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CONSISTENT SITE RESPONSE - SSI CALCULATIONS

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ABSTRACT

This report presents recommendations that are intended to provide guidance for performance of deterministic soil-structure interaction (SSI) analyses that are consistent with the ground motions generated as part of the probabilistic site response analyses typically performed for generation of site-specific uniform hazard spectra. The site response calculation is intended to generate the ground response spectra defined at some elevation in the site profile which is intended to be compared with the response spectra used for the facility design. In addition, the site response analyses are intended to generate the best estimate, upper bound and lower bound soil velocity and damping profiles used to define the site characteristics in the SSI analyses. In the site response calculations, all nonlinear soil strain effects need to be included. The resulting iterated velocity and damping profile is used directly in the SSI calculation with no further nonlinear soil behavior considered. The consistency between these calculations is critical to ensure that the seismic demands on the facility are conservatively calculated. Numerical problems may be encountered when these response spectra are defined at different elevations in the site profile and therefore need to be transferred to mutually convenient depths for comparison with the design response spectra.

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1 INTRODUCTION

This report summarizes recommendations that are intended to provide guidance and evaluation procedures that can be used for performing deterministic soil-structure interaction (SSI) analyses (typically performed with the SASSI computer code, Lysmer et al, 2000) using as input the ground motion output from probabilistic site response calculations. For a given site, the probabilistic site response calculations are typically performed to generate a mean estimate of the Uniform Hazard Spectrum (UHS) as well as development of best estimate (BE), upper bound (UB) and lower bound (LB) soil columns of iterated site velocity and damping profiles. The procedures used in these probabilistic site response analyses are those described in NUREG/CR-6728 (McGuire et al, 2001). The SASSI SSI calculations then use these three site profiles, defined in terms of their iterated velocity and hysteretic damping profiles, directly as input to this linear code, with no further nonlinear strain iteration performed. The ground motion time history to the SASSI calculation is determined from the UHS defined from the site response analysis. For correctness of the complete analyses, it becomes essential to ensure that the details of the deterministic SSI calculations, both the site profiles and corresponding time history, are consistent with the results from the site response analyses.

The ground motion input to these deterministic SASSI SSI computations depends to a great extent on the analyses being performed (generic design for a wide range of site conditions or a site-specific evaluation) and at what elevation level the input ground motion is defined. With the advent of the performance-based criteria defined in RG 1.208 (2007), input ground motions can be defined at different elevations in the site profile. The transfer of these motions to different elevations needed for the SSI analyses require careful consideration of the details of the analyses to ensure that the resulting computed responses are consistent with the site response input. The analyses performed for site response and SSI are typically performed by different organizations with inconsistencies sometimes found upon detailed review.

The ground motion response spectra that have been defined recently in the new performance-based criteria presented in RG 1.208 are:

1. Certified Seismic Design Response Spectra (CSDRS)
2. Ground Motion Response Spectra (GMRS)
3. Foundation Input Response Spectra (FIRS)

The CSDRS are site-independent seismic design response spectra that have been approved under Subpart B, "Standard Design Certifications," of Title 10, Part 52, "Early Site Permits: Standard Design Certifications; and Combined Licenses for Nuclear Power Plants," of the *Code of Federal Regulations* (10 CFR Part 52) as the seismic design response spectra for an approved certified standard design nuclear power plant. The GMRS are site-specific ground motion response spectra characterized by horizontal and vertical response spectra determined as free-field motions on the ground surface or as free-field outcrop motions on the uppermost in-situ competent material using performance-based procedures. The GMRS are typically being computed from the probabilistic site response analyses described above. The guidance currently presented in NUREG-0800, Section Review Plan, Section 3.7, indicates that when the site-specific GMRS and the CSDRS are determined at different elevations, the site-specific GMRS need to be transferred to the foundation elevations of each seismic Category I foundation. This transfer is needed in order to be able to compare the CSDRS-consistent spectra at the foundation level with the site-specific GMRS defined at the foundation level of each Category I structure. The FIRS are to be derived as free-field outcrop spectra. If the SSI analyses are to be performed using motions defined at the free ground surface, the procedures used to transfer ground motion spectra from the elevation of the GMRS to the FIRS and then onto the free ground surface need to be performed in such a manner to ensure that these motions are consistent. One would expect that the surface spectra generated after transfer between the elevations of the GMRS, the FIRS and then the ground surface result in surface spectra that are essentially the same as would result if the UHS were performed originally with the soil profile defined directly to the ground surface. Since the site response problem is potentially a highly nonlinear problem, particularly for softer soil sites, it is important to ensure that the site response procedures utilized will result in such equivalence.

2.0 OUTCROP DEFINITIONS

One significant issue that needs evaluation or clarification is, in fact, the definition of the term "outcrop" spectra. The guidance provided in the SRP (NUREG-0800) and RG 1.208 indicates that the outcrop spectra need to be determined at the free ground surface with no soil layers above the elevation of the outcrop. However, one might generate outcrop spectra from the various site response codes (e.g. SHAKE, CARES, RASCALS) which include the effects of the soil profile above the elevation of the outcrop. If this is done, the computed outcrop motion can be significantly different from that computed if the outcrop were defined as a true free surface since the effects of the down-coming waves from the profile above the outcrop elevation are included in the response at the outcrop elevation. These effects will tend to reduce the computed peak outcrop motions as will be seen from some examples presented herein. The resulting motions may then serve to reduce input into the SSI analyses and therefore reduce computed seismic demands and in-structure response spectra (ISRS) on the facility being designed.

Using the general approach described in the SHAKE Users Manual (1972) or by Kramer (1996), the difference between the two outcropping motions can be illustrated by a simple one-dimension system with two soil layers over an elastic layer of rock that extends to infinite depth, as illustrated in Figure 1a. Each layer is homogeneous and isotropic and is characterized by thickness h, density ρ, complex shear modulus G^*, and s-wave velocity β. If the subscripts *1*, *2*, and r refer to the two soil layers and rock, respectively, the horizontal displacements due to vertically propagating harmonic s-waves in each material can be written as

$$u_1(z_1,t) = A_1 e^{i(\omega t + k_1^* z_1)} + B_1 e^{i(\omega t - k_1^* z_1)} \tag{1}$$

$$u_2(z_2,t) = A_2 e^{i(\omega t + k_2^* z_2)} + B_2 e^{i(\omega t - k_2^* z_2)} \tag{2}$$

$$u_r(z_r,t) = A_r e^{i(\omega t + k_r^* z_r)} + B_r e^{i(\omega t - k_r^* z_r)} \tag{3}$$

where the first term represents the incident wave travelling in the negative z-direction (upwards) and the second term represents the reflected wave traveling in the positive z-direction (downwards), ω is the circular frequency of the harmonic wave, and k^* is the complex wave number. The shear stress on a horizontal plane is

$$\tau(z,t) = G^* \frac{\partial u}{\partial z} \tag{4}$$

and since no shear stress can exist at the ground surface (z_1=0):

$$\tau_1(0,t) = G_1^* \frac{\partial u_1(0,t)}{\partial z_1} = 0 \tag{5}$$

Substituting Equation (1) into Equation (5) and differentiating results in A_1=B_1. Similarly, applying the compatibility of displacements and continuity of stress at the other two interfaces

$$u_1(z_1 = h_1) = u_2(z_2 = 0) \text{ and } \tau(z_1 = h_1) = \tau_2(z_2 = 0) \tag{6}$$

$$u_2(z_2 = h_2) = u_r(z_r = 0) \text{ and } \tau(z_2 = h_2) = \tau_r(z_r = 0) \tag{7}$$

results in equations for the amplitudes of the incident and reflected waves in layer 2 and the rock halfspace

$$A_2 = \frac{1}{2} A_1[(1+\alpha_{12}^*)e^{ik_1^*h_1} + (1-\alpha_{12}^*)e^{-ik_1^*h_1}] = a_{12}(\omega)A_1 \tag{8}$$

$$B_2 = \frac{1}{2} A_1[(1-\alpha_{12}^*)e^{ik_1^*h_1} + (1+\alpha_{12}^*)e^{-ik_1^*h_1}] = b_{12}(\omega)A_1 \tag{9}$$

$$A_r = \frac{1}{2} A_2(1+\alpha_{2r}^*)e^{ik_2^*h_2} + \frac{1}{2} B_2(1-\alpha_{2r}^*)e^{-ik_2^*h_2} \tag{10}$$

$$B_r = \frac{1}{2} A_2(1-\alpha_{2r}^*)e^{ik_2^*h_2} + \frac{1}{2} B_2(1+\alpha_{2r}^*)e^{-ik_2^*h_2} \tag{11}$$

where

$$\alpha_{ij}^* = \frac{G_i^* k_i^*}{G_j^* k_j^*} = \frac{\rho_i \beta_i^*}{\rho_j \beta_j^*}$$

is the complex impedance ratio.

2.1 Correct Outcrop Motion

If a vertically propagating shear wave of amplitude A_r traveled upward through the rock and the soil was not present, the free surface effect at the rock outcrop would produce a bedrock outcropping motion of amplitude $2A_r$ as shown in Figure 1c. Similarly, if we remove layer 1, then the amplitude of the motion at the surface of layer 2 would be $2A'_2$, where the prime indicates a different amplitude for the new single layer system over a rock halfspace, as shown in Figure 1b. Defining the transfer function as the ratio of the layer 2 soil surface amplitude to the rock outcrop amplitude and substituting $A'_2$for A_2 and B_2 in Equation (10) gives

$$F'(\omega) = \frac{2A_2'}{2A_r} = \frac{2}{(1+\alpha_{2r}^*)e^{ik_2^*h_2} + (1-\alpha_{2r}^*)e^{-ik_2^*h_2}} \tag{12}$$

For the case where the GMRS is defined as the free surface motion of the uppermost competent soil layer (i.e., layer 2 for our simple system), Equation (12) gives the correct transfer function that should be applied to the input rock motion to obtain the correct competent layer free surface motion.

2.2 Approximate Outcrop Motion

If on the other hand we do not remove layer 1, which can be thought of as a fill layer, before determining the outcropping motion at the surface of the uppermost competent soil layer (layer 2), we will obtain an approximate outcropping motion. This is the case for the various site response codes, which simply define the outcropping motion as two times the incident wave at any layer. For the case of a free surface, the incident wave and reflected wave are equal and the result is a true outcropping motion. However, if layer 1 is not removed, then the incident and reflected wave amplitudes in the competent layer are influenced by the wave field in layer 1. Defining the transfer function as the ratio of the layer 2 soil surface amplitude to the rock outcrop amplitude for this case gives

$$F(\omega) = \frac{2A_2}{2A_r} = \frac{2a_{12}(\omega)}{a_{12}(\omega)(1+\alpha_{2r}^*)e^{ik_2^*h_2} + b_{12}(\omega)(1-\alpha_{2r}^*)e^{-ik_2^*h_2}} \tag{13}$$

Comparing Equation (13) to Equation (12) shows that the transfer function for the approximate outcrop motion has terms from the overlying layer 1, which will produce a different outcropping motion after application to the input bedrock motion. The transfer function for the approximate outcrop motion converges to the correct function as the layer 1 thickness, $h1$, approaches 0 and the complex impedance ratio, α_{12}, approaches 1.

The difference between the two results is also shown by determining the reflection and transmission coefficients, *R* and *T*, for different layer 1 and layer 2 soil properties. For normally incident horizontally polarized shear wave (SH), the reflection and transmission coefficients are given by

$$R = \frac{B_2}{A_2} = \frac{\rho_2\beta_2 - \rho_1\beta_1}{\rho_2\beta_2 + \rho_1\beta_1} \tag{14}$$

$$T = \frac{A_1}{A_2} = \frac{2\rho_1\beta_1}{\rho_2\beta_2 + \rho_1\beta_1} \tag{15}$$

Obviously, for the case where layer 1 is removed before calculating the outcrop motion $R = 1$ and $T = 0$. For each of the examples shown later in Section 4, we have determined values for R and T to highlight the contrast between the true and approximate outcropping motions.

It should also be noted that such a definition that includes the effects of down-comers in the site response analyses is different from that which is often considered in site hazard analyses. For example, when performing PSHA calculations to generate bedrock or hard rock UHS spectra, the soil column is never incorporated on top of the rock profile. The rock surface is treated as a free surface in the site response analyses to generate the rock hazard. The advantage of this definition is that the bedrock UHS can then be used directly as input to any soil profile that is placed on top of the bedrock to generate the UHS at the top of soil that is consistent with the bedrock UHS. Such a process is typically done at sites where a number of critical facilities may be located, each having different soil conditions beneath their foundation. If, however, the GMRS or FIRS is computed at depth in a soil profile including the effect of the soil layers above, it cannot be used as input to any other site soil profile if the velocity profile of the soil column above the elevation of the GMRS or FIRS is modified from that originally used in its development.

Several additional issues need to be considered in the site response calculation. First, if the GMRS is to be computed at some depth in the soil profile and the soil above the elevation of the outcrop elevation is not incorporated into the site column response calculation, the effect of weight of this soil on producing confinement needs to be captured in the calculation. Since the soil behaves in a nonlinear fashion, the effect of this added confining pressure will play a significant role in computing nonlinear properties of the soil. Therefore, the weight of the soil column above the outcrop elevation needs to be included in all computation of overburden pressures to ensure that the nonlinear effects computed in the strain iteration process is done consistently to match the final configuration of the site profile.

Secondly, any convolution or deconvolution that needs to be performed to transfer the FIRS or GMRS to different elevations or the free ground surface should make use of the actual soil profiles between these elevations. Often, the transfer process makes use of the strain iterated soil properties output from the site response phase of the calculations and the motion transfer is made in the SSI phase of the analysis. The iterated site profiles from the site response problem are considered to be linear elastic velocity profiles in the deterministic SASSI analyses. However, there may be other cases where the strain iterated values are not available for portions of the site column above the elevation of the GMRS and iteration must then be performed within the transfer process. The recommended transfer procedures described later in this report have tried to capture these effects to obtain a consistent set of procedures for each case being evaluated.

3.0 SIMPLIFIED SITE RESPONSE CHARACTERISTICS

Before moving on to the details of the motion transfer process, three simple site response calculations were performed to try to indicate the impact of varying site profile characteristics on computed surface and FIRS spectra. These response calculations were performed deterministically (that is, only one response calculation was performed for each profile) and nonlinear strain effects were neglected. In each case, the site is divided into three layers or zones, namely, Layer 1 from the ground surface down to a depth of 15m, Layer 2 from the depth of 15m down to the top of the elastic halfspace at a depth of 40m (25m thickness) and a uniform elastic halfspace of constant velocity below. The definition of outcrop level in these problems assumes no soil above the outcrop level. In the first problem (Case 1 Soil Column of Figure 1), all properties (velocity, unit weight, material damping, etc.) of all soil layers are set equal to each other so that in fact the result is a single uniform profile. The input motion is defined as a FIRS motion (motion H1) that is then deconvolved as an outcrop down to the top of the elastic halfspace to generate the corresponding outcrop motion at the top of the elastic halfspace (H2). This H2 outcrop motion is then convolved upward to the free ground surface to generate the surface response (H3). As a check, the surface motion H3 is then deconvolved back down to the foundation level at 15m to generate an outcrop motion at this depth (H4 motion). As can be seen from the corresponding spectra plot, the spectrum of the outcrop motion H2 at the top of the elastic halfspace at the 40m depth is somewhat larger than that of the input at the foundation level, particularly at higher frequencies due to material damping effects. However, its spectral shape is consistent with that of the input H1 motion. The spectrum of the surface H3 motion is somewhat lower than the H1 spectrum due to the same effect. The deconvolution back down to the foundation level gives back the input (H4 equals H1) as expected for this uniform velocity profile problem.

The Case2 Soil Column of Figure 2 was run exactly the same way, except now the upper layer (Layer 1) was made softer while Layer 2 and the halfspace properties were kept the same. The results indicate that the H2 motions at the 40m depth are the same as the Case 1 Soil Column H2 motions, but the H3 surface motions are now significantly different due to the different frequency characteristics of Layer 1. The deconvolution back down to the foundation level (H4) results again in the same H1 motion as for the Case 1 Soil Column. The surface motions (H3) associated with the H1 motions are now significantly different than for Case 1 due to the change in velocity profile of the soil column. Therefore, one would expect the FIRS generated for a variable soil profile from a given GMRS to be significantly different from the corresponding result for a uniform soil column.

The third case (Case 3 Soil Column of Figure 3) again used the same process, but now one in which the properties of the uniform halfspace were made stiffer than the other layer properties (as is typically the case in site response analyses). In addition, the deconvolution from the surface motion (H3) no longer gives back the input motion (H1). The H4 spectrum is now significantly different from the original H1 input motion. This result indicates first that the surface motion associated with a given FIRS input is very sensitive to the details of the site velocity profile. In addition, the development of the FIRS from the GMRS must characterize the entire soil column down to and including the uniform halfspace. One cannot simply convolve the FIRS (H1) up to the ground surface considering the soil column above the foundation level alone. If one were to do this, the result would be a surface spectrum that is significantly lower than the correct H3 spectrum. Therefore, any linear SASSI SSI analysis conducted without performing this step correctly could result in an unconservative estimate of seismic demands. In the procedures recommended for the various cases that are considered in the following sections, the uniform halfspace is always included in the definition of the soil column.

4.0 IMPACT OF OUTCROP DEFINITIONS ON COMPUTED SPECTRA

To try to quantify the effect of the differences between outcrop definitions on computed response spectra, a number of site convolution calculations were performed and outcrop spectra computed both including and removing the soil column above the foundation level from the calculation. These computations were all computed with one response code (SHAKE), although previous results have shown that the various codes generate essentially the same responses with some minor differences resulting from differences in details of the individual calculations. As before, the calculations were performed linearly to simplify the analyses.

In these calculations, the responses of a site column were generated two ways as indicated in Figure 4. In the first case (Soil Column 1), a given rock outcrop motion was input at the top of a uniform halfspace and the corresponding surface and FIRS responses at a depth of 50 feet below the surface generated including the effect of soils above the foundation elevation. This outcrop spectrum is labeled the FULL COLUMN OUTCROP spectrum. In the second case (Soil Column 2), the top 50 feet of the soil is removed and the corresponding free surface motion generated at the same depth of 50 feet. This outcrop is labeled the GEOLOGIC OUTCROP motion. The ratio of spectra (GEOLOGIC OUTCROP/FULL COLUMN OUTCROP) is then computed frequency by frequency to measure the effect of the outcrop definitions on the FIRS calculation.

Calculations were performed for seven (7) different input outcrop motions at the depth of the uniform halfspace and five (5) different soil columns. The objective was to try to discern the sensitivity of the results to these different site profiles and ground motion characteristics. Figure 5 presents a plot of the seven different response spectra characterizing the input motions, with the spectra all scaled to 1g. They range from generic low frequency spectral motions (RG 1.60, WUS SOIL 0098), high frequency rock motions (OR510-10K, OR510-25K), an intermediate motion (SRS-PC3) and a very broad-banded low and high frequency combination (HCB1). These motions were taken from a variety of projects evaluated recently.

Figure 6 presents a plot of the 5 soil columns used in the calculations. They range from a relatively soft SRS profile carried to a depth of 300 feet over hard rock, a stiffer YMP profile extended to a depth of 325 feet over intermediate rock and the three 3-layer generic soil profiles used in the previous calculations described previously. The results of the individual calculations are presented in figures shown in Appendices A through E for each soil profile. Figures 7 through 11 present the spectral ratios of Column 2 surface/Column 1 outcrop at 50 feet (or GEOLOGIC OUTCROP/FULL COLUMN OUTCROP). The characteristics of the spectral ratios for each input motion are similar for each profile; namely, the peaks of the outcrop spectrum from Column 2 (GEOLOGIC OUTCROP) are larger than the FIRS spectrum at the same frequency computed at the 50 foot depth in Column 1 but incorporating the down-comer waves from the soil profile above the FIRS level (FULL COLUMN OUTCROP). For these linear problems, the characteristics of the ground motion (low frequency, high frequency, etc.) are relatively unimportant.

Figure 12 presents the same results for a particular input motion (the SRS-PC3 input) to the various soil columns. The amplitudes of the peaks are noted to be extremely sensitive to the characteristics of the site profile (velocity distribution). The more uniform the site, and the stiffer the site, the less the magnitude of the differences between the two outcrop definitions. However, the differences are always there. The more important issue is can these differences be predicted for any given soil profile definition.

5.0 MOTION TRANSFER RECOMMENDATIONS

In the recommendations developed in the following paragraphs, the first consideration presents requirements associated with calculations that need to be included in the PSHA site response calculations. These typically generate iterated soil velocity profiles at the BE, UB and LB levels (associated with the ± one-sigma level). Full nonlinear strain iteration is included in these calculations. If the objective of the PSHA calculation is to compute FIRS spectra or GMRS below the foundation depth, the soil column above the foundation depth must be removed from the randomly generated profiles. However, the full weight of the soil above the soil column needs to be included so as to capture the correct overburden stress effects on the strain calculation. In addition, the effect of the mass and frequency of the soil column above the foundation needs to also be included in this calculation so as to be able to generate proper values of the effective strains in the soil column near the foundation level.

5.1 Case A - Fully Embedded Plant, GMRS at Ground Surface

If the probabilistic response calculations are carried to the free ground surface, the resulting mean surface spectrum corresponds to the site GMRS. The three (BE, UB, LB) soil columns from the site response calculation will correctly include both confinement and mass effects in the entire soil column. The SSI configuration for this case (labeled CASE A) is shown in Figure 13. It will probably be simpler to generate the FIRS after the surface GMRS spectra and site BE, UB and LB soil columns are generated by doing a simpler elastic calculation from the GMRS down to the FIRS using the velocity profiles generated from the GMRS calculations. All soil nonlinear effects are included in the site response calculation and no further strain iteration needs to be included in the SSI calculations.

The velocity profiles used in the three SSI case are taken directly from the BE, UB and LB site profiles. The same GMRS is used to define the input motion for each of the three SSI cases and ISRS spectra are typically generated from the envelope of the three SSI cases. For the generic or certified designs, the objective of the site response calculations is to determine if the GMRS falls below the CSDRS at all frequencies of interest. If the GMRS exceeds the CSDRS at some or all frequencies of interest, further evaluation of the generic design needs to be performed. The remaining check is that the peak acceleration associated with the FIRS is at least 0.1g. Since the CSDRS at the ground surface is typically defined at 0.3g or greater, the PGA associated with the FIRS is expected to be greater than 0.1g based on the results of these calculations.

If the FIRS is to be determined using the GEOLOGIC OUTCROP definition, the GMRS defined at the free ground surface can be deconvolved to the top of the effective uniform halfspace and this motion convolved to the foundation level with the portion of the soil column above the foundation level removed. All the deconvolution/convolution calculations can be performed linearly using the iterated soil profiles generated from the site response calculation for each realization of the site profile used in the probabilistic analyses. The confinement effect due to the weight of soil above the foundation depth is not an issue for this calculation since all these effects have already been properly accounted for in the nonlinear site response calculation.

For this case, the FIRS PGA may be computed from the FULL COLUMN OUTCROP calculation for simplicity rather than the more appropriate but more computationally difficult GEOLOGIC OUTCROP approach. However, the reporting of the FIRS calculation should clearly indicate that the FULL COLUMN OUTCROP method of calculation is used and details of the site profile provided for future use. In addition, the FIRS computed from the FULL COLUMN OUTCROP computation is not considered appropriate to be used for any other SSI studies.

It should be noted that the calculational procedure using the GEOLOGIC OUTCROP definition for development of the FIRS motion for this case includes the following steps:

- The probabilistic site response calculations are carried up the soil column from the uniform halfspace at depth to the free ground surface, and the resulting mean surface spectrum corresponds then to the site GMRS.

- All randomized soil profiles are iterated to fully incorporate nonlinear soil behavior, properly incorporating both confinement and mass effects for the entire soil column. The set of randomized iterated velocity profiles are evaluated to determine the mean (BE) and ± one sigma soil columns (LB, UB).

- The FIRS can be generated by using the same iterated velocity profiles from the depth of the uniform halfspace to the foundation depth, with the soil layers above the foundation level removed from each of the randomized profiles. No further strain iteration is performed in these convolutions. The resulting mean spectrum at the foundation depth is the FIRS and incorporates the effects of the GEOLOGIC OUTCROP at this depth.

- The deterministic motions needed for the SSI calculations for each of the BE, LB and UB soil velocity profiles are generated from the FIRS motion from Step 3. For each of the three deterministic velocity profiles, the FIRS motion is deconvolved down to the uniform halfspace, again with no further strain iteration performed. The motion at the depth of the uniform halfspace is then convolved up the same deterministic profiles but with the iterated velocity profiles from the foundation depth to the ground surface added to the top of these profiles. For each profile case, the output can be generated at the free ground surface or at some depth in the profile as an in-column motion. Either of these motions can then be used directly as input to the SASSI SSI calculation.

- All convolution and deconvolution computations in this process are performed linearly since the velocity profiles generated from the GMRS calculations incorporate all nonlinear effects. No further strain iteration needs to be included in the site profiles used in the SSI calculations.

- It should be noted that using this outcrop definition in the deterministic calculations with the SSI profiles can lead to large computed strains at depth but these have no impact on the computed motions at the free ground surface since no nonlinear effects are incorporated into the process.

5.2 Case B - Surface Founded Plant, GMRS at Ground Surface

In this case, shown in Figure 14, where the foundation is placed at the free ground surface, the GMRS and the FIRS are the same. All nonlinear site response effects are properly included in the probabilistic site response analyses and no further strain effects need to be accounted for. In the SSI calculations, the input motion is the FIRS applied at the soil column free surface. No further motion transfer is needed. For generic facility design, where each SSI calculation is performed for the same configuration (foundation at ground surface, different velocity profiles for a range of potential site conditions), the envelope of seismic demands from the various cases is considered appropriate since the same motion is used as input to each site case.

5.3 Case C - Fully Embedded Plant, GMRS Defined at Foundation Level

In this case, shown in Figure 15, several aspects need to be considered to decide if the SSI analyses are being performed in a compatible way with the probabilistic site response analyses and if the analyses are appropriate for comparison with the CSDRS. If the CSDRS is defined at the foundation level as a FIRS, the definitions must be maintained compatible for each site profile considered so that the input motion to each of the various site profiles can be consistent. This will allow enveloping of the results to be appropriate since each problem is using the same input motion at a given elevation. For each profile, the FIRS or site-specific GMRS computed at the foundation level need to be deconvolved down to an effective uniform halfspace assuming that the soil column above the foundation level is removed. The FIRS is then defined as an GEOLOGIC OUTCROP for each of the site profiles considered in the range of interest. The outcrop at the uniform halfspace then needs to be convolved up to the free surface at ground level for each site to generate the surface motion compatible with the FIRS. These cases can also include enveloping of responses with the surface founded cases (Case B) since they would all have the same input motion. The SSI cases would use the soil profiles appropriate from each of the site columns considered.

The GMRS calculation at the foundation level for a specific site profile needs to include nonlinear probabilistic calculations from rock outcrop elevation to the foundation level neglecting the effect of the soil column above the foundation level, but including its effect on confinement pressure for adequate computation of nonlinear site effects. The adequacy of the strain computation at the foundation level also needs to be considered in this calculation.

If the FIRS are calculated using the FULL COLUMN OUTCROP definition, then inclusion of the results of surface founded (Case B) results would be problematic since they would not be defining the FIRS as a free surface input in each case being considered in the enveloping process. In addition, the individual embedded cases would be using ground surface inputs for each SSI case based on surface motions which are expected to be lower than those that would result from the GEOLOGIC OUTCROP definition as described in Section 4.

5.4 Case D - Fully Embedded Plant, GMRS Defined Below the Foundation Level

This problem definition is shown in Figure 16. The considerations that need to be made for this configuration are similar to those described for Case C except that motion transfer needs to be made to transfer the computed GMRS upward for both the FIRS at foundation level and the free surface motions. In that sense, it is a more complex configuration if the GMRS transferred to the FIRS at the foundation level is going to be compared to the CSDRS for the generic designs. If the CSDRS is going to be defined at the free ground surface, the problem is similar to that of Case A and the issue of the site specific GMRS defined at foundation level or below is unimportant. However, the same site-specific probabilistic site response calculation needs to be used to generate the GMRS to the free surface.

6.0 RECOMMENDATIONS FOR SSI EVALUATIONS CONSISTENT WITH SITE RESPONSE

Some basic considerations need to be made in deciding how to perform both probabilistic site response and deterministic SSI calculations so that the resulting seismic demands used in the designs are considered consistent. The Probabilistic Seismic Hazard Analysis (PSHA) provides ground motion (spectra) and iterated soil profiles (V_s, V_p, D_s and D_p) at the mean and ± one sigma (BE, UB and LB) levels. These are intended to be used directly as inputs into the deterministic SSI analyses. No further nonlinear soil behavior needs to be considered. If the base case soil column in the PSHA site response analyses is carried to the free ground surface (CASE A), the output GMRS can be used directly as input to the SSI analyses. The only need to compute the FIRS is for comparison with 0.1g minimum foundation level PGA. This is a simple linear transfer calculation. Based on these calculations, the issue of considerations of differences between the FULL COLUMN OUTCROP and GEOLOGIC OUTCROP is probably not significant. However, the details of how outcrop motions are calculated need to be clarified for evaluation of the results and future use of the data.

If the base case soil columns used in the PSHA are carried to the foundation level for non-embedded facility configurations (CASE B), the ground motion (GMRS) corresponds to the FIRS (no soil above the foundation level). This allows for direct comparison with the 0.1g foundation criteria as well. However, difficulty may be encountered when comparing results from these surface founded cases with the results from embedded SSI solutions with the CSDRS again defined at the foundation level (CASE C). The difficulties may arise because of inconsistency between the FULL COLUMN OUTCROP and GEOLOGIC OUTCROP definitions in the FIRS computations. If the base case soil columns in the PSHA are carried to a level below the foundation level (CASE D), the computed GMRS corresponds to neither the FIRS nor the surface SSI input motion. The GMRS may also need to be properly transferred to the free ground surface for SSI analysis and to foundation level (FIRS) for comparison with the 0.1g foundation level criteria.

Wherever the GMRS is defined, there is a need to transfer motion to another level(s) properly capturing nonlinear soil effects in the site response characteristics using the full soil profile and the soil columns used for the SSI behavior. For CASES B, C and D described previously, the full weight of soil from the foundation level to the ground surface needs to be properly included for evaluating confinement effects in order to estimate nonlinear soil behavior. The effect of mass above the foundation level also needs to be properly included to evaluate strains in the soil column at and below the foundation level. These issues do not occur in the Case A formulation.

Finally, in transferring the GMRS (or FIRS) from the foundation level to the free ground surface for input to the SSI problem, the entire profile from the foundation level down to an effective uniform halfspace needs to be incorporated into the profile response calculations to ensure that the effects of velocity discontinuities in the profiles are properly captured. However the GMRS and FIRS are calculated and where and how the CSDRS is defined, it is important that analysts, designers and reviewers be aware of the processes being used. The objective is to ensure consistency in the calculations. If any disconnects occur, the conservatism in the calculation of seismic demands can be compromised.

7.0 REFERENCES

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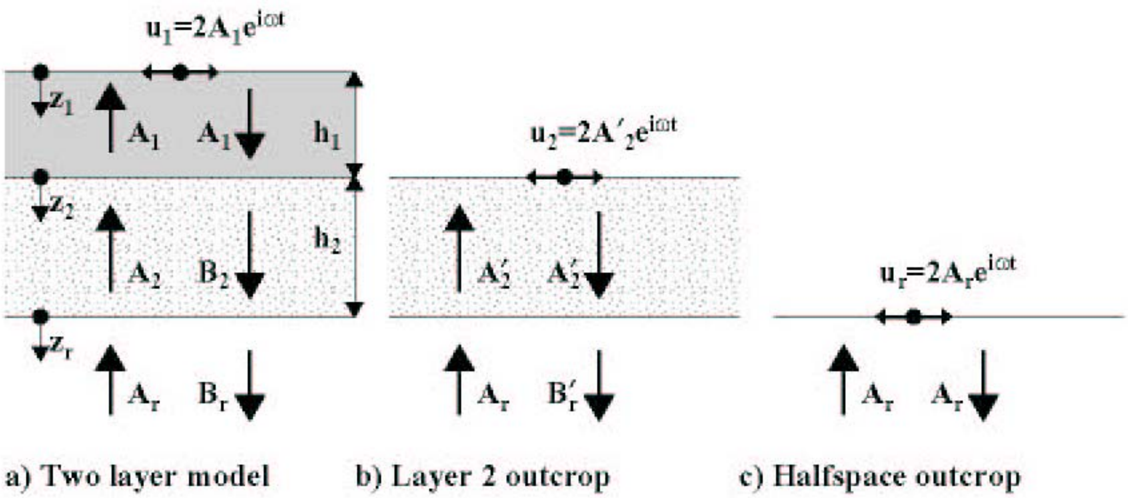


FIGURE 1
ONE-DIMENSIONAL SYSTEM WITH
OUTCROPPING LAYERS

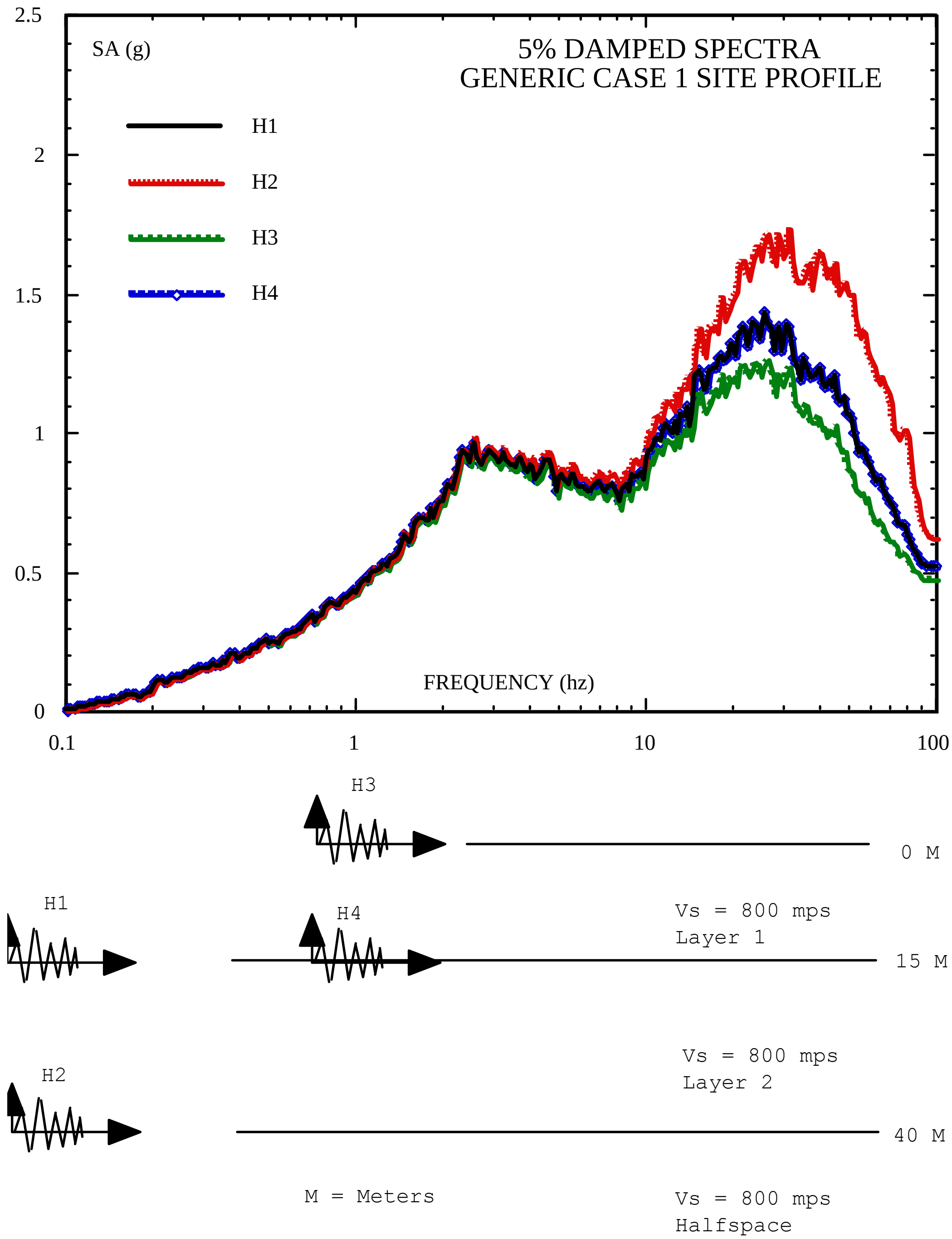


FIGURE 2 SPECTRA FROM GENERIC CASE 1 SITE PROFILE

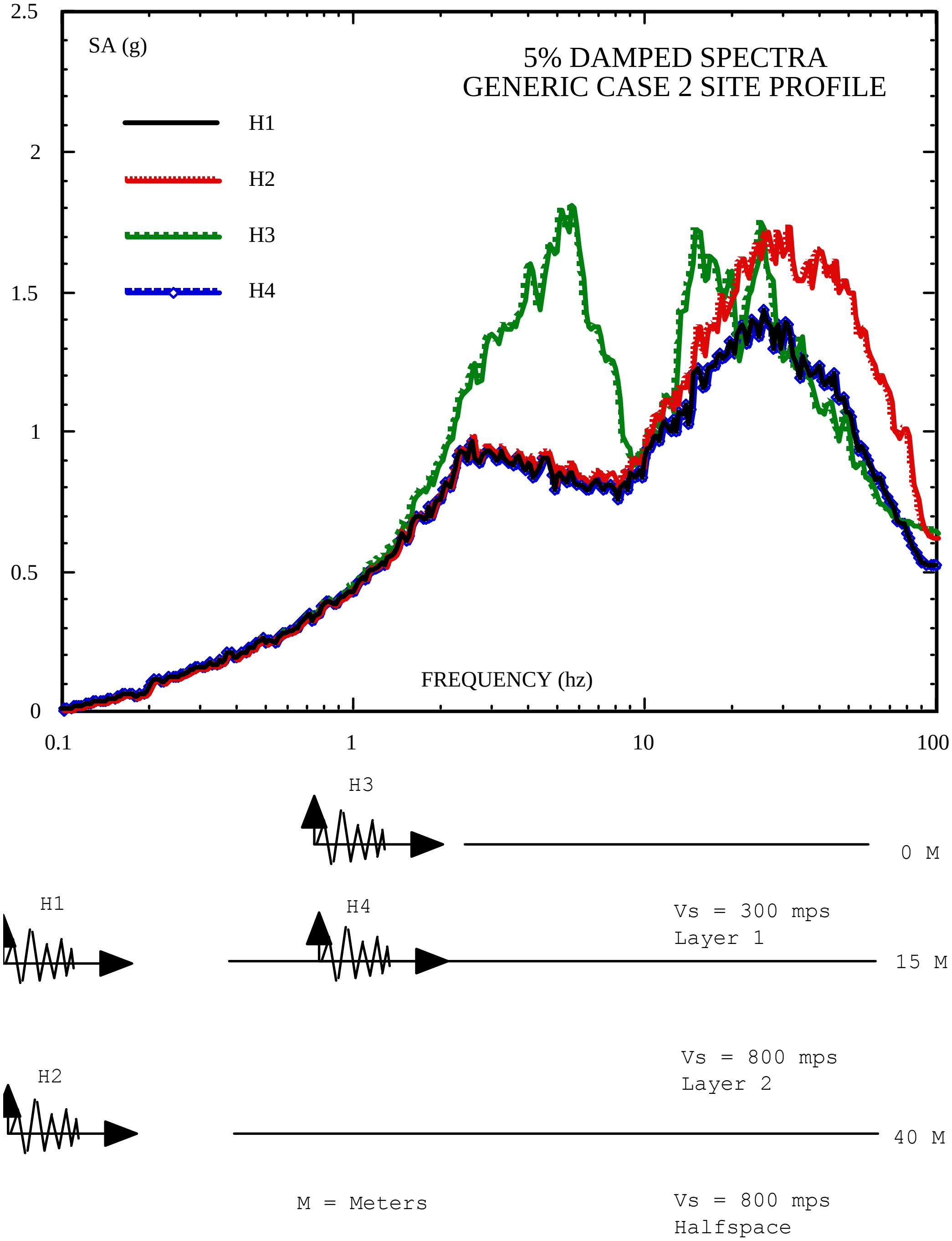


FIGURE 3 SPECTRA FROM GENERIC CASE 2 SITE PROFILE

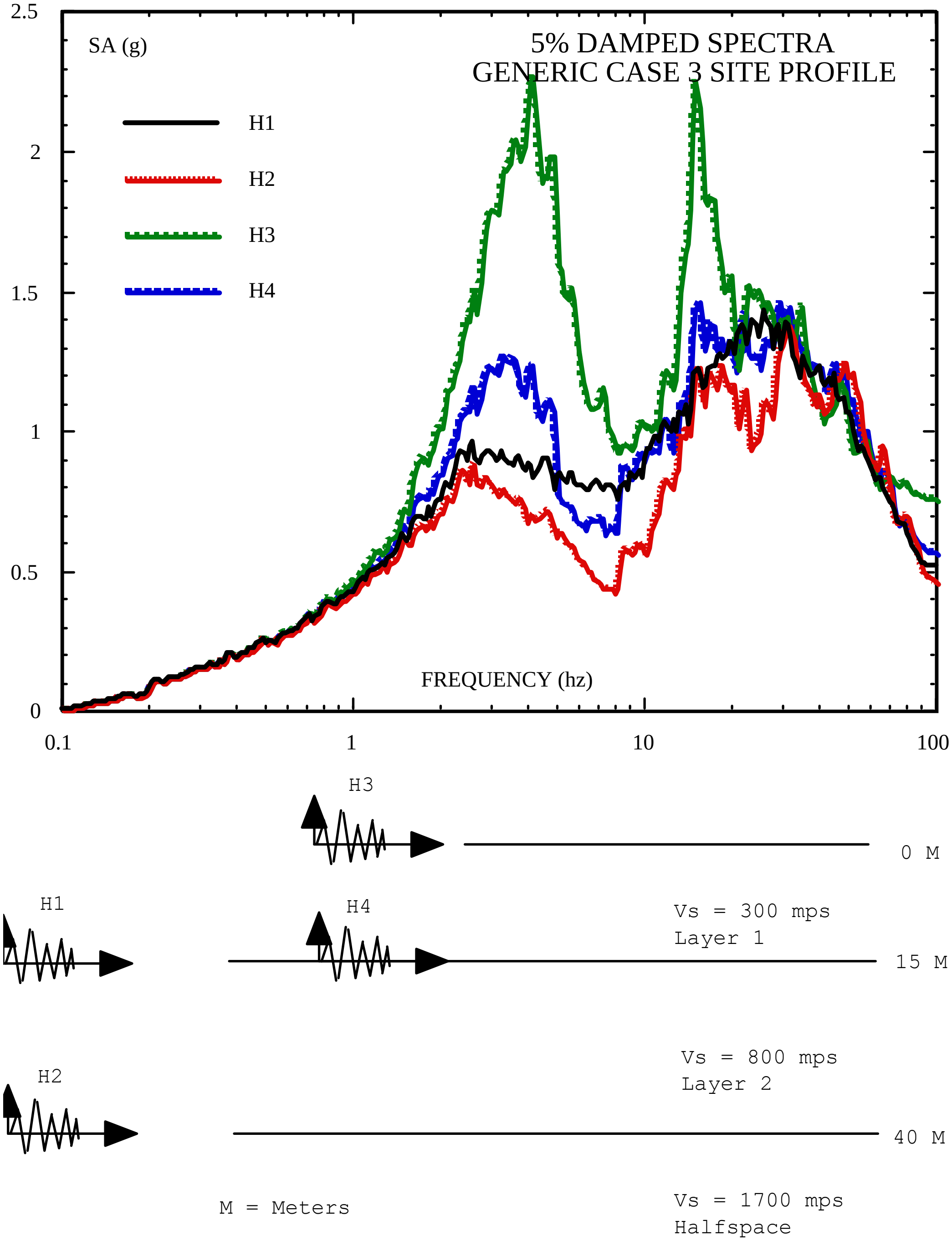


FIGURE 4 SPECTRA FROM GENERIC CASE 3 SITE PROFILE

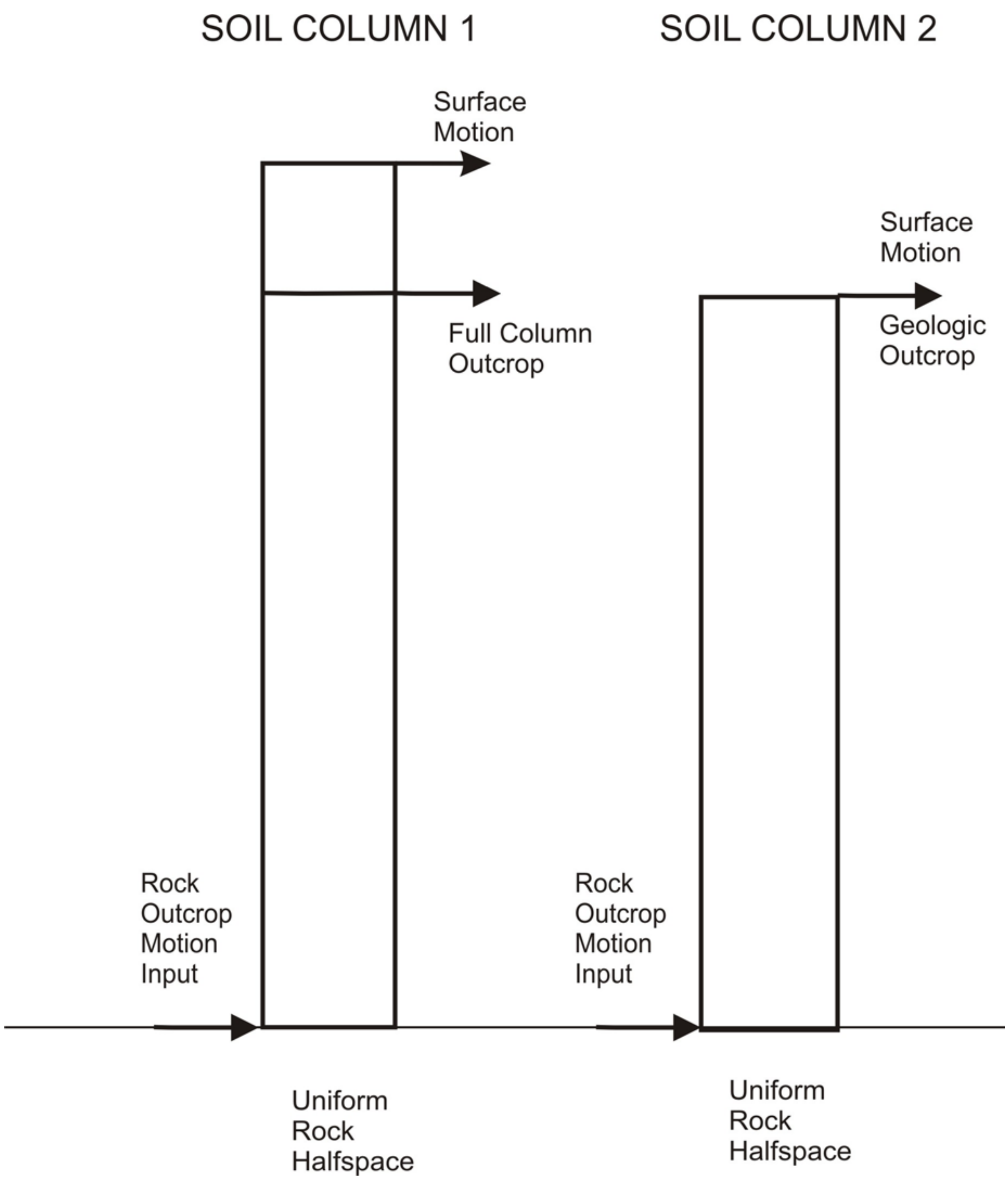


FIGURE 5 COMPARATIVE FIRS COMPUTATIONS

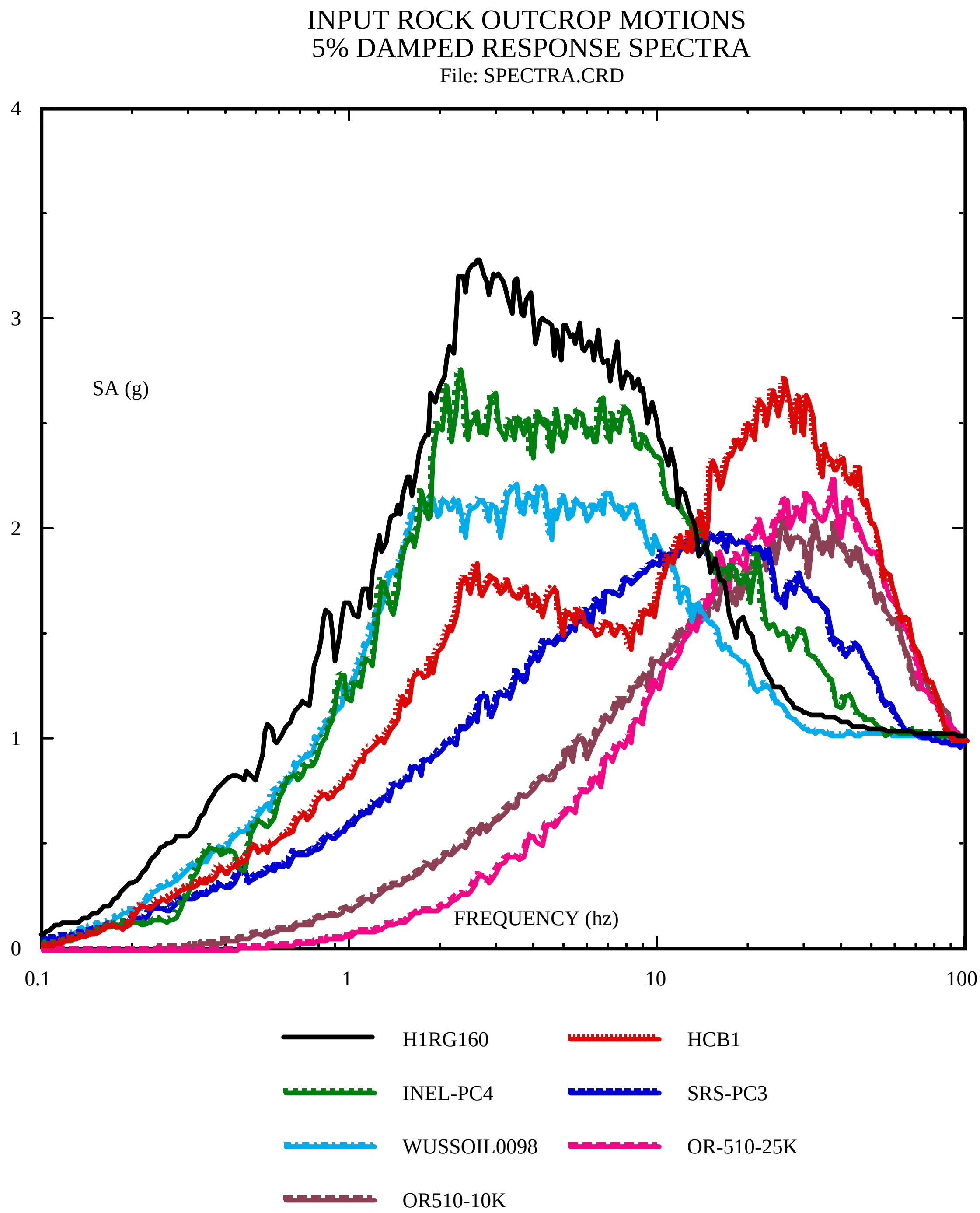


FIGURE 6 RANGE OF ROCK OUTCROP MOTIONS USED

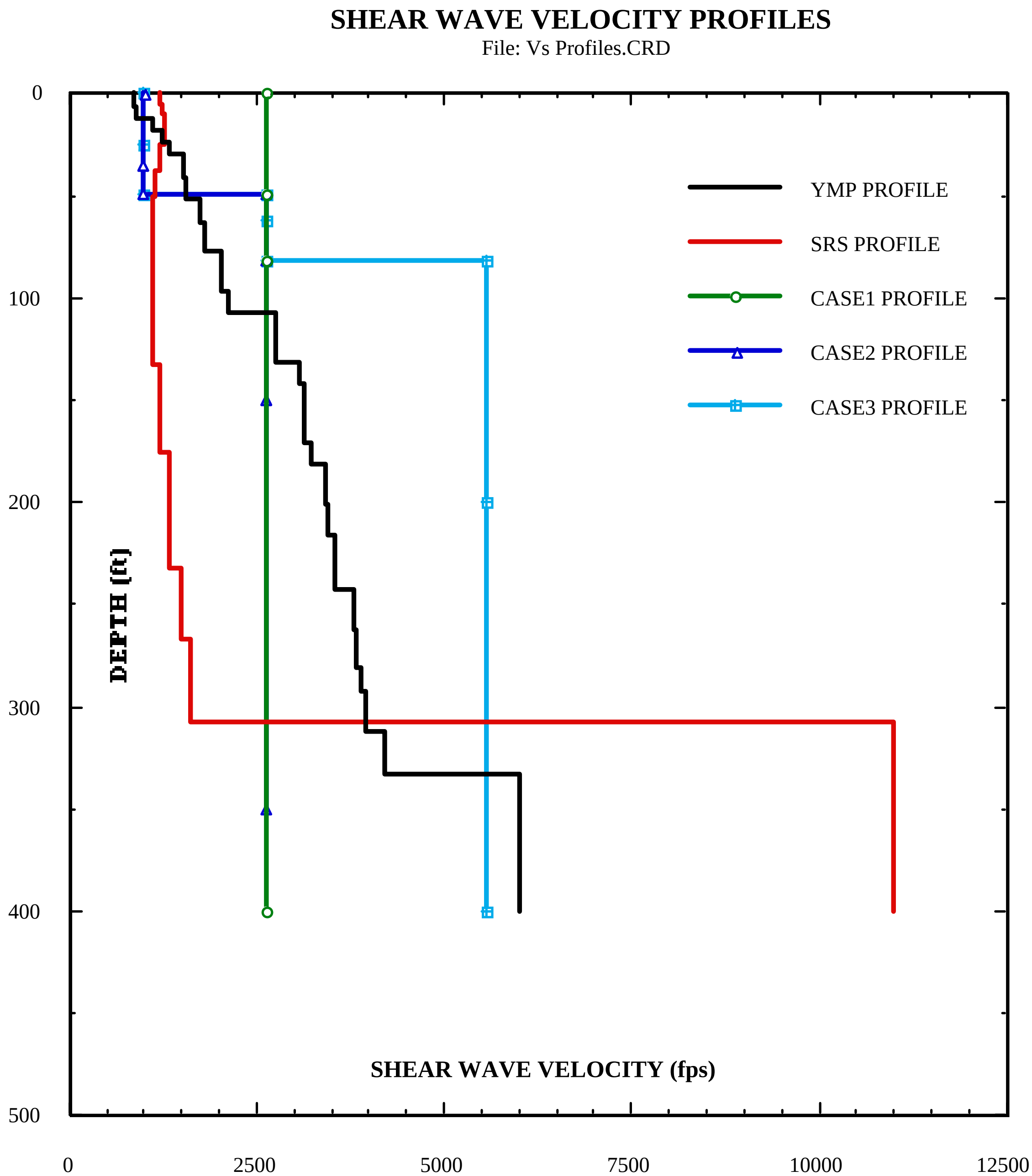


FIGURE 7 RANGE OF SOIL PROFILES CONSIDERED

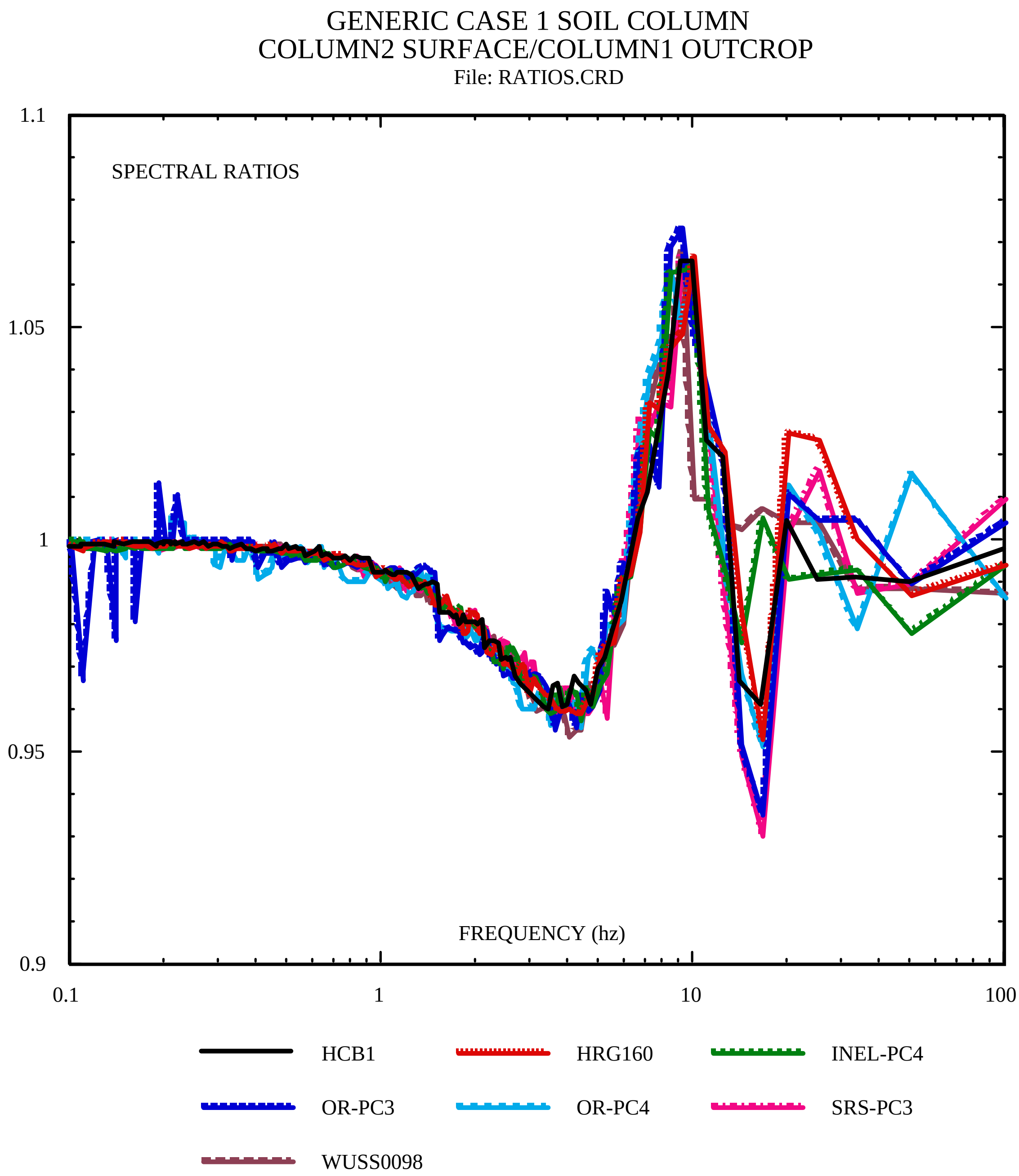


FIGURE 8 RELATIVE SPECTRAL RATIOS GENERIC CASE 1

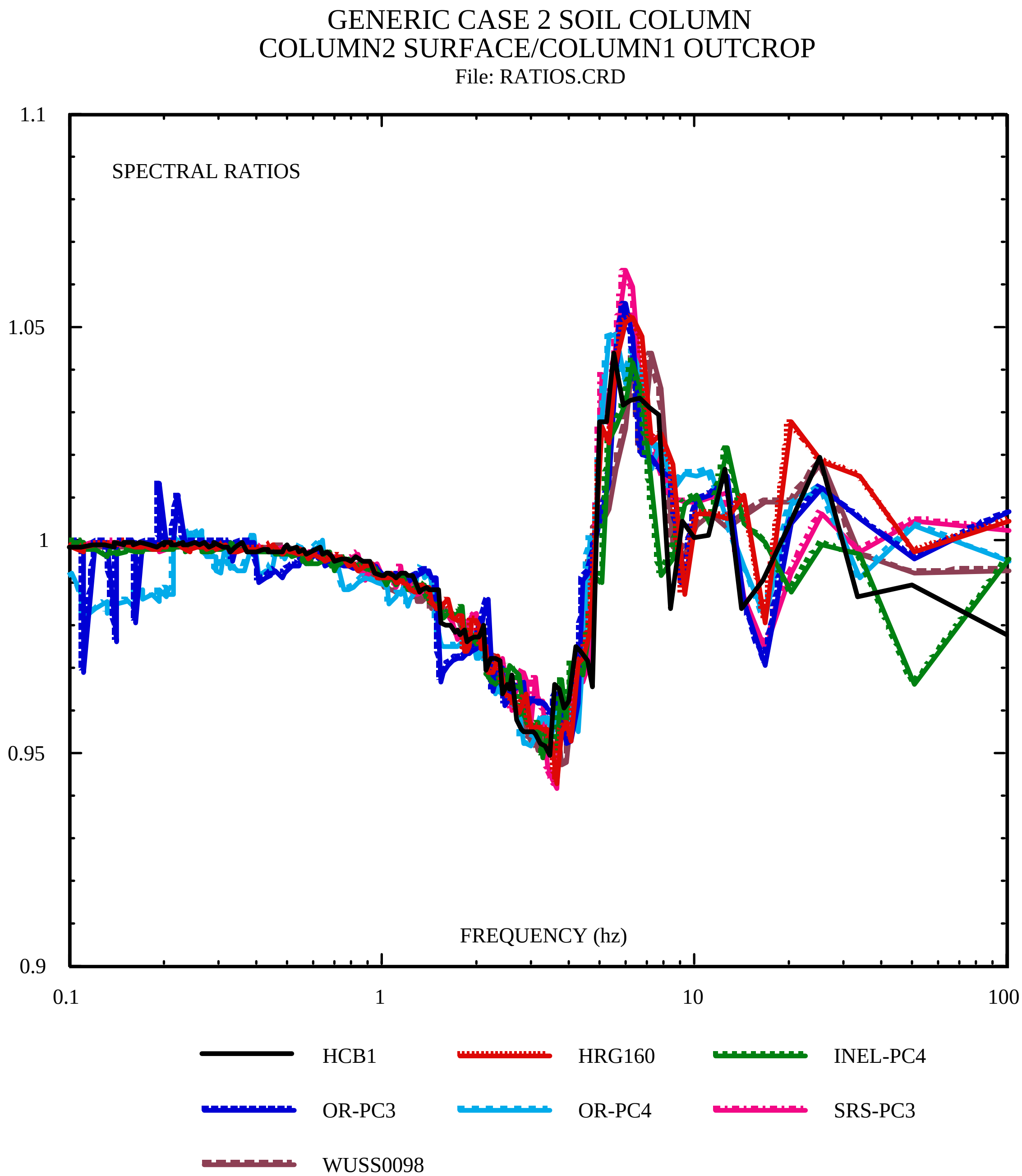


FIGURE 9 RELATIVE SPECTRAL RATIOS GENERIC CASE 2

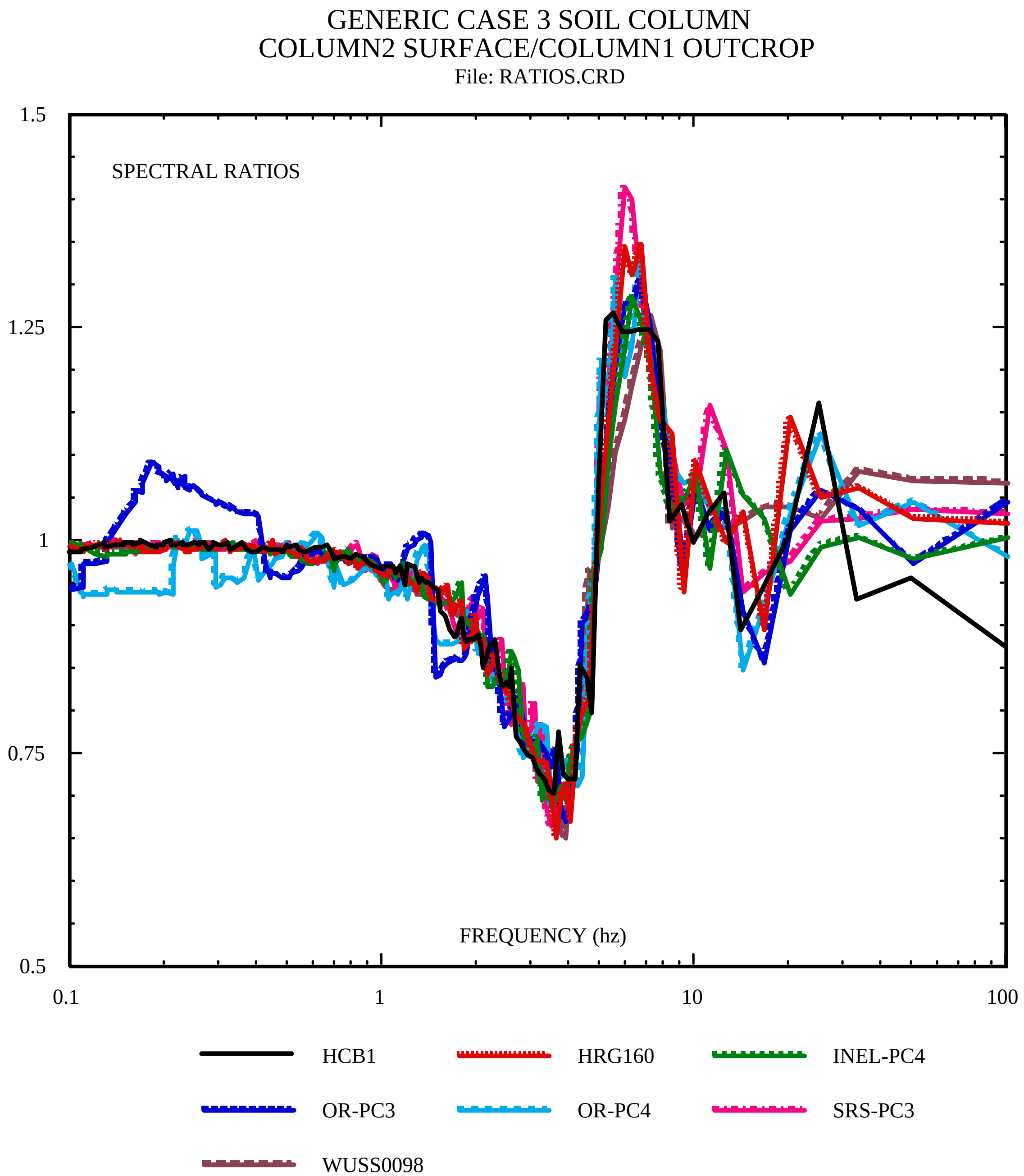


FIGURE 10 RELATIVE SPECTRAL RATIOS GENERIC CASE 3

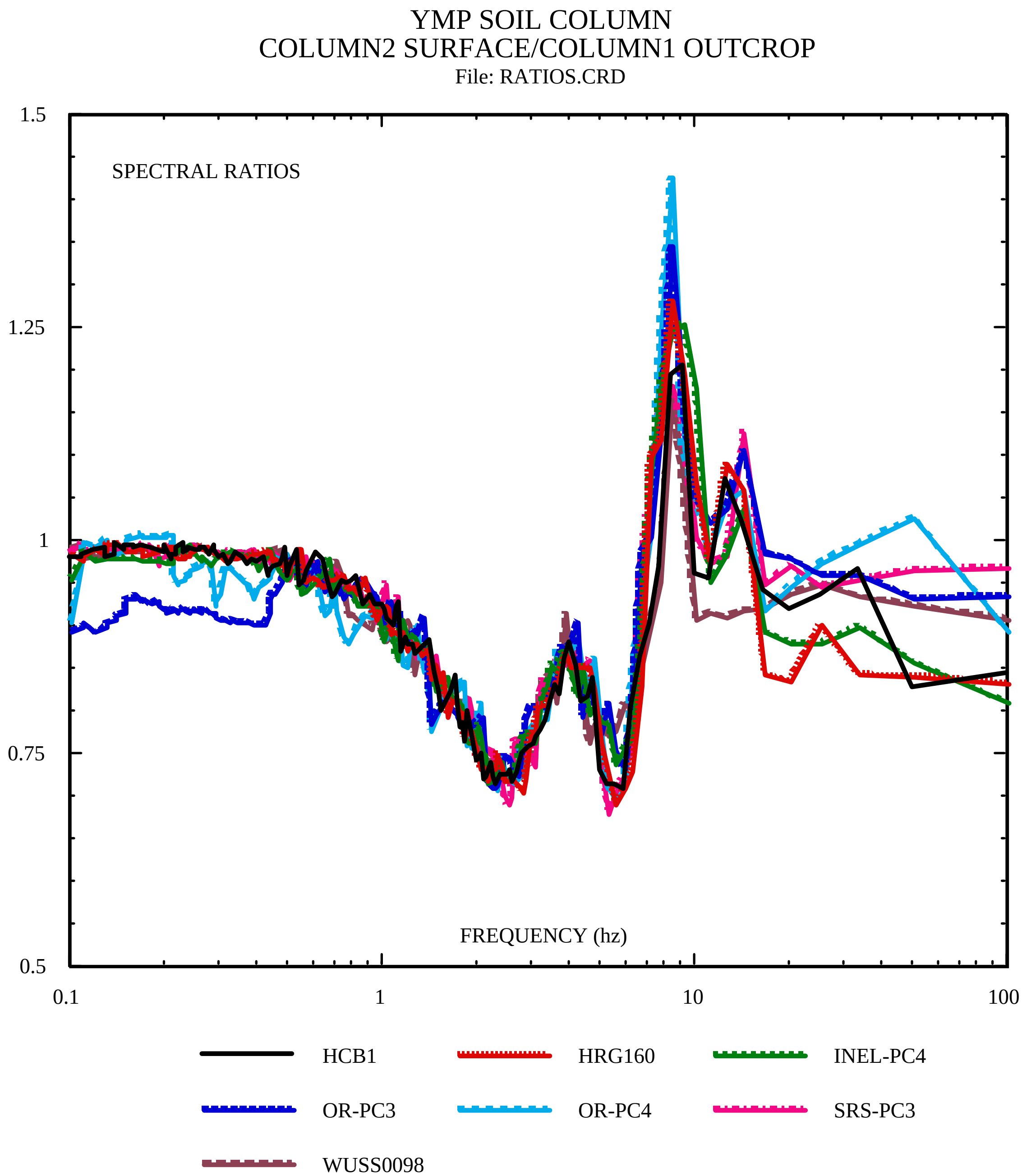


FIGURE 11 RELATIVE SPECTRAL RATIOS YMP SOIL COLUMN

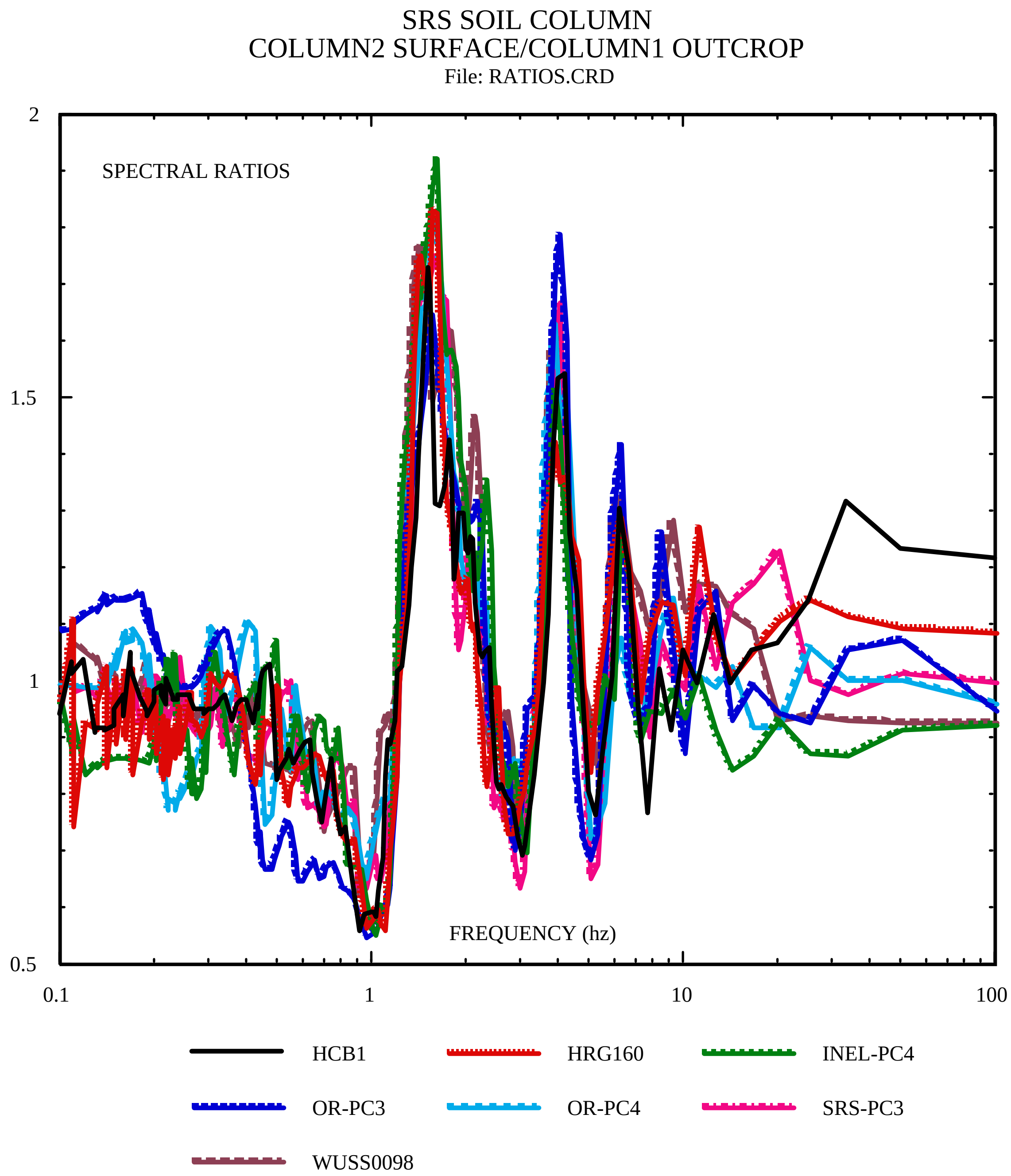


FIGURE 12 RELATIVE SPECTRAL RATIOS SRS SOIL COLUMN

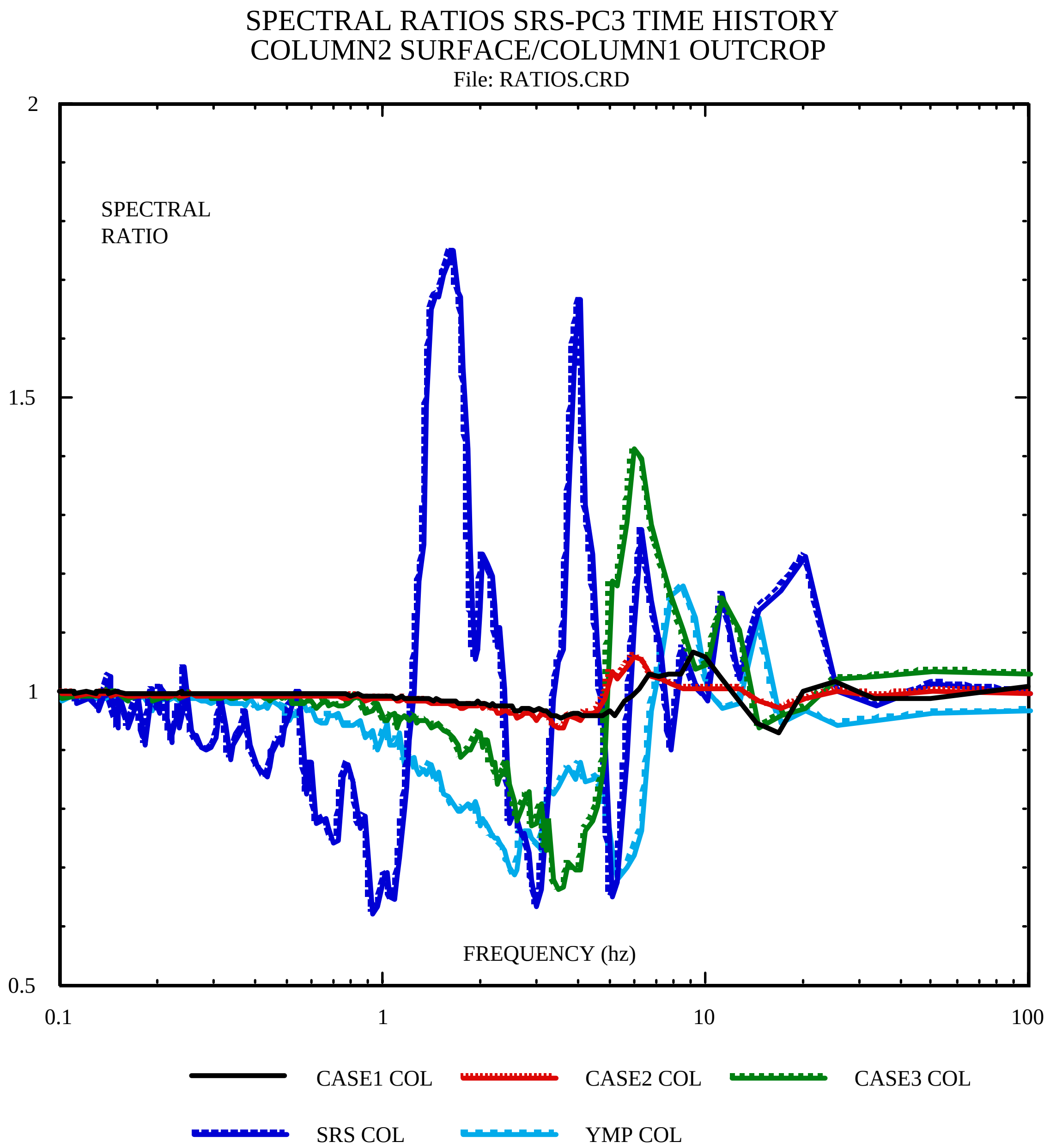


FIGURE 13 RELATIVE SPECTRAL RATIOS SRS-PC3 TIME HISTORY

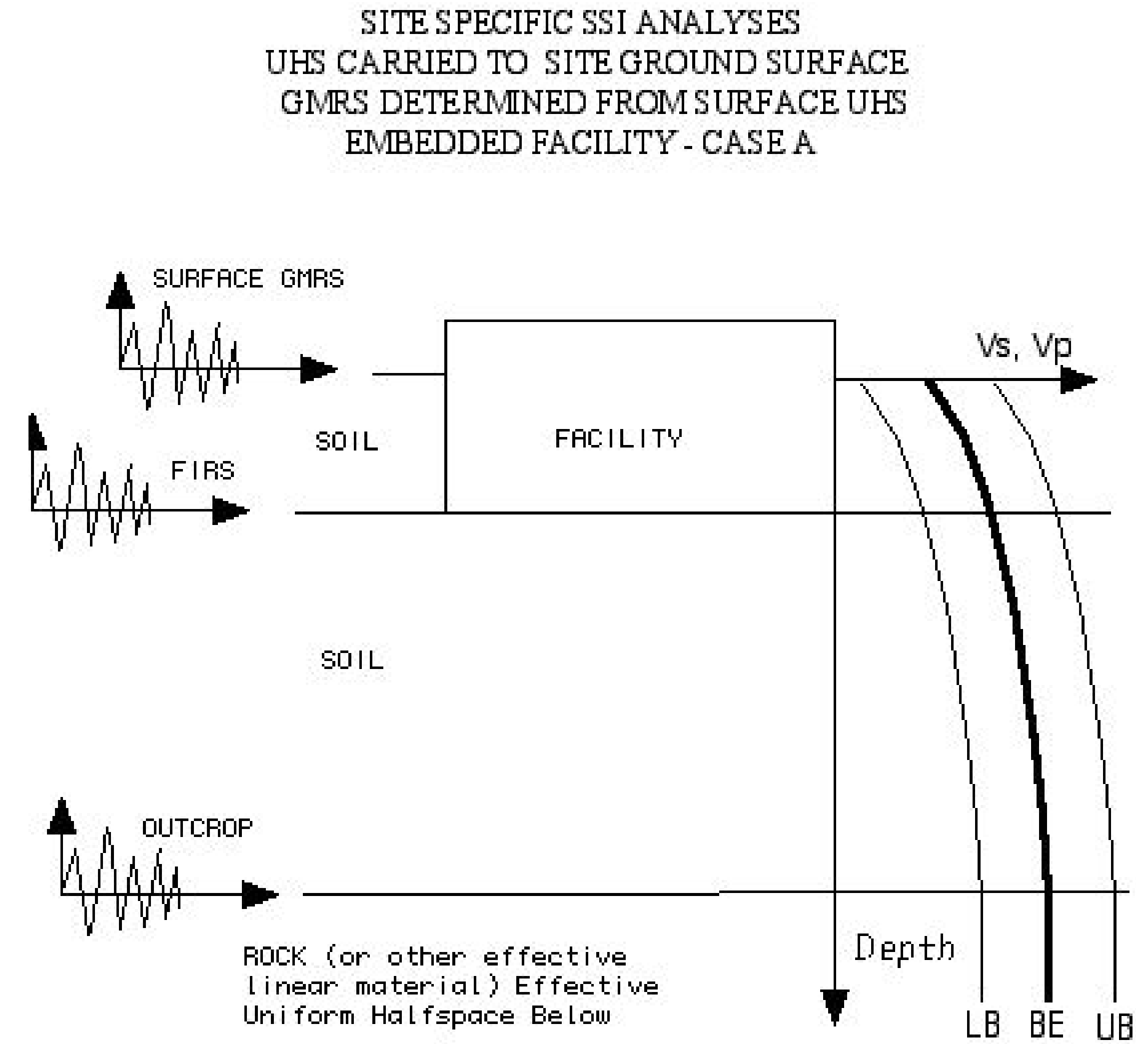


FIGURE 14
SSI CONFIGURATION FOR CASE A
EMBEDDED FACILITY
PROBABILISTIC UHS CARRIED TO GROUND SURFACE

UHS CARRIED TO SITE GROUND SURFACE
GMRS DETERMINED FROM SURFACE UHS
SURFACE FOUNDED - CASE B

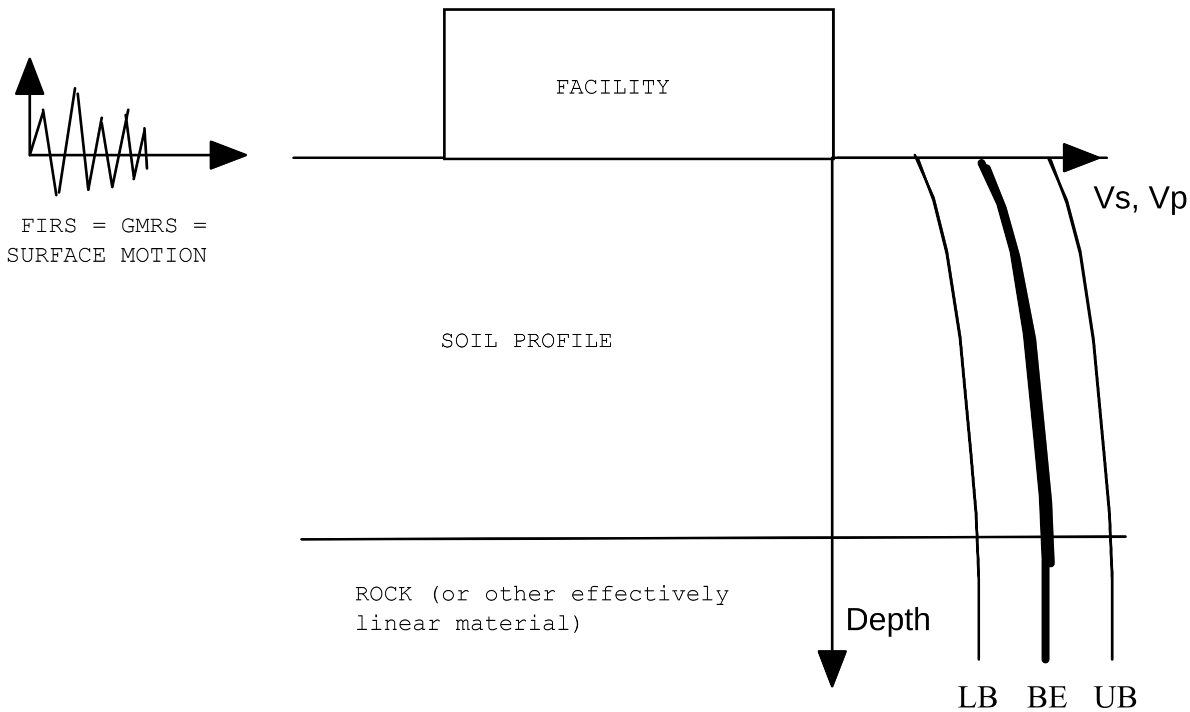


FIGURE 15
SSI CONFIGURATION FOR CASE B
SURFACE FOUNDED FACILITY
PROBABILISTIC UHS CARRIED TO GROUND SURFACE

UHS CARRIED TO SITE FOUNDATION LEVEL □
GMRS DEFINED AS FIRS □
EMBEDDED FACILITY - CASE C

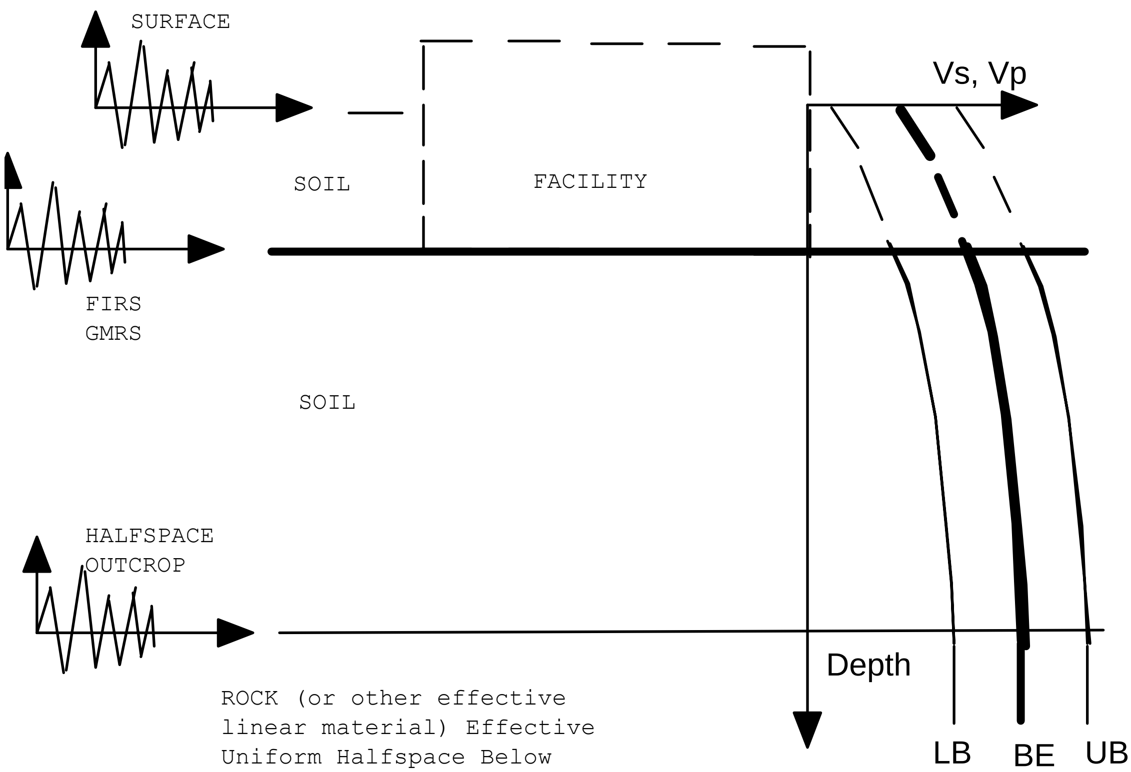


FIGURE 16
SSI CONFIGURATION FOR CASE C
EMBEDDED FACILITY
PROBABILISTIC UHS CARRIED TO FOUNDATION LEVEL

UHS CARRIED TO SITE LEVEL BELOW FOUNDATION
GMRS DETERMINED AT INTERMEDIATE DEPTH
EMBEDDED FACILITY - CASE D

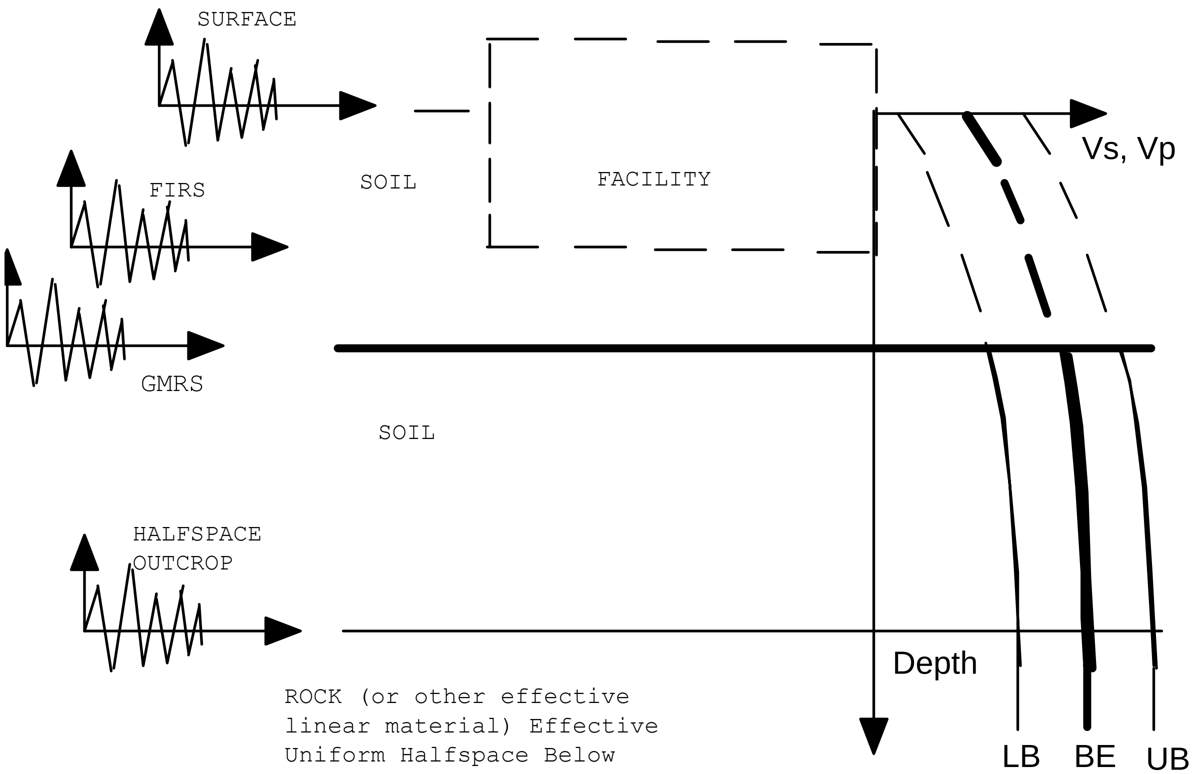
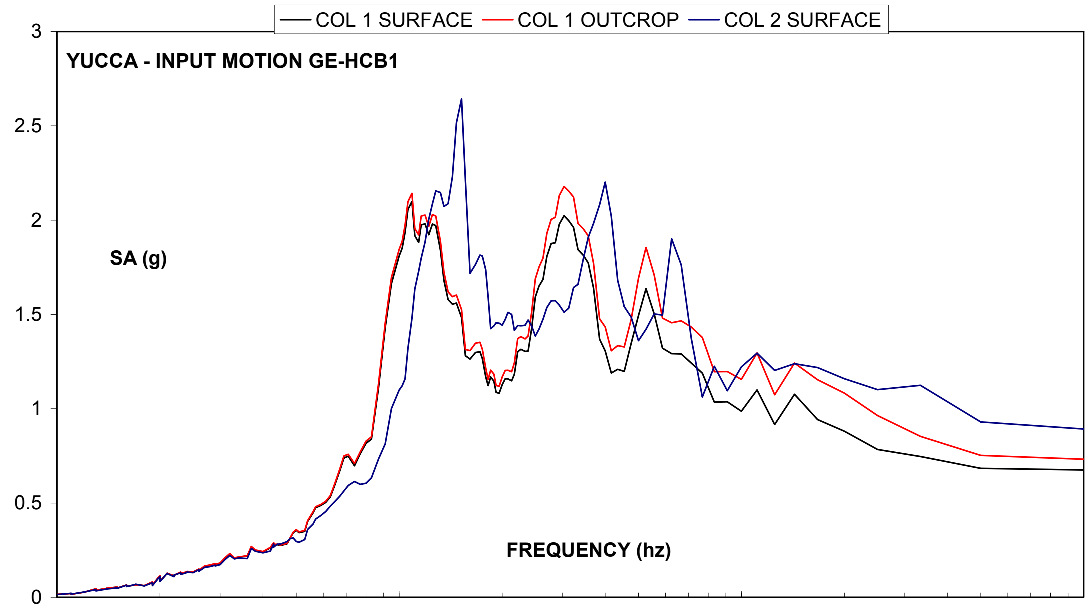


FIGURE 17
SSI CONFIGURATION FOR CASE D
EMBEDDED FACILITY
PROBABILISTIC UHS CARRIED TO BELOW FOUNDATION LEVEL

APPENDIX A

SRS SOIL COLUMN


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA - INPUT MOTION GE-HCB1
SA (g)
FREQUENCY (hz)
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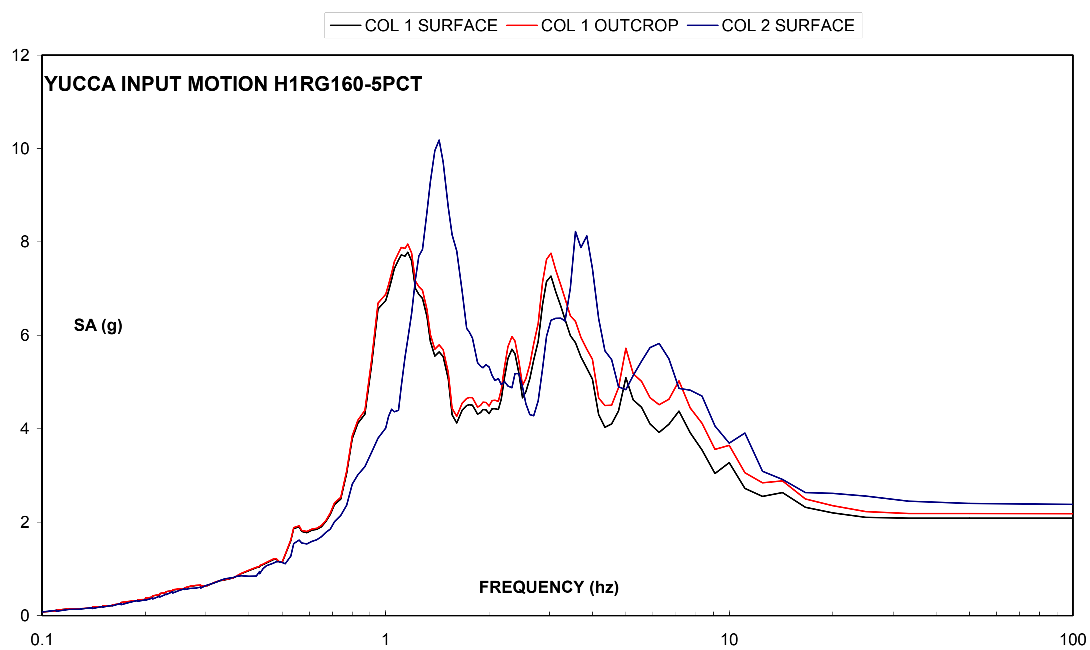
0.5
1
1.5
2
2.5
3


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION H1RG160-5PCT
SA (g)
FREQUENCY (hz)
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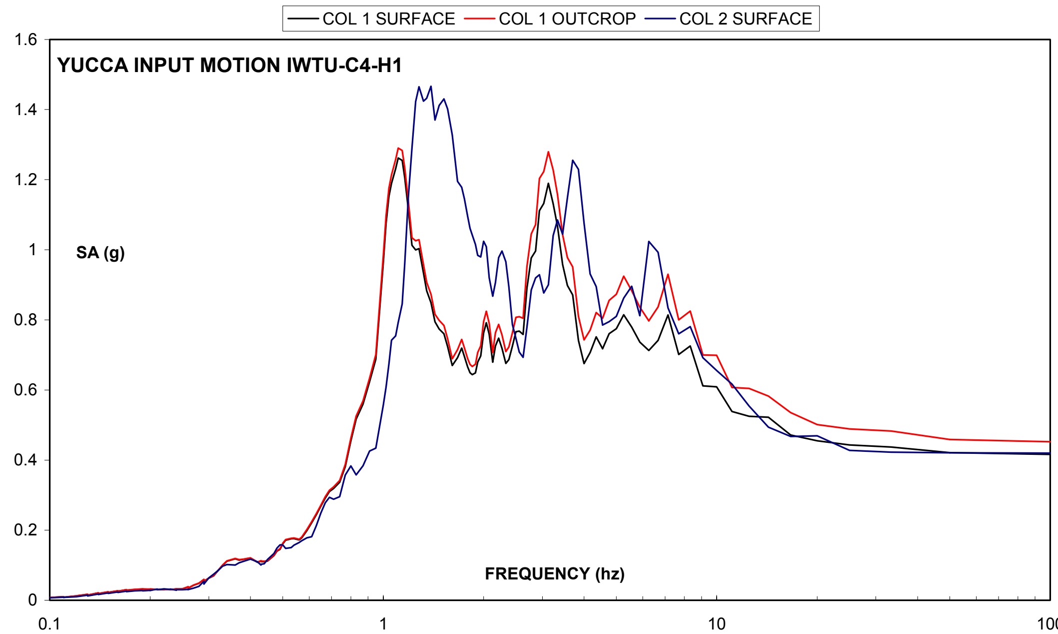
2
4
6
8
10
12
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION IWTU-C4-H1
SA (g)
FREQUENCY (hz)
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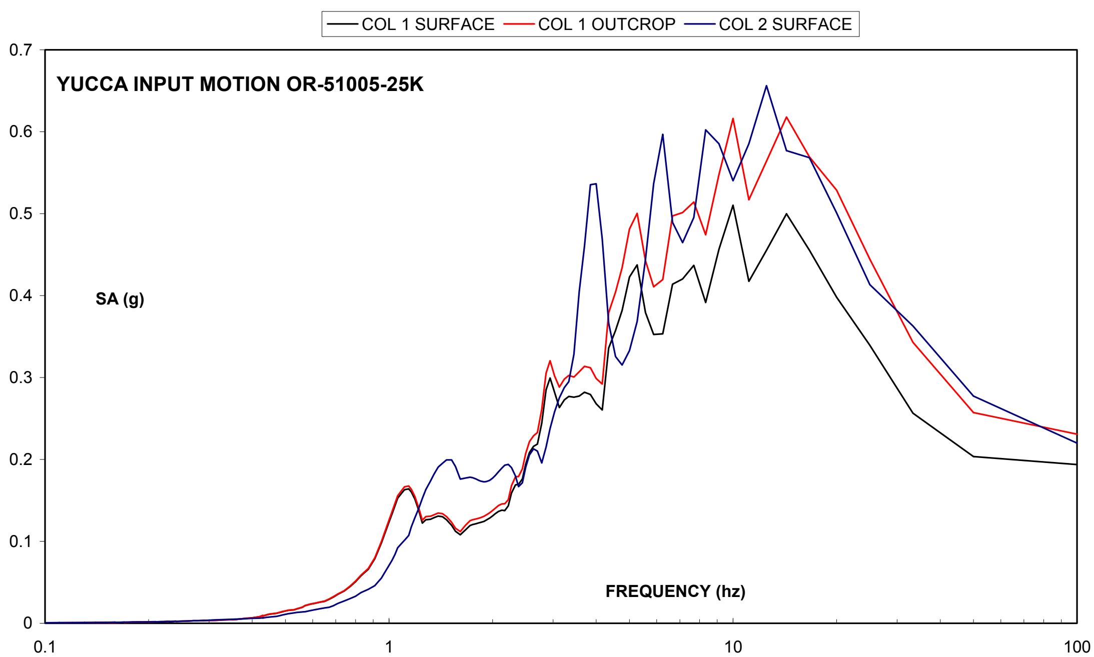
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION OR-51005-25K
SA (g)
FREQUENCY (hz)
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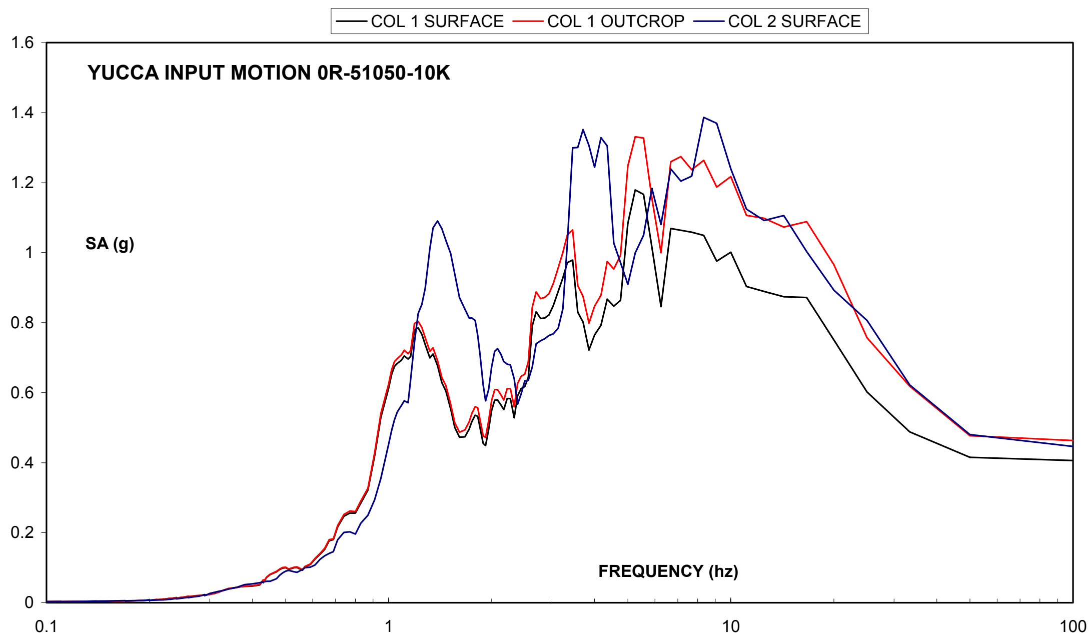
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION 0R-51050-10K
SA (g)
FREQUENCY (hz)
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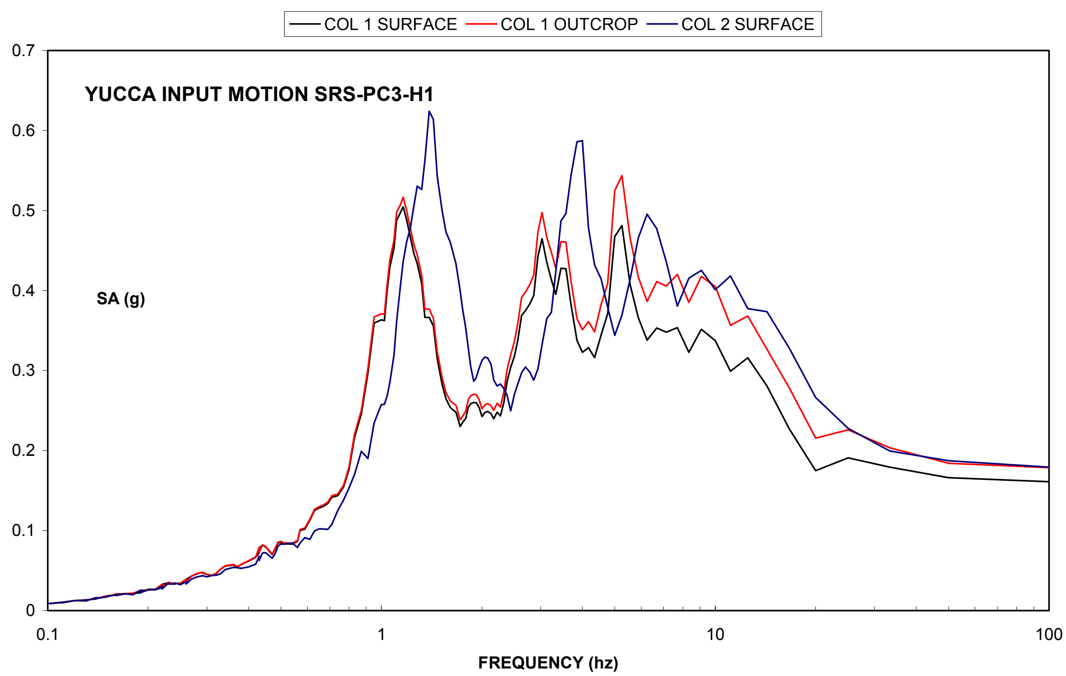
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION SRS-PC3-H1
SA (g)
FREQUENCY (hz)
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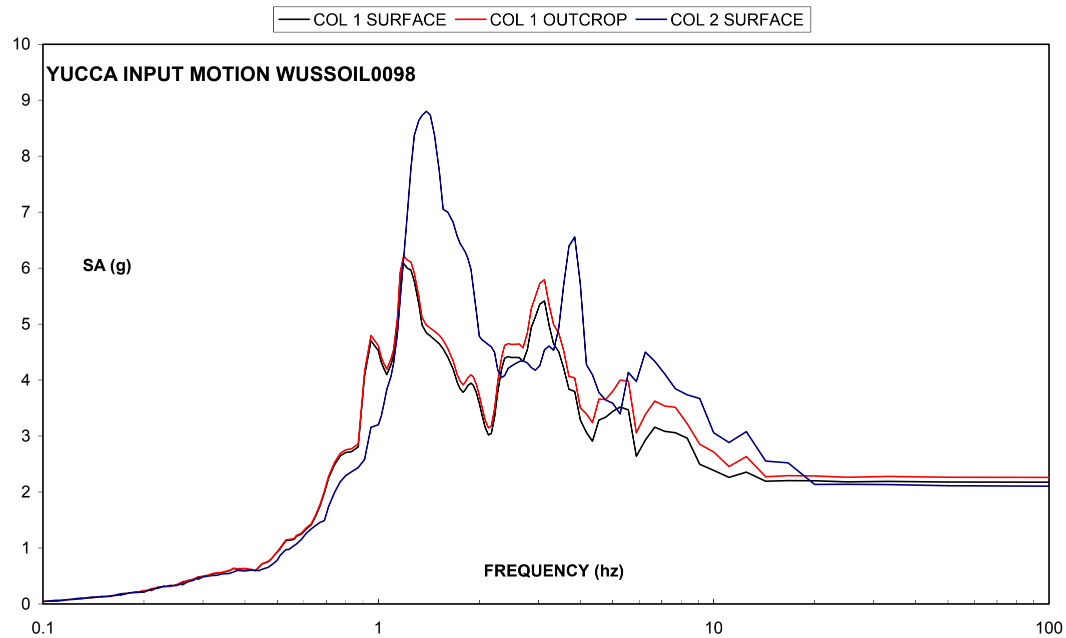
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION WUSSOIL0098
SA (g)
FREQUENCY (hz)
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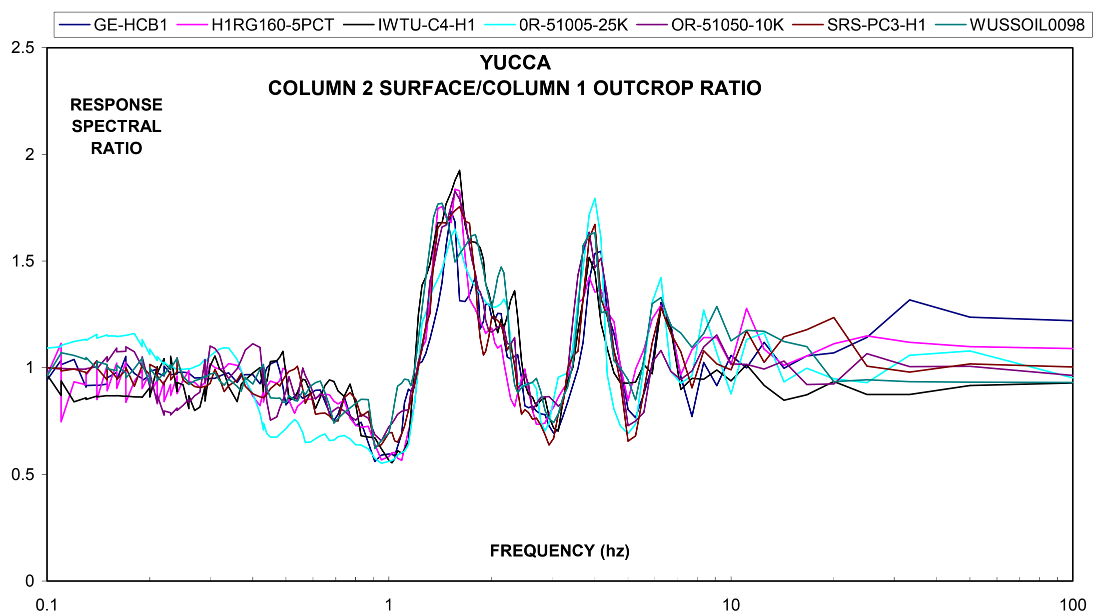
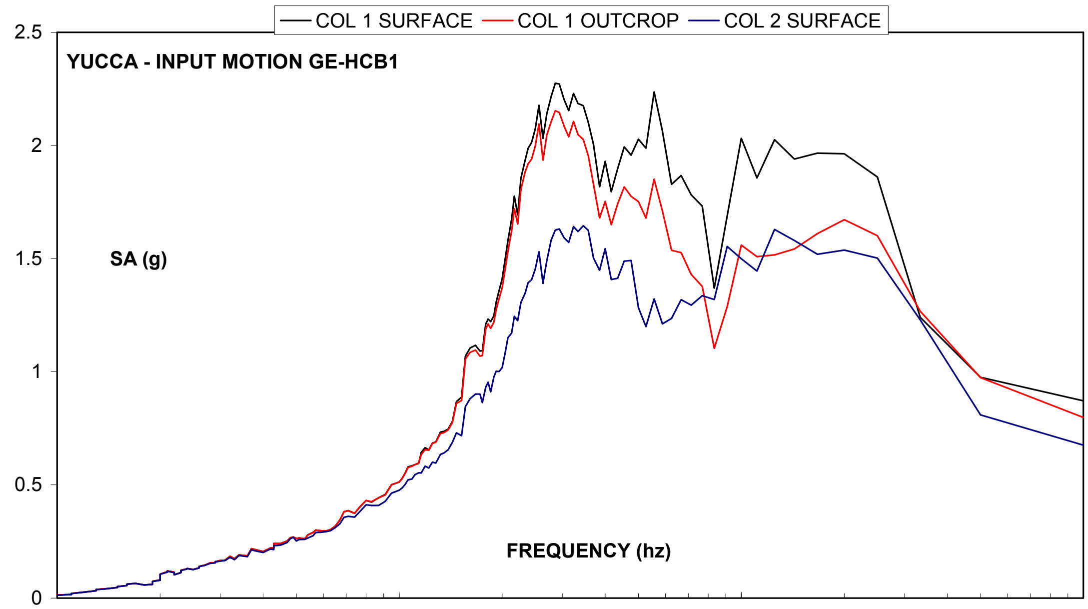
1
2
3
4
5
6
7
8
9
10
0.1
1
10
100


GE-HCB1
H1RG160-5PCT
IWTU-C4-H1
0R-51005-25K
OR-51050-10K
SRS-PC3-H1
WUSSOIL0098
YUCCA
COLUMN 2 SURFACE/COLUMN 1 OUTCROP RATIO
RESPONSE
SPECTRAL
RATIO
FREQUENCY (hz)
0
0.5
1
1.5
2
2.5
0.1
1
10
100

APPENDIX B
YMP SOIL COLUMN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COL 1 OUTCROP
COL 2 SURFACE
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SA (g)
FREQUENCY (hz)
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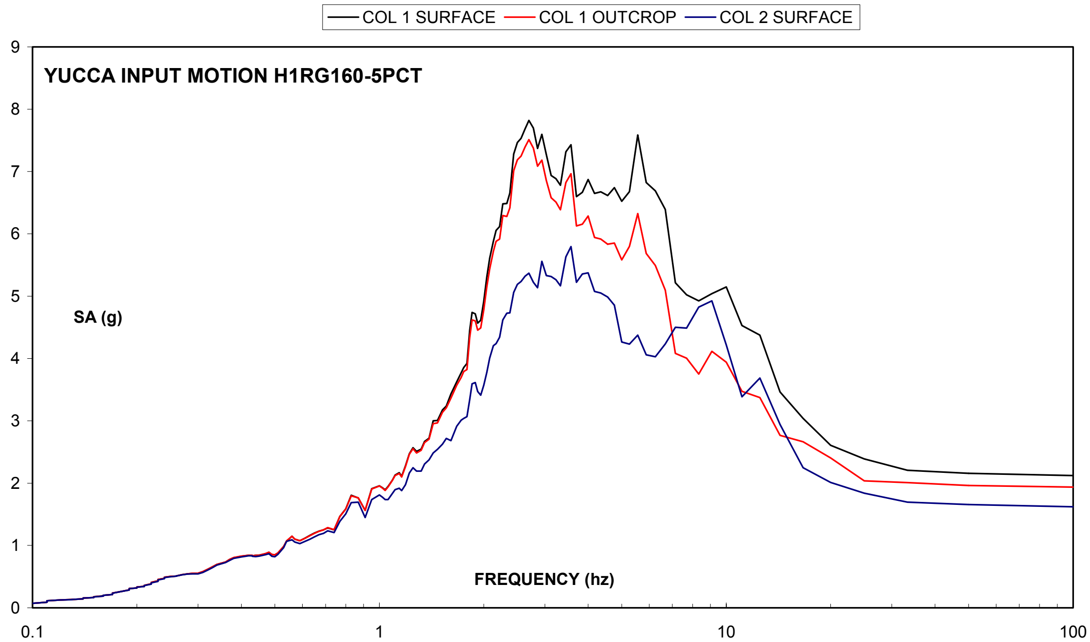
1.5
1
0.5
0


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION H1RG160-5PCT
SA (g)
FREQUENCY (hz)
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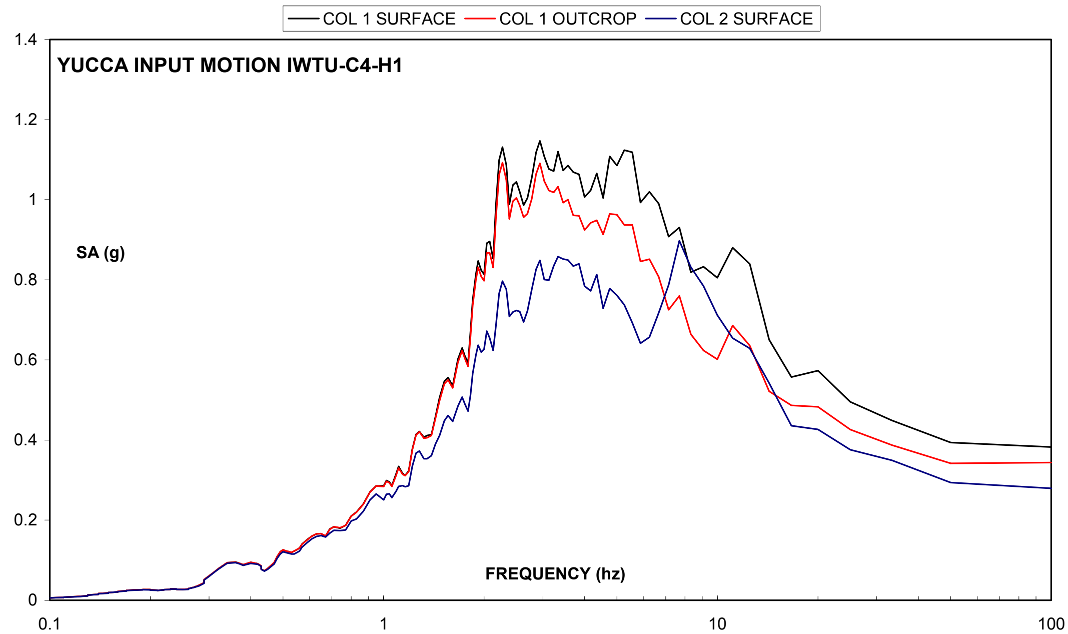
8
7
6
5
4
3
2
1
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION IWTU-C4-H1
SA (g)
FREQUENCY (hz)
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1.2
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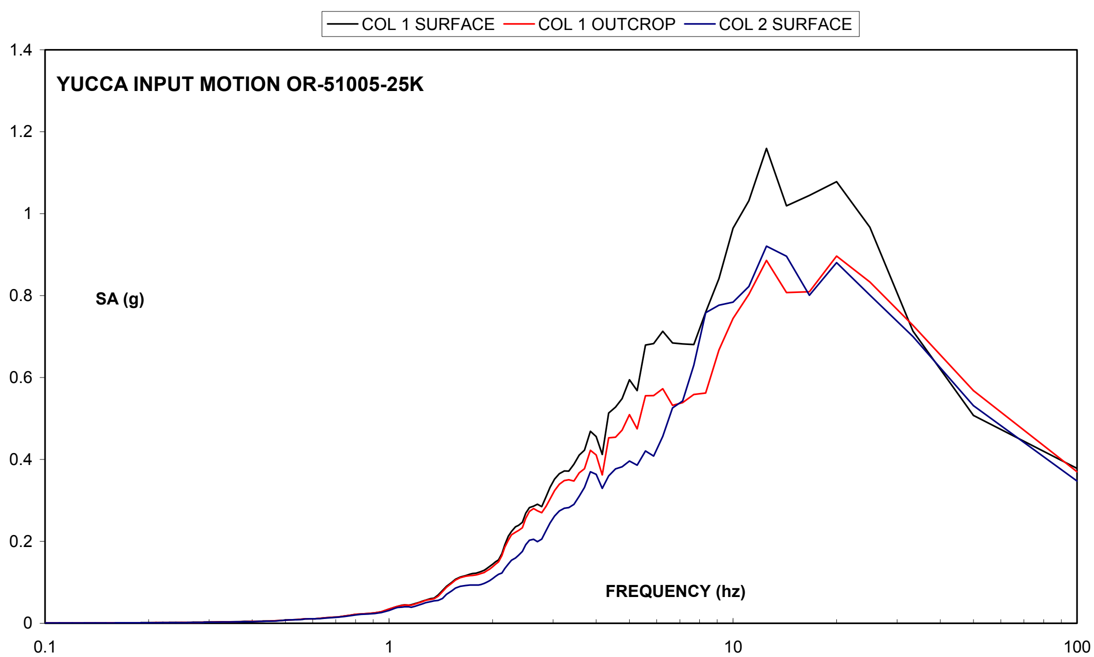
0.8
0.6
0.4
0.2
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION OR-51005-25K
SA (g)
FREQUENCY (hz)
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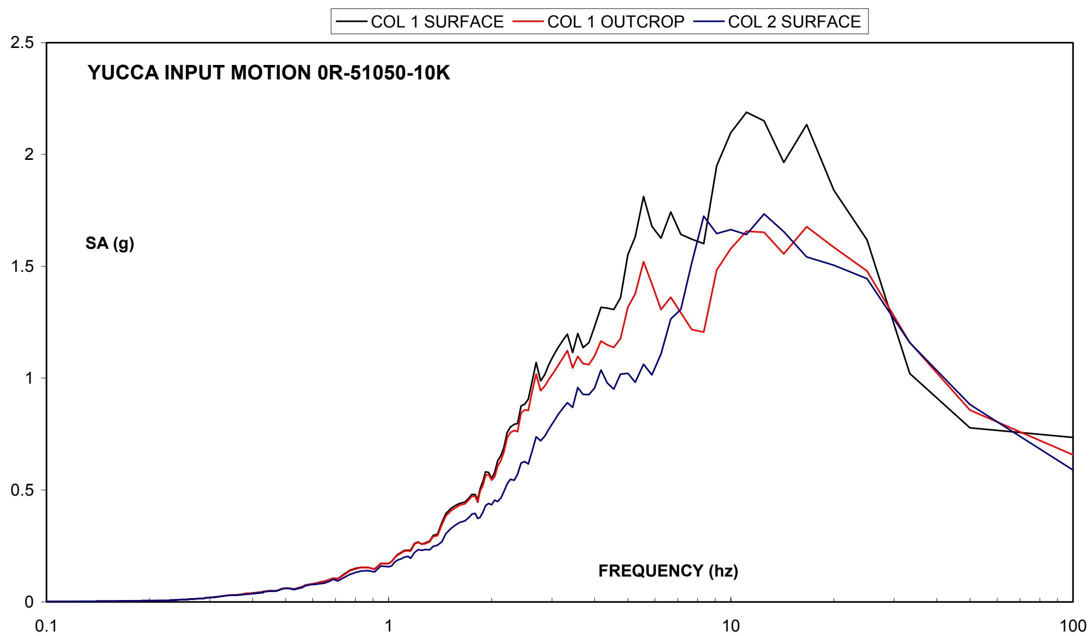
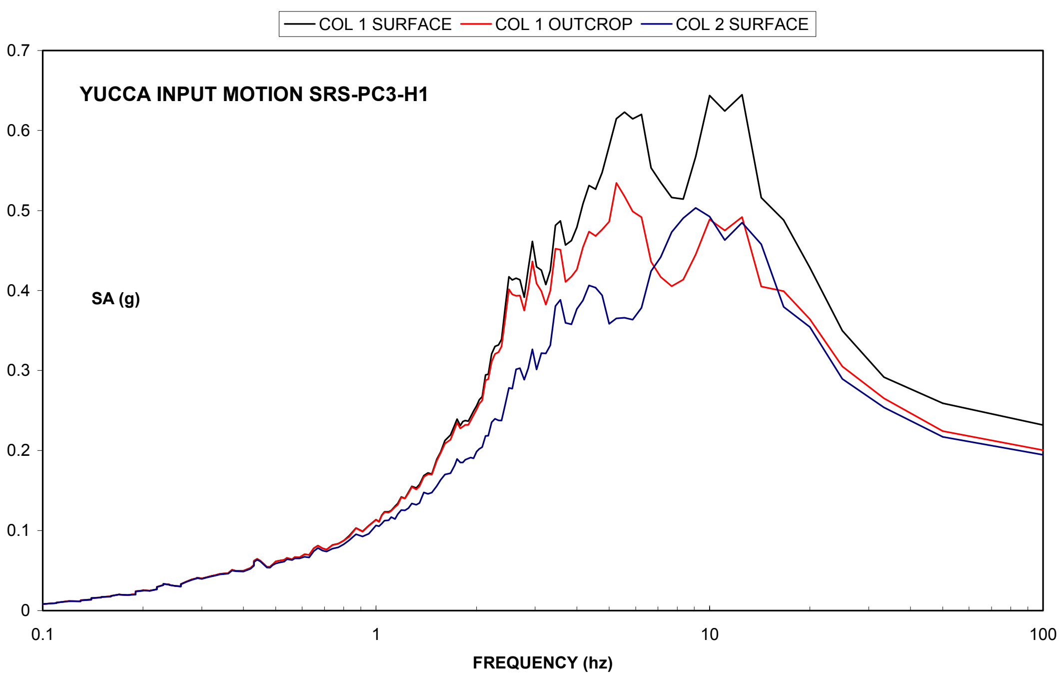
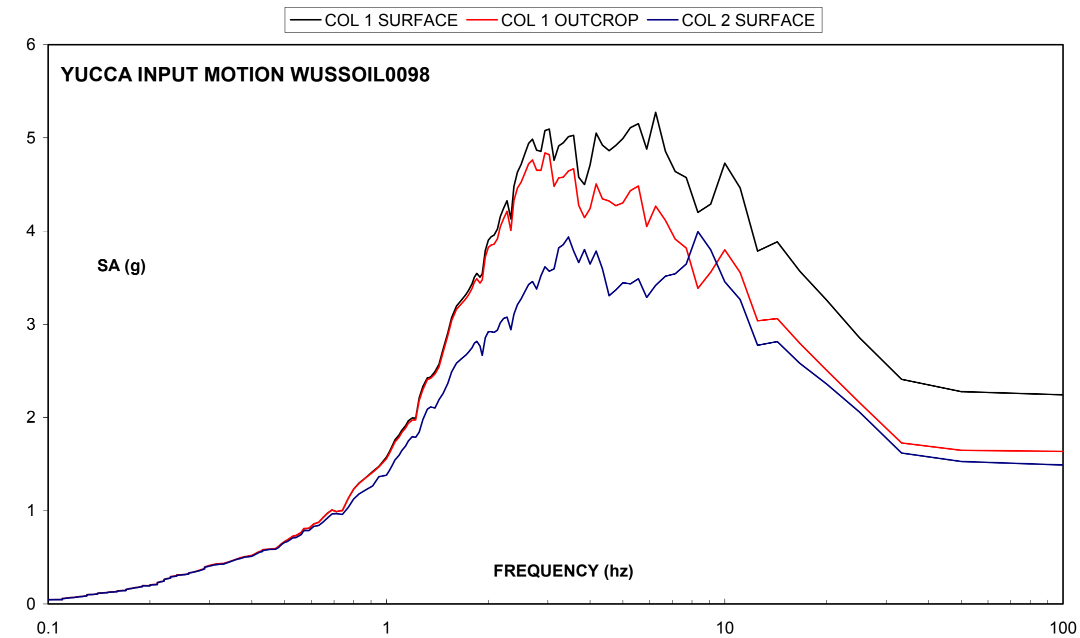
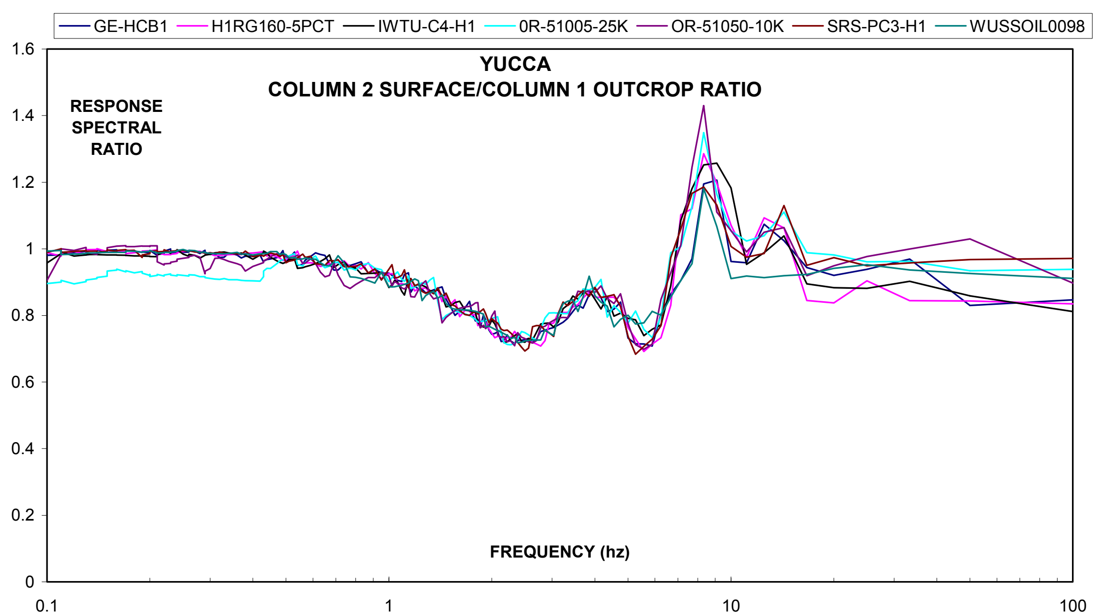
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION 0R-51050-10K
SA (g)
FREQUENCY (hz)
2.5
2
1.5
1
0.5
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION SRS-PC3-H1
SA (g)
FREQUENCY (hz)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
100

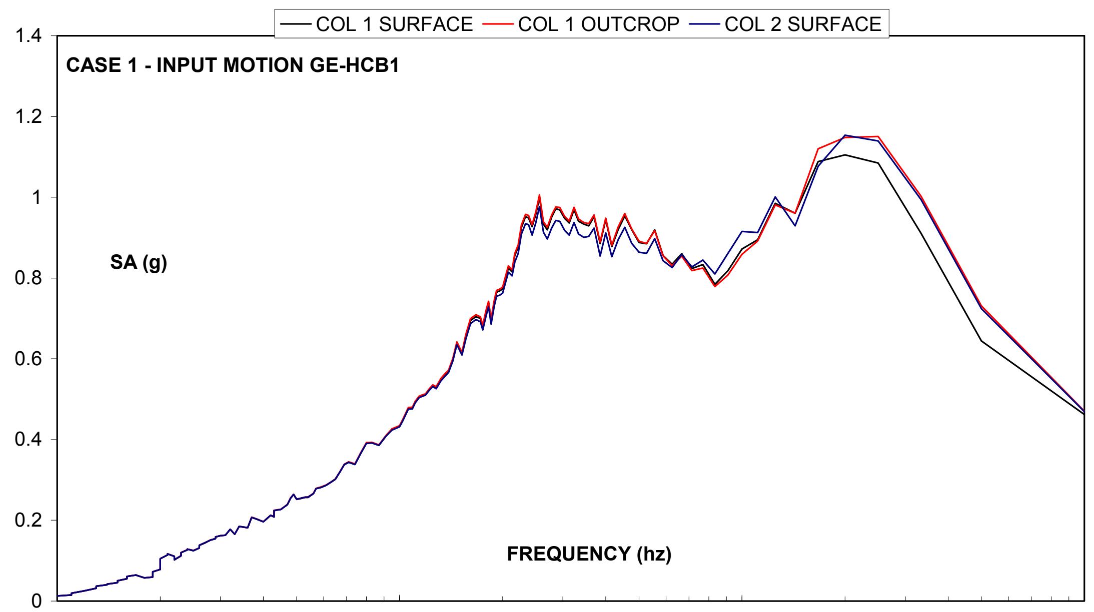


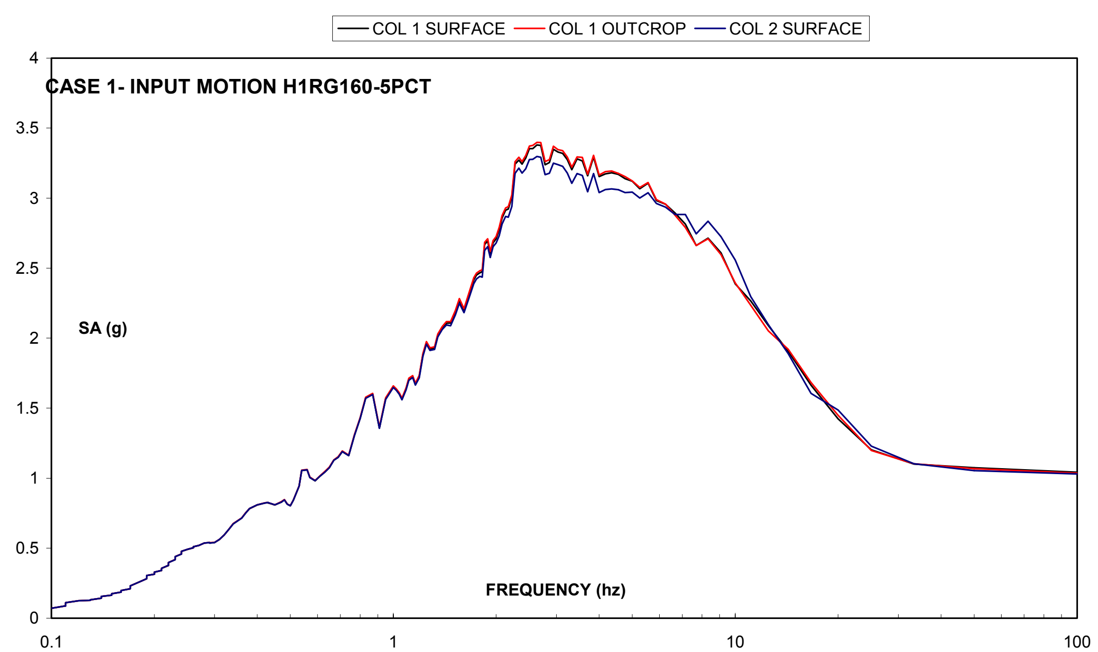
COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
YUCCA INPUT MOTION WUSSOIL0098
SA (g)
FREQUENCY (hz)
6
5
4
3
2
1
0
0.1
1
10
100

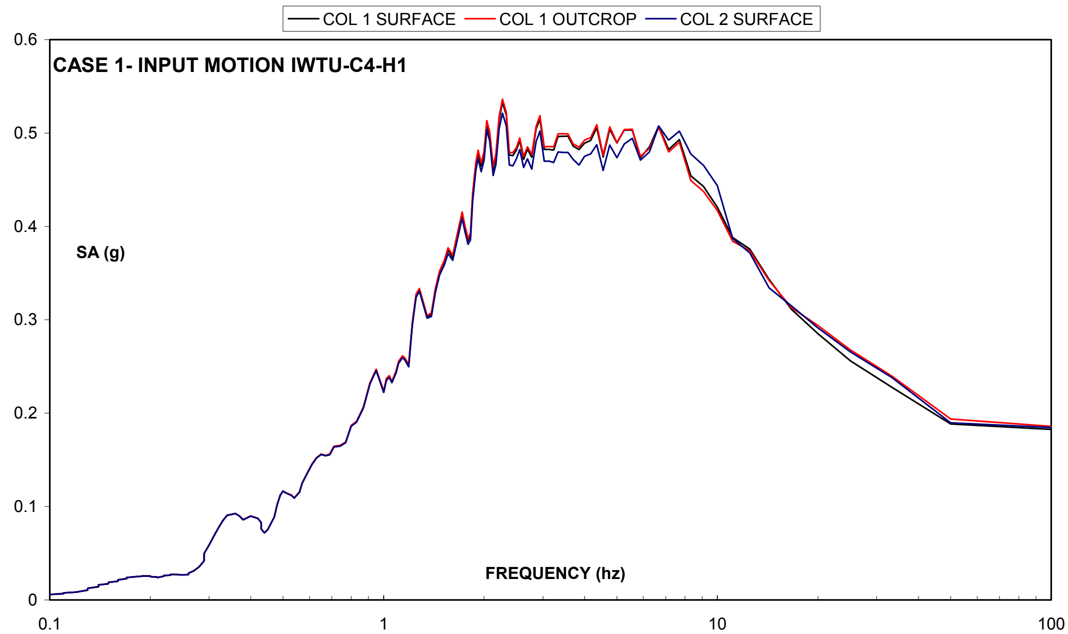


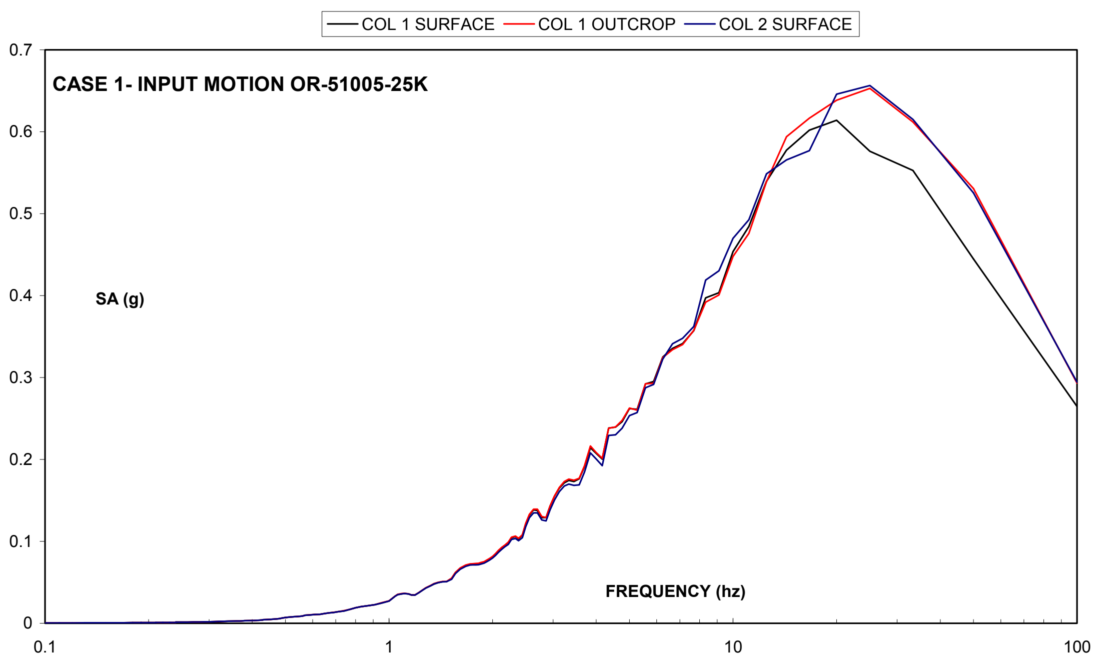
GE-HCB1
H1RG160-5PCT
IWTU-C4-H1
0R-51005-25K
OR-51050-10K
SRS-PC3-H1
WUSSOIL0098
YUCCA
COLUMN 2 SURFACE/COLUMN 1 OUTCROP RATIO
RESPONSE
SPECTRAL
RATIO
FREQUENCY (hz)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100

APPENDIX C
GENERIC CASE 1 SOIL COLUMN


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 1 - INPUT MOTION GE-HCB1
SA (g)
FREQUENCY (hz)
1.4
1.2
1
0.8
0.6
0.4
0.2
0


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 1- INPUT MOTION H1RG160-5PCT
SA (g)
FREQUENCY (hz)
4
3.5
3
2.5
2
1.5
1
0.5
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 1- INPUT MOTION IWTU-C4-H1
SA (g)
FREQUENCY (hz)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 1- INPUT MOTION OR-51005-25K
SA (g)
FREQUENCY (hz)
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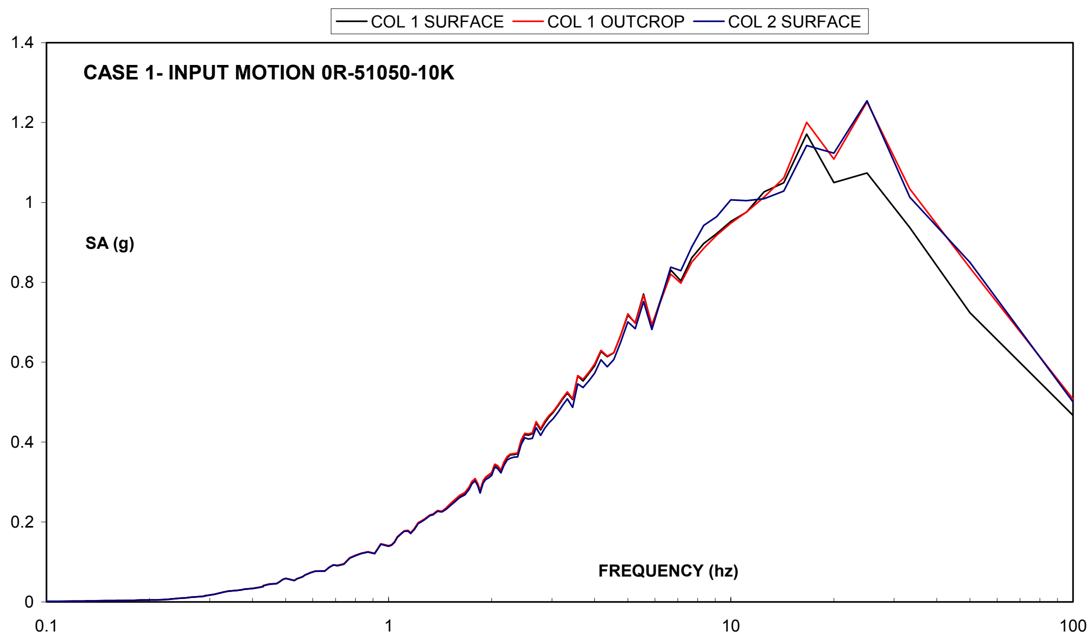
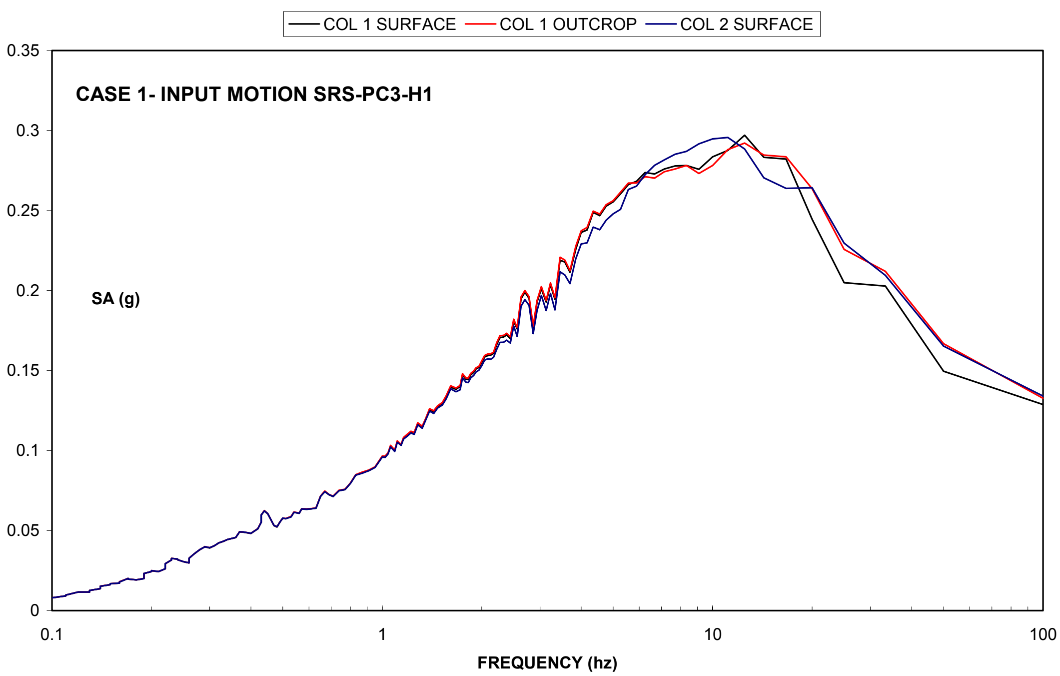
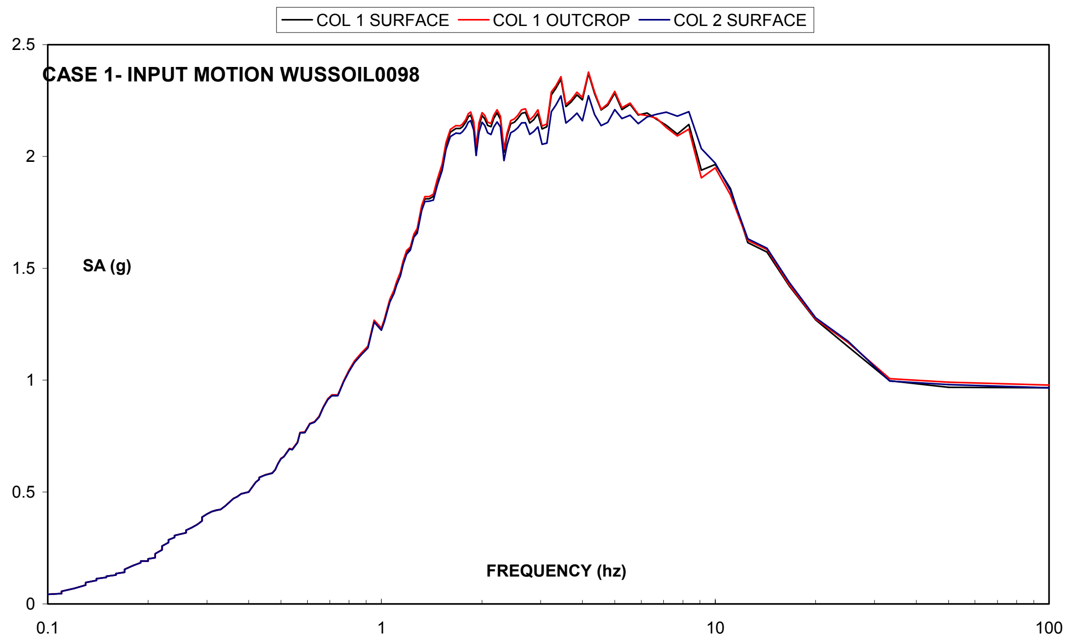
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.1
1
10
100

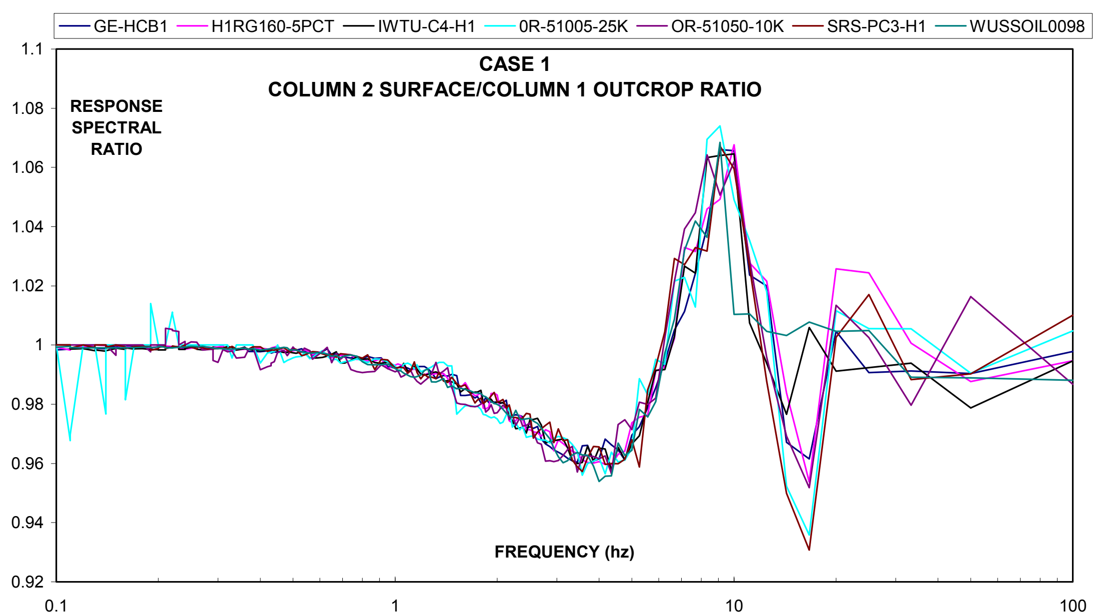


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 1- INPUT MOTION 0R-51050-10K
SA (g)
FREQUENCY (hz)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100

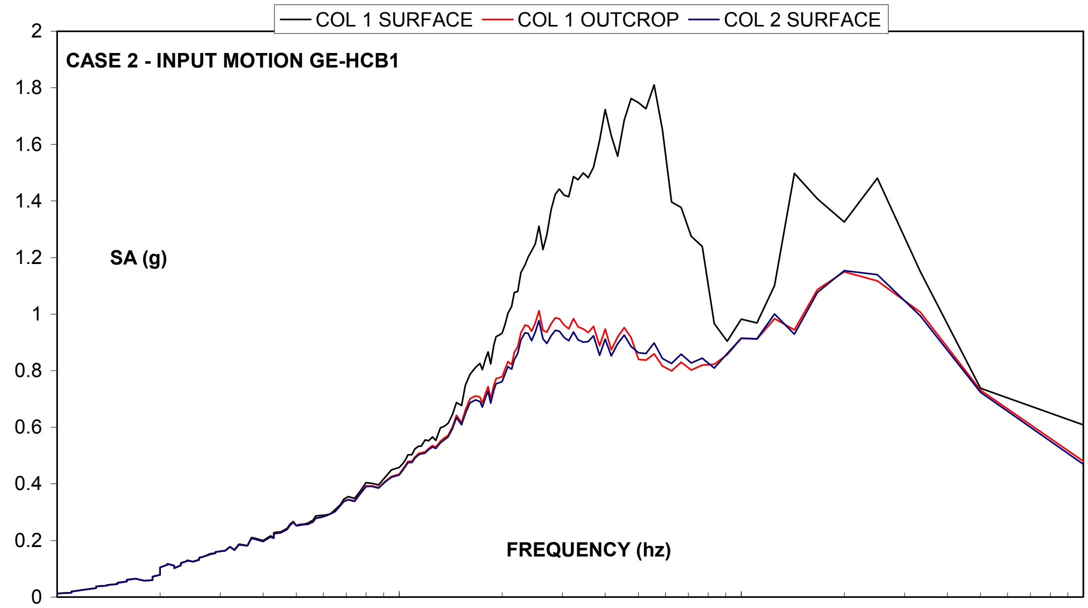


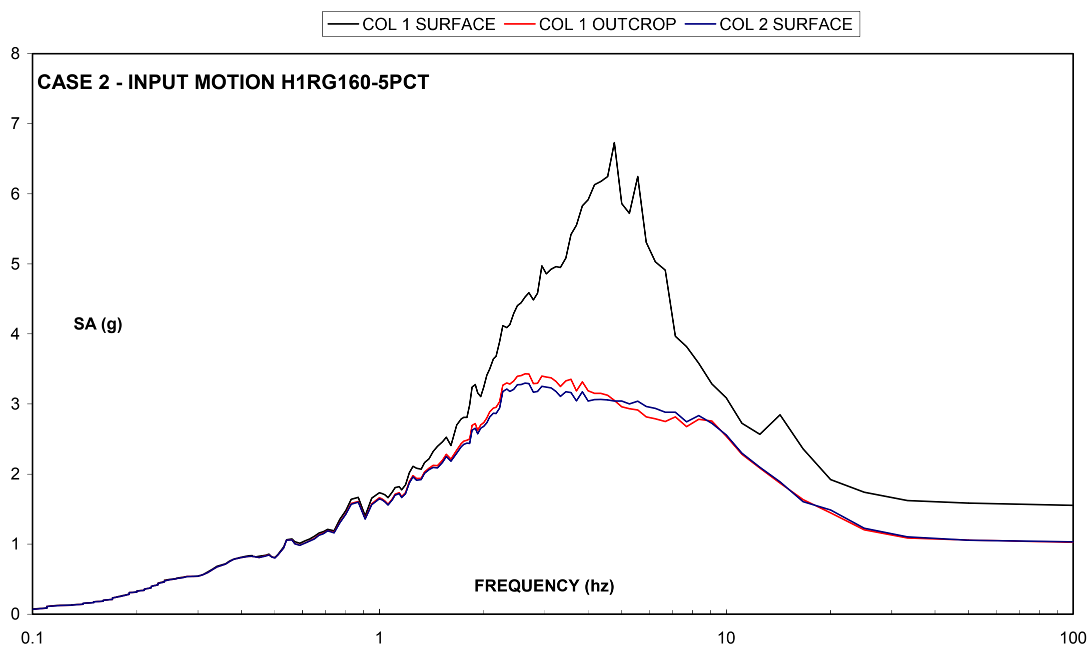
COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 1- INPUT MOTION SRS-PC3-H1
SA (g)
FREQUENCY (hz)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0.1
1
10
100

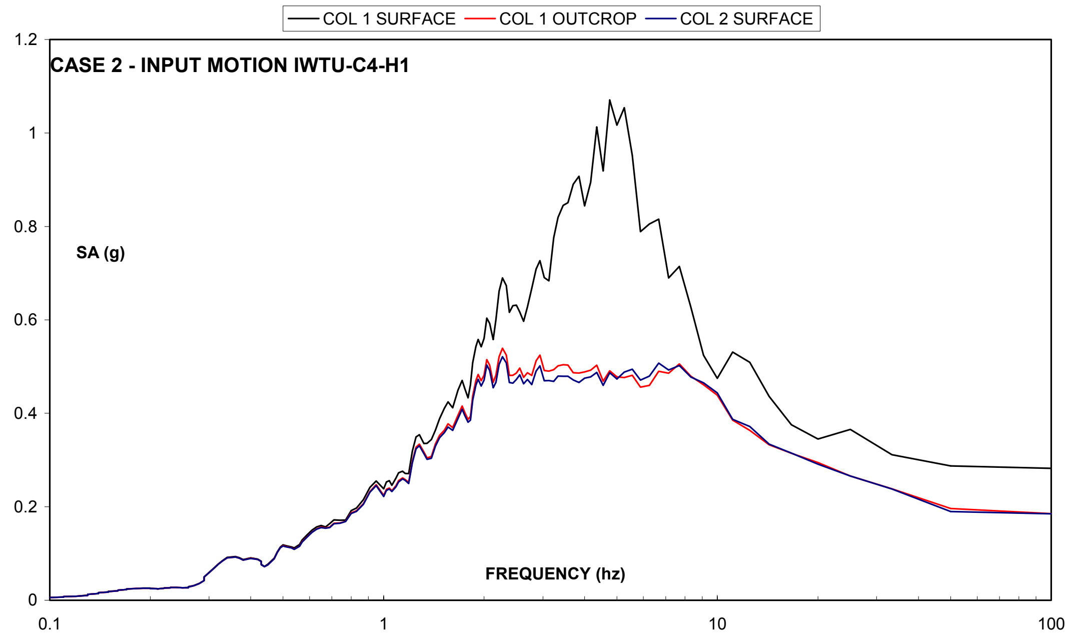

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 1- INPUT MOTION WUSSOIL0098
SA (g)
FREQUENCY (hz)
2.5
2
1.5
1
0.5
0
0.1
1
10
100

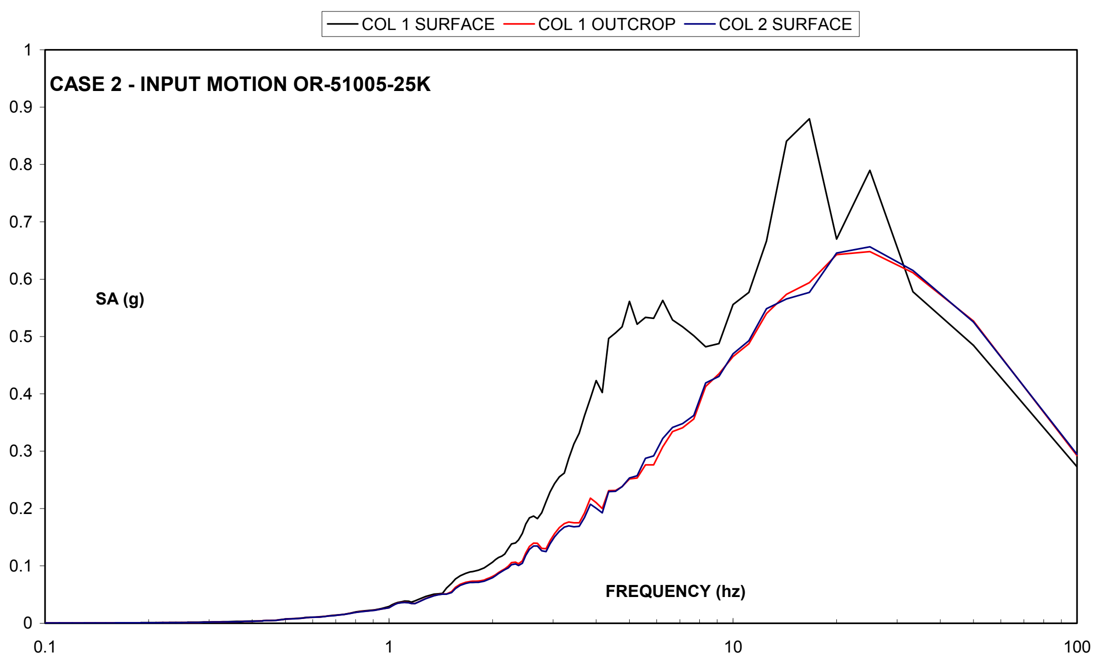

GE-HCB1
H1RG160-5PCT
IWTU-C4-H1
0R-51005-25K
OR-51050-10K
SRS-PC3-H1
WUSSOIL0098
CASE 1
COLUMN 2 SURFACE/COLUMN 1 OUTCROP RATIO
RESPONSE SPECTRAL RATIO
FREQUENCY (hz)
1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0.92
0.1
1
10
100

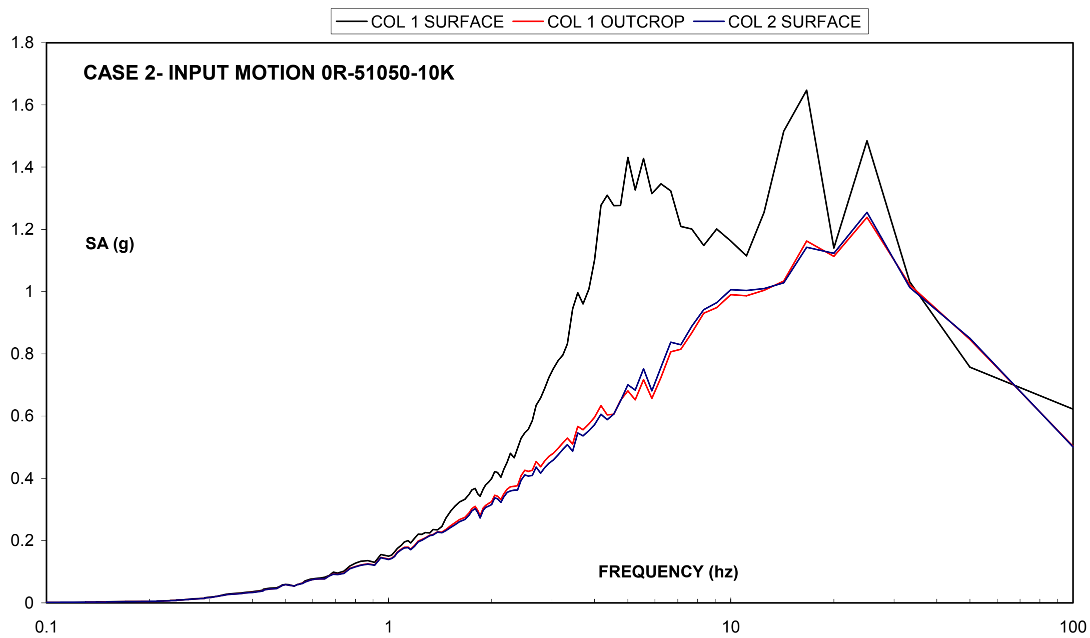
APPENDIX D
GENERIC CASE 2 SOIL COLUMN

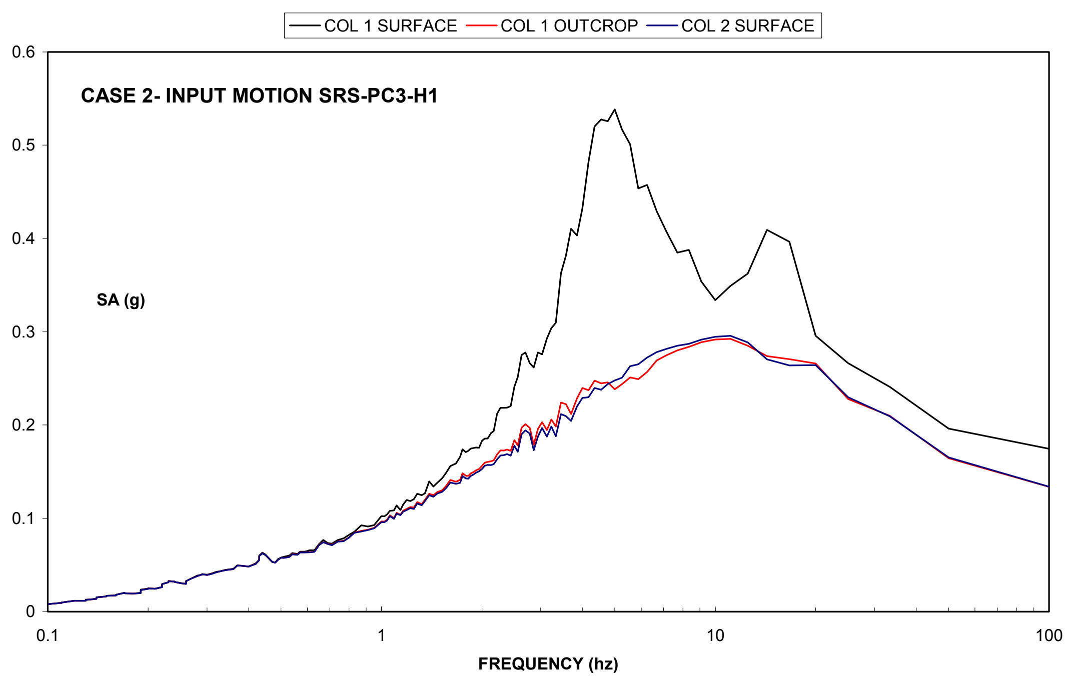

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 2 - INPUT MOTION GE-HCB1
SA (g)
FREQUENCY (hz)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

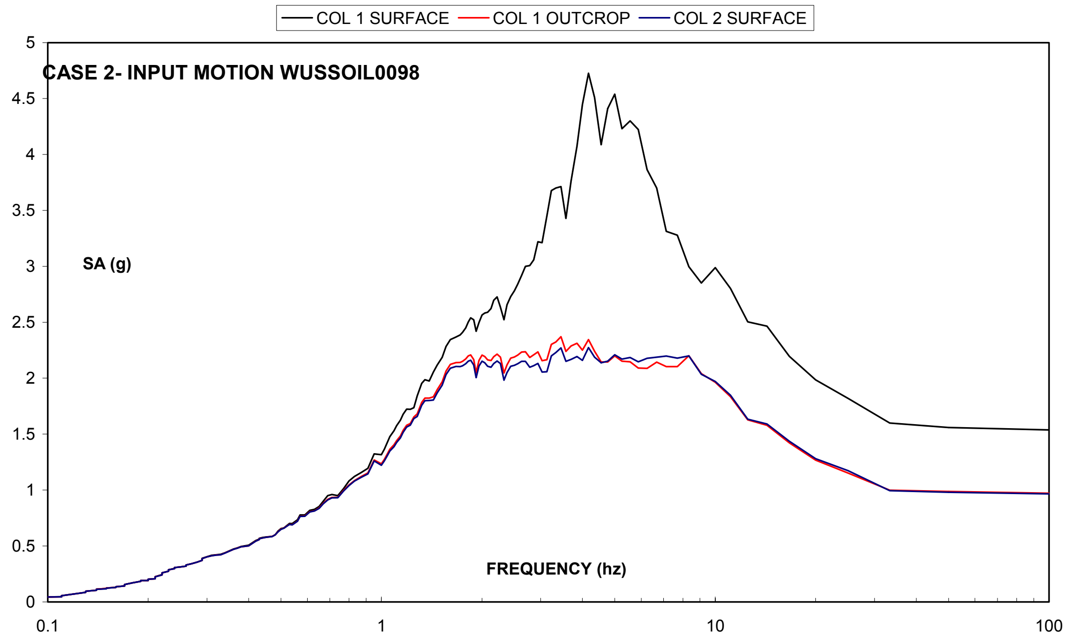

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 2 - INPUT MOTION H1RG160-5PCT
SA (g)
FREQUENCY (hz)
8
7
6
5
4
3
2
1
0
0.1
1
10
100

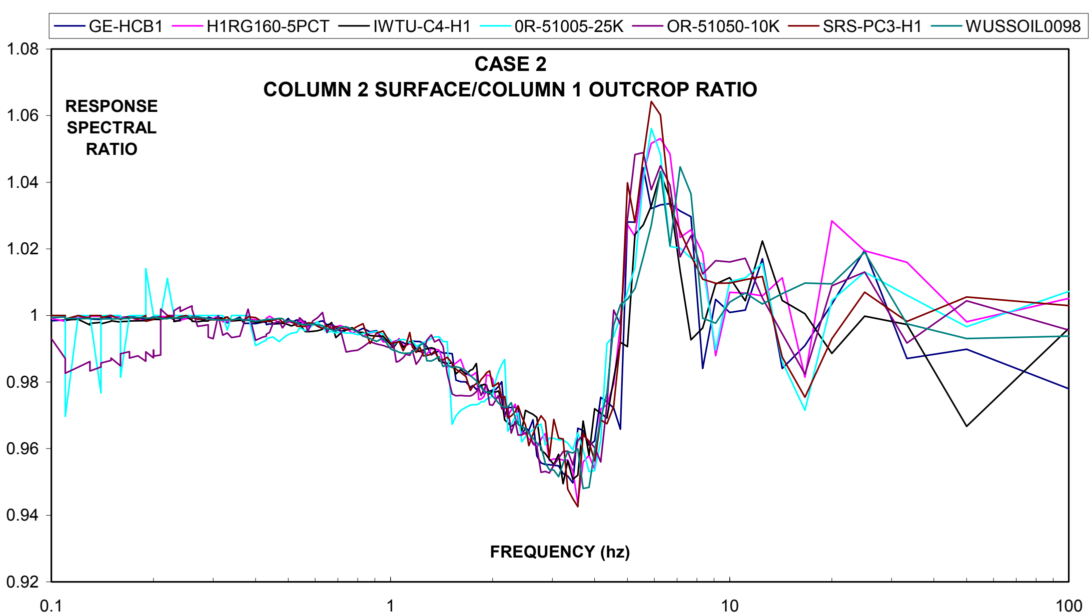

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 2 - INPUT MOTION IWTU-C4-H1
SA (g)
FREQUENCY (hz)
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 2 - INPUT MOTION OR-51005-25K
SA (g)
FREQUENCY (hz)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
100

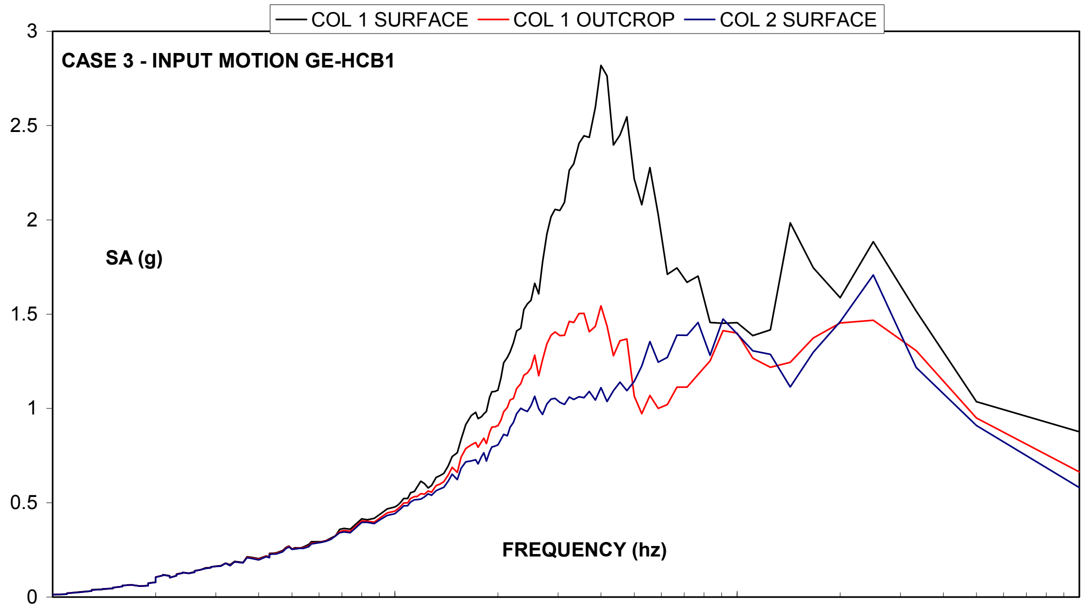

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 2- INPUT MOTION 0R-51050-10K
SA (g)
FREQUENCY (hz)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100

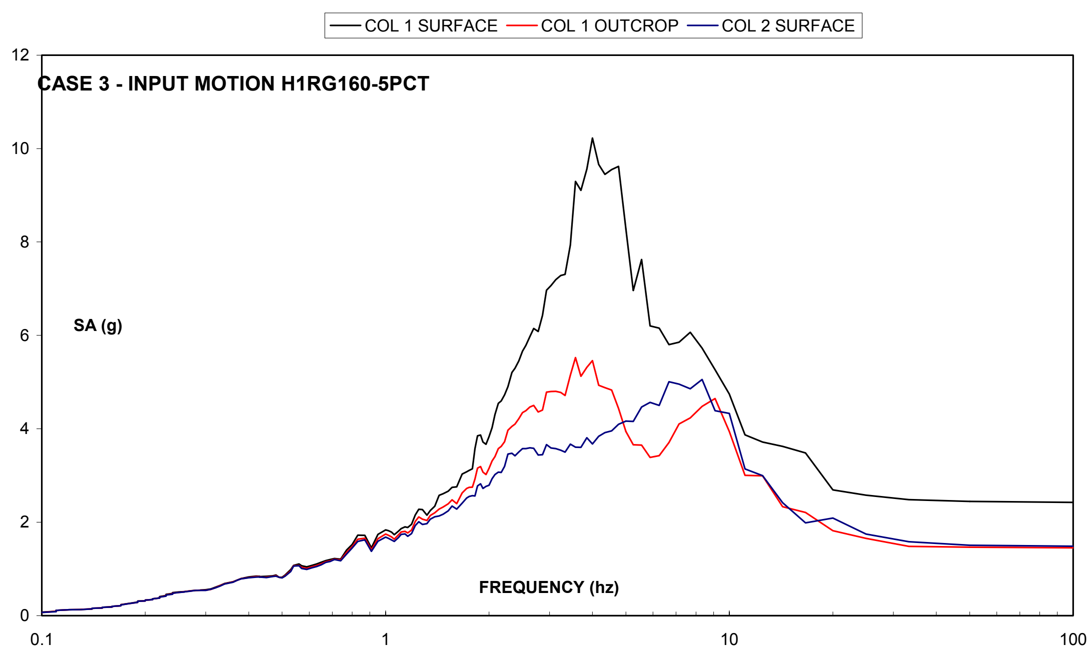

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 2- INPUT MOTION SRS-PC3-H1
SA (g)
FREQUENCY (hz)
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
100

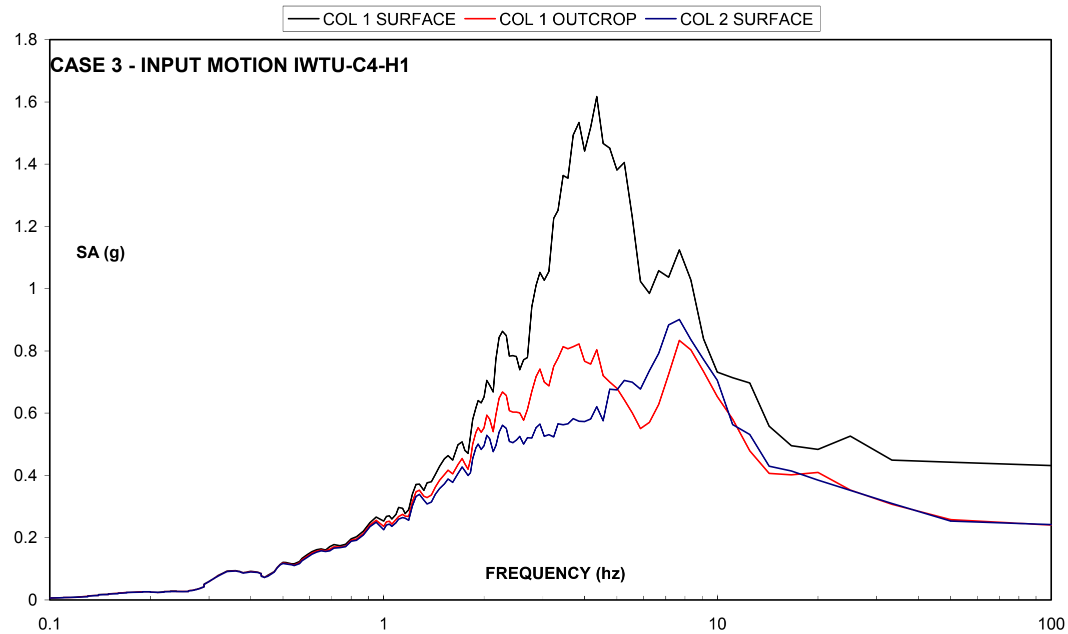

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 2- INPUT MOTION WUSSOIL0098
SA (g)
FREQUENCY (hz)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0.1
1
10
100

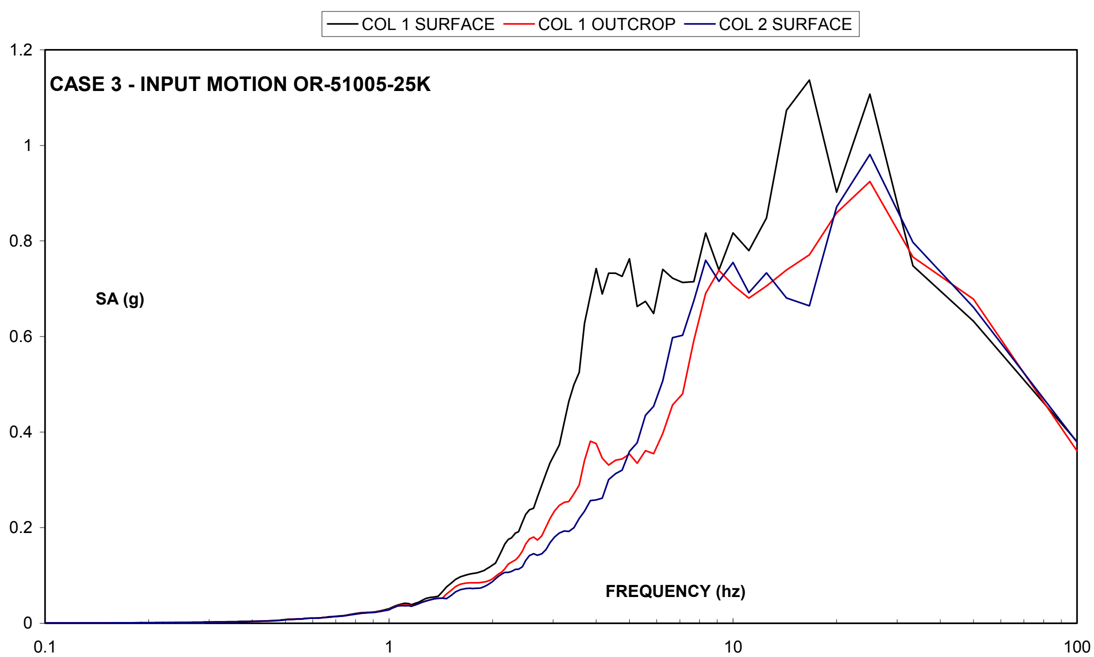

GE-HCB1
H1RG160-5PCT
IWTU-C4-H1
0R-51005-25K
OR-51050-10K
SRS-PC3-H1
WUSSOIL0098
CASE 2
COLUMN 2 SURFACE/COLUMN 1 OUTCROP RATIO
RESPONSE SPECTRAL RATIO
FREQUENCY (hz)
0.92
0.94
0.96
0.98
1
1.02
1.04
1.06
1.08
0.1
1
10
100

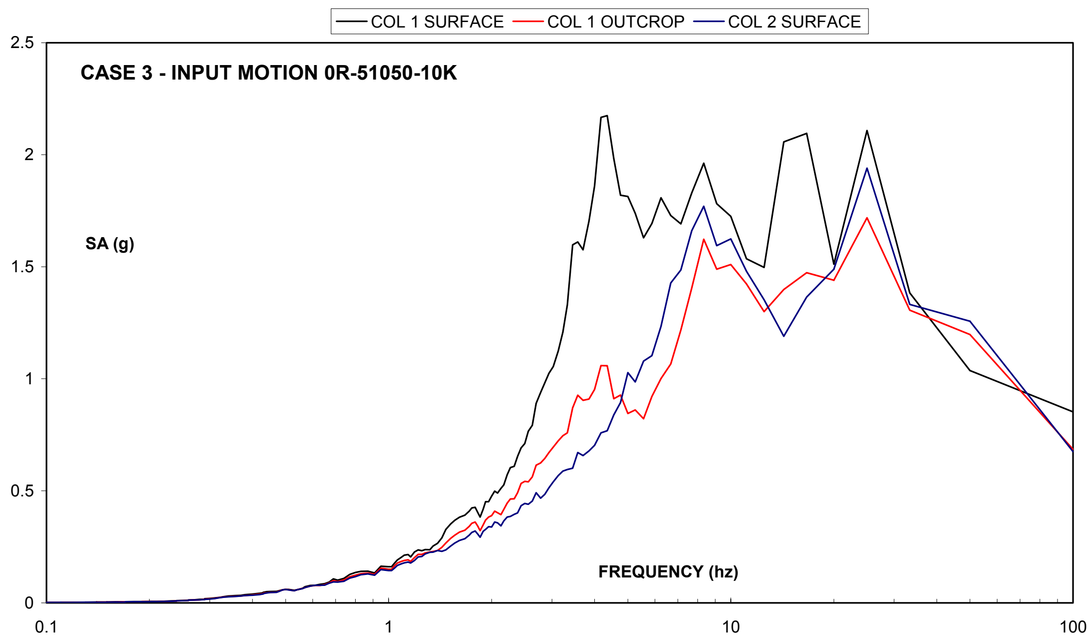
APPENDIX E
GENERIC CASE 3 SOIL COLUMN

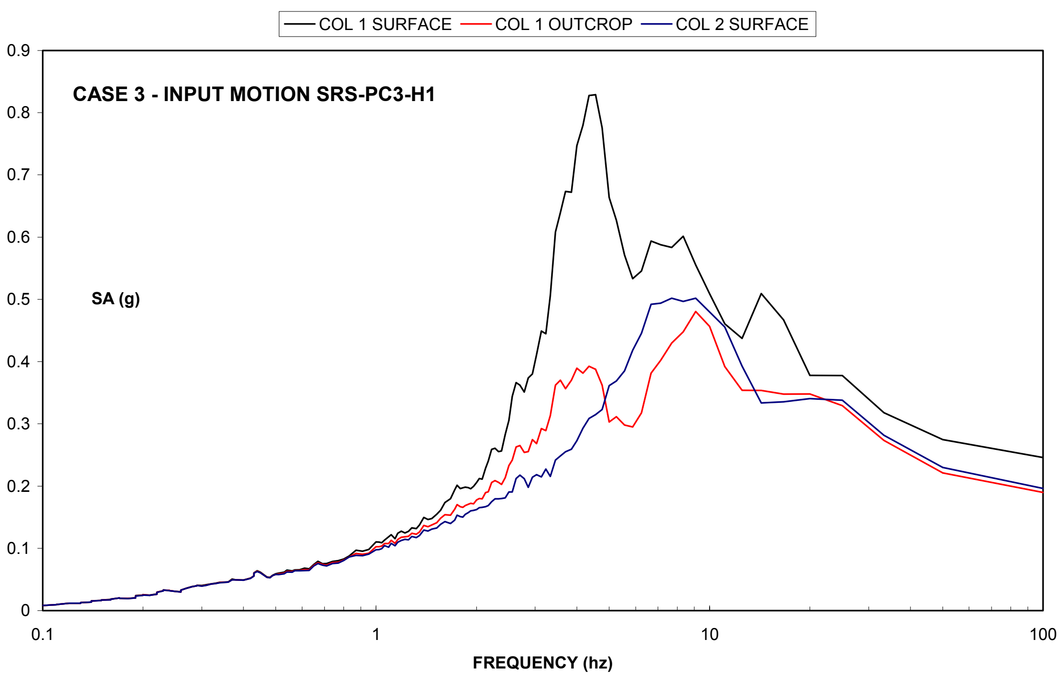

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 3 - INPUT MOTION GE-HCB1
SA (g)
FREQUENCY (hz)
3
2.5
2
1.5
1
0.5
0

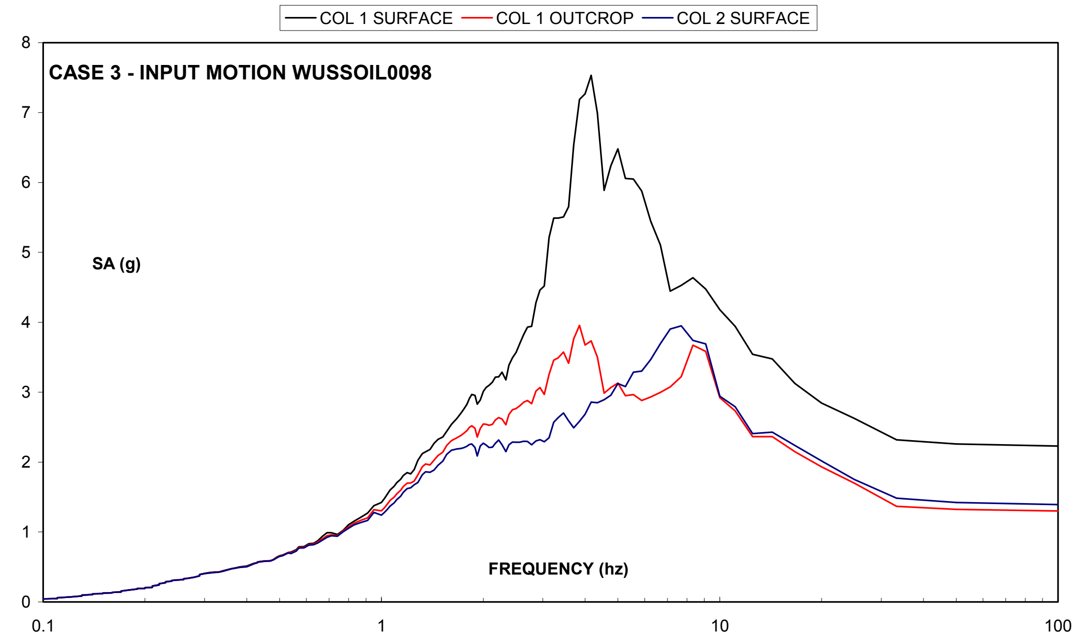

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 3 - INPUT MOTION H1RG160-5PCT
SA (g)
FREQUENCY (hz)
12
10
8
6
4
2
0
0.1
1
10
100

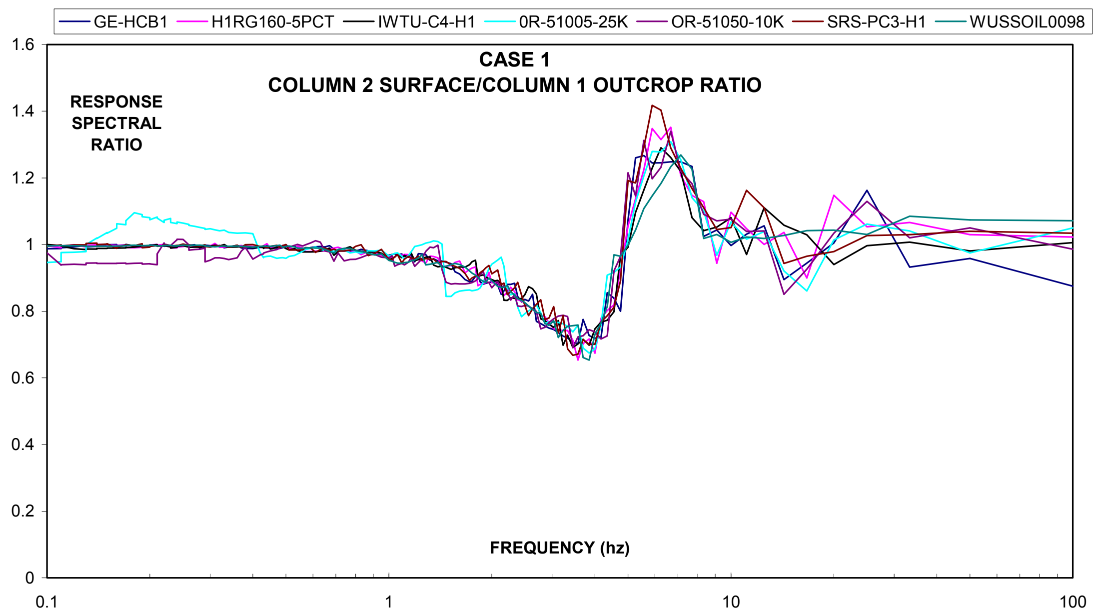

COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 3 - INPUT MOTION IWTU-C4-H1
SA (g)
FREQUENCY (hz)
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 3 - INPUT MOTION OR-51005-25K
SA (g)
FREQUENCY (hz)
1.2
1
0.8
0.6
0.4
0.2
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 3 - INPUT MOTION 0R-51050-10K
SA (g)
FREQUENCY (hz)
2.5
2
1.5
1
0.5
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 3 - INPUT MOTION SRS-PC3-H1
SA (g)
FREQUENCY (hz)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
1
10
100


COL 1 SURFACE
COL 1 OUTCROP
COL 2 SURFACE
CASE 3 - INPUT MOTION WUSSOIL0098
SA (g)
FREQUENCY (hz)
0
1
2
3
4
5
6
7
8
0.1
1
10
100


GE-HCB1
H1RG160-5PCT
IWTU-C4-H1
0R-51005-25K
OR-51050-10K
SRS-PC3-H1
WUSSOIL0098
CASE 1
COLUMN 2 SURFACE/COLUMN 1 OUTCROP RATIO
RESPONSE
SPECTRAL
RATIO
FREQUENCY (hz)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
0.1
1
10
100