers were used to approximate the velocity-gradients expected in the soils. The soil transfer function, shown in Figure 6, is much more complicated and has higher peaks than those previously considered. The rock and soil surface motions for one realization of the process (Figure 7) clearly shows the filtering and amplification produced by the soils. As before, the average amplification of the peak accelerations (a factor of 3.4) is less than would have been predicted from either the peaks in the transfer function or considerations of energy flux. The rock to soil-surface transfer functions for Fourier spectra and response-spectra are shown in Figure 8, both for individual simulations and averaged over 20 runs. As expected, the soil column produces major changes in shape and amplitude of the spectrum of the input motion. As before, however, these changes are not nearly as large as would have been expected from considerations of the Fourier spectral transfer function.

## CONCLUSIONS

A simple, yet powerful, method for constructing ground motions and response spectra at the surface of soil sites underlain by sediments has been presented. The method uses, as input to a sediment column, stochastic simulations of time series whose amplitude spectra and duration are controlled by seismological considerations. Applications to a simple and complex soil profiles suggest the following conclusions:

- The amplification of peak acceleration on soil sites is less than expected from considerations of peak in soil transfer functions and from energy conservation arguments.

- The large variations expected in Fourier spectral transfer functions are subdued when damped response spectra are considered. This suggests caution in either using Fourier spectra to characterize site response for engineering purposes, or in using ratios of response spectra to infer the properties of the underlying sediments.

- Large scatter can be introduced in ratios of response spectra from a number of events recorded at a given pair of stations, scatter that would not be present in ratios of Fourier spectra.

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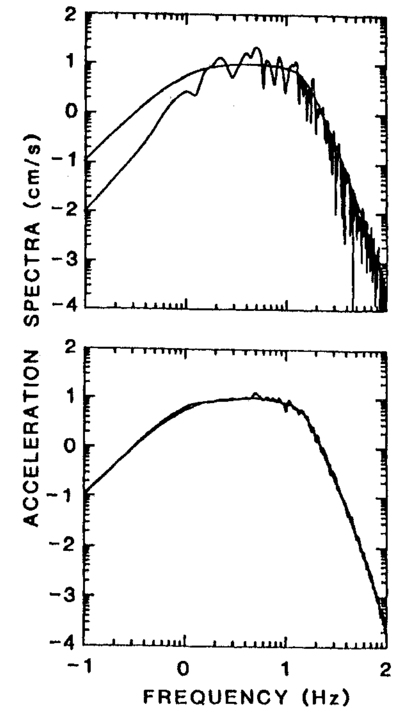


Figure 1. Acceleration Fourier spectra at 10 km from a magnitude 5 earthquake. Smooth curves: model spectra. Jagged curves: spectra from 1 simulation (top) and average of 20 simulations (bottom).

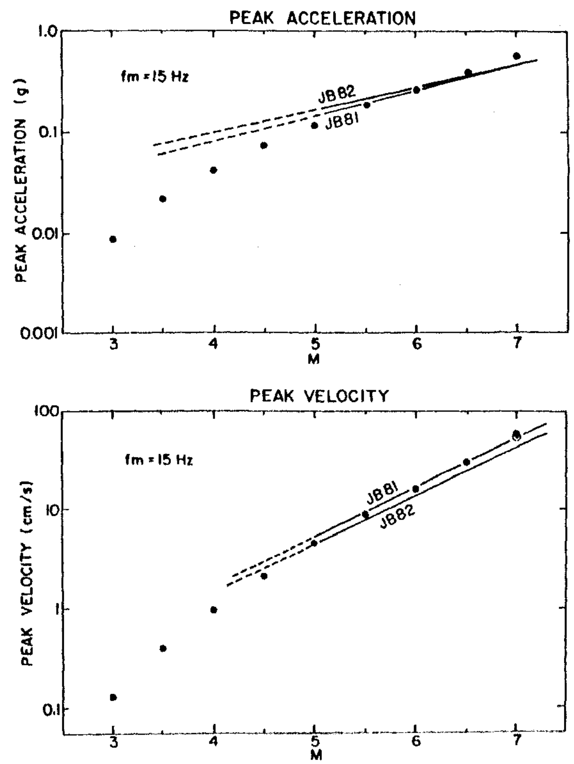


Figure 2. Comparison of mean peak acceleration and peak velocity, derived from 20 simulations (circles), and curves determined from regression studies of data (Ref. 2; Ref. 3). No data from earthquakes less than magnitude 5 were used in the regression analyses, and therefore the curves have been dashed for $M < 5$.

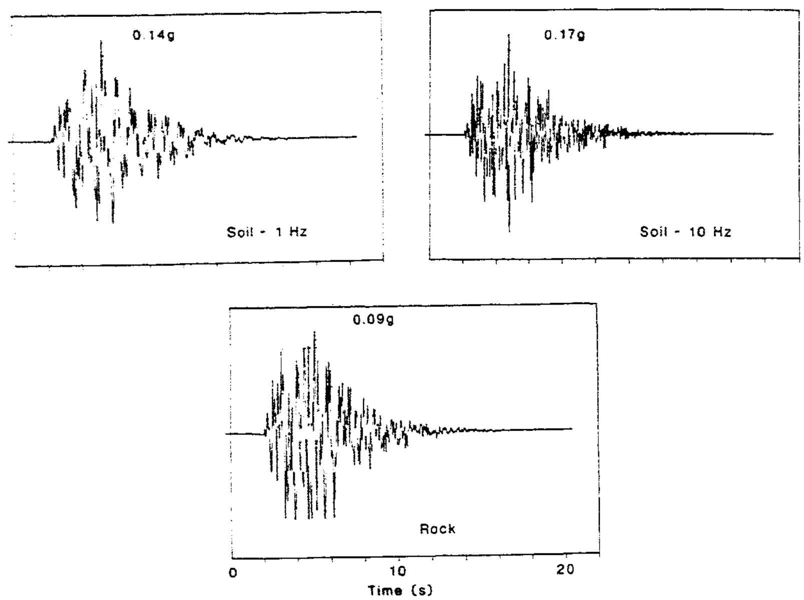


Figure 3. Accelerograms for magnitude 6.5 earthquake at 30 km at rock site (bottom) and two single-layer soil sites. Average peak accelerations from 20 simulations are shown.

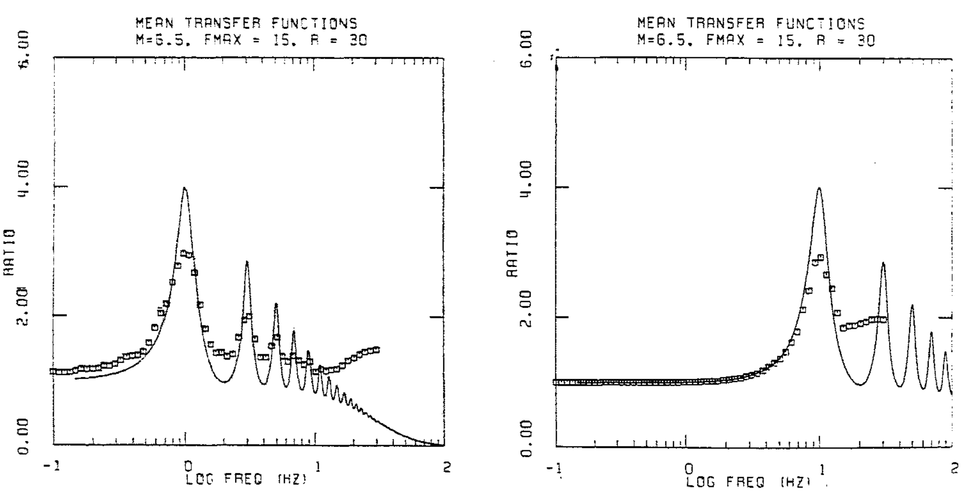


Figure 4. Comparison of Fourier soil transfer functions (solid lines) and averaged ratios of response spectra (symbols) for the two single-layer soil models.

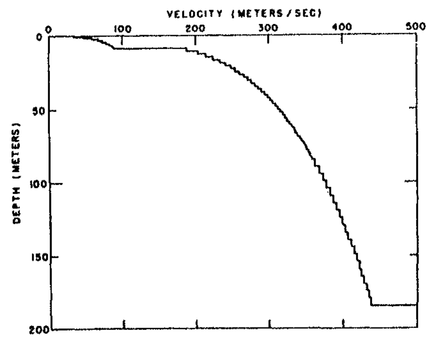


Figure 5. Shear velocity-depth function (Ref. 8).

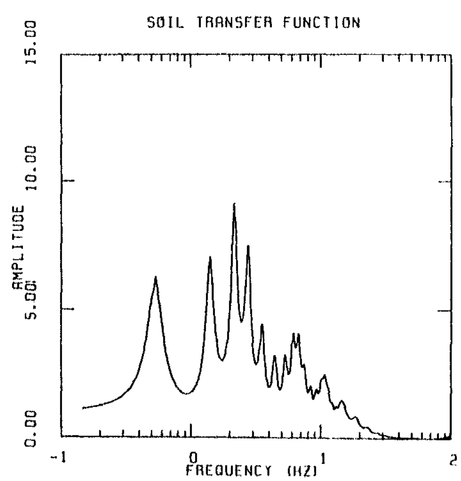


Figure 6. Soil transfer function for model of bay sediments.

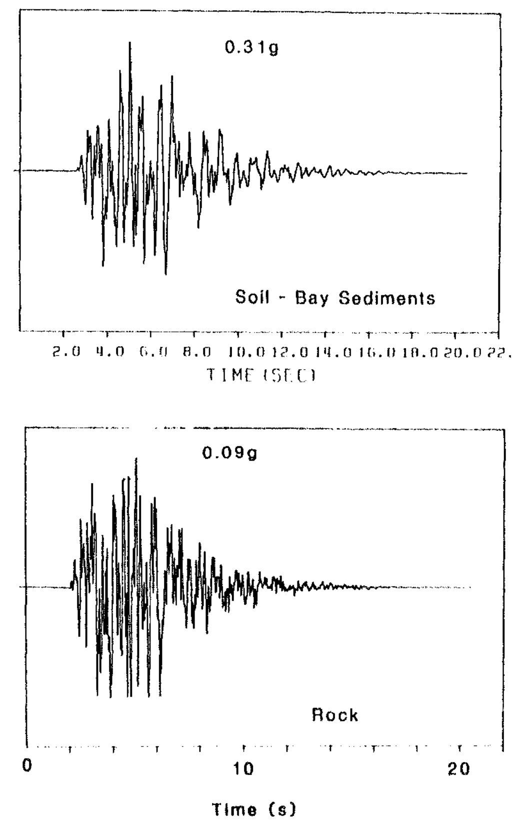


Figure 7. Accelerograms for magnitude 6.5 earthquake at 30 km at rock site (bottom) and bay sediment site (top). Peak accelerations shown are averages for 20 simulations.

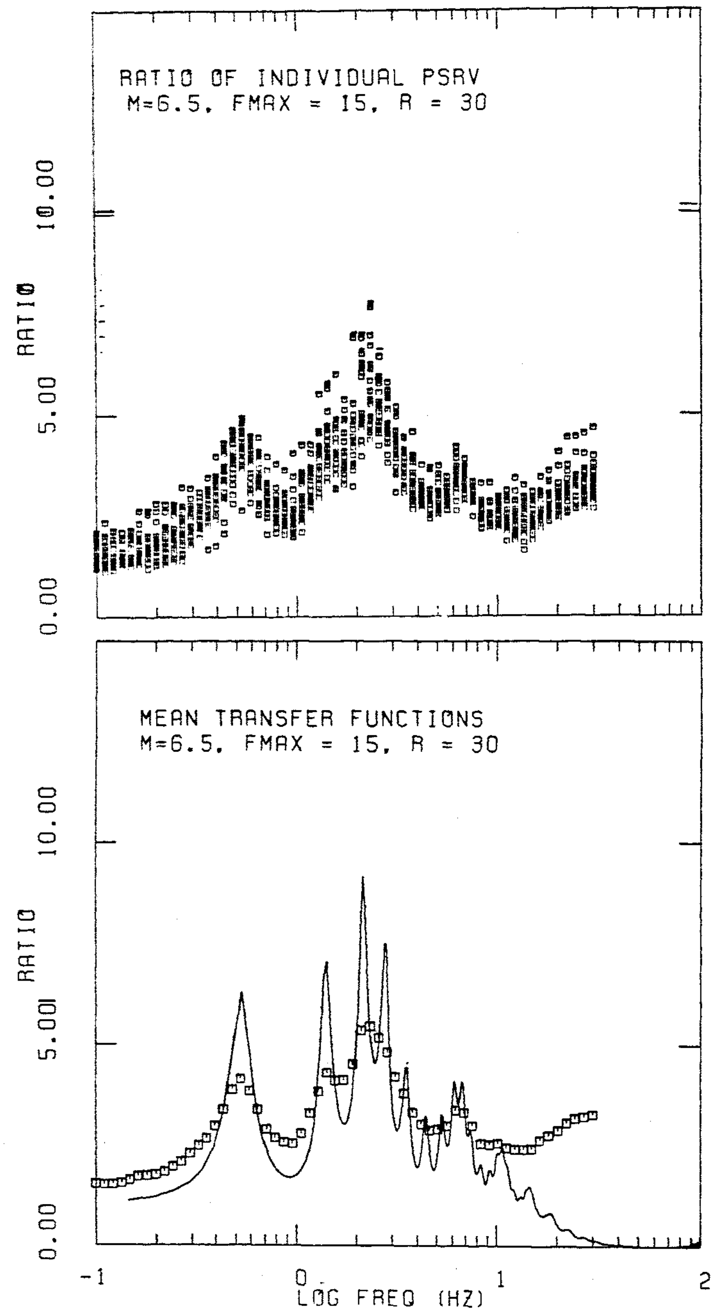


Figure 8. Ratios of response spectra (top) individual ratios; (bottom) averaged ratios (symbols) and Fourier transfer function (line).