# Appendix F

# Impact of Deep Rock Column on Soil Response Spectra

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## F.1 Background

Dr. Costantino was requested to review the use of the design rock motions developed by URSG-WCFS (2000) for site response analyses at INEEL. A concern was raised on how the deep rock column of basalt interbedded with sedimentary layers could effect soil response calculations. Dr. Costantino was asked to assess whether input rock motions could be represented by uniform rock half-space. This appendix contains the report of his findings.

In most site response calculations, the response spectrum at the soil ground surface is generated by performing site response analyses using as input the ground motion defined at the top of rock known as a rock outcrop. As currently recommended for site response analyses, multiple convolution calculations are performed by randomizing the site soil properties, using either site-specific or generic properties, in a Monte Carlo approach. In each of the individual soil column realizations, the bedrock is typically represented as a uniform half-space with specific average shear wave velocity and material damping properties. At INEEL, the rock profile is not uniform but is interspersed with a series of soil interbeds within the rock profile. Both deterministic and Monte Carlo site response calculations were performed to try to evaluate the impact of the interbeds on the computed spectra at the soil surface.

## F.2 INEEL Bedrock Column Definition

A plot of the velocity profile to a depth of about 2740 m (9,000 ft) is shown in Figure F-1 which indicates that the shear wave velocities through the interbeds are almost one-half those through the surrounding rock. A more detailed profile to a depth of 300 m (1,000 ft) is shown in Figure F-2, in which the thickness of the interbeds can be better visualized. This profile is obviously significantly different than those typically defined for site response evaluation and is certainly significantly different than a (relatively) uniform rock half-space. The impact of the interbeds on the response of soil columns appended above the bedrock profile is the issue of interest to this evaluation. It should be noted that the impact of the interbeds on the development of the design rock outcrop motions themselves are not considered in this discussion. Rather, this evaluation is limited to the potential impact of the interbeds on the soil column responses computed, given the rock outcrop motions as input.

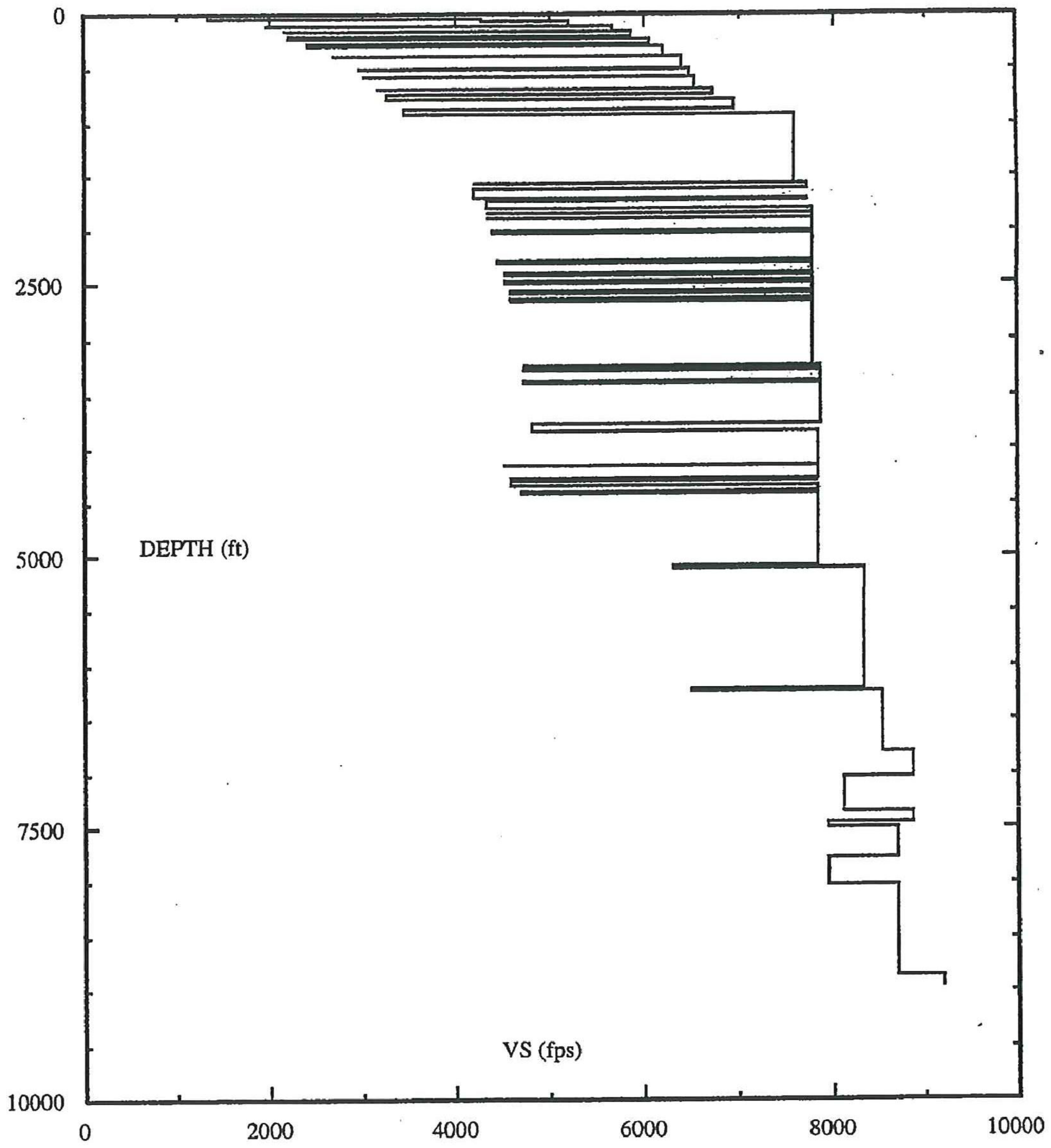

**Figure F-1.** Deep rock column for INTEC.

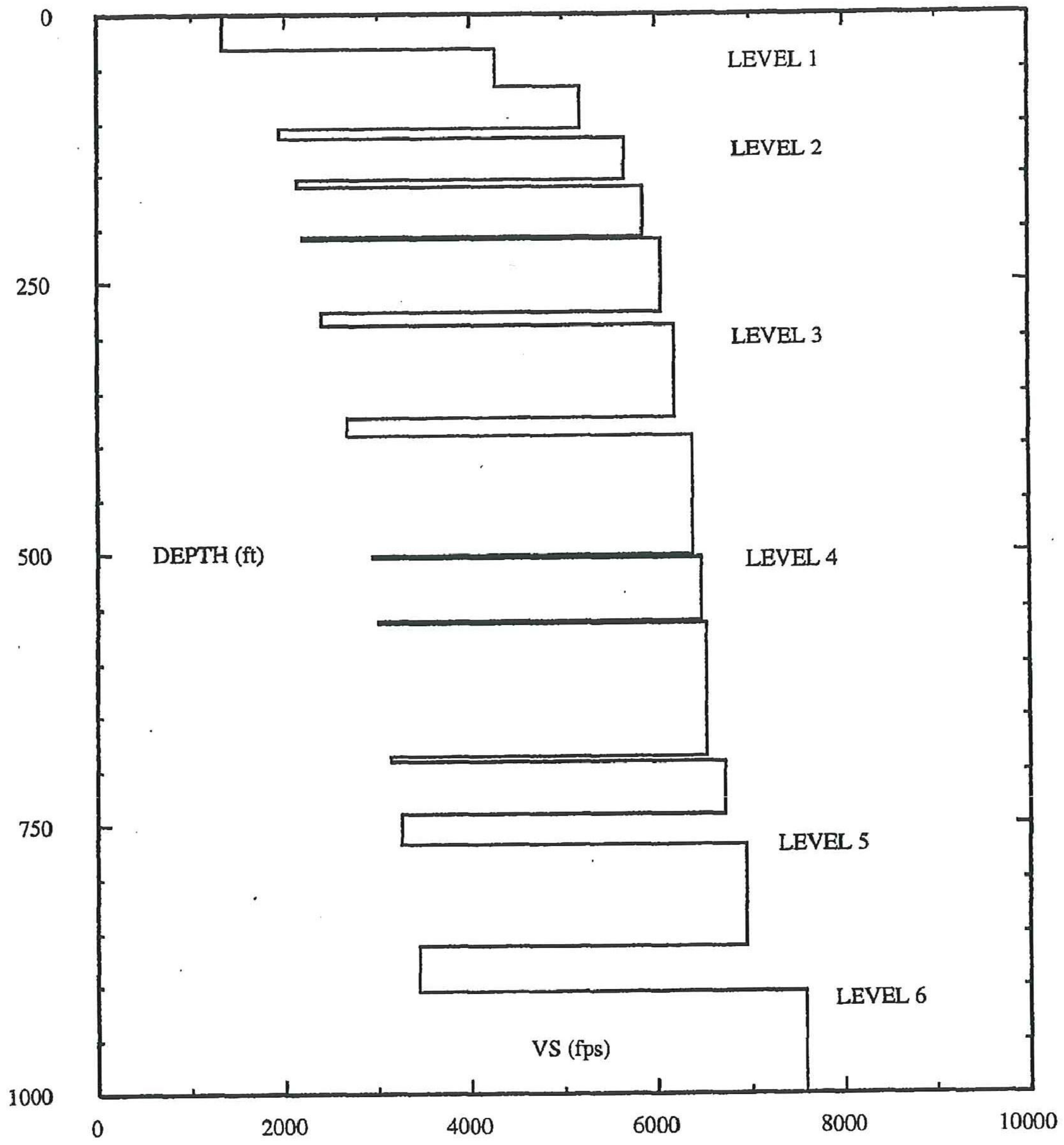

**Figure F-2.** Upper section of the deep rock column at INTEC.

## F.3 Deterministic Site Response

The results of a series of deterministic site response calculations were performed in which the given bedrock outcrop motion was first deconvolved through the rock profile to an arbitrary depth, assuming that no soil is in place above the bedrock, to obtain the bedrock motion at this depth associated with the rock outcrop motion. The specific rock outcrop motion used in these evaluations was defined as the time history associated with the PC-3 (2,500 year) rock DBE (URSG-WCFS, 2000b). The deconvolution was performed assuming that the rock is linear (that is, has no stiffness degradation with strain), has the given shear velocity profile indicated in Figure F-2 and has a uniform hysteretic damping ratio of 1%. This deeper computed ground motion was then input to the base of the rock column with a given soil profile added to the top of the rock column. For the convolution calculation, the rock was also assumed to be linear, but the soils added above the rock were given nonlinear degradation properties appropriate for INEEL. The rock below the selected cutoff depth was assumed to be a uniform half-space.

Calculations of site response were then performed assuming two different soil thicknesses above the bedrock, one a very shallow soil cover 6 m (20 ft) thick and a second thicker soil profile of 15.2 m (50 ft) total thickness. Both profiles are considered appropriate for INEEL. The conclusions reached from both sets of these calculations are similar so that only the results from the thicker 15.2 m soil layer are presented in this report. The soil profile properties for these particular calculations were selected from the data available from the CPP-651 site at INEEL (Structural Dynamics Engineering, 2000). The deconvolution/convolution calculations were performed using the CARES computer code (Costantino et al., 1996) which assumes the standard site response due to vertically propagating shear waves.

A similar set of convolution calculations were then performed in which the specified rock outcrop motion was applied to the same soil column, but in this case the rock profile below the soil contact was assumed to be a uniform half-space. Calculations were performed for three different average values of uniform bedrock shear wave velocity:

1. 1300 m/s (4268 ft/s) which is the shear wave velocity of bedrock at the top of the column in Figure F-2;
2. A higher value of uniform shear wave velocity of 1645 m/s (5400 ft/s)
3. An even higher value of uniform shear wave velocity of 1950 m/s (6400 ft/s).

These additional cases were selected by averaging the rock shear velocity over specific depths of the rock column. In the deconvolution through the rock column, calculations were performed for a number of depths, six of which are shown in Figure F-2. The deepest depth of the column shown is Level 6 that is immediately below the interbed at about the 274-m (900 ft) depth. Calculations performed to deeper depths did not lead to significantly different conclusions and the interbeds within this depth range captured most of the impact of the interbeds on the soil site response.

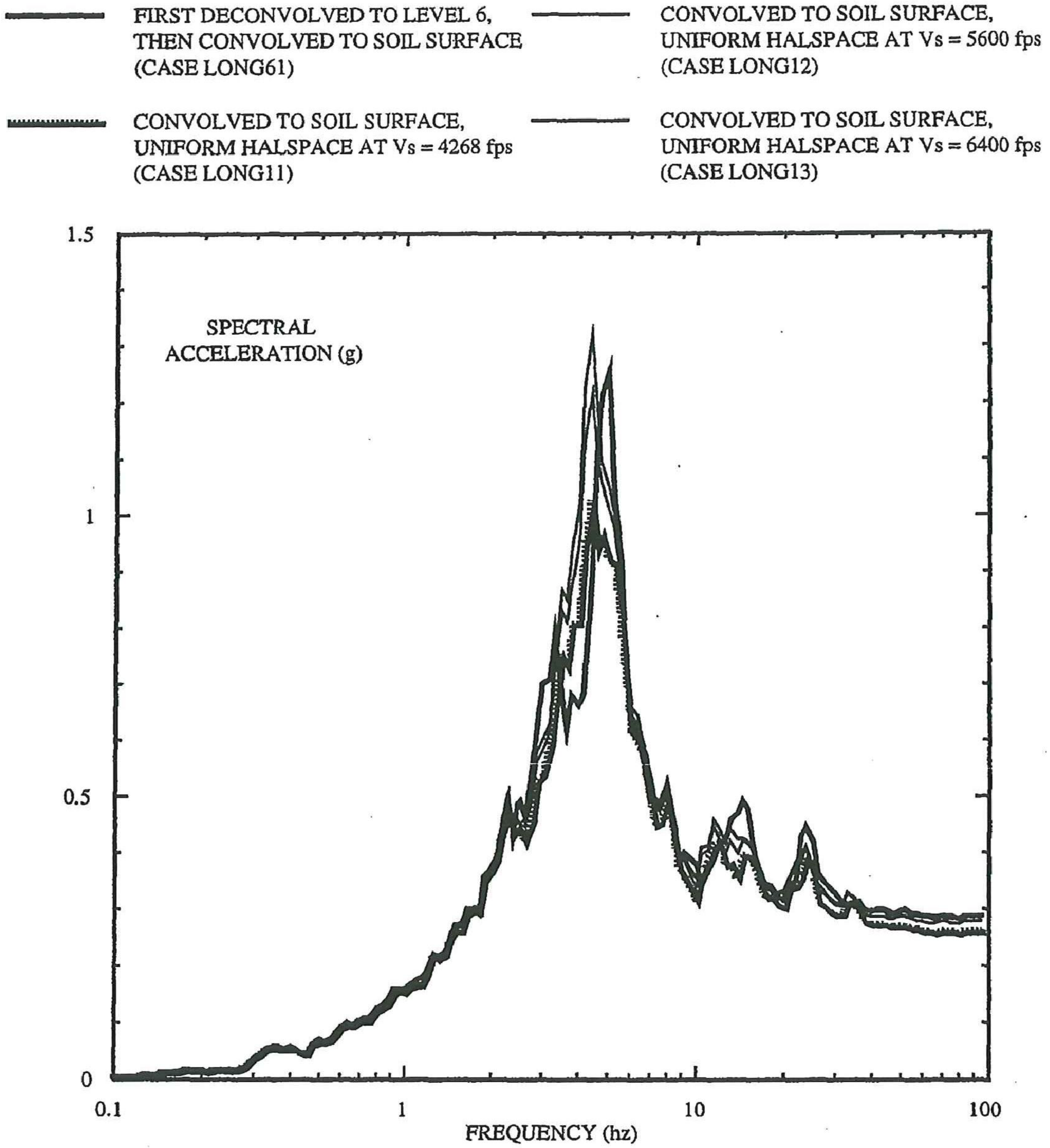

**Figure F-3.** Soil surface spectra from deterministic calculations.

Figure F-3 presents a comparison of the results obtained when:

a) The rock outcrop motion is first deconvolved down to Level 6 (of Figure F-2) through the interbeds and reconvolved upward through the rock column with the 15.2 m thick soil layer added on top of the rock;

b) The rock outcrop motion is convolved upward through the soil layer assuming that the rock is a uniform half-space.

The solid curve represents the computed 5% damped surface spectrum when the interbeds are included within the rock profile. The heavy dashed curve is the corresponding result obtained at the top of soil when the bedrock is assumed to be a uniform half-space with a shear wave velocity of 1300 m/s. As can be noted, the spectral peak obtained by including the interbeds reaches a value of about 1.25 g, while the peak assuming the bedrock is uniform reaches a value of about 1.02 g. This increase indicates the effect of the interbeds as well as the variability of the rock shear wave velocity with depth. The increase obtained for calculations conducted for deeper depths in the soil column did not significantly change the peak values nor the spectral shape shown in Figure F-3.

Since it is not desirable to force analysts to perform computations by first deconvolving the rock outcrop motion down through the rock column and then reconvolving the generated motion up through the corresponding rock/soil column, a simple scheme was investigated to try to match peaks, and this was simply to increase the average shear velocity of the uniform rock half-space. This increases the energy transferred to the soil, increasing its surface response. Figure F-3 presents the results of two such calculations, one where the rock velocity was increased to 1645 m/s, and a second where the velocity was increased to 1950 m/s. As can be noted, the spectral peak does increase to match the "target" better than the initial results. However, a small shift in frequency of the peak is noted indicating the nonlinear effects of overdriving the soil column. In addition, the increase in the shift in peak values and column frequencies are somewhat dependent on the total thickness of the soil cover above the bedrock.

## F.4 Monte Carlo Simulations

To follow more closely currently recommended procedures for site response evaluations, a number of different sets of Monte Carlo calculations were run, each using 30 sets of soil column realizations. The following sets of calculations were performed:

1. The PC-3 DBE rock outcrop motion was first deconvolved to Level 6 of the rock column (Figure F-2) and then convolved upward through the rock/soil columns to the top of the soil surface. For each of the column realizations, variability in material properties was included for both the soil and bedrock portions of the site columns.

2. The PC-3 DBE rock outcrop motion was first deconvolved to Level 6 of the rock column and then convolved upward through the rock/soil columns to the top of the soil surface. For each of the column realizations, variability in material properties was included only for the soil portions of the site columns.

3. The PC-3 DBE rock outcrop motion was convolved upward through the soil column assuming a uniform rock half-space with a shear wave velocity of 1300 m/s (soft rock stiffness case). Soil variability was included in selection of the 30 soil columns, with no variability included in the rock properties.

4. The PC-3 DBE rock outcrop motion was convolved upward through the soil column assuming a uniform rock half-space with a shear wave velocity of 1645 m/s (intermediate rock stiffness case). Soil variability was included in selection of the 30 soil columns, with no variability included in the rock properties.

5. The PC-3 DBE rock outcrop motion was convolved upward through the soil column assuming a uniform rock half-space with a shear wave velocity of 1950 m/s (hard rock stiffness case). Soil variability was included in selection of the 30 soil columns, with no variability included in the rock properties.

The appropriate method of analysis would follow the procedures of Set 1, in which uncertainty in both rock and soil properties is incorporated into the set of response calculations. A much simpler engineering evaluation of the site, assuming a uniform rock half-space, would result from a calculation similar to those of Set 3 in which only soil variability is considered. It should be noted that in the previous development of the site hazard at INEEL at the soil surface (URSG-WCFS, 1999), calculations similar to those of Set 2 were performed, in which uncertainty in definition of soil properties were included but uncertainty in the rock properties were not incorporated into the response calculations.

In the calculations performed for these five sets of site response evaluations, the coefficient of variations (COV) for the soil portion of the rock/soil columns were taken from the data available in the CPP-651 evaluation (Structural Dynamics Engineering, 2000), in which site-specific boring data were used to calculate the statistical properties. For the rock portion of the site profiles, values of COV were selected to be somewhat smaller than for the site soils, and uncertainty in the COV for the interbed sands were selected to be the same as for the bottom soil layer above the bedrock columns and gradually reduced with depth. Mean values of the surface spectra were defined by determining the averages of the logs of the acceleration spectra generated from the column realizations, assuming that the spectra are log-normally distributed.

The results obtained from these calculations can be summarized as follows. As expected, when determining mean spectral responses, the peak of the mean spectrum is typically smaller than the peak of any individual spectrum since the frequencies of the peaks shift somewhat in the various site realizations. The resulting mean spectrum than has a somewhat lower peak value but a somewhat broader shape. Figure F-4 presents the results obtained from the deep column calculations (Sets 1 and 2 above). As may be noted, the peak for the case of uncertainty in both the rock and soil (about 0.9 g) is somewhat lower than that resulting from the set with uncertainty defined in the soil alone (about 1.02 g). The Set 1 results show a slightly broader spectral shape as expected. Figure F-5 presents a comparison of the Set 1 results (variability in both rock and soil) with Set 3 (uniform half-space of soft rock and variability in soil only). Again, performing the full deconvolution/convolution analyses with variability in both the deep rock and soil leads to a peak spectral value which is somewhat lower than those resulting from the uniform half-space results. Figure F-6 presents a comparison of the results obtained from the uniform half-space sets, indicating the increase in computed surface spectra as the average rock velocity increases. It should be noted that no significant shift in peaks in the mean spectra can be noted since shifting is to some degree accounted for in the averaging process. Figure F-7 presents a comparison of the Set 2 results with those from the Set 3 uniform half-space results. These indicate similar values of the peaks of the spectra as well as similar shapes.

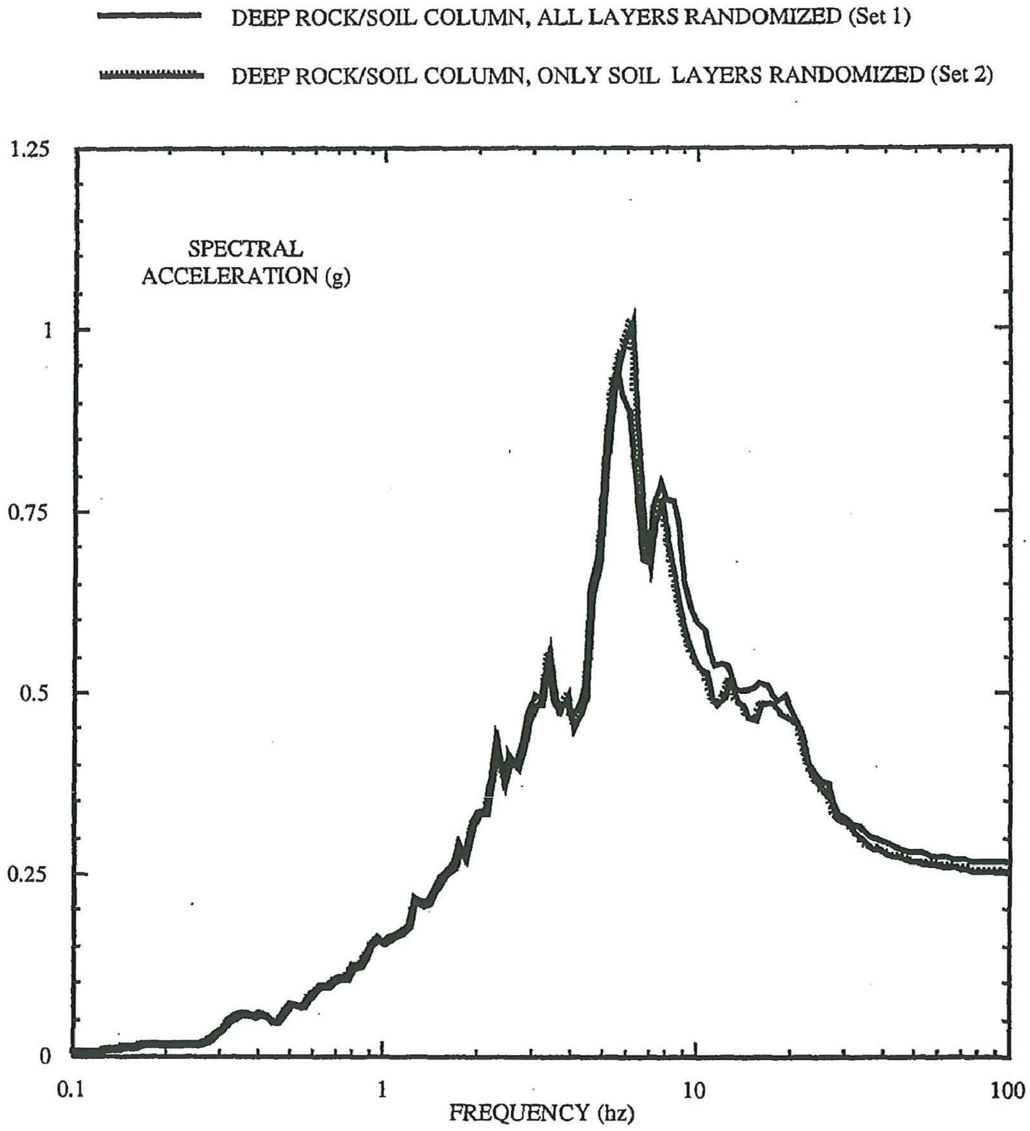

**Figure F-4.** Soil surface spectra from randomized deep rock calculations.

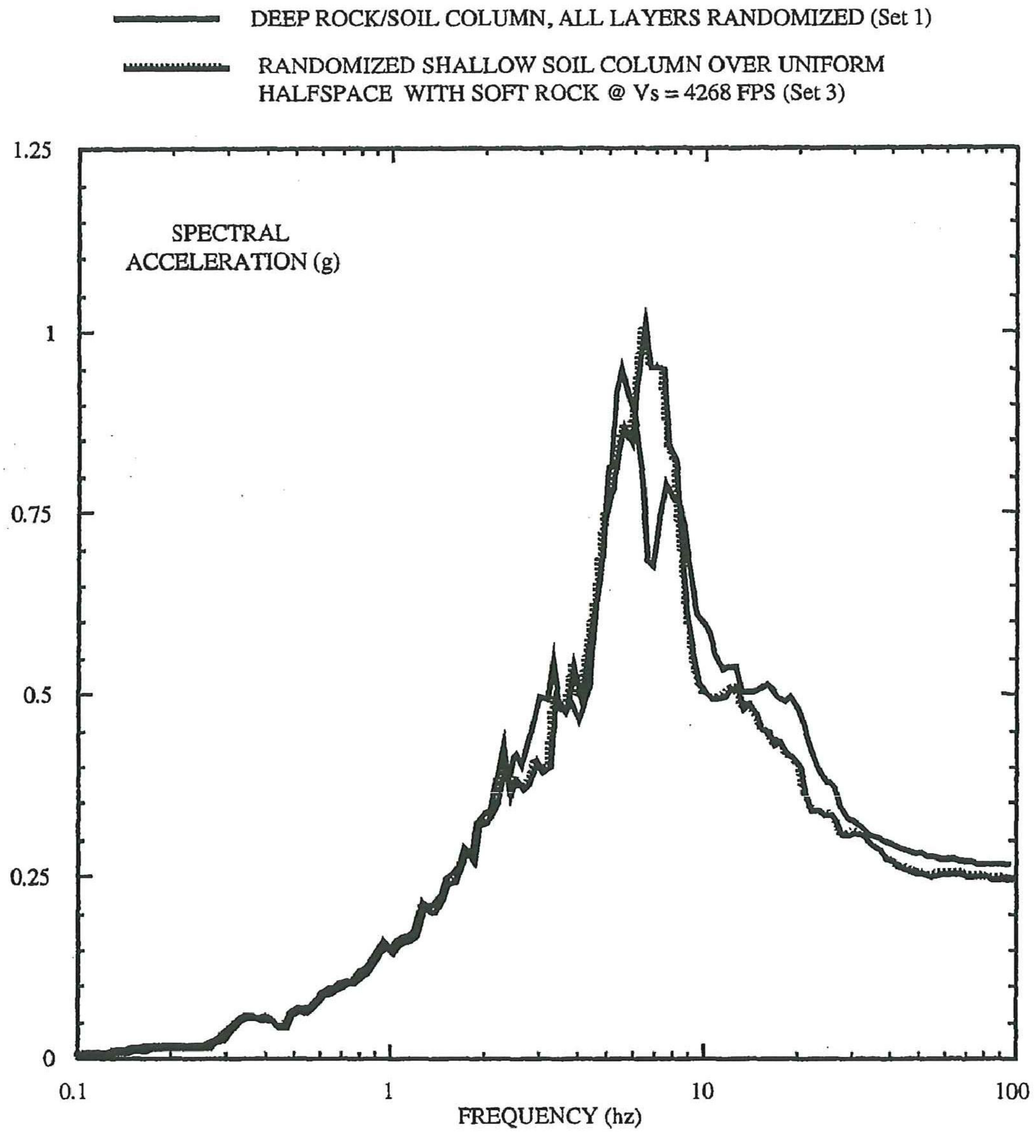

**Figure F-5.** Comparisons of soil surface spectra from randomized calculations.

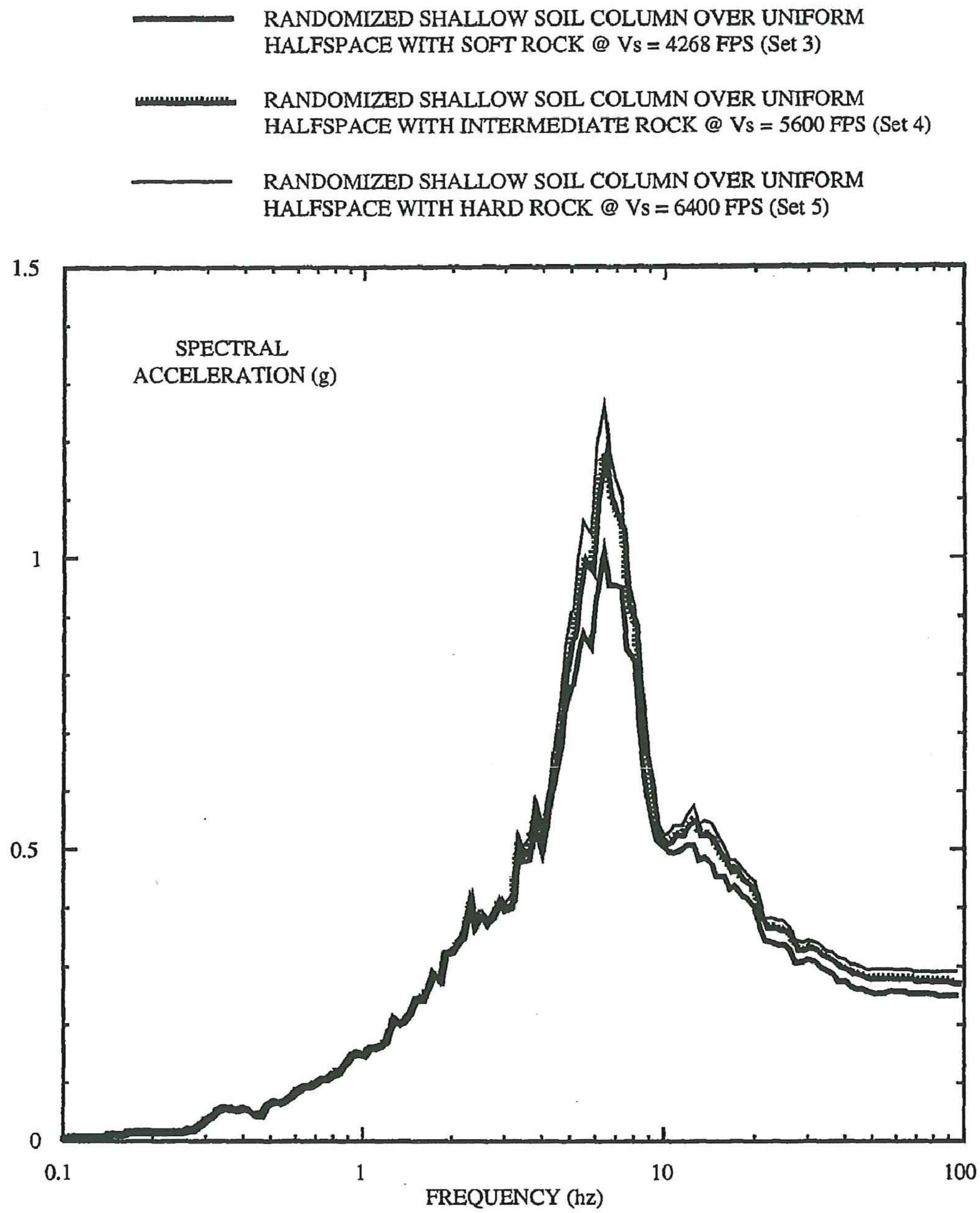

**Figure F-6.** Soil surface spectra from randomized soil columns over uniform half-space.

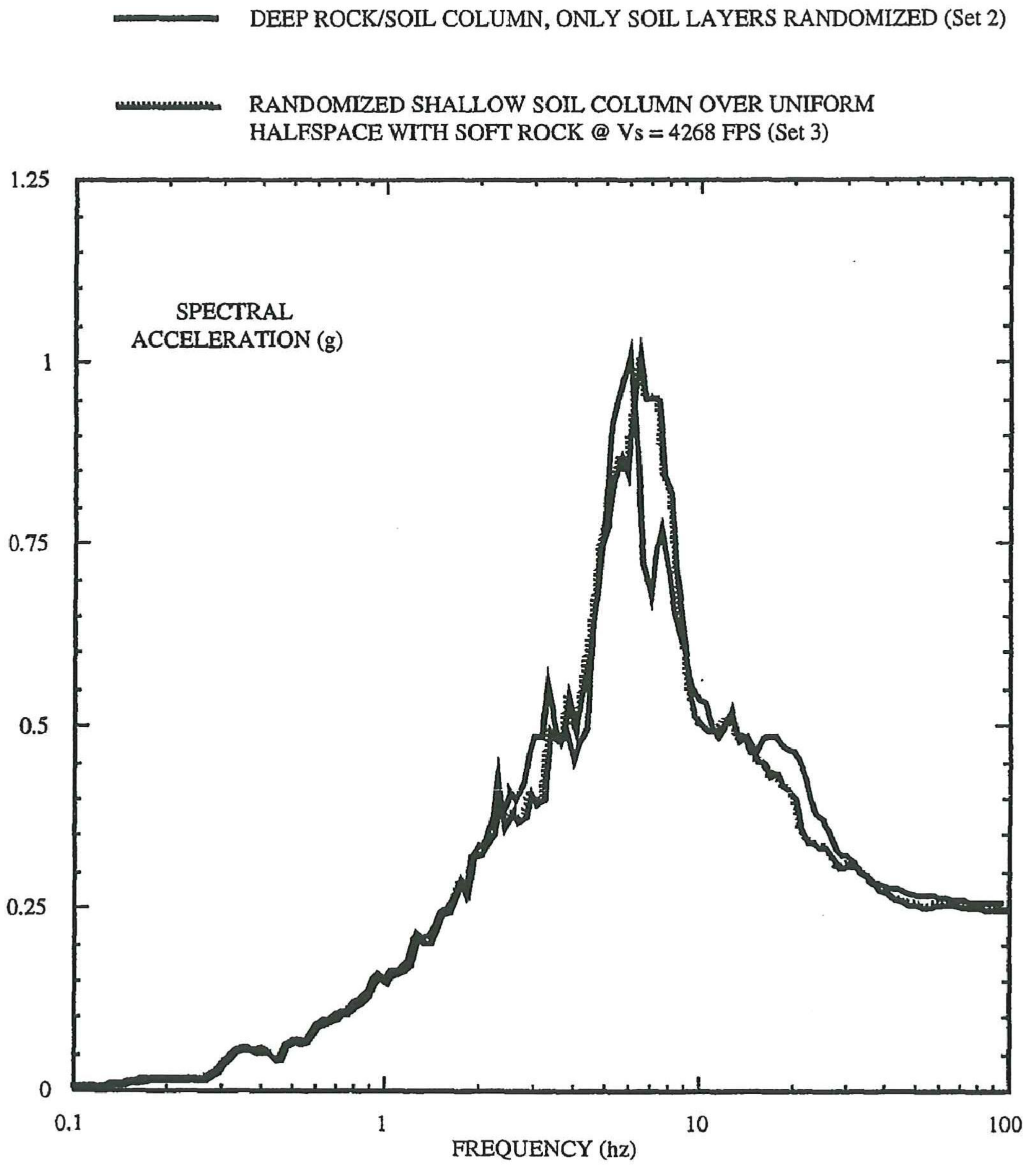

**Figure F-7.** Soil surface spectra from randomized soil columns.

## F.5 Conclusions

Based on these calculations, the following conclusions can be drawn. For any one deterministic calculation of column response, the effect of the interbeds causes an increase in the spectral peak of the order of 25% over that which would normally be calculated assuming a uniform rock half-space. However, incorporating uncertainty in material properties into the calculation within the Monte Carlo process removes this exceedance. The spectral shapes are so peaked for these relatively thin soil covers considered that the averaging process reduces these effects. It is concluded that any increase in mean surface spectra caused by the impact of the deeper interbed layers is not significant when compared to results generated assuming a uniform rock half-space. Incorporating uncertainty in both the rock, interbed soils and surface soils of the soil columns produces a computed mean spectrum which has a peak value somewhat lower than would result from a calculation considering uncertainty in the surface soils alone. Finally, it should be noted that data from a number of tests performed on rock samples taken in the local area indicate a variation in density from 125 pcf to 180 pcf and uniaxial compressive strength from 4,000 psi to 17,000 psi (Per. Comm. T. Houston, 2000). It is presumed that such variability will also carry over to in situ shear wave velocity. This implies that the COV used in these calculations is much too low, further reducing the peak spectral values from those computed herein.

## F.6 Recommendation

As a result of these calculations, the following recommendation is made. For response studies performed at sites similar to those considered herein, that is, sandy gravelly soils similar to those at CPP-651 and with total thicknesses above bedrock of the order of about 18 m (60 ft) or less, the normal analysis procedures can be used. The INEEL PC 3 and PC 4 DBE rock motions can be treated as normal outcrop motions at the top of a uniform half-space, provided that randomization techniques are used to determine mean soil surface spectra. The limitation of 18 m assigned to the total soil thickness can probably be extended to 30 m, but no calculations are available to support this contention. Similar conclusions can probably also be applied at sites where the soils are predominantly silts and clays since the key issue is parameter uncertainty which serves to reduce the spectral peaks. Again, no specific calculations are available to support this contention. The rock velocity used in these calculations should be selected based on an appropriate site average value of not less than 1100 m/s.