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August 12, 2015

PG&E Letter DCL-15-095

U.S. Nuclear Regulatory Commission
ATTN: Document Control Desk
Washington, D.C. 20555-0001

10 CFR 50.54(f)

Docket No. 50-275, OL-DPR-80
Docket No. 50-323, OL-DPR-82
Diablo Canyon Units 1 and 2
Response to NRC Request for Additional Information Regarding Recommendation 2.1 of the Near-Term Task Force Seismic Hazard and Screening Report

References:
1. PG&E Letter DCL-15-035, "Response to NRC Request for Information Pursuant to 10 CFR 50.54(f) Regarding the Seismic Aspects of Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident: Seismic Hazard and Screening Report," dated March 11, 2015
2. NRC Letter, "Diablo Canyon Power Plant, Unit Nos. 1 and 2 - Request for Additional Information Associated with Near-Term Task Force Recommendation 2.1, Seismic Reevaluations (Tac Nos. MF5275 and MF5276)," dated June 29, 2015

Dear Commissioners and Staff:

On March 11, 2015, Pacific Gas and Electric Company (PG&E) submitted, "Response to NRC Request for Information Pursuant to 10 CFR 50.54(f) Regarding the Seismic Aspects of Recommendation 2.1 of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident: Seismic Hazard and Screening Report," (Reference 1).

On June 29, 2015, the NRC Staff requested additional information required to complete the review of PG&E's response (Reference 2). PG&E's responses to the Staff's questions are provided in the Enclosure.

PG&E makes no regulatory commitments (as defined by NEI 99-04) in this letter. This letter includes no revisions to existing regulatory commitments.

If you have any questions, or require additional information, please contact Mr. Hossein Hamzehee at (805) 545-4720.

I state under penalty of perjury that the foregoing is true and correct.

Executed on August 12, 2015.

Sincerely,

Barry S. Allen
Vice President, Nuclear Services

mjrm/50465913-98/4557
Enclosure:
cc: Diablo Distribution
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Response to NRC Request for Additional Information Regarding Seismic Hazard and Screening Report

NRC Request

Consistent with the request for information issued pursuant to Title 10 of the Code of Federal Regulations, Part 50, Section 50.54(f) and the Screening Prioritization and Implementation Details (SPID) guidance, a supplemental response to the March 2015 seismic hazard reevaluation that develops site amplification factors as recommended in Section 2.4 and Appendix B of the SPID is requested. Please provide (1) a detailed description of the subsurface profile properties including uncertainties, (2) the potential for nonlinear behavior at the strain levels produced by the scenario earthquakes of interest, and (3) the control point elevation. In addition, provide the adjustment factors (VS-kappa corrections) needed to modify the median ground motion models for the selected reference or baserock elevation and velocity. Also include in the response, as a figure and a table, control point seismic hazard curves developed using the site amplification factors and their uncertainties through the hazard integral as recommended in Appendix B of the SPID.

Pacific Gas and Electric Company (PG&E) Discussion

Ergodic ground-motion prediction equations (GMPEs) model provide a median spectral acceleration based on world-wide data. In these models, the systematic differences in the site amplification between different sites within the same site class (or with the same shear wave velocity (VS)30) are treated as aleatory variability and are included in the aleatory standard deviation of the GMPE. These differences in the systematic site amplification do not apply to all sites. Each site will have its own average amplification, but there will be epistemic uncertainty in the estimation of the site specific amplification. That is, the systematic differences in site amplification from site to site represent epistemic uncertainty, not aleatory variability.

The single-station sigma approach addresses the differences in the average site amplification by removing the site to site differences from the ergodic standard deviation of the GMPE. The estimate of the site-specific site amplification and the epistemic uncertainty in the site amplification for a given site needs to be incorporated in the hazard study. This is called the partially nonergodic approach.

In the partially nonergodic approach, the median ground motion at a site is given by:

$$\ln PSA(M,R,Site,f,...) = GMPE(M,R,VS30_{REF},f,...) + \hat{A}mp(f,PSA_{REF})$$

where PSA is the median spectral acceleration at the site for a given event, GMPE is the median spectral acceleration based on the global models, and $\hat{A}mp(f,PSA_{REF})$ is the site-specific systematic site amplification relative to the global model for the reference site condition. The aleatory standard deviation is given by the single-station sigma.

The hazard for the reference site condition can be computed using the global model and the single-station sigma. The site-specific hazard can be computed by including the site-specific amplification, which requires estimating the site-specific $\hat{A}mp(f, PSA_{REF})$ term and the epistemic uncertainty in the $\hat{A}mp(f, PSA_{REF})$. The $\hat{A}mp(f, PSA_{REF})$ term is an average site term and does not include aleatory variability of the site amplification that may arise from different input ground motions. Because the single-station sigma only removed the effects of the average site amplification from the ergodic standard deviation, the aleatory variability of the site amplification is still part of the single-station sigma. The standard deviation for GMPEs is computed from ground motions that are mainly in the linear range, so the single-station sigma represents the aleatory site amplification in the linear range. If there is increased variability for highly nonlinear cases, then that additional aleatory variability is not captured in the single-station sigma model. This additional aleatory variability at high ground motion levels is included in the soil hazard calculation (see response to Question 4).

To compute the hazard at the control point requires estimation of the $\hat{A}mp(f, PSA_{REF})$ term including the epistemic uncertainty. There are two approaches that can be used to estimate $\hat{A}mp(f, PSA_{REF})$: observed ground motions at the site, and analytical modeling of the site response.

Pacific Gas and Electric Company (PG&E) used the observed ground motion approach in the March 2015 submittal. The empirical site-term approach is preferred because site-specific empirical ground motion data are available at Diablo Canyon Power Plant (DCPP) and these data provided the best information on the site response because they sample the actual conditions at DCPP. In particular, the data provide a better representation of the effects of the deeper structure that are important to the kappa and to the low-frequency response, which many not be captured in the analytical modeling of the shallow velocity structure. Using only analytical modeling, there can be a large uncertainty of the amplification due to uncertainty in the kappa value, however, using the empirical data, the effect of kappa on the high frequency amplification can be constrained by the observed ground motion data. Using empirical ground motions at the site also captures the effect of the averaging the velocity structure over the wavelength of ground motion in the complex three dimensional (3-D) profile at DCPP in contrast to analytical modeling that use one dimensional (1-D) velocity profiles, which can over-estimate site resonance effects. Finally, the consistency of the high frequency site terms for the two different earthquakes recorded at DCPP indicates that the empirical data is capturing an average site term. As noted in the question, a key limitation of the empirical method is that it is based on a small number of recordings. This is captured in the epistemic uncertainty of the site terms. As shown in the March 2015 submittal (Reference 1), there is a large epistemic uncertainty in the estimates of the DCPP site terms, however, it is smaller than the uncertainty resulting from the uncertainty in the inputs to the analytical modeling.

The alternative approach to estimating the site terms is the analytical site response modeling approach. This still uses the partially nonergodic methodology, but uses site response calculations to estimate the $\hat{A}mp(f, PSA_{REF})$ terms.

To address this request for additional information, an alternative analytical approach was used to develop site-specific amplification factors, following the guidelines from the NRC endorsed 2013 EPRI Technical Report No. 1025287, Appendix B, "Seismic Evaluation Guidance, Screening Prioritization and Implementation Details (SPID)." From the analytical approach the following were developed: (1) a suite of shear-wave velocity profiles, kappa values, and nonlinear material properties were developed to adequately reflect the uncertainty in site-specific dynamic material properties; and (2) amplification factors (median estimates and aleatory variability) relative to generic rock (VS30 – 760 meters per second (m/s)) as reflected in Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation model (NGA) West-2 ground motion prediction equations (GMPEs), which is the reference rock condition used in the Probabilistic Seismic Hazard Analysis (PSHA). At each ground motion level, thirty realizations were developed varying the site-specific shear-wave velocity and G/Gmax and hysteretic damping curves. The profile randomization is based on the footprint correlation model with plus or minus 2 sigma bounds as per the SPID (Reference 6). Depth to rock was not randomized because there is a gradient in the VS profile and there is not a clear depth to rock parameter. Using these analytical amplification factors, new control point hazard curves and ground motion response spectra were calculated.

The alternative model parameters are described in the response to NRC Question 1. The potential for nonlinearity of the site response is described in response to NRC Question 2. The resulting control point hazard curves and ground motion response spectrum (GMRS) are given in response to NRC Question 4.

A comparison of the resulting site amplifications from the analytical modeling approach and the empirical data approach is shown in Figure 1. The black curves show the mean and range of the empirical site terms used in the March 2015 submittal. The blue curve shows the mean amplification from the analytical modeling for a kappa of 0.040 seconds (sec) for a reference rock peak acceleration of 0.1g that is representative of the linear response range which is consistent with the level of shaking from the empirical data used to compute the empirical site terms. The gray curves show range of the amplification for different assumptions of the velocity profile and the nonlinear site parameters for a kappa of 0.040 sec. These alternative cases are described in detail in the response to the questions.

Figure 1 shows that the site terms from empirical model are generally consistent with the site terms from the analytical modeling for the high frequencies. Stronger resonances are seen in the analytical model results (e.g., 12 hertz (Hz)) which is a common feature of site response based on 1-D velocity models. At the 1-3 Hz range, the analytical modeling leads to lower amplification than the empirical model because the shallow velocity model using in the analytical modeling does not capture the effects of the site-specific deep velocity profile, whereas, the empirical model captures the effects of the full velocity profile.

The analytical model described in the response to the questions also includes a broad uncertainty in the site kappa value, which leads to a broader range of amplifications in the high frequency range than shown in Figure 1. The uncertainty range with kappa is much broader than the uncertainty range from the empirical approach. This shows the value of using observed ground motions over assumed parameter distributions from generic correlations. Because the large amplification that results from the lower kappa value is not seen in the recorded ground motions at DCPP, the lower kappa value (0.024 sec) is not consistent with the observed ground motions. The broad uncertainty range for kappa is included in the response to the questions to be consistent with the SPID methodology. However, based on the high frequency content of the observed ground motions at DCPP, PG&E considers the low kappa value to be not applicable to DCPP. The high kappa value of 0.07 sec is also inconsistent with the frequency content of the recorded ground motions at DCPP.

A key difference between the analytical site factors and the empirical site factors is how nonlinear site effects are incorporated. In the empirical approach the nonlinearity is included to the extent that it is represented in the empirical GMPEs. The empirical GMPEs include nonlinear site response at the level of the median ground motion. The nonlinear behavior at the median level is extrapolated to higher ground motion levels (in terms of the effect on the standard deviation). In contrast, the analytical modeling includes the nonlinear effects at the level of shaking of interest (e.g., including the epsilon of the input motion) and not just at the median ground motion level (e.g., epsilon = 0). For VS30=760 m/s, the empirical GMPEs are linear at the median ground motion level. Therefore, they remain linear at higher levels of epsilon as well.

Figure 2 shows the same comparison of the analytical results and the empirical factors for a reference rock Peak Ground Acceleration (PGA) of 1.1 gravity, acceleration of (g), which is close to the reference rock PGA for the 1E-4 hazard level. As a result of the nonlinearity in the analytical model, the analytical site factors depend on the amplitude of reference rock ground motion. The mean site factors based on the analytical model at a 1.1g reference rock PGA level are similar to or lower than the empirical site factors. The full soil hazard curves use all of the ground motion levels utilizing Approach 3 that is described in Reference 6. While the full soil hazard curves use all of the ground motion levels, the amplification factors near the 1E-4 hazard level approximate the site factors for the GMRS. The full soil hazard curves are presented in the response to Question 4.

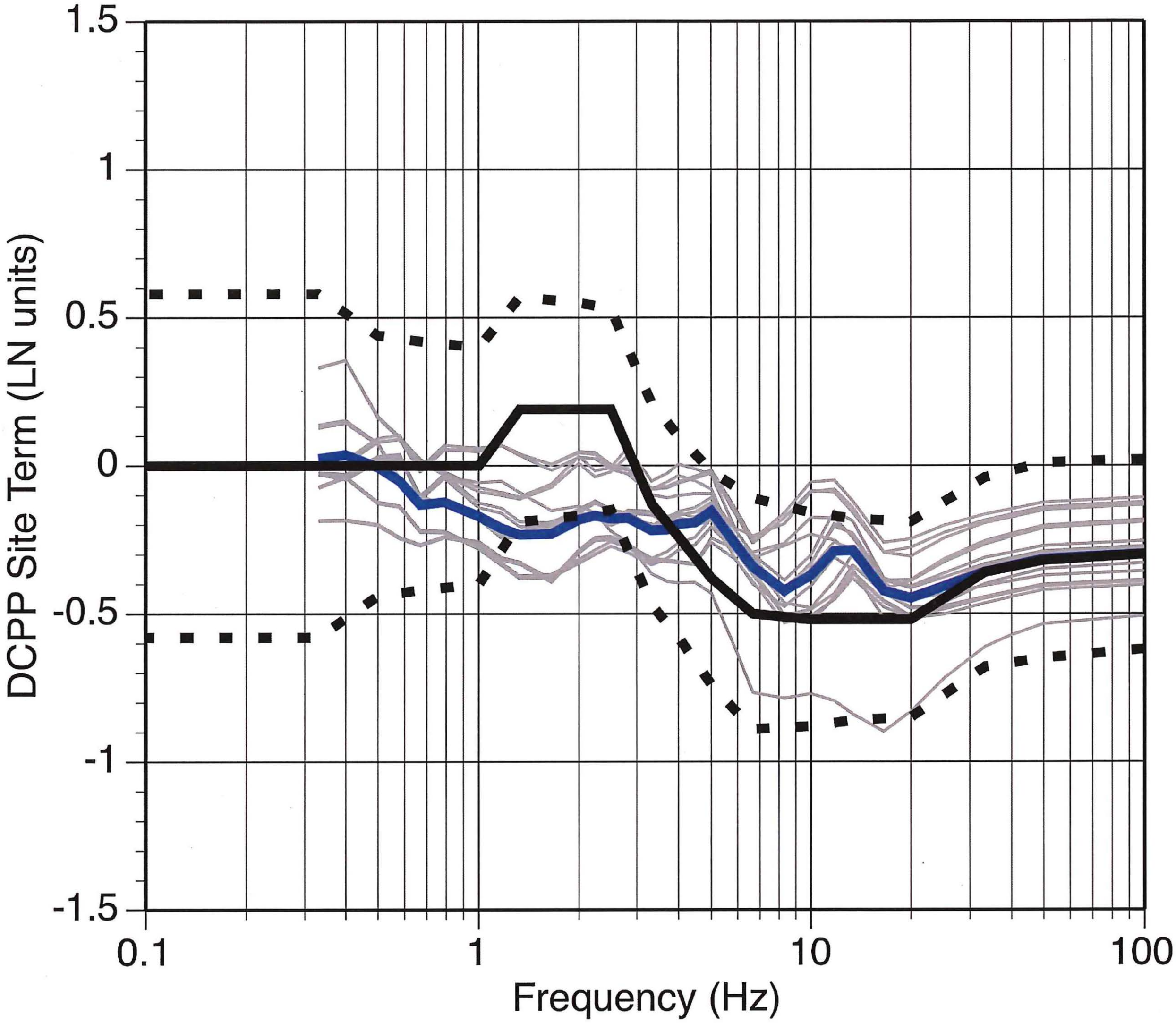

Figure 1: Comparison of the estimates of the DCPP site term for the empirical approach (black lines) and the mean amplification from the analytical modeling approach (blue curve) for a kappa of 0.040 sec and a reference rock peak acceleration of 0.1g. The thin gray lines are results for the alternative velocity profiles and nonlinear properties for a kappa of 0.040 sec.

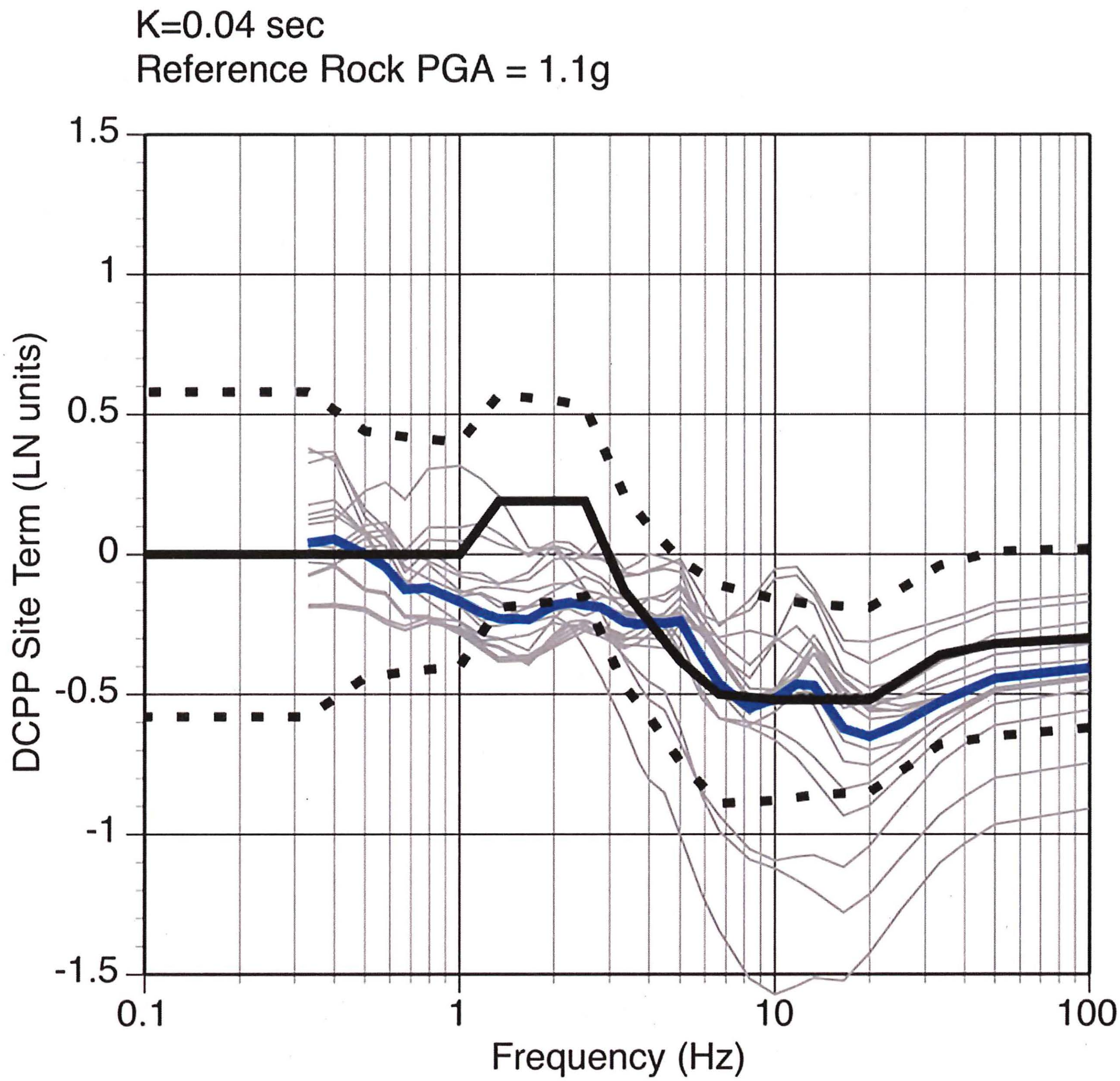

Figure 2: Comparison of the estimates of the DCPP site term for the empirical approach (black lines) and the mean amplification from the analytical modeling approach (blue curve) for a kappa of 0.040 sec and a reference rock peak acceleration of 1.1g. The thin gray lines are results for the alternative velocity profiles and nonlinear properties for a kappa of 0.040 sec.

NRC Question 1

Please provide a detailed description of the subsurface profile properties including uncertainties.

PG&E Response

A description of geologic units in the subsurface material was provided in Section 2.3.1 of PG&E's Seismic Hazard Screening Report. The shear-wave velocity in the DCPP site region is described in the Fugro May 2015 report (Reference 3). This report provides an update to the 3-D VS model using additional surface-wave dispersion information. These surface-wave dispersion analyses were followed by additional 3-D VS model refinements and uncertainty analyses using Vibroseis ground motion time history data and full-waveform modeling to constrain the shallow VS profile. The resulting central VS profile for the control point differs from the VS profile provided in the Central Coast California Seismic Imaging Project (CCCSIP) report. The details of how the updated profiles were developed are given in Reference 3. A copy of Fugro (2015) and external independent peer review of the report is made publically available on the following website:

www.pge.com/dcpp-ltsp

For the Free-Field Seismic Instrument Control Point (ESTA28, Elevation 85 ft), the VS profile was developed using a representative 1-D profile from the 3-D model (given in Appendix H of Reference 3). The uncertainty in the 3-D velocity model was also addressed in Reference 3 (Section 3) and the recommended uncertainty range is listed in Table 1-1 below. Using this uncertainty estimate, the epistemic uncertainty in the VS profile at ESTA28 was developed using plus or minus 1.6 times the standard deviation (approximates the 5^{th} to 95^{th} fractile for the uncertainty) at all depths. The three alternative base velocity profiles for the shallow part of the profile (to a depth of 126 meters (m)) are plotted in Figure 1-1 below. Because these profiles represent the 5 to 95 percent range, the logic tree weights are 0.6 for the central model and 0.2 each for the upper and lower models.

The site response calculation computes the ground motion starting at the source at a depth of 8 kilometers (km). The three shallow VS profiles are extended to larger depths using a gradient model and the extended profile is then merged with the generic velocity profile for VS30=760 m/s in California down to a depth of 8 km.

Two alternative models are used for the deep profile as shown below in Figures 1-2, 1-3, and 1-4: deep gradient (P1) and a shallow gradient (P2). There is no strong basis for preferring one gradient model over the other. Therefore, these two models are given equal weight (Reference 4).

Combining the three alternative shallow VS profiles with the two alternative deep gradients leads to six alternative base-case VS profiles. The digital values for these six base-case profiles are provided as an attachment to the Pacific Engineering and Analysis Report (Reference 4).

The material models (damping and modulus reduction) are modeled using three models: linear (M1), EPRI (1993) rock (M2), and Peninsula Range (M3). For the linear model, the small strain damping is from the Peninsula Range model, however, the results are not sensitive to the selected small strain damping because additional small strain damping is added to the deeper part of the profile so that the total kappa matches the specified kappa value (Reference 4). The modulus and damping curves for the two nonlinear models are shown below in Figures 1-5 and 1-6. The nonlinear model is applied to the layers at depths up to 500 ft (152 m). Below a 500 ft depth, a linear model is used. The linear and nonlinear approaches are given equal weight. The two nonlinear models are also given equal weight. The logic tree weights are 0.5 for the linear model (M1) and 0.25 each for the two nonlinear models (M2 and M3) (Reference 4).

For each alternative model, the kappa due to the low strain damping in the shallow layers was computed and additional damping was added to the deep layers so that the total kappa was consistent with the surface kappa. The best estimate kappa value for control point is 0.04 sec based on the evaluation of the spectral shape from the 2003 Deer Canyon Earthquake (Reference 5). Following the SPID, uncertainty in kappa was addressed by assuming an uncertainty of 0.4 ln units (Reference 4). Using the 10 percent to 90 percent range (scale factor of 1.7), the resulting alternative kappa values are 0.024, 0.040, and 0.070 sec. Pacific Engineering and Analysis recommended weights of 0.3, 0.4, and 0.3, for the three kappa values (Reference 4), but because there are other recordings from the San Simeon and Parkfield earthquakes that are also consistent with the kappa near 0.04 sec, the weights were modified to give less weight to the upper and lower values; the weights for the three kappa values are set at 0.2, 0.6, and 0.2 as shown in Figure 1-7. The Research Information Letter (RIL) published by the NRC (Reference 7) also evaluated the kappa from the three available recordings and showed that the kappa ranged from 0.03 sec to 0.056 sec with a median of 0.04 sec.

For the reference rock profile, the bedrock kappa is 0.03 sec based on inversions for bedrock kappa using the NGA West-2 GMPEs for a reference site with VS30=760 m/s (Reference 4).

For Material Model M1 (linear), the site response was computed for all 18 cases (3 shallow VS, 2 deep gradient, and 3 kappa). To limit the total volume of calculations for material models M2 and M3 (nonlinear), the site response was computed for only the central kappa value for a total of 6 cases for each material model (3 shallow VS, 2 deep gradient, and 1 kappa). The nonlinear effects are captured for the best estimate kappa case, which is kappa that is consistent with the spectral content of the observed ground motions at DCPP. As is shown later in response to Question 2, the nonlinear model reduces the amplification at high frequencies as the level of the reference rock ground motion increases. Therefore, including the additional nonlinear cases would lead to a small reduction in the high frequency (greater than 2.5 Hz) ground motion at hazard levels of 1E-4 to 1E-5 that affect the GMRS. At low frequencies (less than 1 Hz), the nonlinearity leads to a small increase in amplification at large ground motion levels (see response to Q2) for just two cases. Including the additional nonlinear cases would lead to a very small increase to the hazard for low frequencies. To demonstrate the expected size of the effect of using only the linear models for the high and low kappa branches, Figure 1-8 compares the site terms based on the weighting of 0.5 linear (M1) and 0.5 nonlinear (M2 and M3) are compared to the site terms for linear only for k=0.04 sec and a reference rock PGA=1.1g. The largest difference is in the 12 Hz range; the inclusion of the nonlinear model leads to site terms that are near 0.2 ln units lower in this frequency range. If this same difference is assumed to apply to the other kappa values, then mean site terms including nonlinear models for all three kappa values would be about 0.08 ln units lower in the 12 Hz range (0.2 difference times the combined weight of 0.4 for the other kappa values). At other frequencies, the difference would be smaller than 0.08.

In all, there are 30 cases for the site response. The cases and weights used in the site response are shown below in the logic tree in Figure 1-7. For the reference rock profile, a linear model is used to be consistent with the linear scaling in the NGA West-2 GMPEs for VS30=760 m/s.

Table 1-1: Epistemic uncertainty in the 3-D VS model (from Table 3.4-1 of Reference 3)

Depth Range (m)	Standard Deviation of VS (ln units)	Standard Deviation of VS (ln units) used to develop alternative profiles
0-10	0.15	0.15
10-50	0.10	0.10
50-60	0.10 – 0.15	0.10 + 0.005*(depth-50)
60-120	0.15 – 0.18	0.165

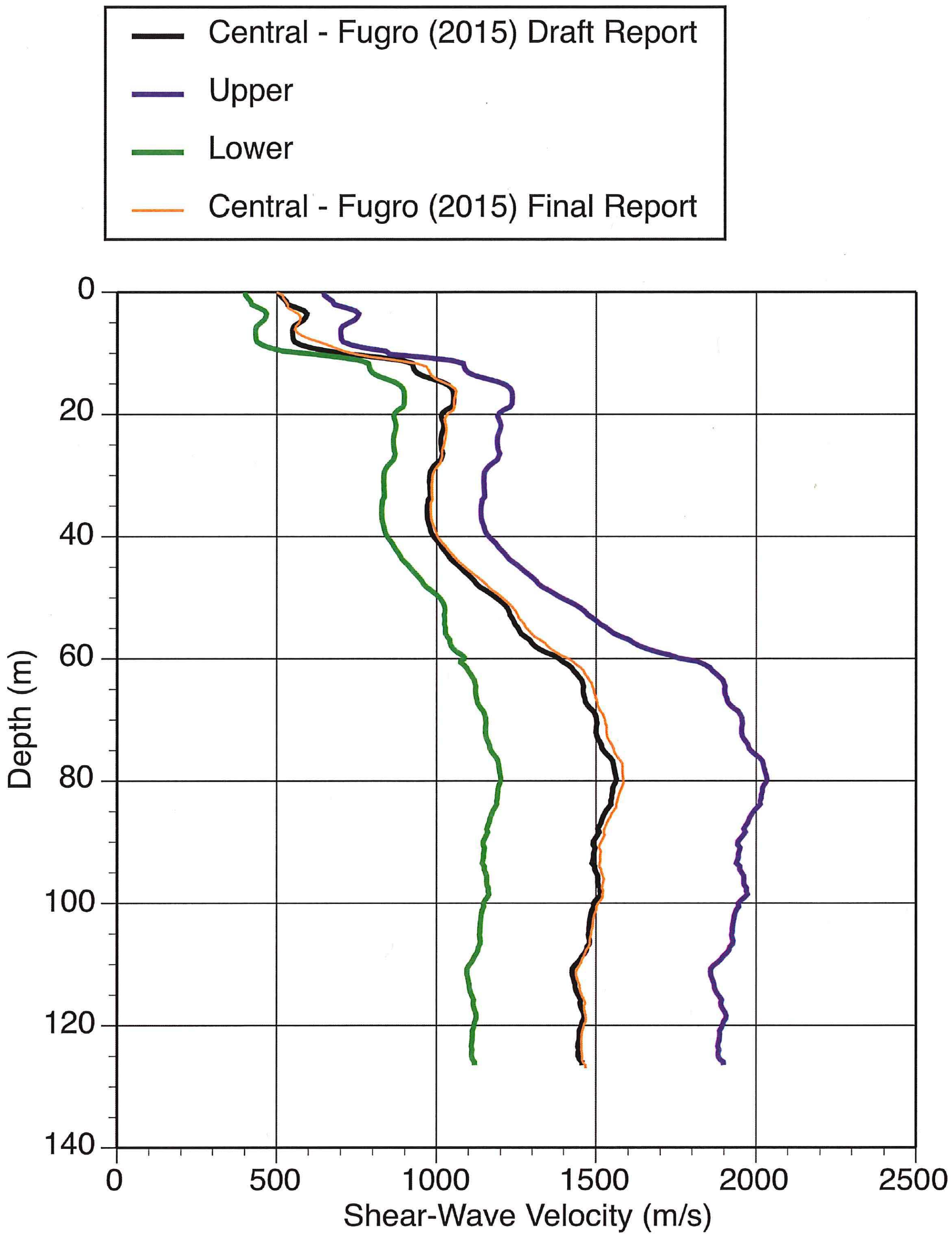

Figure 1-1: Three alternative shallow VS profiles for the Free-Field Seismic Instrument Control Point (ESTA28) based on the uncertainty in Table 1-1. The central profile is based on the draft Fugro report. The final Fugro report included an update to the velocity profile for ESTA28, but the change is small and does not lead to a significant difference in the computed amplification.

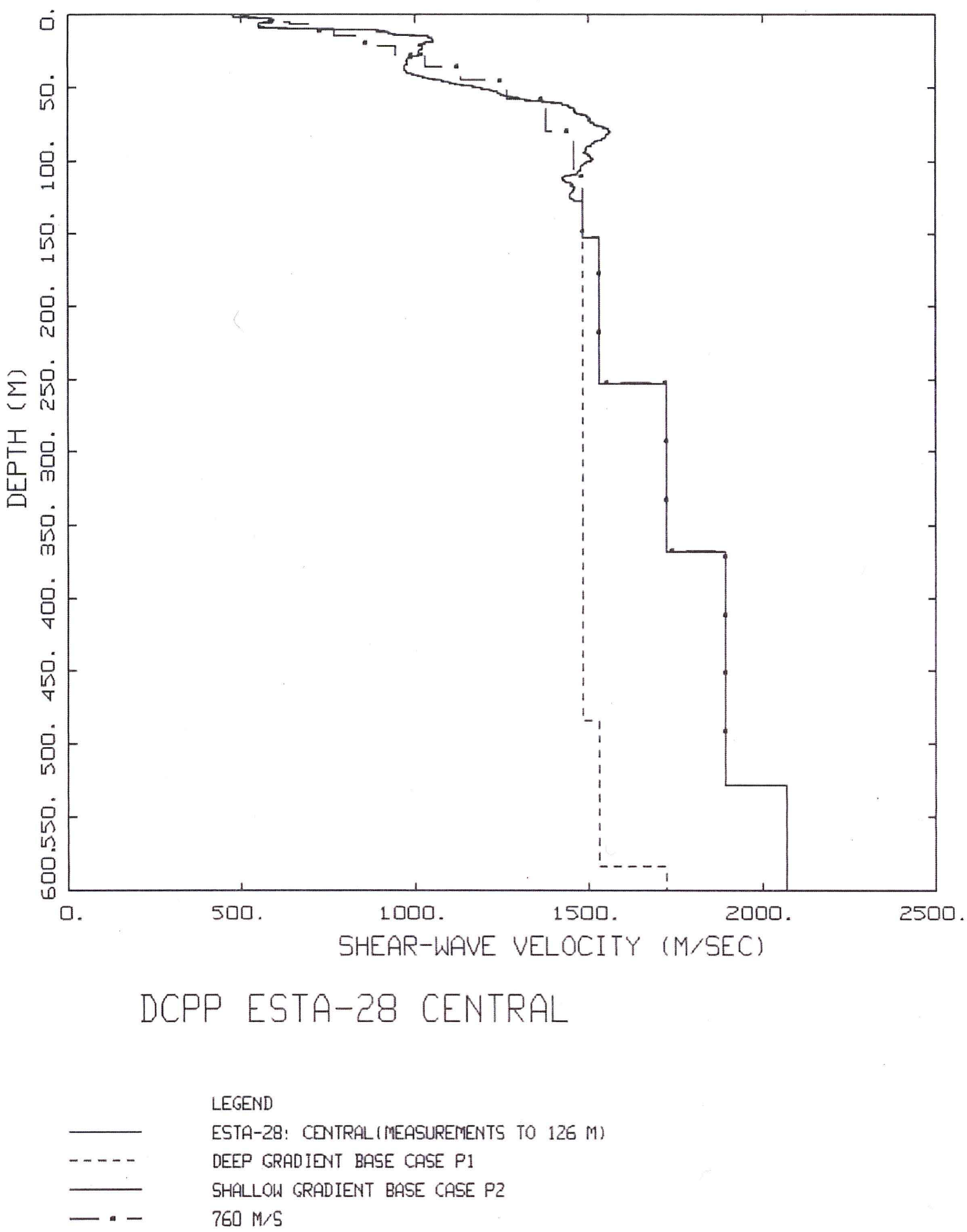

Figure 1-2: Alternative models for the extension of the shallow VS profile (central model) to depth.

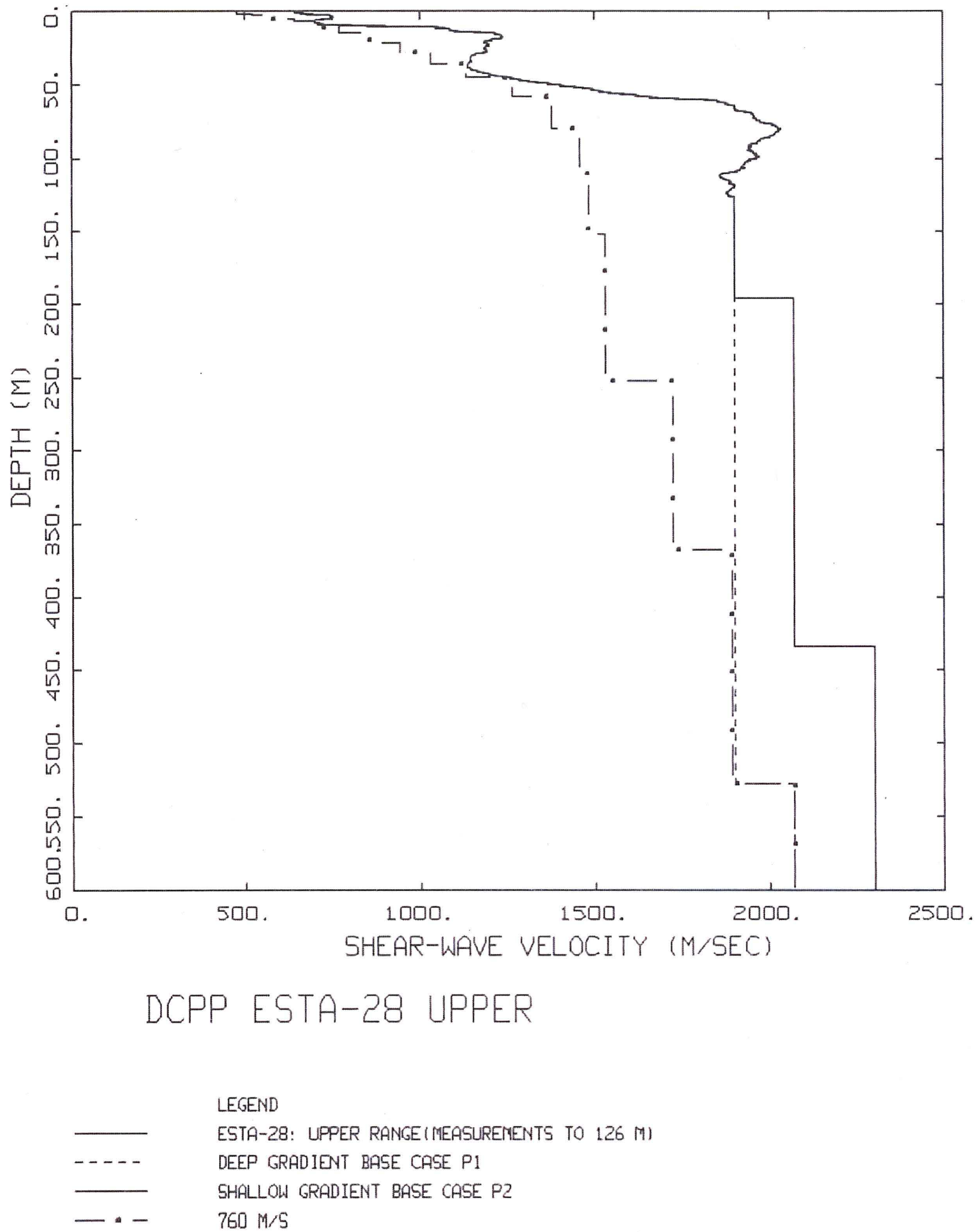

Figure 1-3: Alternative models for the extension of the shallow VS profile (upper model) to depth.

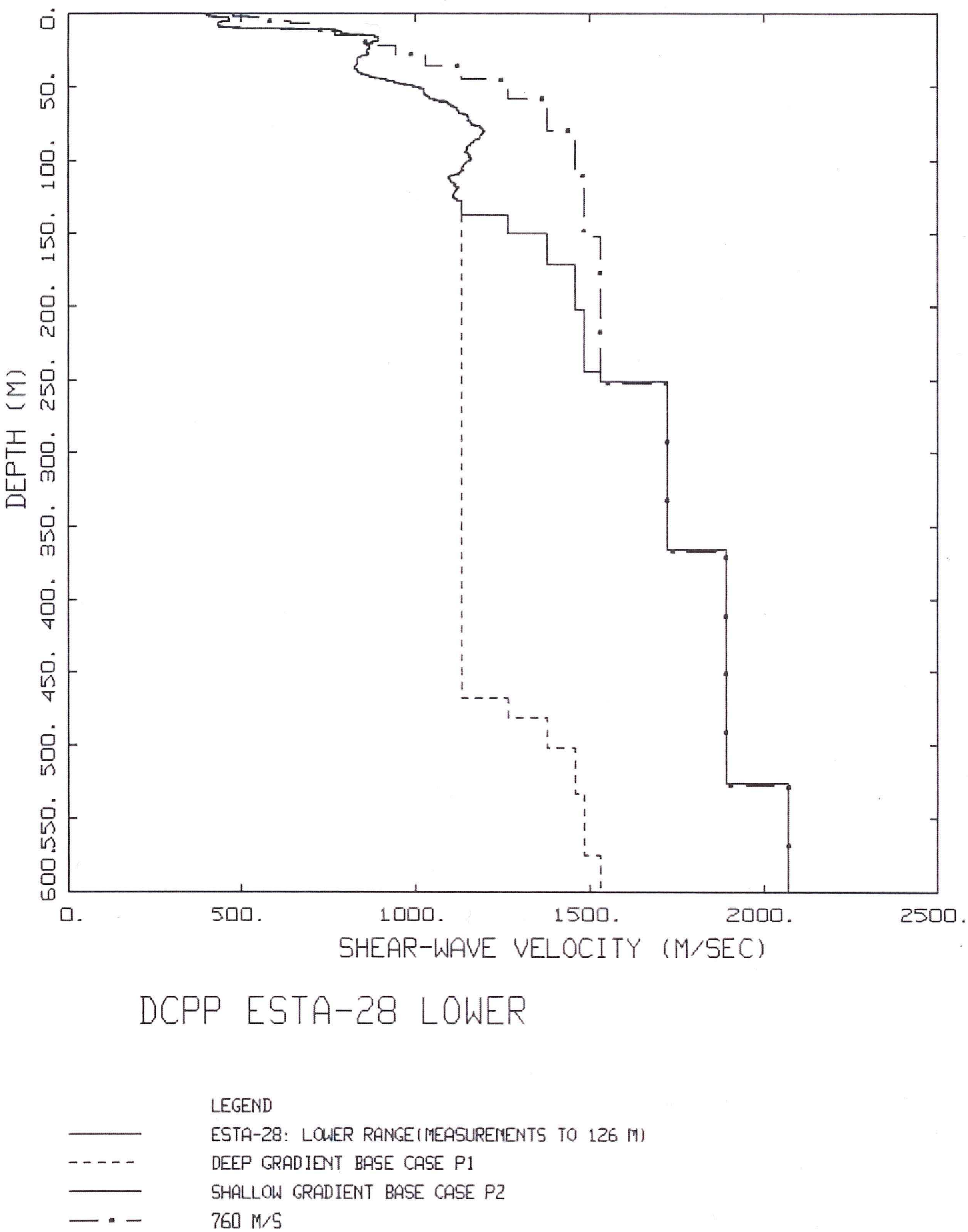

Figure 1-4: Alternative models for the extension of the shallow VS profile (lower model) to depth.

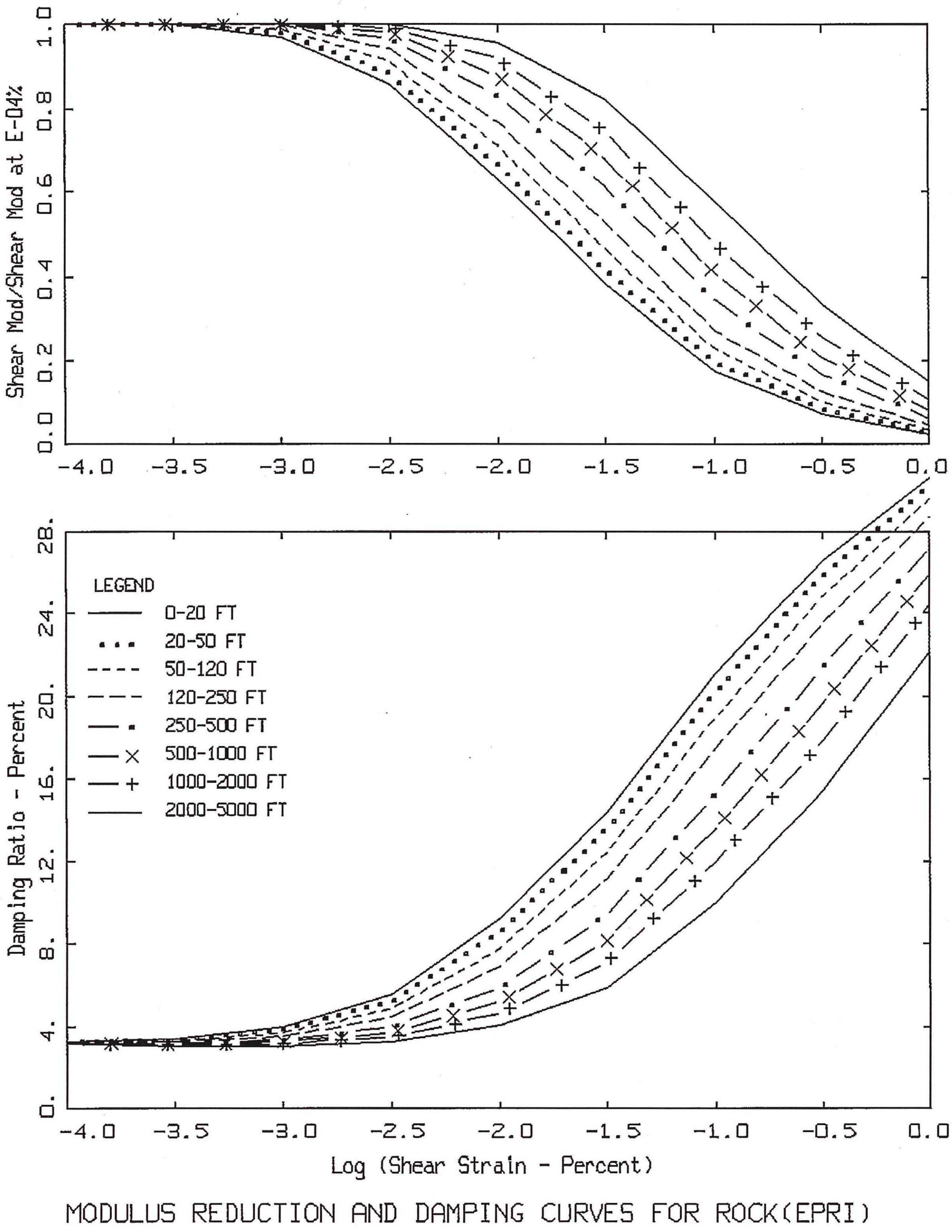

Figure 1-5: Modulus and damping curves for the EPRI Rock model (M2)

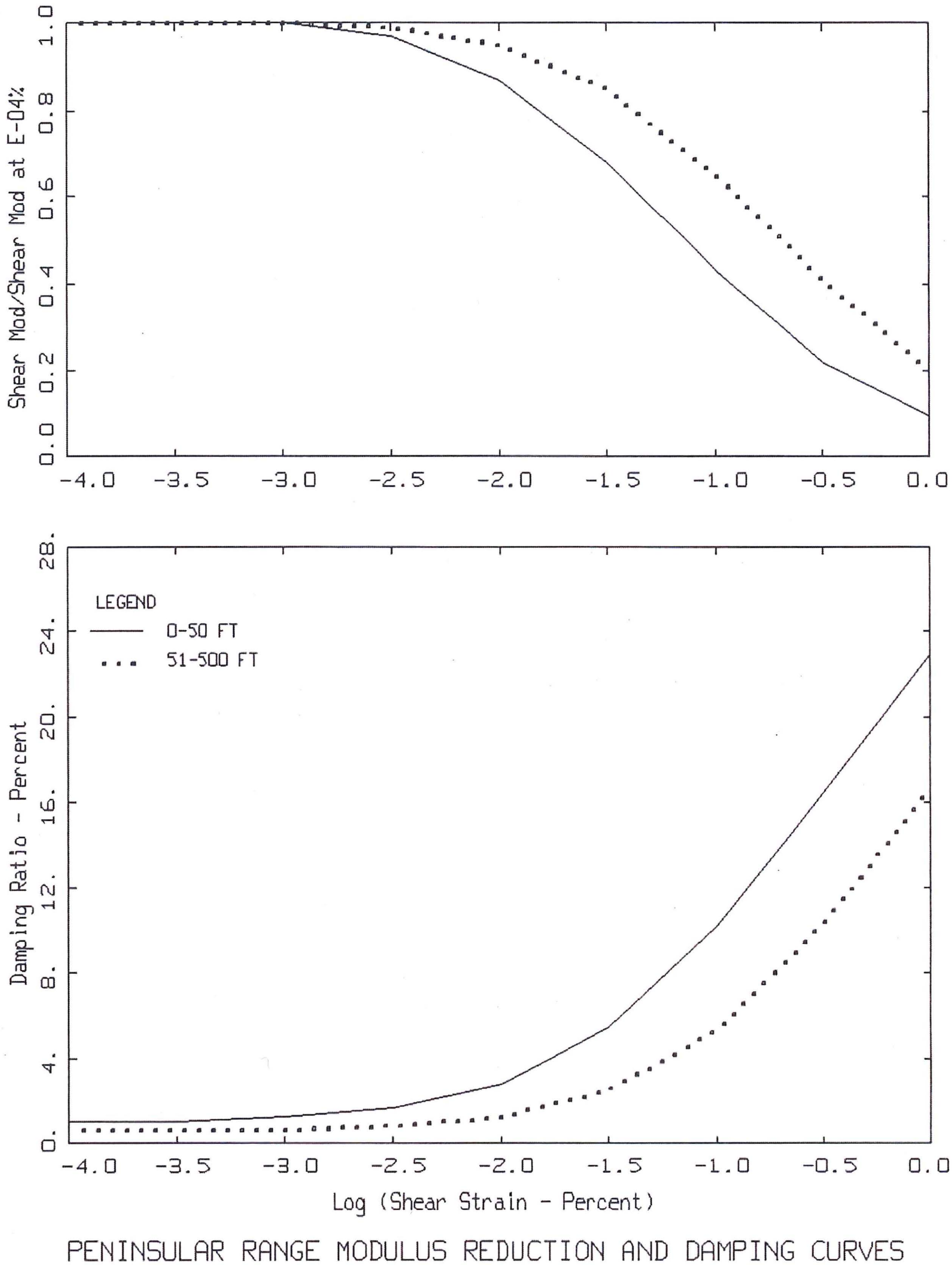

Figure 1-6: Modulus and damping curves for the Pen Range model (M3)

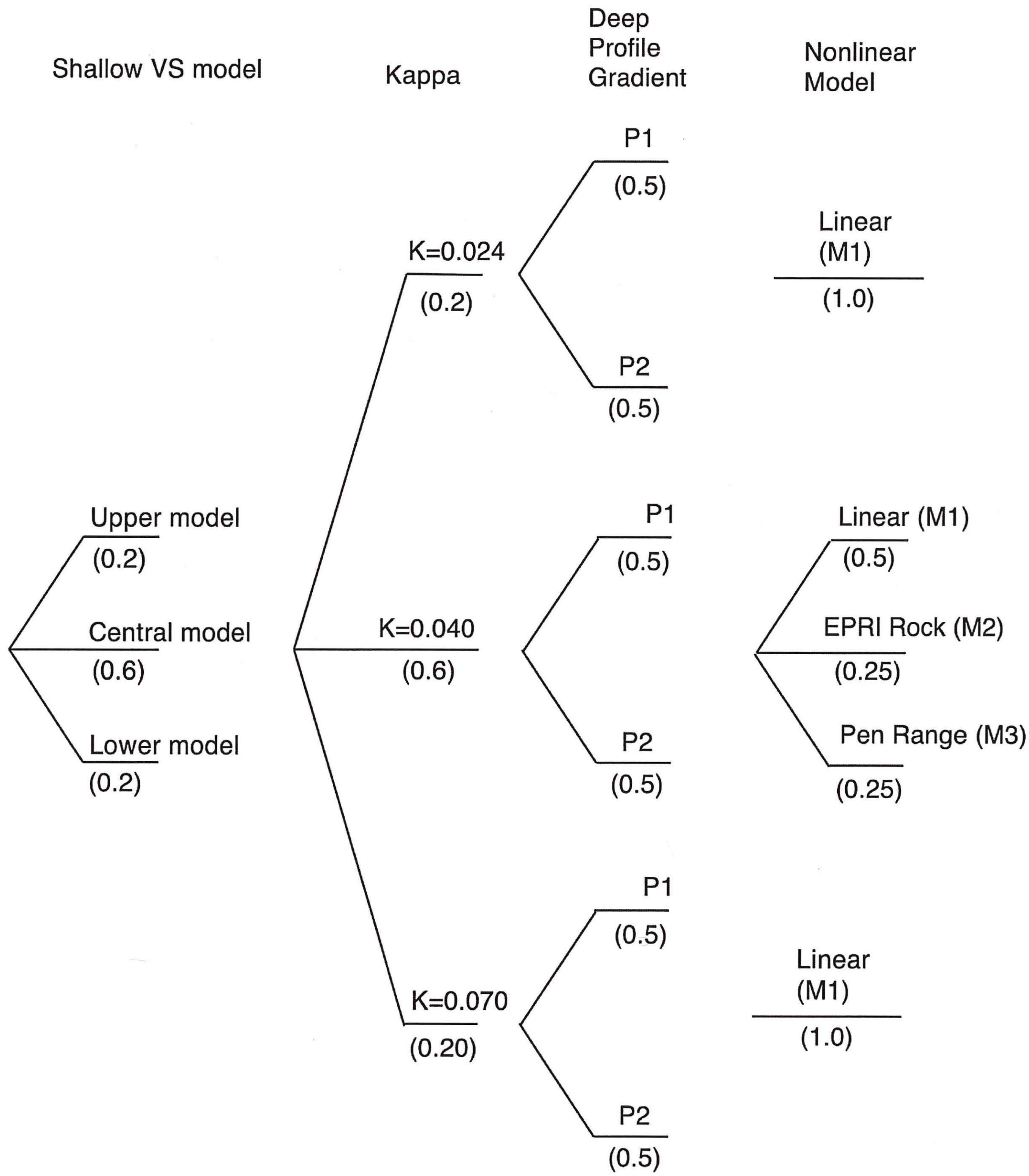

Figure 1-7: Logic tree for site response model inputs

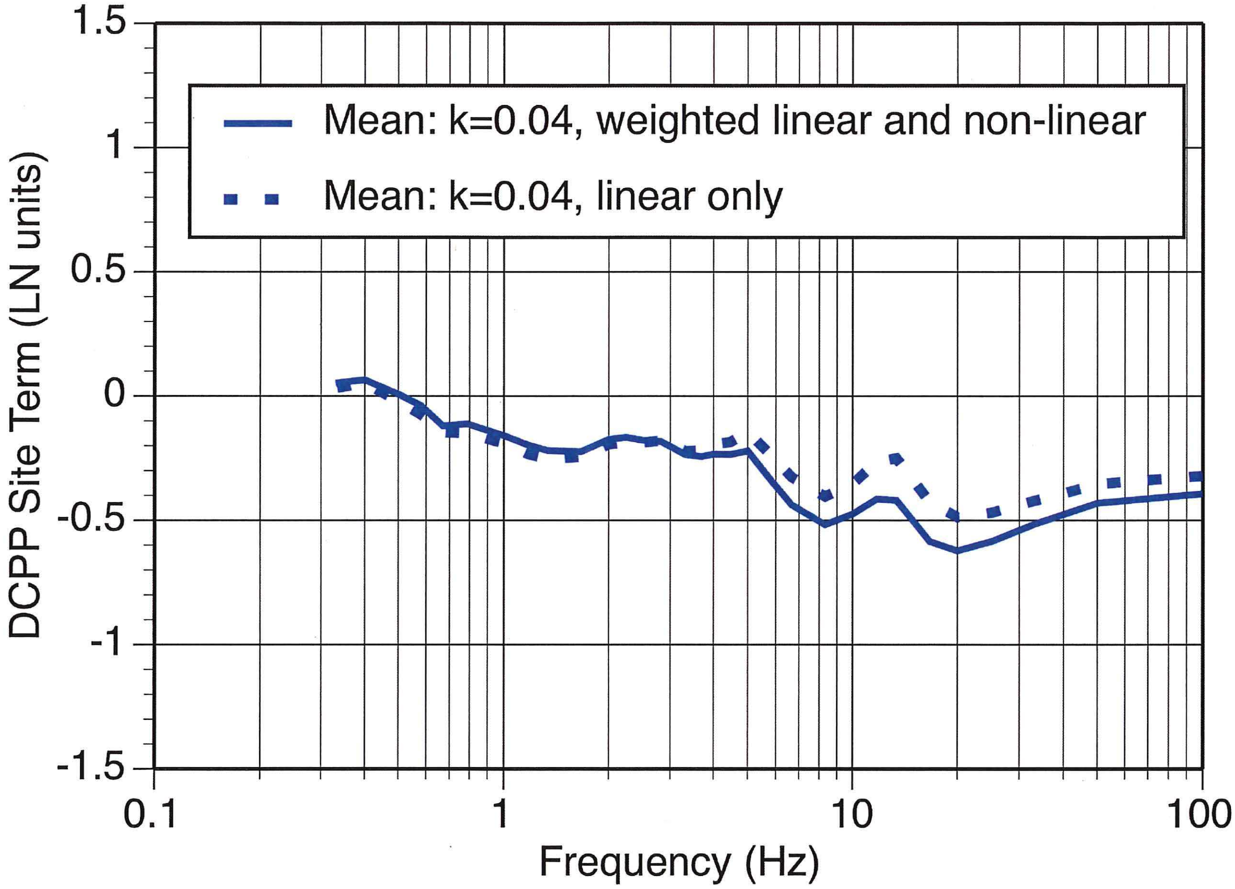

Figure 1-8: Effect of the weighting for the linear and nonlinear material models for kappa =0.04 sec and a reference rock PGA of 1.1g.

NRC Question 2

Please provide the potential for nonlinear behavior at the strain levels produced by the scenario earthquakes of interest

PG&E Response

The potential nonlinear behavior of the rock is evaluated using equivalent linear site response (Reference 4). The resulting amplification is shown below as a function of the PSA for the reference rock condition (VS30=760 m/s with linear site response) for PGA and 5 spectral frequencies (1 Hz, 2.5 Hz, 5 Hz, 10 Hz, and 20 Hz) in Figures 2-1 to 2-6. The range of the amplification for the 30 alternative models of the VS, kappa, and material properties is shown for each frequency. For reference, the 1E-4 hazard for the reference rock case corresponds to a peak acceleration of about 1 g.

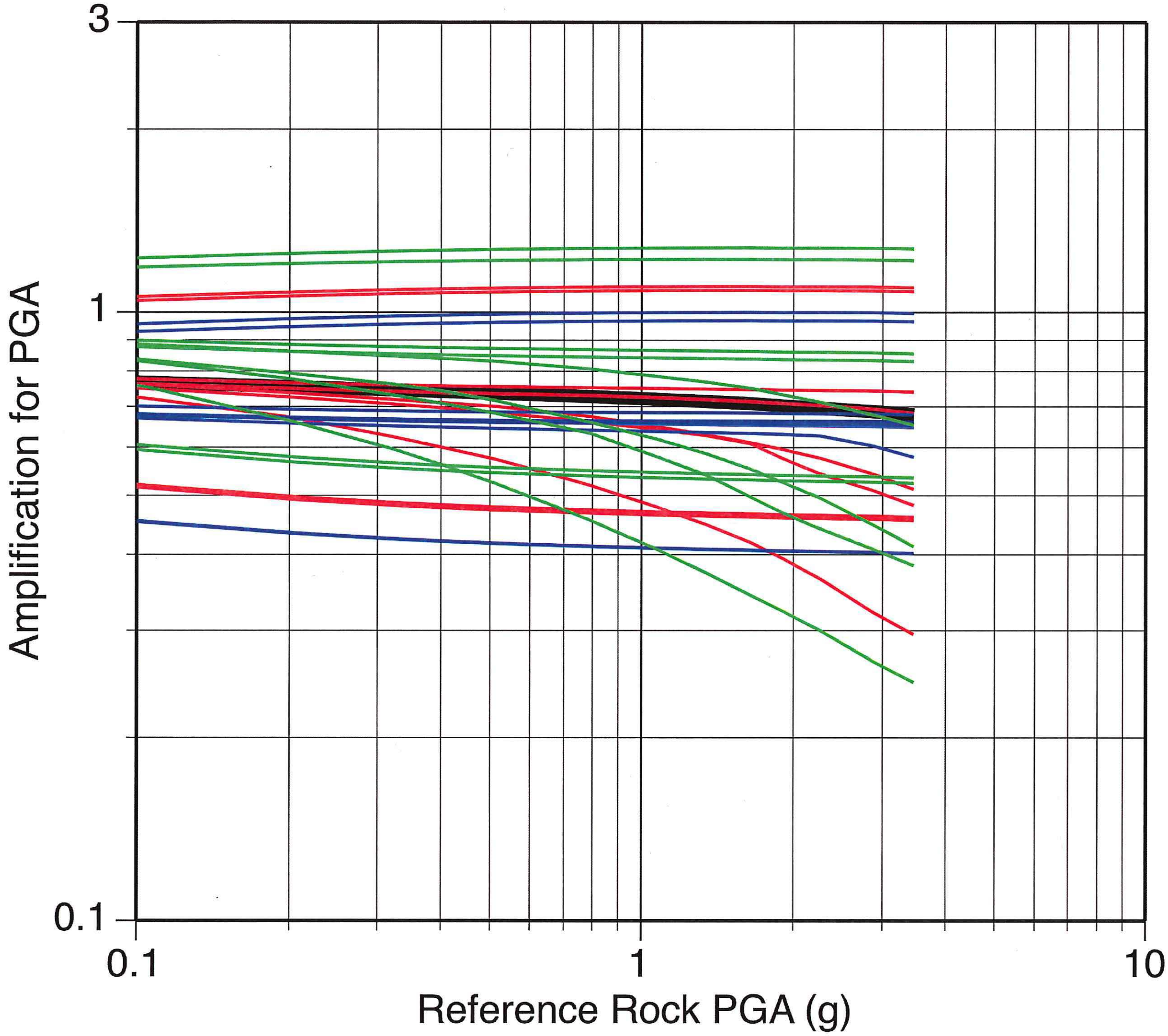

Figure 2-1: Potential for nonlinear amplification for PGA. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively.

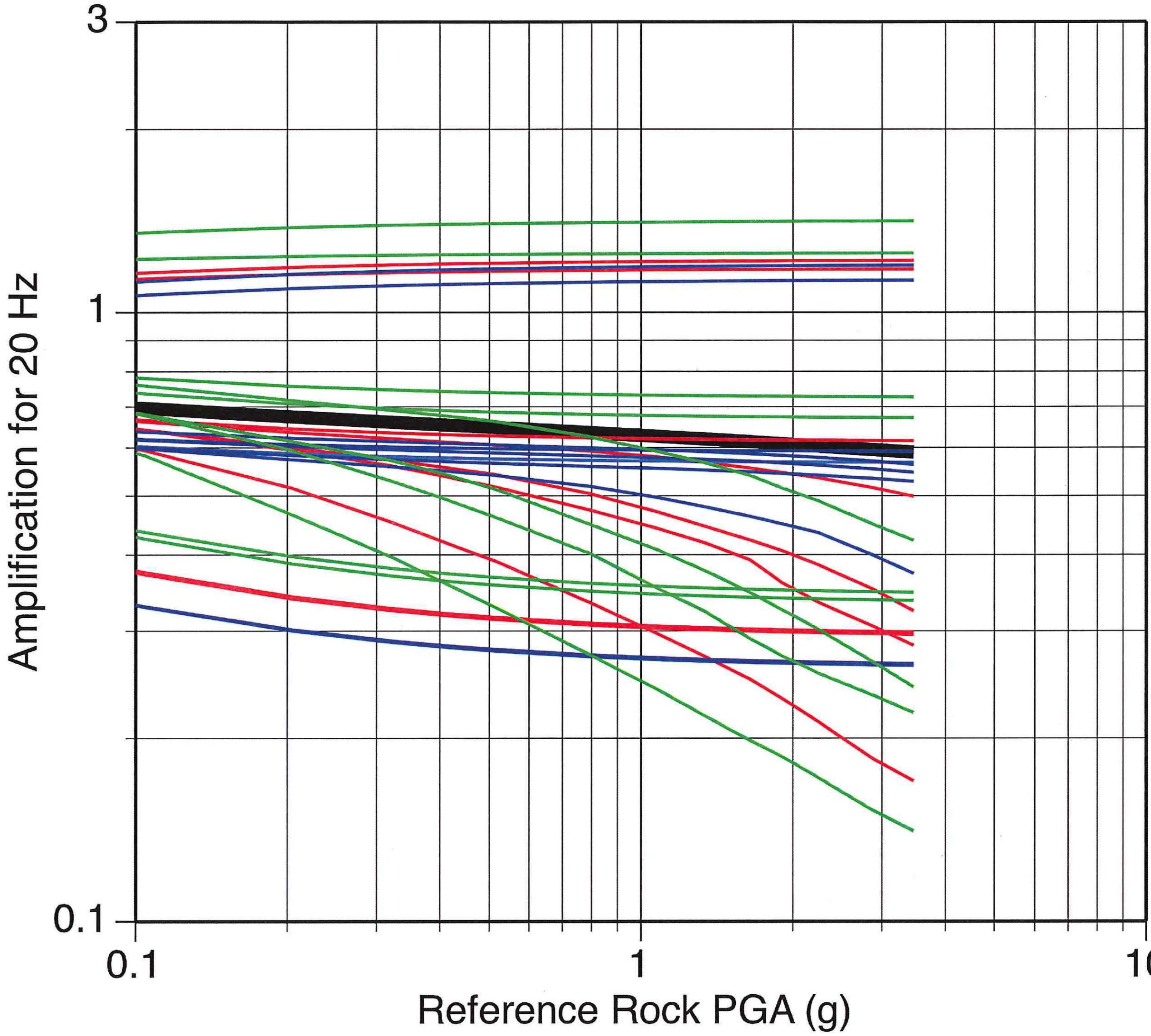

Figure 2-2: Potential for nonlinear amplification for 20 Hz. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively.

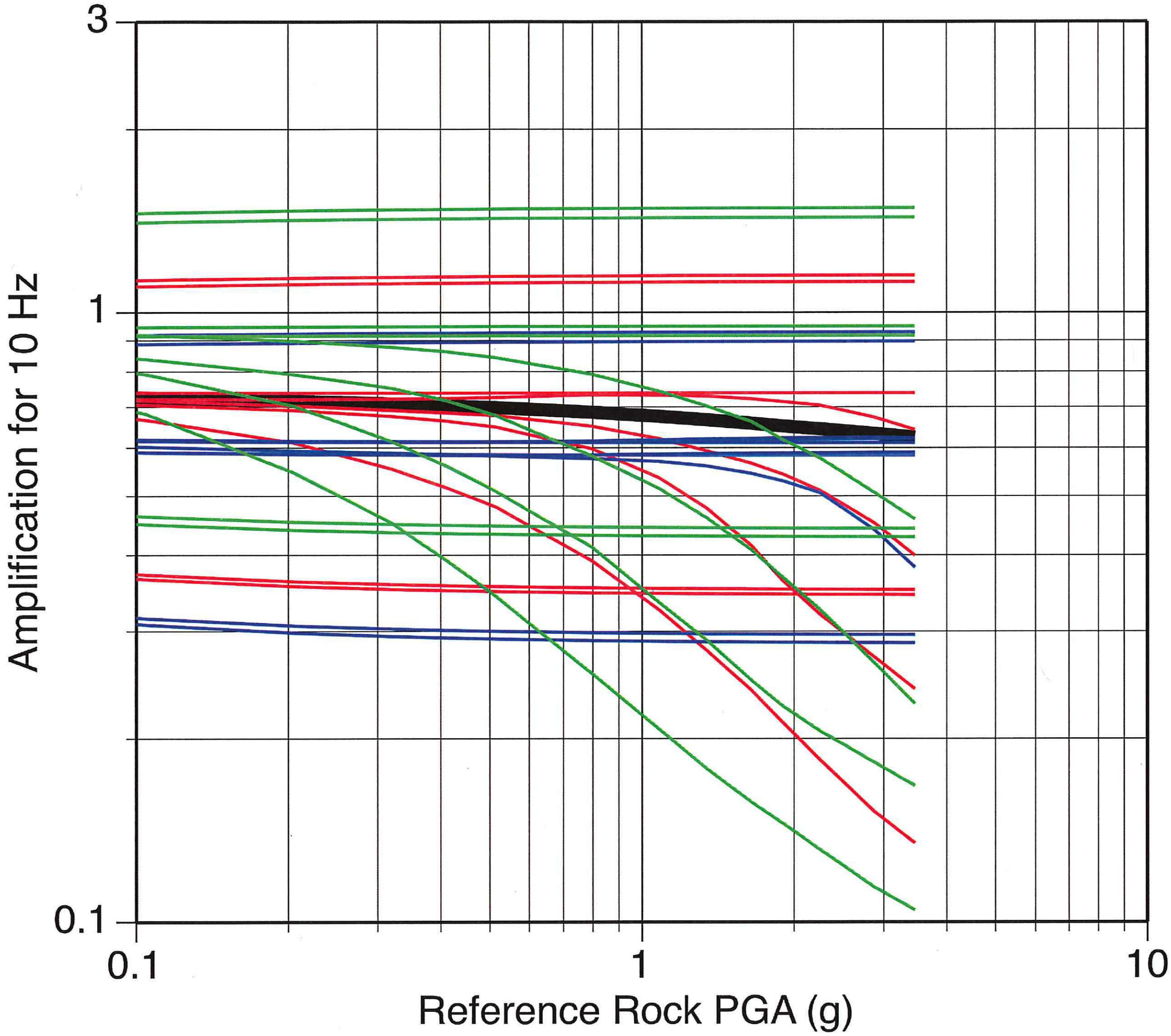

Figure 2-3: Potential for nonlinear amplification for 10 Hz. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively.

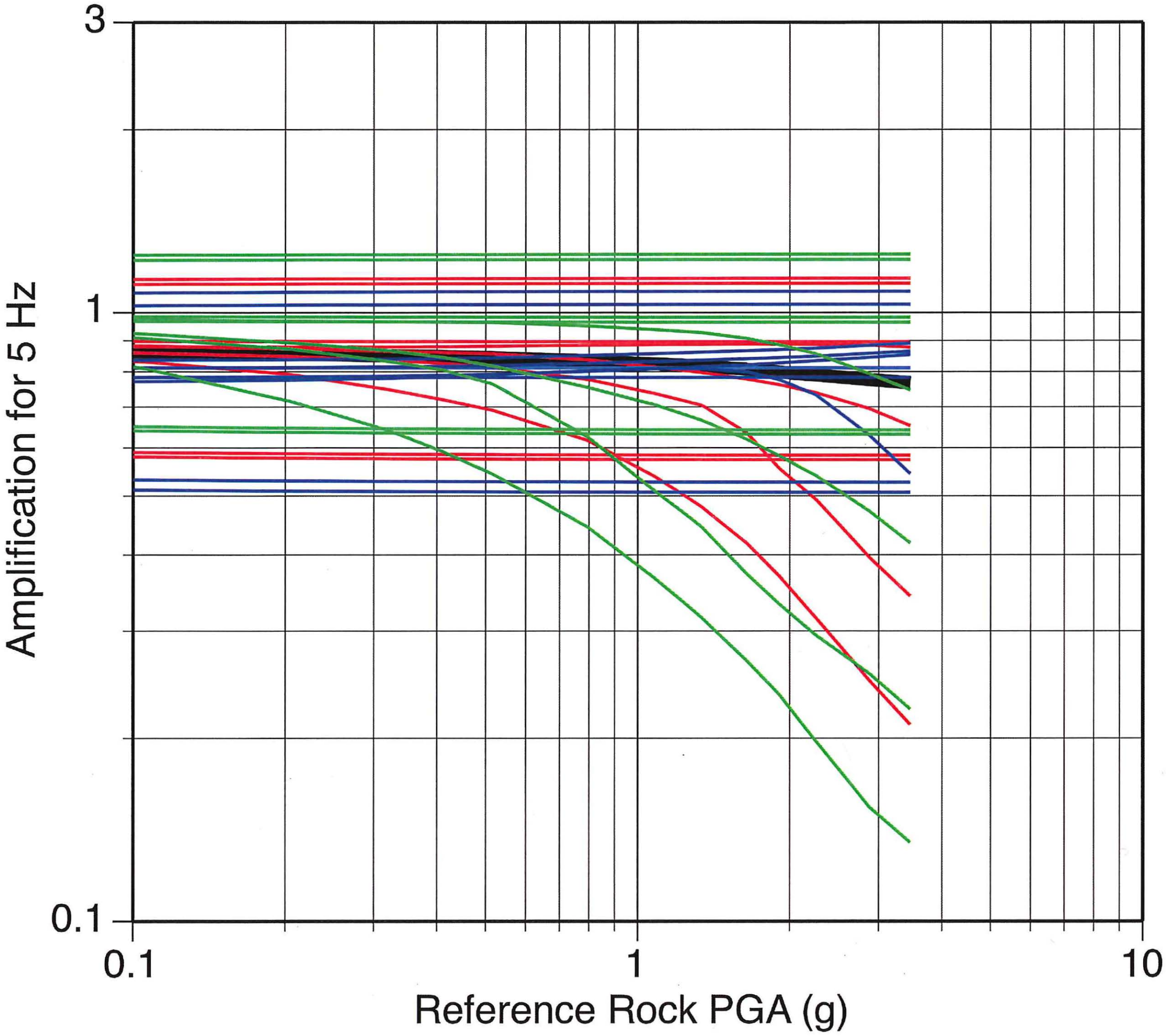

Figure 2-4: Potential for nonlinear amplification for 5 Hz. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively.

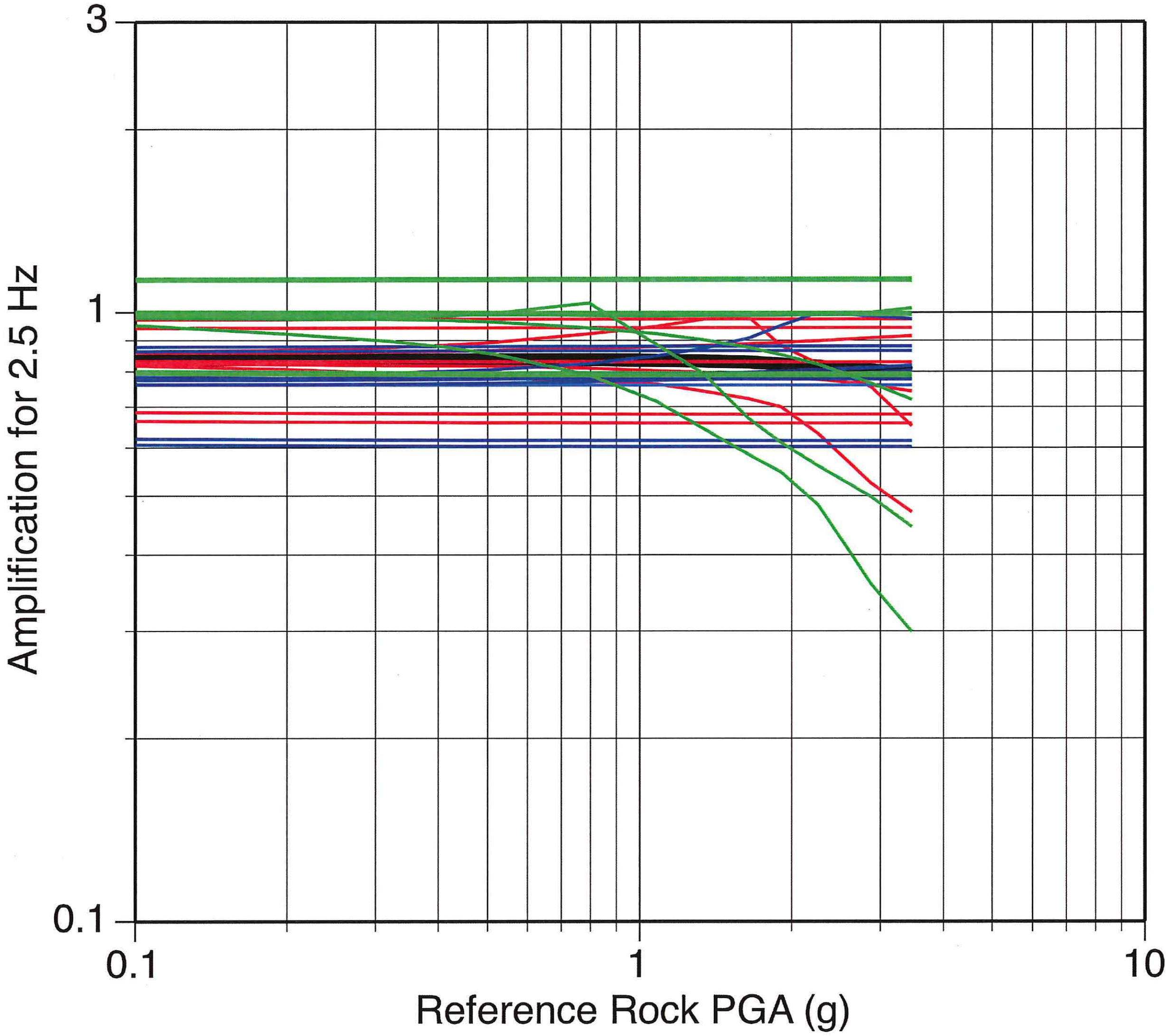

Figure 2-5: Potential for nonlinear amplification for 2.5 Hz. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively.

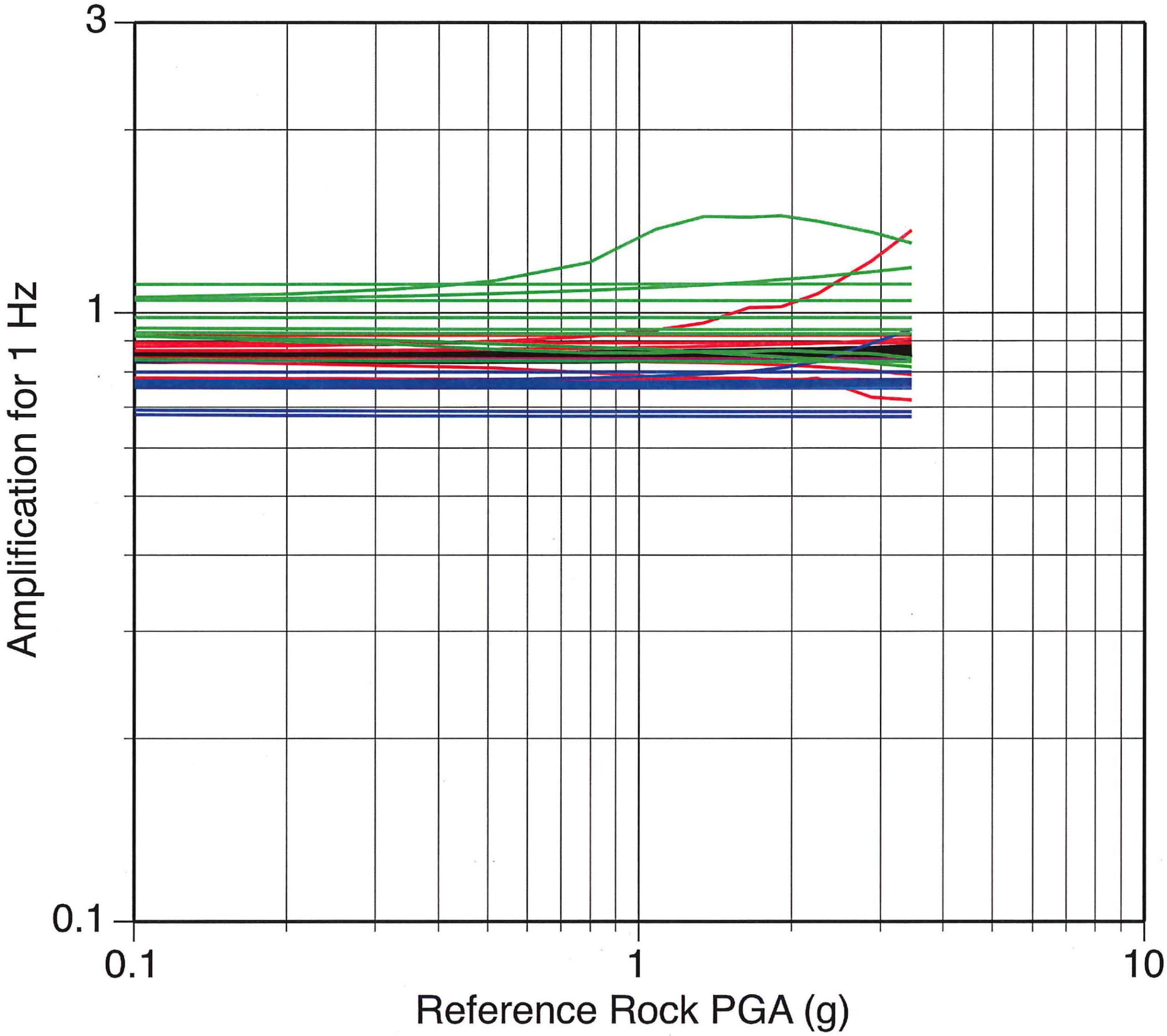

Figure 2-6: Potential for nonlinear amplification for 1 Hz. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively.

NRC Question 3

Please provide the control point elevation.

PG&E Response

The control point, for comparison of the Safe Shutdown Earthquake (SSE) (the Double Design Earthquake (DDE) for DCPP) to the GMRS, is at the finished grade which corresponds to 85 feet (26 meters) mean sea level. The DCPP Updated Final Safety Analysis Report (UFSAR) does not explicitly define a control point for the ground motions, but it can be derived from the seismic analyses described in the UFSAR Section 3.7, *Seismic Design*. From the seismic analyses of the major structures, as described in UFSAR Section 3.7.2.2, *Description of Seismic Analyses*, the control point for seismic analyses is the finished grade level, which corresponds to 85 ft mean sea level at the location of the major structures.

Since the site-amplification is based on the free-field recordings, the control point is specifically at the location of the free-field seismic instrument ESTA28, located at elevation 85 ft. Section 3.2 of PG&E Letter DCL-15-035 (Reference 1) provided additional information.

NRC Question 4

In addition, provide the adjustment factors (VS-kappa corrections) needed to modify the median ground motion models for the selected reference or baserock elevation and velocity. Also include in the response, as a figure and a table, control point seismic hazard curves developed using the site amplification factors and their uncertainties through the hazard integral as recommended in Appendix B of the SPID.

PG&E Response

Using the material properties described in the response to NRC Question 1, the amplification factors (VS-kappa corrections) for the median ground motion are shown in Figures 4-1, 4-2, and 4-3 for reference rock PGA values of 0.2g, 0.8g, and 1.6g, respectively. The group of larger amplification factors at high frequencies is associated with the lower kappa value of 0.024 sec.

These adjustment factors are used to compute the control point hazard. The hazard is computed using the following method:

$$Haz(PSA > z, f) = \sum_{i=1}^{N} rate(zREF_i, f) P\left(PSA > z \mid Amp(zREF_i, f), \phi_{amp\_NL}(zREF_i, f)\right)$$

Equation (4-1)

where $rate(zREF_i, f)$ is the rate of occurrence of reference rock ground motion level $zREF_i$ computed from the hazard curves, and the aleatory term, $\phi_{amp\_NL}(zREF_i, f)$, is given by the increase in the variance of the computed site amplification due to nonlinear effects. The increase in the variance is computed by subtracting the variance from 0.1g input motion, which is taken to represent the linear range. The aleatory term used in the soil hazard is given by:

$$\varphi_{amp\_NL}(zREF, f) = \begin{cases} \sqrt{\varphi^2_{Amp}(zREF, f) - \varphi^2_{Amp}(zREF = 0.1g, f)} & for \varphi^2_{Amp}(zREF, f) > \varphi^2_{Amp}(zREF = 0.1g, f) \\ 0 & for \varphi^2_{Amp}(zREF, f) \le \varphi^2_{Amp}(zREF = 0.1g, f) \end{cases}$$

where $\phi^2_{Amp}(zREF, f)$ is the standard deviation of the site amplification due to the randomization of the soil properties. If the aleatory variability at high ground motion levels is smaller than at low ground motion levels, then the aleatory term is zero. As an example, the $\phi^2_{Amp}(zREF,f)$ and $\phi_{amp\_NL}(zREF,f)$ terms are shown in Figure 4-4 for the EPRI nonlinear model, (M2, central profile, gradient P1, k=0.04 sec) for 10 Hz.

Using Equation 4-1, the hazard for the control point is computed. The mean hazard curves for seven frequencies are shown in Figure 4-5 and are listed in Table 4-1. The uniform hazard spectra (UHS) for hazard levels of 1E-4 and 1E-5 are shown in Figure 4-6 along with the GMRS. The GMRS includes the epistemic uncertainty in the base 30 case profiles through the use of the mean amplification. The UHS and the GMRS are listed in Table 4-2.

Finally, as a sensitivity, the effect on the GMRS of using the full variability of the site response ($\phi^2_{Amp}(zREF,f)$ in the soil hazard is shown in Figure 4-7. The GMRS is not sensitive to the use of $\phi^2_{Amp}(zREF,f)$ or $\phi_{amp\_NL}(zREF,f)$ in the soil hazard calculation.

Table 4-1: Mean hazard curves for the control point.

PSA (g)	PGA	20 Hz	10 Hz	5 Hz	2.5 Hz	1 Hz	0.5 Hz
0.01	1.73E-01	2.06E-01	2.52E-01	3.11E-01	2.78E-01	1.32E-01	5.21E-02
0.021	7.51E-02	9.42E-02	1.32E-01	1.70E-01	1.32E-01	4.85E-02	1.88E-02
0.03	4.51E-02	5.87E-02	8.78E-02	1.16E-01	8.43E-02	2.64E-02	9.65E-03
0.04	3.18E-02	4.20E-02	6.55E-02	8.93E-02	6.17E-02	1.75E-02	6.19E-03
0.052	2.18E-02	2.95E-02	4.75E-02	6.57E-02	4.28E-02	1.13E-02	3.92E-03
0.069	1.47E-02	2.05E-02	3.36E-02	4.63E-02	2.87E-02	7.12E-03	2.38E-03
0.091	9.85E-03	1.40E-02	2.35E-02	3.23E-02	1.90E-02	4.50E-03	1.43E-03
0.12	6.47E-03	9.36E-03	1.63E-02	2.23E-02	1.24E-02	2.84E-03	8.35E-04
0.158	4.17E-03	6.15E-03	1.12E-02	1.52E-02	7.99E-03	1.79E-03	4.76E-04
0.209	2.63E-03	3.98E-03	7.55E-03	1.02E-02	5.11E-03	1.10E-03	2.65E-04
0.275	1.61E-03	2.51E-03	5.03E-03	6.78E-03	3.24E-03	6.59E-04	1.35E-04
0.363	9.12E-04	1.53E-03	3.26E-03	4.47E-03	2.01E-03	3.78E-04	6.73E-05
0.479	4.85E-04	9.22E-04	2.06E-03	2.89E-03	1.20E-03	1.95E-04	3.12E-05
0.631	2.35E-04	5.02E-04	1.24E-03	1.83E-03	6.94E-04	9.74E-05	1.33E-05
0.832	1.05E-04	2.70E-04	7.10E-04	1.09E-03	3.64E-04	4.33E-05	5.60E-06
1.096	4.22E-05	1.34E-04	3.82E-04	6.07E-04	1.76E-04	1.83E-05	2.20E-06
1.445	1.57E-05	5.95E-05	1.89E-04	3.10E-04	7.88E-05	7.32E-06	8.49E-07
1.905	5.46E-06	2.57E-05	8.65E-05	1.45E-04	3.16E-05	2.74E-06	3.13E-07
2.512	1.73E-06	9.79E-06	3.60E-05	6.02E-05	1.15E-05	1.01E-06	1.07E-07
3.311	5.10E-07	3.39E-06	1.36E-05	2.26E-05	4.05E-06	3.73E-07	3.41E-08
4.365	1.37E-07	1.08E-06	4.66E-06	7.62E-06	1.31E-06	1.34E-07	1.00E-08
5.754	3.29E-08	3.15E-07	1.43E-06	2.25E-06	3.71E-07	4.51E-08	2.71E-09
7.586	6.08E-09	7.40E-08	3.61E-07	4.63E-07	7.31E-08	1.36E-08	6.29E-10

Table 4-2: UHS and GMRS for the control point.

Frequency (Hz)	1E-4 UHS for Control Point (g)	1E-5 UHS for Control Point (g)	GMRS (g)
100	0.846	1.631	0.858
50	0.893	1.741	0.914
40	0.958	1.905	0.996
33	1.003	2.031	1.058
25	1.125	2.302	1.197
20	1.212	2.497	1.297
16.6	1.380	2.818	1.466
13.3	1.823	3.686	1.921
11.8	1.907	3.836	2.001
10.0	1.815	3.593	1.881
8.3	1.708	3.303	1.737
6.7	1.890	3.590	1.895
5.9	1.984	3.771	1.990
5.0	2.147	4.086	2.156
4.5	1.952	3.705	1.955
4.0	1.854	3.516	1.856
3.7	1.700	3.221	1.701
3.3	1.550	2.928	1.550
2.8	1.463	2.826	1.487
2.5	1.337	2.609	1.369
2.2	1.244	2.435	1.277
2.0	1.126	2.208	1.158
1.7	0.925	1.860	0.970
1.3	0.786	1.640	0.849
1.2	0.710	1.490	0.771
1.0	0.625	1.317	0.681
0.79	0.501	1.079	0.555
0.67	0.410	0.883	0.455
0.58	0.362	0.801	0.410
0.50	0.311	0.694	0.355
0.40	0.237	0.526	0.269
0.33	0.186	0.411	0.211

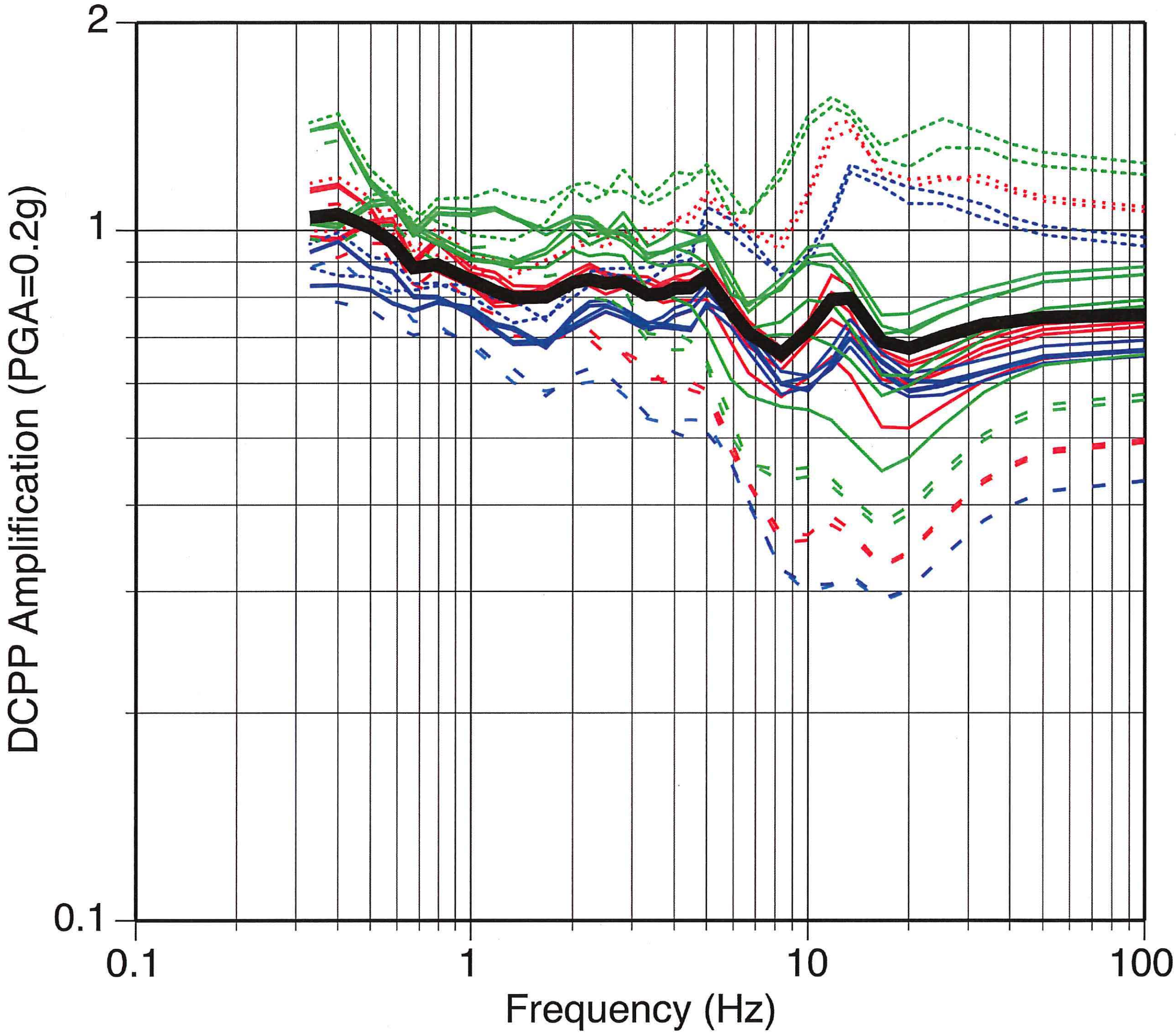

Figure 4-1: VS-kappa adjustment factors for a reference rock PGA of 0.2g. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively. The short dashed lines are for kappa=0.024 sec, the long dashed lines are for kappa=0.07 sec, and the solid lines are for kappa = 0.04 sec.

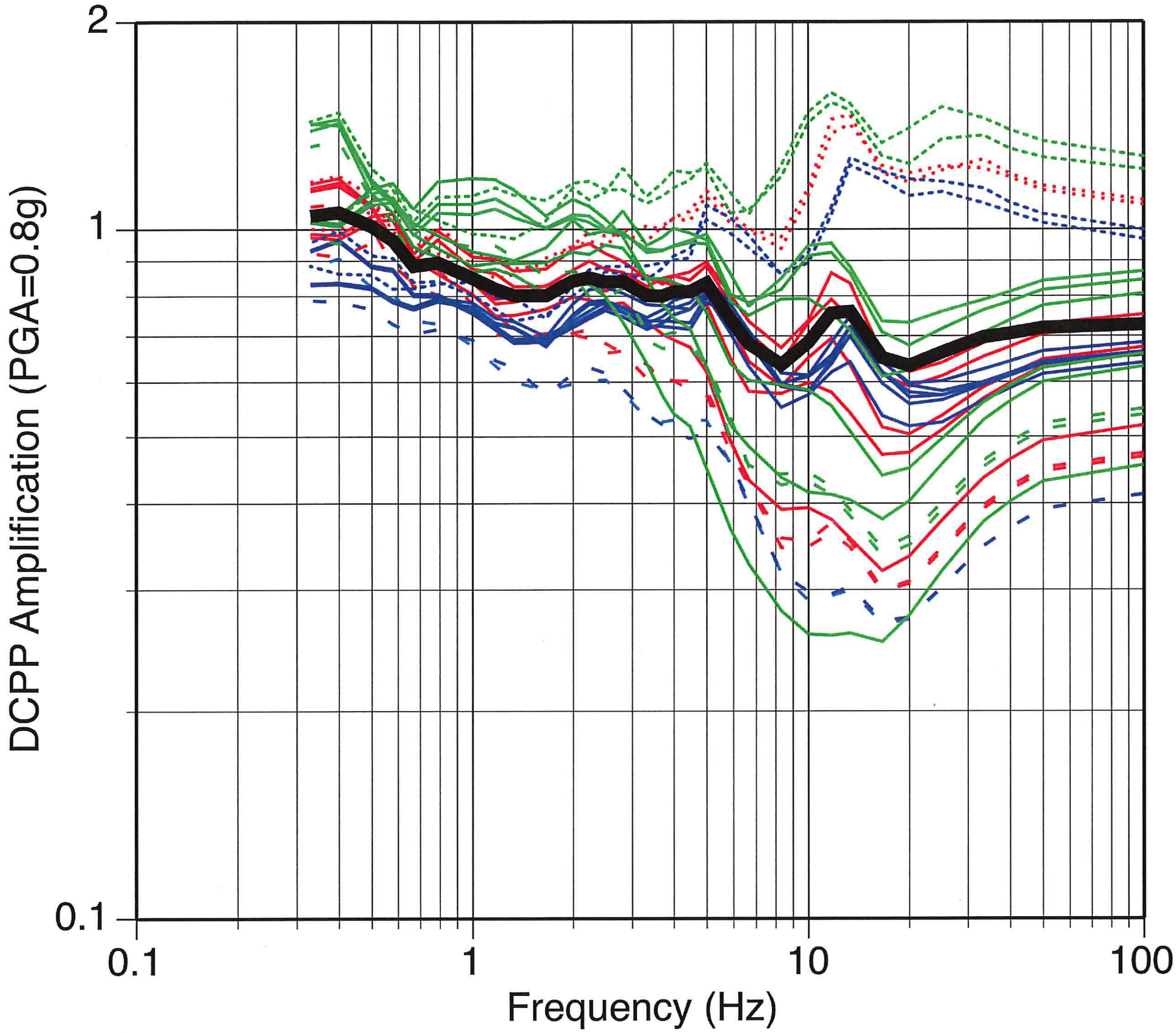

Figure 4-2: VS-kappa adjustment factors for a reference rock PGA of 0.8g. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively. The short dashed lines are for kappa=0.024 sec, the long dashed lines are for kappa=0.07 sec, and the solid lines are for kappa = 0.04 sec.

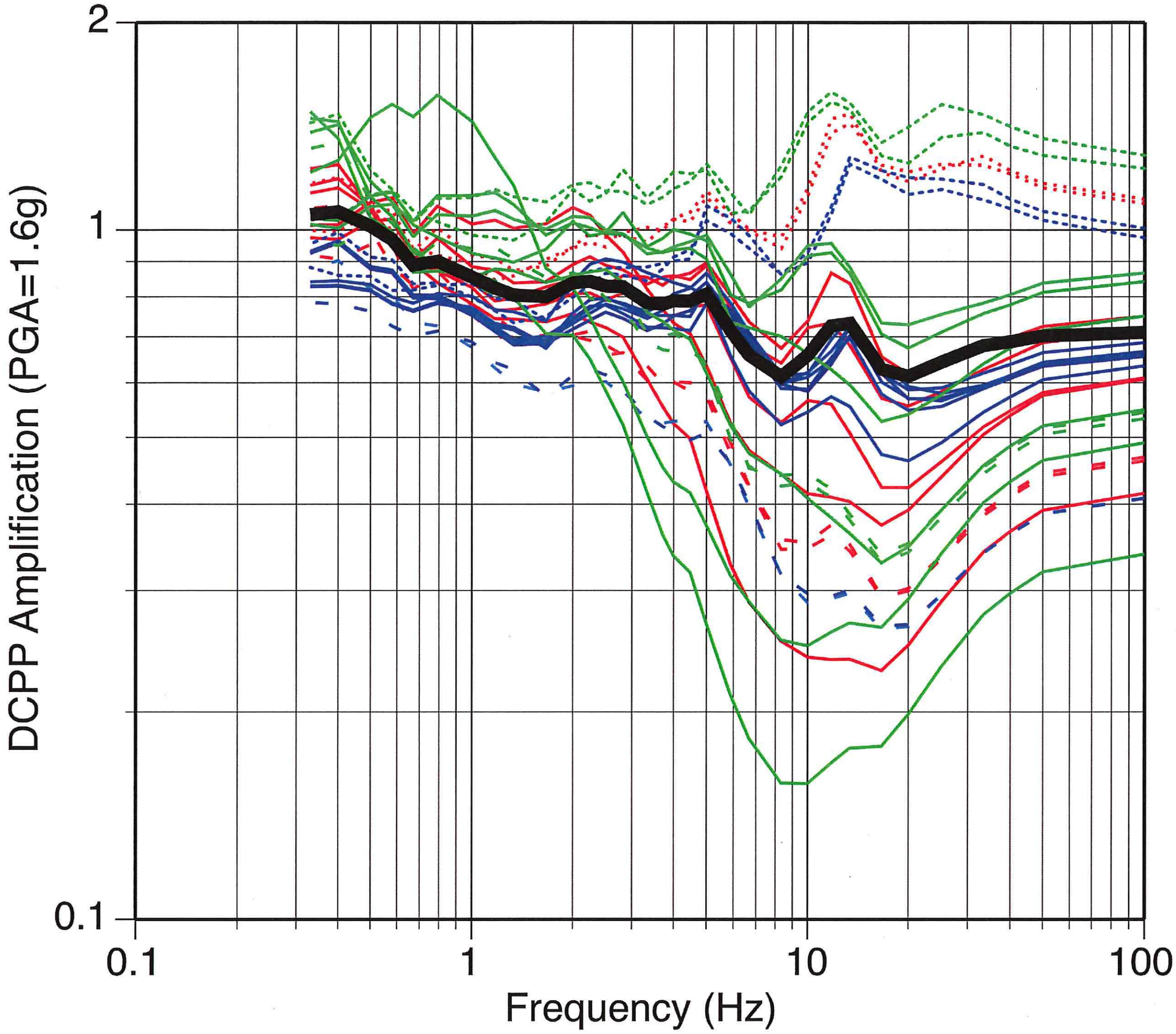

Figure 4-3: VS-kappa adjustment factors for a reference rock PGA of 1.6g. The black curve is the mean amplification. The red, blue, and green curves are for the central, upper, and lower VS profiles, respectively. The short dashed lines are for kappa=0.024 sec, the long dashed lines are for kappa=0.07 sec, and the solid lines are for kappa = 0.04 sec.

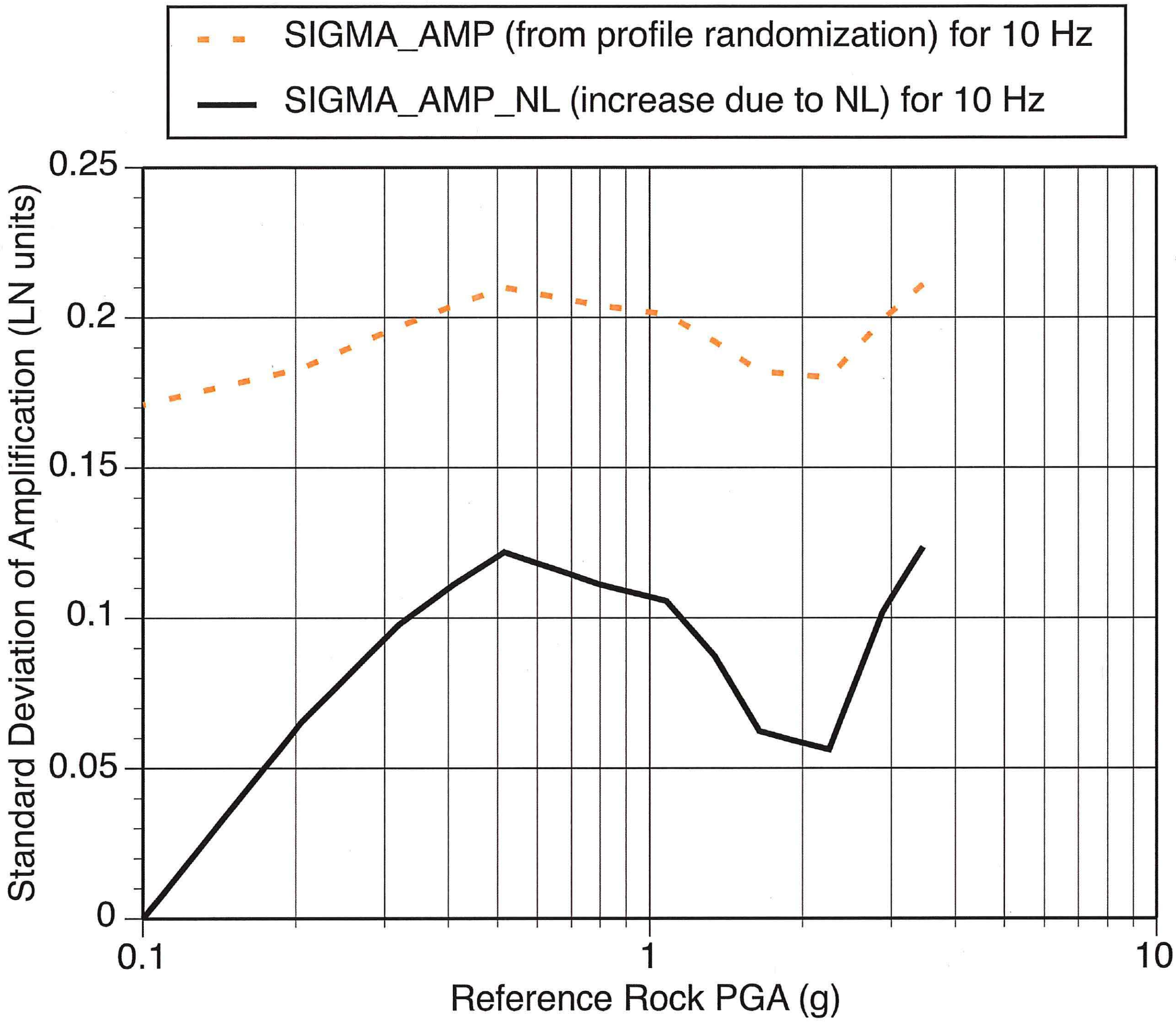

Figure 4-4: Example of the standard deviation of the site amplification for 10 Hz.

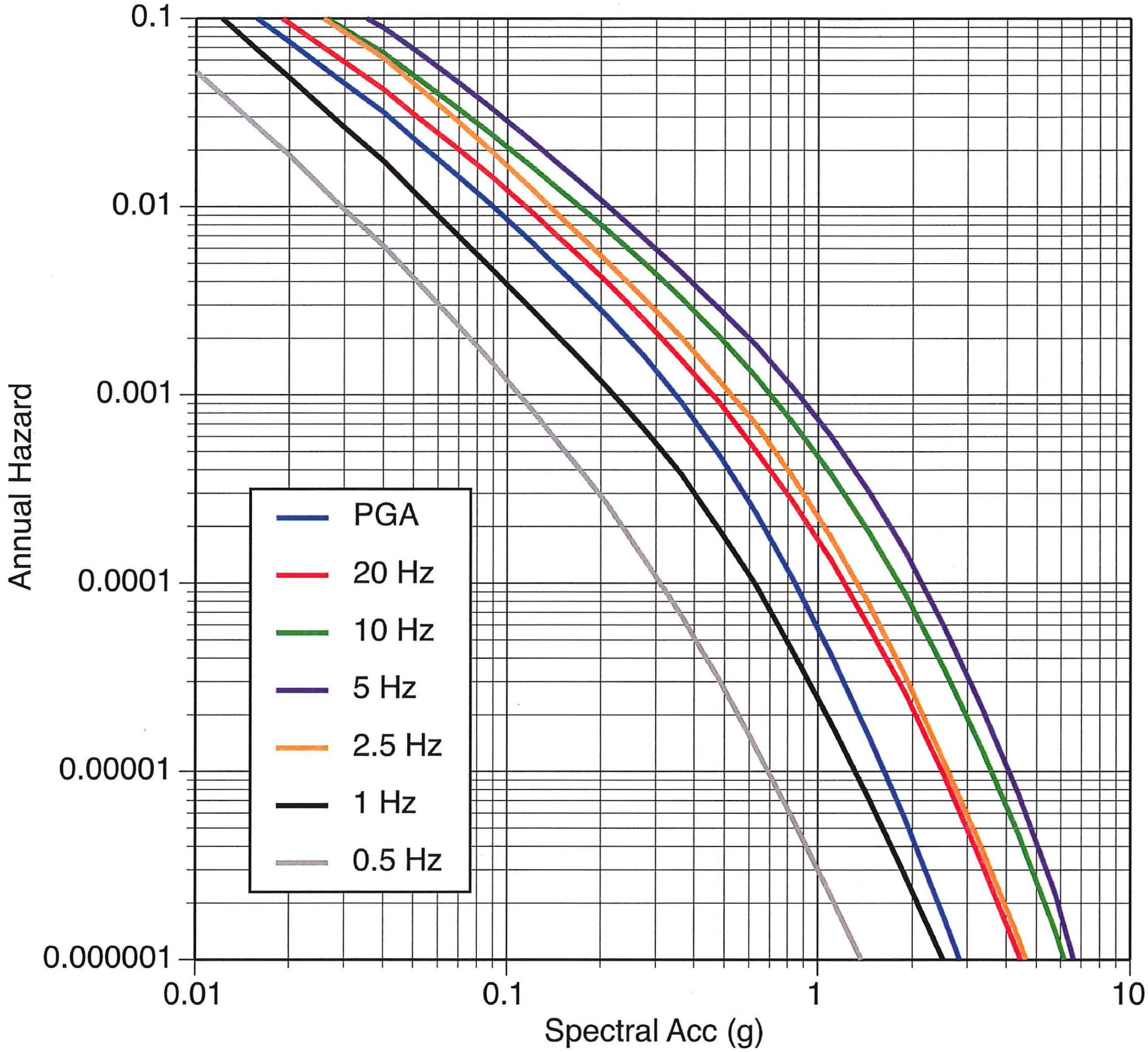

Figure 4-5: Hazard curves for the control point using the analytical method for estimating the DCPP site term for the control point.

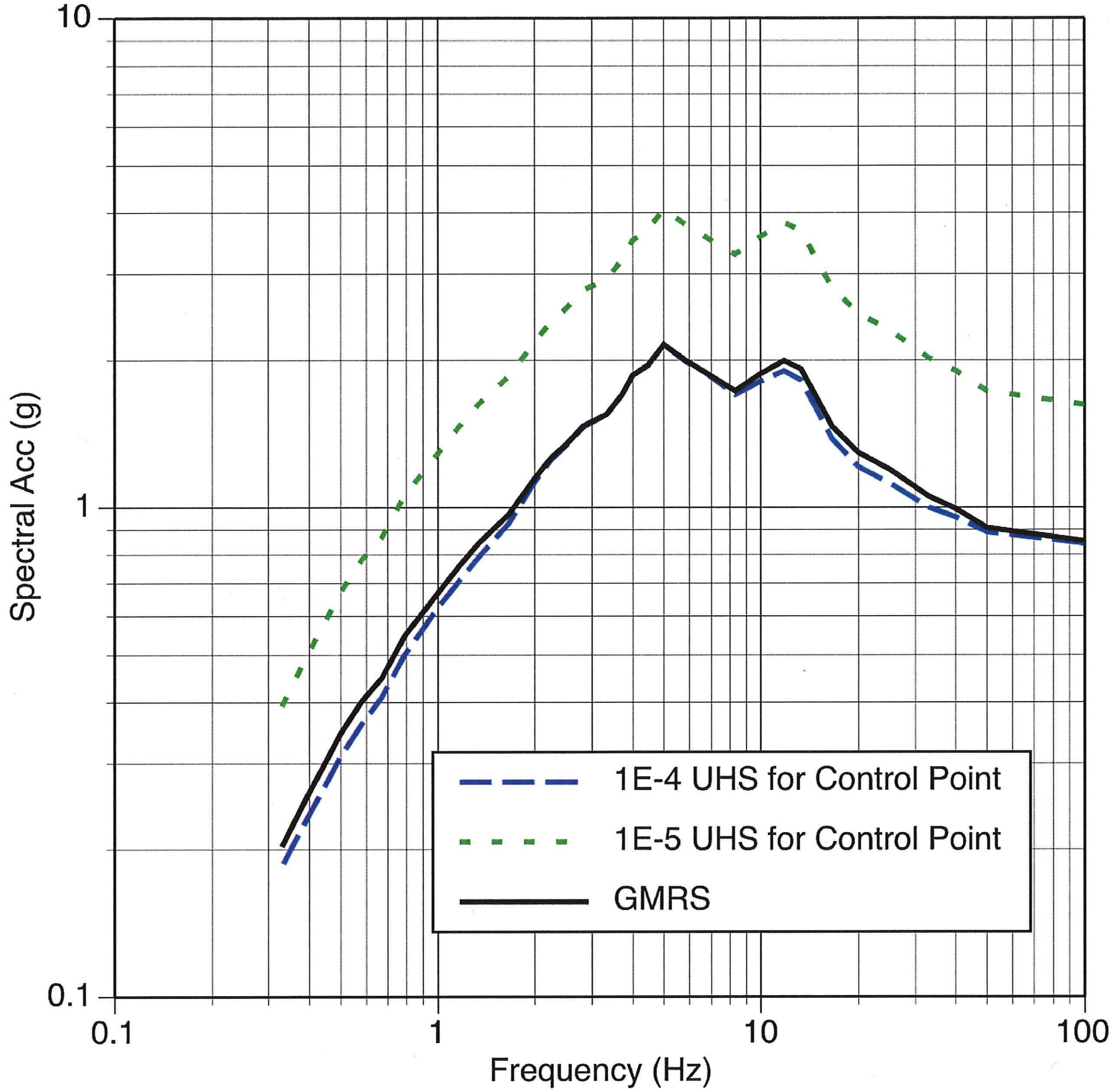

Figure 4-6: UHS and the GMRS for the control point using the analytical method for estimating the DCPP site terms.

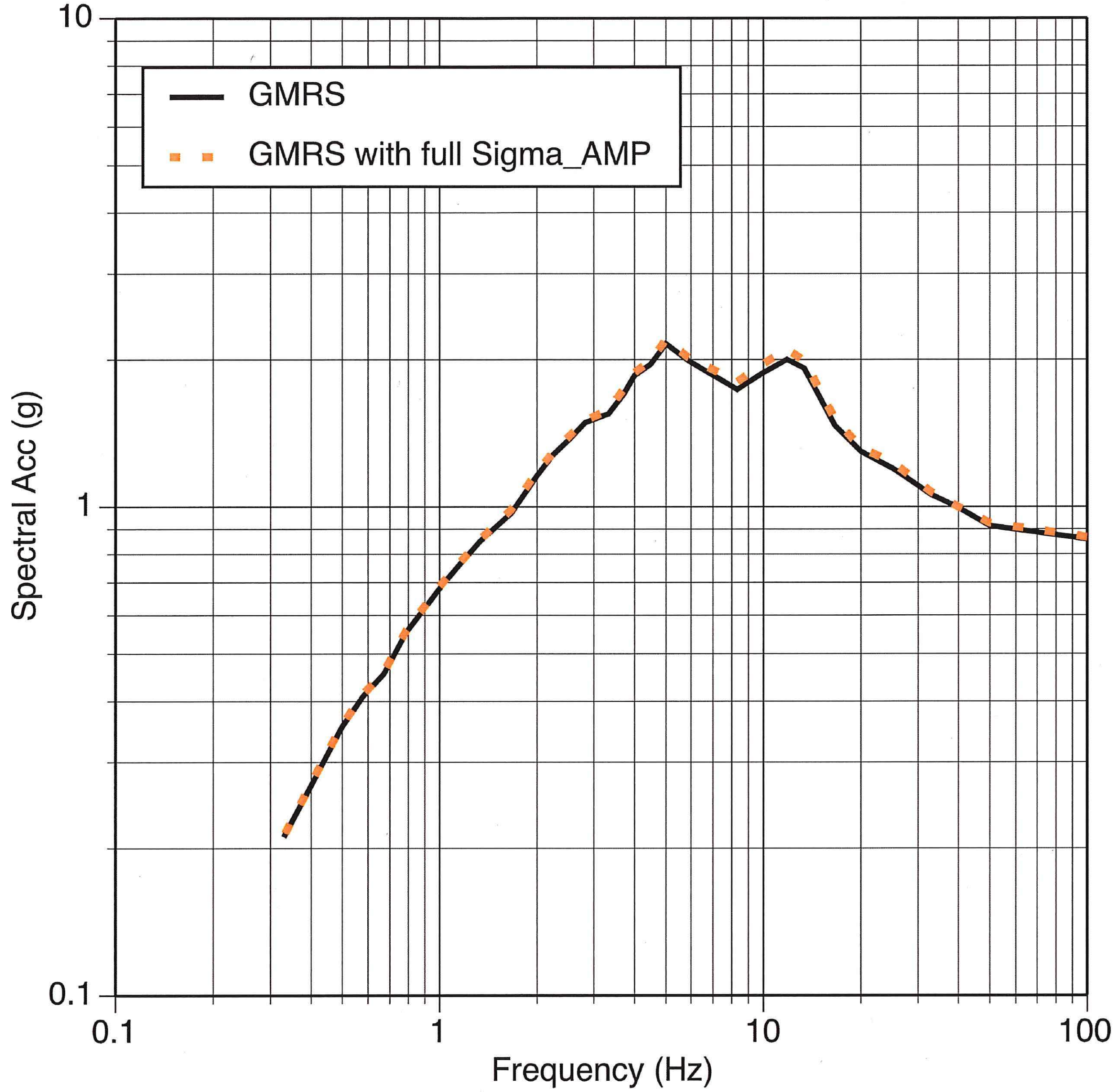

Figure 4-7: Effect on the GMRS of including the full SIGMA_AMP in the soil hazard

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