6.0 ESTIMATION OF UNIFORM HAZARD SPECTRA ON SOIL

6.1 Background on estimation of uniform hazard spectra for horizontal motions

The objective in developing site specific soil motions for engineering design is to produce seismic demands that reflect a desired hazard level or degree of conservatism that is uniform across structural frequency. An essential aspect of this process is the accommodation of appropriate degrees of uncertainty and variability in source, path, and site processes.

The usual approach to developing site specific soil motions involves defining regionally generic rock (or very firm conditions) outcrop motions and then performing site response analyses to accommodate the effects of local soils. In this approach the hazard level is usually set at the base of the soil column (in defining the control motions) and the actual hazard level corresponding to the resulting soil motion is not well known. To provide conservatism, that is, to ensure that the resulting soil motions do not reflect a higher hazard level than the control motions at some frequencies, parametric site response analyses are performed to incorporate both uncertainty and variability in dynamic material properties and to account for site response model deficiencies. The resulting suite of soil motions is then either smoothly enveloped or the mean value is computed. Since the effects of site variability have been counted twice, once in developing the control (rock outcrop) motions and again in the parametric site response analyses, the resulting soil motions can reflect significantly different hazard levels than desired, as well as hazard levels that vary with frequency. This is particularly true for frequencies near soil column resonances. Design motions then generally reflect both unknown as well as highly variable hazard levels, making the achievement of risk consistency or uniformity in structural analyses a difficult task.

To evaluate approaches to achieving hazard consistent soil spectra (consistent with rock motions) in the context of probabilistic seismic hazard analyses, a suite of site response analyses using rock outcrop UHS are compared to site-specific soil UHS.

6.1.1 Overview of approaches to developing hazard-consistent site-specific soil motions incorporating profile uncertainties

The conventional approach to developing site-specific soil motions involves convolutional analysis, either equivalent-linear or fully nonlinear, using rock outcrop control motions at the soil/rock transition zone. For "bottomless" profiles the "rock" control motions may be input at a sufficiently deep location such that soil amplification extends to the lowest frequency of interest, about 0.5 Hz (generally about 500 ft, McGuire et al., 2001). In the convolutional analyses, uncertainty in dynamic material properties is generally accommodated through parametric variations, either deterministically with upper-, mid-, and lower-range moduli or through a Monte Carlo approach using randomly generated properties with statistically based distributions. Uncertainties in soil properties and in model deficiencies (in the convolutional formulation) are accommodated by either smoothly enveloping the deterministic variations, or by selecting the mean (or a fractile level) for the Monte Carlo approach. Both of these procedures often result in conservative spectral estimates since site variability is already accommodated in the variability associated with the attenuation relations used in developing the control (rock) motions. The approach that uses randomized material properties is preferred since the conservatism is quantified, provided the parameter distributions reflect a realistic assessment of uncertainty in the base case profile and nonlinear properties (epistemic uncertainty) and variability over the site or footprint (aleatory uncertainty). One motivation for using the more conservative mean rather than median spectral estimates, which acknowledges double counting site variability, is to accommodate a degree of model uncertainty (vertically propagating shear-waves and equivalent-linear approximation) in the convolutional formulation. Since this component of model uncertainty is currently unquantified, it is not possible to add it explicitly. It is, however, thought to be relatively small, based on validation exercises of a complete model (including source, path, and site, see Silva et al., 1997). As a result, the possible double counting of site variability may be largely offset by neglecting the deficiencies in the convolutional formulation. For attenuation relations based solely on validated stochastic point- or finite-source models (Silva et al., 1997) the inclusion of model uncertainty accommodates the site model deficiencies for the vertically propagating shear-wave model using the equivalent-linear approximation.

The various approaches to developing hazard-consistent site-specific soil spectra in increasing order of accuracy are listed in Table 6-1. Approaches 1, 2A, 2B, 3, and 4 are compared in the following sections. Approach 1 involves driving the soil column with the broad rock UHS spectrum (control motions) and may result in unconservative high frequency motions, particularly in the context of equivalent-linear site response analyses. Additionally, the appropriate magnitude and time history duration are ambiguous using Approach 1 for hazard environments that do not result in strongly unimodal **M** and *R* deaggregation. Approach 2A recognizes that different earthquakes may dominate the high and low frequencies, and uses separate transfer functions for these events. This is the approach recommended by Regulatory Guide 1.165 (USNRC, 1997). Approach 2B requires some elucidation. In this approach, mean, high and low percentile magnitudes from deaggregations for each design earthquake (e.g., 1 Hz and 10 Hz) are used to scale spectral shapes to the 1 Hz and 10 Hz rock UHS, and the resulting control motions are used to develop weighted mean transfer functions for each design earthquake. The transfer functions are then used to scale each design earthquake or are combined to scale the rock UHS (illustrated in the following sections). The use of a three-point magnitude distribution for each design earthquake accounts for non-linear effects caused by a wide range of earthquake magnitudes contributing to the hazard.

To provide some insulation from the effects of inappropriate nonlinear dynamic material properties, principally in the context of equivalent-linear analyses, Approach 2 uses the envelope of the two (or more) transfer functions to scale the rock outcrop UHS (McGuire et al., 2001). In this approach, for frequencies above the fundamental column resonance, the soil amplification resulting from the lowest input (control) motion is used to scale the rock UHS. If there is high confidence that the nonlinear properties reflect in-situ conditions, the analyst may use either the mean (of the two or more) transfer function or a composite that, at any frequency, simply uses the transfer function appropriate for the controlling scaled earthquake.

Approach 3 involves approximations to the hazard integration using suites of transfer functions. Its development is recent (Bazzurro, 1998; Bazzurro et al., 1999) and it has been implemented at the Department of Energy site Savannah River (Richard Lee, personal communication, 1998). In this approach, complete hazard curves may be generated, as this approach is a direct approximation to

Approach 4, essentially substituting suites of transfer functions in place of the site specific soil attenuation relation. The approach is attractive, although requiring significant computations in site response and hazard deaggregation. The approximations implemented in the hazard integrations have been evaluated for a limited number of profiles and loading conditions (Bazzurro et al., 1999). An approximate form of Approach 3 is described in the next section and is used in Section 8 to estimate spectra on soil.

In Approach 4, as Table 6-1 states, a site specific soil attenuation relation is used in the hazard analysis. This approach assumes that appropriate parametric variations are incorporated in the development of the attenuation relation and that they are also reflected in the uncertainty about the median ground motions.

6.1.2 Theoretical basis of methods for soil analyses

The previous section gave a general overview of four approaches to estimating seismic hazard for soil sites; this section presents the theoretical basis for those approaches. In developing this theoretical basis we have benefitted from discussions with C.A. Cornell and P. Bazzurro, who have pursued similar work, most recently documented in Bazzurro (1998) and Bazzurro et al (1999).

Available approaches to estimating soil UHS can be divided into two broad categories. First are those that integrate over multiple rock amplitudes to calculate soil hazard (probability of exceedence vs. amplitude), from which UHS on soil can be derived. Second are approaches that use the rock UHS at a given annual probability to derive a soil UHS at that same probability. Both approaches and their variants are described here, and in subsequent sections we present examples of applications using soil data from actual sites. Table 6-2 lists these approaches, with a short description and an indication of whether the approach integrates over multiple earthquakes and multiple amplitudes. A more detailed description of each approach is given in McGuire et al., (2001). It is most convenient to start with the most accurate method, Approach 4.

<u>Approach 4 (Based on Integration)</u>. If we define the amplitude on soil at a certain natural frequency to be A_s, then the straightforward approach to calculate soil hazard is directly through a PSHA:

$$P[A_s > z] = \int\int P[A_s > z \mid m, r] f_{m,r}(m,r)\, dm\, dr \tag{6-1}$$

which is the standard PSHA equation in which z is soil amplitude, m is magnitude and r is distance. (Equation (6-1) ignores, for simplicity, rates of occurrence on different faults and is therefore the probability of exceedence for one random earthquake. Rates of occurrence from multiple sources could be incorporated into this and subsequent equations, at the expense of more cumbersome equations.) We call this "Approach 4." It can lead to a defensible representation of soil hazard. Approach 4 is used as the baseline for evaluating other approaches in subsequent sections.

<u>Approach 3 (Based on Integration)</u>. Approach 4 can be simplified by recognizing that soil response can be determined from the level of input motion and the magnitude and distance of the causative earthquake. Thus we can modify equation (6-1) to the following:

$$P[A_s > z] = \int\int\int P[A_s > z \mid m, r, a] f_{M,R|A}(m, r; a) f_A(a)\, dm\, dr\, da \tag{6-2}$$

or

$$P[A_s > z] = \int\int\int P[AF > \frac{z}{a} | m,r,a] f_{M,R|A}(m,r;a) f_A(a) dmdrda \qquad (6\text{-}3)$$

where a is the amplitude of shaking on rock, for example the spectral acceleration at the same frequency as A_s, and $f_A(a)$ is derived from the hazard curve for this frequency. We call this "Approach 3." The first equation above calculates $P[A_s > z]$ from the deaggregated rock hazard, i.e. from *[a,m,r]* sets. The second equation is equivalent except that it defines soil response by an amplification factor:

$$AF = A_s / a \qquad (6\text{-}4)$$

where AF is a random variable with a distribution that can potentially be a function of m and r as well as a.

Approach 3 can be approximated by recognizing that soil response is governed primarily by the level of rock motion and the magnitude of the event; given these two variables, distance does not have a significant effect. Thus:

$$P[A_s > z] = \int\int P[A_s > z | m,a] f_{M|A}(m;a)\ f_A(a) dmda \qquad (6\text{-}5)$$

$$P[A_s > z] = \int\int P[AF > \frac{z}{a} | m,a] f_{M|A}(m;a)\ f_A(a) dmda \qquad (6\text{-}6)$$

For this variant of Approach 3, we would need only the conditional magnitude distribution for relevant amplitudes of a.

There are several ways to implement equations (6-5) and (6-6) in practice. We can represent the magnitude distribution $f_{M|A}(m;a)$ with a continuous function, with three discrete points, or with a single point located for example at the mean magnitude given a. Also, the probabilities of $A_S > z$ or of $AF > z/a$ can be calculated from a broad-banded motion or from motions scaled to specific frequencies (see Approaches 1 and 2 below). We present a comparison of several implementations in Section 6.2 below.

Approach 1 (based on UHS Scaling). Approach 3 above prompts the idea of further simplification by eliminating the integrals on magnitude and spectral amplitude, and scaling the rock UHS to calculate a soil UHS. If soil uncertainties are small, or if we can account for them explicitly, we can estimate the soil UHS accurately, for a given rock UHS. This would certainly be the most straightforward, intuitive approach. We label the simplest scaling "Approach 1."

This scaling works as follows. For a chosen annual probability p′, the corresponding rock UHS is calculated. This UHS becomes a target spectrum, and one (or preferably multiple) rock motions are matched to the target. These rock motions are then used to drive a model of the soil column that includes uncertainties in soil properties. From all of the rock motions and soil properties, the mean soil spectrum is calculated, and this is the Approach 1 estimate of the soil UHS corresponding to annual probability p′. Of course a less accurate estimate could be obtained by ignoring uncertainty in soil properties.

Approach 2 (Based on UHS Scaling). Approach 1 implies that a single, broadband motion representing the rock UHS will be used to drive the soil calculations. It has been recognized that a broadbanded motion may be inaccurate in many applications (e.g. USNRC, 1997) and may in fact be unconservative. The reason is that one earthquake (e.g., a small, local event) may dominate the high-frequency hazard, but a different event (e.g. a large, distant shock) may dominate the low frequencies. In this case a single earthquake that drives all frequencies to the UHS level is unlikely. As an alternative, two earthquakes can be used: one that dominates at high frequencies (10 Hz) and another that dominates at low frequencies (1 Hz). Approach 1 can be reformulated in terms of two spectra: one representing high-frequency events that is scaled to the UHS at 10 Hz, and a second representing low-frequency events that is scaled to the UHS at 1 Hz.

Using the amplitudes of 10 Hz and 1 Hz will simplify the analysis since, where magnitude values are required, they will be available from the rock PSHA results. The resulting soil UHS can be plotted and enveloped to obtain an overall UHS for soil. If more than two frequencies are necessary on rock to define specific events whose envelope matches the UHS, then these same frequencies can (and should) be used to calculate soil UHS. The use of two frequencies in this way is labeled "Approach 2A."

A variant of this approach recognizes that the magnitudes of earthquakes, for a given rock amplitude, may have a strong effect on non-linear soil behavior (through the duration of shaking and long period effects). The magnitude deaggregation at rock amplitude a′(at, say, 10 Hz) can be discretized into three magnitudes m_L , m_m , and m_H . Then the rock amplitude a′ can be translated into soil distributions for each magnitude. These can be weighted (using weights derived from the deaggregation) to produce an overall distribution, the mean of which becomes a set of soil responses used to form the UHS. (The estimated UHS is the envelope of the mean soil responses calculated for 10 and 1 Hz.) This is labeled "Approach 2B." Because of nonlinear behavior in the soil, the mean soil amplitude considering **M** variability may be higher than if **M** variability is ignored.

Combination Approaches. It is possible to use combinations of the approaches described above, and in fact a combination of Approaches 3 and 2A is recommended below for calculating soil UHS. Specifically, it is recommended that Approach 3 be used to calculate UHS on soil, e.g. that z be determined for $P\,[A_S > z\,]$ = 1E-4 and 1E-5 in equations (6-5) and (6-6). Within equations (6-5) and (6-6), it is recommended that Approach 2A be used to calculate $P[A_S > z|m,a]$ or $P[AF > z/a|m,a]$.

6.2 Steps for estimating uniform hazard spectra for horizontal motions

The recommended approach for estimating soil UHS is a combination of Approaches 3 and 2A described in the previous section. We herein label this "Approach 2A/3."

The steps necessary to implement this combined approach are as follows:

1. Determine the soil distribution $P[A_S > z|m', a]$ or $P[AF > z/a \mid m', a]$ for several values of rock amplitude a and the corresponding dominant magnitude m', using Approach 2A.

2. Integrate over rock amplitude a to calculate $P[A_S > z]$ using equation (6-5) or (6-6) for a range of soil amplitudes z (Approach 3).

3. Interpolate the results from step 2 at each frequency to obtain, the 10^{-4} and 10^{-5} UHS on soil.

We then use the slope of the soil hazard from 10^{-4} to 10^{-5} to calculate a soil URS from the 10^{-4} soil UHS.

An expanded description of these three steps for Approach 2A/3 follows. This is written in terms of the amplification factor AF, but a parallel procedure applies for computing soil response A_S directly.

Step 1. The soil response AF is calculated for three values of rock motion a: the amplitudes corresponding to the 10^{-3}, 10^{-4} and 10^{-5} hazard. This is achieved by making soil calculations with six sets of rock input motions: one with the high-frequency (10 Hz) magnitude shape scaled to the 10^{-3} UHS at 10 Hz, a second with the low-frequency (1 Hz) magnitude shape scaled to the 10^{-3} UHS at 1 Hz, and similarly for the 10^{-4} and 10^{-5} UHS. These calculations follow Approach 2A, include soil uncertainties, and yield the mean amplification AF for the scaled spectra at 10 and 1 Hz, from which the envelope is created. The calculations also yield a standard deviation of AF.

Step 2. Integrate over rock acceleration a using a simplification of equation (6-6) to calculate $P[A_S>z]$ for a range of soil amplitudes z:

$$P[A_S > z] = \int P[AF > \frac{z}{a}|a, m'(a)] f_A(a) da \tag{6-7a}$$

In this simplification the distribution of m given a has been replaced with a single value of m′ (the mean value from deaggregation), representing a discrete distribution with a single value. This value of m' is different at the 10^{-3}, 10^{-4}, and 10^{-5} UHS levels. Step 1 gives us the mean and standard deviation of $[AF \mid a, m'(a)]$. Assuming a lognormal distribution we calculate $P[AF > z/a]$. (Because the standard deviation varies somewhat with amplitude and frequency in a non-monotonic way, it is convenient to use an average standard deviation for the calculation of $P[AF > z/a]$, which for the examples here is calculated to be 0.2.) For amplitudes below the 10^{-3} UHS or above the 10^{-5} UHS it is generally accurate to use the mean amplification at 10^{-3} and 10^{-5}, respectively (this can be confirmed with a sensitivity study).

An alternative solution to integrating over rock acceleration a in equation (6-7a) is to use the closed-form approximation:

$$z_{rp} = a_{rp} \overline{AF_{rp}} \exp\left(\frac{1}{2} k \sigma_\delta^2 / d_3^2\right) \tag{6-7b}$$

where z_{rp} is soil amplitude z associated with return period rp, $\overline{AF_{rp}}$ is the mean amplification factor for the rock motion with return period rp, k and d_3 are derived from the slope of the rock hazard curve and AF, and σ_δ is the log standard deviation of AF described above. Appendix A contains the derivation of equation (6-7b). This formulation, which is demonstrated below to be accurate, offers a convenient, intuitive way to obtain the soil UHS given a rock UHS and amplification factors. The first two terms on the right-hand-side of equation (6-7b) (a_{rp} $\overline{AF_{rp}}$) are Approach 2A, i.e. the rock UHS times the mean amplification factor. The last term (exp $[1/2\, k\, \sigma_\delta^2 / d_3^2]$) is a correction that accounts for uncertainty in soil amplification (σ_δ), the slope of the rock hazard curve (k), and the slope of AF (d_3). This term is typically 1.05 to 1.25.

Step 3. With the annual probability of exceedence for a range of soil amplitudes z, we interpolate to obtain the UHS on soil corresponding to 10^{-4} and 10^{-5} annual frequency (note that, at these levels, annual probability of exceedence ≈ annual frequency of exceedence).

To derive the URS on soil, at each structural frequency we calculate A_R, which is the ratio of spectral amplitudes at 10^{-5} to those at 10^{-4} (see Section 7.3 of McGuire et al., 2001). We then calculate the scale factor SF:

$$SF = \max\{0.7,\ 0.35\, A_R^{1.2}\} \tag{6-8}$$

which is equation (7-18) from McGuire et al., 2001 and equation (4-2) from this report. The 10^{-4} uniform reliability spectrum is calculated using the 10^{-4} UHS as:

$$URS = SF\ x\ UHS \tag{6-9}$$

which is equation (4-1) from this report.

The specific form of SF in equation (6-8) depends on the assumptions of a seismic margin factor of 1.67 in the design level, and a factor of 20 to 40 between the UHS frequency and the component failure frequency. Other conservatisms or factors could be used, in which case the specific form of SF would change, but the calculation of the URS would be as represented here with a slightly different form for SF. See Section 9.1 for further discussion of the form of equation (6-8).

The advantage of procedure 2A/3 is that the UHS on soil can be calculated from the UHS on rock and from just a few soil amplification studies conducted at selected amplitude levels to establish the slope of AF. The procedure makes several approximations about the distribution of soil response but includes the major effect: soil amplification is a function of the rock input motion and the dominant earthquake magnitude.

6.3 Approaches for vertical motions

Assessment of site specific soil vertical motions to accompany corresponding horizontal motions is a perplexing issue, particularly if it is desirable to maintain hazard consistency with the horizontal motions. Rarely are separate hazard analyses performed for horizontal and vertical control or rock outcrop motions (currently no vertical relations are available for the CEUS) and there are no widely accepted site response methodologies currently available to accommodate vertical analyses (Silva, 1998).

Commonly, equivalent-linear site response analyses for vertical motions have used strain iterated shear moduli from a horizontal motion analysis to adjust the compression-wave velocities assuming either a strain independent Poisson's ratio or bulk modulus. Some fraction (generally 30% to 100%) of the strain iterated shear-wave damping is used to model the compression-wave damping and a linear analyses is performed for vertically propagating compression waves using the horizontal control motions scaled by some factor near 2/3.

Alternatively, fully nonlinear analyses can be made using two- or three-component control motions (Costantino, 1967; 1969; Li et al., 1992; EPRI, 1993). These nonlinear analyses require two- or three-dimensional soil models that describe plastic flow, yielding, and the accompanying volume changes as well as coupling between vertical and horizontal motions through Poisson's effect. These analyses are important to examine expected dependencies of computed motions on material properties and may have applications to the study of soil compaction, deformation, slope stability, and component coupling. However, the models are very sophisticated and require specification of many parameters, at least some of which are difficult to measure both in mean or central values as well as expected ranges (uncertainties).

The equivalent-linear approach implicitly assumes some coupling between horizontal and vertical motions. This is necessitated by the lack of well determined G/G_{max} and hysteretic damping curves for the constrained modulus. Ideally, the strain dependency of the constrained modulus should be determined independently of the shear modulus. Also, the conventional approach assumes vertically-propagating compression waves and not inclined P-SV waves. Additionally, the use of some fraction of the horizontal control motion is an approximation and does not reflect the generally greater high-frequency content of vertical component motions at rock sites due to lower kappa values (EPRI, 1993). More recently, use is made of V/H ratios for rock computed from empirical attenuation relations. This process accommodates observed trends in magnitude and distance dependencies of vertical motions (EPRI, 1993; Silva, 1998) and results in vertical control motions appropriate for the controlling earthquakes, generally based on UHS 1 Hz deaggregation, as this usually results in the largest earthquakes. For cases that result in very large distances (>100 km) for 1 Hz and very close distances for 10 Hz (< 10 km) or peak acceleration deaggregation, it would be more appropriate to use two design spectra (e.g. 1 Hz and 10 Hz) or to envelop the 1 Hz and 10 Hz (or PGA) V/H ratios to develop a conservative vertical rock outcrop spectrum. This approach should not be followed for cases where nonlinear (equivalent-linear) site response analyses are planned to estimate the vertical site specific soil motions. For these cases two (or more) spectra should be used.

The approach taken here makes use of generic soil V/H ratios to scale the site specific horizontal soil motions. This approach maintains as many site specific attributes as possible through the use of the horizontal soil motions (soil column) and generic soil V/H ratios (controlling magnitudes and distances) while avoiding the currently inherent ambiguity in vertical site response analyses. This is the case for WUS where vertical and horizontal component empirical attenuation relations for soil exit. For the CEUS, this approach relies on generic soil V/H ratios based on a validated site response methodology (EPRI, 1993; Silva, 1998). In this case, in an effort to preserve as many empirical attributes as possible and to remove any model deficiencies, we adopt an approach similar to that used in developing the recommended CEUS single- and double-corner spectral shapes (McGuire et al., 2001). In this approach WUS-to-CEUS scale factors are developed and used to scale an empirical

WUS deep soil V/H ratio. The scale factors are ratios of WUS and CEUS V/H ratios computed for generic deep soil, representative of deep soils beneath the WUS strong motion recording sites and assumed to occur both in the WUS and CEUS. To compute the V/H ratios, a generic deep soil column in placed on the generic WUS and CEUS crustal models in a manner analogous to developing the soil attenuation relations (Section 2). In this case, inclined P-SV waves are used to model the vertical motions. This approach was also used to supplement the CEUS analyses time history bins by scaling WUS records to CEUS conditions (McGuire et al., 2001; Section 3).

6.4 Horizontal motions for Mojave site

6.4.1 Results for Approaches 1, 2A, and 2B

Section 6.1 presented a number of approaches to estimating site-specific soil spectra that are consistent with a specified hazard level that accommodate uncertainties in soil properties. In this section, comparisons are made among several of these approaches, and site-specific soil UHS are computed for the Meloland soil profile located in the WUS at the Mojave site. The site-specific soil UHS (following Approach 4) reflect the desired hazard level with which to evaluate the various degrees of approximations using rock outcrop UHS and site response analyses. However, an issue exists in the soil UHS calculated with Approach 4 involving long return periods where the hazard may result from motions that significantly exceed the median ground shaking during earthquakes contributing to the hazard. Under these conditions for highly nonlinear profiles, the site-specific UHS may overestimate the hazard at high frequency, as the residual dispersion does not reflect the soils limited capacity to transmit high levels of motion (i.e. its non-linearity). This is an important issue and requires further elaboration.

Approach 4 was considered to represent "truth" in the context of the analyses of Section 6.1, as these spectra consist of amplitudes computed for the same probability of exceedence across structural frequency. However, at high strains soil profiles tend to saturate (material damping increases), transmitting proportionally less high-frequency motion as loading levels increase. This artifact is enhanced by the equivalent-linear approach and is one of the motivating factors for developing Approaches 2A and 2B. For soil columns near or into failure, when pore pressure has increased to very high levels, high frequency energy may again be transmitted through the column as hysteresis loops become S-shaped (material becomes dilatant) and material damping decreases with increasing strains. At this point, however, motions of significance to structures are generally lower and foundation stability is more of an issue than design ground motions. While this tendency to saturate is reflected in the convolution analyses used to develop both the site-specific soil motions and the soil attenuation relations, the residual dispersion computed in a conventional (homoskedastic) regression analysis is a combination over all event (causative) conditions (all magnitudes and distances). As a consequence, for long return periods, much of the contribution to the soil UHS results from motions that significantly exceed median estimates for the magnitudes and distances dominating the hazard. These contributions are reflected in the deaggregation ε values (McGuire, 1995). This process can conceivably result in soil motions that imply control motions sufficiently high enough to fail the soil column. This apparent paradox suggests that in the context of probabilistic seismic hazard analyses involving nonlinear site response, a magnitude- and distance-*independent* residual distribution (uncertainty about the median attenuation estimates) may be inappropriate and can result in overly conservative soil motions. The "truth" or benchmark site-specific hazard analysis therefore should represent the distribution of residuals to be magnitude- and distance-*dependent*. There is also a possibility that, at high median response levels, the distribution should be negatively skewed, i.e. that a long positive tail would have very low probability. Detailed analysis of residual distributions from synthetic soil response calculations where Meloland soil properties were varied did not reveal such a skewness, however. Therefore the standard lognormal distribution of soil response was retained, but with a standard deviation dependent on magnitude and distance.

This treatment of soil response uncertainty should be viewed in the context of Meloland site characteristics. Although this profile is considered soft (Figure 2-6), its material strain dependencies are relatively weak (Figure 2-8) resulting in a system (initial stiffness and material strain dependencies) that is considered only moderately nonlinear (as implied by the recordings of the 1979 Imperial Valley earthquake across the El Centro array). Thus the use of a magnitude- and distance-dependent uncertainty in the attenuation relation (Section 3) is sufficient to capture the essential effects of soil saturation. For other profiles that exhibit more non-linear behavior, it would be appropriate to examine the distribution of residuals at high median response levels, to determine if skewness is apparent and should be modeled. For consistency in the current application, a hetero-skedastic residual dispersion is used in developing the WUS rock UHS.

It should be noted that the use of a homoskedastic distribution for uncertainty in soil motion is consistent with current practice in the CEUS. WUS attenuation models typically include a magnitude dependency in their standard errors (Abrahamson and Shedlock, 1997) resulting in a large decrease as magnitude increases for $\mathbf{M} \geq 6.5$. However, the high frequency motions (≥ 5 Hz) are affected most by nonlinear saturation because of the contribution of low-magnitude ($\mathbf{M} < 6.5$) close-in earthquakes. The magnitude dependency currently incorporated in WUS attenuation relations does not represent soil response because it is site independent, and is applied at both rock and soil sites.

High soil responses may result from moderate or high input rock motions combined with randomly selected linear properties (a stiff column, high G/G_{max}, or low damping curves). Therefore, a range of rock motions contribute to the frequency of exceeding a high soil spectrum. As a result, Approaches 1, 2A, and 2B (which are fundamentally deterministic in nature, being based on a fixed control motion and mean soil response) will underestimate the motions for Approach 4 (the site-specific UHS) at some low hazard level (high soil motion), unless higher fractile levels are used. For the Mojave site, this occurs at the annual probability of exceedence of 10^{-5}.

The development of Approach 3, described in Sections 6.1 and 6.2, avoids the deterministic aspects of Approaches 1, 2A and 2B, while approximating the integration over a range of input rock amplitudes.

Figure 6-1 shows a comparison of the WUS and CEUS rock outcrop UHS. The effects of both the hazard environment and attenuations relations (Section 2) are evident, with the WUS motions generally exceeding the CEUS motions by a factor of five or more for frequencies below about 10 Hz.

To correct the control motions to be appropriate for base-of-soil conditions (shear-wave velocity of 1 km/sec), the effects of the shallow (top 30m) soft rock profile (Figure 2-4) must be removed. Since the Meloland profile (Figure 2-6) was placed on top of the Wald and Heaton (1994) Southern California crustal model (Table 2-3), use of the WUS rock spectra as control motions contain the additional amplification of the materials above the 1 km/sec layer. To accomplish this, response spectral adjustment or correction factors have been developed (McGuire et al., 2001). These factors accommodate nonlinear response of the shallow material (Figure 2-5) and are based on the rock UHS peak acceleration value. The effects of these factors are shown in Figure 6-2, which compares the WUS rock UHS (Figure 6-1) and the corrected (to 1 km/sec material outcropping) UHS. The correction reduces the motions 10% to 20% over much of the frequency range with a maximum reduction near 2 Hz. The plots of control motions in this section include the corrections. Uncorrected motions are shown in Section 4.

Design spectra scaled to 1 and 10 Hz are shown in Figures 6-3 and 6-4 for the WUS and CEUS respectively. The difference in the hazard environments between the WUS and CEUS is evident in the large differences in the 1 Hz and 10 Hz magnitude values from deaggregation. The difference in magnitudes for the 1 Hz and 10 Hz design earthquakes is 1.2 units for the CEUS (Figure 6-4) and only 0.5 units for the WUS (Figure 6-3). The effects of magnitude distribution in the rock UHS on nonlinear soil response are much less an issue for WUS conditions than CEUS, at least for the example sites, which were chosen to maximize the differences at 1 and 10 Hz (Section 2).

In the site response analyses, two issues are important: the degree of fit of artificial motions to the control motion spectra and the effect of control motion variability on median soil spectra. The first issue involves developing appropriate Fourier amplitude spectra for use in the RVT equivalent-linear soil analyses that result in response spectra consistent with target response spectra. To illustrate the RVT spectral matching process (Silva and Lee, 1987), Figure 6-5 compares a target response spectrum to a spectrum resulting from spectral matching. The difference is less than a few percent over the entire frequency range.

The second issue involves the representation of control motion variability, and this is potentially significant because Approaches 1, 2A, and 2B assume fixed or constant control motion while varying site properties. This is different from the process used to develop site specific attenuation relations (Approach 4) where source, path, and site parameters are varied simultaneously. The implicit assumption involved in comparing results from these two different processes is that soil response is either independent or weakly dependent on control motion variability. To demonstrate the validity of this assumption, Figure 6-6 shows median and $\pm$ 1 σ spectral estimates for WUS conditions at $\mathbf{M} = 7.5$ and $R = 1$ km varying only site properties while Figure 6-7 shows results for varying source, path, and site parameters simultaneously. Although the variability is significantly larger when source and path parameters variations are added ($\sigma_{\ln\ PGA}$ increases from 0.14 to 0.35, a factor of about 2), the median spectra are virtually identical as illustrated in Figure 6-8.

Meloland profile

The Meloland profile, located in the Imperial Valley of southern California and northern Mexico, is considered a soft profile (Figure 2-6) and has a column frequency of about 0.5 Hz. While it is considered "bottomless" and extends kilometers in depth, it was truncated at a depth of 304m (1,000 ft) for these analyses. This site has a recently installed (Caltrans/CDMG) vertical strong motion array, and the nearby CDMG strong motion site recorded the **M** 6.5 1979 Imperial Valley earthquake at a rupture distance of 0.5 km (with an average horizontal component peak acceleration of about 0.3g). The modulus reduction and damping curves representing the Meloland profile are shown in Figure 2-8. They are based on modeling strong motions from the 1979 Imperial Valley earthquake recorded at Meloland and nearby sites (Silva et al., 1997) and reflect relatively weak strain dependencies. The profile is considered nonlinear to a depth of 150m (500 ft).

To begin the approach comparisons for the Mojave site, Figure 6-9 shows the soil UHS computed using Approaches 1, 2A, 2B, and 4. Approach 2A uses the envelope of the 1 Hz and 10 Hz mean spectra computed using 10 Hz and 1 Hz control motions to scale the rock UHS. The spectra may also be used independently to produce soil design spectra for cases where it may be desirable to perform two sets of design analyses. Approach 2B uses multiple (3) sets of control motions to compute both 1 Hz and 10 Hz weighted mean transfer functions. The envelope of the mean transfer functions times their respective control motion spectra becomes the Approach 2B spectrum (Table 6-1). Figure 6-9 shows very similar results for Approaches 2A and 2B, both of which show higher motions than Approach 1 for frequencies above about 1 Hz. This is a consequence of using a single broad UHS spectrum (Figure 6-3) as a control motion. The soil column is being softened more by the broad-banded rock motion of Approach 1 than by either of the scaled design spectra, each of which reflects a single earthquake. In general both Approach 2A and 2B approximate the motions of Approach 4 (soil UHS) from about 0.3 Hz to 100 Hz (PGA). In this case, little difference is seen in Approaches 2A and 2B and Approach 2A is recommended because of its simplicity. Approach 1 is not recommended.

To illustrate the levels of loading in the soil column, Figure 6-10 shows the median and $\pm$ 1σ effective strains for the Approach 1 analysis. The effective strains are large, with median values near 0.3 and + 1σ values near 0.6 in the intermediate portion of the profile.

The transfer functions (5% damped response spectra) used to scale the rock outcrop spectra are shown in Figures 6-11 to 6-13. Figure 6-11 shows the ratios computed for the 1 Hz scaled design earthquake and Figure 6-12 the corresponding ratios for the 10 Hz design earthquake. Figure 6-13 compares the two (1 Hz and 10 Hz) mean ratios, of which the envelope is used to scale the rock outcrop UHS (Approach 2B).

Magnitude dependencies in the transfer functions, Figures 6-11 and 6-12, are weak below 10 Hz for the 1 Hz scale design outcrop spectrum and strong below 10 Hz for the corresponding 10 Hz spectrum. Due to the similarity in the 1 Hz and 10 Hz scaled rock spectra (Figure 6-3), the corresponding weighted mean transfer functions are similar (Figure 6-13).

6.4.2 Results for Approach 2A/3

An example of the recommended procedure for calculating soil hazard was conducted at the Mojave site in California, using the Meloland soil profile, which was selected because it has the capability of demonstrating the most non-linearity at high input amplitudes. The 10^{-3}, 10^{-4}, and 10^{-5} rock spectra are shown in Figure 6-14.

Deaggregation of the rock seismic hazard at 10^{-3}, 10^{-4}, and 10^{-5} leads to the **M**-R plots shown in Figures 6-15, 6-16, and 6-17 for 10 and 1 Hz. For each of the three amplitudes, soil motion was calculated by Approach 2A using the magnitudes and distances in Table 6-3.

The soil amplification factors calculated from Approach 2A are shown in Figure 6-18; Approach 2A is the recommended way to calculate soil amplitudes, as will be demonstrated below.

A soil seismic hazard analysis was conducted following Approach 3 (equation (6-7a)) at 25 frequencies using, for starting values of z, the rock amplitudes at 10^{-4} and 10^{-5} times the respective mean values of AF(a,m′). Once $P(A_s>z)$ was calculated for these values of z, the estimated 10^{-4} and 10^{-5} soil amplitudes were calculated by interpolation and extrapolation. These preliminary estimates of $A_S(10^{-4})$ and $A_S(10^{-5})$ then became the new values for z, and the process was repeated until stability was reached (always within five iterations). Approach 3 was also calculated with equation (6-7b), in which case no iteration is required.

The application of equation (6-7a) or (6-7b) requires an estimate of σ_δ at each frequency, for the **M** and R value dominating the hazard for that calculation. These estimates come from the soil amplification studies conducted using as input the design spectra scaled to the UHS at 10 and 1 Hz. These indicated an average σ_δ of 0.2.

Spectra estimated for 10^{-4} and 10^{-5} annual probabilities are shown in Figures 6-19 and 6-20, using several methods. Approach 4 is a direct calculation of seismic hazard on soil, using a site-specific soil attenuation equation with a standard deviation that varies with **M** and R. Approach 2A/3 applies equation (6-7a) using Approach 2A (which scales spectral shapes at 10 and 1 Hz) to estimate P[AF $> z/a$]. Table 6-3 indicates the **M** and R values for these spectral shapes. "Approximate Approach 2A/3" is identical to Approach 2A/3 except that it uses the approximate equation (6-7b).

Note that in this application, Approach 2A was applied using amplification factors from the 1 Hz spectrum at low frequencies ($f < 2$ Hz), and using the amplification factors from the 10 Hz spectrum at high frequencies ($f \geq 2$ Hz). This is slightly different from the Approach 2A application of the previous section, which uses the envelope of the amplification factor at any frequency (See Figure 6-13). Frequency 2 Hz was chosen as the cross-over frequency because the 1 Hz scaled spectrum dominates at lower frequencies and the 10 Hz scaled spectrum dominates at higher frequencies (see Figure 4-3).

Using Approach 4 as the spectra of merit, Figures 6-19 and 6-20 indicate that both Approaches 2A/3 are generally accurate. The integral Approach 2A/3 (equation (6-7a)) is slightly more accurate than the closed-form solution (equation (6-7b)) at 10^{-5} annual frequency (Figure 6-20). There is a slight underestimation of the Approach 4 spectral amplitudes from 7 to 30 Hz, amounting to less than 10%, for the 10^{-5} spectrum. This is acceptable, given that the soil conditions were chosen to accentuate nonlinear behavior and that the 10^{-5} amplitude is used only to calculate the slope in the soil hazard curve, for purposes of deriving the URS. Approach 2A is slightly less accurate for both the 10^{-4} and the 10^{-5} spectrum.

If more accurate soil spectra are desired for a site, the best alternative is to develop site-specific soil attenuation equations for the site, and conduct a full seismic hazard analysis (Approach 4). If this is done, the soil attenuation equation must represent all epistemic and aleatory uncertainties in the soil amplitudes, and the resulting standard deviations should be compared to standard deviations from empirical soil equations.

6.5 Horizontal motions for Columbia site

6.5.1 Results for Approaches 1, 2A, and 2B

The Savannah River generic profile was adopted from measured shear-wave velocity profiles at the DOE Savannah River site. It is generally stiff but contains a broad soft zone at intermediate depths (around 25m) with a steep gradient thereafter (Figure 2-6b). The low-strain column resonance is near 0.8 Hz. G/G_{max} and hysteretic damping curves based on modeling strong ground motions in the Los Angeles area recorded at cohesionless soil sites from the **M** 6.7 1994 Northridge earthquake are used for this site (Figure 2-8b).

For the approach comparison, Figure 6-21 shows results for 1, 2A, and 2B with Approach 4 reflecting the site specific soil UHS. As with the WUS site, Approach 1 underestimates the UHS at the higher frequencies while Approaches 2A and 2B are generally slightly above the UHS, except at very low frequency. Approaches 2A and 2B are nearly identical and both are conservative above 10 Hz while Approach 2B remains closer to the soil UHS at very low frequency (<0.4 Hz). Cyclic shear strain (effective) levels are illustrated in Figure 6-22, which shows much lower values than the corresponding WUS analyses. Maximum median strains developed in the soft zone have values near 0.02% compared to about 0.3% for the WUS Meloland profile (Figure 6-10). The loading levels are much lower and the profile is significantly stiffer.

The transfer functions (5% damped response spectra) are shown in Figures 6-23 to 6-25. Figures 6-23 and 6-24 show the amplification factors for the 1 Hz and 10 Hz scaled design spectra along with the weighted mean ratios. The effects of magnitude on the transfer functions are less than in the WUS (Figures 6-11 and 6-12) due to lower levels of control motions, a stiffer profile, and a smaller magnitude range (ML to MH), at least for the 1 Hz factors.

Figure 6-25 shows the weighted mean transfer functions. They show large differences at high frequency (f > 30 Hz). The 1 Hz transfer functions are larger than the 10 Hz transfer functions at high frequency due to lower loading levels (see Figure 6-4). The 10 Hz scaled rock outcrop design spectrum has significantly larger high frequency motions than the 1 Hz spectrum resulting in high cyclic shear strains in the soil column.

6.5.2 Results for Approach 2A/3

The procedure recommended in Section 6.2 was conducted at the Charleston site in the CEUS, using the generic Savannah profile. The 10^{-3}, 10^{-4}, and 10^{-5} spectra for rock conditions are shown in Figure 6-26 for the 1- and 2-corner ground motion models and for the mean. (Note that the mean is calculated by weighting the two ground motion models 0.5 each and calculating the hazard. The mean is not the average of the two uniform hazard spectra.)

Deaggregation of the rock seismic hazard at 10^{-3}, 10^{-4}, and 10^{-5} is different for each of the two ground motion equations. **M**-R deaggregation plots are shown in Figures 6-27, 6-28, and 6-29 for 10 and 1 Hz, for the 1-corner model (part a of each figure) and for the 2-corner model (part b). For each of the three amplitudes, soil motion was calculated by Approach 2A using the magnitudes and distances shown in Table 6-4.

A soil seismic hazard analysis was conducted following Approach 3 (equation (6-7a)) at 25 frequencies using an iterative procedure to calculate amplitudes associated with 10^{-4} and 10^{-5} annual frequencies. The iterative procedure was identical to that used for the Mojave site. For these calculations, σ_δ was taken from the Approach 2A calculations of soil amplification (average of 0.2 over all frequencies). Equation (6-7b) was also applied, for which no iteration is required. Amplification factors used to apply Approach 3 are shown in Figure 6-30.

Spectra estimated for 10^{-4} and 10^{-5} annual frequencies are shown in Figures 6-31 and 6-32, using four methods. Approach 4 is the direct calculation of seismic hazard on soil, using the site-specific soil attenuation equation with a standard deviation that varies with **M** and R. Approach 2A/3 applies equation (6-7a), using Approach 2A to estimate P[AF>z/a]. In addition, "Approximate Approach 2A/3" uses equation (6-7b) to calculate $z_{.0001}$. Finally, "Approach 2A" is the direct scaling of the 10^{-4} rock UHS to the 10^{-4} soil UHS described in the previous subsection, using the envelope of the amplification factors at each frequency.

Using Approach 4 as the spectra of merit, Figures 6-31 and 6-32 indicate that "Approach 2A/3" and "Approximate Approach 2A/3" are very similar, and both give generally accurate estimates compared to Approach 4, particularly for 10^{-4} (Figure 6-21). These two Approaches underestimate the 10^{-5} UHS at high frequencies (f> 15 Hz), where the amplification factor is lowest (see Figure 6-30). Because the 10^{-5} UHS is used only to calculate the slope of the hazard curves in order to obtain the URS, this underestimation is acceptable. Approach 2A is accurate except for f> 20 Hz, where the 1 Hz amplification factor exceeds that for 10 Hz (see Figure 6-25). For the Columbia site, the hazard curve slope and amplification factors (Figure 6-30) are such that the "correction factor" (see the discussion of equation 6-7b) is on the order of 1.05, so Approach 2A is expected to be close to Approach 2A/3, except at high frequencies.

6.6 Vertical motions

6.6.1 Mojave site

To estimate vertical soil motions consistent with the horizontal soil motions, a WUS empirical generic soil V/H ratio was developed for **M** = 6.6 and *R* = 18 km, based on the rock UHS deaggregation at 1 Hz. The empirical V/H ratio (Figure 6-33) is an average of ratios from Abrahamson and Silva (1997) and Campbell (1997), which were selected because these two relations cover the widest frequency range. The vertical motions exceed the horizontal between 10 and 20 Hz due to the close distance (18 km) and large magnitude (EPRI, 1993; Silva, 1998). These ratios are used to develop vertical design spectra, as discussed in Section 7.1

6.6.2 Columbia site

As discussed in Section 6.3, the approach used to develop site specific vertical motions relies on modeling results to produce WUS-to-CEUS V/H scale factors for deep soil applied to a WUS empirical deep soil V/H ratio. This process results in a generic soil CEUS V/H ratio which is applied to the site specific horizontal design spectrum (smoothed version of Approach 2A/2B spectrum). To illustrate this process, Figure 6-34 shows the WUS-to-CEUS V/H scaling factors (dash-dotted line), the WUS deep soil empirical V/H ratio (dotted line), and the resulting CEUS deep soil V/H ratio (solid line). The empirical WUS deep soil V/H ratio was taken from Abrahamson and Silva (1997) as it is the only currently available ratio valid beyond 80 km (McGuire et al., 2001). The WUS-to-CEUS scale factors were taken from the factors used to scale the WUS analysis time histories to CEUS conditions (McGuire et al., 2001; Section 3). They are appropriate for the **M** and *R* of the 1 Hz CEUS rock UHS, 7.2 and 110 km respectively. These ratios are used to develop vertical design spectra as discussed in Section 7.2.

The exceedence of the vertical spectrum over the horizontal at high frequency ($f \geq 10$ Hz) is larger than expected for a distance of 110 km and should be closer to the horizontal, at least for rock sites (Atkinson, 1993). However, there is a large contribution to high-frequency hazard for $R \approx 10$ km (see Figure 3-29, particularly for the 1-corner model). This contribution at 10 km suggests an appropriate high frequency V/H ratio (Silva, 1997; McGuire et al., 2001) and indicates caution in selecting V/H ratios for cases where high and low frequency contributions to the UHS reflect both near and far distance contributions. Enveloping the 10 Hz and 1 Hz V/H ratios may be appropriate in these cases.

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Table 6-1
Overview of Approaches for Developing Soil UHS

Approach 1:	Rock UHS used as control motions to drive soil column.
Approach 2A:	Use scaled 1 Hz and 10 Hz design earthquakes as control motions to develop 1 Hz and 10 Hz soil motions (R.G. 1.165 approach) or develop transfer function for 1 Hz and 10 Hz design earthquakes, using a single control motion (scaled shape) for each frequency; either envelope the transfer functions or switch from the 1 Hz transfer function to the 10 Hz transfer function at the frequency where the scaled spectra cross.
Approach 2B:	Develop weighted mean transfer functions for 1 Hz and 10 Hz design earthquakes accommodating magnitude distributions; use the 1 Hz transfer function at low frequencies and the 10 Hz transfer function at high frequencies, switching at the frequency where the scaled spectra cross.
Approach 3:	Perform PSHA with rock attenuation relation; deaggregate by **M**, and *R* and calculate soil response with appropriate control motions for each **M**, and *R* bin.
Approach 4:	UHS computed directly from PSHA using site-specific soil attenuation relations.

Table 6-2
Details of Approaches for Developing Soil UHS

Description	Frequencies Used	Integration	Label
PSHA using site-specific soil attenuation	multiple	over m and r	Approach 4
Calculate soil hazard from rock hazard and m and r deaggregation	several	over a, and over m and r given a	Approach 3
Scale rock UHS to soil UHS accounting for soil parameter uncertainty	two, e.g. 10 and 1 Hz	none	Approach 2A
Scale rock UHS to soil UHS accounting for soil parameter uncertainty and m deaggregation	two, e.g. 10 and 1 Hz	none	Approach 2B
Scale rock UHS to soil UHS using broadbanded input motion	none	none	Approach 1

Table 6-3
Magnitudes and Distances Used for Soil Amplification Calculations
at Mojave Site

		10 Hz			1 Hz		
UHS	Approach	**M**	R	wt	**M**	R	wt
1E-3	1	M = 6.5, R = 22					
	2A	6.5	23	1.0	7.1	30	1.0
	2B	5.1	10	0.2	5.6	10	0.1
		6.5	22	0.6	7.0	28	0.6
		7.7	30	0.2	7.7	30	0.3
1E-4	1	M = 6.1, R = 14					
	2A	6.1	14	1.0	6.6	18	1.0
	2B	5.1	10	0.2	5.4	10	0.2
		6.1	14	0.6	6.6	18	0.6
		7.8	30	0.2	7.8	30	0.2
1E-5	1	M = 6.0, R = 12					
	2A	6.0	12	1.0	6.4	14	1.0
	2B	5.0	10	0.2	5.5	10	0.2
		6.0	12	0.6	6.4	14	0.6
		7.0	30	0.2	7.0	30	0.2

Table 6-4
Magnitudes and Distances Used for Soil Amplification
Calculations at Columbia Site

UHS	Approach	Ground motion model	10 Hz			1 Hz		
			M	*R*	wt	**M**	*R*	wt
1E-3	1	1-corner	**M** = 6.4, *R* = 85					
		2-corner	**M** = 6.8, *R* = 102					
		mean	**M** = 6.6, *R* = 94					
	2A	1-corner	5.9	62	1.0	6.9	109	1.0
		2-corner	6.4	83	1.0	7.2	120	1.0
		mean	6.2	73	1.0	7.1	115	1.0
	2B (low)	1-corner	4.6	10	0.36	5.4	10	0.26
		2-corner	5.4	10	0.50	6.0	10	0.12
		mean	5.0	10	0.43	5.7	10	0.14
	2B (mod)	1-corner	5.9	62	0.33	6.9	109	0.25
		2-corner	6.4	83	0	7.2	120	0.59
		mean	6.2	73	0.17	7.1	115	0.47
	2B (high)	1-corner	7.4	130	0.31	7.7	7.7	0.49
		2-corner	7.4	130	0.50	7.7	130	0.29
		mean	7.4	130	0.40	7.7	130	0.39
1E-4	1	1-corner	**M** = 6.3, *R* = 64					
		2-corner	**M** = 6.9, *R* = 94					
		mean	**M** = 6.6, *R* = 79					
	2A	1-corner	5.6	26	1.0	7.0	101	1.0
		2-corner	6.4	66	1.0	7.4	121	1.0
		mean	6.0	46	1.0	7.2	111	1.0
	2B (low)	1-corner	4.6	10	0.19	5.7	10	0.07
		2-corner	4.7	10	0.24	6.2	10	0.07
		mean	4.7	10	0.22	6.0	10	0.07

UHS	Approach	Ground motion model	10 Hz			1 Hz		
			M	*R*	wt	**M**	*R*	wt
1E-4 *(cont'd)*	2B (mod)	1-corner	5.6	26	0.72	7.0	101	0.80
		2-corner	6.4	66	0.45	7.4	121	0.65
		mean	6.0	46	0.58	7.2	110	0.72
	2B (high)	1-corner	7.7	130	0.09	7.7	130	0.13
		2-corner	7.7	130	0.31	7.7	130	0.28
		mean	7.7	130	0.20	7.7	130	0.21
1E-5	1	1-corner	**M** = 6.2, *R* = 40					
		2-corner	**M** = 6.7, *R* = 70					
		mean	**M** = 6.5, *R* = 55					
	2A	1-corner	5.5	10	1.0	6.8	69	1.0
		2-corner	6.0	30	1.0	7.4	110	1.0
		mean	5.8	20	1.0	7.1	90	1.0
	2B (low)	1-corner	4.6	10	0.02	6.1	10	0.40
		2-corner	4.7	10	0.21	6.4	10	0.16
		mean	4.7	10	0.11	6.3	10	0.28
	2B (mod)	1-corner	5.5	10	0.97	6.8	69	0.20
		2-corner	6.0	30	0.63	7.4	110	0.31
		mean	5.8	20	0.81	7.1	90	0.26
	2B (high)	1-corner	7.7	130	0.01	7.6	130	0.40
		2-corner	7.7	130	0.16	7.7	130	0.53
		mean	7.7	130	0.08	7.7	130	0.46

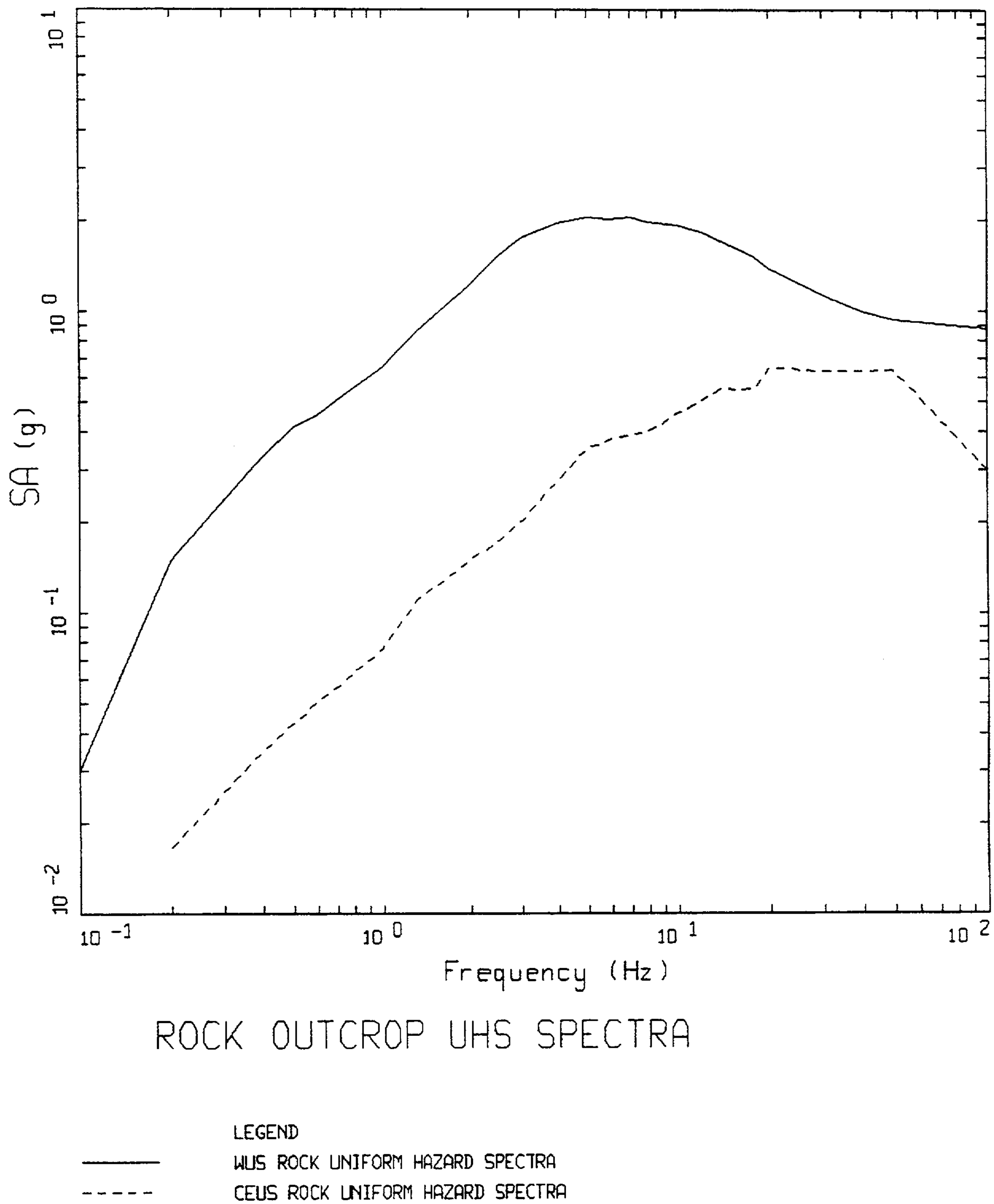


Figure 6-1. Comparison of 5% damped rock outcrop 10^{-4} UHS spectra for CEUS and WUS conditions.

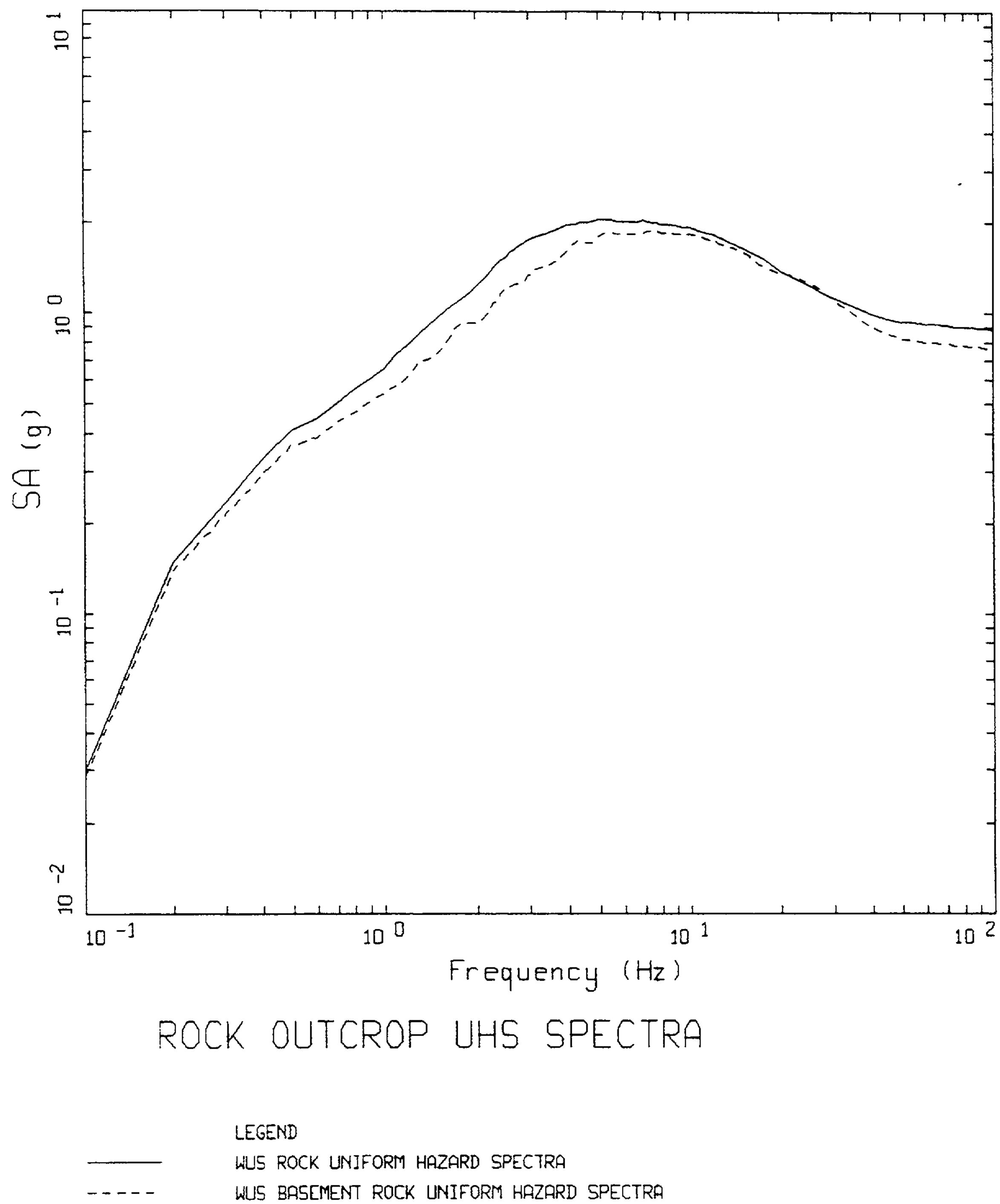


Figure 6-2. Comparison of WUS rock 10^{-4} UHS (solid line) with UHS corrected for base-of-soil conditions (dashed line).

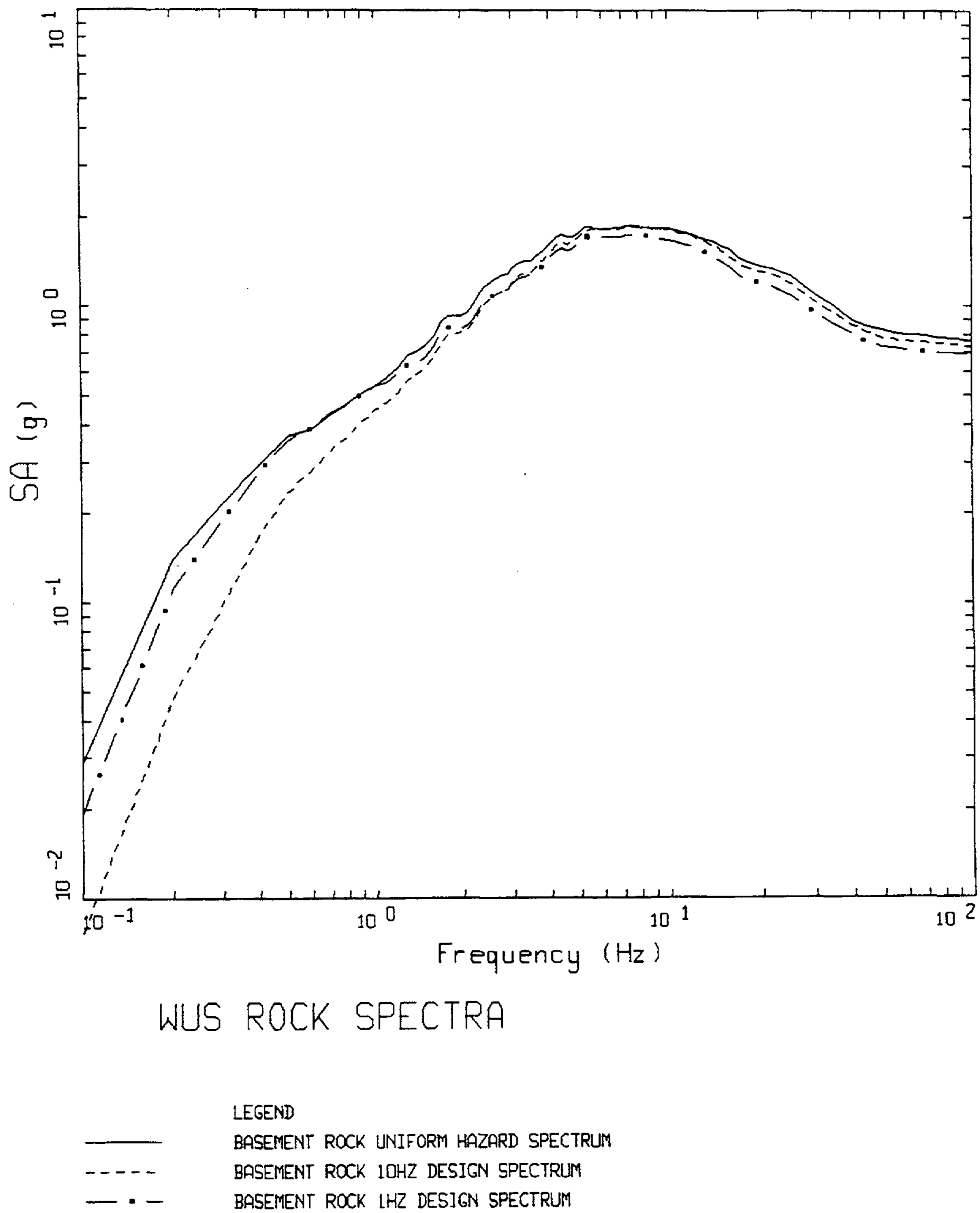


Figure 6-3. Mojave site, rock, 1 Hz, 10 Hz and UHS corrected to base of soil.

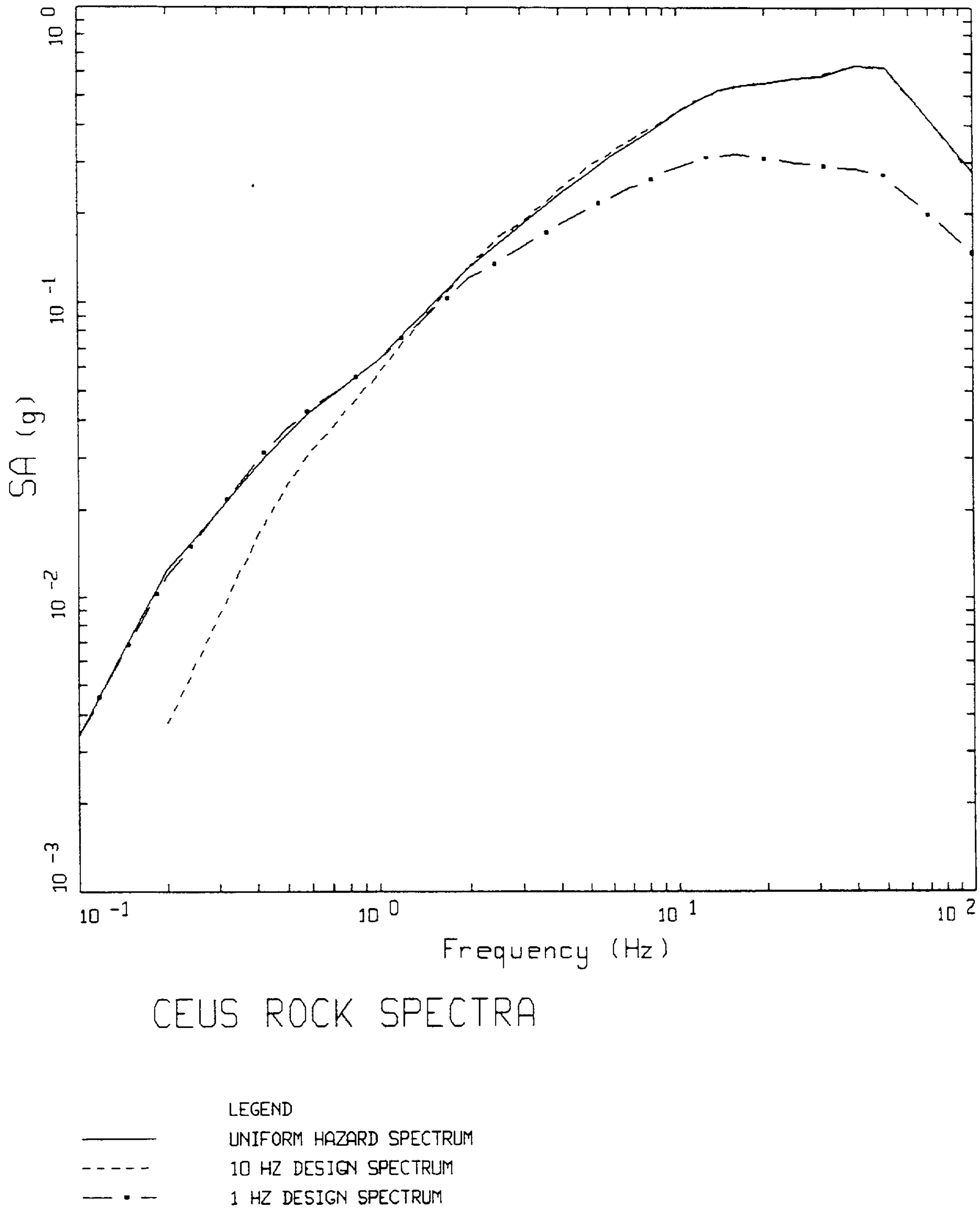


Figure 6-4. Columbia site, rock outcrop 1 Hz, 10 Hz and UHS.

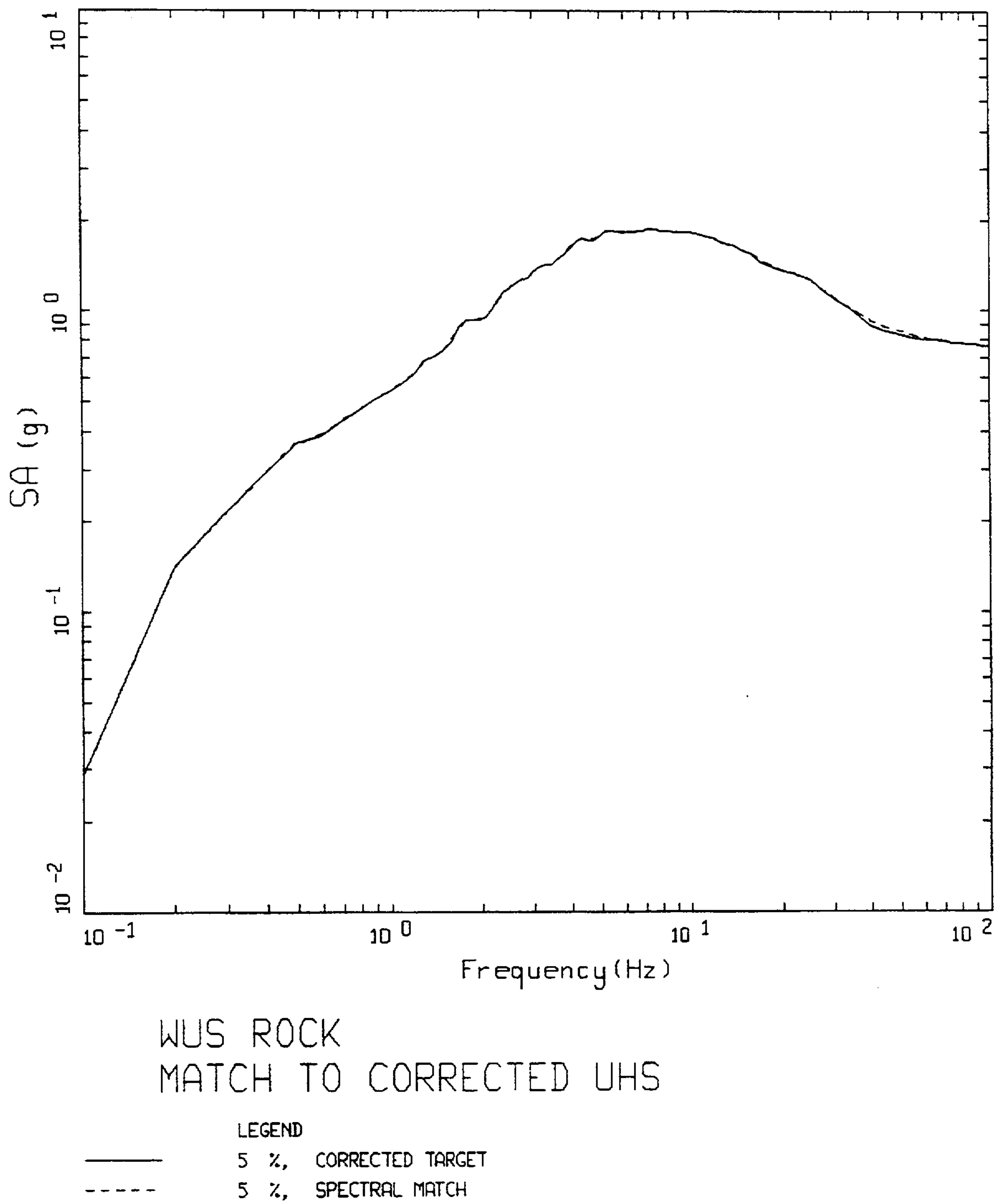


Figure 6-5. Comparison of spectral match (dotted line) to corrected WUS rock UHS.

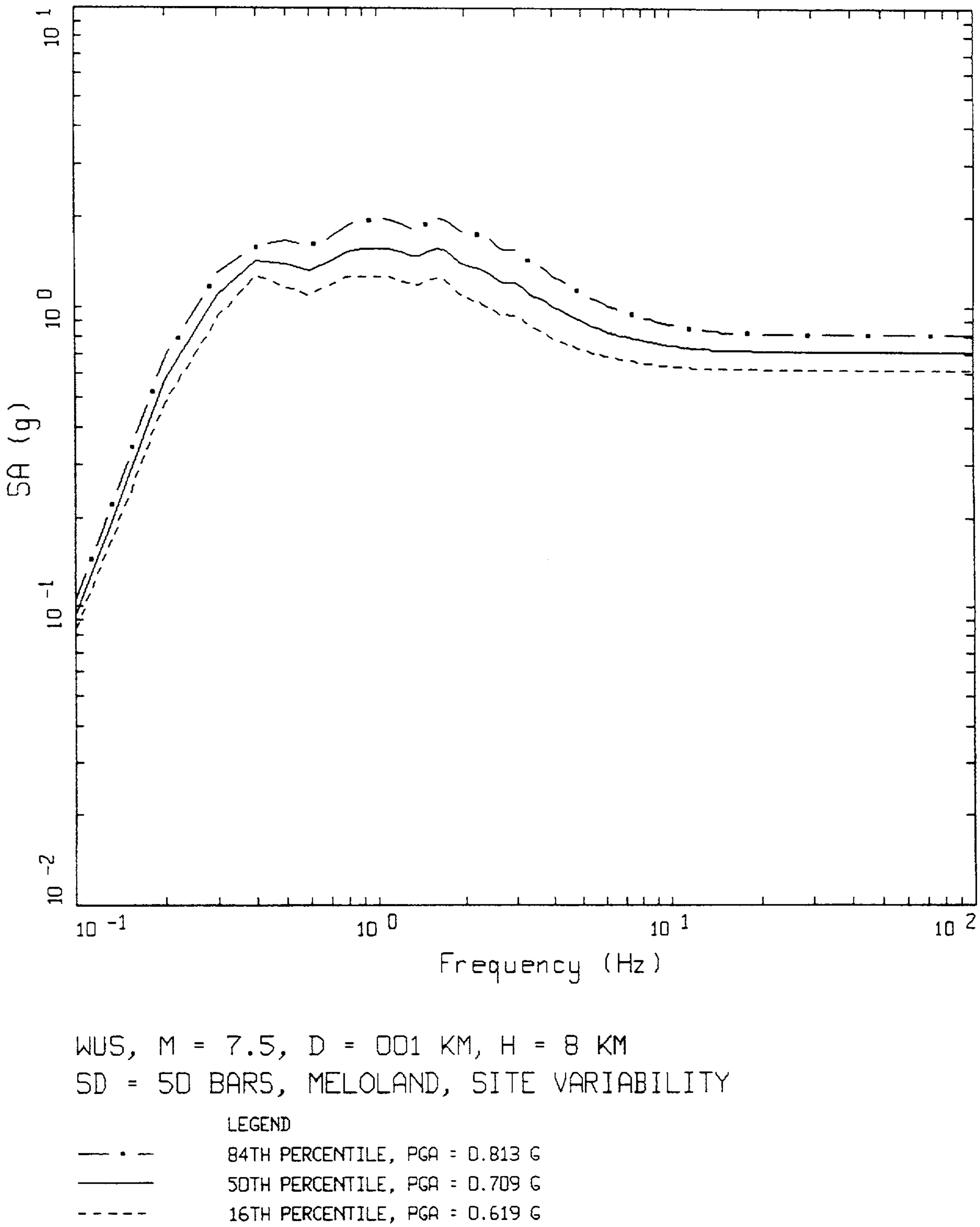


Figure 6-6. Median and $\pm\ \sigma$ spectra computed for **M** = 7.5 at a distance of 1 km using the Meloland profile with site variations only (profile, G/G_{max}, and hysteretic damping): WUS conditions.

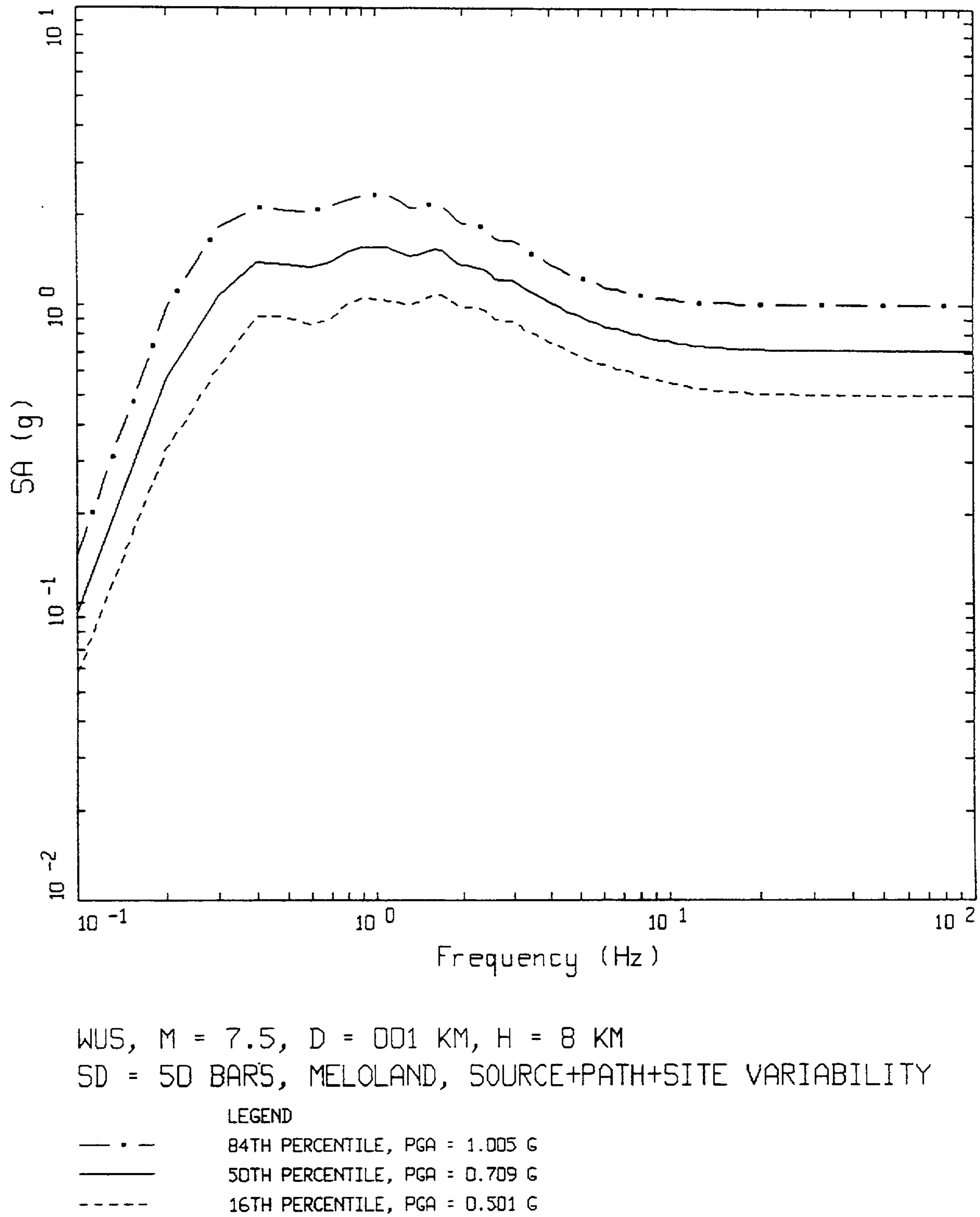


Figure 6-7. Median and $\pm\sigma$ spectra computed for **M** = 7.5 at a distance of 1 km using the Meloland profile with source, path, and site variations: WUS conditions.

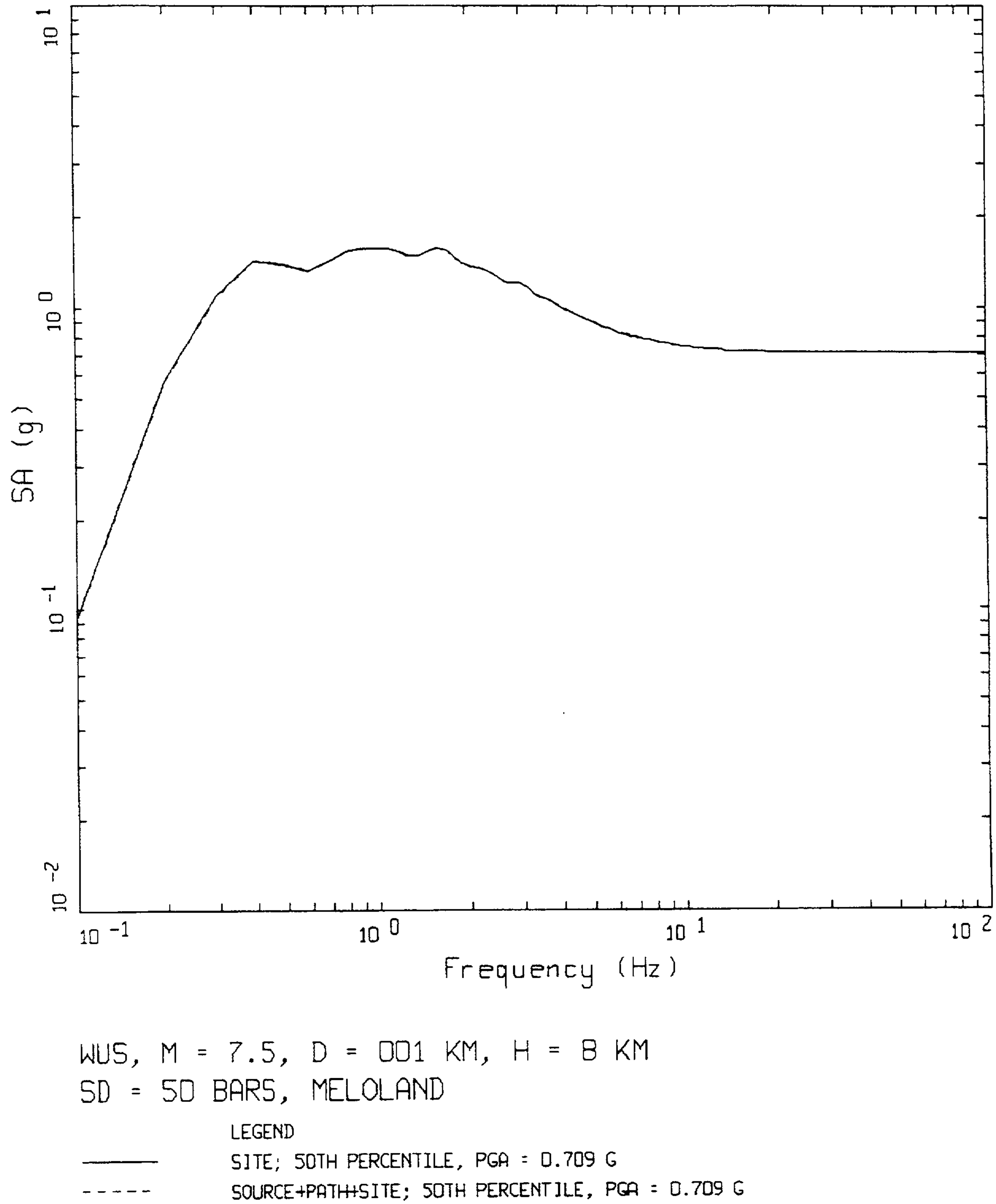


Figure 6-8. Comparison of median spectral estimates computed for **M**=7.5 at a distance of 1 km using the Meloland profile: varying site properties only (solid line) and varying source, path, and site properties (dashed line); WUS conditions.

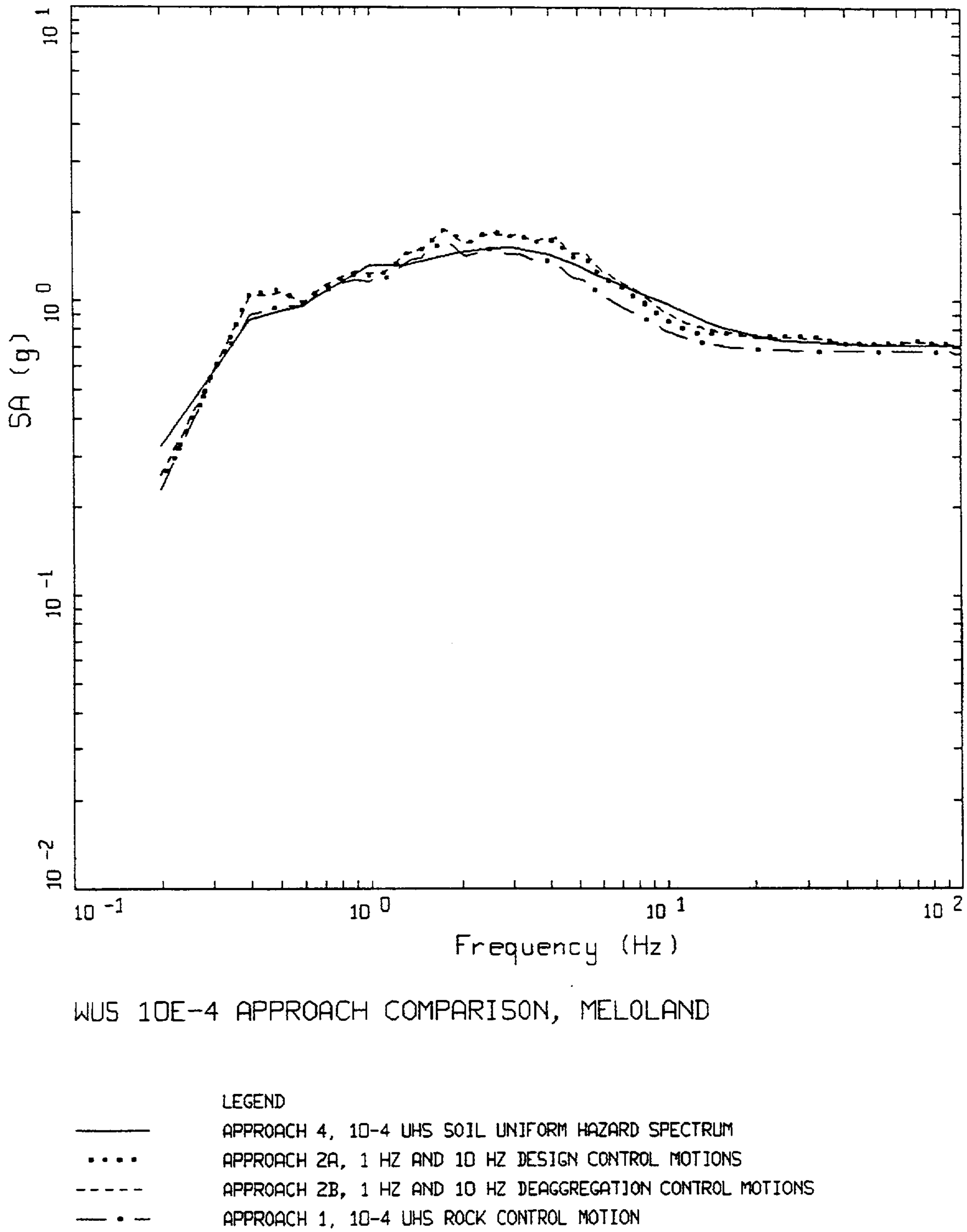


Figure 6-9. Comparison of soil spectra computed using Approaches 1, 2A, 2B, and 4 (Table 6-1) for Meloland profile, WUS conditions.

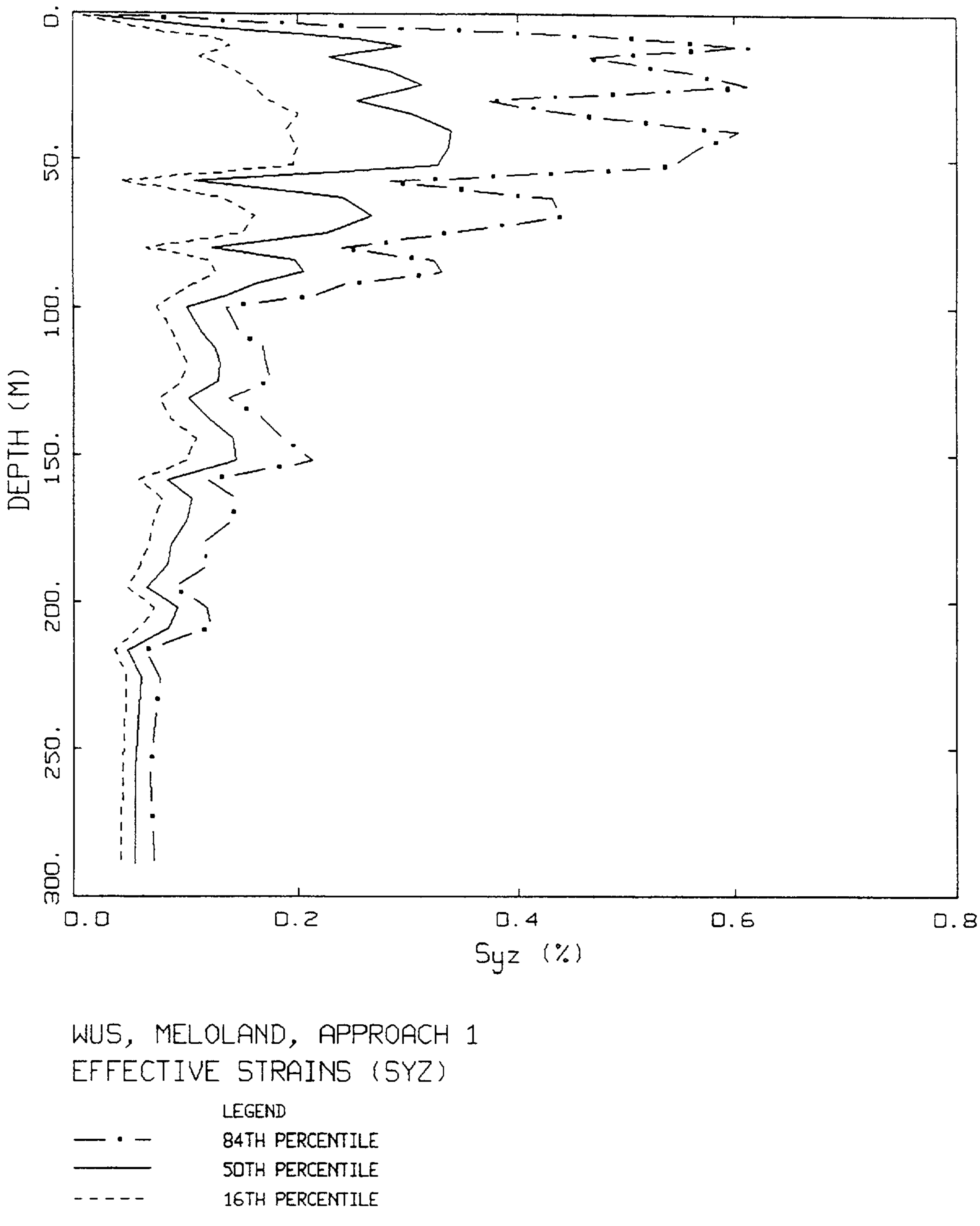


Figure 6-10. Median and ± 1σ effective strains for Meloland profile using Approach 1, WUS conditions.

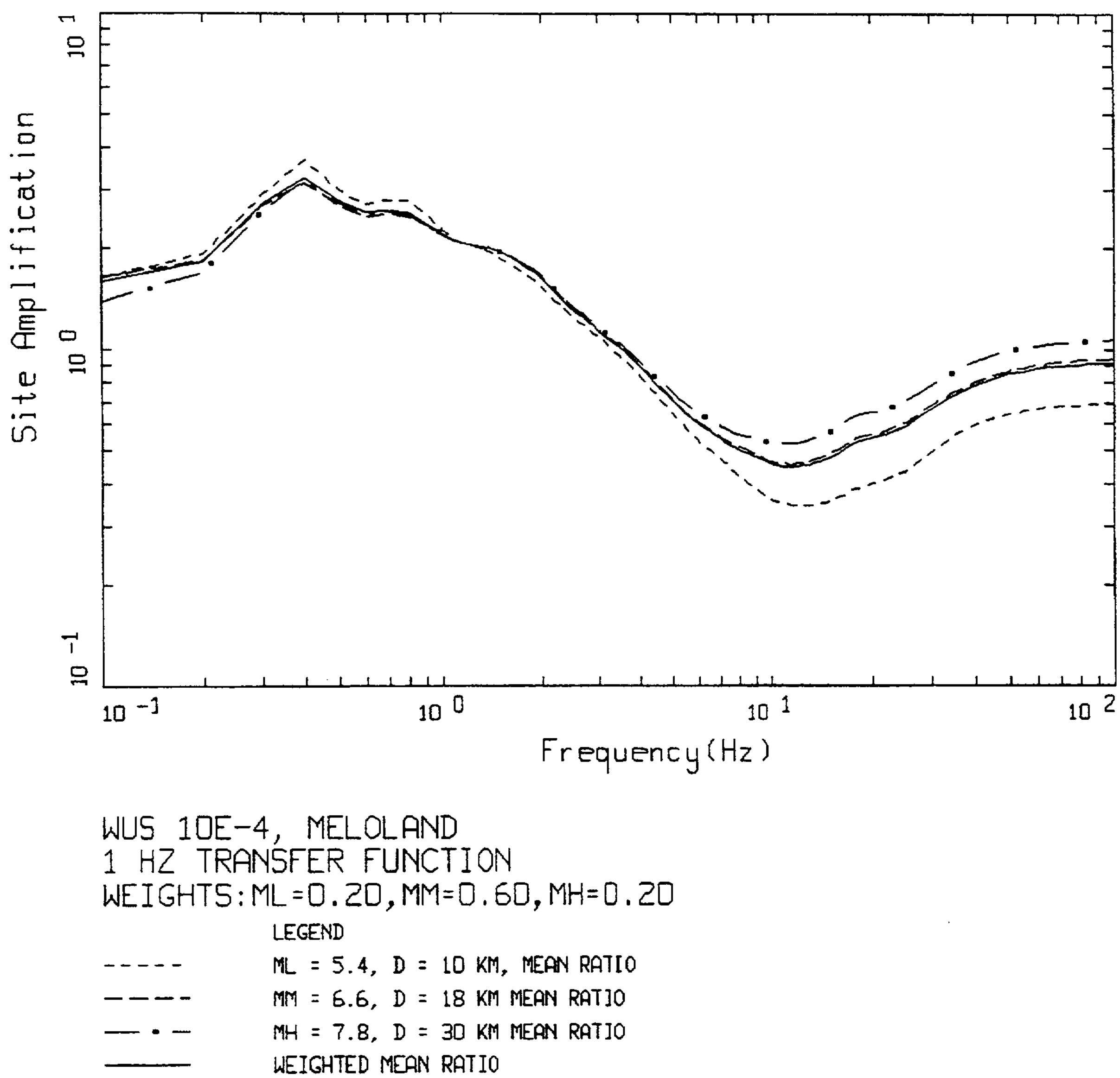


Figure 6-11. Comparison of transfer functions computed for the scaled 1 Hz design earthquake for the Meloland profile, WUS conditions.

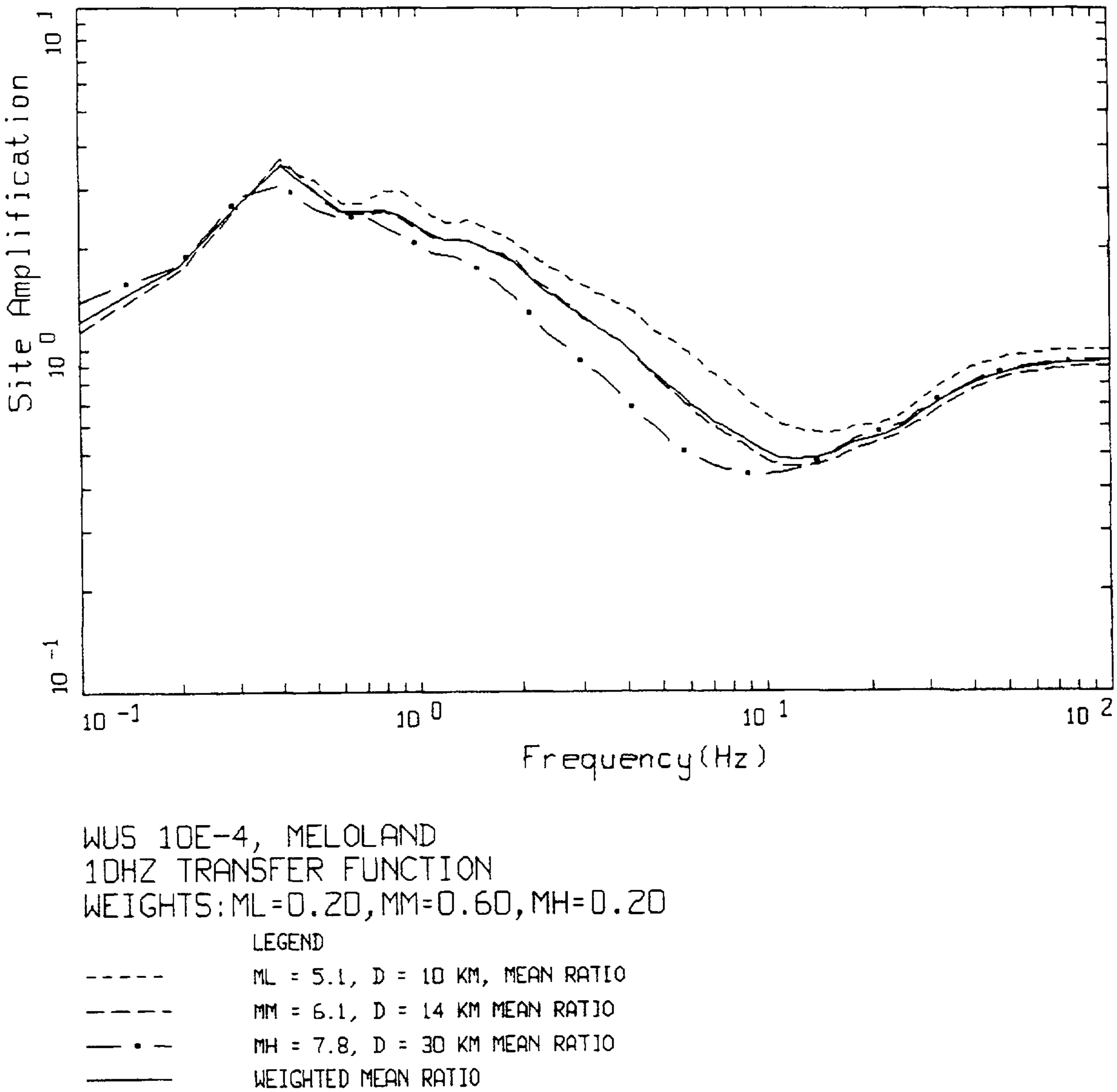


Figure 6-12. Comparison of transfer functions computed for the scaled 10 Hz design earthquake for the Meloland profile, WUS conditions.

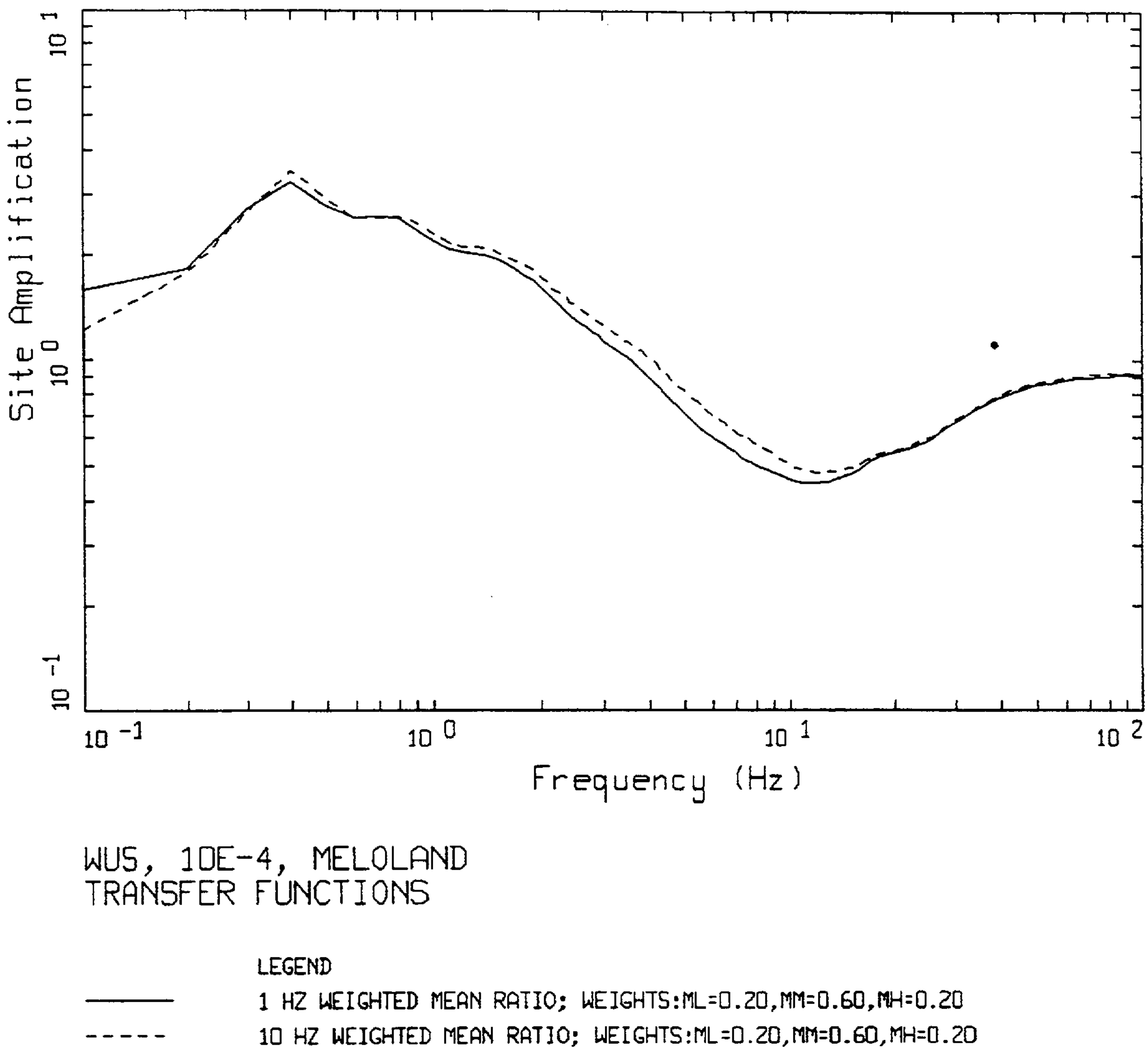


Figure 6-13. Comparison of weighted mean transfer functions computed for the 1 Hz and 10 Hz scaled spectra for the Meloland profile, WUS conditions.

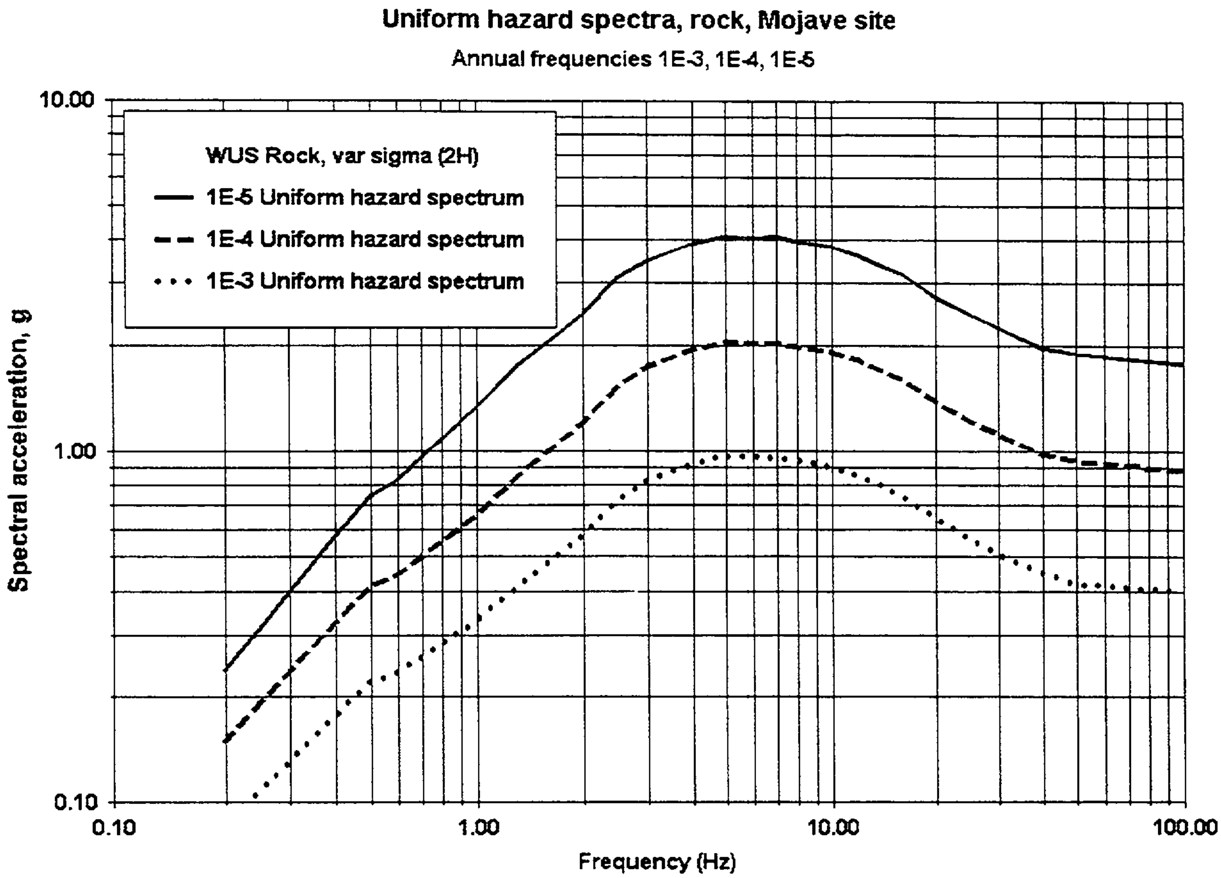
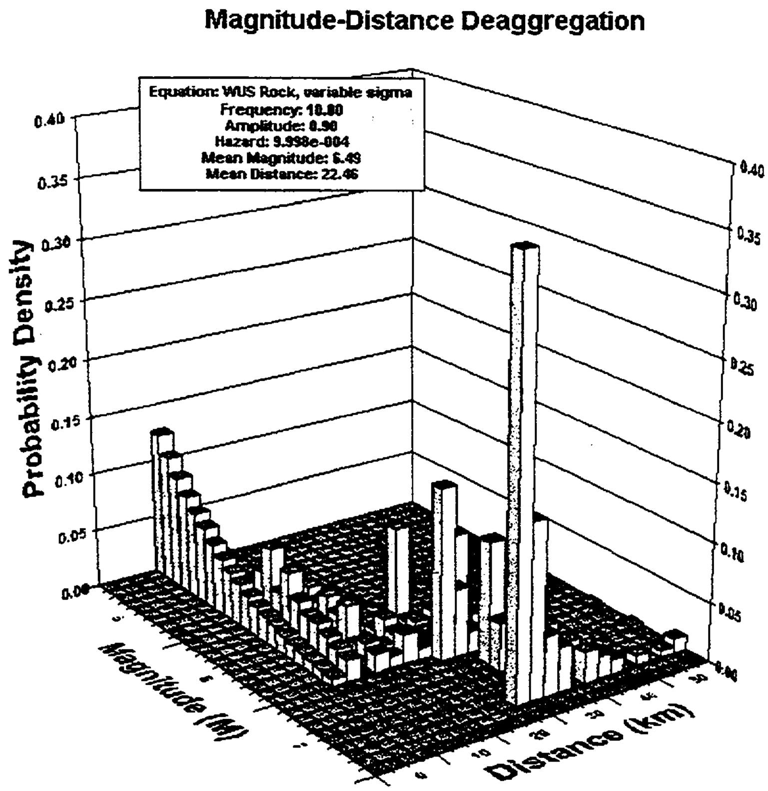


Figure 6-14. Mojave site rock spectra for 10^{-3}, 10^{-4}, and 10^{-5} annual frequencies.



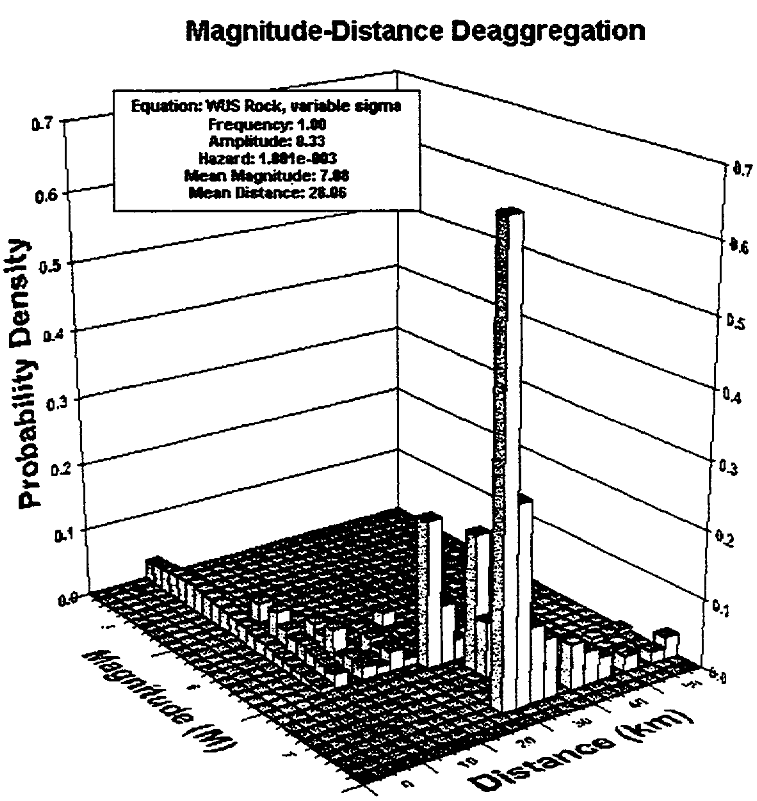
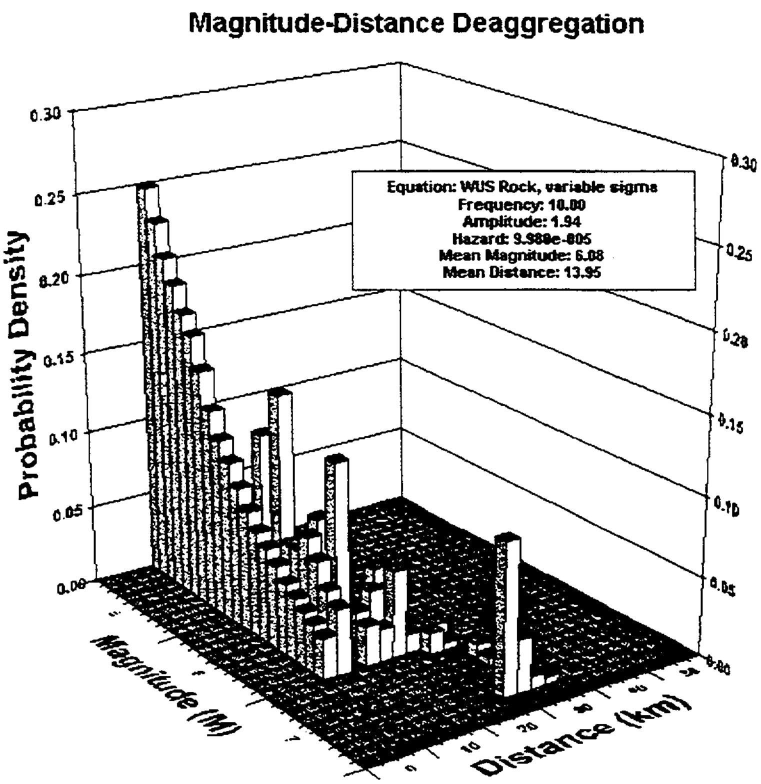


Figure 6-15. Mojave site, **M**-R deaggregation of rock seismic hazard for 10^{-3}. Top: 10 Hz Bottom: 1 Hz



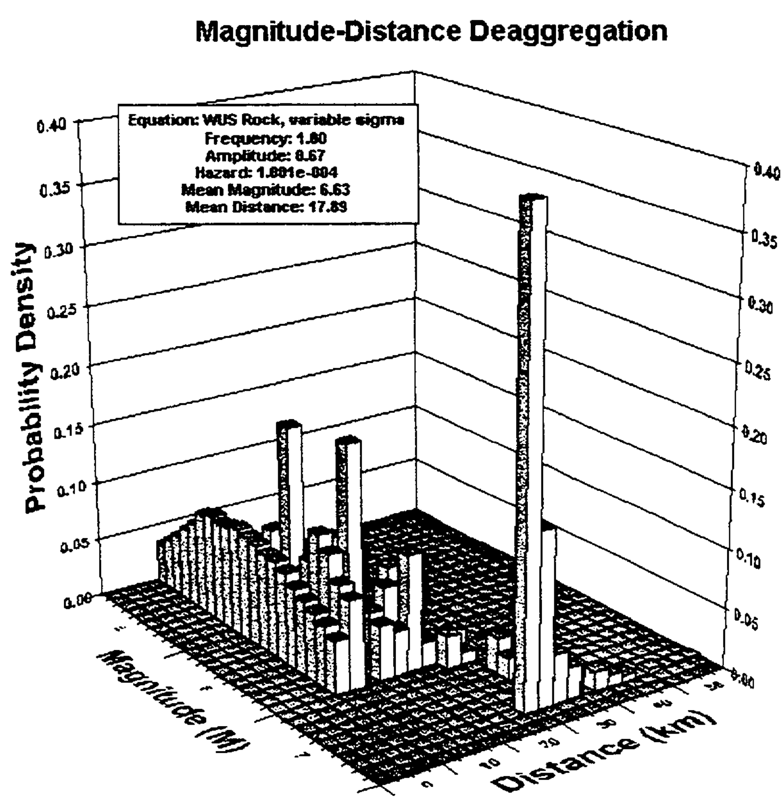
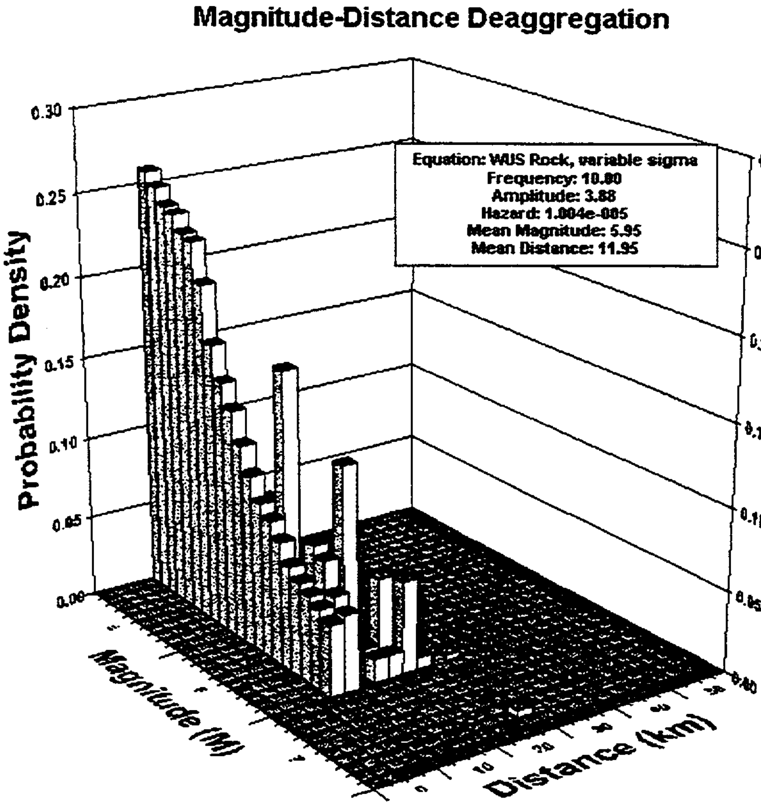


Figure 6-16. Mojave site, **M**-R deaggregation of rock seismic hazard for 10^{-4}. Top: 10 Hz Bottom: 1 Hz



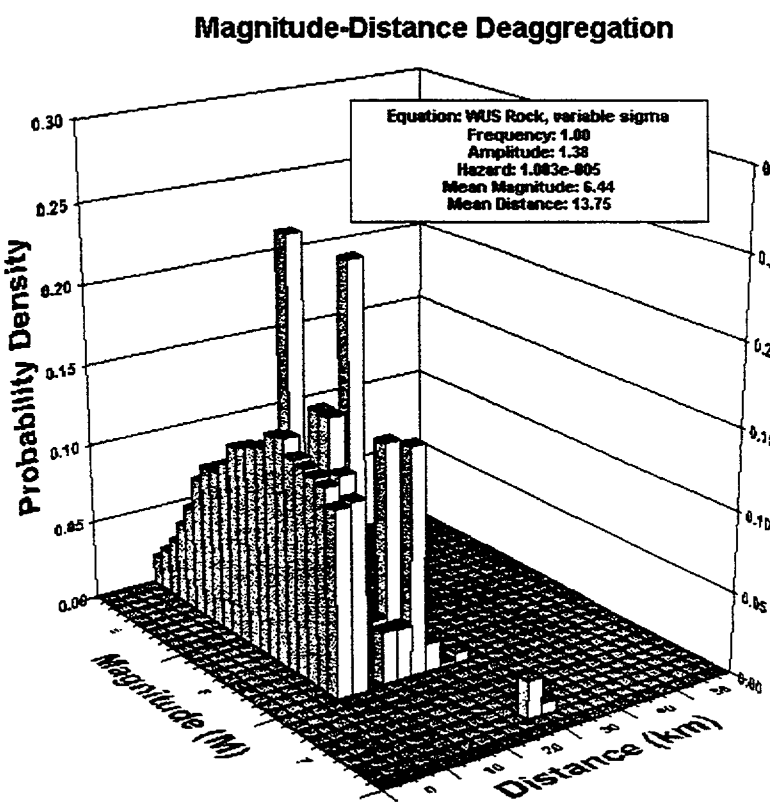


Figure 6-17. Mojave site, **M**-R deaggregation of rock seismic hazard for 10^{-5}. Top: 10 Hz Bottom: 1 Hz

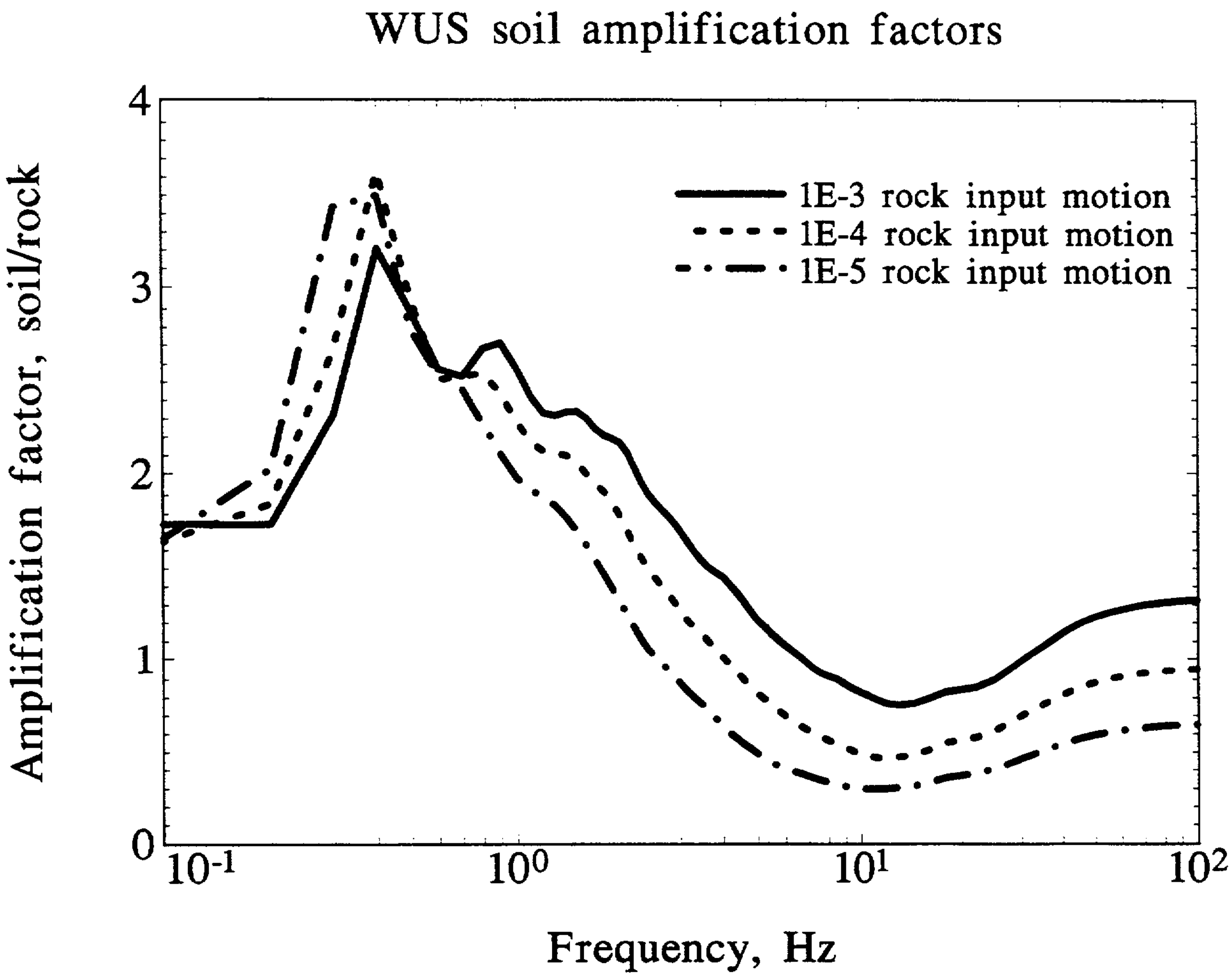


Figure 6-18. Mean amplification factor, soil/rock, from Approach 2A for 10^{-3}, 10^{-4}, and 10^{-5} rock input motions, Mojave site, Meloland profile.

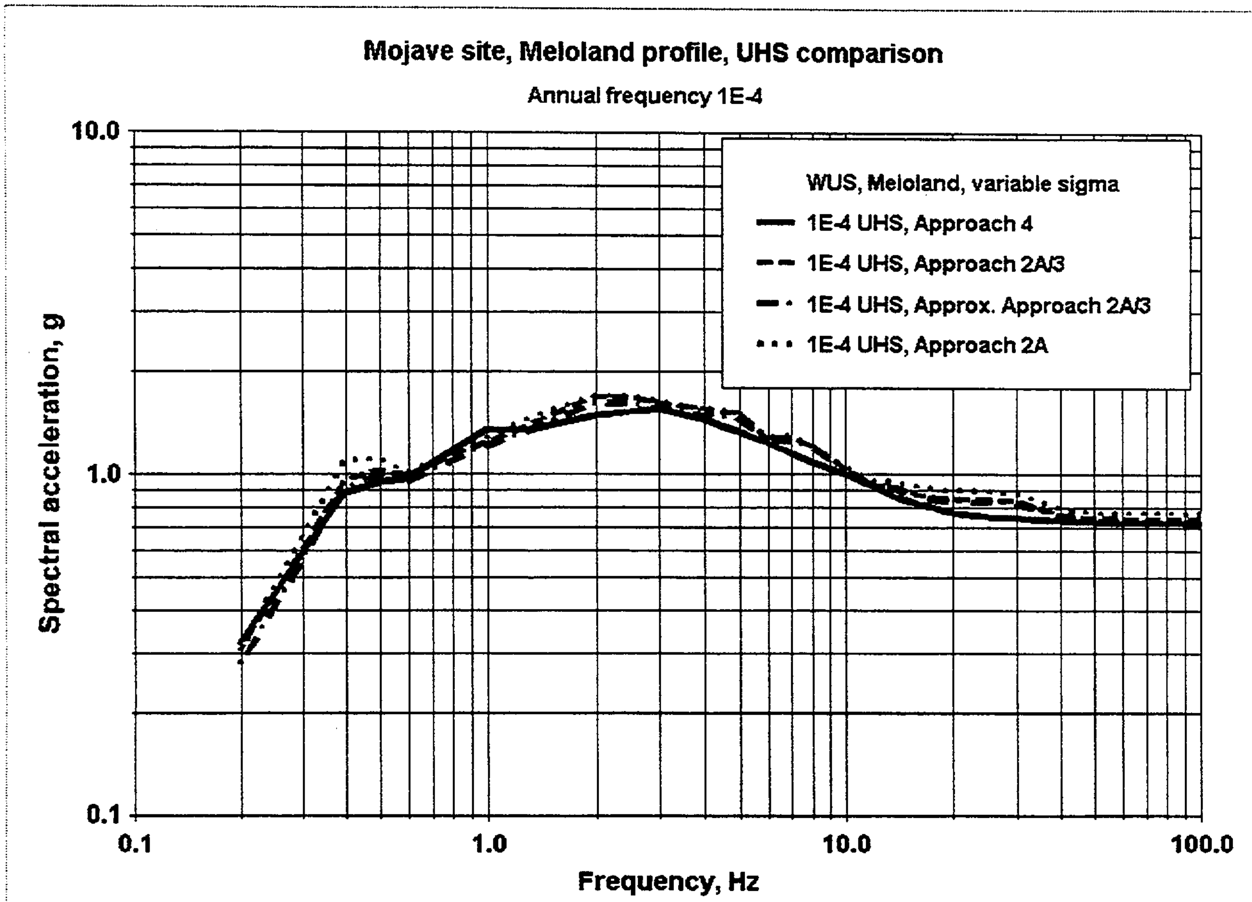


Figure 6-19. Mojave site 10^{-4} UHS for Meloland profile from Approach 4 (direct method) and Approaches 2A and 2A/3.

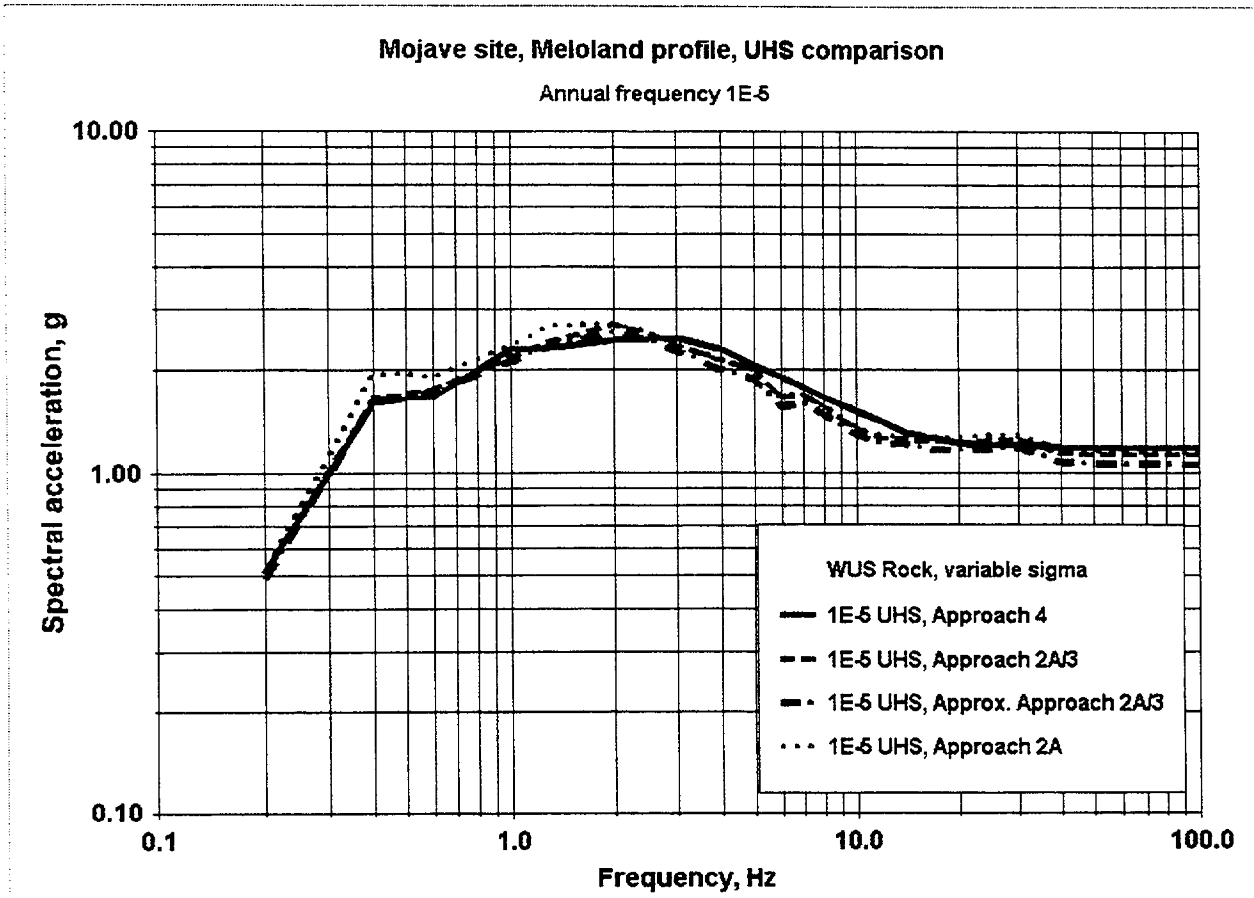


Figure 6-20. Mojave site 1E-5 UHS for Meloland profile from Approach 4 (direct method) and Approaches 2A and 2A/3.

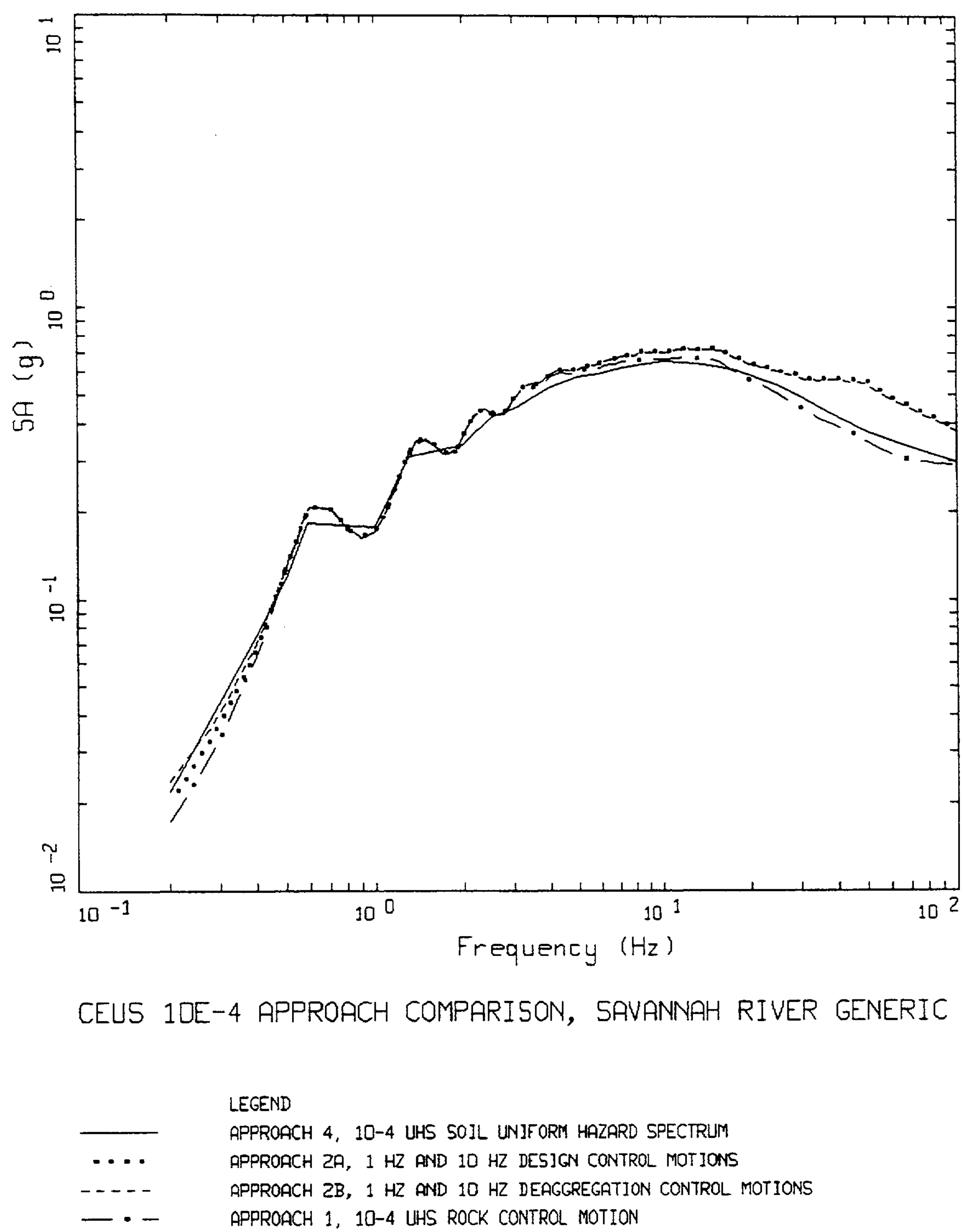


Figure 6-21. Comparison of soil spectra computed using Approaches 1, 2A, 2B, and 4 (Table 6-1) for Savannah profile, CEUS conditions.

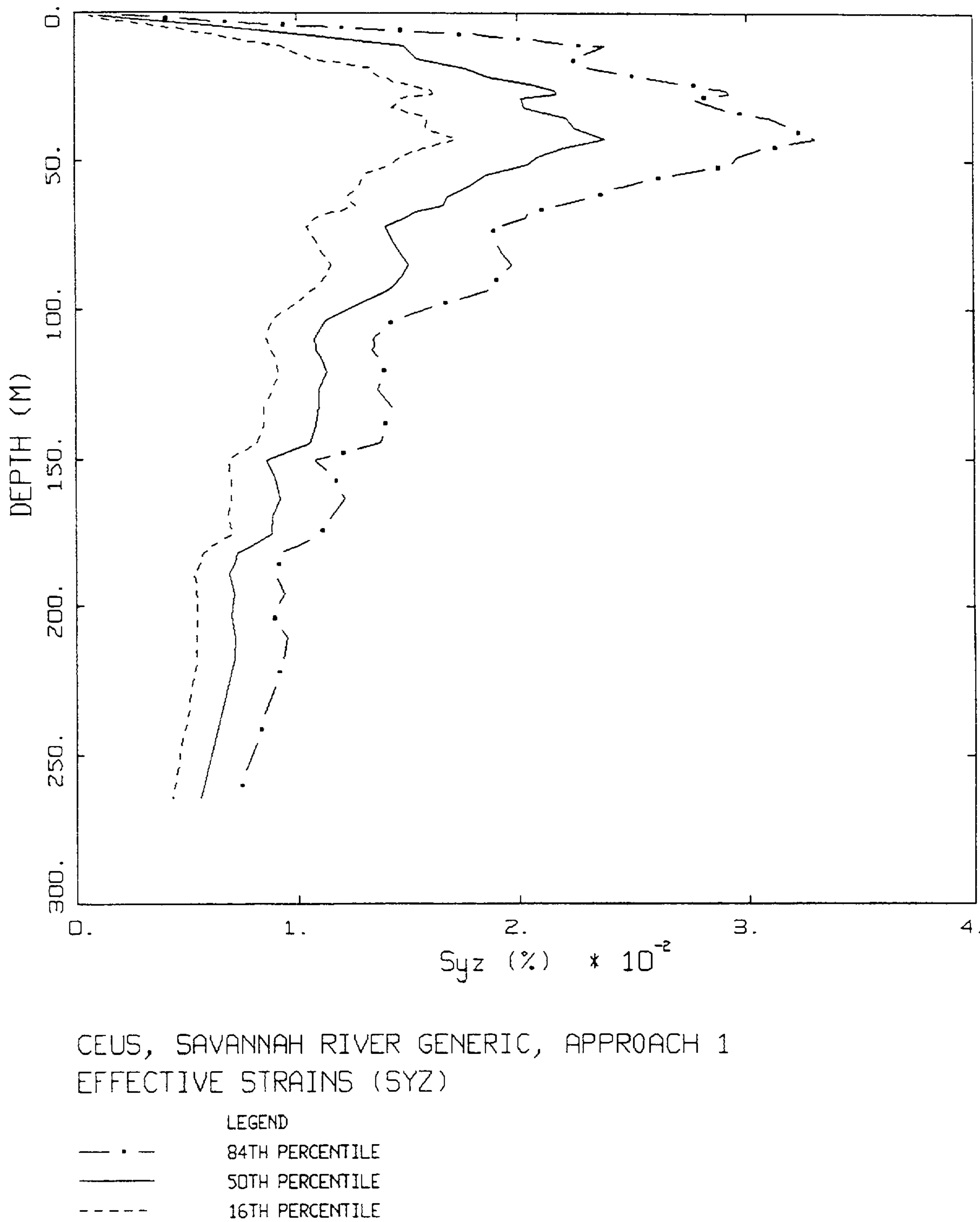
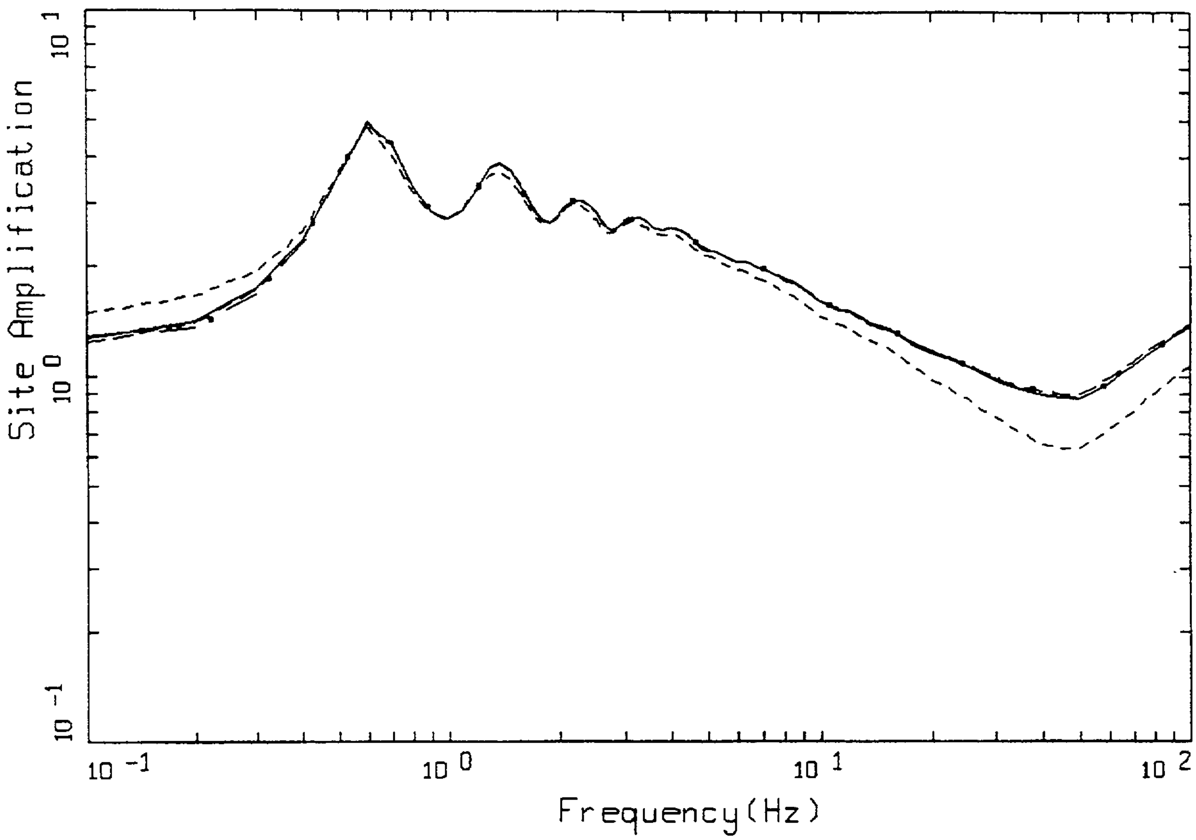


Figure 6-22. Median and $\pm 1\sigma$ effective strains for Savannah profile using Approach 1: CEUS conditions (note scale on strain axis).



CEUS 10E-4, SAVANNAH RIVER GENERIC
1 HZ TRANSFER FUNCTION
WEIGHTS: ML=0.07, MM=0.73, MH=0.20

LEGEND

- - - - - ML = 6.0, D = 10 KM, MEAN RATIO
— — — — MM = 7.2, D = 110 KM MEAN RATIO
— • — MH = 7.7, D = 130 KM MEAN RATIO
———— WEIGHTED MEAN RATIO

Figure 6-23. Comparison of transfer functions computed for the scaled 1 Hz motion for Savannah profile, CEUS conditions.

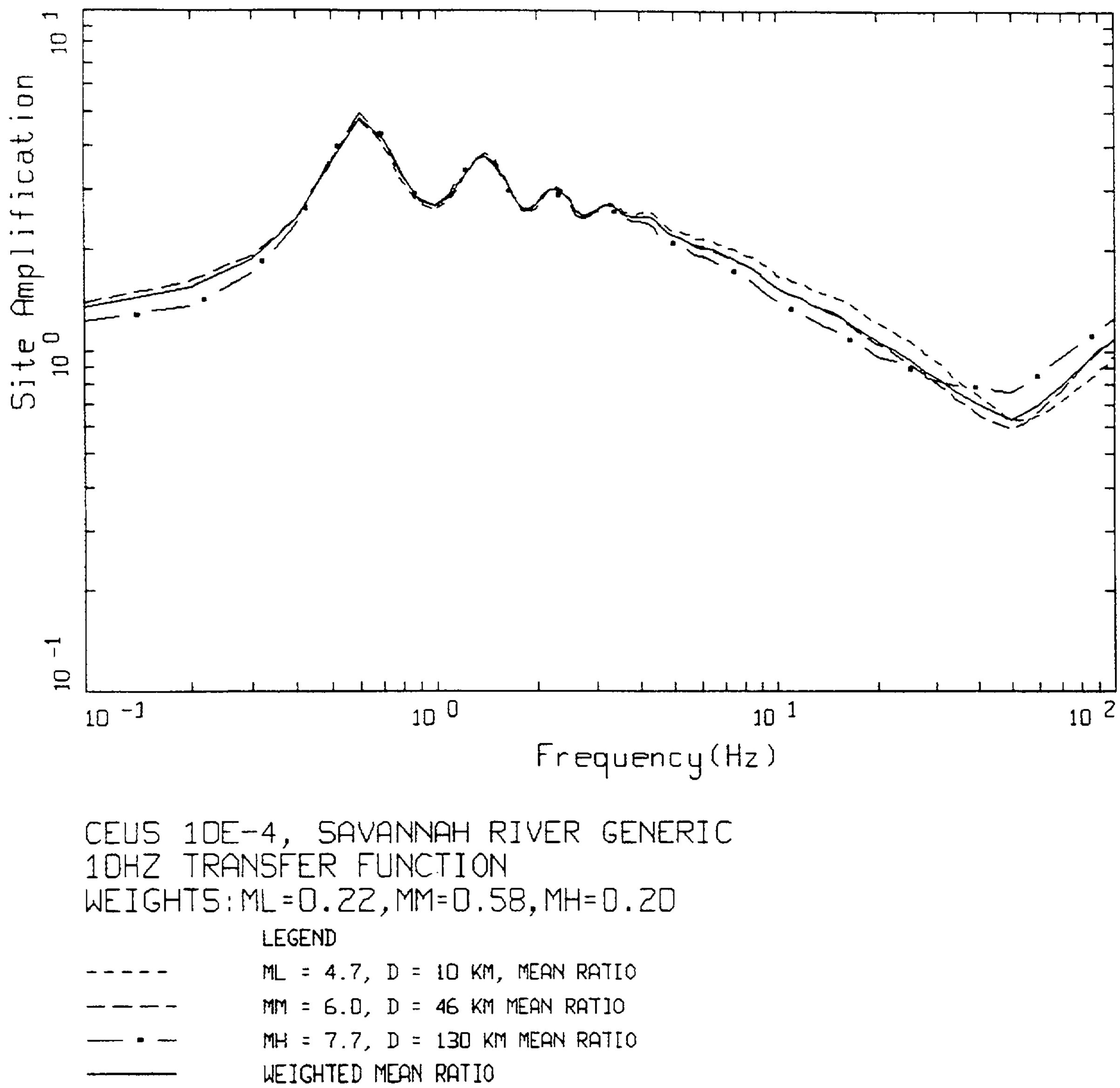


Figure 6-24. Comparison of transfer functions computed for the scaled 10 Hz motion for Savannah profile, CEUS conditions.

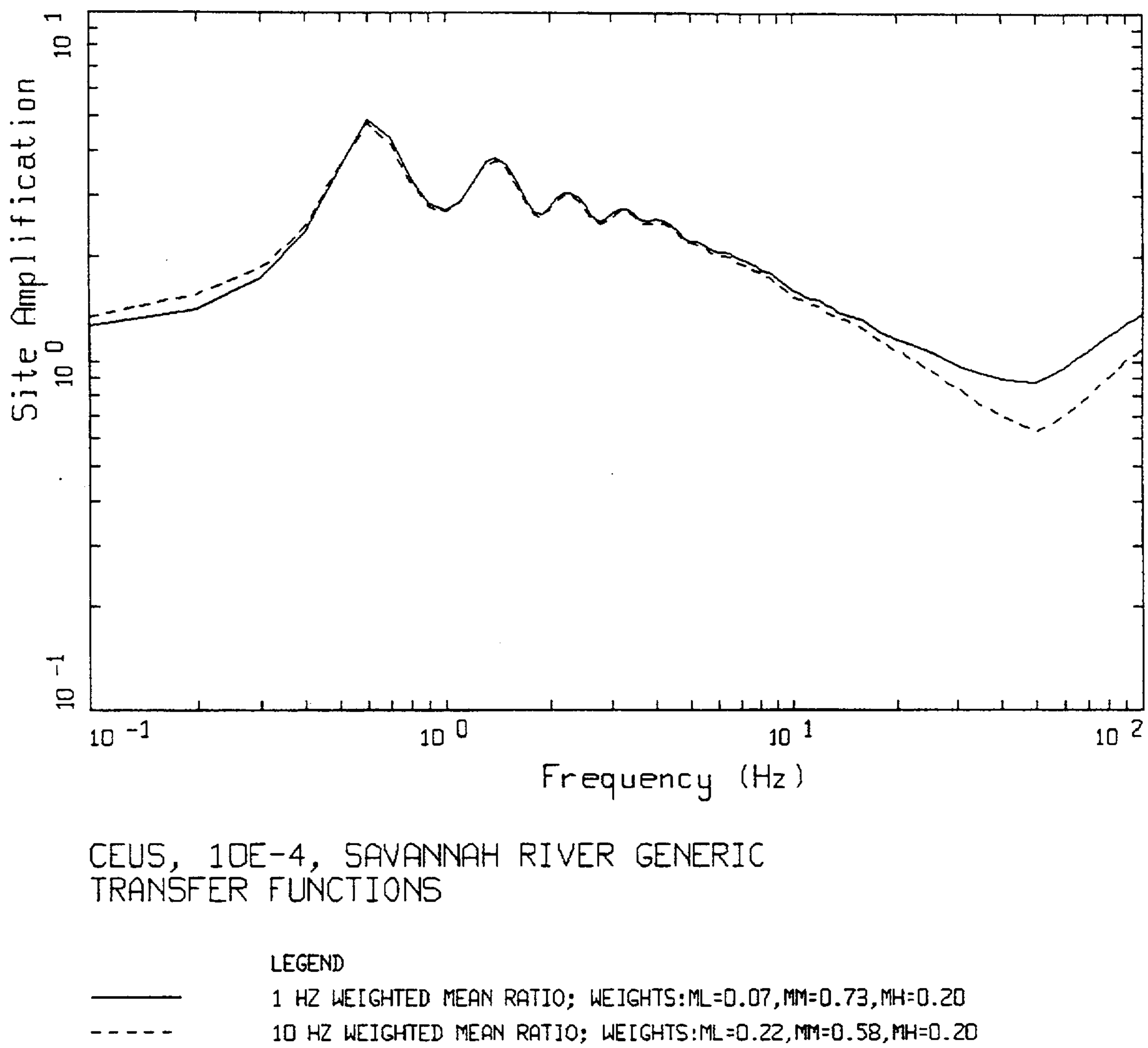


Figure 6-25. Comparison of weighted mean transfer functions computed for the scaled 1 Hz and 10 Hz motions for Savannah profile, CEUS conditions.

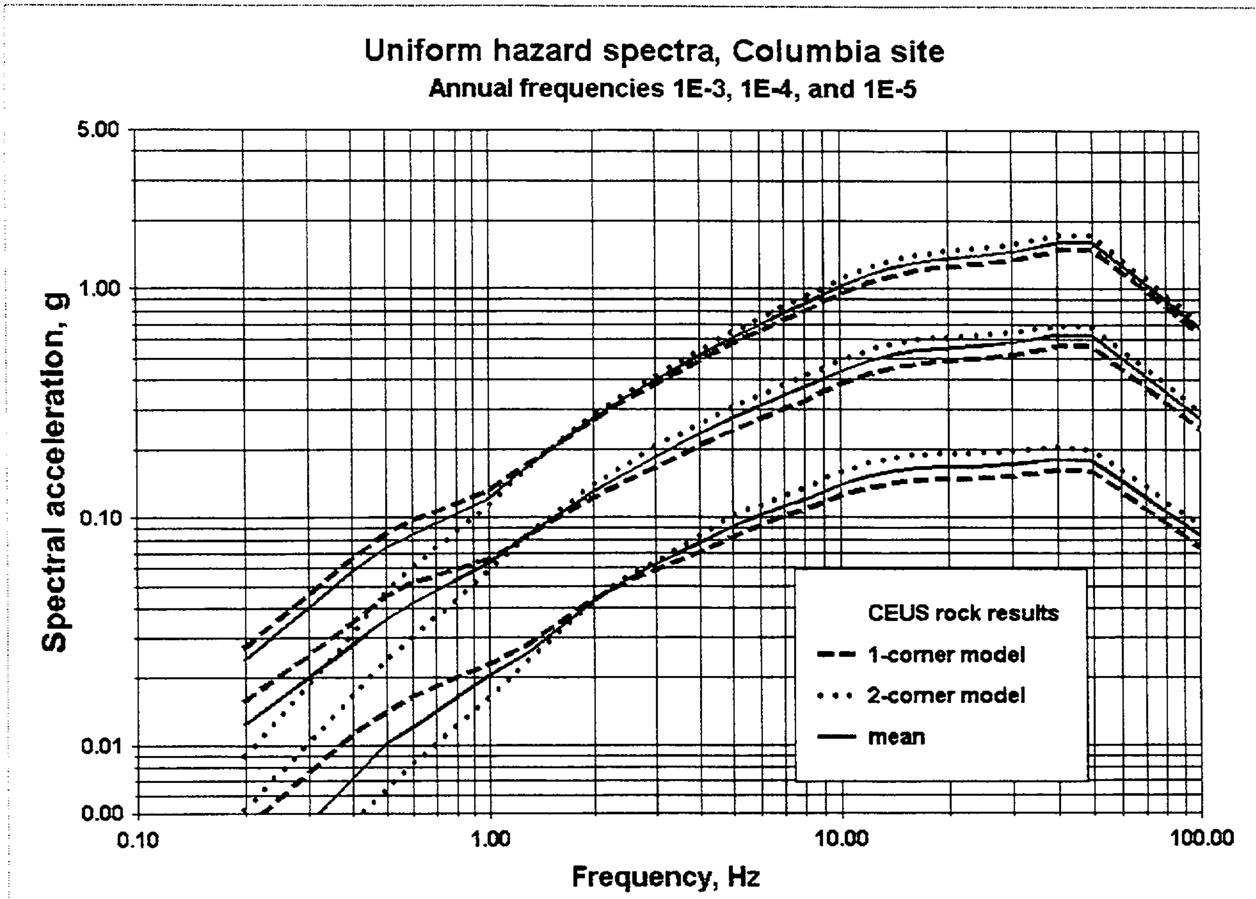
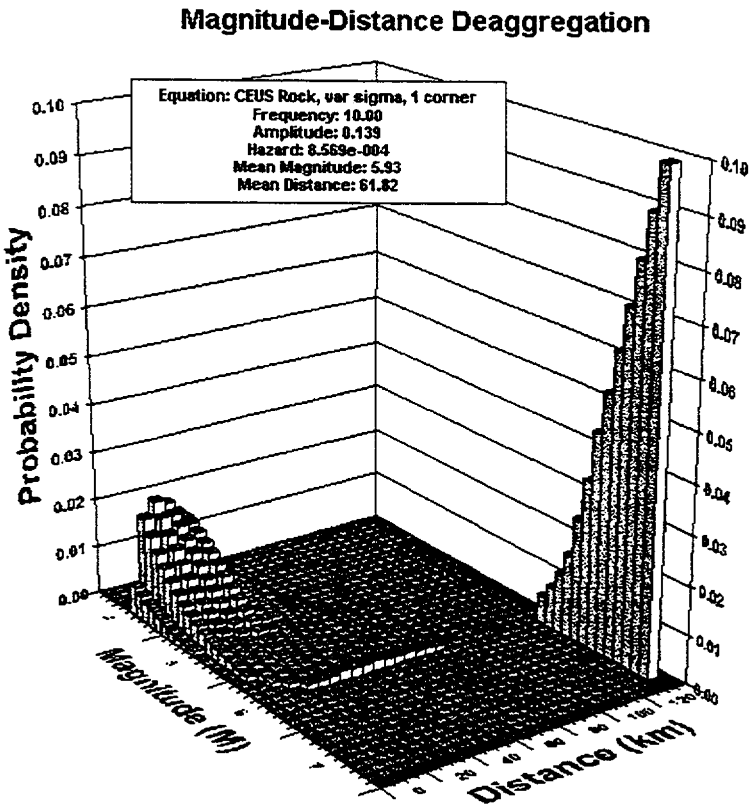


Figure 6-26. Columbia site UHS for 1- and 2-corner models and mean, for 10^{-3} (lower 3 curves), 10^{-4} (middle 3 curves), and 10^{-5} (top 3 curves).



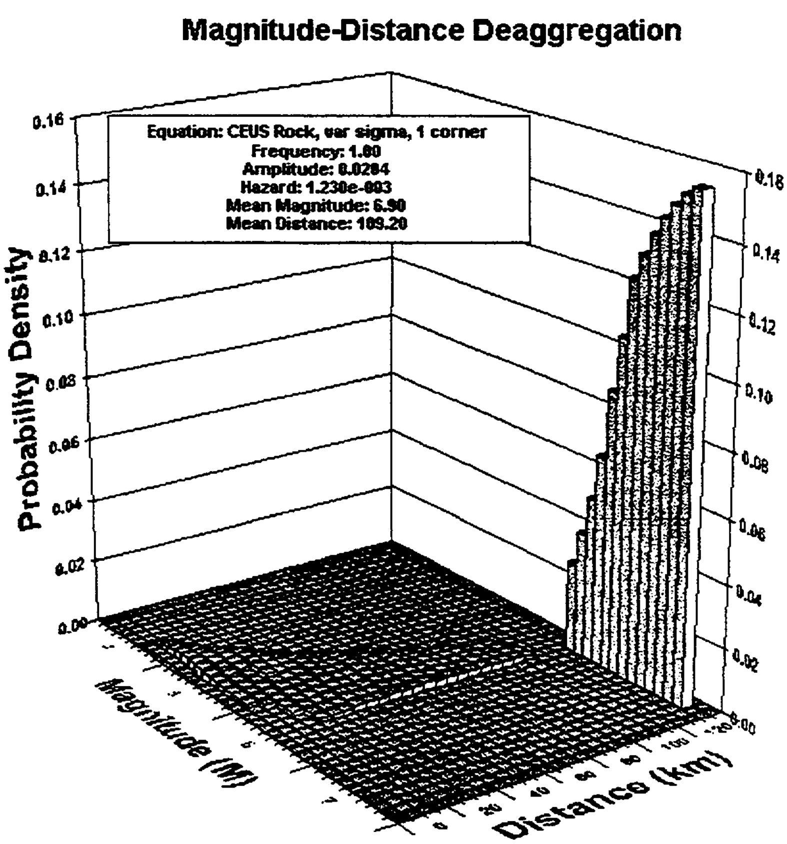
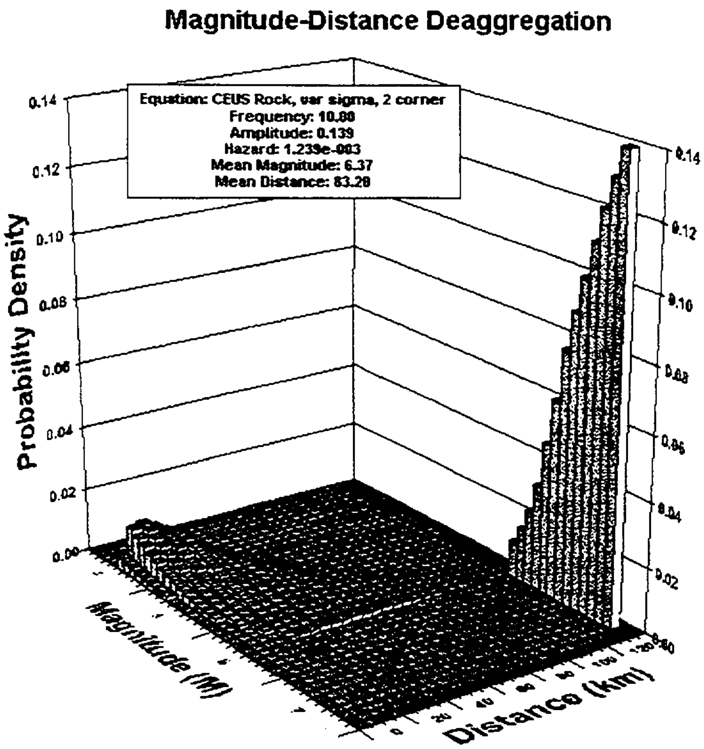


Figure 6-27a. Columbia site **M**-*R* deaggregation for 10^{-3}, 1-corner model, 10 Hz (top) and 1 Hz (bottom).



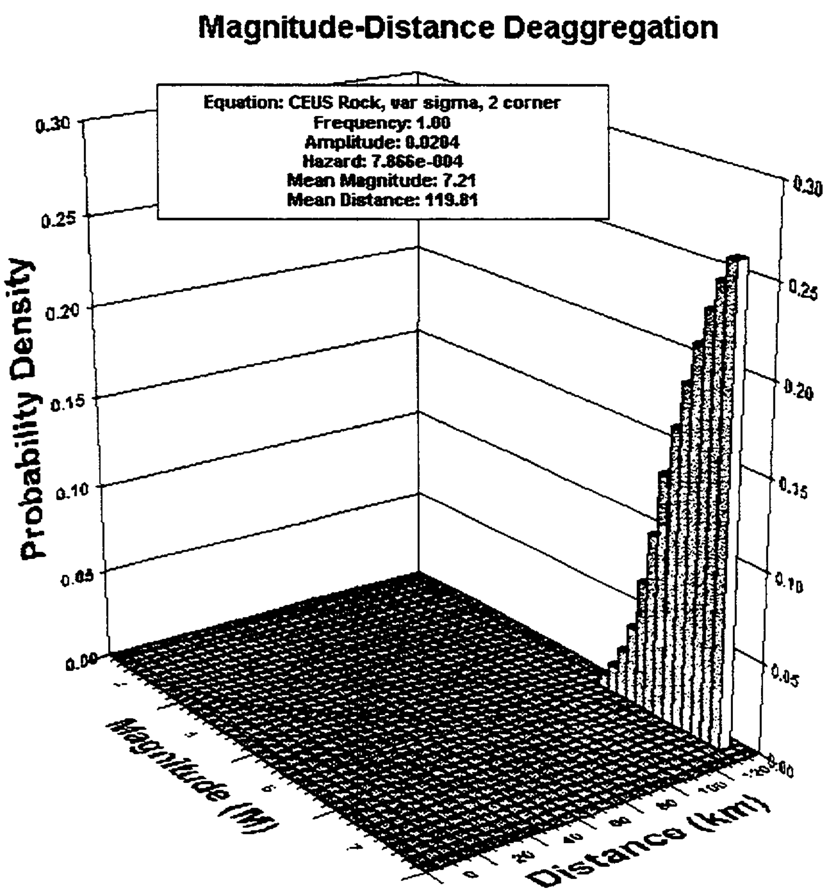
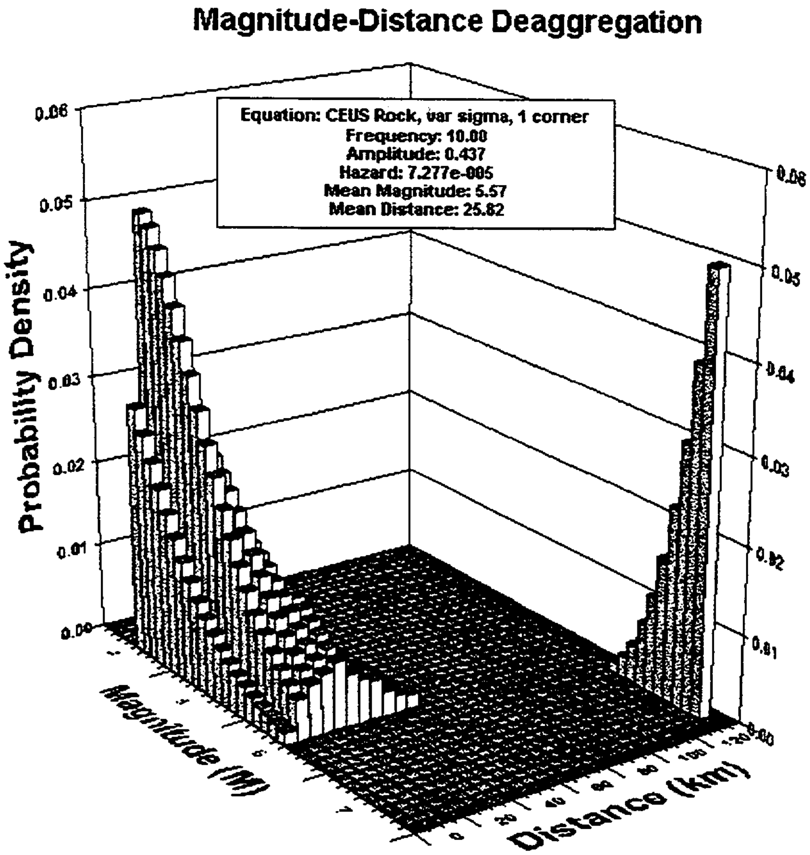


Figure 6-27b. Columbia site **M**-*R* deaggregation for 10^{-3}, 2-corner model, 10 Hz (top) and 1 Hz (bottom).



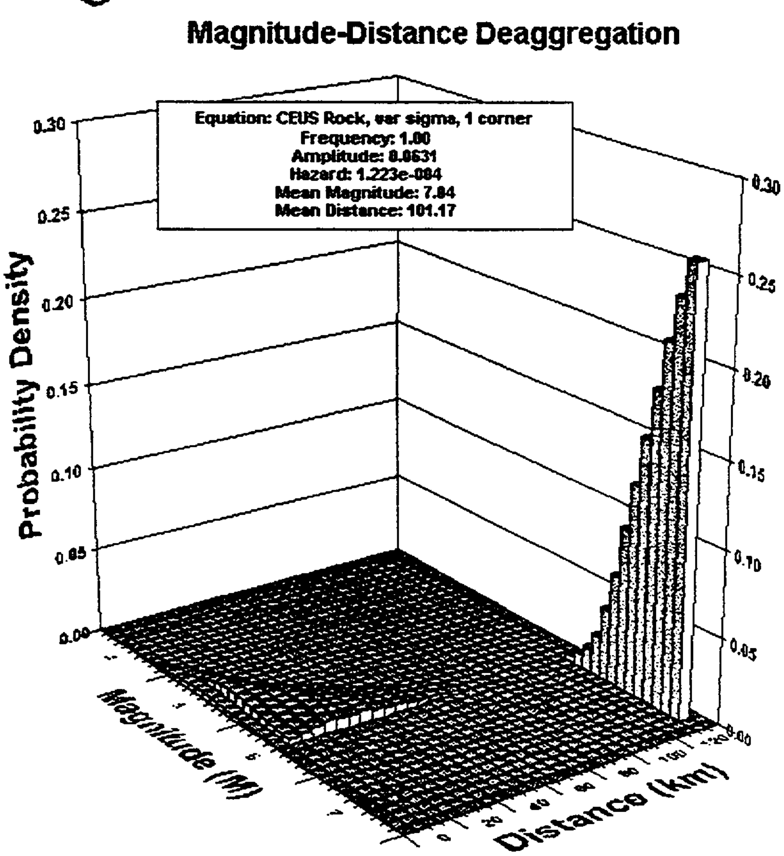
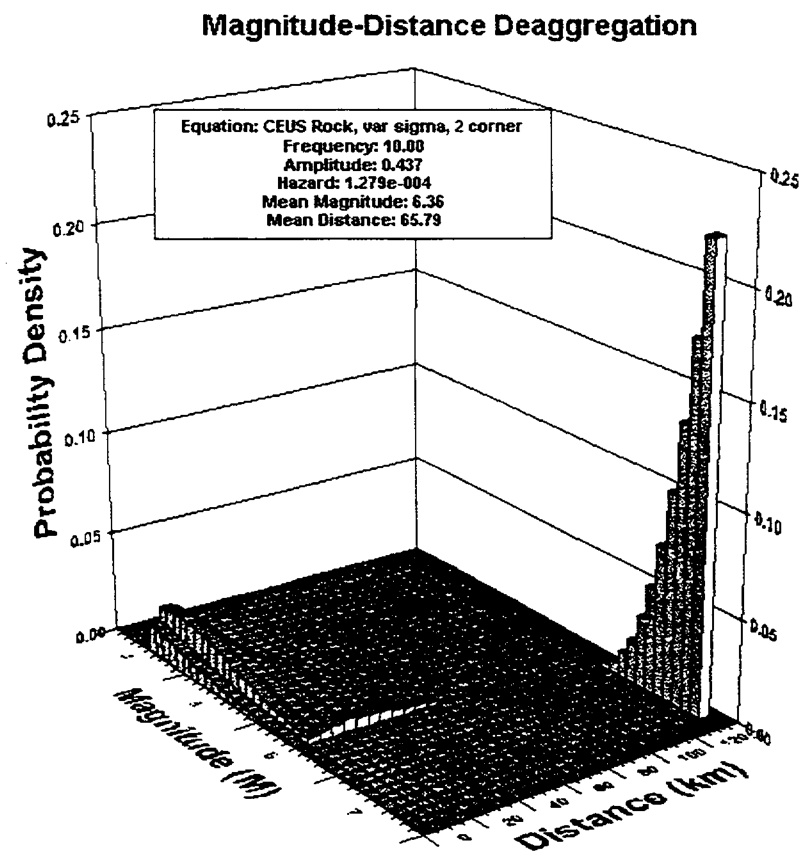


Figure 6-28a. Columbia site **M**-*R* deaggregation for 10^{-4}, 1-corner model, 10 Hz (top) and 1 Hz (bottom).



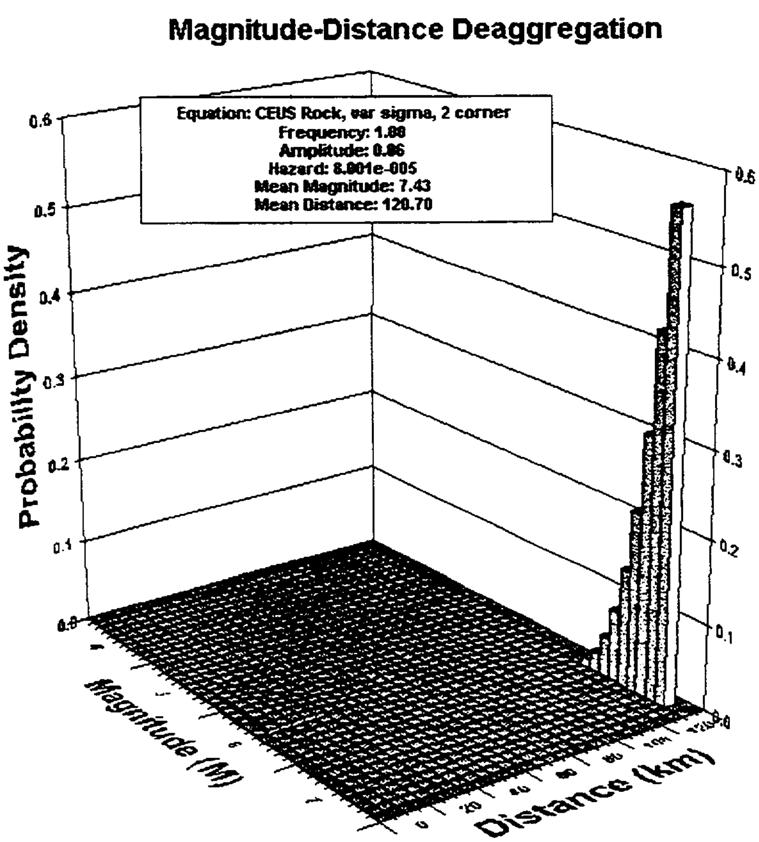
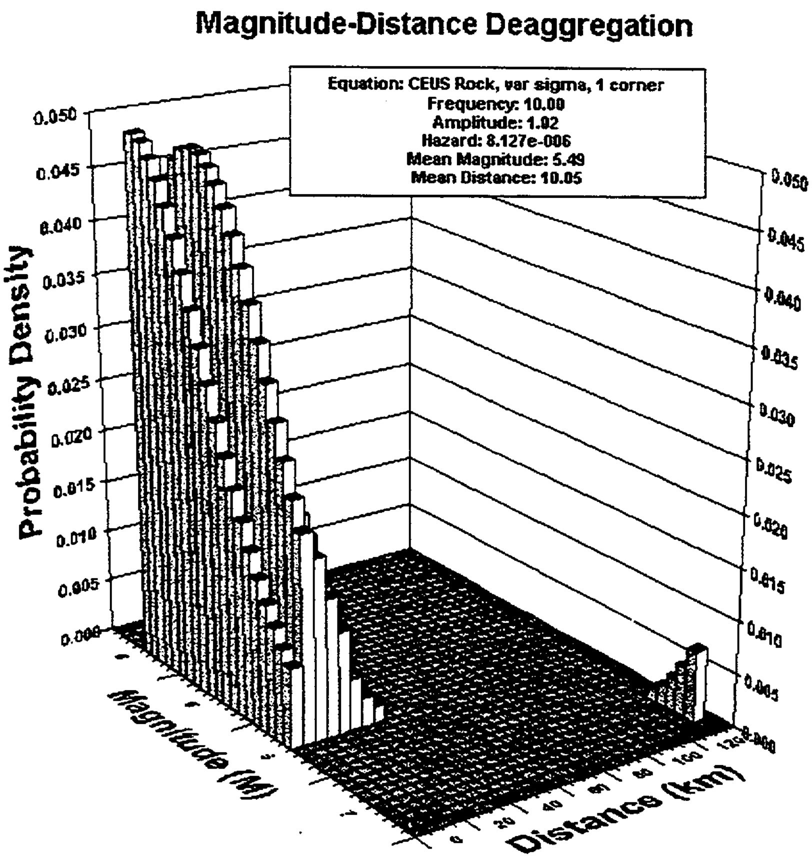


Figure 6-28b. Columbia site **M**-*R* deaggregation for 10^{-4}, 2-corner model, 10 Hz (top) and 1 Hz (bottom).



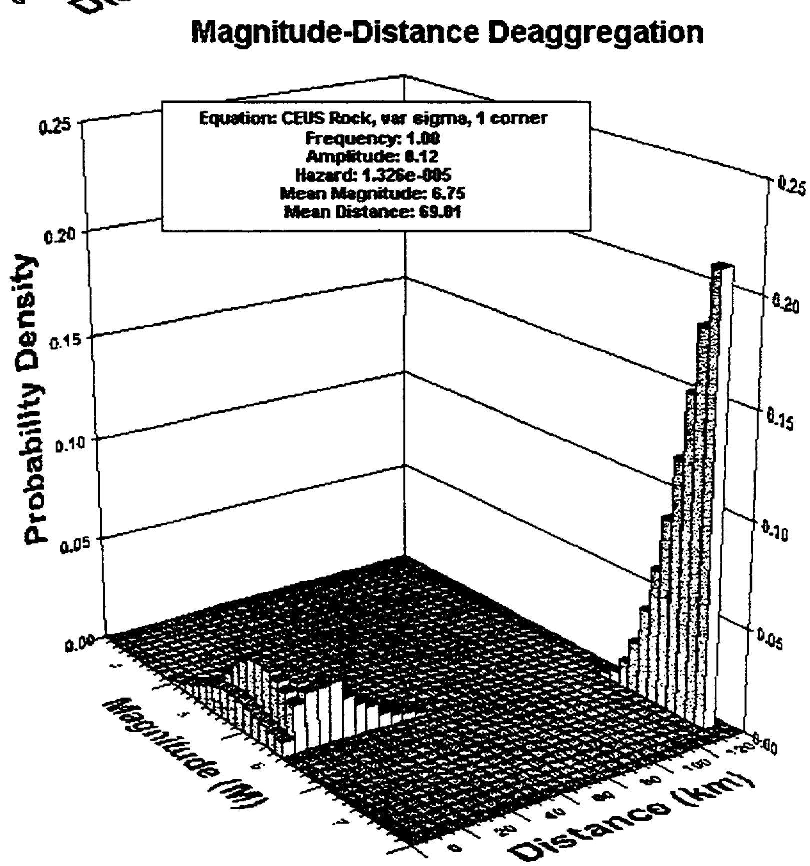
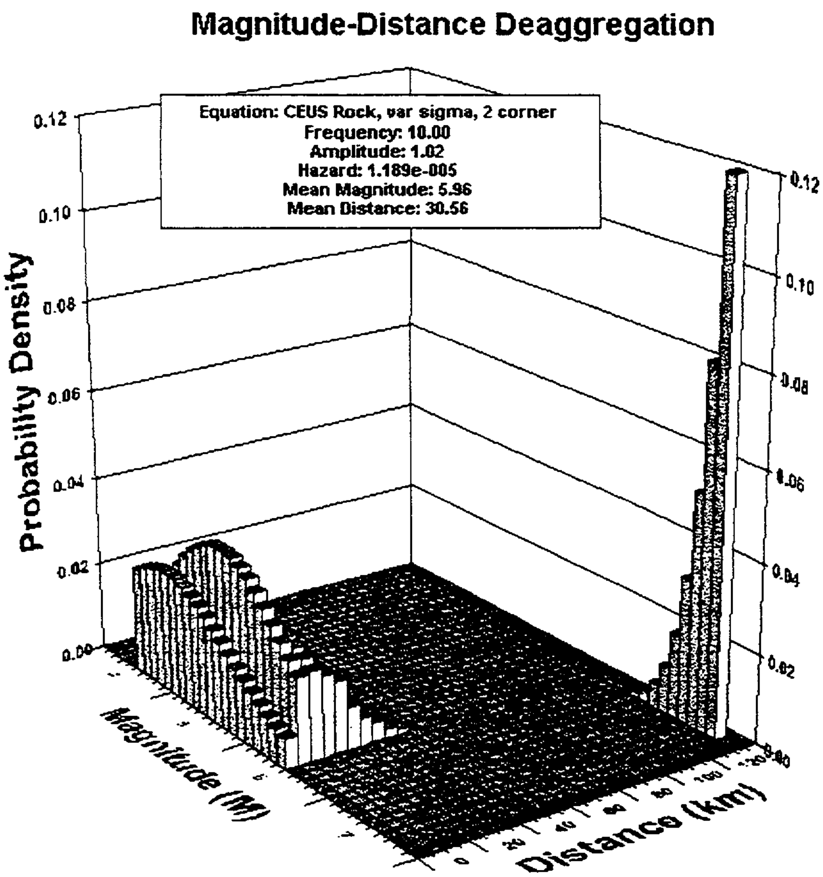


Figure 6-29a. Columbia site **M**-*R* deaggregation for 10^{-5}, 1-corner model, 10 Hz (top) and 1 Hz (bottom).



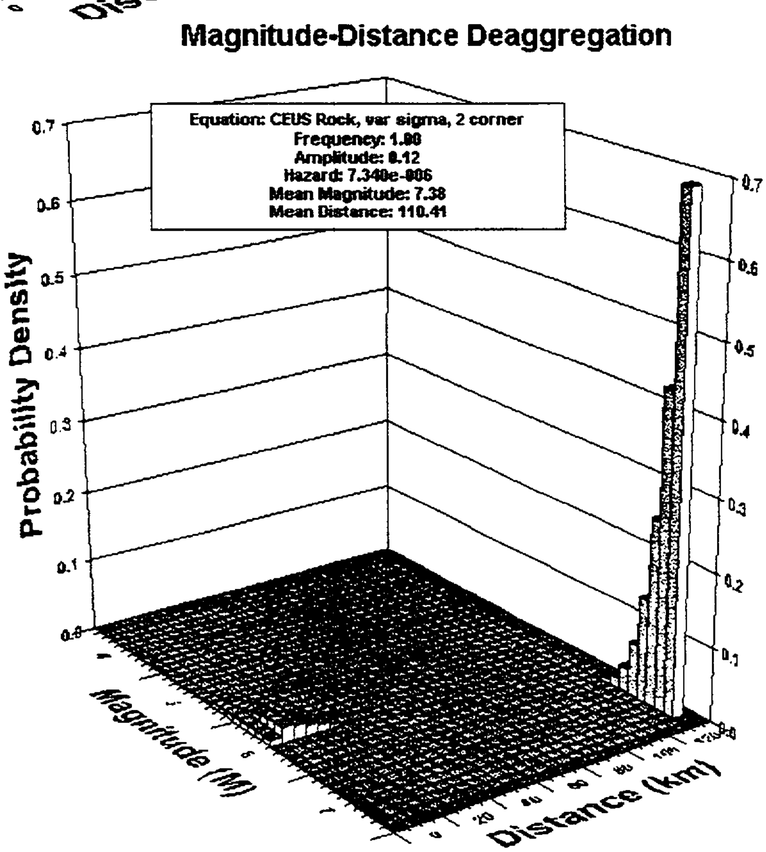


Figure 6-29b. Columbia site **M**-*R* deaggregation for 10^{-5}, 2-corner model, 10 Hz (top) and 1 Hz (bottom).

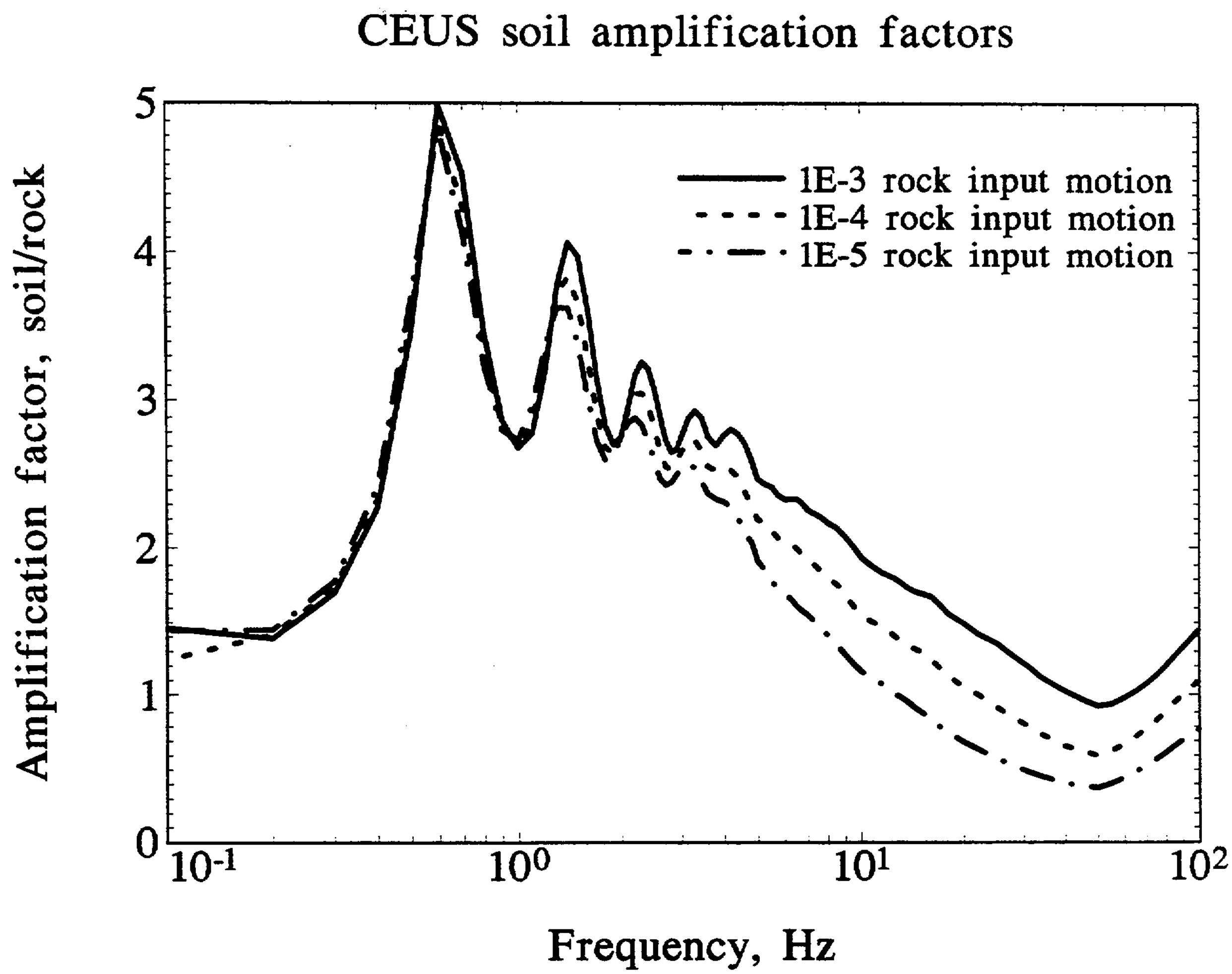


Figure 6-30. Mean amplification factor, soil/rock, from Approach 2A for 10^{-3}, 10^{-4}, and 10^{-5} rock input motions, Columbia site, Savannah profile.

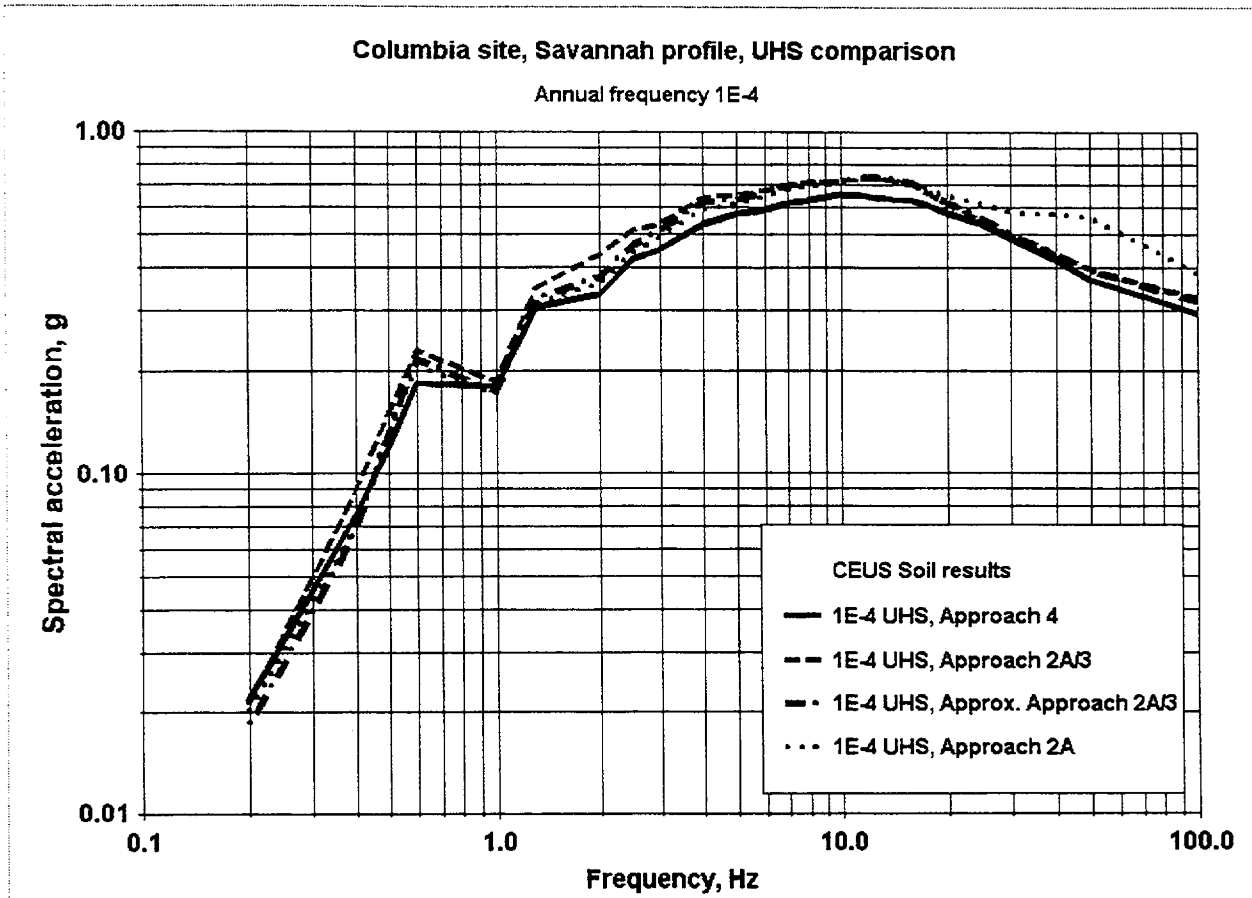


Figure 6-31. Columbia site 10^{-4} UHS for Savannah profile from Approach 4 (direct method) and Approaches 2A and 2A/3.

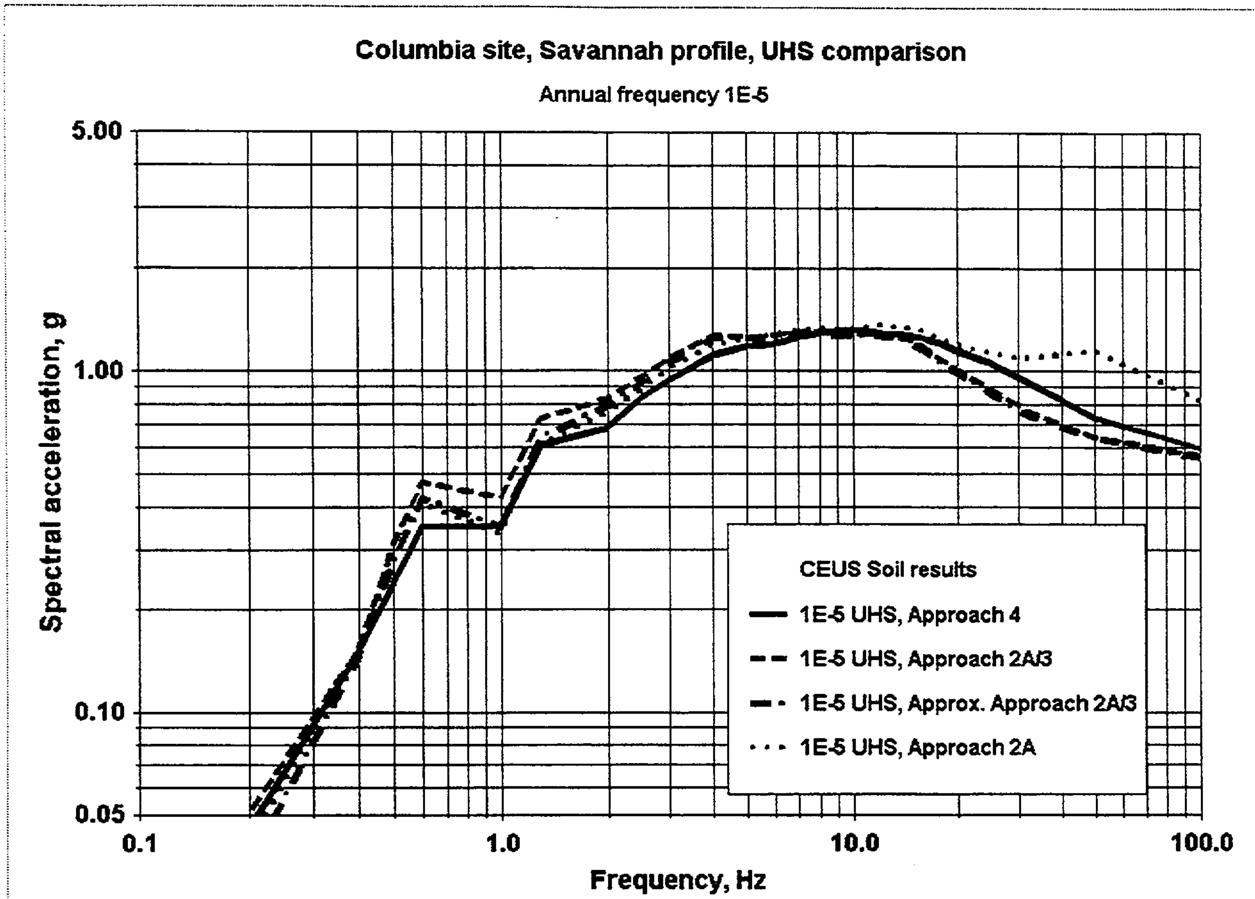


Figure 6-32. Columbia site 10^{-5} UHS for Savannah profile from Approach 4 (direct method) and Approaches 2A and 2A/3.

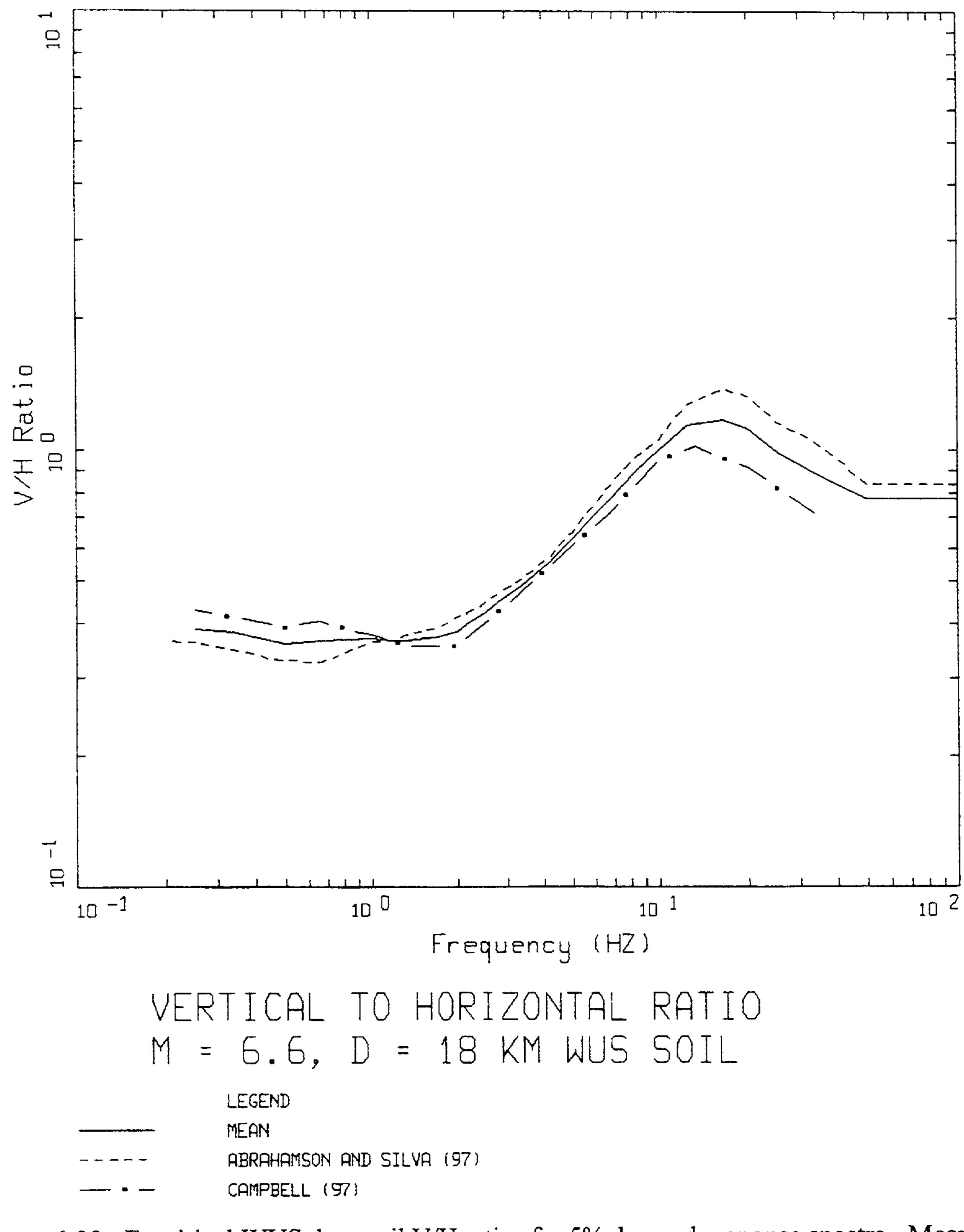


Figure 6-33. Empirical WUS deep soil V/H ratios for 5% damped response spectra. Mean ratio is used to scale the horizontal soil design spectrum.

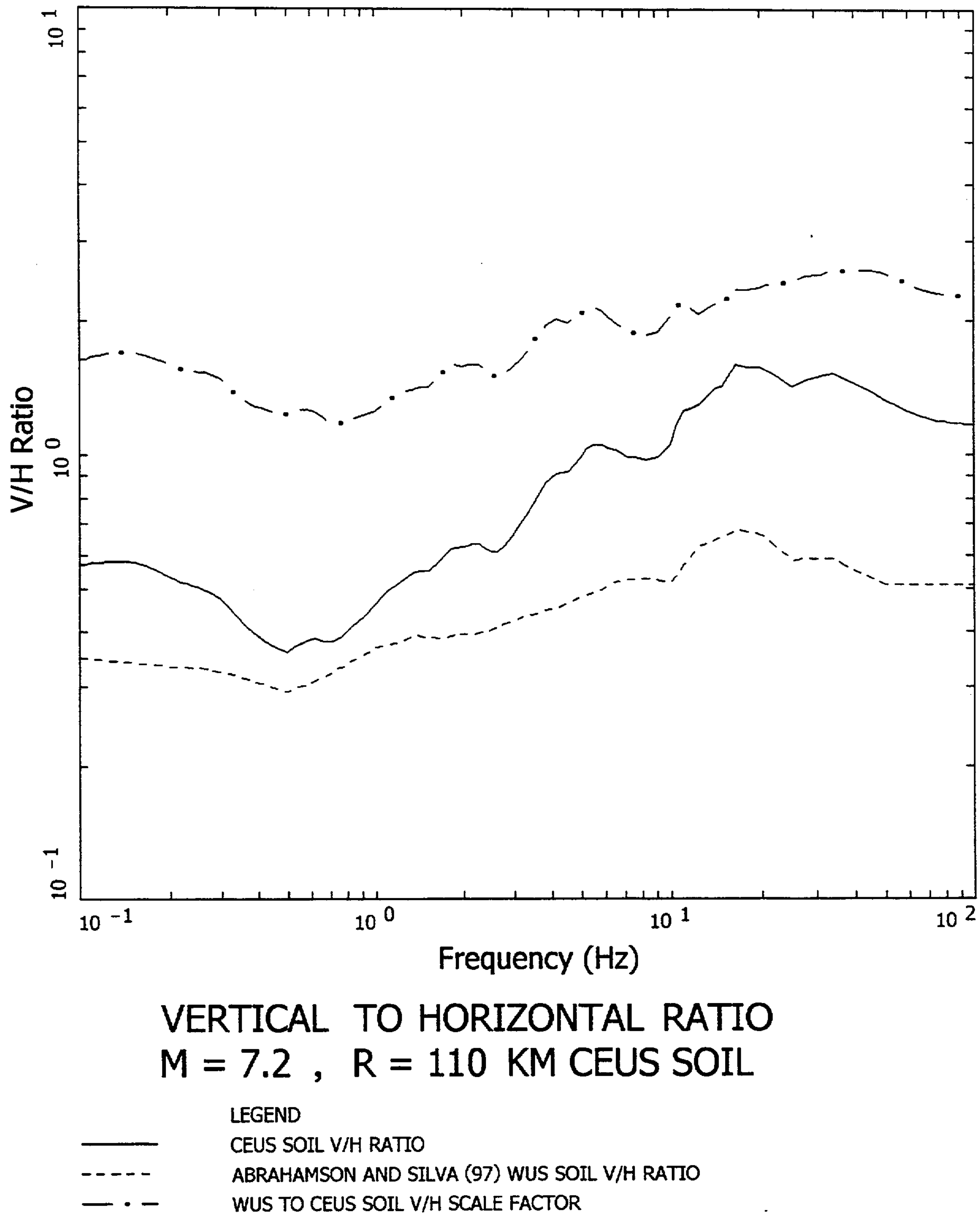


Figure 6-34. Elements used to develop CEUS deep soil V/H ratio. The solid line is used to scale the horizontal soil spectrum to produce the vertical soil spectrum.

7.0 UNIFORM RELIABILITY SPECTRUM ON SOIL

7.1 Mojave site

7.1.1 Derivation of uniform reliability spectrum (URS)

The URS for soil is derived in a manner similar to that used for rock conditions (Section 4), with several differences. The recommended steps are as follows:

1. Estimate the 10^{-4} and 10^{-5} UHS from Approximate Approach 2A/3 (equation (6-7b)) as described in Section 6.2.

2. Calculate factor A_R from the estimated 10^{-4} and 10^{-5} UHS, apply equations (4-1) and (4-2), and calculate the URS from the UHS estimated from Approximate Approach 2A/3.

These steps were applied to the Mojave site, and Table 7-1 documents the scale factor and URS. For this site, with its high seismic hazard, the soil response is well into the non-linear range at 10^{-4} annual frequency of exceedence levels, so the soil hazard curves are falling off very quickly (with a high negative slope). Hence the calculated scale factor is at its minimum value of 0.7 for all frequencies. Figure 7-1 shows the soil UHS and URS, the latter obtained by multiplying the UHS at each frequency by the scale factors in Table 7-1. For comparison purposes, Table 7-2 shows the URS calculated from Approach 4, and Figure 7-1 includes the URS from Approach 4. There is good agreement between the URS calculated by the two methods.

7.1.2 Scaled spectra on soil

Calculating scaled spectra for soil conditions requires calculating soil response for individual earthquakes and scaling those soil spectra to the soil URS. The dominant **M** and R values for the rock seismic hazard analysis are used to calculate the soil response, as there is no direct evaluation of the soil hazard and the contribution by **M** and R for soil conditions.

As documented in Section 3.1 and 4.1, deaggregation of the rock seismic hazard indicates that the following mean magnitudes and associated distances dominate for 10 and 1 Hz and for 10^{-4} annual frequency of exceedence:

10 Hz: **M** = 6.1, R = 14 km,
1 Hz: **M** = 6.6, R = 18 km.

These **M** and R values are used to generate soil spectral shapes that are then scaled to the URS at 10 and 1 Hz, respectively.

For comparison purposes, Figure 7-2 shows the estimated UHS on soil (from Approach 2A) and two spectra obtained by multiplying the rock UHS at 1E-4 annual frequency by soil amplification factors derived from 10 and 1 Hz design earthquakes. This illustrates that the simple scaling of rock UHS to estimate soil UHS is inaccurate.

Figure 7-3 shows the recommended scaling of soil spectra to the URS. The individual soil spectra estimated for the 10 and 1 Hz dominant earthquakes (with magnitudes and distances given above) are scaled to the 10 and 1 Hz URS amplitudes. This ensures that the site-specific soil characteristics are maintained in the final spectra. Figure 7-3 shows the 10^{-4} URS for the Meloland profile at the Mojave site, with the two scaled spectra representing the dominant earthquakes. In a design application the scaled spectra and the URS would be smoothed to remove calculated site resonances and frequency-to-frequency variations that result from attenuation coefficient variations. This has not been done here in order not to arbitrarily change the comparison between design spectra and scaled spectra. These individual spectra can be used to generate artificial time histories of motion, if desired, or a broad-band motion can be fit to the overall soil URS. These motions would be used as input to the analysis of structures and equipment founded on soil.

A vertical design spectrum is compared to the horizontal URS in Figure 7-4. The vertical spectrum is scaled from the horizontal spectrum as discussed in Section 6.

7.2 Columbia site

7.2.1 Derivation of URS

The URS for the Columbia site is derived in a manner similar to that for the Mojave site, using the two steps described in Section 7.1.1. Table 7-3 documents the scale factors and URS. The high frequency amplitudes show nonlinearity of soil response, with steep hazard curves. As a result the URS is below the UHS for high frequencies ($f \geq 10$ Hz) by the factor 0.7. At lower frequencies ($f < 10$ Hz) soil amplitudes are slightly more shallow, so the URS is below the UHS by factors that range from 0.71 to 0.87. For comparison purposes, Table 7-4 shows the URS calculated from Approach 4.

Figure 7-5 compares the 1E-4 UHS and the URS calculated by approximate Approach 2A/3 and by Approach 4. The two URS spectra are very close, which confirms the use of Approximate Approach 2A/3 to derive the URS.

7.2.2 Scaled spectra on soil

At Columbia the scaled spectra are calculated similarly to these for the Mojave site, i.e. using mean magnitudes and associated distances from rock results. These were presented in Section 4 and are as follows (for 10^{-4} annual frequency of exceedence):

10 Hz $\mathbf{M} = 6.0$, R = 46 km,
1 Hz $\mathbf{M} = 7.2$, R = 110 km.

In Approximate Approach 2A/3 these magnitudes and distances were used to select rock records and compute soil response. The average soil spectra were computed for 10 Hz and 1 Hz, and are scaled to the URS at 10 Hz and 1 Hz, respectively.

For comparison purposes, Figure 7-6 shows the 1E-4 UHS from Approach 2A compared to the spectra from deriving the soil with 10 Hz and 1 Hz motions scaled to the rock 1E-4 UHS. This again indicates (as Figure 7-2 does) that simple scaling of the rock UHS to estimate the soil UHS is inaccurate.

The appropriate scaled spectra are shown in Figure 7-7, which indicates the 10 and 1 Hz spectra scaled to the 10^{-4} URS. This is the URS derived from Approximate Approach 2A/3 as shown in Figure 7-5. In a design application the scaled spectra and the URS would be smoothed to remove calculated site resonances and frequency-to-frequency variations that result from attenuation coefficient variations. This has not been done here in order not to arbitrarily change the comparison between design spectra and scaled spectra. The individual spectra can be used to generate artificial time histories, or a broad-banded motion can be fit to the URS. These motions would then be used for the design and analysis of structures and equipment founded on soil.

Figure 7-8 compares the 10^{-4} horizontal URS for the Columbia site to a vertical design spectrum obtained by scaling the horizontal spectrum. This scaling was discussed in Section 6.

Table 7-1
Scale factor for soil URS
Mojave site, Approximate Approach 2A/3

Frequency, Hz	Approx. 10^{-4} UHS	Approx. 10^{-5} UHS	A_R	K_H	Scale Factor	10^{-4} URS
100	7.40E-1	1.05	1.42	6.51	7.0E-1	5.18E-1
50	7.43E-1	1.05	1.42	6.58	7.0E-1	5.20E-1
40	7.63E-1	1.07	1.40	6.81	7.0E-1	5.34E-1
31	8.32E-1	1.17	1.41	6.73	7.0E-1	5.82E-1
25	8.41E-1	1.17	1.39	6.94	7.0E-1	5.89E-1
20	8.49E-1	1.16	1.36	7.43	7.0E-1	5.94E-1
18	8.56E-1	1.16	1.36	7.52	7.0E-1	5.99E-1
16	8.76E-1	1.18	1.34	7.80	7.0E-1	6.13E-1
14	9.15E-1	1.21	1.32	8.37	7.0E-1	6.41E-1
12	9.35E-1	1.21	1.29	8.97	7.0E-1	6.55E-1
10	1.05	1.29	1.23	11.07	7.0E-1	7.35E-1
8	1.26	1.48	1.18	13.82	7.0E-1	8.80E-1
7	1.34	1.59	1.19	13.02	7.0E-1	9.35E-1
6	1.33	1.56	1.17	14.74	7.0E-1	9.33E-1
5	1.57	1.88	1.19	12.96	7.0E-1	1.10
4	1.60	2.00	1.25	10.22	7.0E-1	1.12
3	1.65	2.27	1.37	7.24	7.0E-1	1.15
2.5	1.71	2.45	1.43	6.42	7.0E-1	1.20
2	1.71	2.57	1.50	5.67	7.0E-1	1.20
1.3	1.40	2.34	1.67	4.48	7.0E-1	9.78E-1
1	1.24	2.11	1.71	4.31	7.0E-1	8.66E-1
.6	9.84E-1	1.72	1.75	4.12	7.0E-1	6.89E-1
.5	1.01	1.66	1.64	4.67	7.0E-1	7.09E-1
.4	9.50E-1	1.62	1.70	4.32	7.0E-1	6.65E-1
.2	2.72E-1	4.83E-1	1.77	4.02	7.0E-1	1.91E-1

Table 7-2
Scale factor for soil URS
Mojave site, Approach 4

Frequency, Hz	10^{-4} UHS	10^{-5} UHS	A_R	K_H	Scale Factor	10^{-4} URS
100	7.18E-1	1.17	1.63	4.71	7.0E-1	5.03E-1
50	7.23E-1	1.18	1.63	4.71	7.0E-1	5.06E-1
40	7.29E-1	1.19	1.63	4.72	7.0E-1	5.10E-1
31	7.40E-1	1.21	1.63	4.73	7.0E-1	5.18E-1
25	7.47E-1	1.20	1.60	4.87	7.0E-1	5.23E-1
20	7.72E-1	1.22	1.58	5.04	7.0E-1	5.40E-1
18	7.97E-1	1.25	1.58	5.06	7.0E-1	5.58E-1
16	8.19E-1	1.27	1.55	5.24	7.0E-1	5.73E-1
14	8.55E-1	1.31	1.53	5.41	7.0E-1	5.98E-1
12	9.23E-1	1.41	1.53	5.43	7.0E-1	6.46E-1
10	9.98E-1	1.51	1.52	5.52	7.0E-1	6.98E-1
8	1.08	1.66	1.54	5.35	7.0E-1	7.58E-1
7	1.16	1.78	1.54	5.37	7.0E-1	8.10E-1
6	1.23	1.90	1.54	5.33	7.0E-1	8.64E-1
5	1.34	2.06	1.54	5.31	7.0E-1	9.35E-1
4	1.45	2.30	1.59	4.99	7.0E-1	1.01
3	1.55	2.49	1.61	4.85	7.0E-1	1.08
2.5	1.53	2.47	1.61	4.81	7.0E-1	1.07
2	1.49	2.43	1.63	4.69	7.0E-1	1.04
1.3	1.35	2.32	1.72	4.25	7.0E-1	9.44E-1
1	1.35	2.28	1.69	4.40	7.0E-1	9.47E-1
.6	9.74E-1	1.65	1.69	4.36	7.0E-1	6.81E-1
.5	9.49E-1	1.65	1.74	4.17	7.0E-1	6.64E-1
.4	8.80E-1	1.59	1.81	3.88	7.13E-1	6.27E-1
.2	3.23E-1	5.14E-1	1.59	4.96	7.0E-1	2.26E-1

Table 7-3
Scale factors for soil URS
Columbia site, Approximate Approach 2A/3

Frequency, Hz	Approx. 10^{-4} UHS	Approx. 10^{-5} UHS	A_R	K_H	Scale Factor	10^{-4} URS
100	3.18E-1	5.56E-1	1.75	4.12	7.00E-1	2.23E-1
50	3.95E-1	6.37E-1	1.61	4.84	7.00E-1	2.77E-1
40	4.41E-1	6.84E-1	1.55	5.24	7.00E-1	3.09E-1
31	4.95E-1	7.56E-1	1.53	5.43	7.00E-1	3.47E-1
25	5.60E-1	8.59E-1	1.53	5.37	7.00E-1	3.92E-1
20	6.20E-1	9.88E-1	1.59	4.95	7.00E-1	4.34E-1
18	6.59E-1	1.06	1.60	4.88	7.00E-1	4.62E-1
16	7.10E-1	1.15	1.62	4.77	7.00E-1	4.97E-1
14	7.27E-1	1.23	1.69	4.40	7.00E-1	5.09E-1
12	7.38E-1	1.26	1.71	4.27	7.00E-1	5.16E-1
10	7.16E-1	1.26	1.75	4.10	7.00E-1	5.01E-1
8	7.08E-1	1.28	1.81	3.89	7.13E-1	5.04E-1
7	6.95E-1	1.28	1.84	3.79	7.26E-1	5.05E-1
6	6.64E-1	1.24	1.87	3.66	7.44E-1	4.94E-1
5	6.33E-1	1.23	1.95	3.45	7.79E-1	4.93E-1
4	6.19E-1	1.24	2.00	3.33	8.02E-1	4.97E-1
3	5.12E-1	1.06	2.06	3.18	8.35E-1	4.27E-1
2.5	4.64E-1	9.20E-1	1.98	3.36	7.96E-1	3.69E-1
2	3.75E-1	7.87E-1	2.10	3.11	8.51E-1	3.19E-1
1.3	3.24E-1	6.37E-1	1.97	3.40	7.88E-1	2.55E-1
1	1.74E-1	3.48E-1	2.00	3.32	8.05E-1	1.40E-1
.6	2.17E-1	4.24E-1	1.96	3.43	7.83E-1	1.70E-1
.5	1.32E-1	2.77E-1	2.11	3.09	8.56E-1	1.13E-1
.4	6.73E-2	1.43E-1	2.13	3.04	8.68E-1	5.84E-2
.2	1.81E-2	3.56E-2	1.97	3.39	7.90E-1	1.43E-2

Table 7-4
Scale factors for soil URS
Columbia site, Approach 4

Frequency, Hz	10^{-4} UHS	10^{-5} UHS	A_R	K_H	Scale Factor	10^{-4} URS
100	2.94E-1	5.93E-1	2.02	3.28	8.12E-1	2.39E-1
50	3.70E-1	7.30E-1	1.97	3.39	7.91E-1	2.93E-1
40	4.22E-1	8.26E-1	1.96	3.43	7.84E-1	3.31E-1
31	4.83E-1	9.48E-1	1.96	3.42	7.86E-1	3.80E-1
25	5.39E-1	1.06	1.96	3.42	7.85E-1	4.23E-1
20	5.81E-1	1.15	1.97	3.38	7.92E-1	4.60E-1
18	6.06E-1	1.20	1.98	3.37	7.95E-1	4.82E-1
16	6.26E-1	1.24	1.98	3.37	7.95E-1	4.98E-1
14	6.36E-1	1.27	2.00	3.31	8.06E-1	5.13E-1
12	6.47E-1	1.29	2.00	3.33	8.03E-1	5.20E-1
10	6.54E-1	1.32	2.02	3.28	8.14E-1	5.32E-1
8	6.28E-1	1.28	2.04	3.23	8.24E-1	5.17E-1
7	6.17E-1	1.26	2.03	3.24	8.21E-1	5.07E-1
6	5.89E-1	1.20	2.03	3.25	8.19E-1	4.82E-1
5	5.75E-1	1.17	2.04	3.23	8.23E-1	4.73E-1
4	5.33E-1	1.10	2.07	3.16	8.39E-1	4.47E-1
3	4.52E-1	9.37E-1	2.07	3.16	8.40E-1	3.80E-1
2.5	4.22E-1	8.31E-1	1.97	3.40	7.88E-1	3.33E-1
2	3.34E-1	6.80E-1	2.03	3.24	8.20E-1	2.74E-1
1.3	3.06E-1	6.04E-1	1.97	3.39	7.90E-1	2.42E-1
1	1.79E-1	3.47E-1	1.94	3.47	7.76E-1	1.39E-2
.6	1.85E-1	3.51E-1	1.90	3.59	7.56E-1	1.40E-1
.5	1.19E-1	2.38E-1	2.00	3.32	8.04E-1	9.57E-2
.4	7.47E-2	1.49E-1	1.99	3.35	7.99E-1	5.97E-2
.2	2.18E-2	4.56E-2	2.09	3.12	8.49E-1	1.85E-2

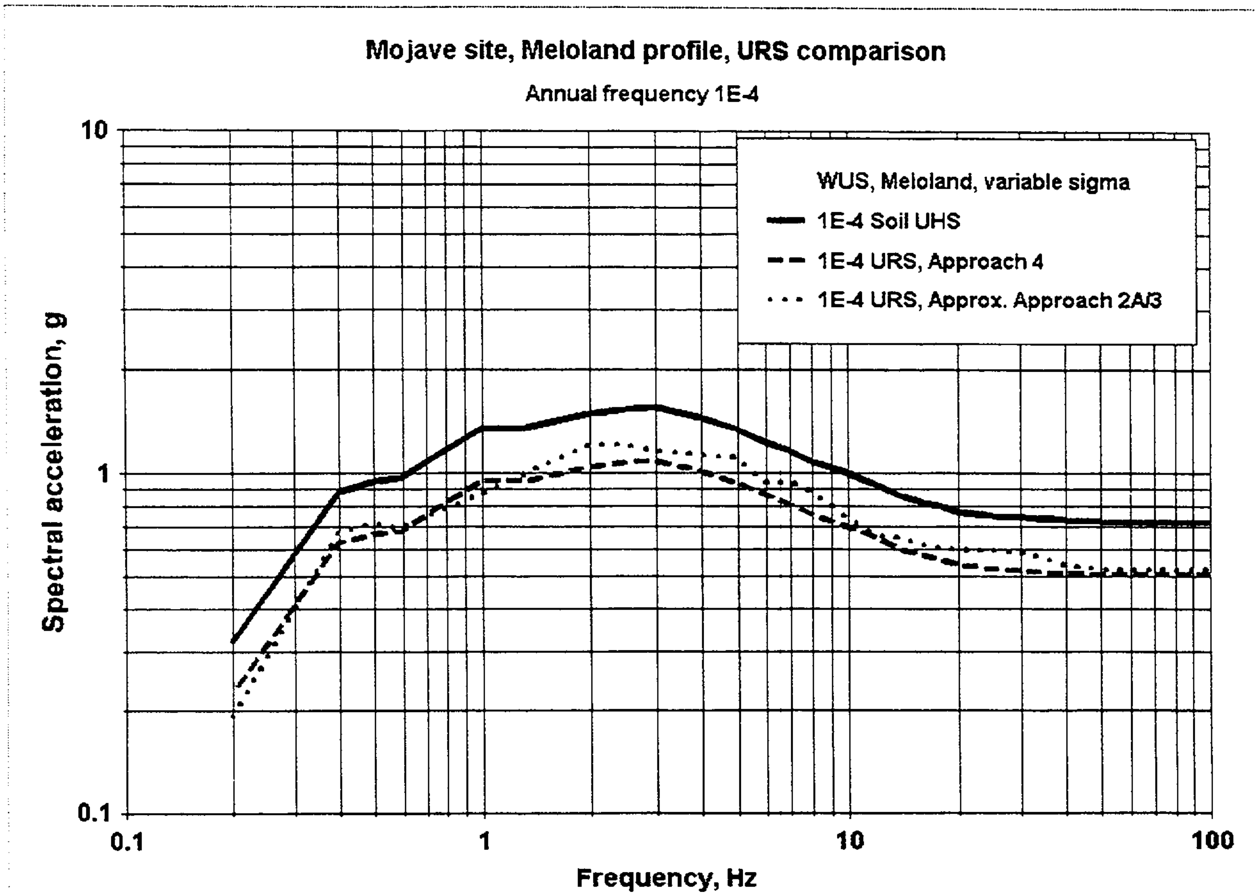


Figure 7-1. Mojave site, 10^{-4} soil URS from Approach 4 and Approximate Approach 2A/3, and 10^{-4} UHS from Approach 4.

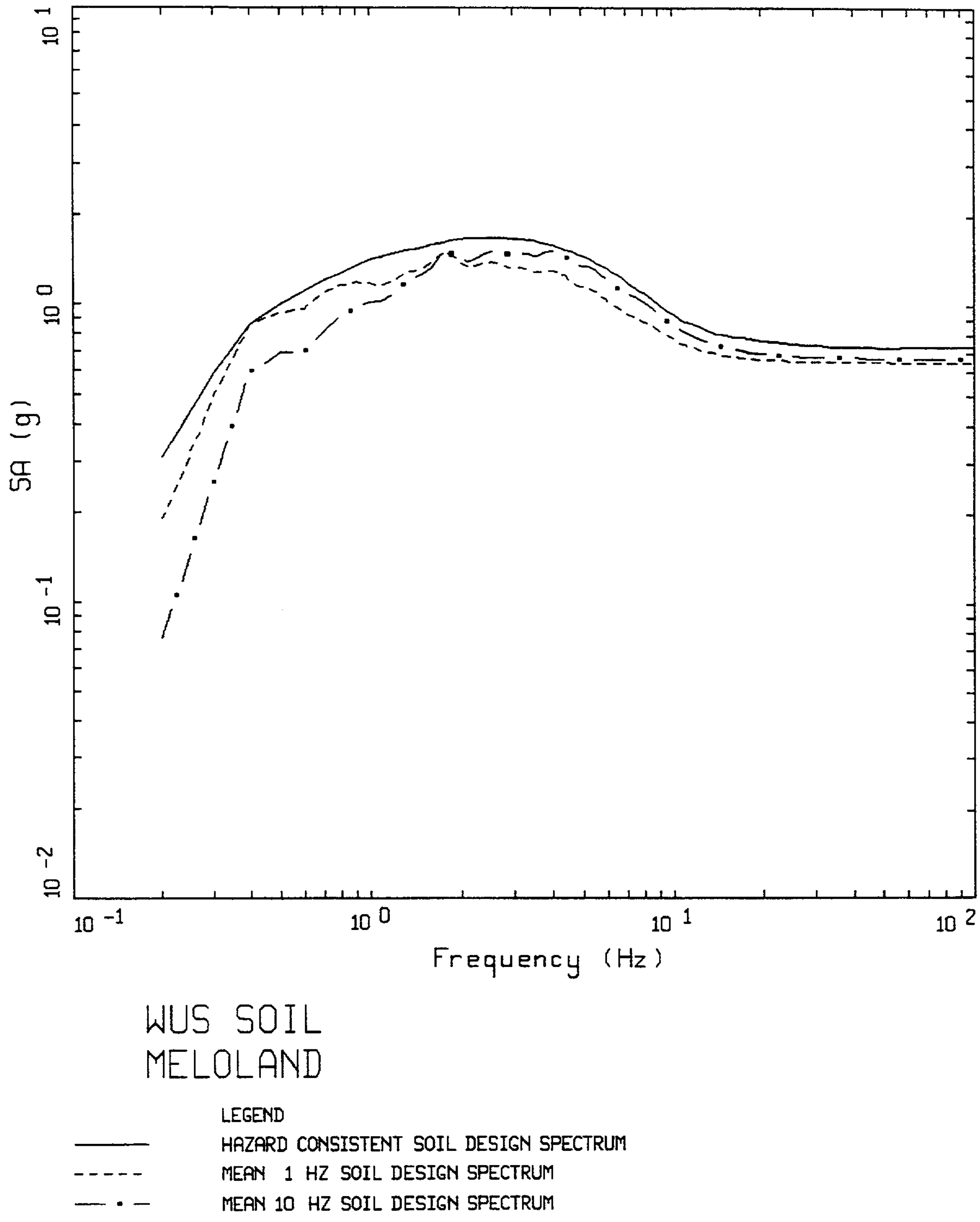


Figure 7-2. Hazard consistent soil spectrum along with 1 Hz and 10 Hz soil spectra, horizontal motions, Mojave site.

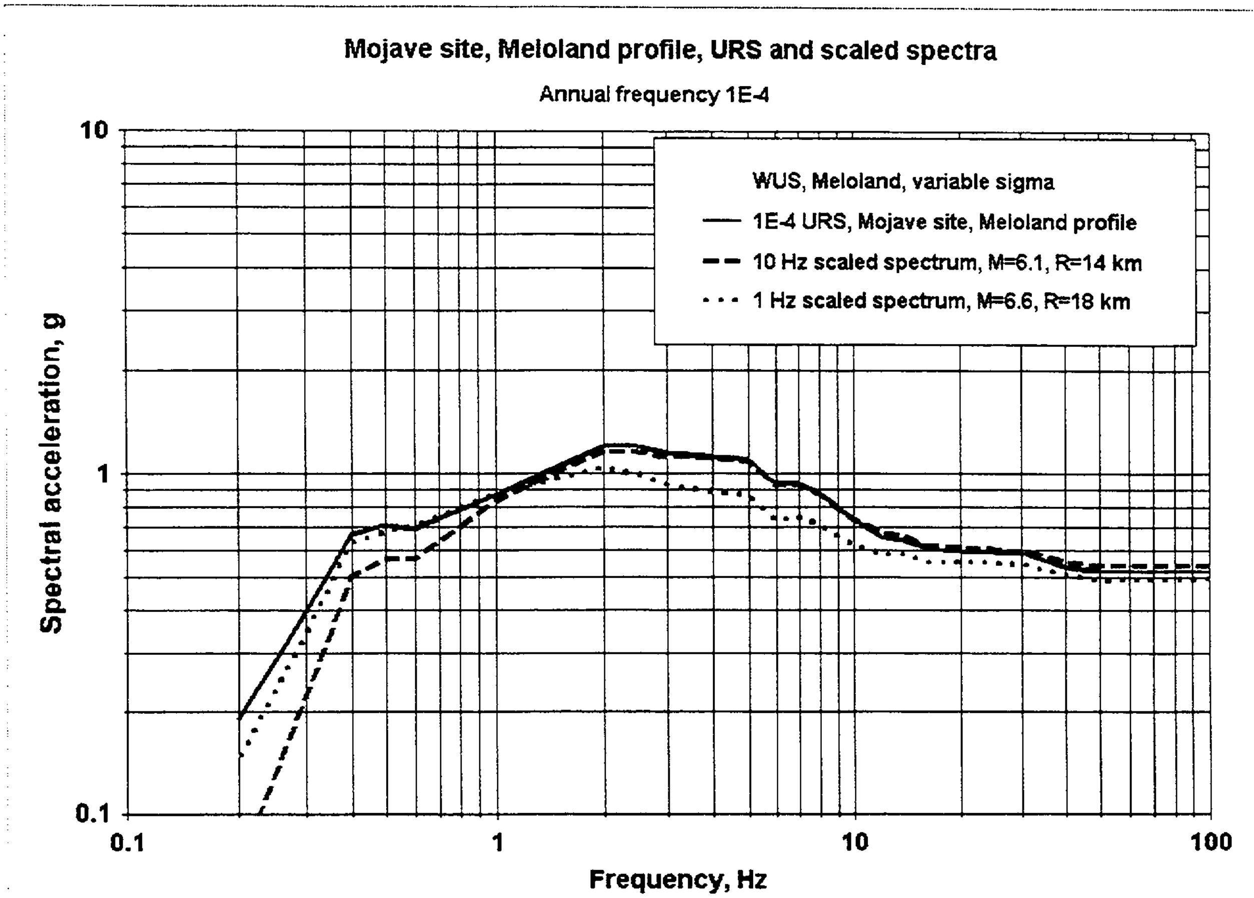


Figure 7-3. Mojave site 10^{-4} soil URS (Approximate Approach 2A/3) and 10 Hz and 1 Hz scaled spectra.

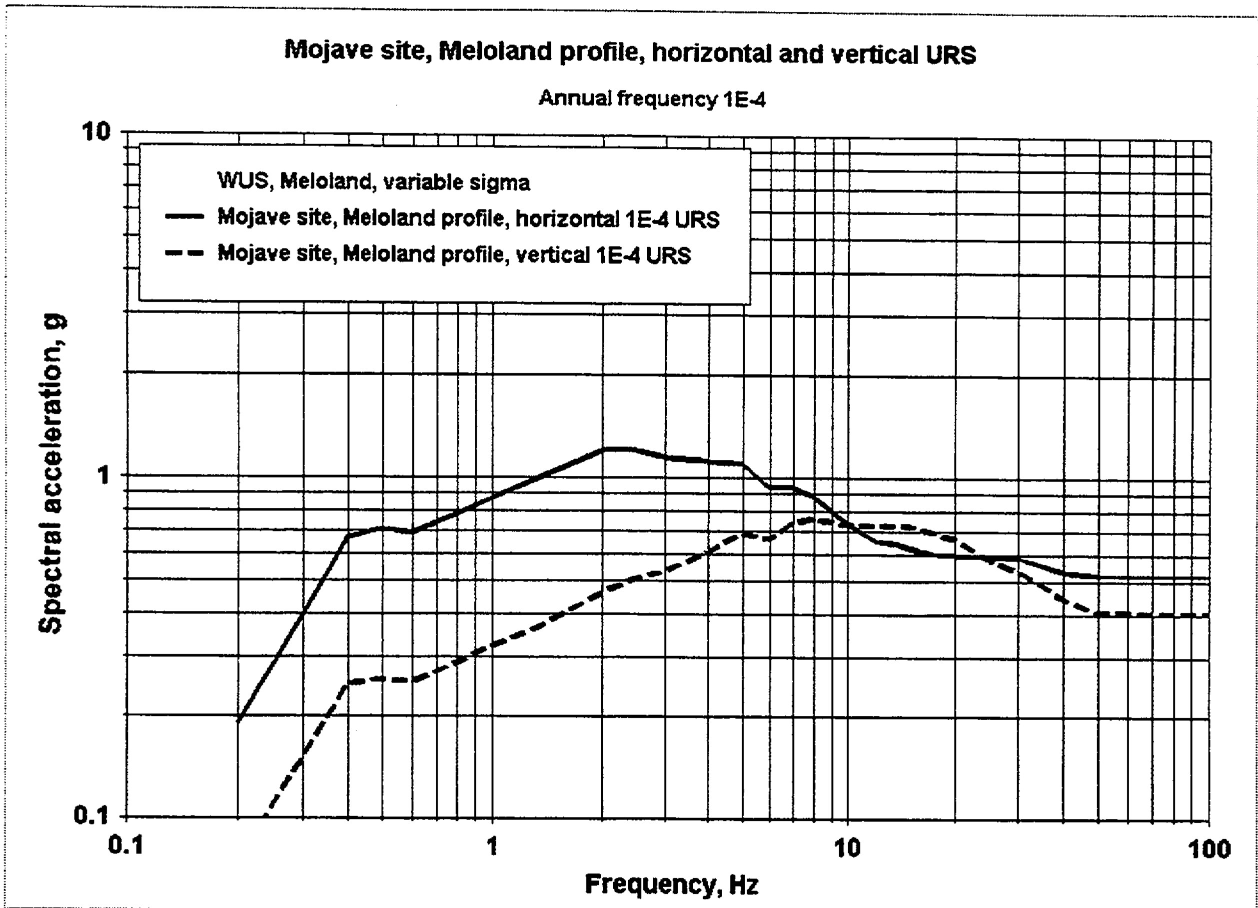


Figure 7-4. Horizontal and vertical URS for the Mojave site, Meloland profile.

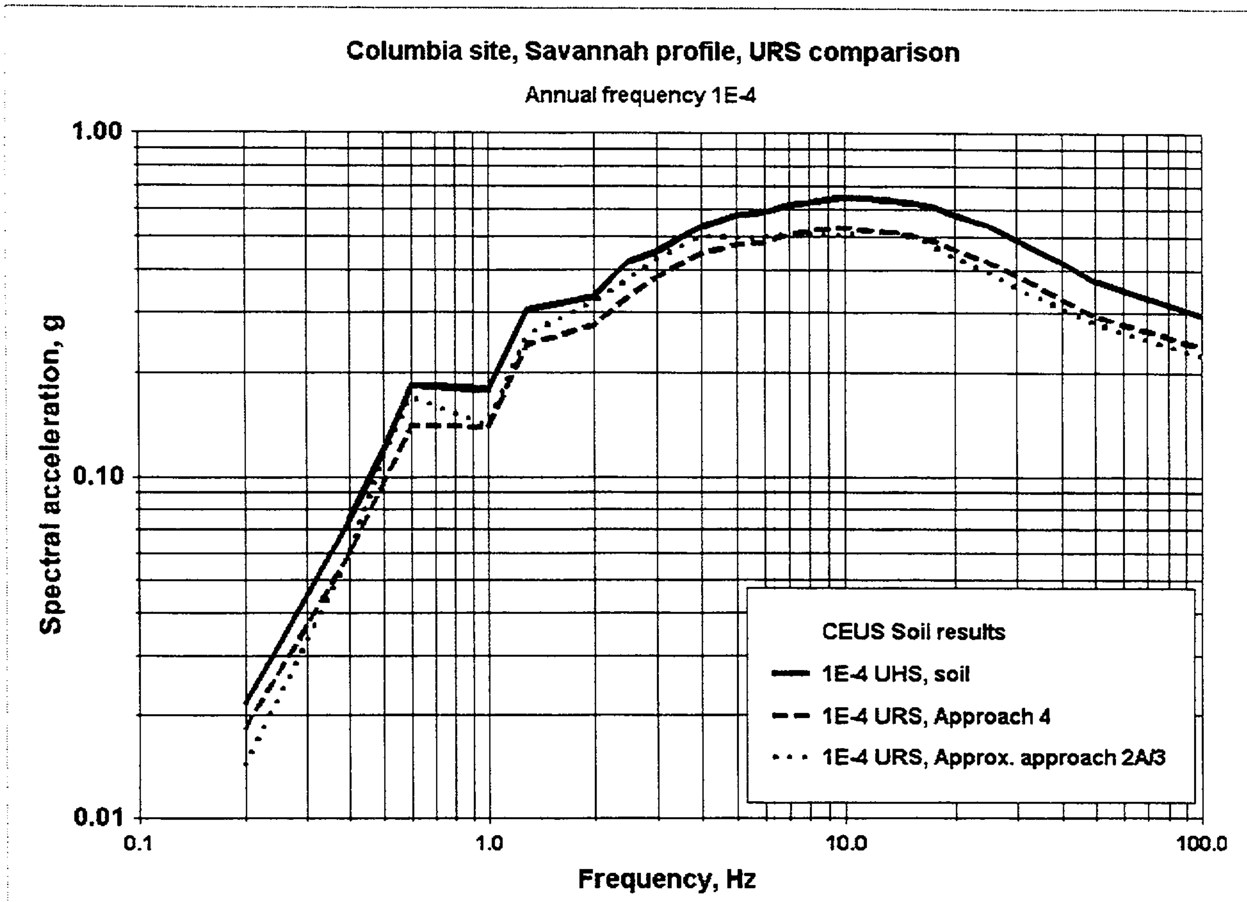


Figure 7-5. Columbia site, 10^{-4} soil URS from Approaches 4 and Approximate Approach 2A/3, and 10^{-4} UHS from Approach 4.

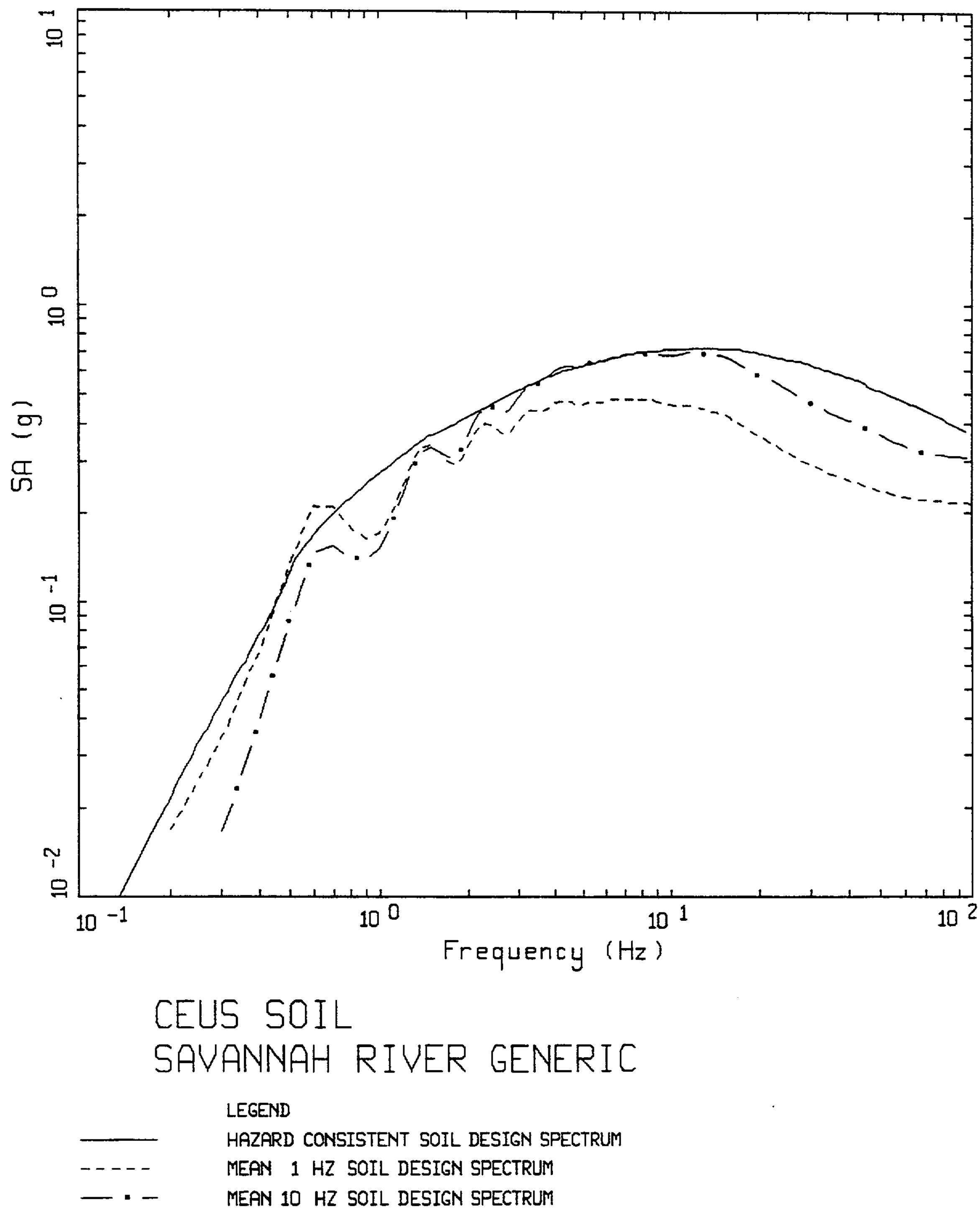


Figure 7-6. Hazard consistent soil spectrum along with 1 Hz and 10 Hz soil spectra, horizontal motions, Columbia site.

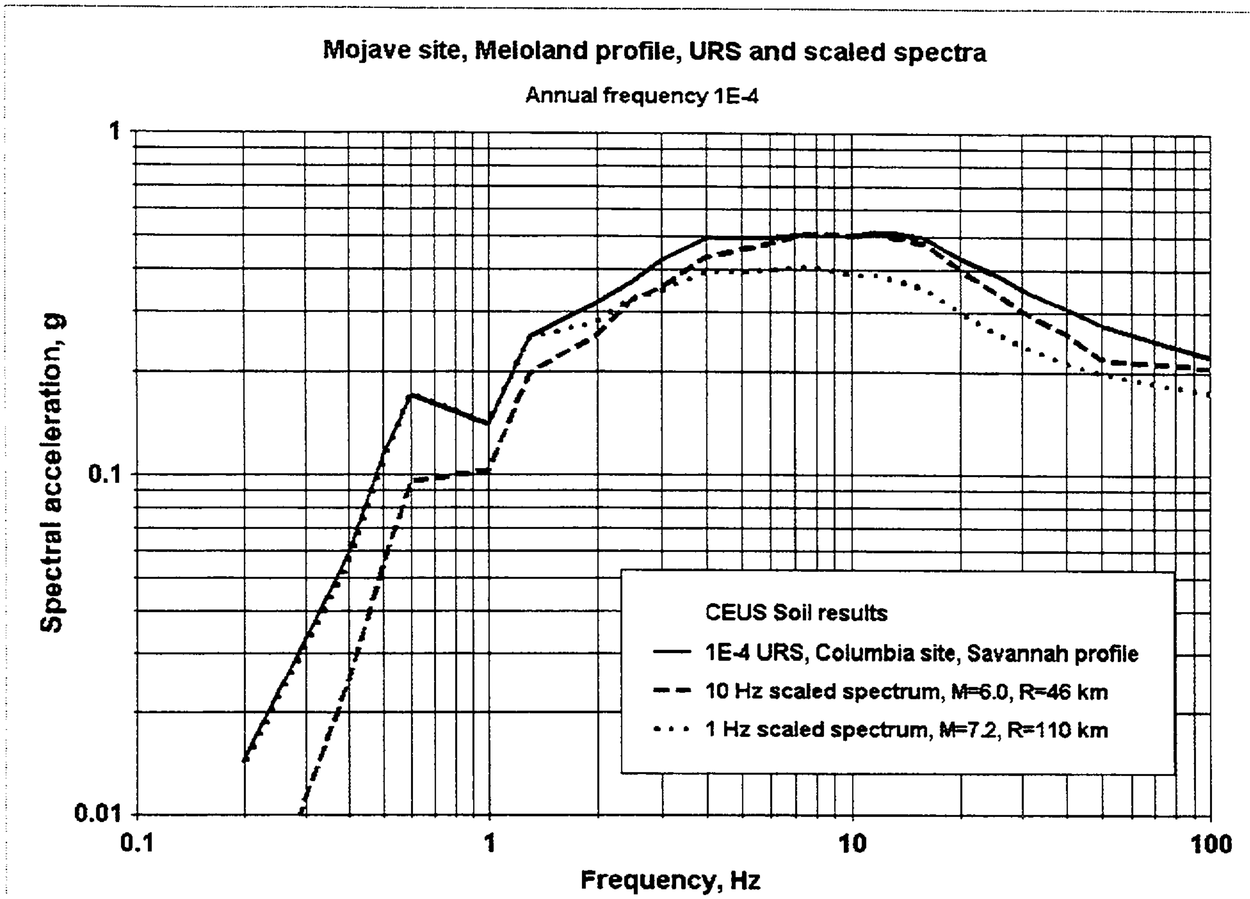


Figure 7-7. Columbia site 10^{-4} soil URS (Approximate Approach 2A/3) and 10 Hz and 1 Hz scaled spectra.

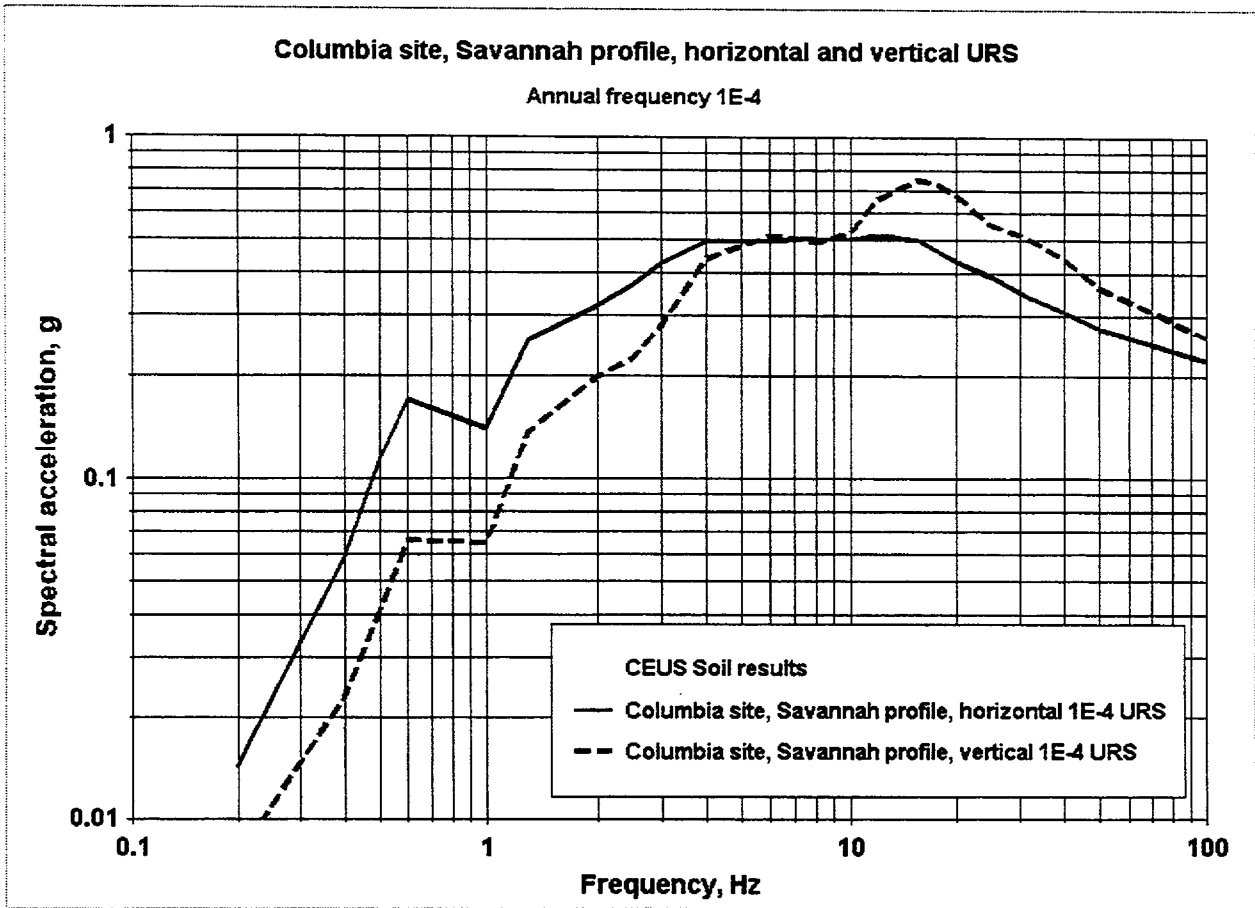


Figure 7-8. Horizontal and vertical URS for the Columbia site, Savannah profile.

8.0 GENERATING ARTIFICIAL MOTIONS FOR SOIL SITES

In this section we describe soil time histories that are generated for the Mojave and Columbia sites using a simple spectral matching procedure (Section 5.1). The guideline on number of spectral frequencies (100 per decade) recommended in McGuire et al., (2001) was followed. However, the corresponding matching criteria, which consist of a target exceedence maximum of 1.3 and minimum of 0.9 with not more than 20 points below the target (0.2 to 25.0 Hz and peak acceleration), was found to result in matched spectra that were biased high with respect to the target. To achieve spectral matches more representative of desired risk levels implied by the uniform reliability spectra (Section 7), an alternative criterion was developed. A band is defined between 95% and 110% of the target spectrum, and virtually all points must fall within the band (up to 5 or 10 points may fall outside the band, but not at adjacent frequencies). This criterion results in a mean-based fit (Chi-square near 1.0) with about 60 to 80 points being below the target (but only slightly), and more than 200 points above the target. The fit is easily obtainable, represents the desired spectral level, and does not permit significant notches or holes to develop in the Fourier amplitude spectrum, as the plots of power spectral density show.

For the WUS Mojave and CEUS Columbia sites, the deaggregation magnitudes (rock outcrop UHS) and distances are listed in Tables 8-1 and 8-2 along with the duration guideline (Table 5-2). The time histories selected from the WUS soil time histories bins for inputs to the spectral matching are listed in Table 8-1 along with their associated durations, both prior, as well as subsequent, to the matching process. For the CEUS Columbia site, WUS records scaled to CEUS conditions (see Section 3 of McGuire et al., 2001) were selected with corresponding parameters listed in Table 8-2. The resulting target spectra, spectral matches, power spectral densities, and time histories are shown in Figure 8-1 through 8-12 for the horizontal (H1 and H2) and vertical (V) components of the WUS motions and in Figures 8-13 through 8-24 for the CEUS motions. The horizontal component target spectra are the URS while the vertical target spectra were developed by applying generic deep soil V/H ratios to the hazard consistent soil spectra (Section 7).

The accompanying smoothed power spectral density (PSD) plots ($\pm$ 20%) were computed using the 5 to 75% Arias intensity durations (Tables 8-1 and 8-2) and show no rapid oscillations or deep minima. The resulting time histories appear realistic in acceleration, velocity, and displacement.

Peak particle ratios (PGV/PGA and PGA•PGD/PGV^2) computed from the matched time histories are listed in Tables 8-1 (WUS) and 8-2 (CEUS) along with statistical shape bin median values (Table 5-2). For the WUS soil motions, the time histories show large PGV/PGA ratios compared to bin medians (~180 cm/sec/g compared to 79 cm/sec/g). These large values are consistent with recorded motions from the **M** 6.5 1979 Imperial Valley earthquake at sites located near the fault rupture (PGA $\geq$ 0.3g). The average horizontal PGV/PGA value for the Meloland site is about 260 cm/sec/g, which is elevated due to the effects of rupture directivity being located near ($\leq$ 5km) the fault trace and with rupture toward the site. With the 1 Hz controlling earthquake at 18 km, extreme directivity enhancements at low frequency ($\leq$ 1 Hz) would not be expected but site location relative to the mapped faults should be investigated for cases with **M** greater than about 6.5 and deaggregation distances within about 20 km. These conditions are considered to apply to spectral levels for frequencies as low as 0.5 Hz as lower frequency considerations are only to assure reasonable PGV/PGA and PGA•PGD/PGV^2 values for the matched time histories.

The PGA•PGD/PGV^2 ratios are 2.6 (Table 8-1), close to the bin medians of 3.1. The cross correlations (Table 8-2) are low (less than 0.1) among all three components.

For the CEUS, the 1 Hz deaggregation magnitude and distance are 7.2 and 130 km respectively (Table 8-2). The bin median PGV/PGA and PGA•PGD/PGV^2 ratios are about 225 cm/sec/g and 3 respectively. The spectral match values are near 50 cm/sec/g for PGV/PGA ratios and around 7 for the PGA•PGD/PGV^2 ratios. These are driven by the low PGV values (Figures 8-16 and 8-20), which are caused by the influence of the double corner source model in the hazard analyses. The difference in the low frequency ($\leq$ 1 Hz) rock motion between the single- and double-corner source models is very large (Figures 2-17a and 2-17b).

As with the WUS site, the cross correlations (Table 8-2) are low for the CEUS, with a maximum of 0.04.

REFERENCES

McGuire, R.K., W.J. Silva, C.J. Costantino (October 2001). "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines." U.S. Nuclear Reg. Comm., Rept NUREG/CR-6728, October.

Table 8-1
WUS Soil Motion Durations

Rock UHS (10^{-4})	Magnitude	Distance (km)	Durations (5 to 75%) (sec)		
			Input	Match	Target
1 Hz	6.7	18	000(H1) 6.20	13.99	3.6 - 8.2
			090(H2) 8.01	14.82	3.6 - 8.2
			up 7.54	12.48	3.6 - 8.2
RECORDS SELECTED					
Target **M**	Earthquake	**M**	Site	Distance (km)	Site Condition
6.7	Loma Prieta	6.9	USGS, WAHO	18.1	Soil
PEAK PARTICLE RATIOS					
Component	PGV/PGA (cm/sec/g)	Bin Median PGV/PGA (cm/sec/g)		PGA•PGD/ PGV^2	Bin Median PGA•PGD/PGV^2
H1	175.0	78.8		2.6	3.1
H2	183.0	78.8		2.6	3.1
V	113.0	----		4.0	----
ABSOLUTE CROSS CORRELATIONS					
Component	Cross Correlation				
H1 H2	0.01				
H1 V	0.04				
H2 V	0.02				

Table 8-2
CEUS Soil Motion Durations

Rock UHS (10^{-4})	Magnitude	Distance (km)	Durations (5 to 75%) (sec)		
			Input	Match	Target
1 Hz	7.2	130	310(H1) 22.23	26.00	16.2 - 36.5
			220(H2) 24.33	28.48	16.2 - 36.5
			up 23.75	23.76	16.2 - 36.5
RECORDS SELECTED					
Target **M**	Earthquake	**M**	Site	Distance (km)	Site Condition
7.2	Landers	7.2	CDMG 90094 Jaboneria	153.9	Soil
PEAK PARTICLE RATIOS					
Component	PGV/PGA (cm/sec/g)	Bin Median PGV/PGA (cm/sec/g)		PGA•PGD/ PGV^2	Bin Median PGA•PGD/PGV^2
H1	47.0	224.8		7.5	3.0
H2	47.0	224.8		6.8	3.0
V	22.7	----		13.9	----
ABSOLUTE CROSS CORRELATIONS					
Component	Cross Correlation				
H1 H2	0.01				
H1 V	0.04				
H2 V	0.03				

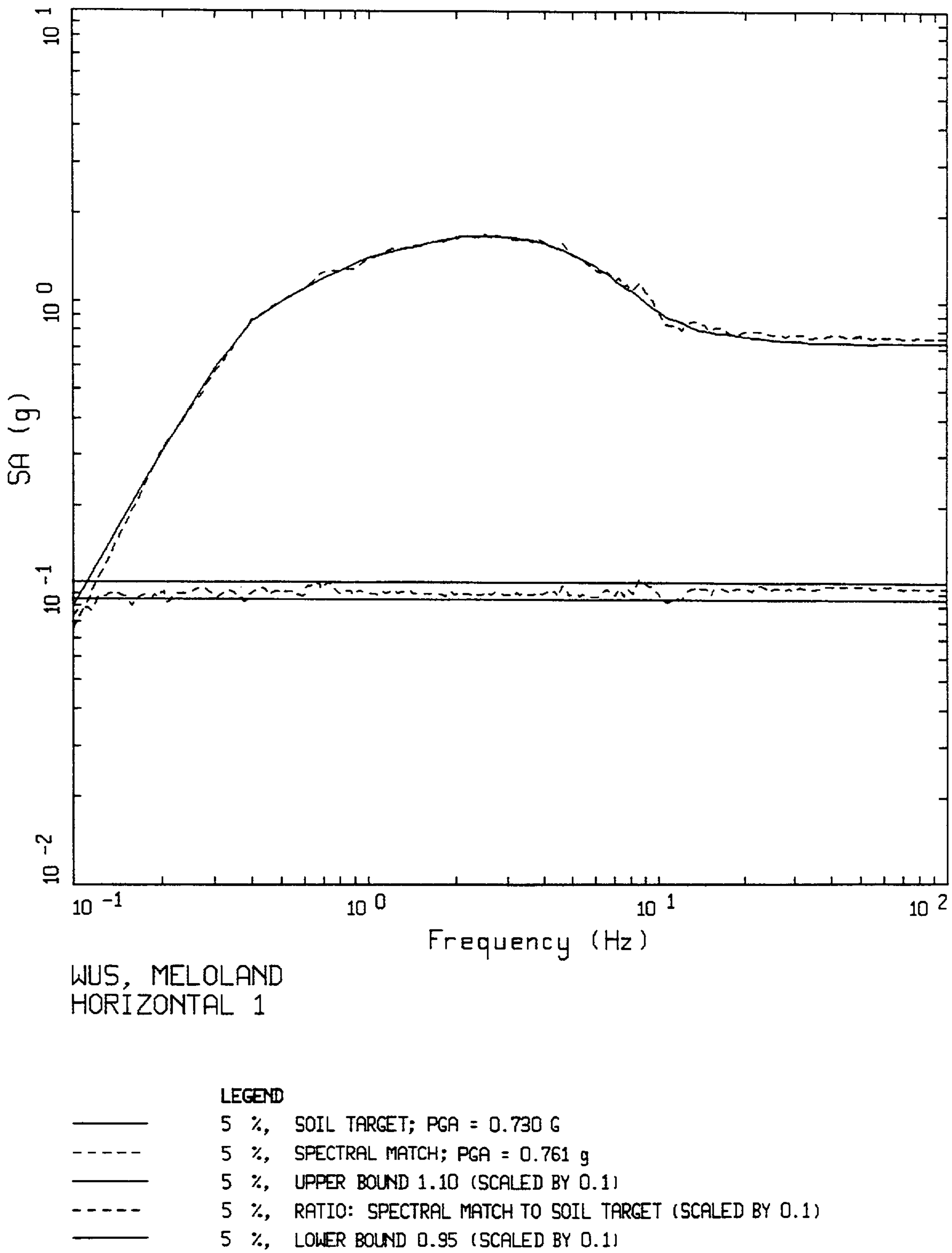


Figure 8-1. Target spectrum, spectral match and spectral ratio, component H1, Mojave site, soil.

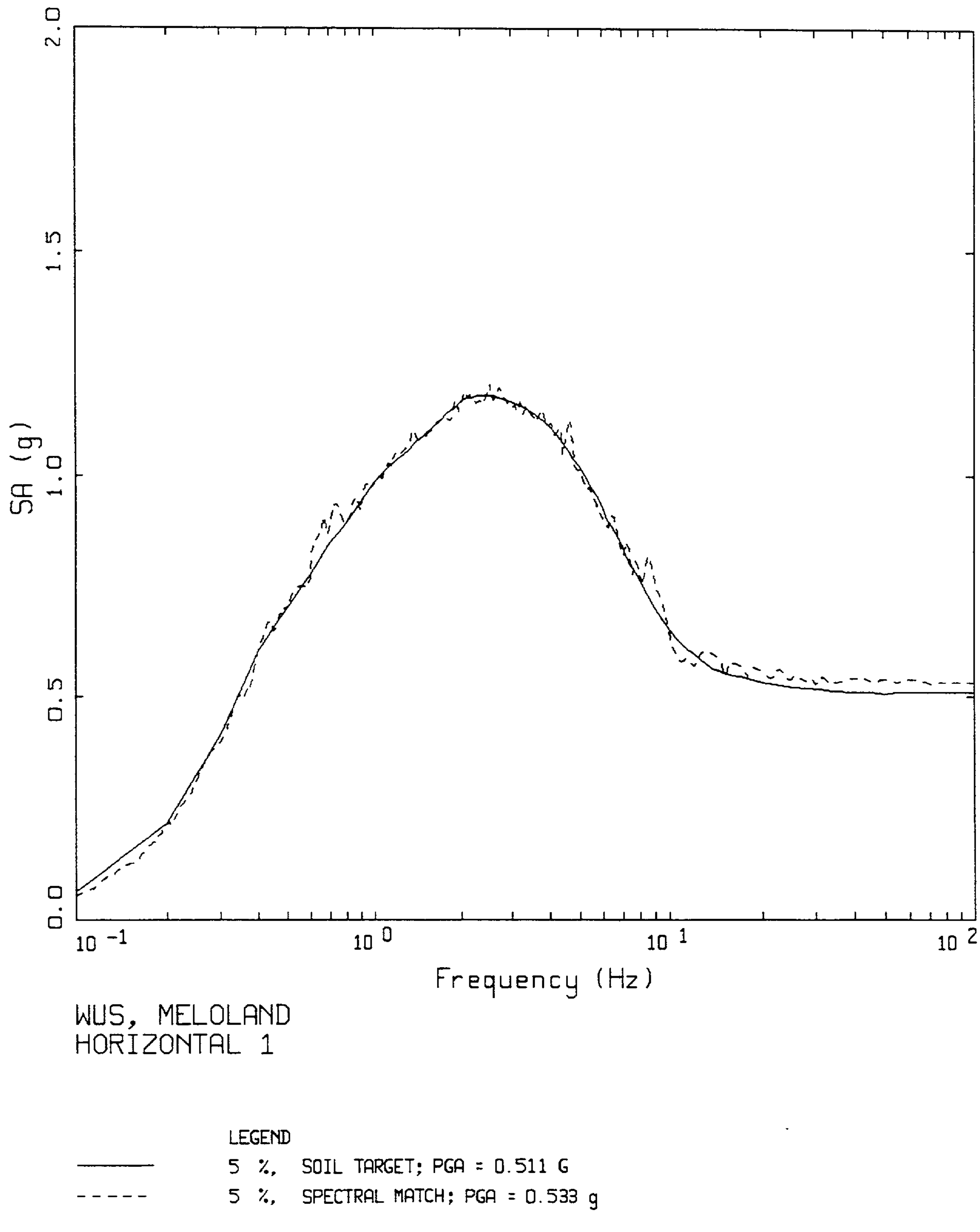


Figure 8-2. Target spectrum and spectral match on linear scale, component H1, Mojave site, soil.

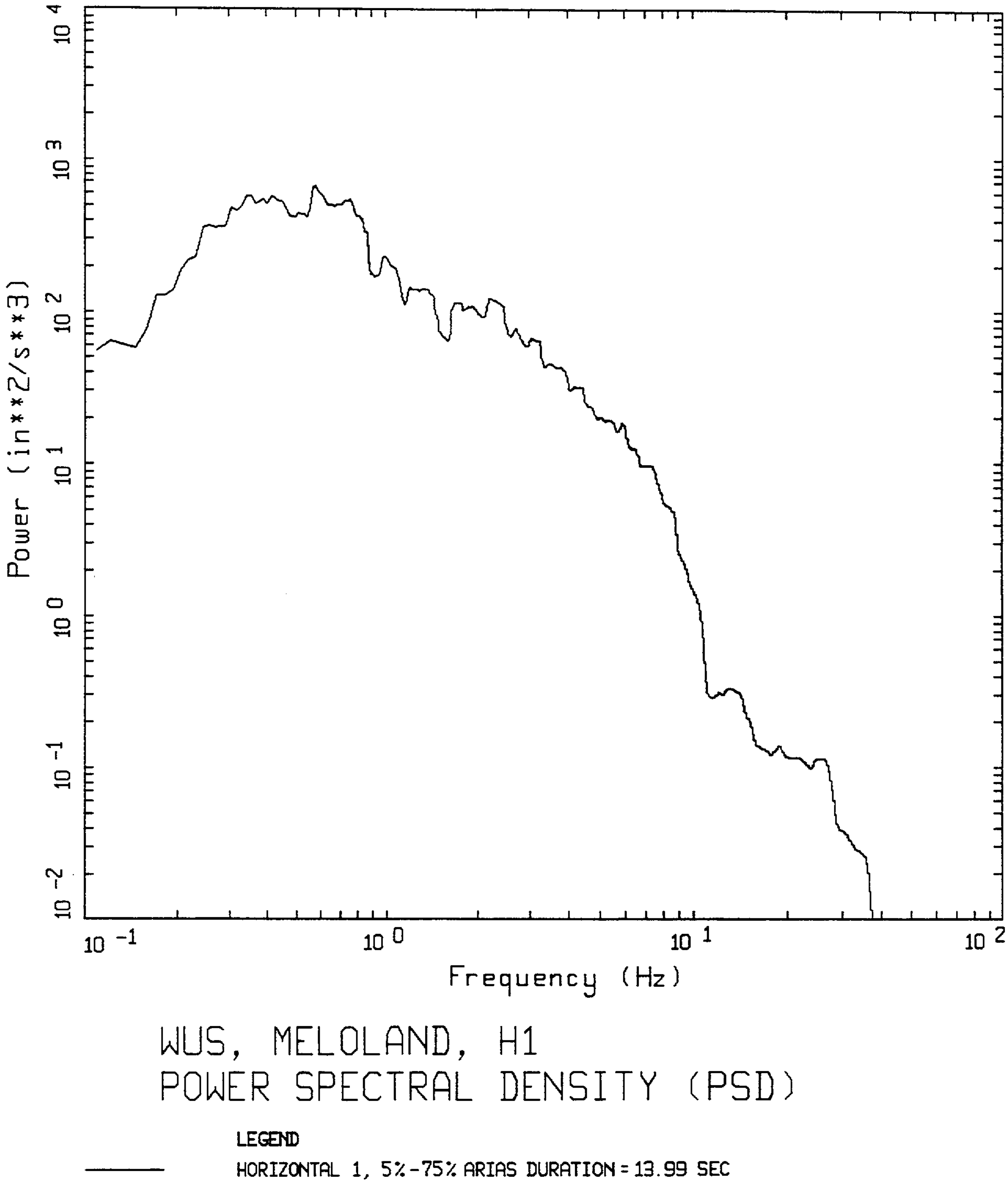


Figure 8-3. Power spectral density for component H1, Mojave site, soil.

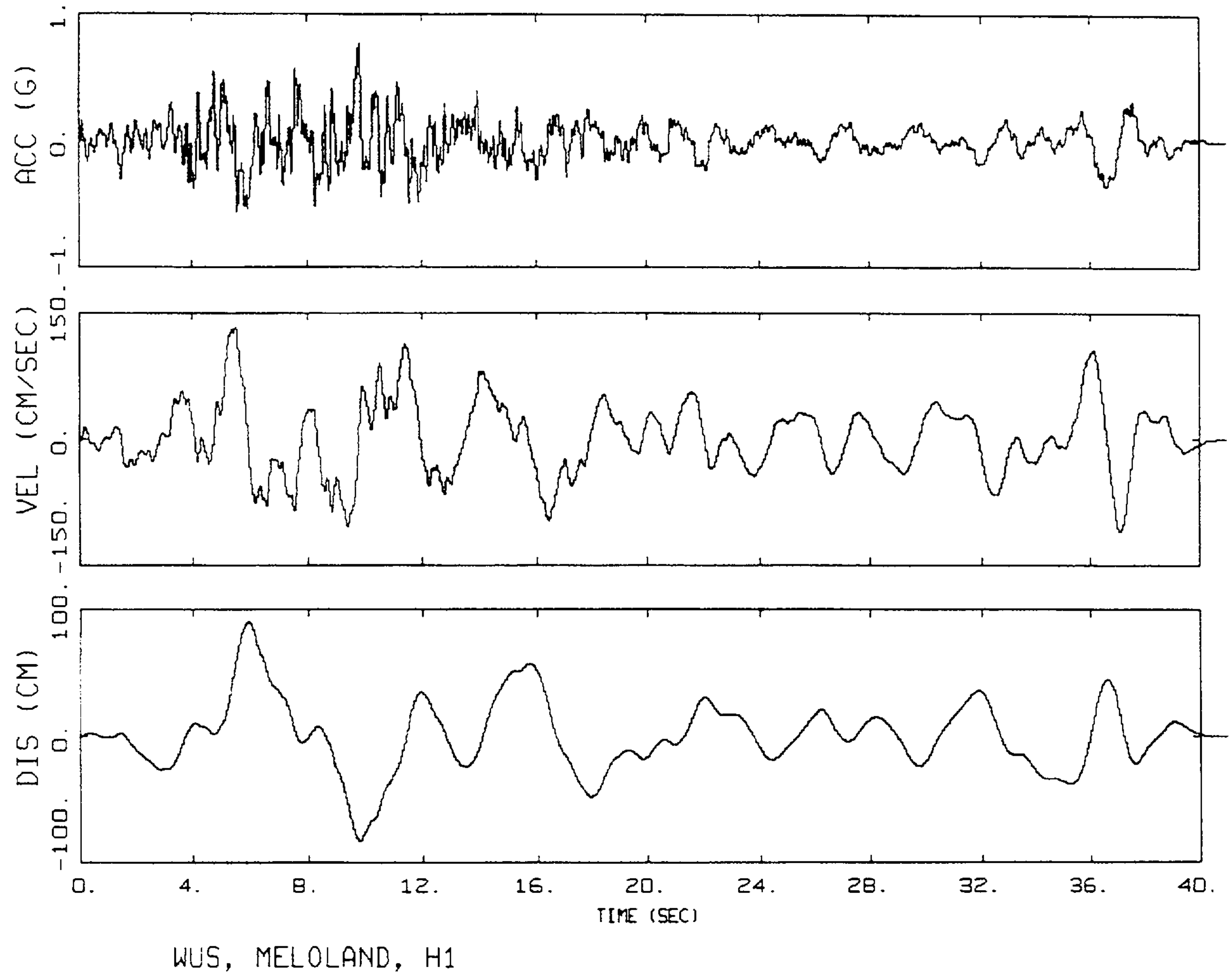


Figure 8-4. Time histories for component H1, Mojave site, soil.

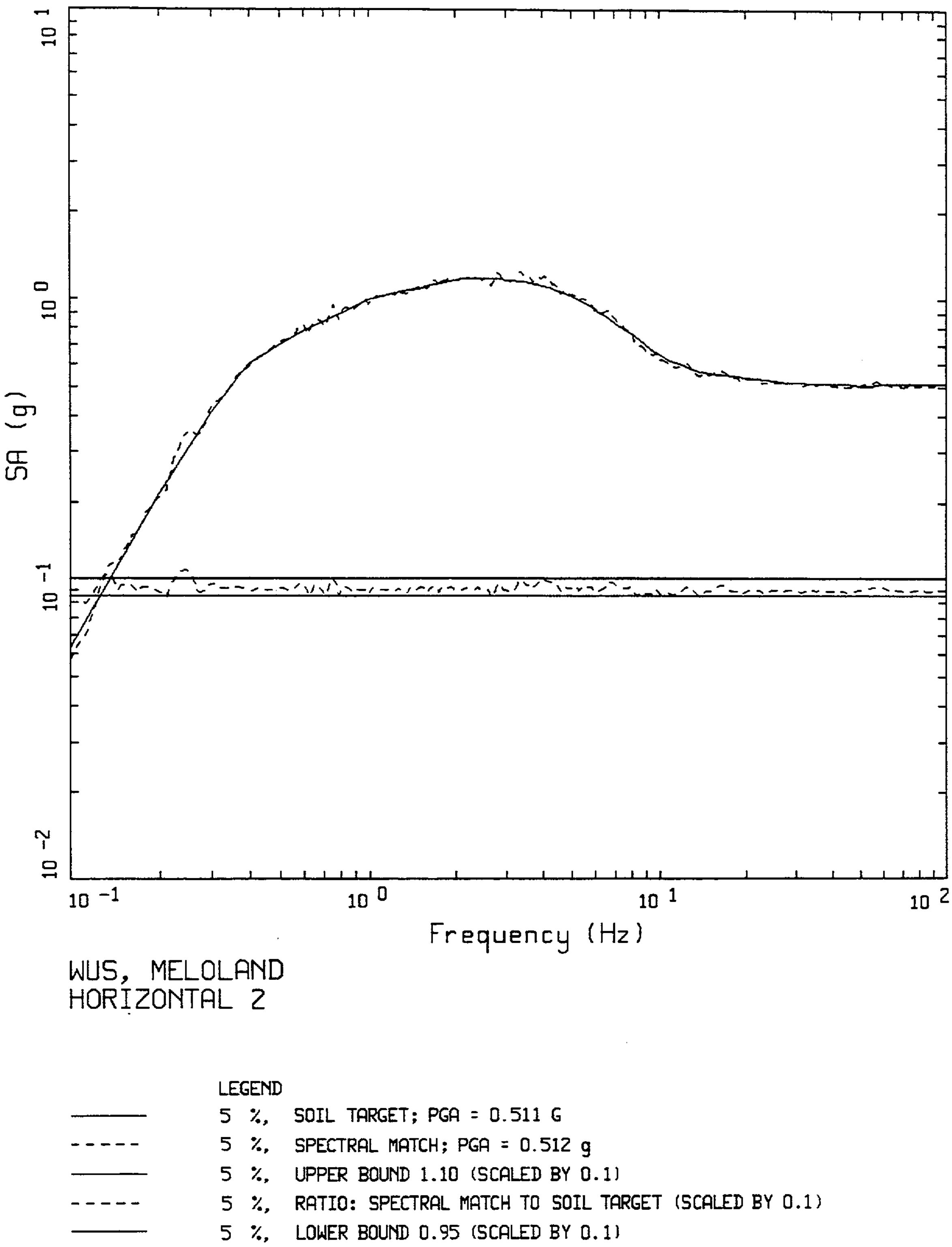


Figure 8-5. Target spectrum, spectral match and spectral ratio, component H2, Mojave site, soil.

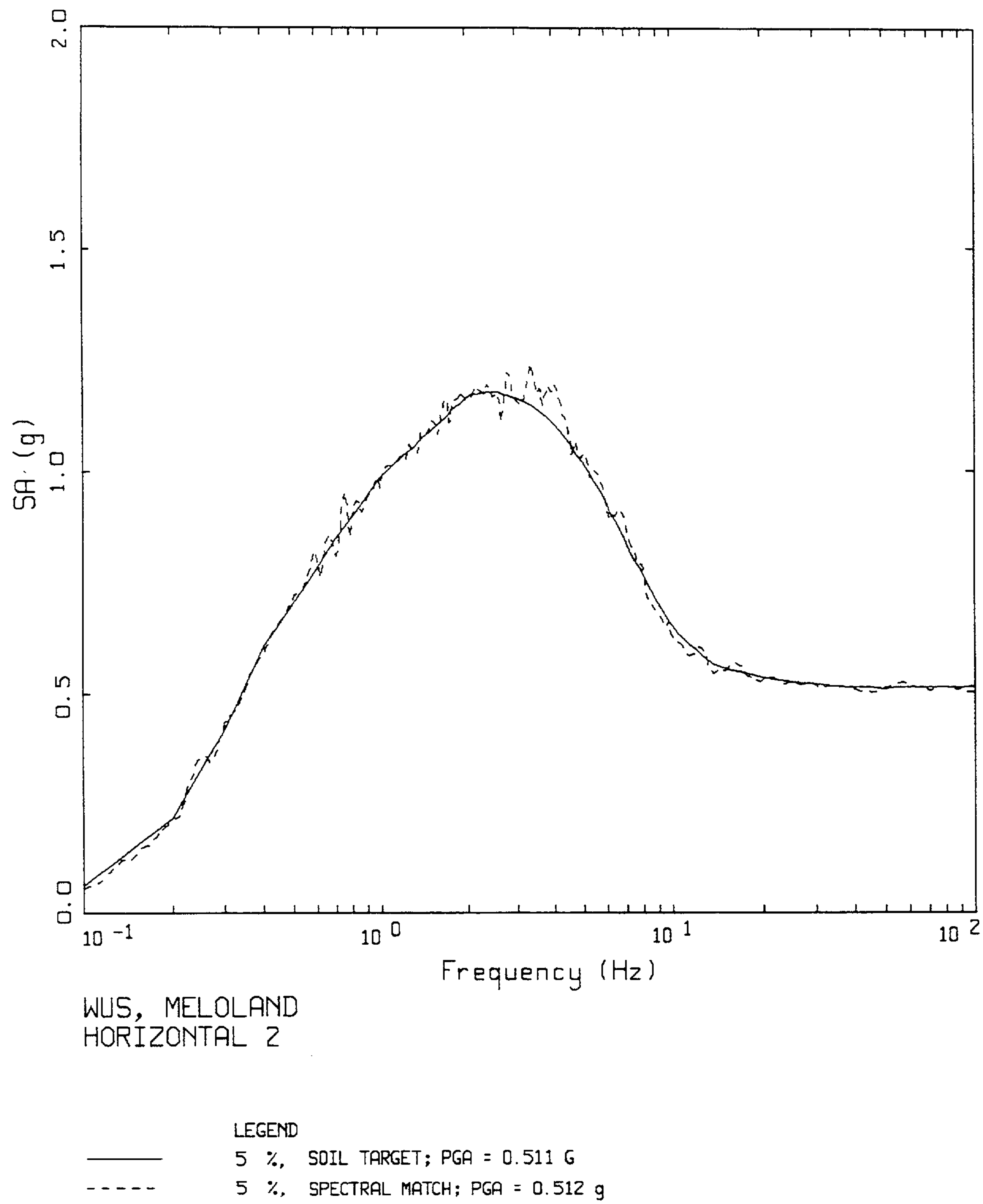


Figure 8-6. Target spectrum and spectral match on linear scale, component H2, Mojave site, soil.

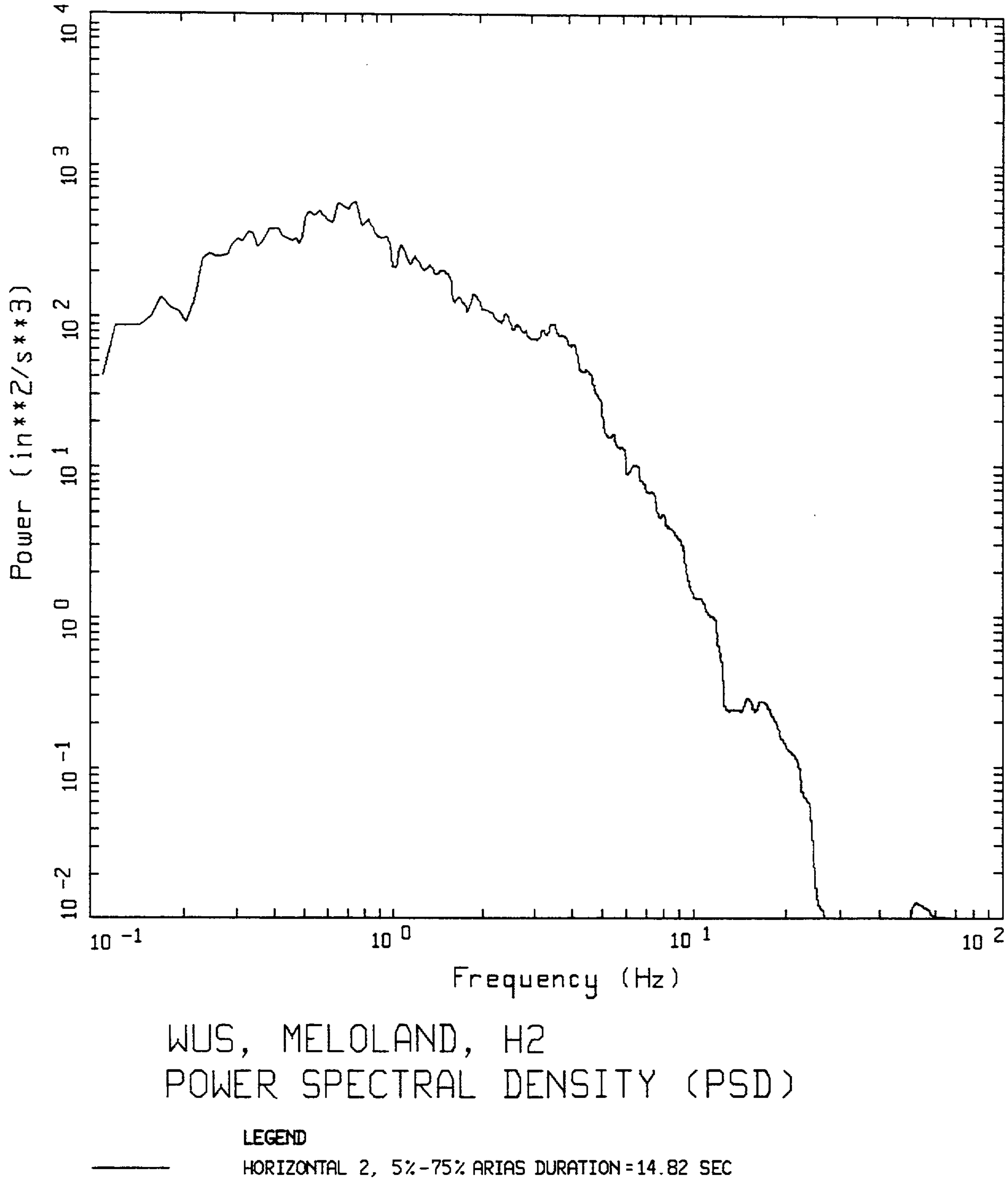


Figure 8-7. Power spectral density for component H2, Mojave site, soil.

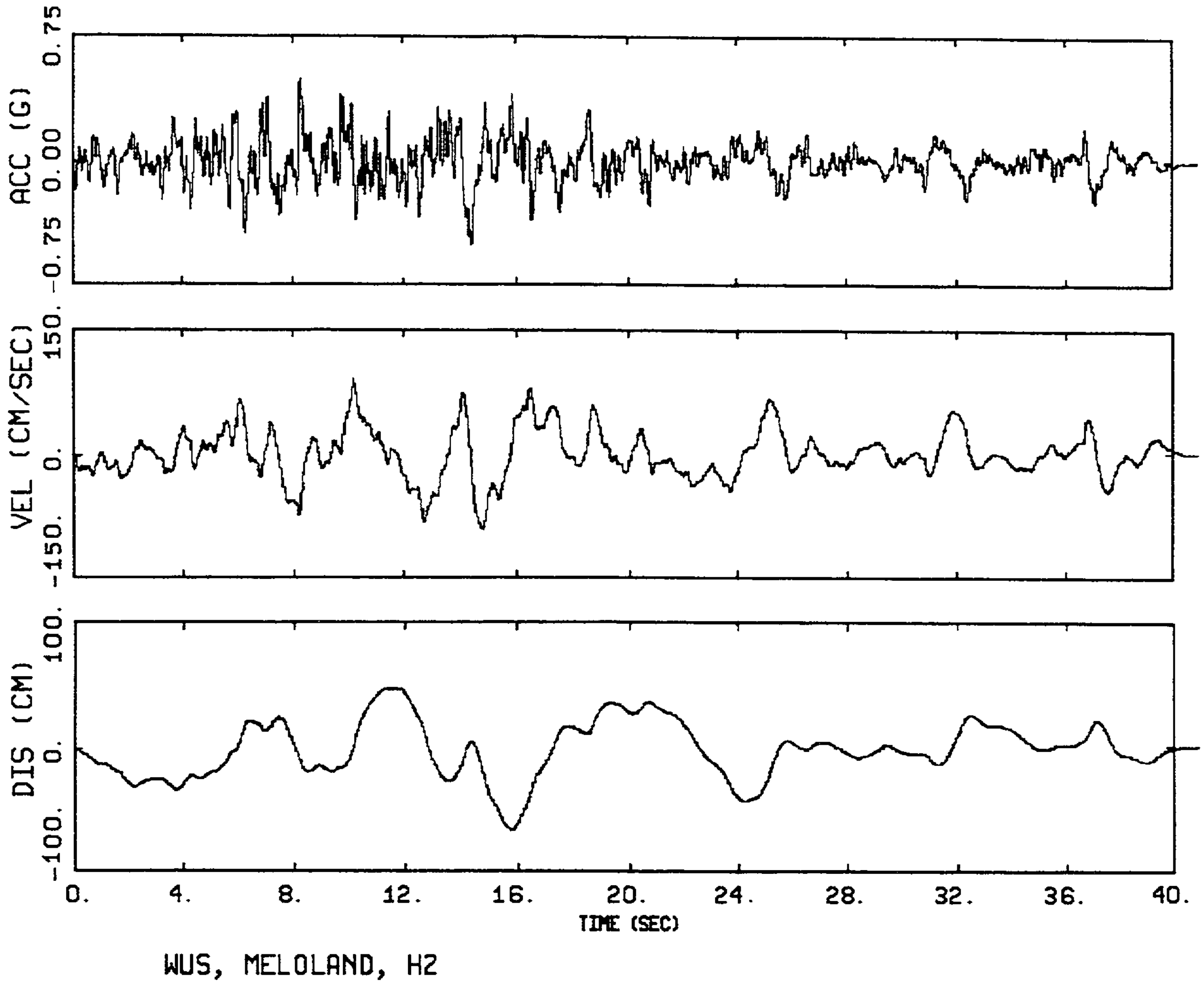
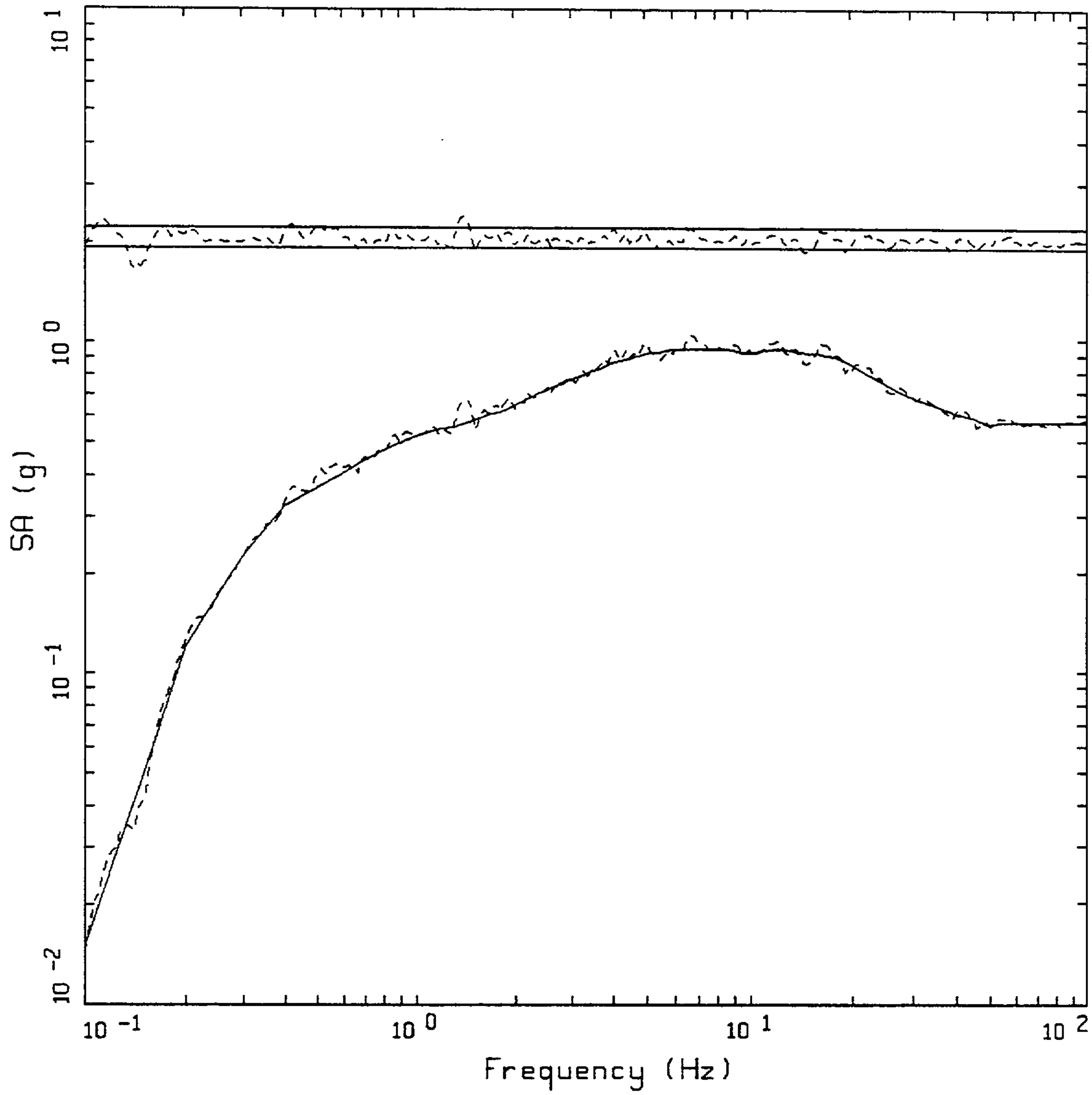


Figure 8-8. Time histories for component H2, Mojave site, soil.



WUS, MELOLAND
VERTICAL

LEGEND

———	5 %, SOIL TARGET; PGA = 0.568 G
- - - - -	5 %, SPECTRAL MATCH; PGA = 0.598 g
———	5 %, UPPER BOUND 1.10 (SCALED BY 2.0)
- - - - -	5 %, RATIO: SPECTRAL MATCH TO SOIL TARGET (SCALED BY 2.0)
———	5 %, LOWER BOUND 0.95 (SCALED BY 2.0)

Figure 8-9. Target spectrum, spectral match and spectral ratio, component V, Mojave site, soil.

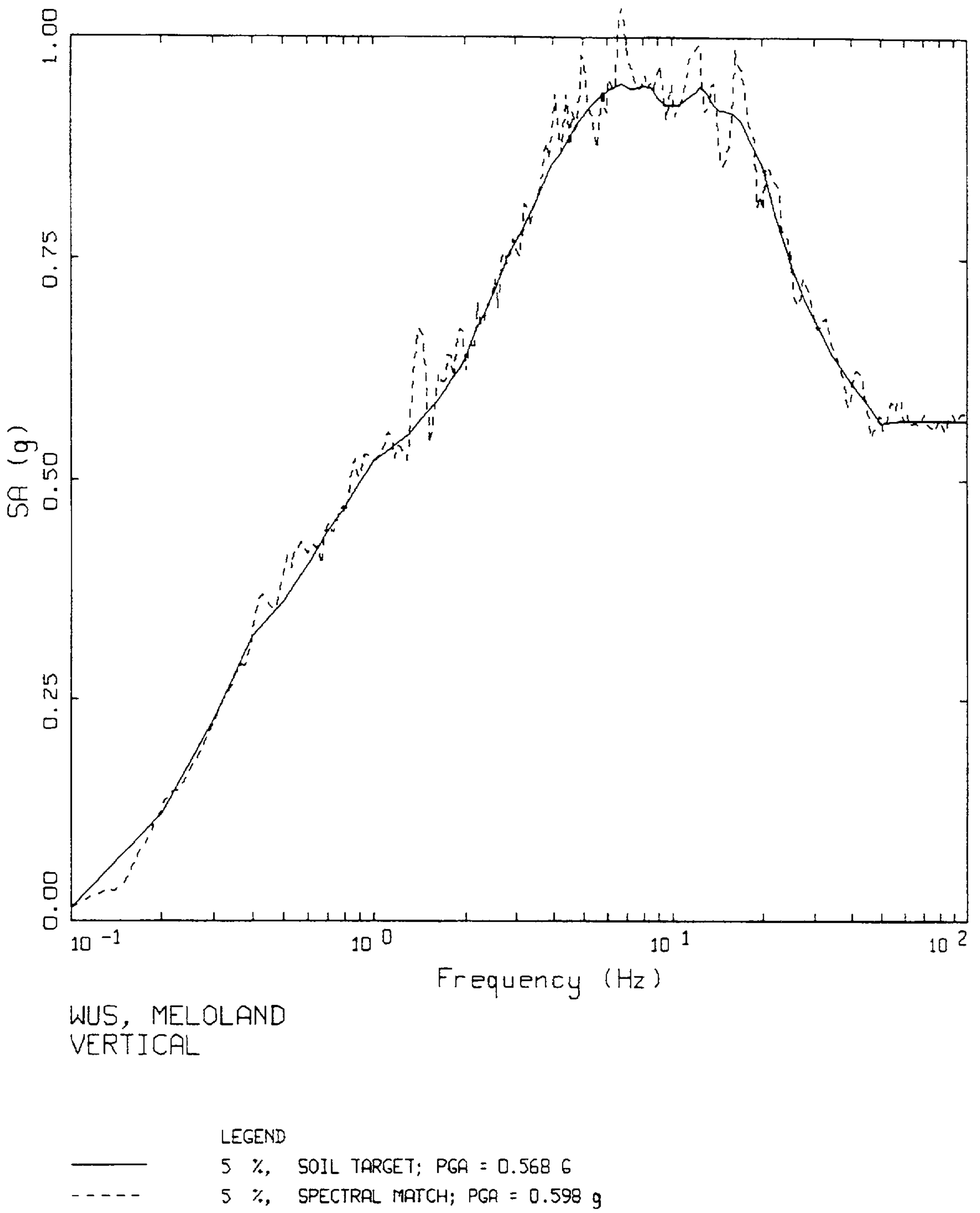


Figure 8-10. Target spectrum and spectral match on linear scale, component V, Mojave site, soil.

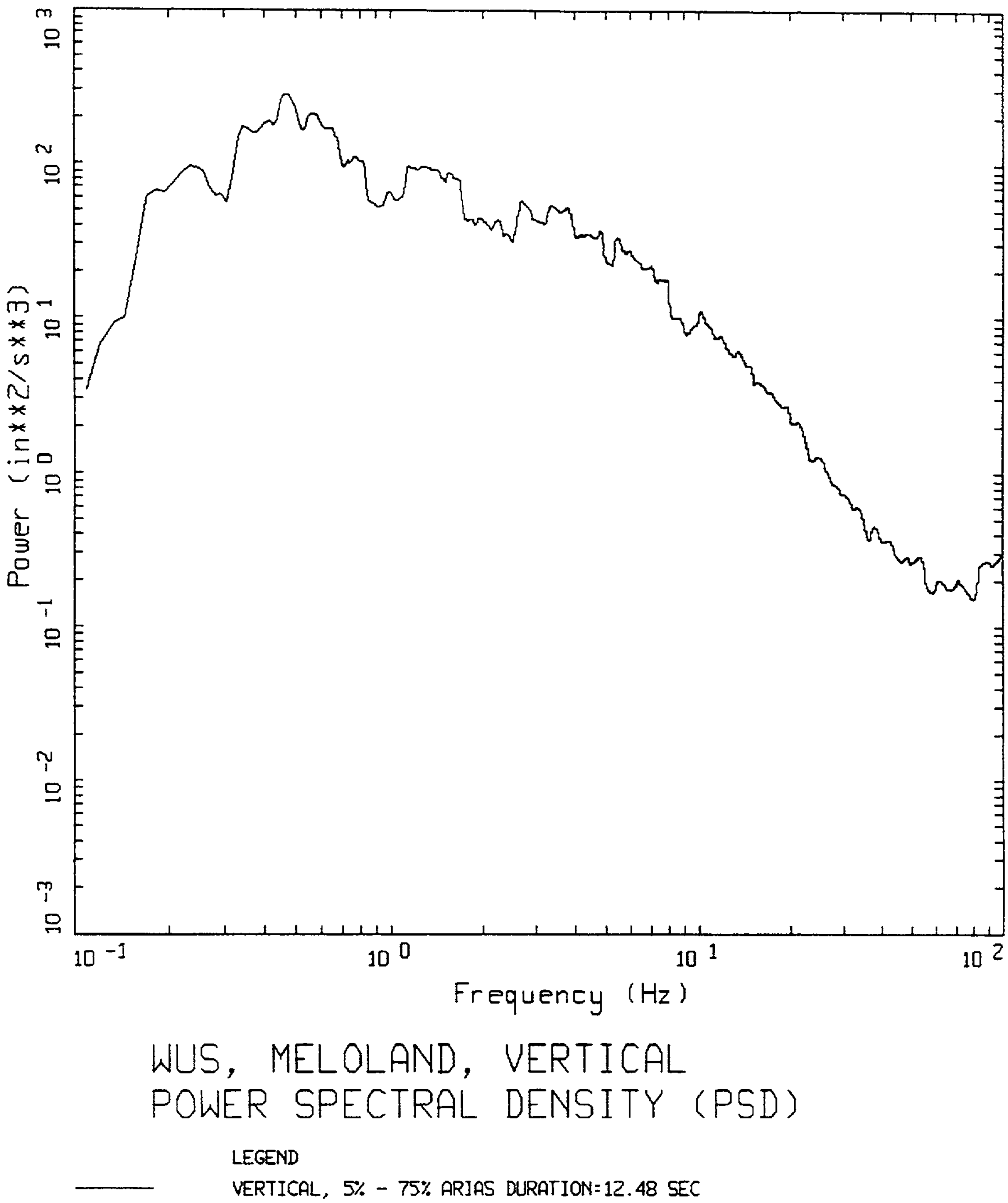


Figure 8-11. Power spectral density for component V, Mojave site, soil.

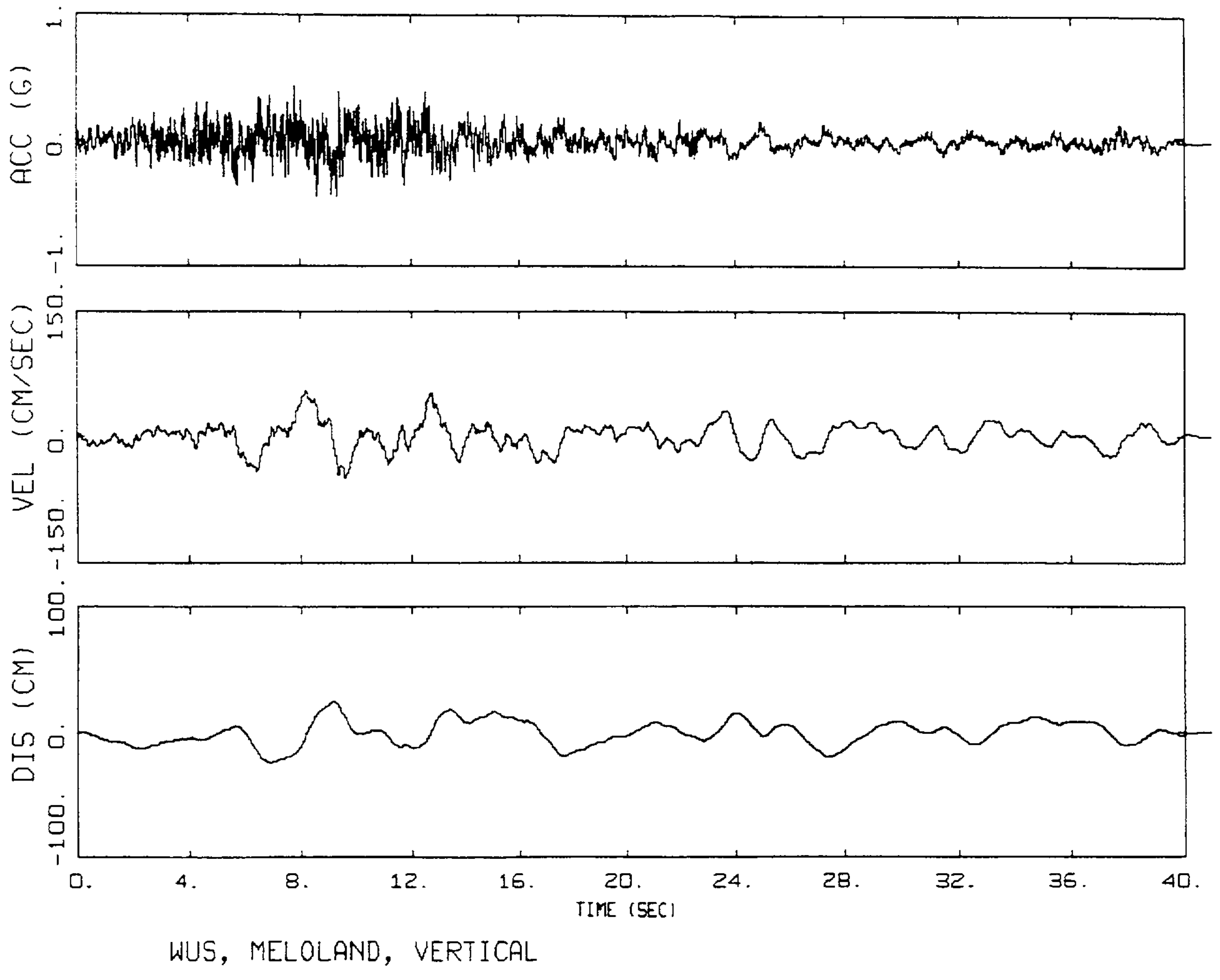


Figure 8-12. Time histories for component V, Mojave site, soil.

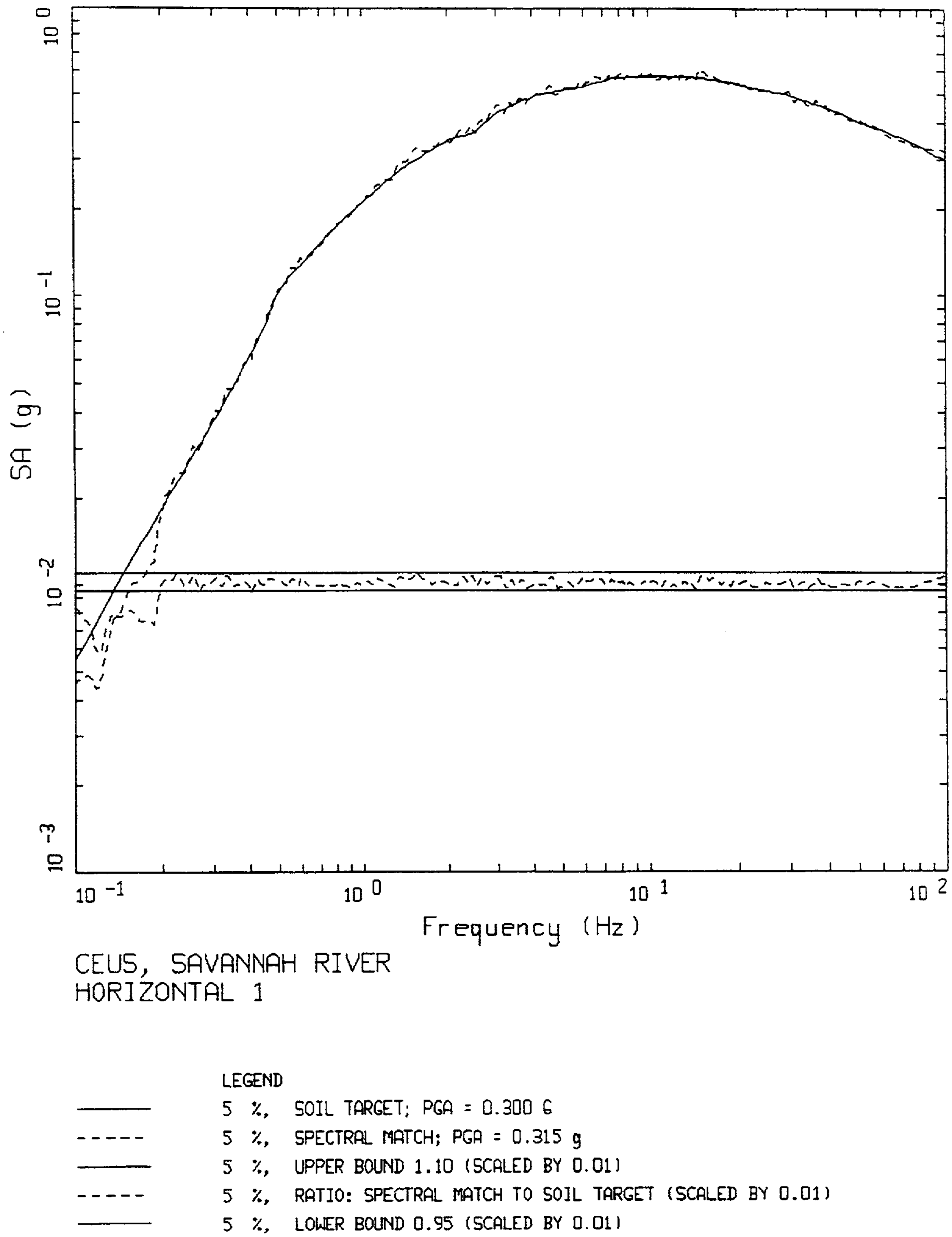


Figure 8-13. Target spectrum, spectral match and spectral ratio, component H1, Columbia site, soil.

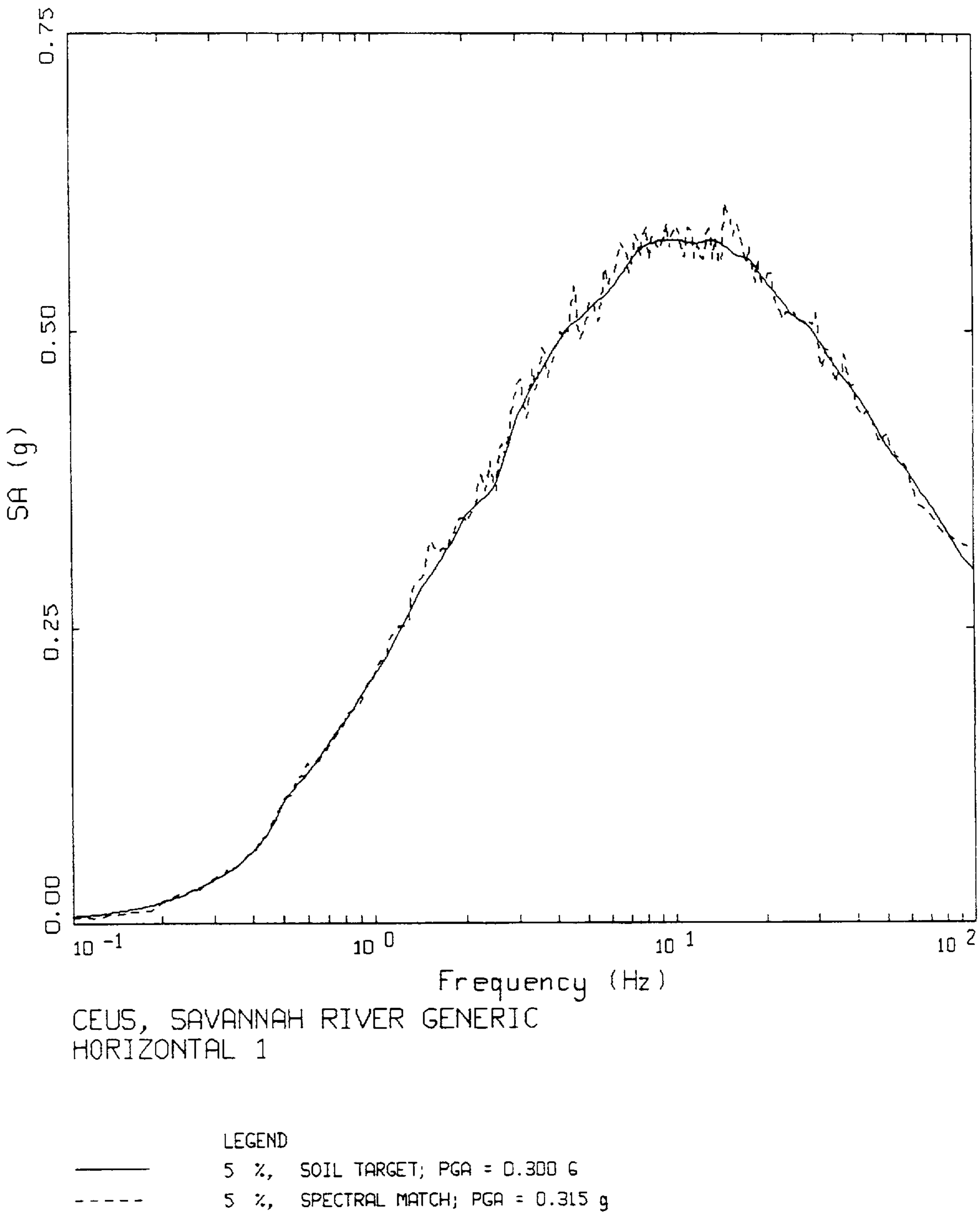


Figure 8-14. Target spectrum and spectral match on linear scale, component H1, Columbia site, soil.

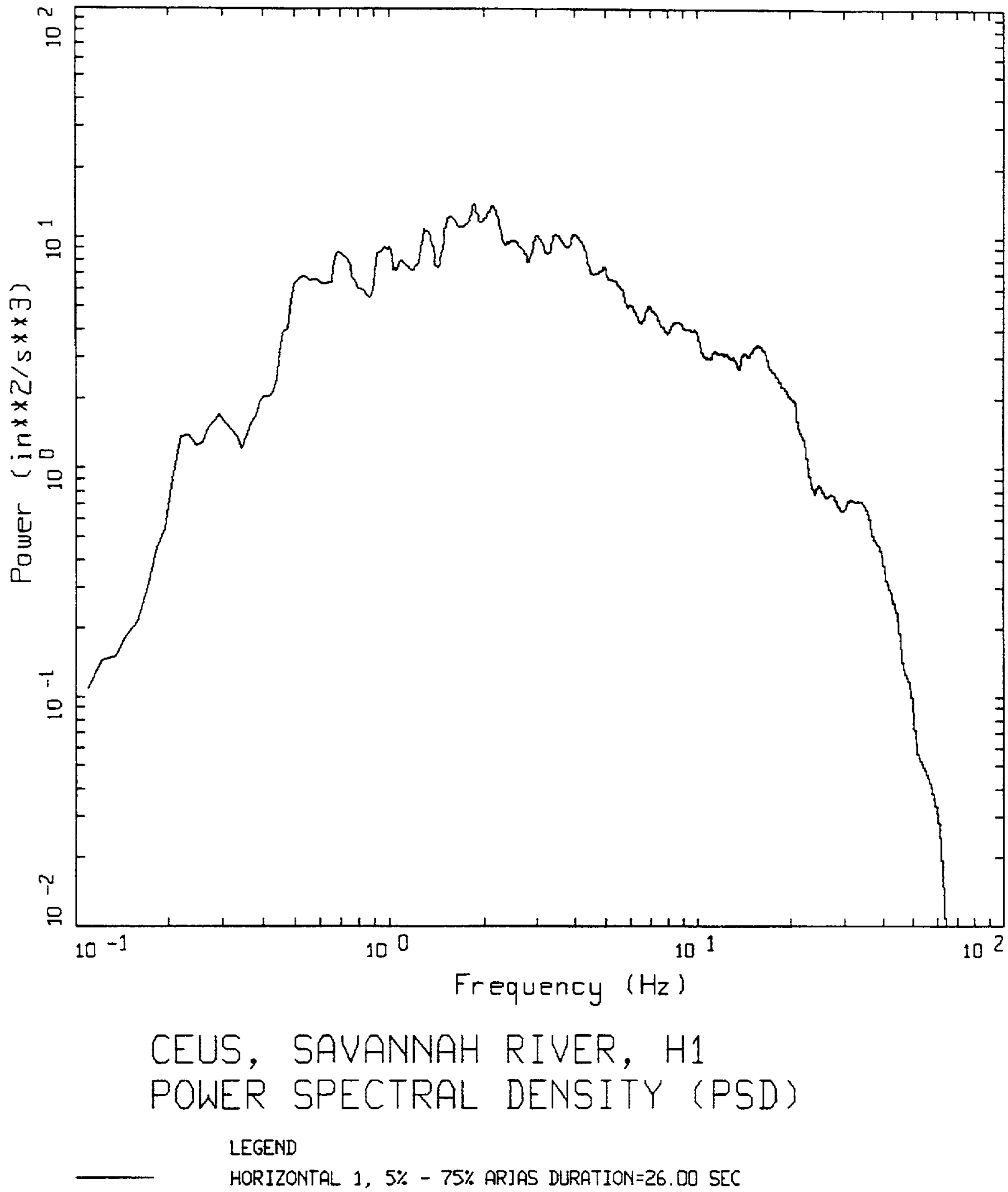


Figure 8-15. Power spectral density for component H1, Columbia site, soil.

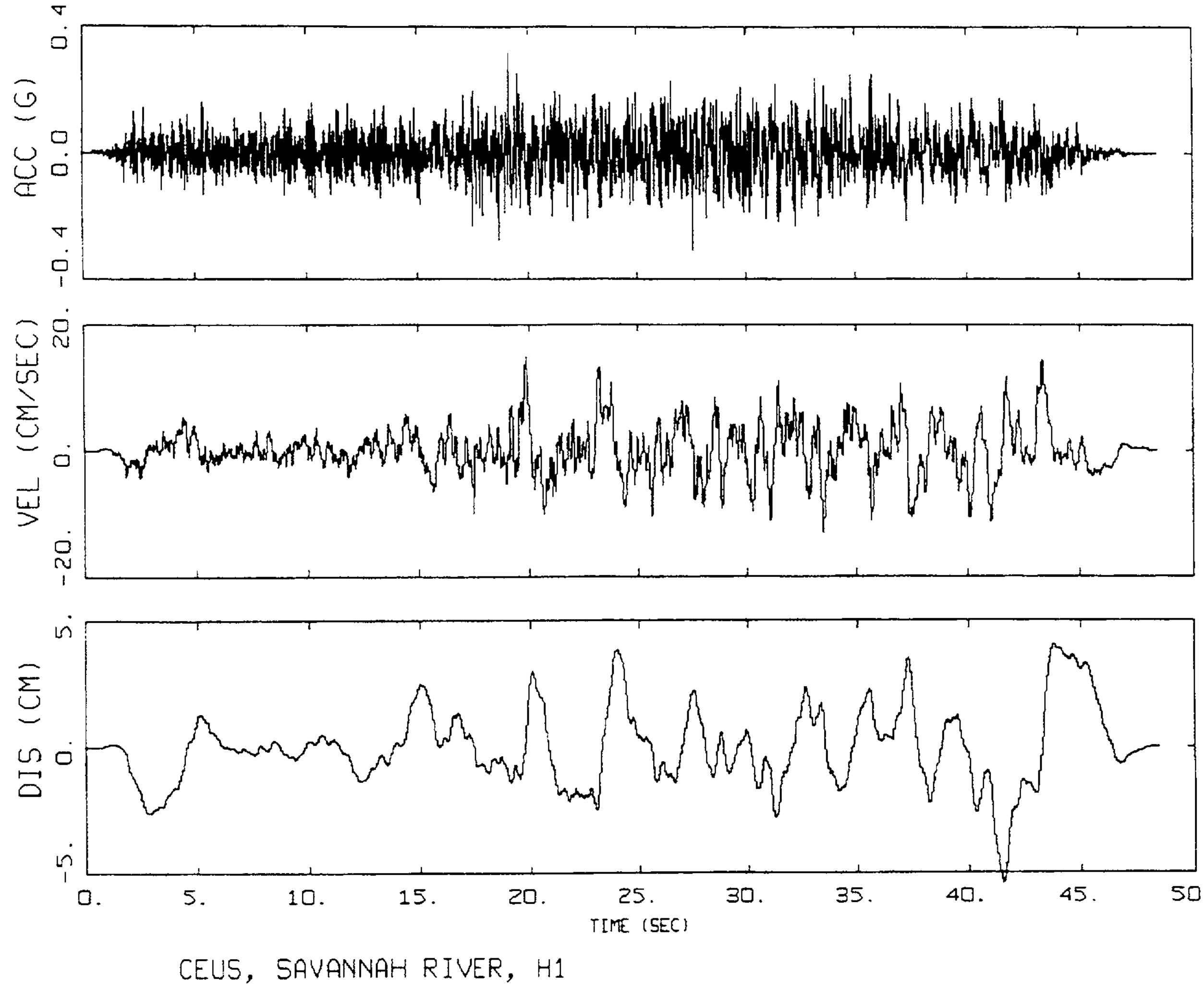


Figure 8-16. Time histories for component H1, Columbia site, soil.

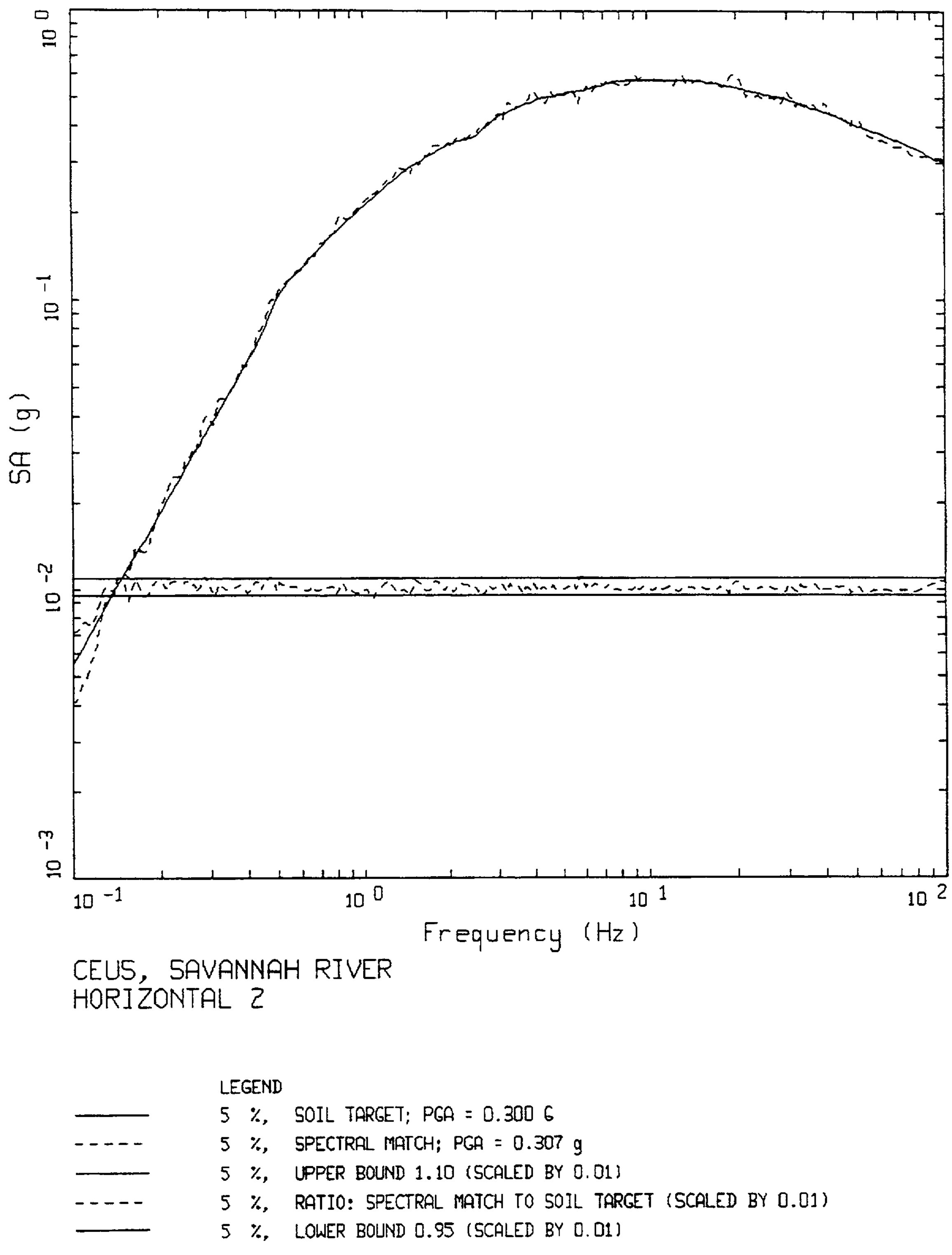


Figure 8-17. Target spectrum, spectral match and spectral ratio, component H2, Columbia site, soil.

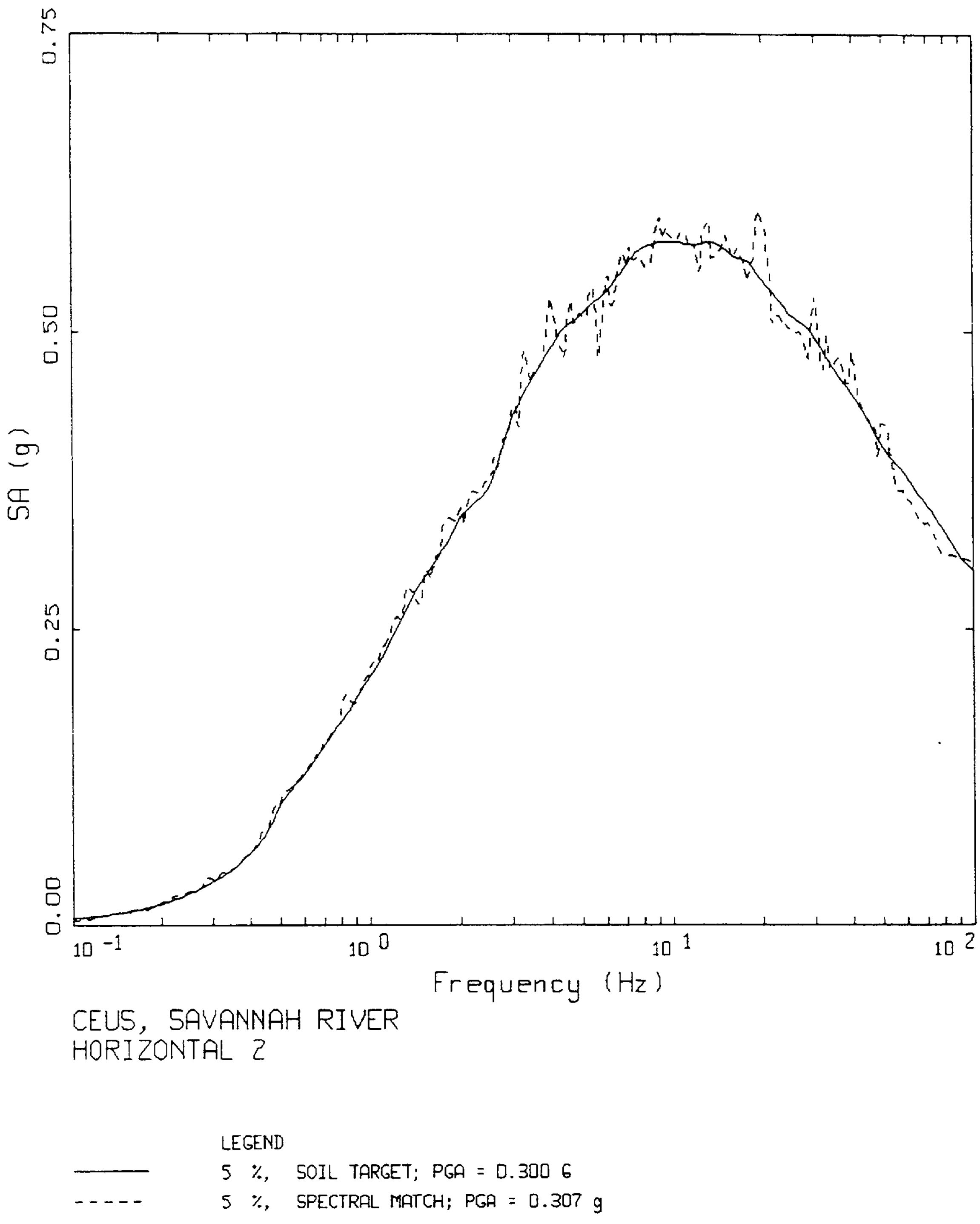


Figure 8-18. Target spectrum and spectral match on linear scale, component H2, Columbia site, soil.

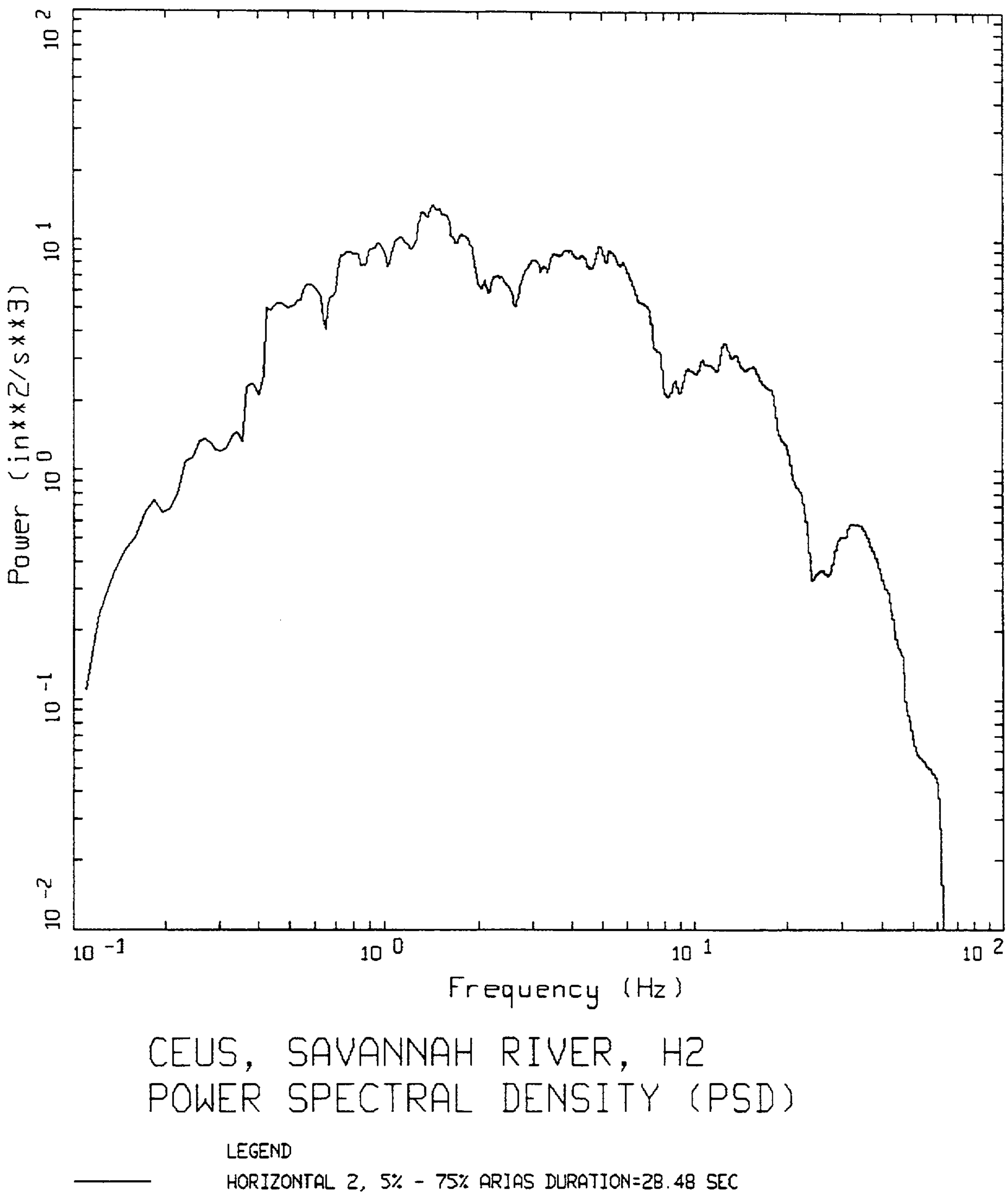


Figure 8-19. Power spectral density for component H2, Columbia site, soil.

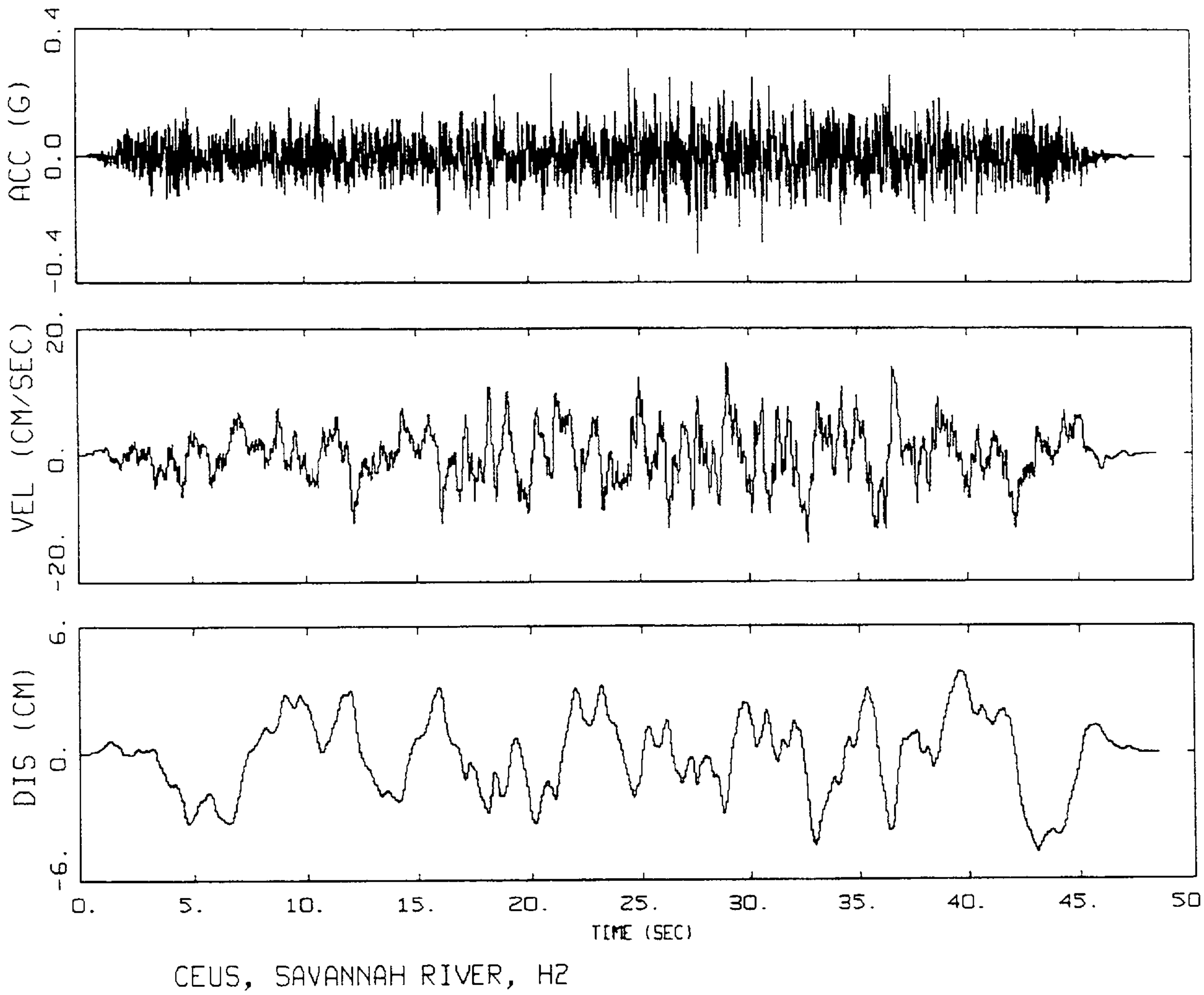


Figure 8-20. Time histories for component H2, Columbia site, soil.

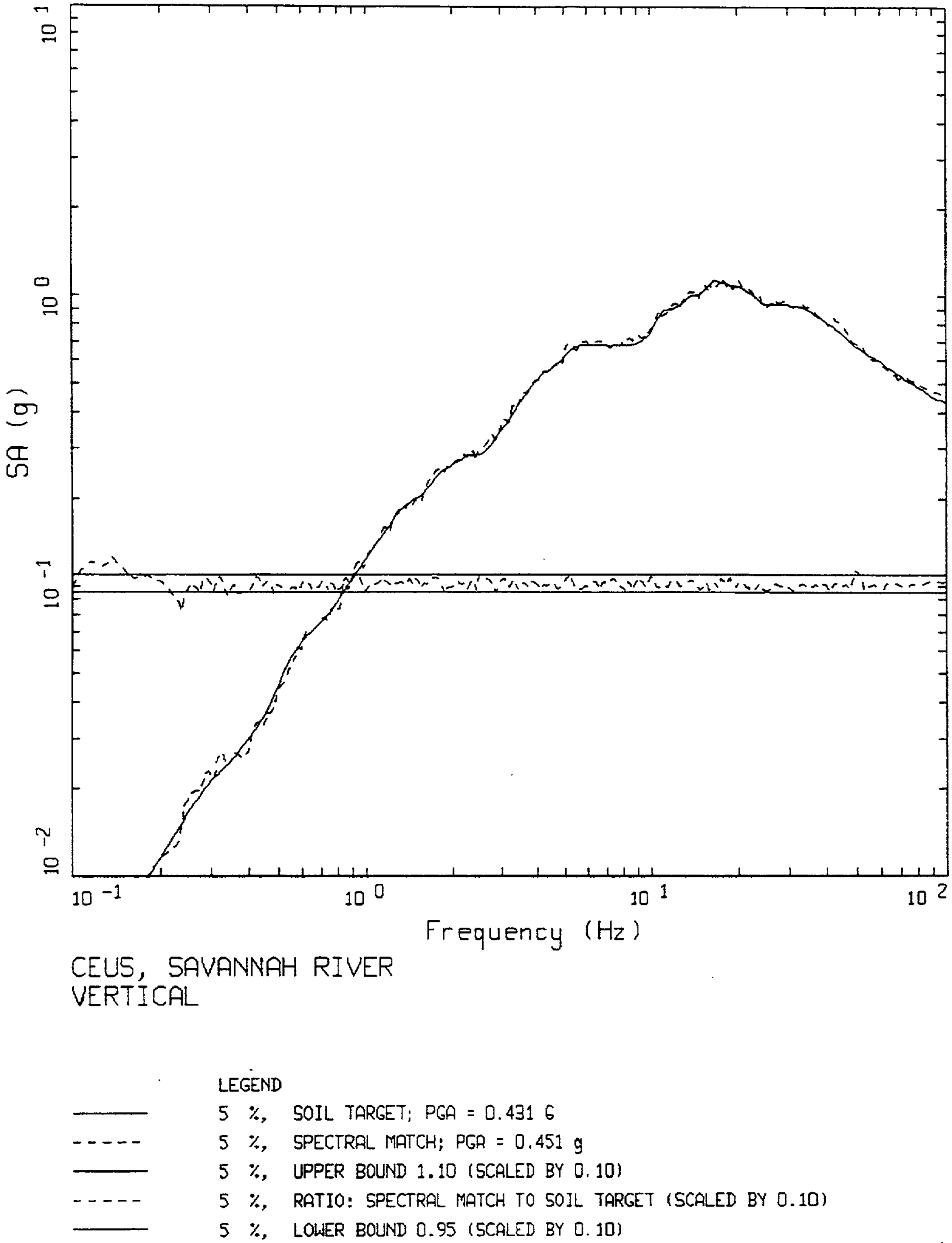
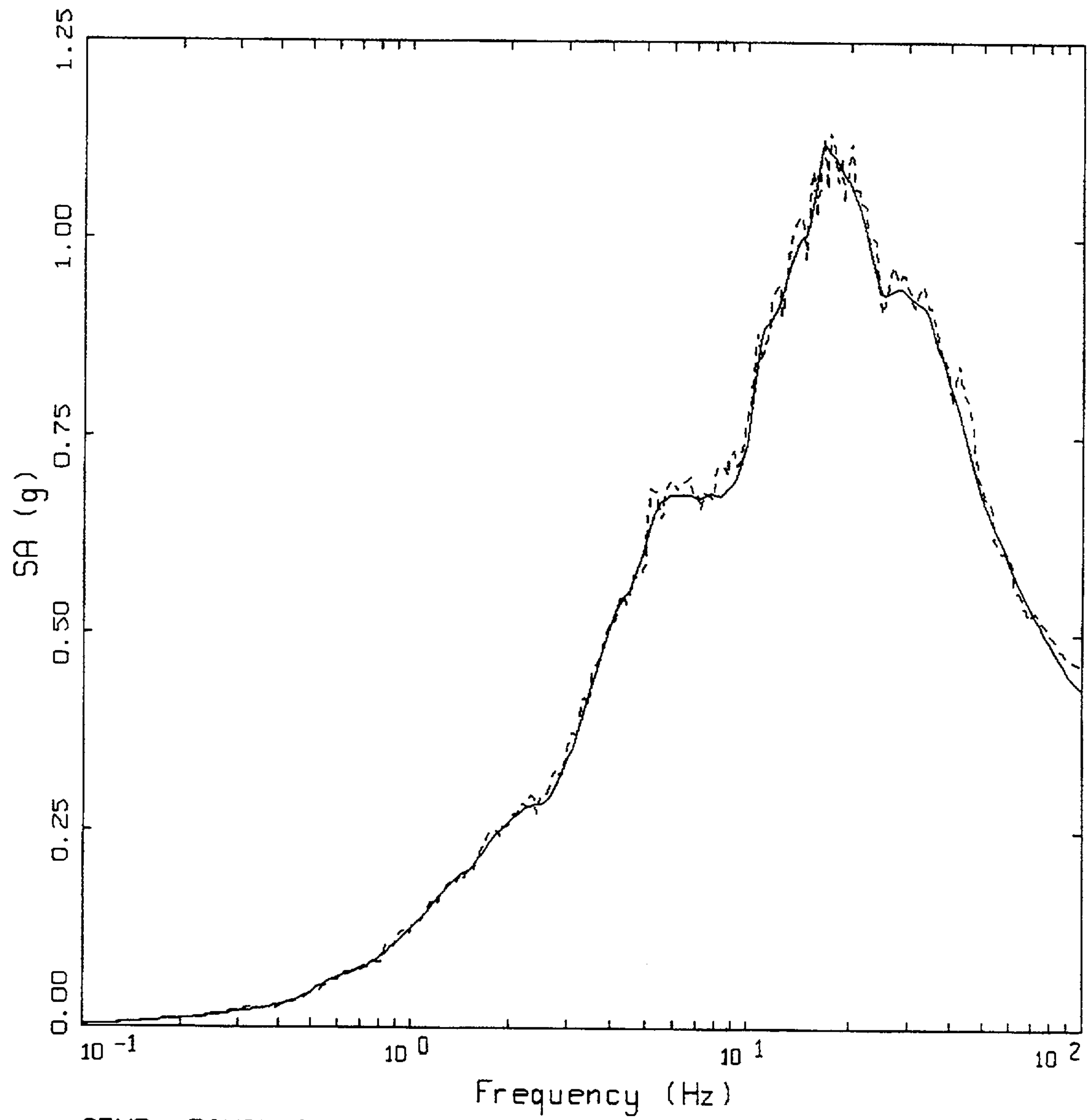


Figure 8-21. Target spectrum, spectral match and spectral ratio, component V, Columbia site, soil.



CEUS, SAVANNAH RIVER
VERTICAL

LEGEND

5 %, SOIL TARGET; PGA = 0.431 G

5 %, SPECTRAL MATCH; PGA = 0.451 g

Figure 8-22. Target spectrum and spectral match on linear scale, component V, Columbia site, soil.

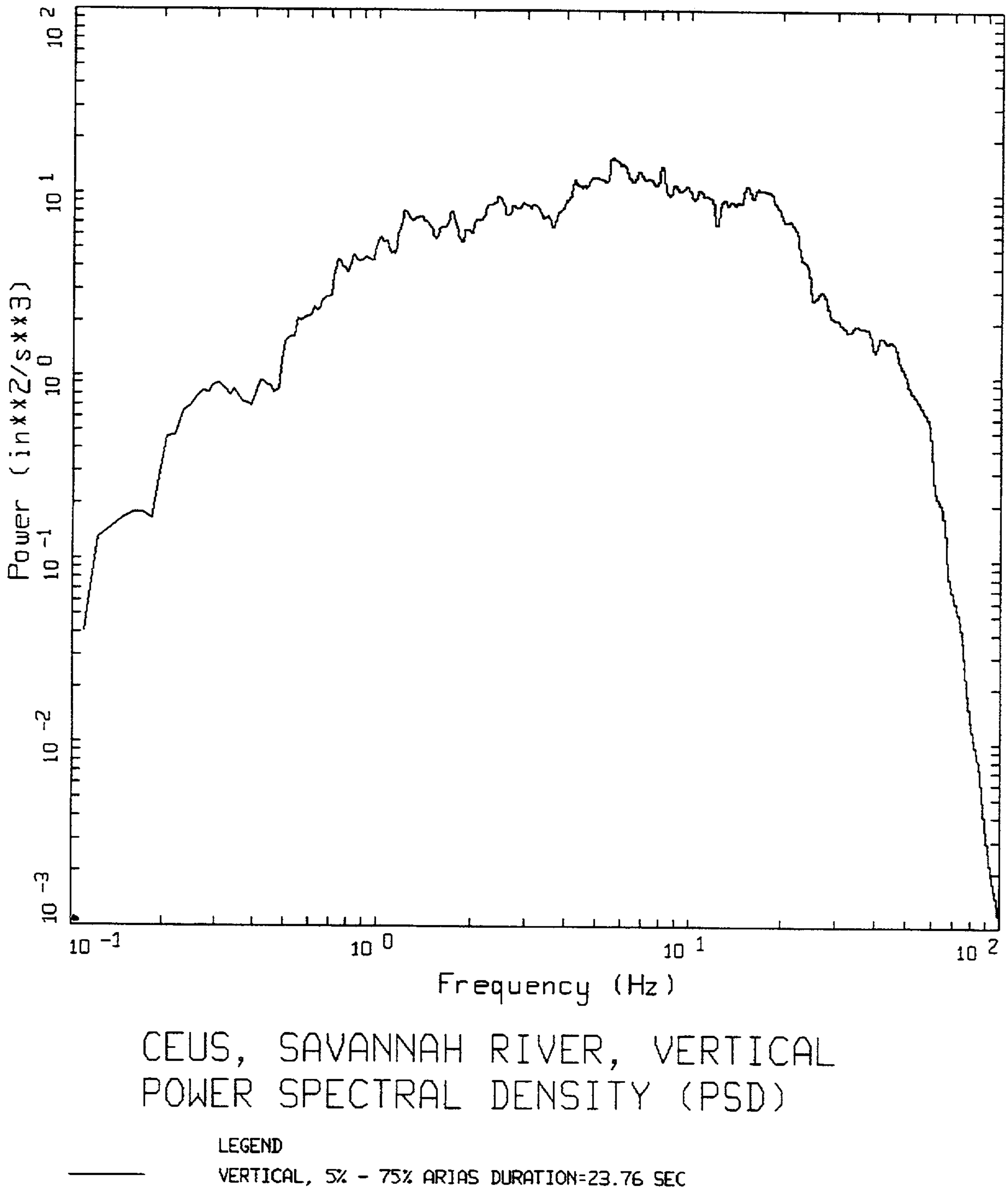


Figure 8-23. Power spectral density for component V, Columbia site, soil.

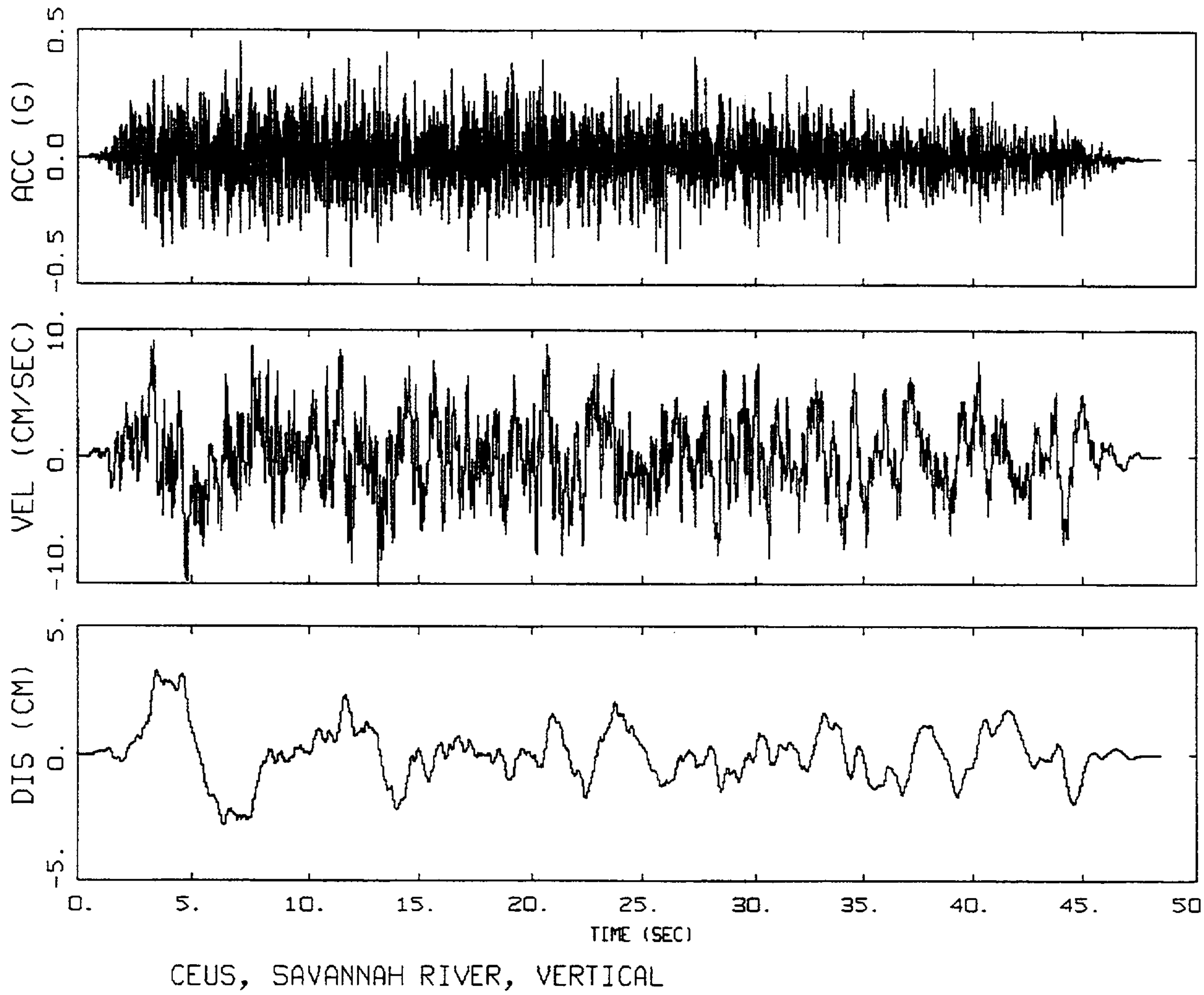


Figure 8-24. Time histories for component V, Columbia site, soil.

9.0 SUMMARY OF RECOMMENDATIONS

This section summarizes recommendations on developing seismic ground motion spectra appropriate for use in designing or evaluating nuclear facilities at any location in the US. This summarizes the work reported herein and in McGuire et al., (2001). The procedure for deriving ground motion spectra for rock sites is summarized in Figure 1-1, and for soil sites is summarized in Figure 1-2.

9.1 Rock sites

Probabilistic seismic hazard analysis

Developing seismic ground motions starts with a probabilistic seismic hazard analysis (PSHA) conducted with up-to-date interpretations of earthquake sources, earthquake recurrence, and strong ground motion estimation, using methods described in the SSHAC report (1997). Epistemic uncertainties must be characterized in a complete and defensible fashion. In particular for the CEUS, our understanding of single- and double-corner ground-motion models is evolving, and future PSHAs must fully document the appropriateness of using either or both of these models. A complete PSHA includes hazard for structural frequencies from 100 Hz to 0.2 Hz, and calculates results for annual frequencies of exceedence from 10^{-2} to 10^{-5}. The PSHA must be conducted at a minimum of 25 frequencies, approximately equally spaced on a logarithmic frequency axis between 100 and 0.2 Hz.

The PSHA must deaggregate the mean seismic hazard by **M** and R to determine the relative contributions to hazard, at 10 Hz and at 1 Hz. Assuming that 10^{-4} is the target hazard level for design, this deaggregation must be done at 10^{-4}. If multiple attenuation equations have been used to characterize epistemic uncertainties, the deaggregation must be done with each attenuation equation weighted by the subjective probabilities that are justified and used in the PSHA.

The current (year 2001) procedure is to conduct the PSHA for horizontal ground motion and to develop vertical motions by scaling the the horizontal motions. This ensures that we derive vertical motions consistent with the horizontals. If defensible attenuation equations are developed for vertical motions, they may be used in a PSHA, but the vertical and horizontal design motions should be evaluated to determine that they are consistent.

Uniform hazard spectra (UHS) and uniform reliability spectrum (URS)

From the PSHA, we should derive the 10^{-4} and 10^{-5} mean uniform hazard spectra (UHS). From these spectra we determine the ratio $A_R(f)$ of the spectral amplitudes at each frequency f. That is,

$$A_R(f) = SA(f, 10^{-5})/SA(f, 10^{-4}) \quad (9\text{-}1)$$

where SA is spectral acceleration. An additional parameter used to characterize the slope is K_H, which is the negative slope of the hazard curve in log space. The two are related by

$$A_R = 10^{\frac{1}{K_H}} \quad or \quad K_H = \frac{1}{\log_{10} A_R}$$

We calculate the *uniform reliability spectrum* URS by multiplying the UHS at each frequency by a scale factor SF:

$$URS = UHS \times SF \tag{9-2}$$

The scale factor SF depends directly on two important policy/decision parameters:

1) the desired probability ratio R_P defined as the ratio of the hazard exceedence frequency H_D for which the UHS is chosen, to the permissible annual frequency P_f of unacceptable seismic performance of a structure, system, or component, i.e.:

$$R_P = \frac{H_D}{P_f}$$

2) the desired minimum seismic margin factor F_{SM} expected to be achieved for structures, systems, and components designed to the Standard Review Plan, and specified Codes and Standards (ACI, AISC, ASME, etc.). F_{SM} is defined by:

$$F_{SM} = \frac{HCLPF\ Capacity}{URS}$$

in which the HCLPF Capacity corresponds to the ground motion level for which there is approximately a mean one-percent conditional probability of unacceptable seismic performance.

In order to achieve a reliability-based design, the NRC must set target values for these two parameters R_P and F_{SM}. Current codes and standards coupled with the Standard Review Plan achieve variable minimum seismic margin factors F_{SM} ranging from about 1.0 to 2.0 with the lower half of this range being typically applicable for brittle failure modes and the upper half of this range being typically applicable for ductile failure modes.

For purposes of this study, the following example values were selected:

Desired $R_P \approx 20$ to 40
Minimum $F_{SM} \approx 1.67$

for which the following scale factor SF is appropriate:

$$SF = \max\{0.7, 0.35\ A_R^{1.2}\} \quad (9\text{-}3)$$

The above R_P and F_{SM} values were chosen only for example purposes. For other desired R_P and F_{SM} values the following table applies:

SF for different F_{SM} and R_P values

F_{SM}	Desired R_P range	
	10 to 20	20 to 40
1.0	$\max\{1.0, .60\ A_R^{0.9}\}$	$\max\{1.2, .60\ A_R^{1.2}\}$
1.33	$\max\{0.8, .45\ A_R^{0.9}\}$	$\max\{0.9, .45\ A_R^{1.2}\}$
1.5	$\max\{0.7, .40\ A_R^{0.9}\}$	$\max\{0.8, .40\ A_R^{1.2}\}$
1.67	$\max\{0.6, .35\ A_R^{0.9}\}$	$\max\{0.7, .35\ A_R^{1.2}\}$
2.0	$\max\{0.5, .30\ A_R^{0.9}\}$	$\max\{0.6, .30\ A_R^{1.2}\}$

Depending upon the desired R_P range and minimum F_{SM} selected, the scale factor SF can be either generally less than or generally greater than unity. In all cases SF increases with increasing A_R for $A_R \geq 1.8$.

Scaled spectra

Scaled spectra are used in two ways: as a consistency check on the UHS, and to derive multiple earthquake design spectra (if desired) from the URS. For the consistency check, we use the appropriate mean **M** and R values from deaggregation of the 10^{-4} amplitudes at 10 and 1 Hz to calculate spectral shapes from each attenuation equation used in the PSHA and from the spectral shapes developed in this project. That is, we use the **M**-R deaggregation values for 10 Hz to calculate the 10 Hz spectral shape, and similarly for 1 Hz. From the attenuation equations we calculate representative spectral shapes using the attenuation equation weights from the PSHA. A representative spectral shape is calculated as the antilog of the average weighted logarithmic spectral values from each attenuation equation. These representative spectral shapes are scaled so that they equal the 10^{-4} UHS at 10 and 1 Hz.

We also derive spectral shapes from the shapes recommended in McGuire et al., (2001) for the mean **M** and R values from deaggregation at 10 and 1 Hz, for the 10^{-4} hazard. This procedure consists of applying either equation (4-8) (for the WUS) or equation (4-9) (for the CEUS) of McGuire et al., (2001), using the coefficients of Table 4-3 of that reference. To calculate the coefficients, we use the appropriate deaggregation **M**-R values. These spectral shapes are scaled to equal the 10^{-4} UHS at 10 and 1 Hz. Again, if both the 1- and 2-corner source models are used for the CEUS (see Table 4-3 of McGuire et al., 2001), we calculate the antilog of the average weighted logarithmic spectral values from each equation.

We compare these sets of spectral shapes (one set from the attenuation equations, a second set from McGuire et al., 2001) to the 10^{-4} UHS. Any substantial differences in shapes (greater than about 20%) must be understood and explained. For example, the CEUS spectral shapes were developed for hard rock conditions, and applications to a site in Texas founded on softer rock would indicate high frequency amplitudes that are too high. Presumably the region-specific attenuation equations used in a PSHA for the Texas site would reflect the correct rock characteristics and would explain why the spectral shapes derived from equation (4-9) of McGuire et al., (2001) do not apply to this site.

The second use of scaled shapes is to develop design spectra for individual earthquakes. One option available to the designer is to use the broad-banded 10^{-4} URS for design, in which case spectra need not be scaled to the URS. However, the designer may wish to avoid having to design to this broad-banded spectrum. If so, the representative spectral shapes from the attenuation equations described above are scaled to the 10^{-4} URS values at 10 and 1 Hz. Only the representative spectral shapes from the attenuation equations used in the PSHA are used for this application, as they will be the most current, up-to-date, and justified spectra. The two scaled spectra must not fall below the URS by more than 10% at any frequency. If the 10 Hz scaled spectrum falls below the URS by more than 10% at a frequency higher than 10 Hz, the 10 Hz scaled spectrum may be increased until the 10% criterion is met. Alternatively, an additional scaled spectrum may be added at the frequency with the largest discrepancy, deaggregating the hazard and calculating the spectral shape from the **M** and R values from hazard deaggregation at this frequency. A similar rule applies for a discrepancy larger than 10% at a frequency below 1 Hz. For frequencies between 10 and 1 Hz, if the envelope of the two scaled spectra falls more than 10% below the URS, both spectra must be increased by the same factor so that the 10% criterion is met. Alternatively, an additional spectrum may be scaled at the frequency with the largest discrepancy, using **M** and R values from deaggregation of the hazard at this frequency to calculate the spectral shape. For application of the 10% criterion, the PSHA must be conducted at a minimum of 25 frequencies, approximately equally spaced on a logarithmic frequency axis between 100 and 0.2 Hz.

<u>Vertical motions</u>

Vertical motion design spectra are scaled from the horizontal motion design spectra using V/H ratios documented in McGuire et al., (2001). The appropriate ratios are listed in Tables 4-4 (for the WUS) and 4-5 (for the CEUS) of that reference. These ratios are based on the horizontal peak acceleration, which should be taken to be the 10^{-4} UHS spectral acceleration at 100 Hz.

An alternative is to conduct a PSHA for vertical motions separately from horizontal motions. If this is done, the same procedures are followed as for horizontal motions. Once the vertical design spectra are obtained, they must be compared to the horizontal design spectra to ensure that consistent motions have been derived.

<u>Damping other than 5%</u>

The procedures above derive design spectra for 5% damping. To obtain spectra for other dampings, three procedures are described in Section 4.9 of McGuire et al., (2001). Any of these three procedures may be used. In these procedures the spectra for other dampings are calculated as multiplicative ratios to the 5% damped spectrum.

Analysis time histories

For analysis, either a single set (3 components) of statistically independent (as defined in McGuire et al., 2001, Section 5.5.3) time histories, or multiple sets may be generated. The time histories must meet the spectral matching criteria described in McGuire et al., (2001), Section 5.6, either individually (for a single set) or in the mean (for multiple sets). These matching criteria are as follows. For a broad-banded spectrum, the 5% damped response spectrum must not be less than 10% below, nor 30% above, the URS, i.e.:

$$0.9*URS < RS < 1.3*URS \qquad \text{for } 0.2 \text{ Hz} < f < 25 \text{ Hz}$$

where RS is the 5% damped response spectrum of the artificial record. For spectra represented by two (or more) scaled spectra, an intersection frequency f_c is defined where the two scaled spectra intersect. The criterion for the artificial motion representing the 1 Hz scaled spectrum is:

$$0.9*URS < RS < 1.3*URS \qquad \text{for } 0.2 \text{ Hz} < f < f_c$$
$$0.9*DES1 < RS < 1.3*DES1 \qquad \text{for } f_c < f < 25 \text{ Hz}$$

where DES1 is the spectrum scaled to the URS at 1 Hz. That is, the response spectrum must fall between 90% and 130% of the URS at low frequencies, and between 90% and 130% of the scaled 1 Hz spectrum at high frequencies. Analogous rules apply for the 10 Hz scaled spectrum, DES10:

$$0.9*DES10 < RS < 1.3*DES10 \qquad \text{for } 0.2 \text{ Hz} < f < f_c$$
$$0.9*URS < RS < 1.3*URS \qquad \text{for } f_c < f < 25 \text{ Hz}$$

If three (or more) scaled spectra are used to represent the URS, analogous rules apply for artificial records used to represent each scaled spectrum. That is, in the frequency range represented by a particular scaled spectrum, RS must match the URS, within 90% to 130%. Outside that range, RS must match the scaled spectrum, within 90% to 130%. The check for response spectrum matching is made for 5% of critical damping only.

Spectral matching procedures that require an input motion (basis time history) are preferred since these approaches preserve a realistic phase spectrum and thereby preserve the character of resulting acceleration, velocity, and displacement time histories. Suites of time histories aggregated by **M**, R, and site condition bin are available for use as basis motions (McGuire et al., 2001). Alternative motions may be used if justified. Final spectrally matched motions must have appropriate time domain characteristics. Specifically, PGV/PGA and PGA•PGD/PGV^2 ratios should be within $\pm 1\sigma$ of bin medians, and durations should be within the bin target ranges (*/1.5 of bin medians). Motions with ratios that fall outside these ranges will be acceptable as long as the difference is documented and justified. For a single 3-component set of motions, each time history should meet these criteria and for multiple sets, median values should be within the specified ranges and the uncertainties should not exceed those of the bin motions.

9.2 Soil sites

Soil sites are those for which a site-specific response analysis is required. The dynamic nonlinear properties (shear wave velocity, modulus reduction and material damping) of the near-surface layers of such soil sites differ significantly from those of rock sites, for which the attenuation equations were derived for use in the PSHA. One alternative is to conduct the PSHA for site-specific conditions (designated "Approach 4" in Section 6.1). In this case, an appropriate profile must be used along with nonlinear properties in developing the site-specific attenuation relations. Also, site-specific variabilities in profile depth, velocities, and layer thicknesses, and dynamic nonlinear material properties, must be included in developing the attenuation relations. Uncertainties in source and path properties should also be modeled, either as aleatory or epistemic uncertainty in the attenuation or in the PSHA. If this method is used, the procedure follows that described in Section 9.1 for rock sites.

For several reasons it may not be desirable to conduct the PSHA for soil conditions. Site-specific soil data may be available only in preliminary form, or different structures at a nuclear facility may rest on different soil properties and/or depths. In these cases it will be appropriate to conduct the PSHA for rock conditions, and then modify the rock results to develop design spectra for the different soil conditions that exist. This means that multiple soil design spectra can be calculated for different structures at a facility, all consistent with a single rock PSHA. Also, soil spectra can be updated at a later time based on additional site-specific data that may be collected.

<u>Defining motions and time histories for rock outcrop as input to soil</u>

For soil design motions developed from rock PSHA, the procedure is outlined in Figure 1-2. The first five steps are similar to those for rock sites, except that the target spectra are scaled to the UHS rather than the URS, because the first goal is to estimate accurate UHS on the soil surface, from which URS can be derived. Control motions corresponding to the target spectra are defined for rock outcrop at the base of the soil column, rather than for rock outcrop at the ground surface. For the CEUS these definitions are identical; for the WUS they differ in that the near-surface highly fractured rock zone is removed to a depth corresponding to the shear-wave velocity at the base of the soil (or to a depth of 150 m [500 ft] in the case of deep profiles). This definition of outcrop rock motion results in rock conditions more reflective of the actual conditions at the base of the soil column. The first five steps are:

1) conduct a PSHA for rock conditions.
2) deaggregate the mean hazard for 10^{-4} at 10 and 1 Hz.
3) define target spectra at 10 and 1 Hz based on spectra (from rock attenuation equations and from the spectral shapes in Section 4 of McGuire et al., 2001) calculated for **M** and R scaled to the 10^{-4} UHS. These sets of spectra are used for a consistency check on the shape of the rock UHS. Once the UHS has been checked and justified, the scaled spectra from the rock attenuation equations are used as target spectra. If the envelope of these spectra falls more than 10% below the 10^{-4} UHS at any frequency between 0.2 and 100 Hz, the spectra must be increased or an additional spectrum must be added, following the rules described in Section 9.1 for rock sites.

4) pick rock time histories from appropriate **M** and R bins.
5) adjust rock time histories to match the target spectra.

For steps 4 and 5, bin time histories from rock records would of course be used for the appropriate region (WUS or CEUS). The subsequent steps to developing soil design motions are as follows.

Site response analysis

We use the spectrally matched rock (i.e. base of soil) time histories as control motions for site response analyses, for horizontal motions (and for vertical motions, if desired). For frequency domain analysis we start with the rock outcrop scaled spectra to define the control motion. Uncertainties in soil depth, velocities, layer thicknesses, and dynamic nonlinear material properties must be modeled. Site response analyses should be performed with the 1 Hz and 10 Hz design spectra to develop mean transfer functions for 10^{-3}, 10^{-4}, and 10^{-5} input motions, and to develop logarithmic standard deviations of soil response at each frequency. This method is labeled "Approach 2A" in Section 6.1. Note that it is *required* to use the two rock outcrop scaled spectra (at 1 and 10 Hz) to calculate soil response, unless one spectrum lies within 10% of the UHS for frequencies between 0.2 to 25 Hz. This requirement is made in order not to drive the soil column with an unrealistically broad-banded motion that will not occur at the site.

Implicit in this process for determining ground spectra (UHS and URS) at soil sites is the requirement to have appropriate nonlinear soil models for use in the site convolution evaluations. These soil models consist of both degradation of shear modulus and increase in hysteretic damping ratio with induced shear strains and have a controlling effect on soil motions at moderate to high loading levels.

It is therefore critical to ensure that where soil models are deduced from laboratory studies, the sampling and testing programs are critically peer reviewed to ensure that the generated soil dynamic nonlinear properties are appropriate to properly characterize site response.

Uniform hazard spectra (UHS)

The UHS on soil is calculated using the method labeled "Approximate Approach 2A/3" in Section 6.2. In this method, the 10^{-4} and 10^{-5} UHS on soil are estimated from equation (6-7b):

$$z_{rp} = a_{rp}\, \overline{AF_{rp}}\, \exp\left(\frac{1}{2} k\, \sigma_\delta^2 / d_3^2\right) \qquad (9\text{-}4)$$

where z_{rp} is soil amplitude z associated with return period rp, $\overline{AF_{rp}}$ is the mean amplification factor for the rock motion with return period rp, k and d_3 are derived from the slope of the rock hazard curve and AF, and σ_δ is the log standard deviation of AF. Equation (9-4) is called Approximate Approach 2A/3 in Section 6.

Uniform reliability spectrum (URS)

With estimated 10^{-4} and 10^{-5} UHS on soil, we calculate the ratio A_R at each frequency (see equation (9-1)). We modify the 10^{-4} UHS by the scale factor SF to determine the URS on soil (see equations (9-2) and (9-3)). Note as discussed in connection with equation (9-3) that SF depends on the selection of a desired probability ratio R_P and a minimum seismic margin factor F_{SM}.

Vertical motions

An acceptable procedure for defining vertical motions is as follows. The final soil surface horizontal design spectra is scaled by a suitable generic or site-specific soil V/H ratio, suitable in the sense of an appropriate **M**, R, and soil condition. For WUS conditions, the use of one or several empirical soil V/H ratios is preferred (see, for example, Figure 6-33). For the CEUS, if appropriate empirical V/H ratios are unavailable, either of the following approaches may be used.

First, the generic soil category CEUS V/H ratios documented in EPRI (1993) may be used. These ratios were developed using a well-validated model, and they have undergone technical review. This method is preferred if the site conditions match those used in EPRI (1993).

Second, the approach used here (Figure 6-34) may be used. This procedure scales a WUS deep soil empirical V/H ratio to CEUS conditions. The scaling must be done by a well-validated model that reproduces the **M**, R, and site condition dependencies of empirical WUS V/H ratios and also that models V/H ratios at rock sites in the CEUS (McGuire et al., 2001, Sections 6.3 and 6.4). For the CEUS, to assess the reasonableness of results, vertical motions computed using multiple methods are encouraged, particularly if either the 1 Hz or 10 Hz controlling earthquakes are within about 20 to 30 km of the site.

As an alternative to scaling horizontal design motions, site response analyses may be performed for vertical motions, in which case the development of vertical design spectra parallels that for horizontal design spectra.

Damping other than 5%

For soil sites, the procedure for calculating spectra for damping other than 5% is the same as for rock sites.

Analysis time histories

For soil sites, the selection and adjustment of analysis time histories is the same as for rock sites.

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McGuire, R.K., W.J. Silva, and C.J. Costantino (2001). "Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-consistent Ground Motion Spectra Guidelines," U.S. Nuclear Reg. Comm., Rept. NUREG/CR-6728, October.

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APPENDIX A APPROXIMATE METHOD TO CALCULATE SOIL HAZARD

This approximation to the probability of exceeding a soil amplitude z was derived by G. Toro; it leads to a simple, closed-form expression for the hazard at a soil site. The derivation is made for the case of correlation between deviations of rock amplitude a and the amplification factor AF from their mean values, although the final recommended form simplifies when zero correlation is assumed. Throughout this discussion, the deviations of rock amplitude and soil amplification are assumed to be logarithmic deviations from the mean logarithmic values.

The rock hazard is written as:

$$P[A>a] = \int\int\int P[A>a|m,r,\varepsilon] f_M(m) f_R(r) f_\varepsilon(\varepsilon) dm\, dr\, d\varepsilon \qquad \text{(A-1)}$$

where ε is the logarithmic deviation of rock amplitude and where $P[\cdot]$ within the integrand is either 0 or 1 depending on the values of a, m, r, and ε. If the uncertainty in ground motion is zero, i.e. $\sigma_\varepsilon=0$, Equation A-1 simplifies to what we can call the "central hazard curve $\overline{H}$," as follows:

$$\begin{aligned} \overline{H}(a) &= P[A>a \text{ when } \sigma_\varepsilon = 0] \\ &= \int\int P[A>a|m,r,\sigma_\varepsilon = 0]\, f_M(m) f_R(r) dm\, dr \end{aligned} \qquad \text{(A-2)}$$

If $\sigma_\varepsilon \neq 0$ but is constant over all values of m and r, the following holds:

$$\int\int P[A>a|m,r,\varepsilon] f_M(m) f_R(r) dm\, dr = \overline{H}(a e^{-\varepsilon}) \qquad \text{(A-3)}$$

That is, the probability of exceeding a can be calculated from the central hazard curve at amplitude $ae^{-\varepsilon}$. If we assume further that the mean rock hazard curve is linear in log-log space:

$$\overline{H}(a) = c(a)^{-k} \qquad \text{(A.4)}$$

then we can substitute (A-3) and (A-4) into (A-1) so that the rock hazard can be written:

$$P[A>a] = c a^{-k} \int e^{\varepsilon k} f_\varepsilon(\varepsilon) d\varepsilon \qquad \text{(A-5)}$$

$$= ca^{-k} e^{k^2 \sigma_\varepsilon^2/2}$$
$$= c' a^{-k} \tag{A-6}$$

where $c' = c \exp(k^2\sigma^2_\varepsilon / 2)$ and σ_ε is the standard deviation of the logarithmic deviation ε. Equation A-6 implies that hazard curves for $\sigma_\varepsilon = 0$ and $\sigma_\varepsilon \neq 0$ have the same slope, provided σ_ε is constant with a.

We write the soil amplification factor AF as:

$$AF = d_1 a^{-d_2} e^{\delta} \tag{A-7}$$

where δ is the logarithmic deviation of AF, which might be correlated with ε. The soil amplitude is then:

$$\begin{aligned} z &= a \cdot AF \\ &= a d_1 a^{-d_2} e^{\delta} \\ &= d_1 [\bar{a} e^{\varepsilon}]^{1-d_2} e^{\delta} \end{aligned} \tag{A-8}$$

where $\bar{a}$ is the mean rock amplitude. Solving for $\bar{a}$ gives:

$$\bar{a} = [z e^{-\delta} / d_1]^{1/d_3} e^{-\varepsilon} \tag{A-9}$$

where $d_3 = 1 - d_2$.

We can write the probability of exceeding soil amplitude z as

$$P[A_S > z] = \int\int P[\bar{a} > (z e^{-\delta}/d_1)^{1/d_3} e^{-\varepsilon}] f_\varepsilon(\varepsilon) f_\delta(\delta) d\varepsilon d\delta \tag{A-10}$$

The probability in the integrand can be written using equation A.4 as:

$$\begin{aligned} P[\cdot] &= c[(z e^{-\delta}/d_1)^{1/d_3} e^{-\varepsilon}]^{-k} \\ &= c(z/d_1)^{-k/d_3} e^{k(\delta/d_3 + \varepsilon)} \end{aligned} \tag{A-11}$$

This probability depends only on the parameter $y = \delta/d_3 + \varepsilon$, which is normally distributed with mean = 0 and standard deviation:

$$\sigma_y = (\sigma_\varepsilon^2 + \sigma_\delta^2/d_3^2 + 2\rho\sigma_\varepsilon\sigma_\delta/d_3)^{1/2} \tag{A-12}$$

where ρ is the correlation coefficient between ε and δ. In terms of y, equation A-10 can be written:

$$P[A_S > z] = \int e^{ky} c(z/d_1)^{-k/d_3} f_Y(y)dy \tag{A-13}$$

which simplifies to:

$$P[A_S > z] = c(z/d_1)^{-k/d_3} \exp\frac{1}{2}k^2[\sigma_\varepsilon^2 + \sigma_\delta^2/d_3^2 + 2\rho\sigma_\varepsilon\sigma_\delta/d_3] \tag{A-14}$$

This can be further simplified to:

$$P[A_S > z] = c'[(z/d_1)^{1/d_3}]^{-k} \exp\{\frac{1}{2}k^2[\sigma_\delta^2/d_3^2 + 2\rho\sigma_\varepsilon\sigma_\delta/d_3]\} \tag{A-15}$$

The first two terms on the right side of the equation A-15, $c'[\cdot]^{-k}$, give the rock hazard associated with a rock amplitude of $\frac{z}{\overline{AF}}$ (see equations A-6 and A-9). The third term, $\exp\{\cdot\}$, is a correction for uncertainties in $\overline{AF}$ and for correlation. If the correlation is zero, the soil hazard simplifies to:

$$P[A_S > z] = P[A > \frac{z}{\overline{AF}}] \exp\{\frac{1}{2}k^2\sigma_\delta^2/d_3^2\} \tag{A-16}$$

where $\overline{AF}$ is the mean amplification factor.

Further, if the soil uncertainty is constant with amplitude, the soil hazard curve will have slope k/d_3, and the soil amplitude associated with a given return period (e.g. 10,000 years) can be computed as:

$$z_{10,000} = a_{10,000}\,\overline{AF}(a_{10,000})\exp(\frac{1}{2}k\sigma_\delta^2/d_3^2) \tag{A-17}$$

Equation (A-17) provides a simple interpretation of the effects of soil amplification and its uncertainty. The first two terms on the right side of equation (A-17), $a_{10,000}\overline{AF}(a_{10,000})$, give the soil amplitude at 10,000 years for a rock amplitude $a_{10,000}$ and a deterministic (i.e. perfectly known) soil amplification. The last term, exp $(\cdot)$, is a correction factor that accounts for the slope k of the rock hazard curve, the uncertainty in soil amplification σ_δ, and the change in soil motion with rock motion d_3. This correction factor is typically in the range 1.05 to 1.25.

APPENDIX B COMPARISON OF HORIZONTAL SOIL RESPONSE USING EQUIVALENT LINEAR AND NONLINEAR METHODS

B.1 Methods of analysis

This section of the report presents results obtained from site response calculations performed using both equivalent linear and fully nonlinear methods of analysis of site response. Calculations were performed for a number of different rock outcrop motions that have been described previously in this report. In all cases, site response evaluations were performed under the simplifying assumption of vertically propagating shear waves moving through a horizontally layered soil column. The analysis therefore is one dimensional, significantly simplifying the response evaluations. This assumption is widely used to estimate surface ground motions and horizontal shear strains developed throughout the soil column. A further benefit from this approach results from the fact that it reduces the complexity of the constitutive models required to define stress-strain properties of the site soils. At any one location in the soil column, one must only be concerned with the shear stress-strain relationship, and the effects of other components of the wave field can be neglected. In addition, the shear properties of the materials can be relatively easily related to test data obtained from relatively simple laboratory tests conducted on soil samples. Of course, the appropriateness of this simplification must be properly evaluated before acceptance of its predictions of site response.

Two separate equivalent linear methods of analysis were used, namely the random vibration model of the RASCAL computer code (Silva and Lee, 1987), in which time histories are defined in terms of power spectral density and conversions between time domain and frequency domain are made in terms of RVT assumptions, and the deterministic method of the CARES computer code (Miller and Costantino, 2000) in which the transfer between time domain and frequency domain is made exactly using Fourier transform calculations. The material constitutive models are assumed to be viscoelastic, and any nonlinearities in site response calculations are treated in an approximate fashion by changing the effective moduli of any soil layer after each calculation based on results from the previous response calculation. The approach is based on the well known procedures presented by Idriss and Seed (1968) and described in many subsequent publications (e.g., Seed and Idriss, 1982; Schnabel, Seed and Lysmer, 1972).

The fully nonlinear analyses were made using the TESS computer code (Pyke, 1984), which performs a deterministic response calculation in the time domain but treats the soil shear stress-strain relation as fully nonlinear throughout the calculation. The shear stress-strain relationship used in TESS is based on the Hardin-Drnevich hyperbolic relationship (Hardin & Drnevich, 1972) modified by the Cundall-Pyke hypothesis (Cundall, 1975; Pyke, 1979) to control cyclic behavior. The soil model simulates in a relatively simple manner the well known shear behavior of degradation of shear modulus and shear strength with cyclic strain levels and change of shape of the shear stress-strain curve with the magnitude of applied cyclic strain. The code also allows evaluation of the impact of saturation on shear behavior, but these features were not used in these calculations.

B.2 Site model

The base case profile of the site soil column analyzed in these calculations is the Imperial Valley soil column described previously. The initial low strain shear wave velocity profile of this site is shown in Figure B-1 in which the site soils extend to a depth of 1000' to bedrock. The bedrock is assumed to have a shear wave velocity of about 3,300 fps. For these site response calculations, the material below this depth is assumed to be a uniform elastic half-space. The low strain shear wave velocity of the site soils vary from 400 fps at the surface to about 2,300 fps immediately above the bedrock contact. For all response calculations using either CARES, RASCAL or TESS programs, an "individual" site response was determined as the mean response resulting from 30 different approximations to the soil column. In each of the 30 cases, properties of the individual soil layers were selected randomly based upon typical values of median and one-sigma percentiles to capture the expected uncertainties of these properties based on typical field results. The variations included variability in low strain shear modulus and damping of each soil layer, thickness of individual soil layers, and total thickness of the soil column. The approach used for selecting specific values of the individual properties is based on the generic results presented by Toro (1997). Variability in shear moduli and damping was assumed to be lognormal while the variability in layer thickness was assumed to be normal.

The variation in total thickness of the soil column for the 30 cases considered in each evaluation extended from 950' to 1050'. For each soil column, surface motions were generated by each analysis (CARES, RASCAL or TESS) and the mean of the surface (5% damped) response spectrum was calculated. The site amplification function was then determined as the ratio (frequency by frequency) of the mean surface spectrum divided by the (5% damped) spectrum of the outcrop motion used as input to the set of calculations. Comparisons of the mean spectrum and site amplification functions from the three approaches were then made.

For the equivalent linear models (CARES and RASCAL) of site response, the viscoelastic soil properties are defined in terms of their low strain shear moduli (or shear velocity) as indicated in Figure B-1 together with the strain degradation properties shown in Figure B-2. As described previously, these degradation properties were determined by inversion methods from recorded site earthquake data. The deeper soils below a depth of 295' were slightly less nonlinear, having both less degradation and damping with peak cyclic shear strain. Soils below 626' were assumed to behave linearly with no degradation considered with shear strain. Calculated shear strains in these lower layers were generally found to be about 0.05% or less.

For the fully nonlinear calculation using TESS, it was first necessary to generate nonlinear soil properties which hopefully closely reproduce the degradation properties developed for the equivalent linear models. This would then allow for a direct comparison of the effects of nonlinear and equivalent linear calculational approaches in the prediction of site response. A sample of the cyclic behavior model assumed in the TESS calculation is shown in Figure B-3 for three different levels of applied cyclic strain. As strain levels increase, the average slope of the shear loops decreases, which simulates the decrease in shear modulus used in the equivalent linear calculation. The increased hysteretic behavior of the loops simulates the increase in cyclic damping ratio with strain used in the equivalent linear model. The resulting TESS degradation properties depend upon the selection of a number of parameters for each soil layer.

After a number of trial calculations, a set of TESS soil parameters were selected that were used to generate equivalent degradation properties. Figures B-4 and B-5 show comparisons of degradation models developed from the TESS site response calculations with the equivalent linear degradation models used in CARES and RASCAL for the two upper soil models of the soil column. For the deeper linear soils below 626', an additional TESS model was developed that matched the linear low strain shear damping of 0.5% used in the linear calculations. As may be noted from these comparisons, the degradation of shear modulus for the linear and nonlinear analyses are reasonably close for shear strain levels below about 1%. However, it was found that with these selected parameters, the resulting hysteretic soil damping moduli in the TESS model were about double the values used in the equivalent damping model for effective soil strains above about 0.1%. In the TESS nonlinear soil model, it was difficult to match results of both shear modulus and hysteretic damping. Since the degradation in shear modulus was considered to be most significant to site response, the parameters that best fit these properties were selected for use.

B.3 Initial computations

In the initial set of calculations performed for this evaluation, the rock outcrop motion used as input to the soil columns was defined in terms of a 5% damped Uniform Hazard Spectrum (UHS) with a PGA of almost 1g. A time history was generated that closely enveloped this spectrum and had a total duration of 20 seconds with a strong motion duration (time from 5% to 75% Arias intensity) of about 6 seconds. This input motion was then used as an outcrop input to the 30 soil columns in each set of calculations, and mean surface spectra were generated. The results obtain from the 30 CARES equivalent linear runs are shown in Figure B-6 and these are considered as typical results from this exercise. The mean surface spectrum computed from either the average of the individual spectra or the average of the logs of the individual spectra is essentially the same across the frequency range considered. Figure B-7 presents a comparison of the mean spectra generated from the two equivalent linear calculations and indicates very similar results. The smoothness of the calculated RASCAL spectrum as compared with the deterministic CARES spectrum results from the assumed smoothness in the RVT conversion of time histories to the frequency domain as opposed to the deterministic calculation in CARES. Figure B-8 presents results comparing the CARES equivalent linear response with the nonlinear TESS calculations while Figure B-9 is a similar comparison of the CARES, RASCAL with the TESS calculations. These figures generally indicate that the equivalent linear assumptions tend to amplify surface responses as compared to the nonlinear calculation, particularly at the higher frequencies above 10 Hz. This behavior at the higher frequencies probably results from the significantly higher equivalent damping embedded within the TESS soil models.

B.4 Revised input motions for WUS sites

Following this initial set of calculations, revised calculations were made using new rock outcrop site motions associated with new UHS definitions and with new spectra for characteristic events associated with this new UHS. These characteristic spectra were then scaled back to the UHS at frequencies of 1 Hz and 10 Hz as is currently recommended for development of design response spectra. Figure B-10 presents these various outcrop spectra considered in these revised site response calculations. It should be noted that the low magnitude characteristic event, when scaled back to the UHS at 1 Hz, leads to the relatively high rock outcrop motion for frequencies greater than 1 Hz, with a PGA significantly higher than 1g.

The first set of calculations performed with CARES, RASCAL and TESS was for the case of an input rock outcrop motion defined by the new UHS spectrum. Again, an artificial time history was generated that closely envelops this target spectrum and that has duration estimates similar to the mean magnitude event (M6.7) associated with the UHS. Figure B-11 presents the mean surface spectra results generated from the CARES and RASCAL equivalent linear methods of analysis. These results are similar to those previously described, with the deterministic CARES and RVT RASCAL approaches yielding similar estimates of surface spectra over the entire frequency range of interest. Again, the CARES spectra are "hashier" than the RASCAL results due to the greater variability in the time/frequency domain transfer in the deterministic approach as opposed to the RVT model. Figures B-12 and B-13 present similar comparisons of the equivalent linear and nonlinear TESS results for the same outcrop input motion. Again, the comparison indicates that the equivalent linear models overpredict the surface motions as compared to the nonlinear model, particularly at frequencies above 10 Hz. Figure B-14 presents comparisons of the spectral ratios (defined as the mean surface spectral acceleration divided by the corresponding outcrop spectral acceleration, all calculated for 5% equipment damping) for the three methods of analyses. The spectral ratios from the nonlinear calculation are lower than the equivalent linear results, particularly at frequencies above 10 Hz.

Figures B-15 through B-18 present similar results obtained for the case of the rock outcrop spectrum defined from the time history which closely envelops the high magnitude event (M7.8) scaled to the UHS spectrum at 1 Hz. As can be noted in Figure B-10, this spectrum is similar in shape and magnitude to the UHS spectrum. The results from the site response calculations lead to similar conclusions as mentioned for the results using the UHS rock outcrop. Figures B-19 through B-21 present results of spectral ratios determined for the median magnitude (6.7) and low magnitude (5.1) outcrop motion scaled back to the UHS at 1 Hz as well as the high magnitude (7.8) event scaled back to the UHS at 10 Hz. Again, the results for the low magnitude event scaled back to the UHS at 1 Hz leads to the highest outcrop input motions at frequencies above 1 Hz, although its spectral accelerations at frequencies below 1 Hz are lower than the UHS. Since these soil columns have their fundamental frequency significantly lower than 1 Hz (mean value about 0.4 Hz), the expected responses relative to the UHS cannot be predicted directly.

The spectral ratios in Figures B-22 through B-24 have similar characteristics to those previously described for the UHS case although some differences in magnitude of these ratios can be noted depending upon the input outcrop motions used. Figure B-22 presents a comparison of the spectral ratios obtained from the CARES equivalent linear computations, Figure B.23 presents a comparison from the RASCAL computations while Figure B.24 presents results from the nonlinear TESS computations. These plots show that the characteristic behavior from the three approaches is relatively similar, with the low magnitude event scaled back to the UHS at 1 Hz always resulting in lower amplifications at the higher frequency range. As was indicated previously, this rock outcrop motion has significantly higher input accelerations than the other characteristic events.

B.5 Conclusions

The results from these many site response calculations performed for this deep soil column, which extends to a depth of over 1,000' to bedrock, can be summarized with two primary conclusions. First, the equivalent linear methods of analysis based upon either deterministic (CARES, SHAKE, etc.) or RVT approaches lead to very similar estimates of site response over the entire frequency range of interest. Second, the fully nonlinear calculation from the TESS soil model leads to generally lower estimates of site response over the entire frequency range of interest, but particularly at frequencies above 10 Hz. Spectral ratios at frequencies above 10 Hz are about 30% lower in the fully nonlinear calculation as compared to the equivalent linear models. This is primarily the result of the higher effective soil damping used in the stress-strain model contained in TESS.

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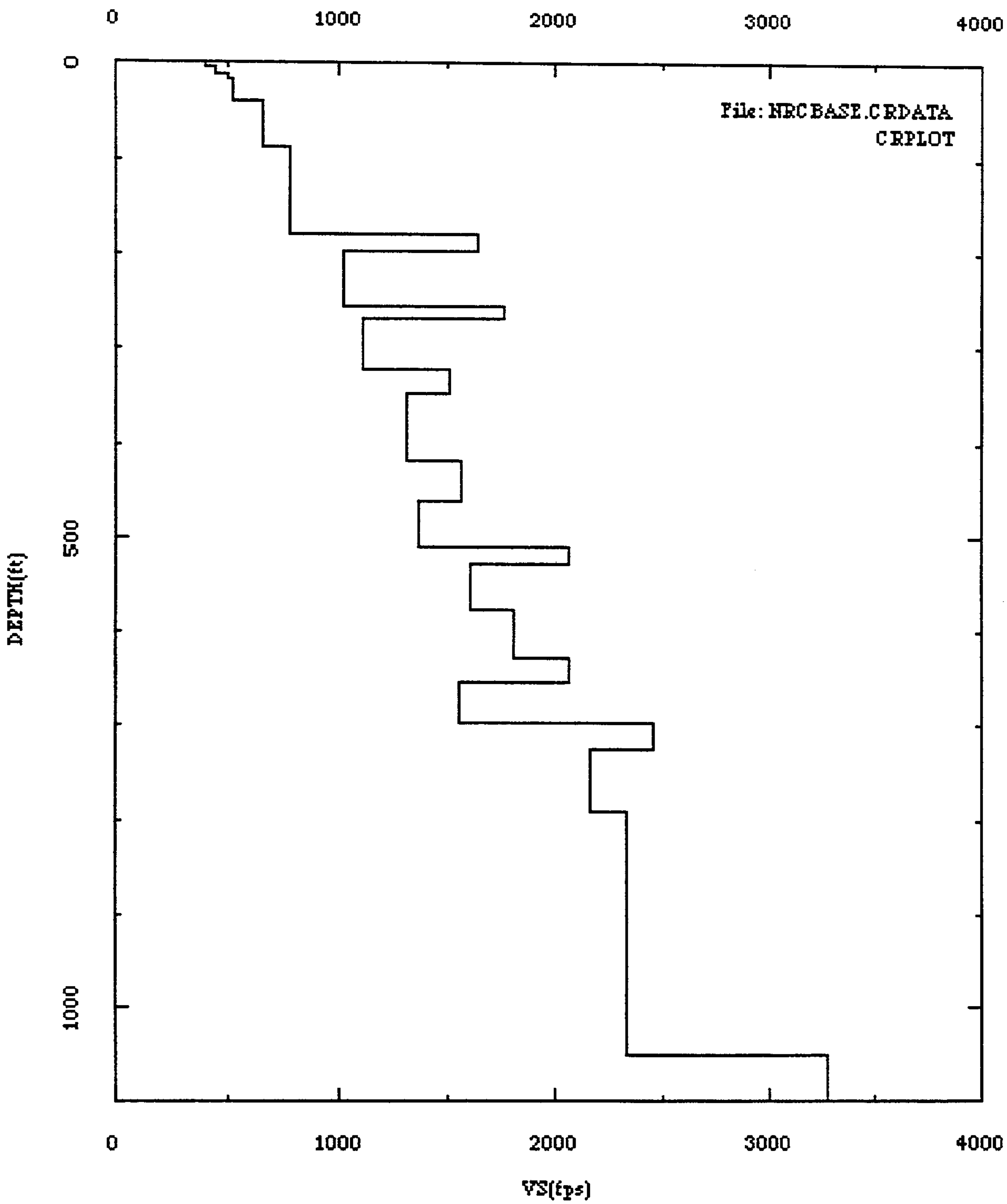


Figure B-1. Initial shear modulus for Imperial Valley soil column.

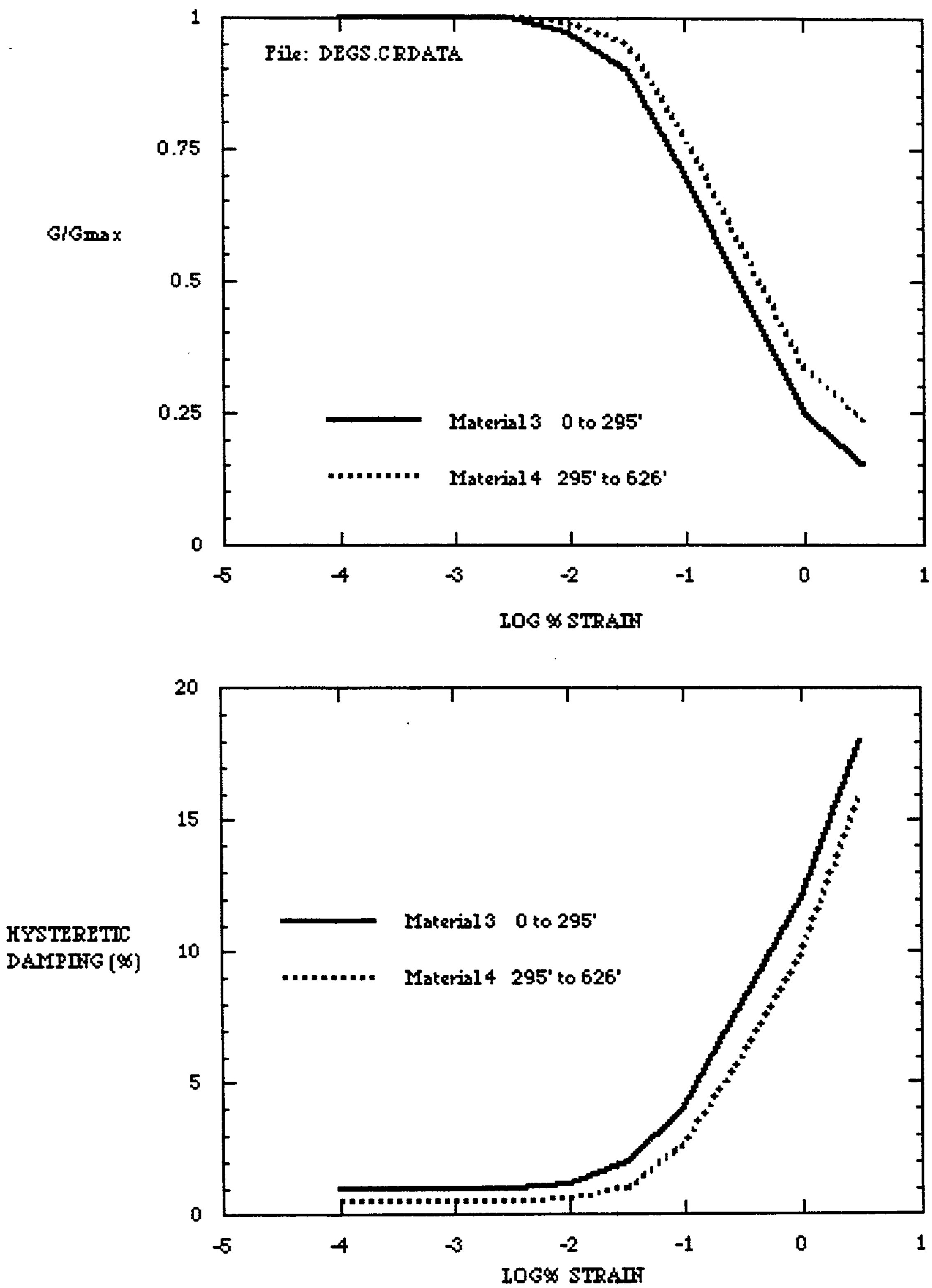


Figure B-2. Imperial Valley degradation model.

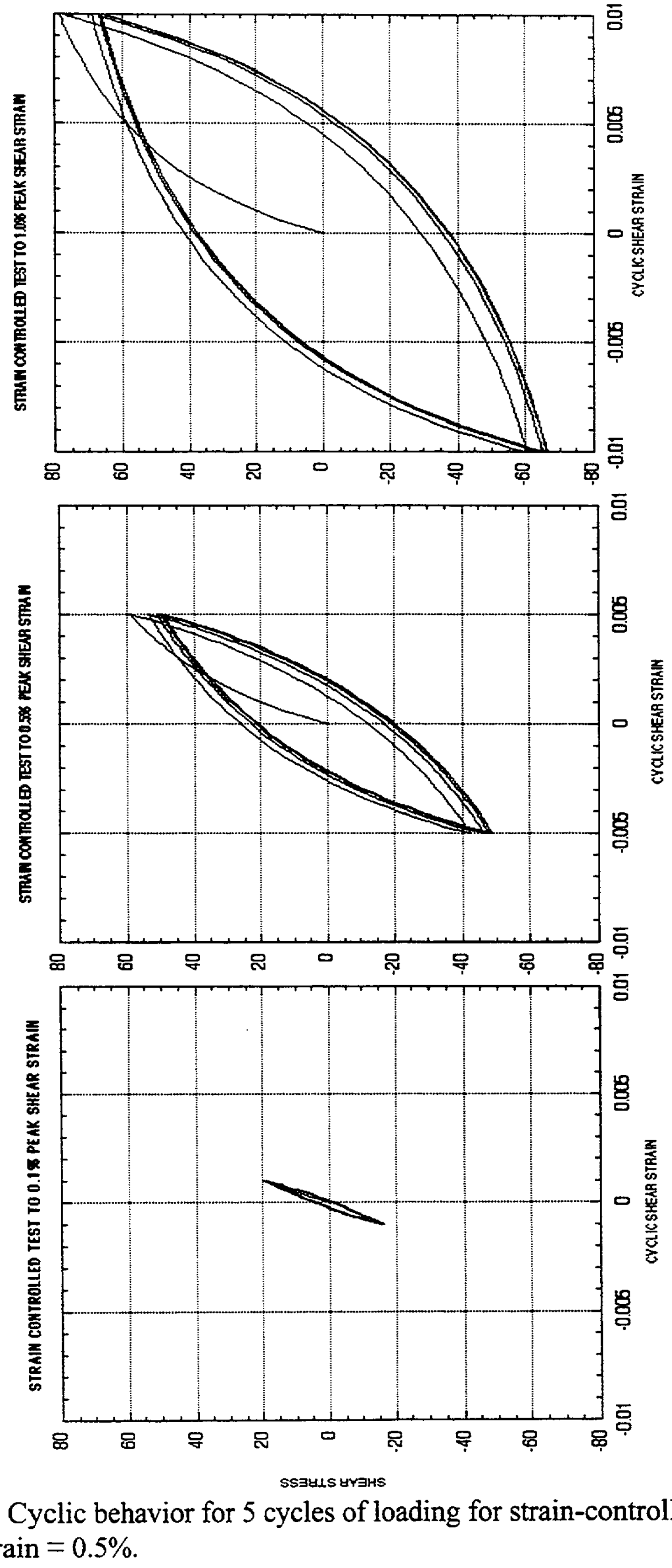


Figure B-3. Cyclic behavior for 5 cycles of loading for strain-controlled cyclic shear test; reference strain = 0.5%.

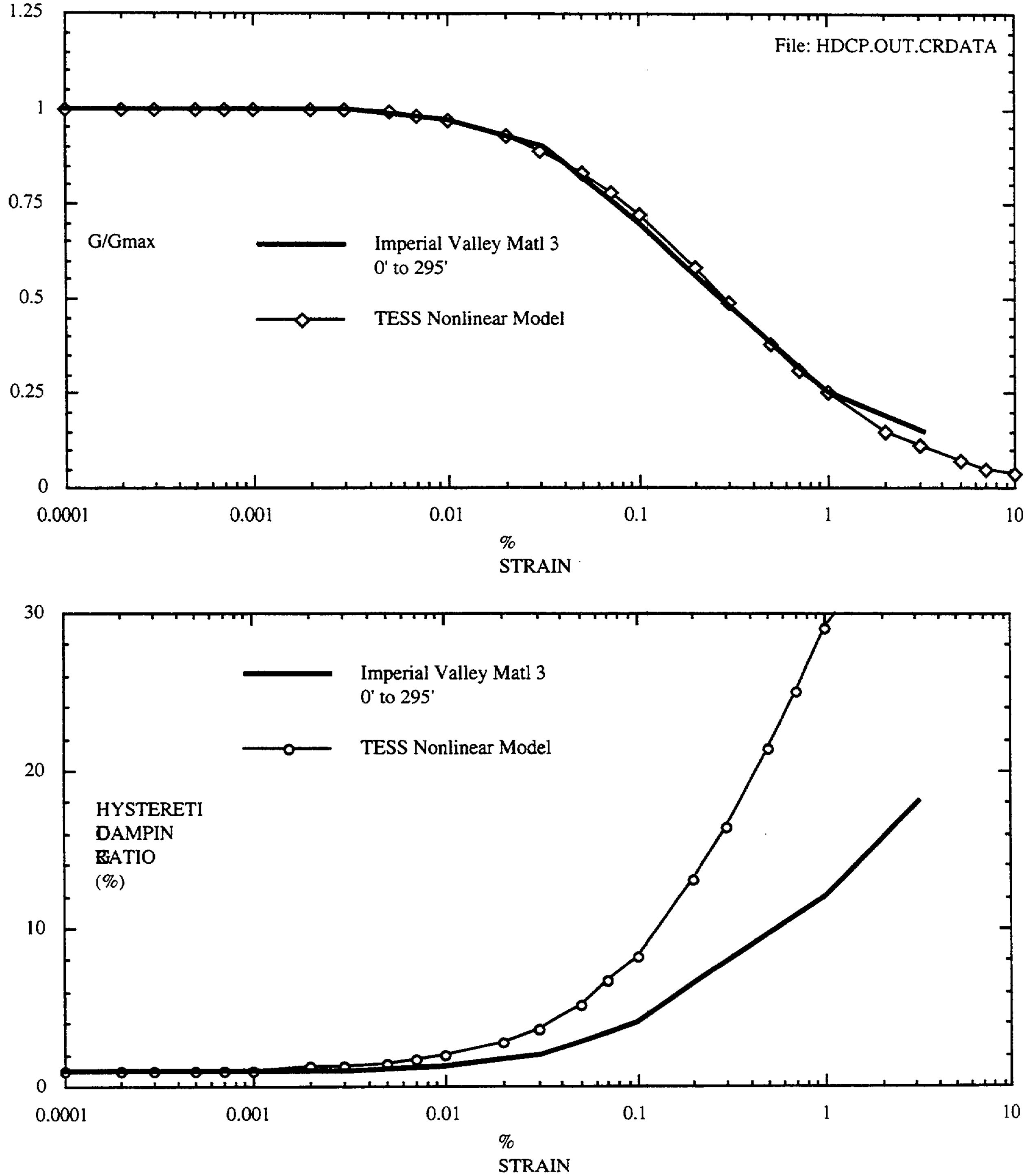
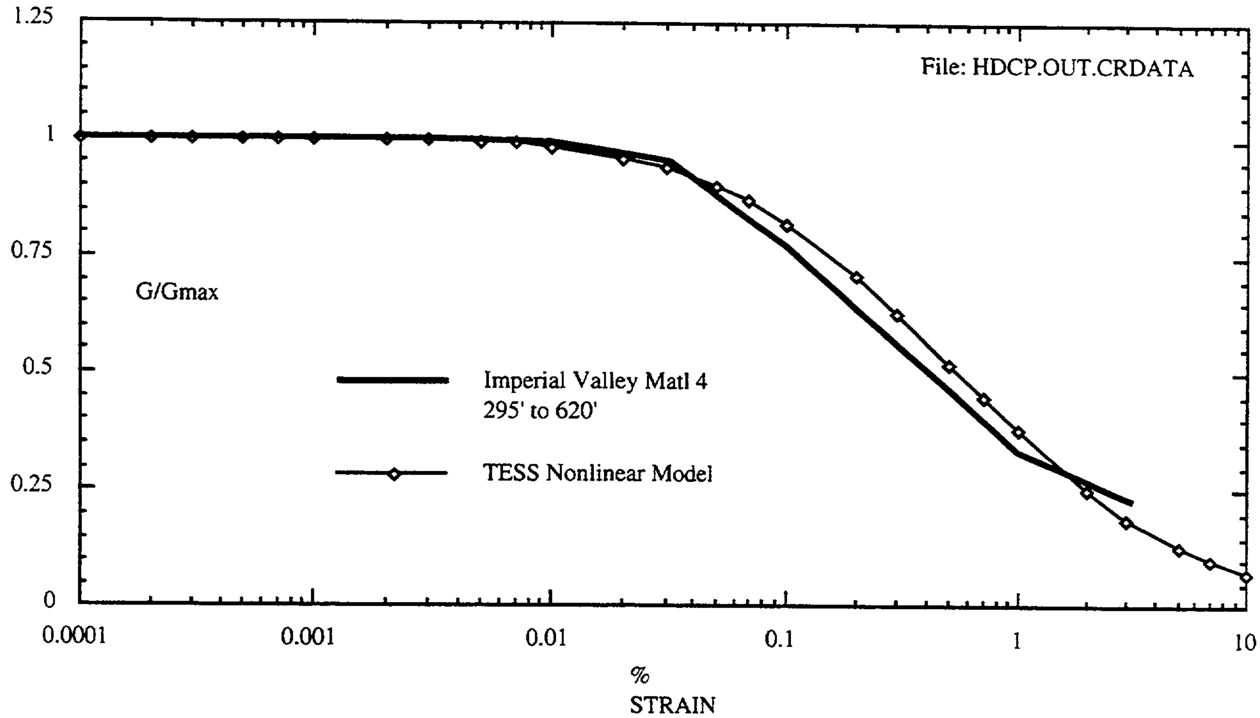


Figure B-4. Comparison of nonlinear degradation model with equivalent linear assumption for Imperial Valley near-surface soils from 0' to 295'.



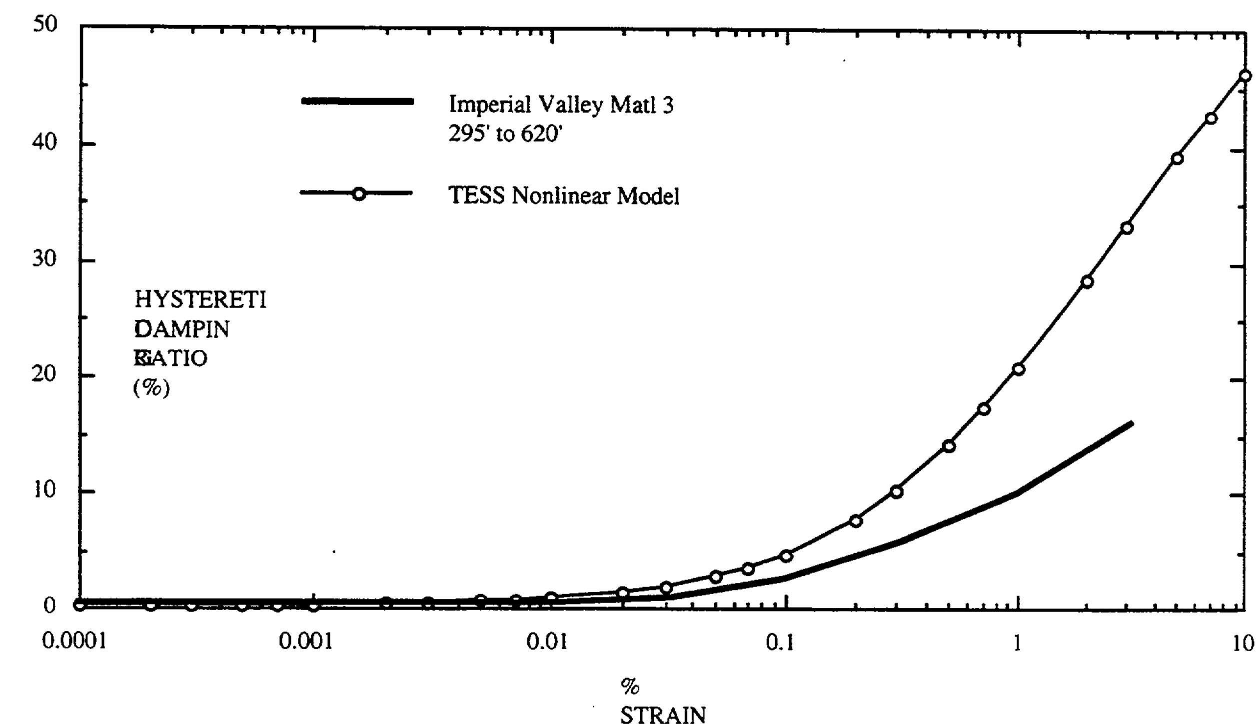


Figure B-5. Comparison of nonlinear degradation model with equivalent linear assumption for Imperial Valley deep soils from 295' to 626'.

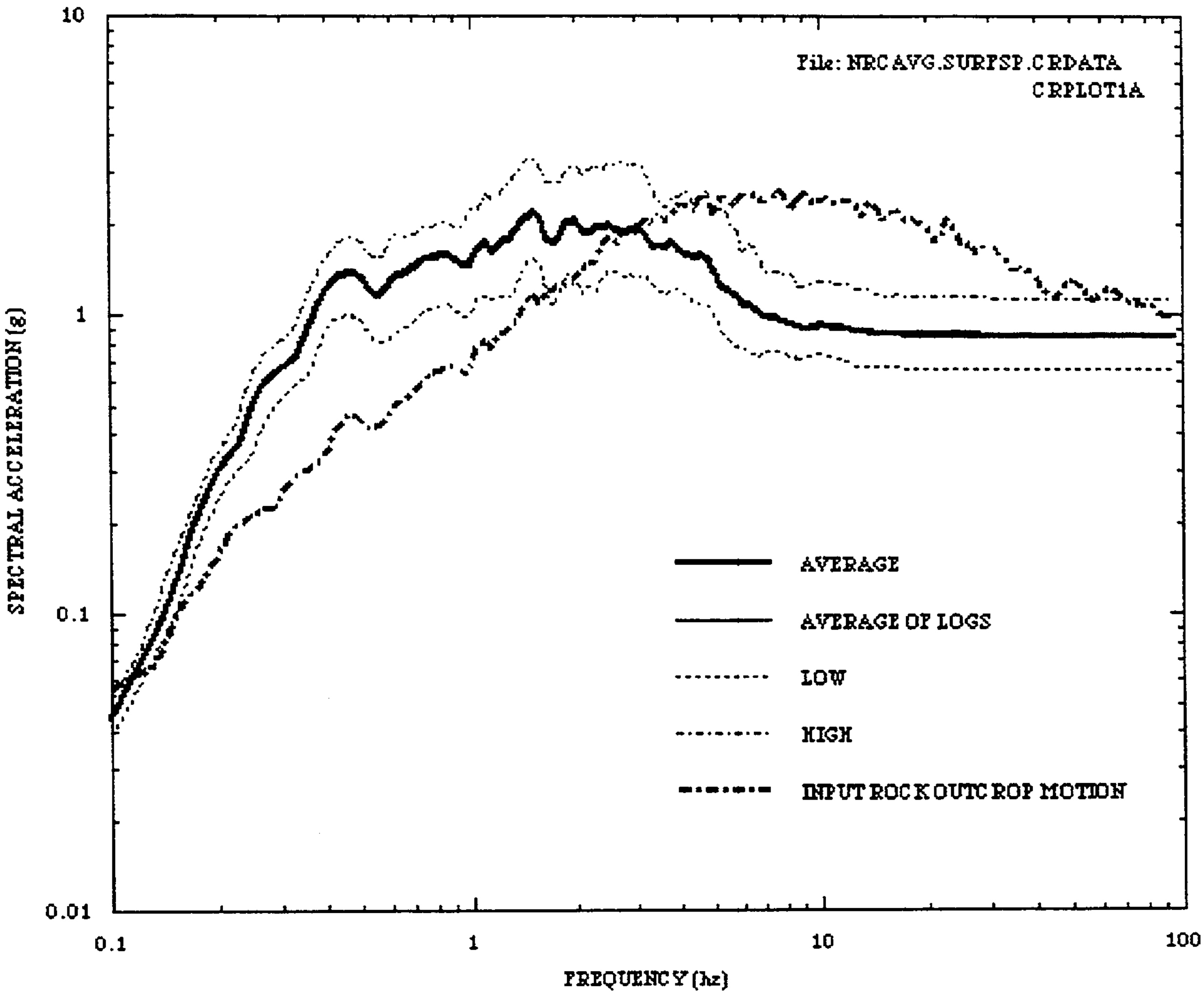


Figure B-6. Mean 5% damped surface spectra for Imperial Valley site column from 30 runs using UHS rock outcrop (CARES equivalent linear time domain solution).

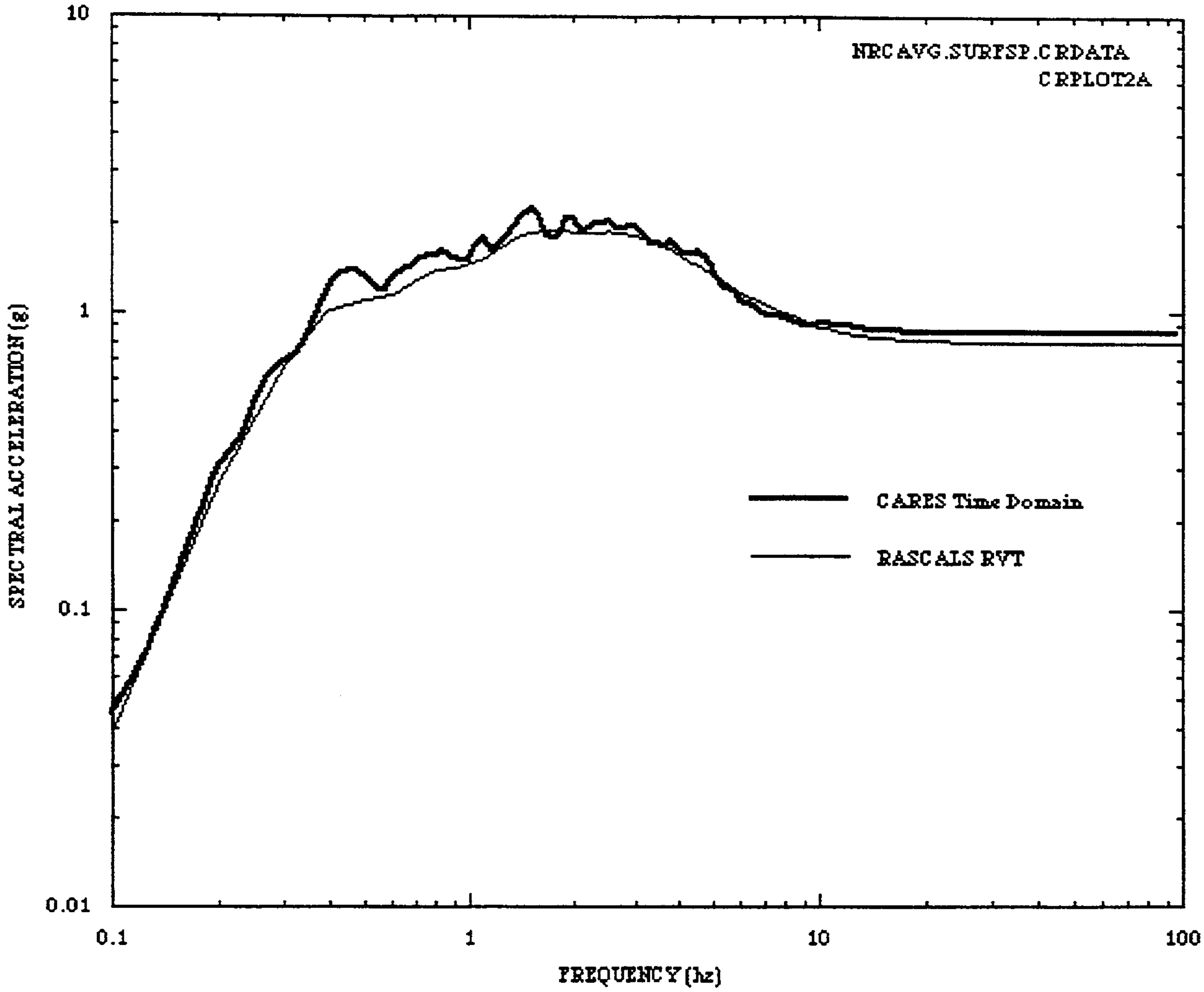


Figure B-7. Comparison of equivalent linear models: mean 5% damped surface spectra Imperial Valley site column from 30 runs using UHS rock outcrop.

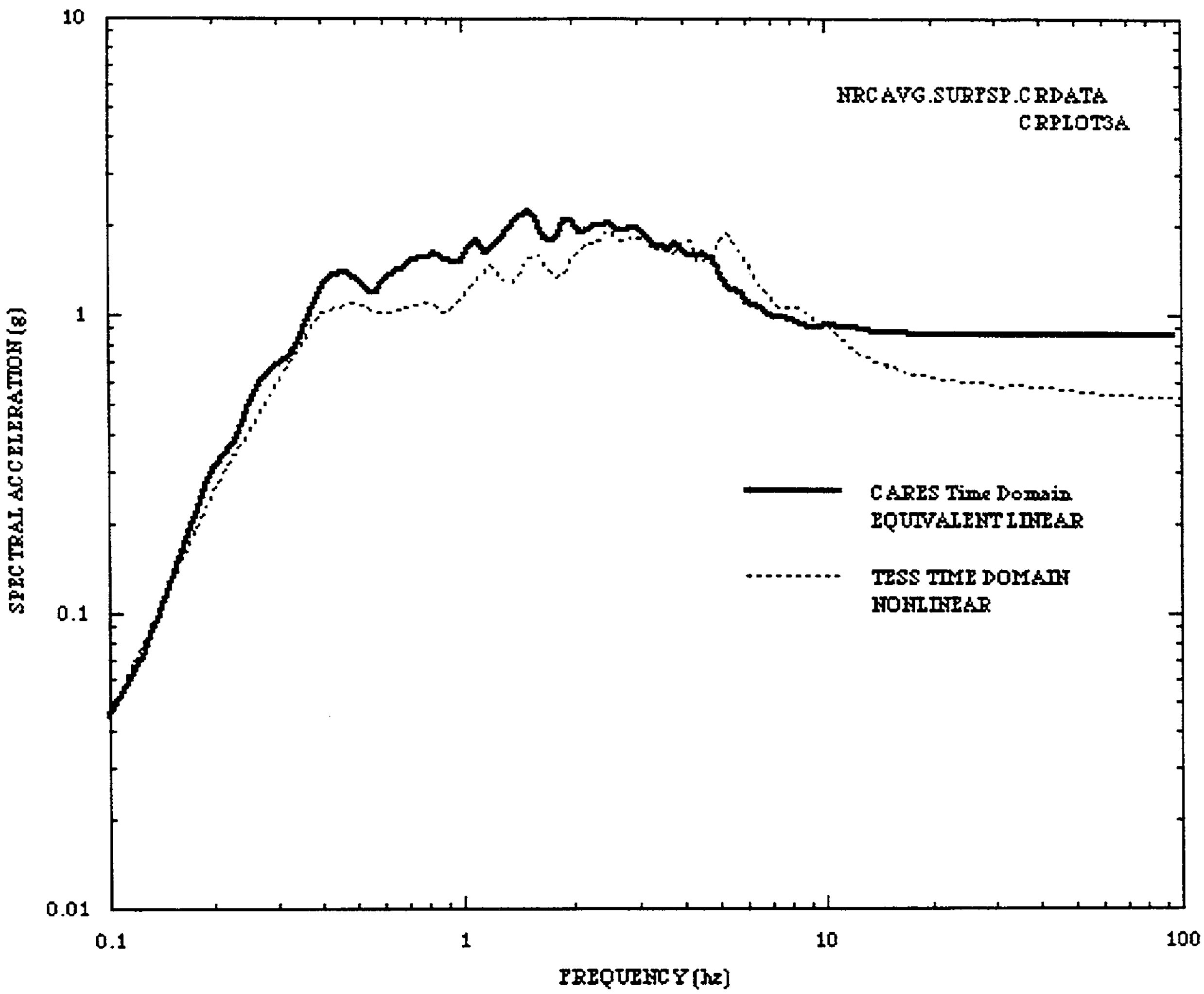


Figure B-8. Comparison of CARES equivalent linear with TESS nonlinear mean 5% damped surface spectra Imperial Valley site column from 30 runs UHS rock outcrop.

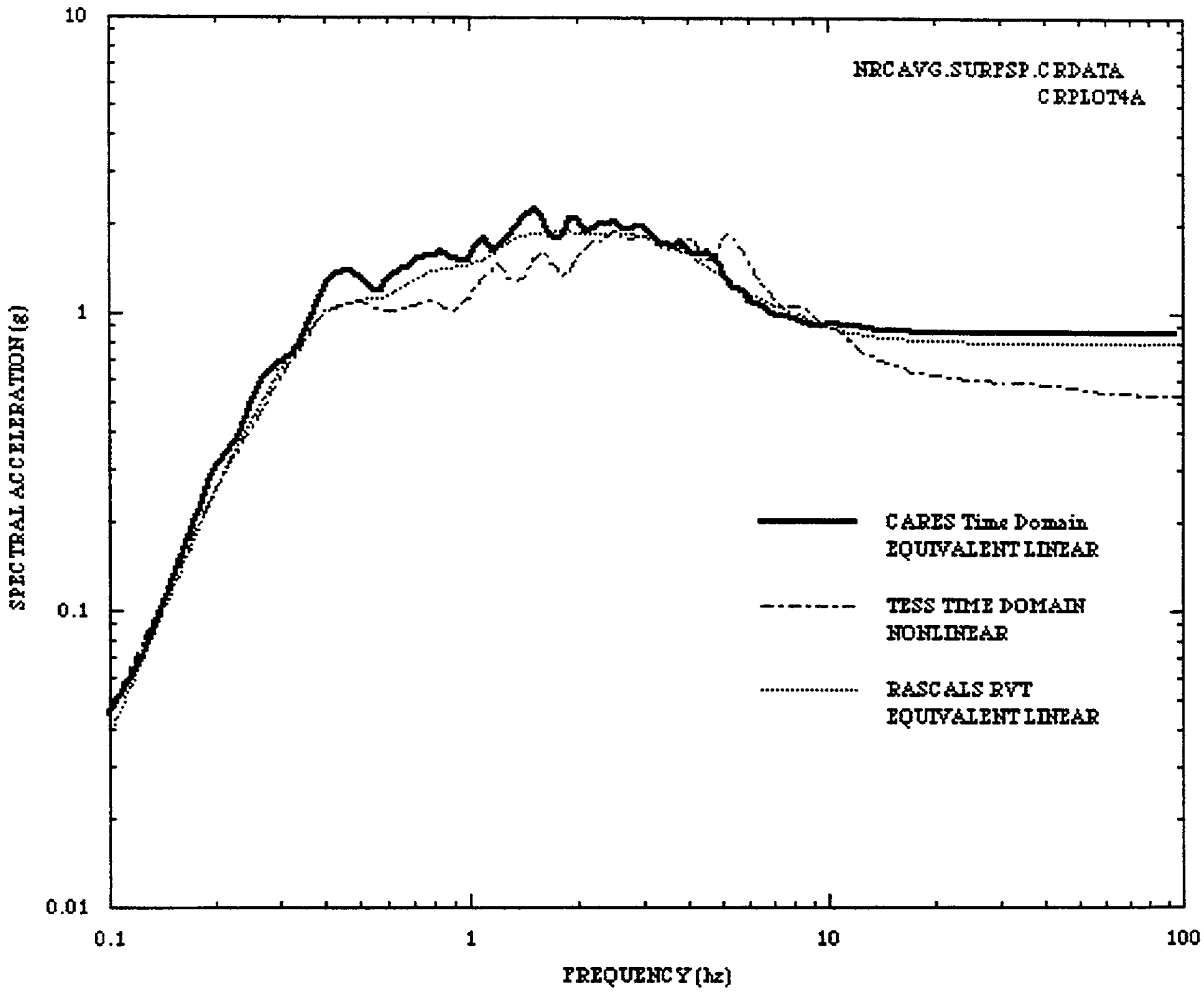


Figure B-9. Comparison of RASCAL equivalent linear with TESS nonlinear mean 5% damped surface spectra Imperial Valley site column from 30 runs UHS rock outcrop.

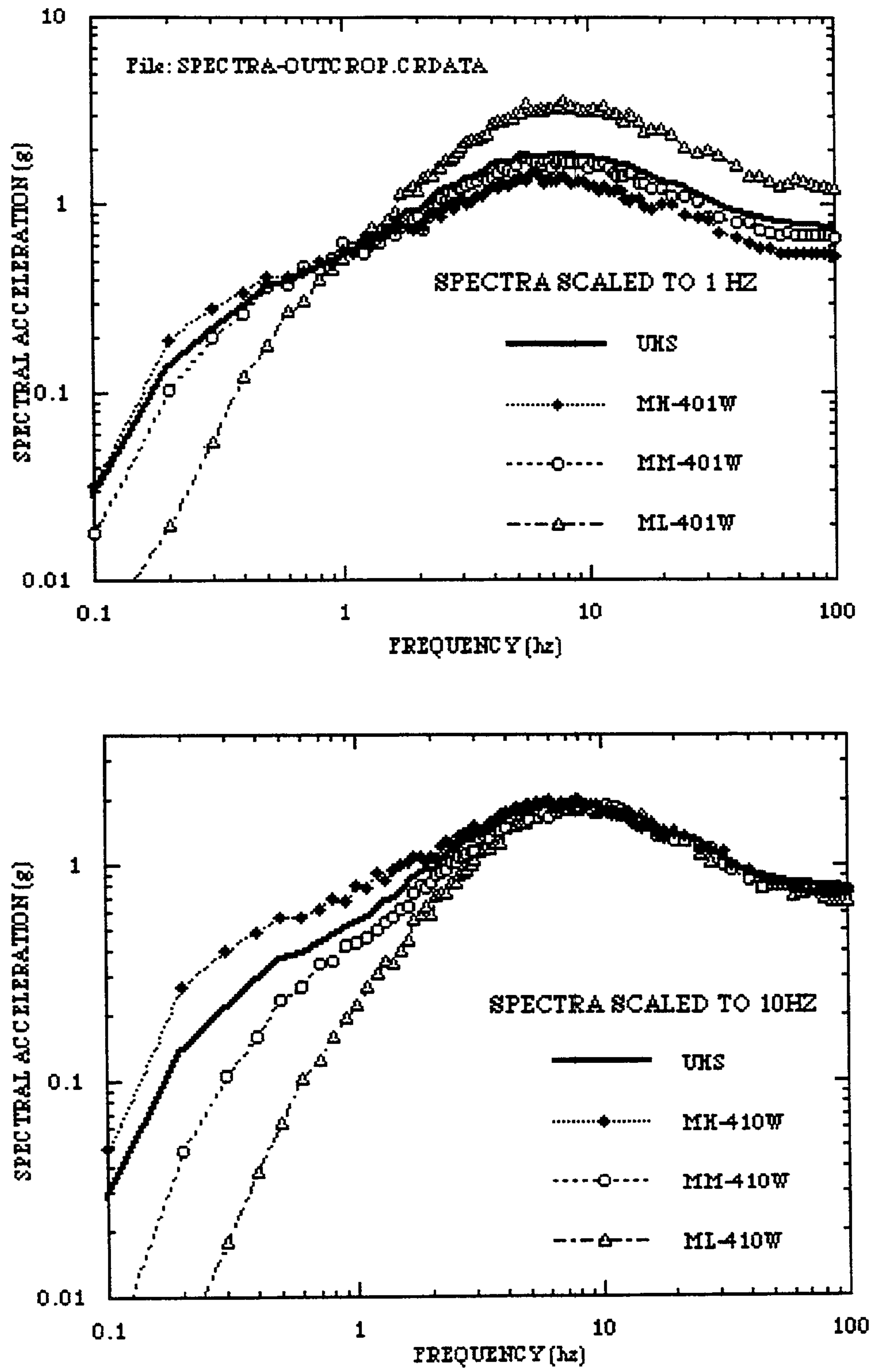


Figure B-10. 5% damped outcrop spectra definitions.

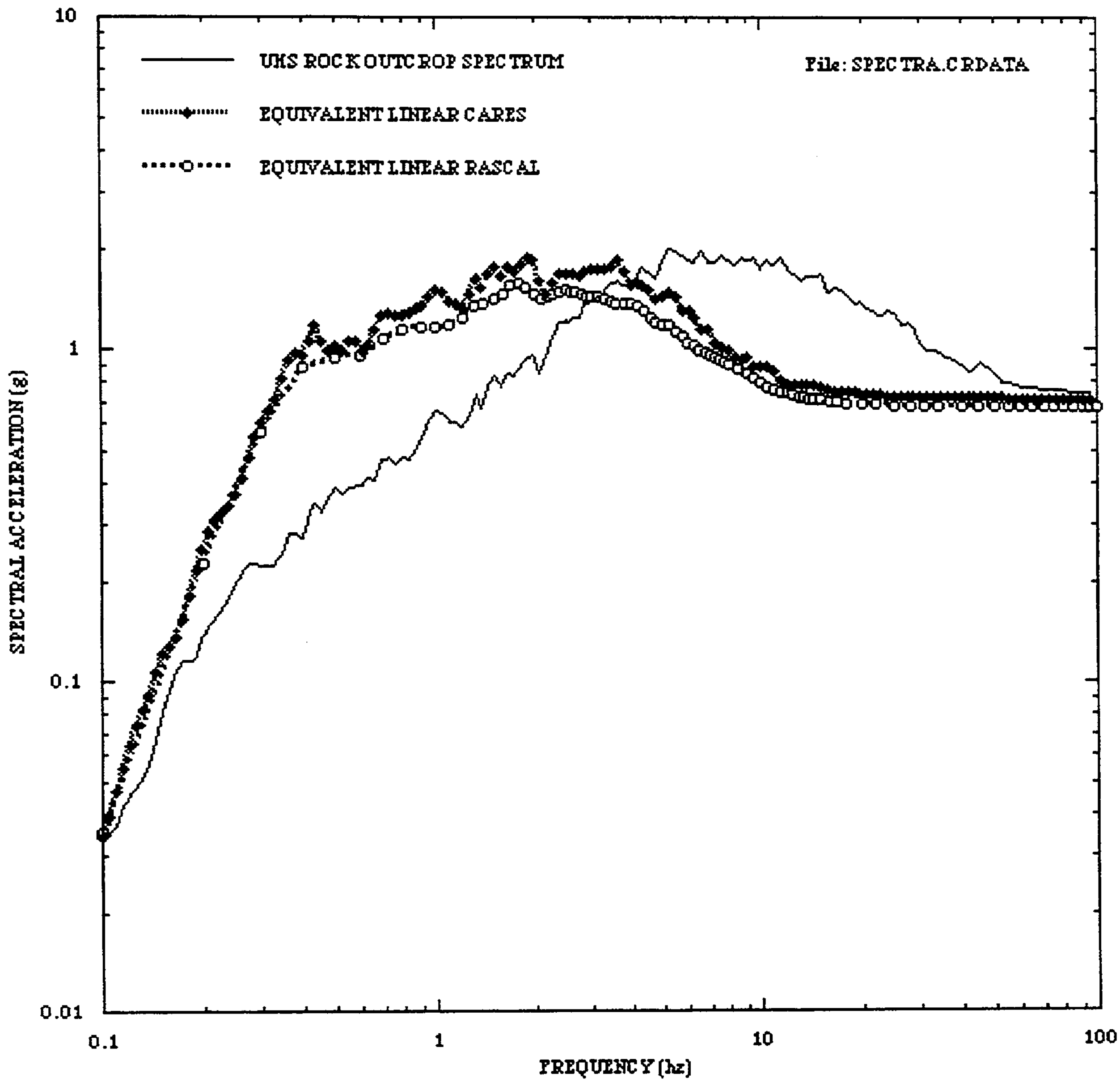


Figure B-11. Comparison of mean surface spectra for Imperial Valley soil columns from equivalent linear CARES and RASCAL calculations (UHS rock outcrop).

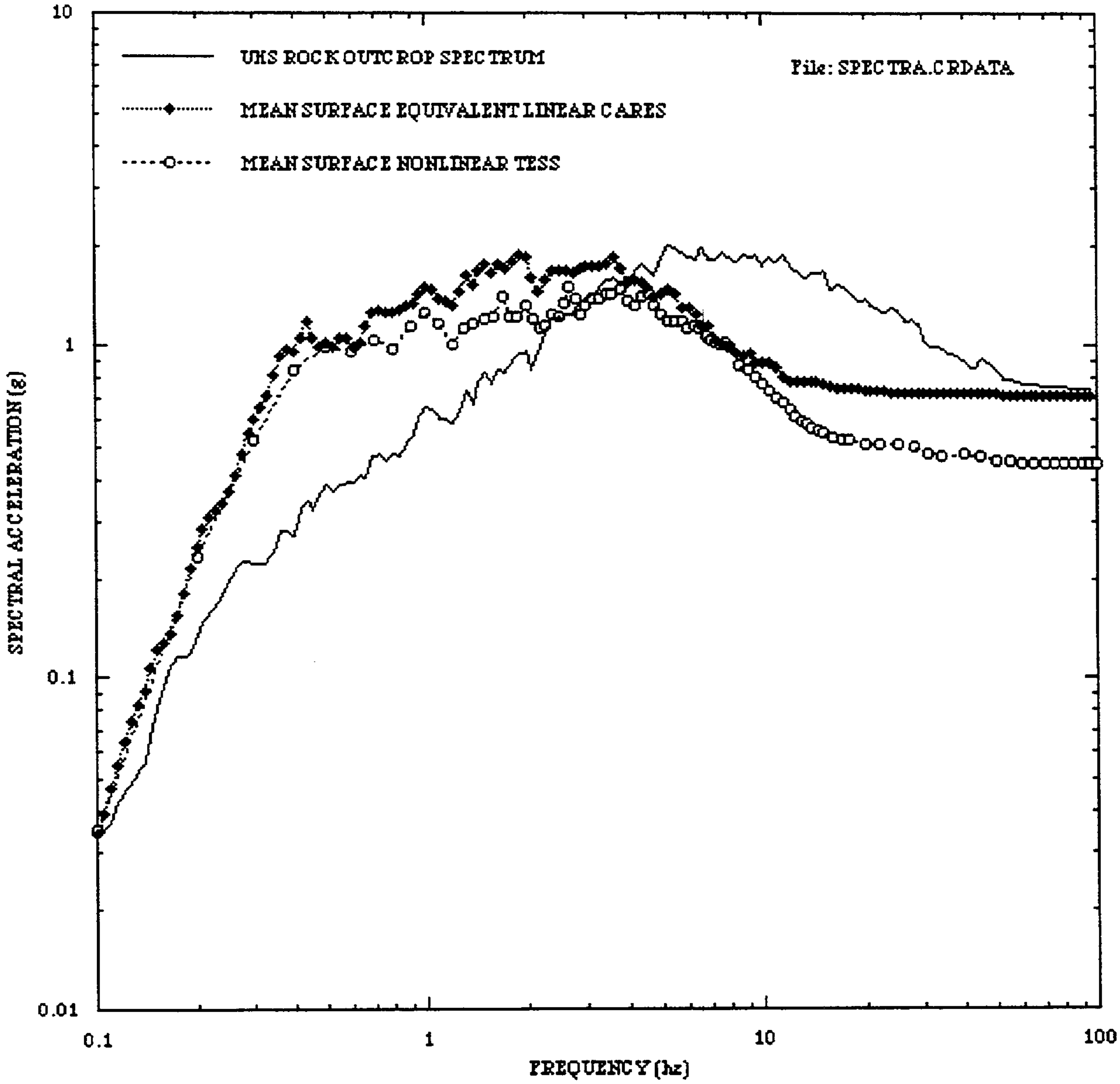


Figure B-12. Mean surface spectra for Imperial Valley soil columns from equivalent linear CARES and nonlinear TESS calculations (UHS rock outcrop motion).

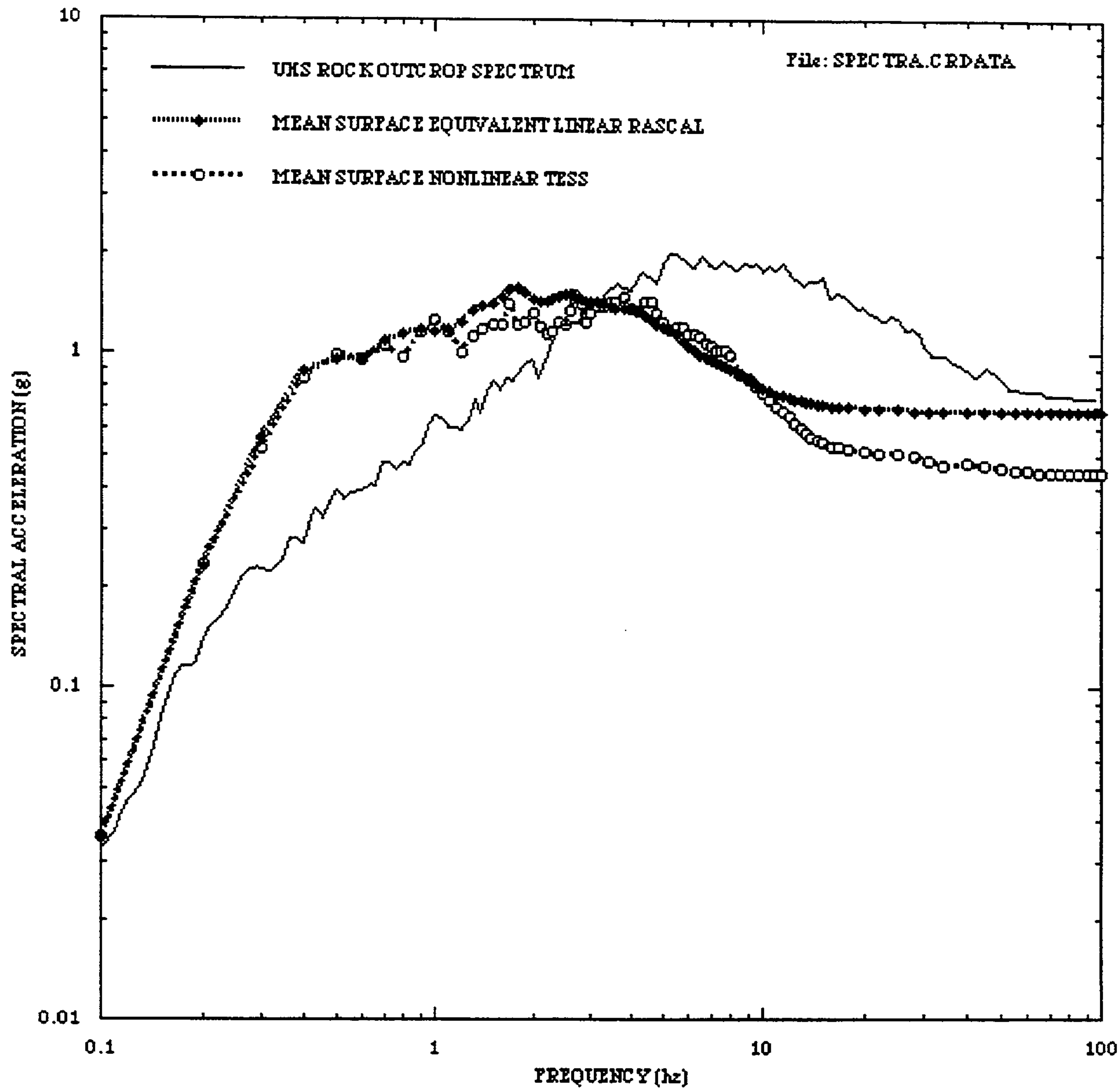


Figure B-13. Comparison of mean surface spectra for Imperial Valley soil columns from equivalent linear RASCAL and nonlinear TESS calculation (UHS rock outcrop).

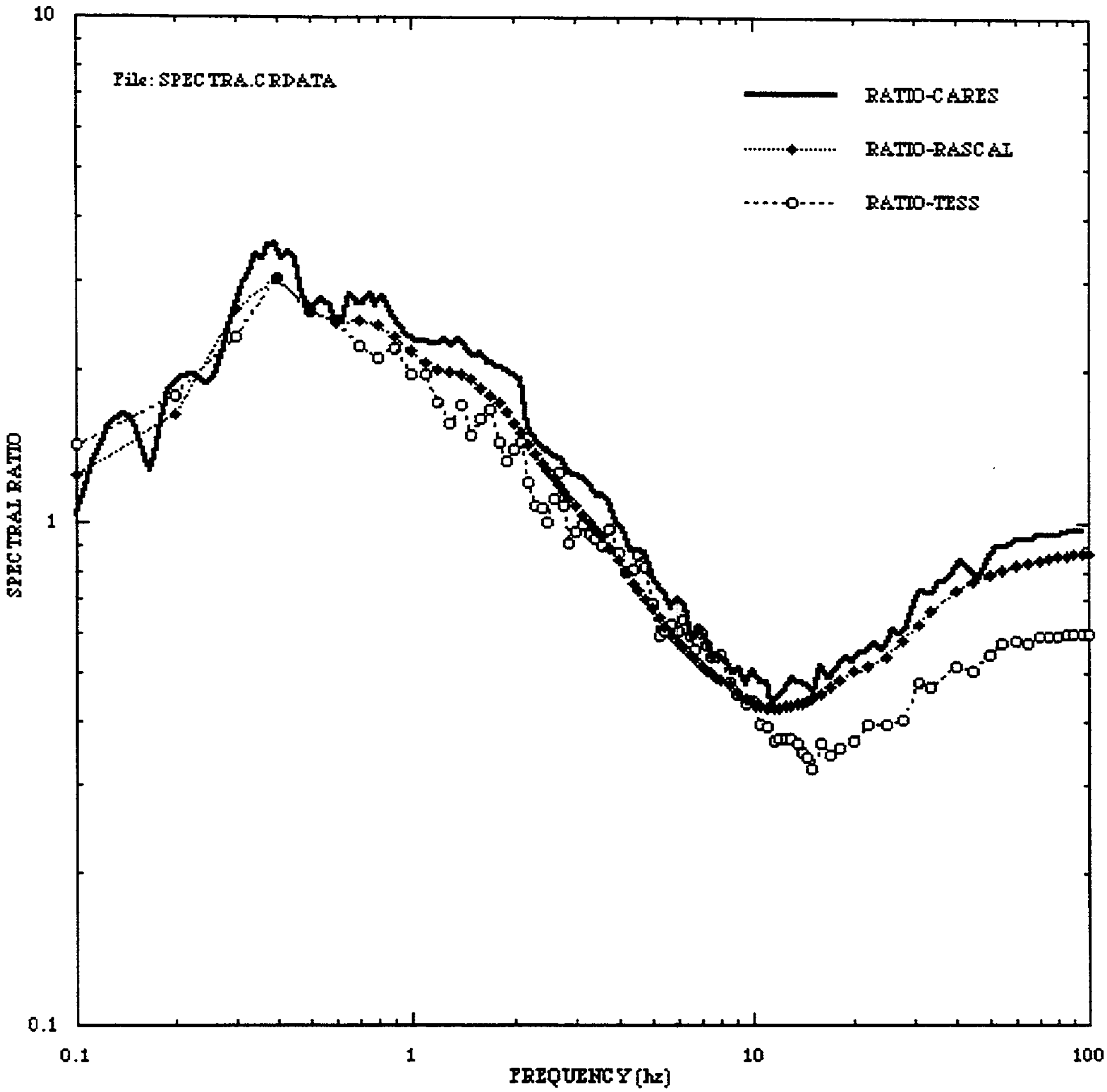


Figure B-14. Mean spectral ratios for Imperial Valley soil columns from CARES, RASCAL and TESS computations for UHS bedrock outcrop input motions.

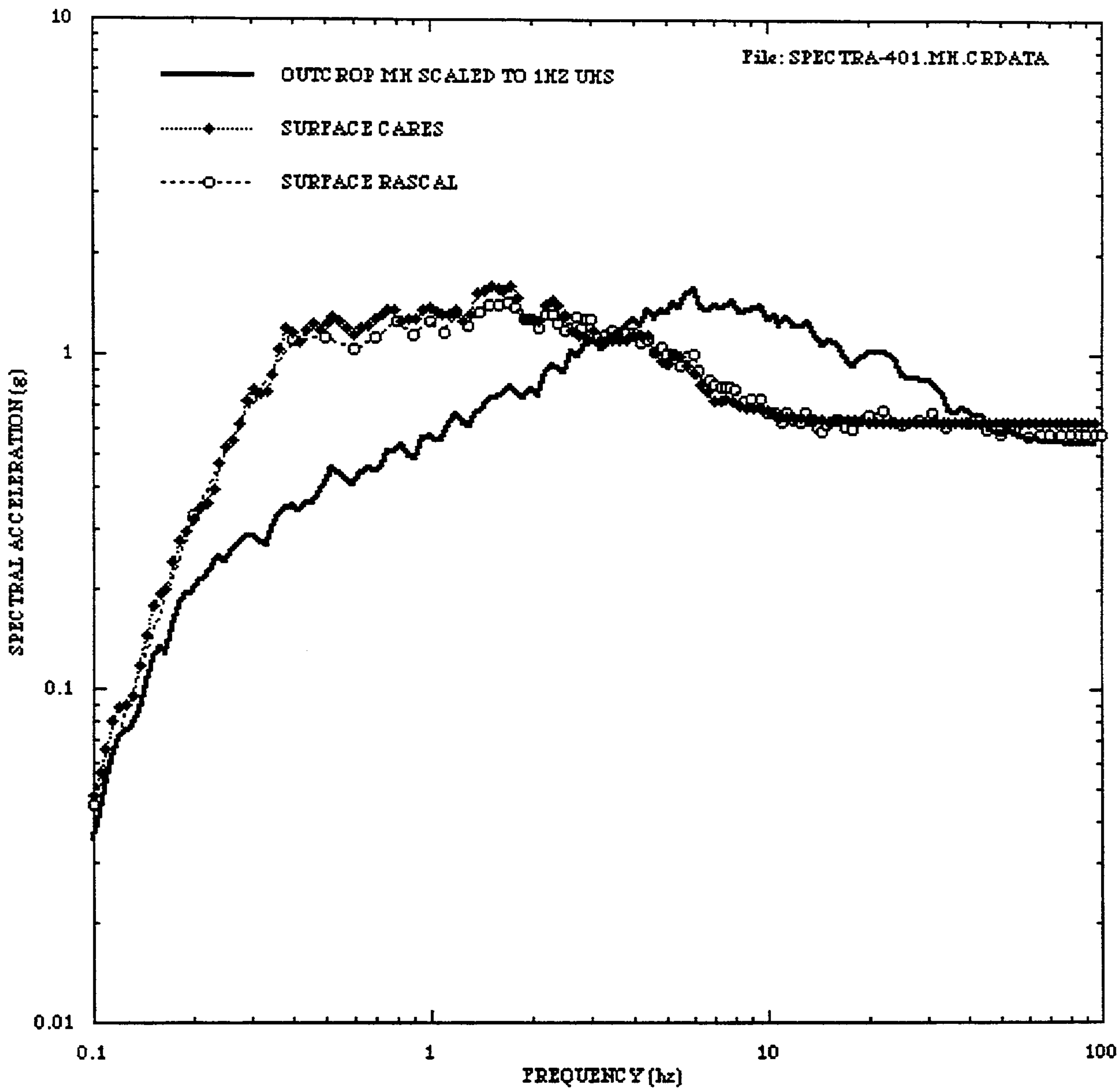


Figure B-15. 5% damped surface spectra for Imperial Valley soil columns from equivalent linear CARES and RASCAL runs for high magnitude event scaled to 1 Hz UHS spectrum.

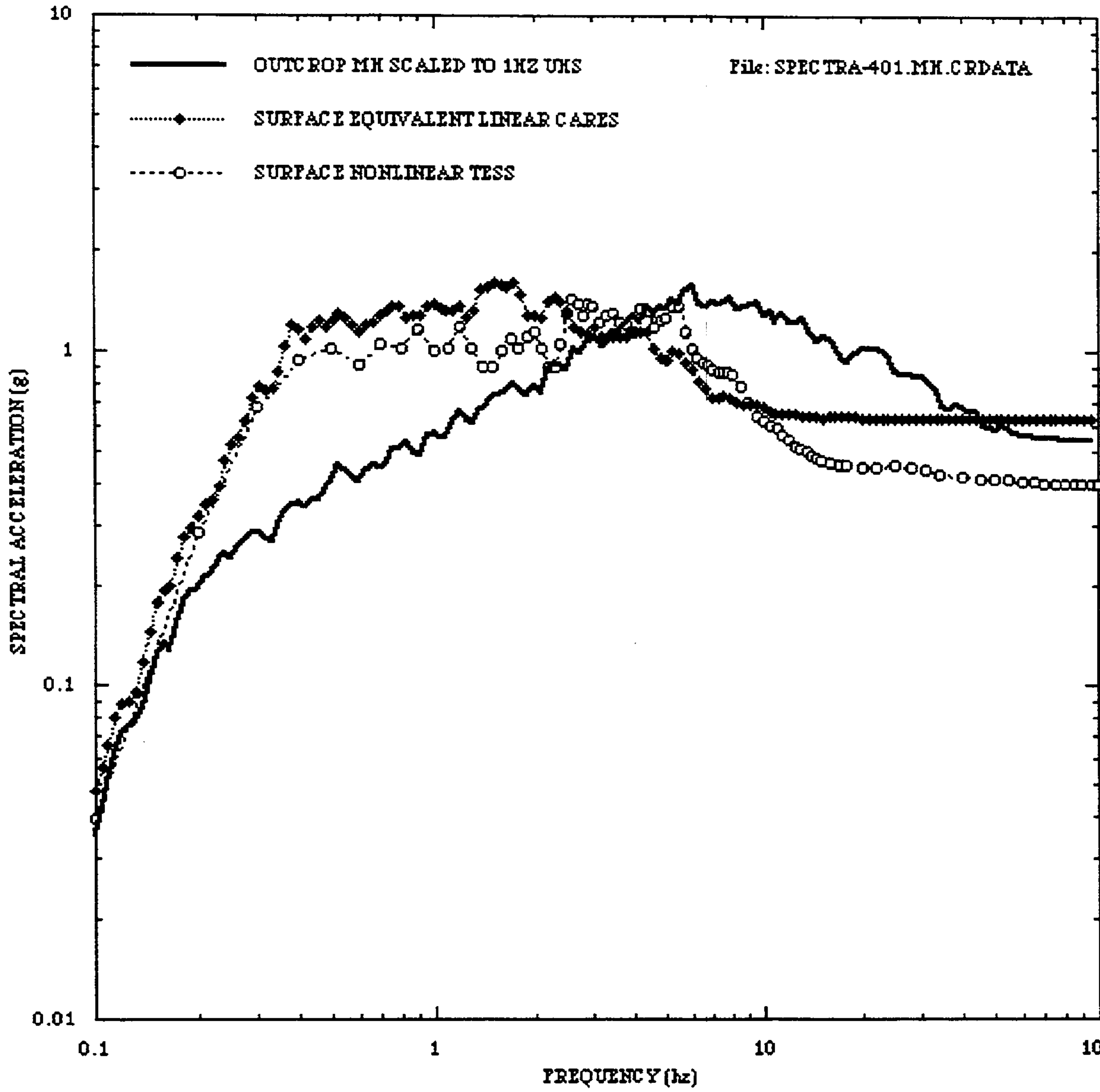


Figure B-16. 5% damped surface spectra for Imperial Valley soil columns from equivalent linear CARES and nonlinear TESS runs for high magnitude event scaled to 1 Hz UHS spectrum.

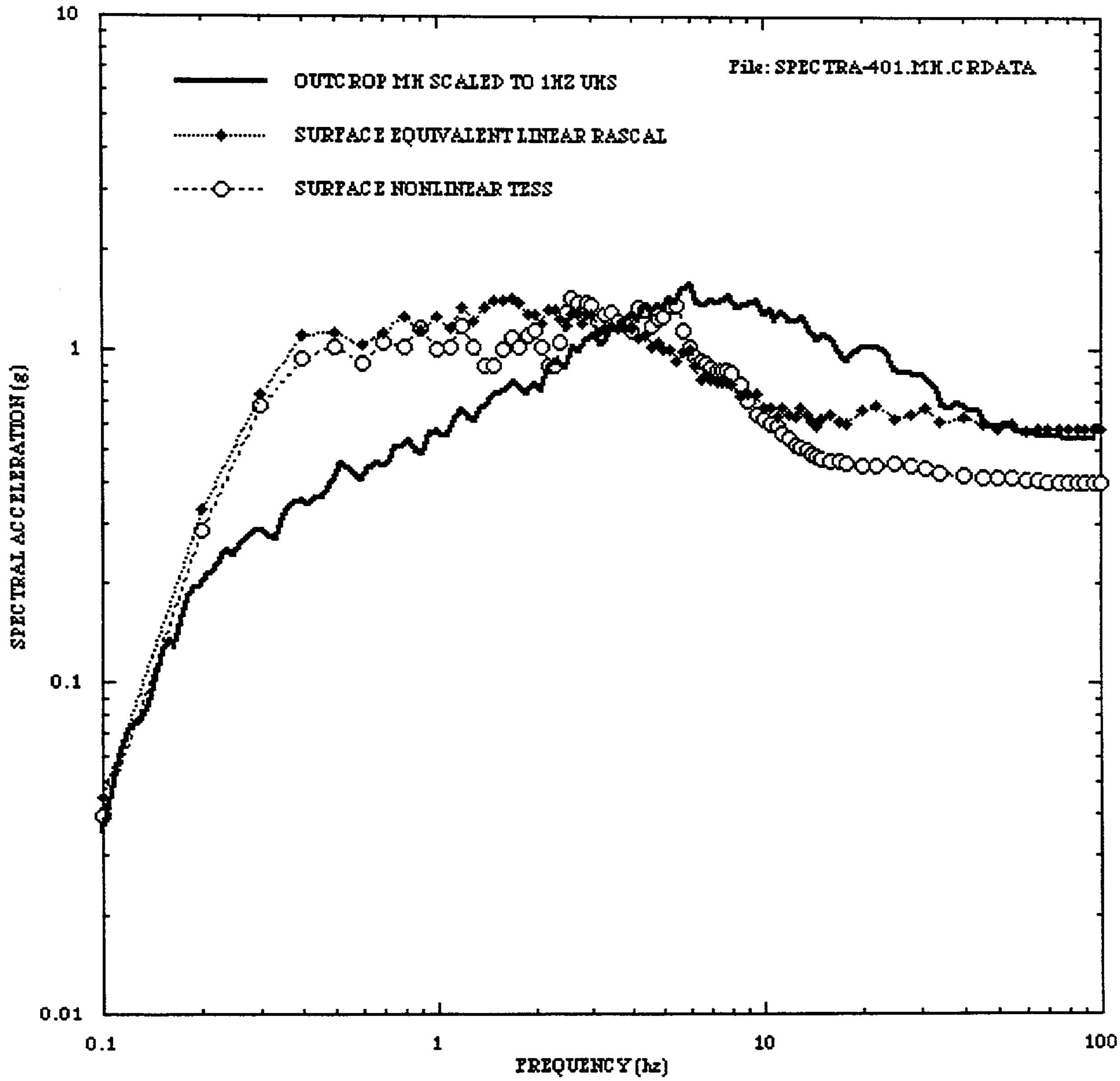


Figure B-17. 5% damped surface spectra for Imperial Valley soil columns from equivalent linear RASCAL and nonlinear TESS runs for high magnitude event scaled to 1 Hz UHS spectrum.

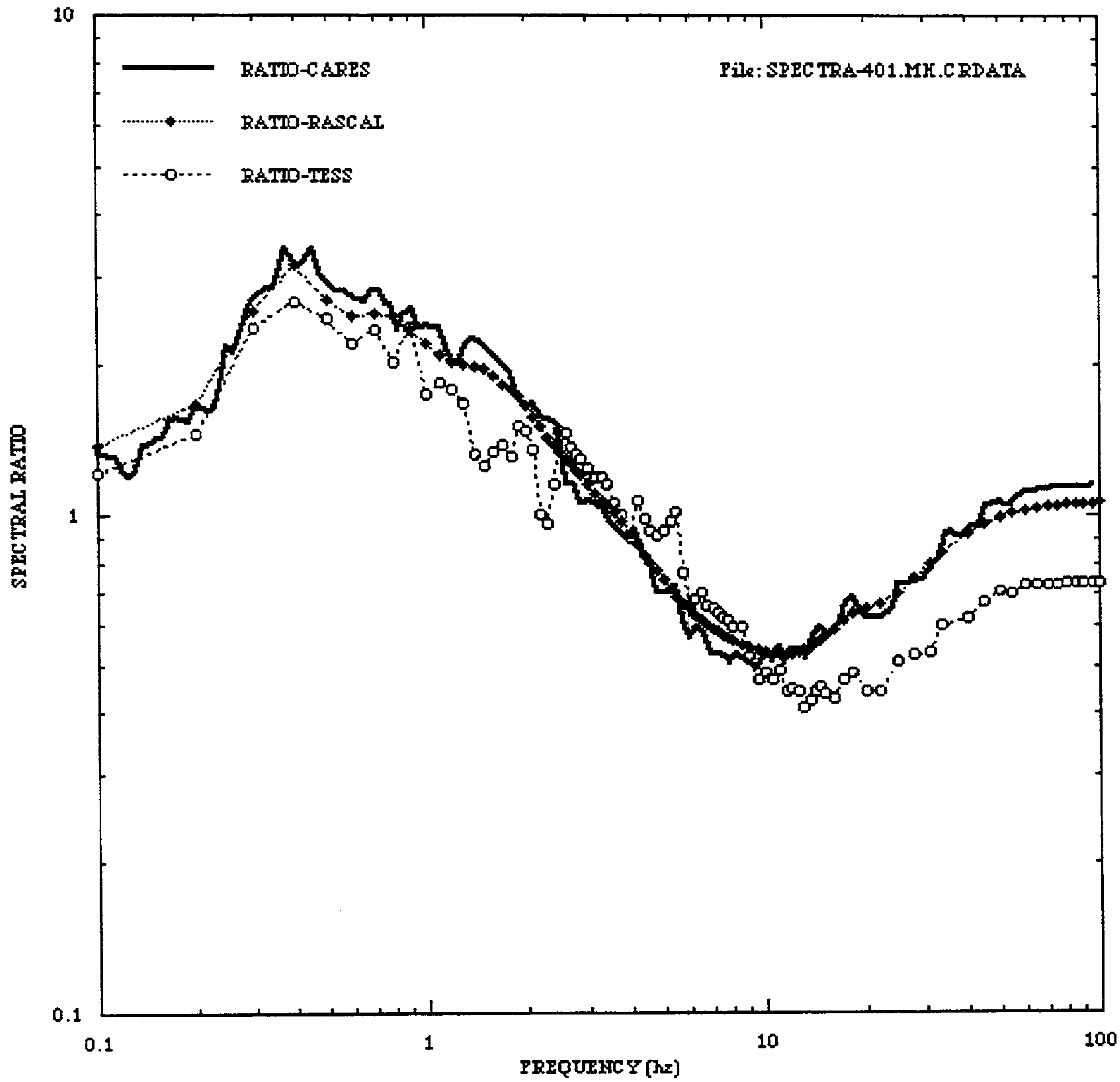


Figure B-18. Mean 5% damped spectral ratios for Imperial Valley soil columns from high magnitude event scaled to 1 Hz UHS spectrum.

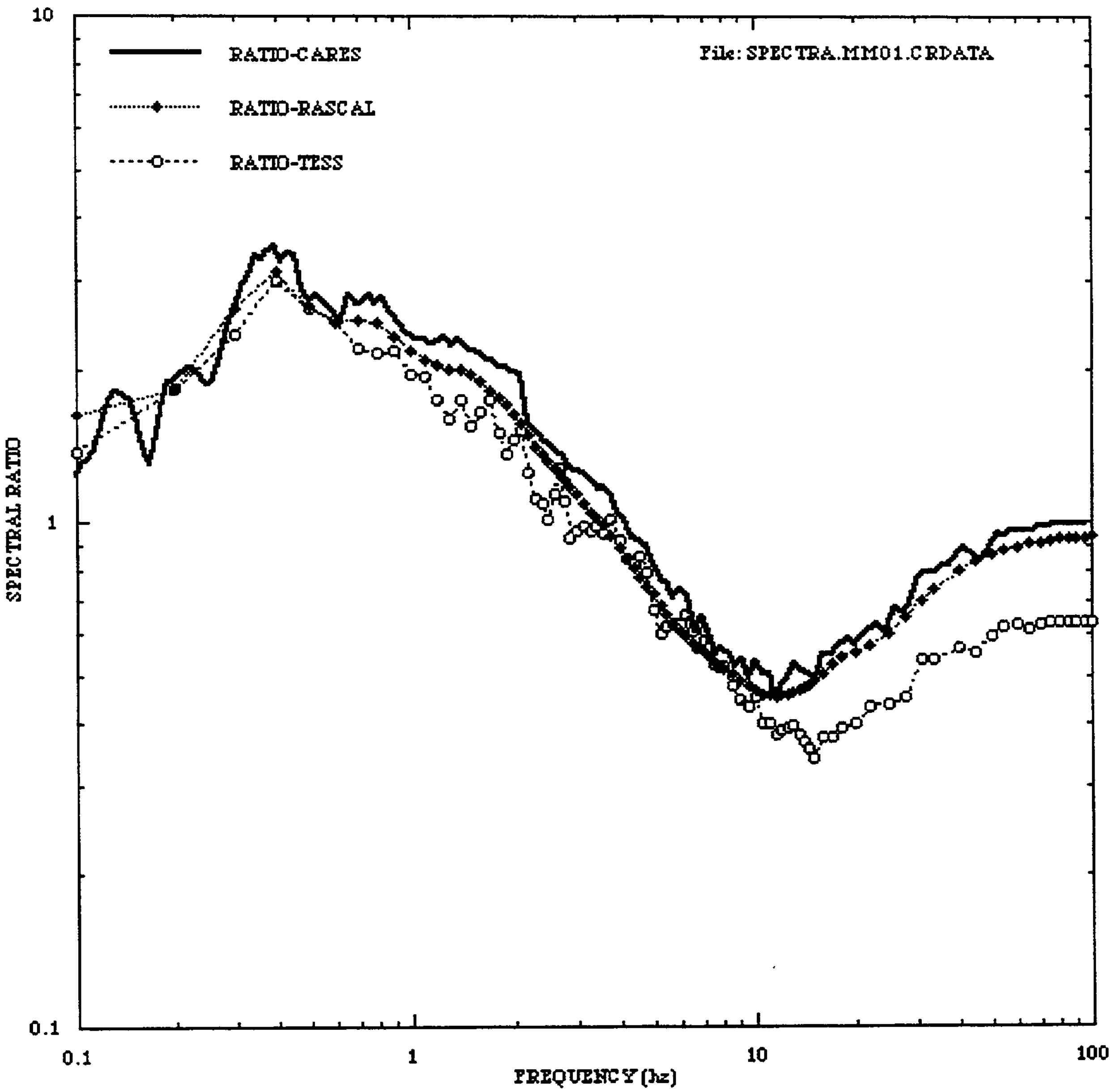


Figure B-19. Mean 5% damped spectral ratios for Imperial Valley soil columns for median magnitude event scaled to 1 Hz UHS spectrum.

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10. SUPPLEMENTARY NOTES
R. M. Kenneally, NRC Project Manager

11. ABSTRACT *(200 words or less)* We illustrate recommendations for design spectra at two example sites, one in the Mojave desert, California, and the second at Columbia, South Carolina. For rock conditions, the uniform hazard spectrum (UHS) is determined at each site with a probabilistic seismic hazard analysis (PSHA). We calculate a scale factor to derive a rock uniform reliability spectrum (URS) based on the slopes of the hazard curves across the frequency range of interest at each site. The database of strong motion records provides a source of rock motions with the correct magnitudes and distances. For soil sites, we illustrate the development of design spectra using a profile of the Savannah River site in South Carolina assumed to lie at the Columbia site. We scale soil spectra to the 10 Hz and 1 Hz UHS and URS, using soil-specific amplification studies, because generic shapes for soil sites are not appropriate. Artificial motions for soil sites are created in a manner similar to that for rock sites.
These recommendations for design spectra illustrate that reliability-consistent spectra can be calculated for both rock and soil sites.

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