APPENDIX 3

Site Response Sensitivity Analysis

Overview

Because all Category 1 structures will be founded directly on Layer C or a leveling fill concrete, the top of Layer C was also defined as the Foundation Input Response Spectra depth (FIRS1) hence, GMRS/FIRS1. The following sensitivity analyses have been developed for the site-specific profile GMRS/FIRS1 to first test the relationship assigned between the layers defining the shallow and deep profile. Next, the computational procedure is tested by following guidance within Interim Staff Guidance, on Ensuring Hazard Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses, DC/COL, ISG-017 and assuming non-linearity of the shallow profile. Last, an alternative model for Layer C will be evaluated by including shale interbedding with non-linear properties.

Sensitivity Run 1 Approach

Sensitivity analysis 1 uses full correlation between all layers in developing the randomized site profiles, in contrast to the randomized profiles presented in the FSAR that use a partial correlation for the shallow profile layers.

The site-response calculations in FSAR Section 2.5 utilize 60 randomized profiles in order to characterize uncertainty in the dynamical properties of the soil column and the effect of these uncertainties on site response. In this randomization, the correlation coefficient between ln[Vs] (the natural logarithm of the shear-wave velocity) values in adjacent layers of the profile is given a value between 0 and 1, which varies as a function of depth and layer thickness, based on a statistical analysis of profiles at many sites with similar soil characteristics (Toro, 1996; see also EPRI, 1993, Risk Engineering, 2005). This choice of correlation coefficients represents standard practice and has been used in other COLA applications.

The uncertainty used in the randomization for ln[Vs] in the deep profile (i.e., coefficient of variation of 0.35) is consistent with the data available for the local geology, and its associated uncertainty. This variation, coupled with the assumption of full Vs correlation, is equivalent to using alternative discrete models for the deep profile. Therefore, one can also use the results from Run 1 to test the sensitivity to the use of alternative deep profiles.

The steps for sensitivity run 1 include the following.

1. Generate a new set of 60 randomized profiles for the GMRS horizon, using a ln[Vs] correlation coefficient of 1 at all depths, and keeping all other input parameters at the same values.
2. Perform site-response calculations for the 1E-5/year broadband rock motions, considering these 60 randomized profiles.
3. Calculate summary statistics (median and logarithmic standard deviation) on the amplification factors for all frequencies of interest.
4. Compare these summary statistics to those obtained in the original calculations for Section 2.5 of the FSAR.

Sensitivity Run 1 Results

Figures A3-1 and A3-2 show the 60 randomized profiles (entire depth, and top portion, respectively). Unlike the profiles used in FSAR Section 2.5, a profile is consistently high or consistently low over the entire depth of the soil column.

Figure A3-3 compares the summary statistics of the computed amplification factors to those used in FSAR Section 2.5 (identified as Original COLA). The logarithmic-mean amplification factors are essentially identical. The standard deviations differ somewhat. These differences are not large, and they do not show a definite pattern. Given the small extent of these differences, and the fact that the model of partial-correlation model for Vs is more credible than the full-correlation model, it is concluded that the amplification factors in FSAR Section 2.5 are adequate.

Sensitivity Run 2 Approach

Sensitivity analysis 2 utilizes the non-linear degradation curves developed in Appendix 2 of this report and will also consider full correlation between layers.

The site-response calculations in FSAR Section 2.5 of the FSAR assumed linear (i.e., strain-independent) behavior of the soils in the shallow portion of the profile (Layers A through I, plus the Strawn formation), on the basis of the low strains that were anticipated for the rock motions at the site. As part of a previous the sensitivity analysis, strain-dependent modulus-reduction and damping curves were developed and are documented in Appendix 2, but were not used in the calculations because the resulting amplification factors were slightly lower than those from linear analyses. The motivation for sensitivity analysis 2 is to test the sensitivity of the amplification factors to using the site response methodology of draft ISG-017 instead of that outlined in FSAR Section 2.5.2. The ISG-017 methodology leads to higher strains because it considers the dynamic strains induced by soil deposits located above the plant foundation.

The steps for sensitivity run 2 include the following.

1. Generate a new set of 60 randomized profiles for a soil column that extends to plant grade, including strain-dependent shear modulus and damping for the shallow profile. Use a ln[Vs] correlation coefficient of 1 at all depths.
2. Perform site-response calculations for the 1E-5/year broadband rock motions, considering these 60 randomized profiles. For this calculation, calculate the amplification factors at the GMRS horizon by following the two-step approach contained in the NEI White Paper, *Consistent Site Response – SSI Calculations.* and accepted by ISG-017 for embedded structures that are analyzed as surface structures.
3. Calculate summary statistics (median and logarithmic standard deviation) on the amplification factors for all frequencies of interest).
4. Compare these summary statistics to those obtained in the original calculations for Section 2.5 of the FSAR.

Sensitivity Run 2 Results

Figure A3-4 shows the peak strains as a function of depth for the 60 randomized profiles. The higher strains occur in the 200-370 feet depth range, with a logarithmic-mean value slightly below 0.01%. This depth range includes limestones, sandstones, and shales, with shear-wave velocities near 3200 feet/second. Recalling Figures A2-1 and A2-2, we note that the behavior of these strata is nearly linear, except for the 62 feet of shale (Layer H),

Figure A3-5 compares the summary statistics of the computed amplification factors to those used in FSAR Section 2.5 (identified as Original COLA). At frequencies above 1 Hz, the logarithmic-mean amplification factors are 10 to 20% lower for the nonlinear runs that for Section 2.5. The standard deviations differ somewhat. As was the case in Figure A3-3, these differences are not large, and they do not show a definite pattern. Figure A3-6 compares the results from Run 1 and Run 2, in order to isolate the effects of nonlinearity from the effects of full Vs correlation. This comparison shows the same reduction in median amplification factors and a slight increase in the standard deviations.

Given the above comparisons, it is concluded that the amplification factors in FSAR Section 2.5 are adequate.

Sensitivity Run 3 Approach

The third sensitivity analysis considers the effect of interbedded shale layers within the foundation bearing Layer C. As in Run2, Run 3 considers the effect of soil nonlinearity and follows the methodology in draft document ISG-017. These shale layers are modeled as nonlinear, with appropriate degradation properties.

The steps for sensitivity run 3 include the following.

1. Develop a model for the location, extent, and dynamic properties of the interbedded shale within Layer C, including low-strain properties and degradation curves.
2. Generate a new set of 60 randomized profiles for the GMRS horizon, including shale interbeds within Layer C, and including strain-dependent shear modulus and damping for the shallow profile. Use a ln[Vs] correlation coefficient of 1 at all depths
3. Perform site-response calculations for the 1E-5/year broadband rock motions, considering these 60 randomized profiles. For this calculation, follow the two-step approach contained in the NEI White Paper and recommended by ISG-017 for embedded structures that are analyzed as surface structures.
4. Calculate summary statistics (median and logarithmic standard deviation) on the amplification factors for all frequencies of interest).
5. Compare these summary statistics to those obtained in the original calculations for Section 2.5 of the FSAR.

Interbedded Layer C Model Development

The category 1 structures are to be founded directly on engineering Layer C which is characterized as a 60 feet thick limestone with a mean shear wave velocity of about 5800 feet/sec. Lying above Layer C are Layers A and B which will be excavated/removed. The uniformity of Layer C has been determined from the review of over 114 geotechnical core borings drilled beneath the CPNPP Units 3 and 4 including a re-evaluation of the boring logs and lithologic descriptions, geophysical measurements and laboratory test results.

Review of Core Lithologic Descriptions and Photographs

The vertical and lateral distribution of shale within Layer C was quantified from a detailed review of each boring log to asses both the total cumulative percentage of shale as well as the lateral continuity of shale layers between borings. During the review of the core boring descriptions and photographs for layer C, four distinct rock lithologies were classified as "shale":

- *Shale* – indicated as having little to no reaction with HCl and signs of dessication upon drying or parting along laminae
- *Laminated Shale/Limestone* - typically has a slight to strong reaction to HCl due to the presence of limestone and thinly, <0.1ft, to thicker, >0.2ft laminations of shale and/or silt
- *Wackestone/Packstone* in Matrix- clasts of limestone in a fine grained matrix
- *Micrite* – a fine grained limestone showing a strong to violent reaction to HCl

Two of these lithologies are more accurately described as fine grained limestone (wackestone/packstone and micrite) that visually resembles shale yet is more cemented than actual shale. However, for the purpose of testing the sensitivity of the site ground motions to the presence of interbedded shale, each interval described as "shale" within the boring logs is considered to have the same shale characteristics described later in this section.

Vertical and Lateral Evaluation of Layer C Uniformity

An extensive review of 114 geotechnical core boring logs was performed to characterize the thickness, elevation and lithology of the "shale" intervals. As described above, irrespective of the actual detailed lithology, each "shale" layer was included in the following evaluation. Within Layer C there is a total of 112.5 feet of "shale" and 9455.9 total feet of limestone. The total percentage of "shale", calculated as the total thickness of "shale" divided by the total cored thickness of Layer C, is approximately 1.2 percent. With the exception of boring B-2002, which has a total of almost 11 cumulative feet of "shale" (all of which is more accurately either micrite or laminated limestone), the mean total shale thickness for all borings is less than 2 feet (1.2 percent) of Layer C.

The potential presence of laterally continuous shale layers was evaluated by plotting the thickness of shale within each boring at the respective elevation as shown on Figure A3-7. Also note on Figure A3-7 that the interface between the overlying Layer B2 and Layer C beneath Unit 4 indicates limited zones of shale in the range of elevation 782, which is the estimated mean average top elevation of Layer C. Subsection 2.5.4.12.4 of the FSAR provides a commitment that top of foundation inspections will identify shale pockets for removal prior to placement of fill or structural concrete, thus this horizon was not included in the following evaluation although the occurrence of shale was included in cumulative thickness and percentage estimates.

The main identified "shale" horizons include the following.

- Horizon CS1 ranges from about Elevation 766-763 and includes shale thicknesses from 0.2 to 1.5 ft thick.
- Horizon CS2 ranges from about Elevation 749-746 and includes shale thicknesses from 0.2 to 1.9 ft thick.
- Horizon CS3 ranges from about Elevation 745-742 and includes shale thicknesses from 0.2 to 2.6 ft thick.
- Horizon CS4 ranges from about Elevation 736-733 and includes shale thicknesses from 0.3 to 1.8 ft thick.

Each of these 4 shale horizons were plotted in plan view to determine their lateral extent, but they cannot be continuously mapped across the site. Regardless, these general characteristics of the site layers are used to develop representative model parameters for shale interbeds in Layer C.

Uniformity of Geophysical Measurements

Resistivity measurements were also used to evaluate the potential shale content within Layer C. The 15 borings with resistivity measurements were evaluated by using data from Layer D, a continuous shale layer beneath Layer C as a known baseline. Layer D has an average Single Point Resistance, (SPR) of approximately 12 to 16 Ohm. Within Layer C SPR varies from 28 to 80 Ohm, higher values than characteristic of shale at the site. SRP values at specific depths of known shale were also examined, and in general these values were also significantly higher than values characteristic of shale at the site. For example, at elevations 750.9 and 748.3 in Boring Log B-1000, a noted "shale" horizon, SPR values are 32-50 and 35-45 Ohm's respectively. These values that are higher than expected for shale are consistent with the detailed lithologic characteristics of the intervals that are more indicative of laminated shale/limestone. In summary, the resistivity measurements indicate that Layer C has relatively uniform characteristics that are more typical of limestone than shale.

Summary of Layer C Uniformity

A thorough evaluation of the core lithologic descriptions, photographs and geophysical measurements determined that shale is mostly limited to isolated pockets and not continuous layers within Layer C. Further, the total percentage of "shale" does not constitute a reduction in the mass properties of Layer C.

Layer C Base Case Parameters

Four base case models of alternate shale interbedding within Layer C were developed for this sensitivity analysis. These base cases were defined by: (1) the elevations and thicknesses of shale layers from the empirical data presented above, and (2) appropriate shear wave velocities of the shale layers and non-linear degredation properties for purposes of the sensitivity analyses.

Shale Interbed Base Case Models

The review of the core boring descriptions identified four specific characteristics of intervals described as "shale". Two of these are likely fine grained carbonate (micrite) as opposed to actual shale. However, for the purpose of this evaluation, each interval described as "shale" was classified in the sensitivity analysis with shale characteristics. The shale layers within Layer C for all borings are shown respective to elevation and noted thickness on Figure A3-7. Although planar maps clearly indicate that the shale cannot be mapped as laterally continuous layers, two alternate Base Case models of interval thickness and elevation were developed that effectively represent the shale interbeds as continuous layers (Figure A3-7).

Determination of Appropriate Shale Degradation Properties and Shear Wave Velocity

Development of representative shear modulus (G/Gmax) and damping ratio (D) versus shear strain relationships were developed through consultation with Dr. Ken Stokoe, Professor University of Texas. The G/G_{max} – log γ and D – log γ relationships for the various rock types at Comanche Peak are presented on Figures A2-1 and A2-2, respectively, in Appendix 2 of this report. As a point of comparison, Dr. Stokoe compared the relationships developed for the CPNPP and the dynamic laboratory test results that were conducted at the University of Texas in 2002 on shale core recovered from Oak Ridge, TN. Relationships for Oak Ridge shale in two conditions (weathered and unweathered) were used as bounding conditions. A more linear G/G_{max} – log γ and D – log γ relationships were noted to represent a lower bound for the unweathered shale (V_s in the lab ~ 4000 fps and V_s in the field ~ 5600 to 6200 fps). More nonlinear relationships were noted to represent weathered shale (V_s in lab ~ 3300 fps and V_s in the field ~ 5100 to 5500 fps). In both cases, the Oak Ridge cores were recovered from depths less than 200 ft.

Upon review, the lower bound relationships for the unweathered Oak Ridge shale are considerably more linear than the "shallow shale" G/G_{max} – log γ and D – log γ relationships presented for Comanche Peak. On the other hand, the weathered Oak Ridge shale relationships are considerably more non-linear than the Comanche Peak "shallow shale" relationships. Considering the unweathered nature and the somewhat lower field Vs values of the Comanche Peak shale, the relationships presented for Curve 4 in Figures A2-1 and A2-2 are considered appropriate for the Base Case models developed for the shale interbeds.

Based on these observations, a Vs of 3000 fps was used for one of the bounding Base Cases. A value significantly lower than measured velocities within Layer C and from weathered shale at Oak Ridge.

Base Case Models for Layer C

The following four cases were used as input to Sensitivity Run 3:

Case 1A: Layering from C Base 1 Model, Vs =5685, Curve 4 Figures A2-1, and A2-2
Case 1B: Layering from C Base 1 Model, Vs =3000, Curve 4 Figures A2-1, and A2-2
Case 2A: Layering from C Base 2 Model, Vs =5685, Curve 4 Figures A2-1, and A2-2
Case 2B: Layering from C Base 2 Model, Vs =3000, Curve 4 Figures A2-1, and A2-2

Sensitivity Run 3 Results

For these sensitivity calculations, the mean + 1 sigma total thickness of shale was used. Figures A3-8 through A3-11 show the calculated peak strains for all four cases considered. In the cases where the shale has a Vs of 5685 feet/sec (cases 1A and 2A), the strain on Layer C and the interbeds (depths of 40 to 105 ft) is fairly constant as a function of depth. In the cases where the shale has a Vs of 3000 feet/sec (cases 1B and 2B), the strain is significantly higher for the shale layers.

Figures A3-12 through A3-15 compare the summary statistics of the computed amplification factors from the four Run 3 cases to those used in FSAR Section 2.5 (identified as Original COLA). At frequencies above 1 Hz, the logarithmic-mean amplification factors are 10 to 25% lower for Run 3 cases than for Section 2.5. The standard deviations differ somewhat. In the cases where the shale has a Vs of 5685 feet/sec (cases 1A and 2A), the standard deviations are similar to Figure A3-3 and are due to the effects of full Vs correlation. In the cases where the shale has a Vs of 3000 feet/sec (cases 1B and 2B), the standard deviation is somewhat higher at frequencies near 20 Hz.

Considering that the shale Vs in cases 1A and 2A are the only ones that are consistent with the field Vs measurements, and that these two cases produce similar results to those in FSAR Section 2.5, it is concluded that the amplification factors in FSAR Section 2.5 are adequate.

Conclusions

The first sensitivity test shows small differences relative to the results in FSAR Section 2.5. The logarithmic-mean amplification factors are essentially identical. The differences in standard deviations are not large, and they do not show a definite pattern. Given the small extent of these differences, and the fact that the model of partial-correlation model for Vs is more credible than the full-correlation model, it is concluded that the amplification factors in FSAR Section 2.5 are adequate.

The second sensitivity test shows that the logarithmic-mean amplification factors obtained using nonlinear analysis are lower by 10 to 20% and the differences in standard deviations are associated with the assumption of full Vs correlation. It is concluded, therefore, that the amplification factors in FSAR Section 2.5 are adequate.

The third sensitivity test indicates that the logarithmic-mean amplification factors are 10 to 25% lower than in Section 2.5. The cases in which the interbedded shale has Vs values consistent with the field Vs measurements, the differences in standard deviations are somewhat different due to the effects of full Vs correlation. It is concluded, therefore, that the amplification factors in FSAR Section 2.5 are adequate.

In summary, the three sensitivity tests performed here indicate small differences with respect to the results contained in FSAR Section 2.5. Given the small extent of these differences, and the fact that the model parameters that lead to these differences are less tenable than the parameters used in FSAR Section 2.5, it is concluded that the results in FSAR Section 2.5 are adequate.

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NEI White Paper, BNL Report N6112-051208, Rev. 1, "Consistent Site Response – SSI Calculations, June 12, 2009"

ISG-017, Interim Staff Guidance, on Ensuing Hazard Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses, DC/COL.

Toro, G.R. (2005). Site-Wide Probabilistic Model of Shear-Wave Velocity Profiles at the Savannah River Site, Aiken, South Carolina. Report by Risk Engineering, Inc. to Bechtel Savannah River Co., October. Report Number WSRC-OS-2006-00514, Revision 1.

EPRI (Electric Power Research Institute) 1993. Appendices for Ground Motion Estimation. Volume 2 of Guidelines for Determining Design Basis Ground Motions. EPRI TR-102293. Palo Alto, California: Electric Power Research Institute.

Toro, G.R. (1996). Probabilistic Models Of Site Velocity Profiles For Generic And Site-Specific Ground-Motion Amplification Studies. Appendix C in Silva, W.J.; Abrahamson, N.; Toro, G.; and Costantino, C. (1996). Description and Validation of the Stochastic Ground Motion Model. El Cerrito, California: Pacific Engineering and Analysis.

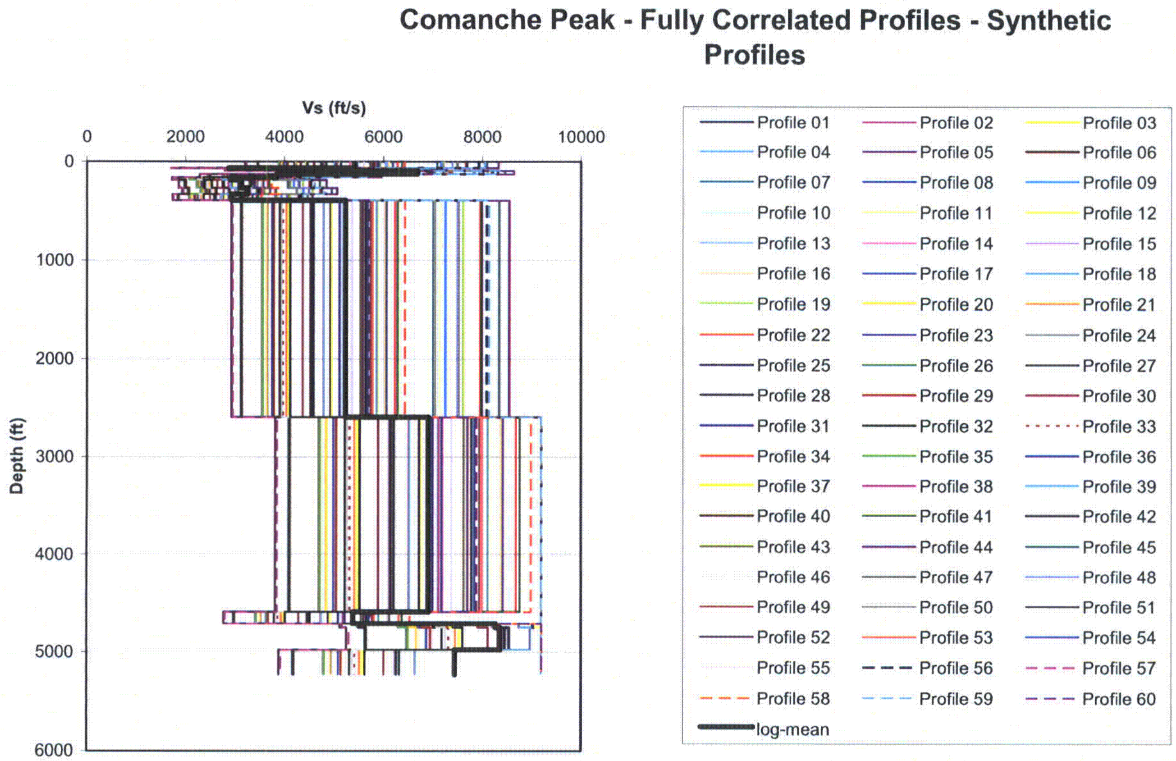


Figure A3-1. Randomized velocity profiles for Sensitivity Run 1 (entire soil column)

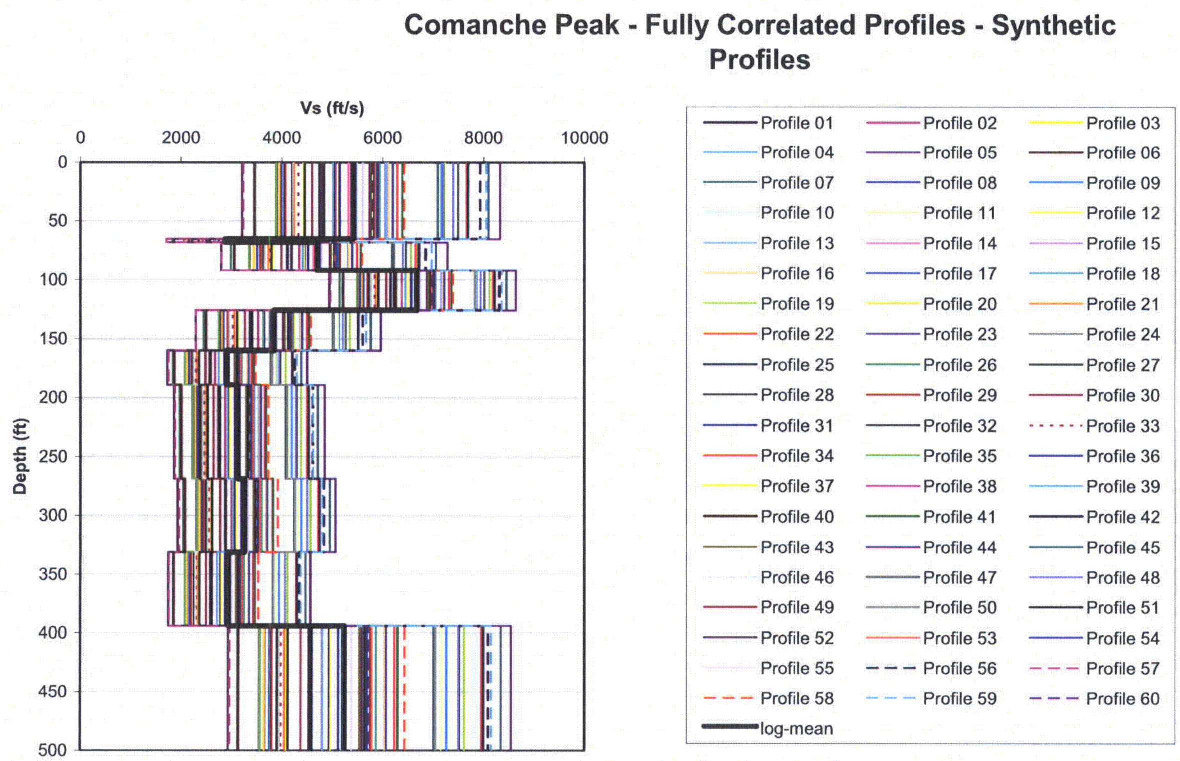


Figure A3-2. Randomized velocity profiles for Sensitivity Run 1 (top 500 feet)

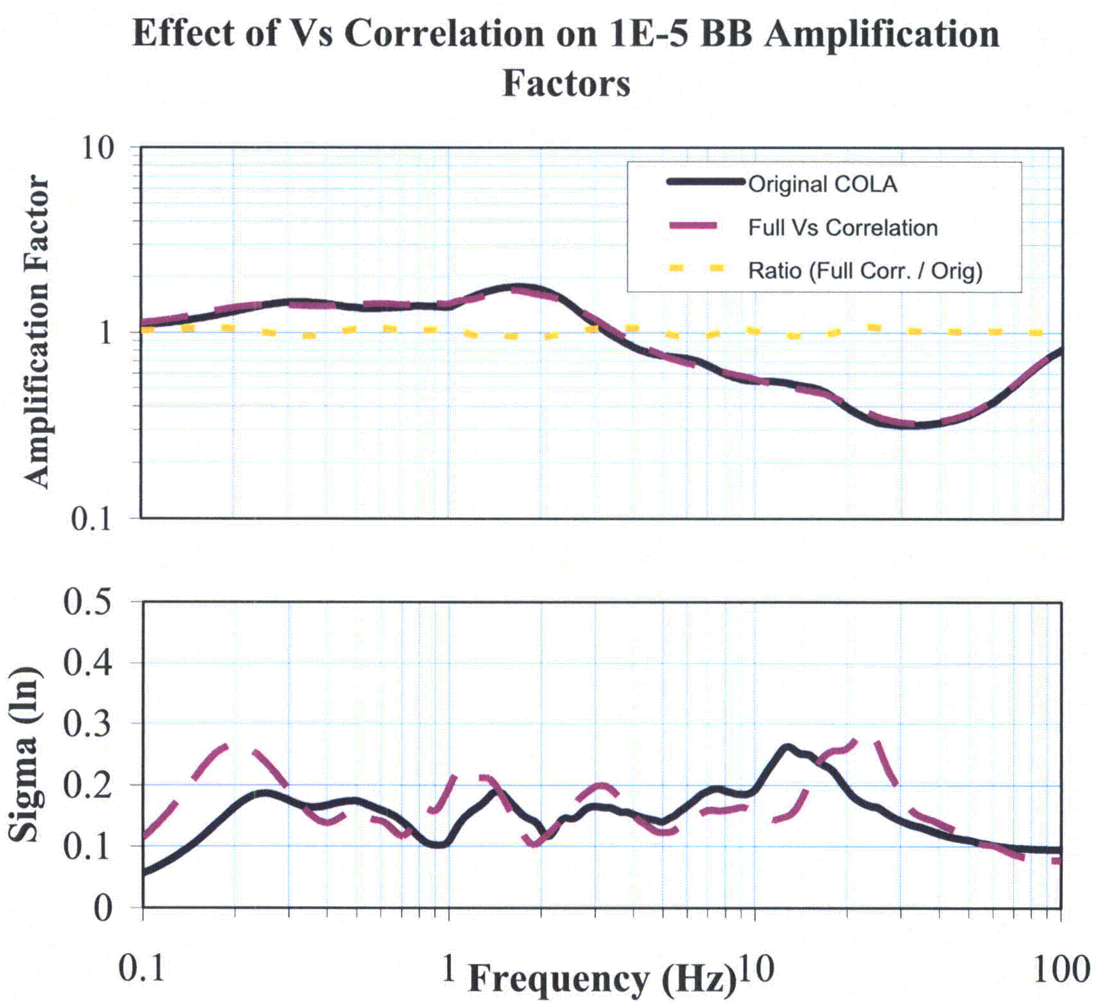


Figure A3-3. Comparison of amplification factors in Section 2.5 (original COLA) to those obtained using full Vs correlation. Top, logarithmic-mean amplification factors; bottom, logarithmic standard deviations.

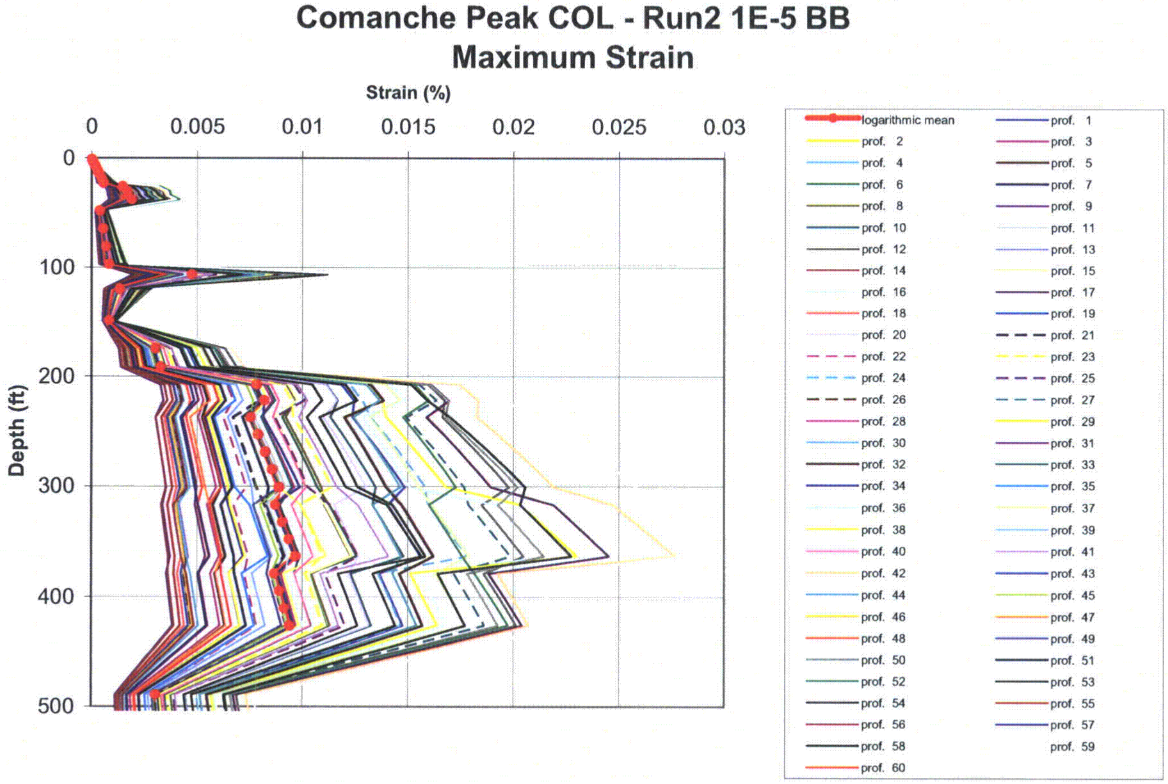


Figure A3-4. Peak strains for all 60 synthetic profiles considered in Run 2 (only the top 500 feet of the soil column are shown).

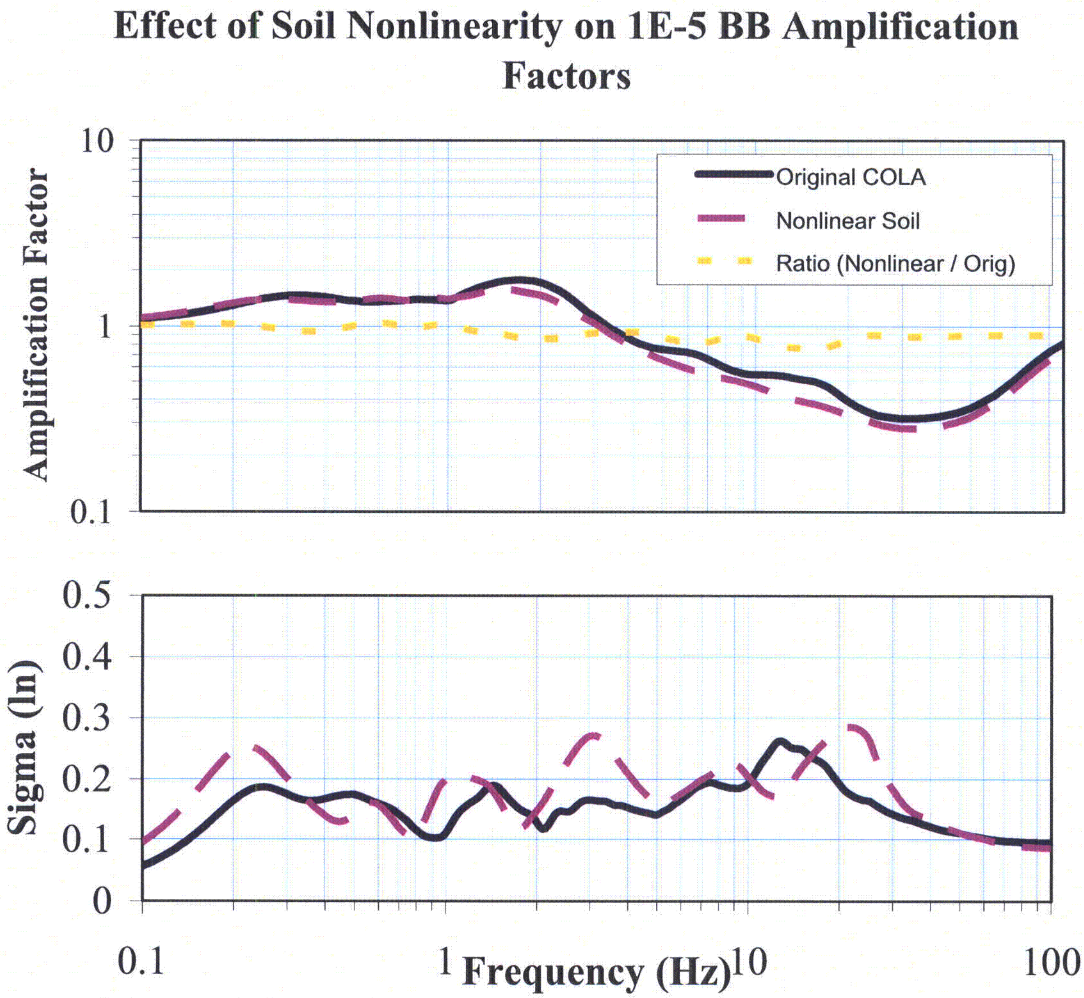


Figure A3-5. Comparison of amplification factors in Section 2.5 (original COLA) to those obtained using nonlinear soil properties and full Vs correlation (Run 2). Top, logarithmic-mean amplification factors; bottom, logarithmic standard deviations.

Effect of Soil Nonlinearity on 1E-5 BB Amplification Factors

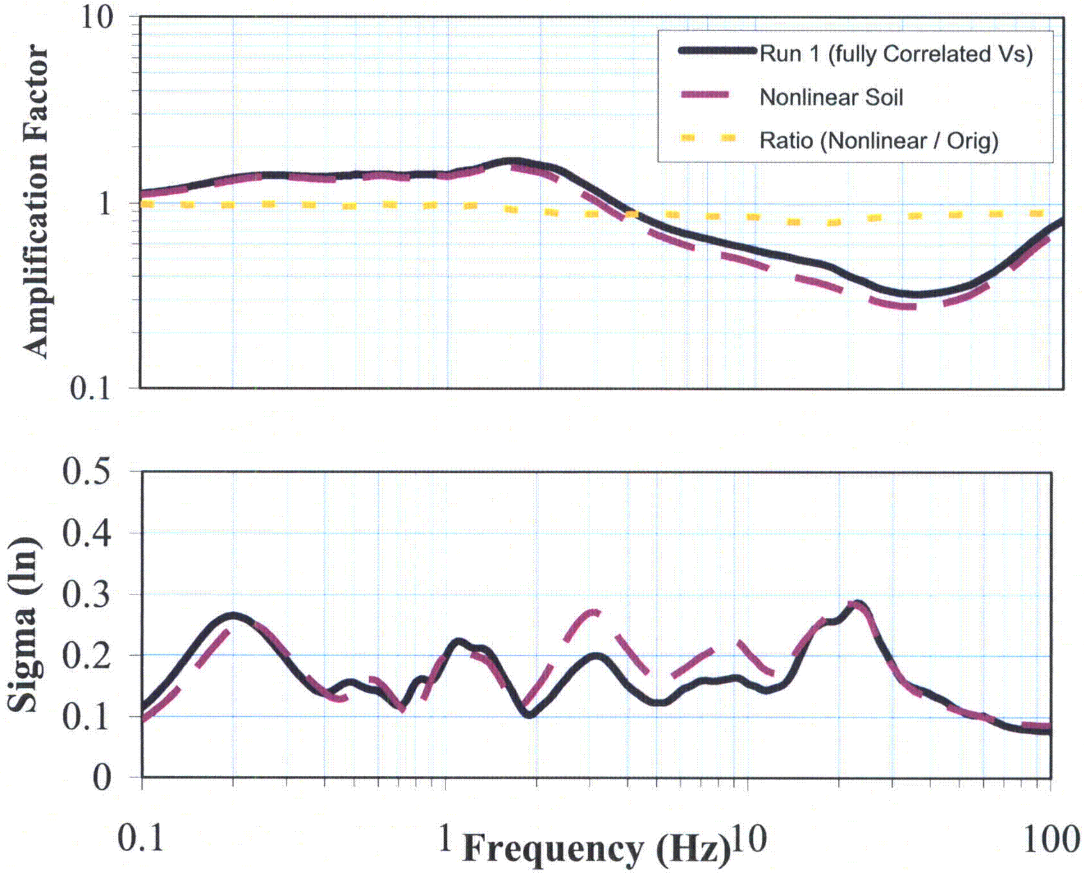


Figure A3-6. Comparison of amplification factors using linear soil properties and full Vs correlation (Run 1) to those obtained using nonlinear soil properties and full Vs correlation (Run 2). Top, logarithmic-mean amplification factors; bottom, logarithmic standard deviations.

FIGURE A3-7 was provided by WLA as a separate document (initially numbered A3-1)

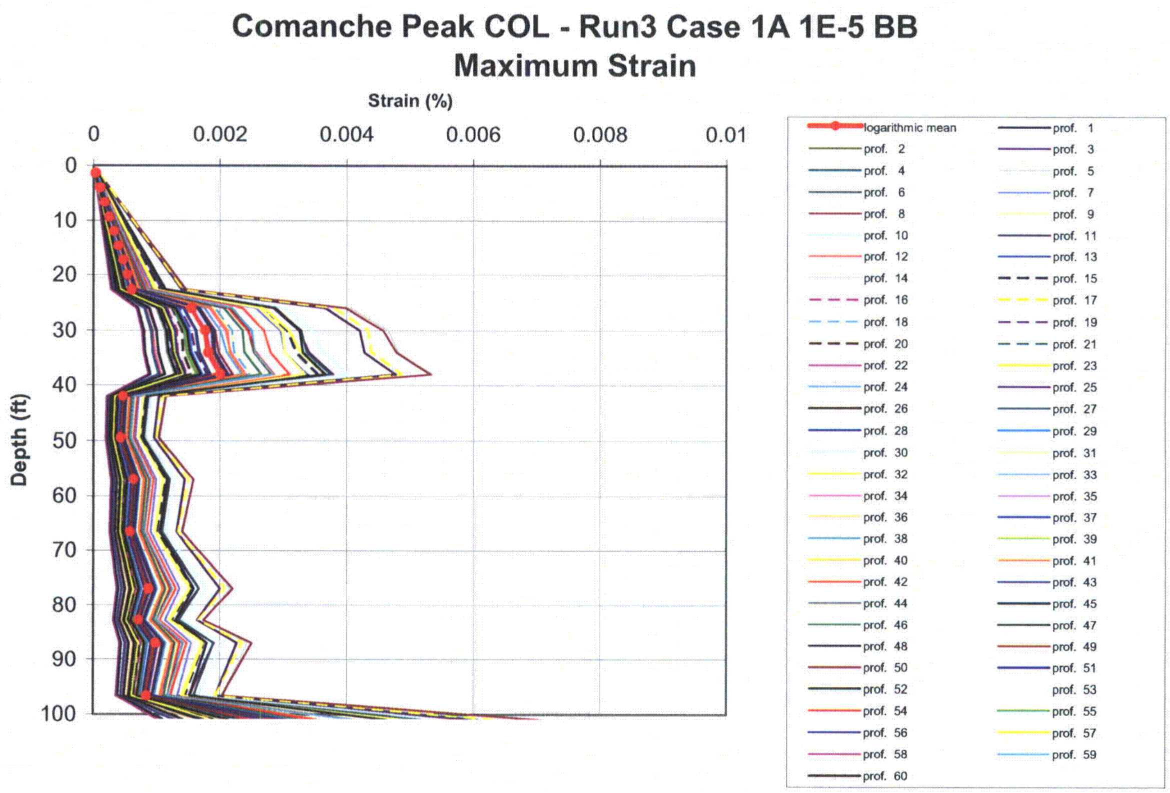
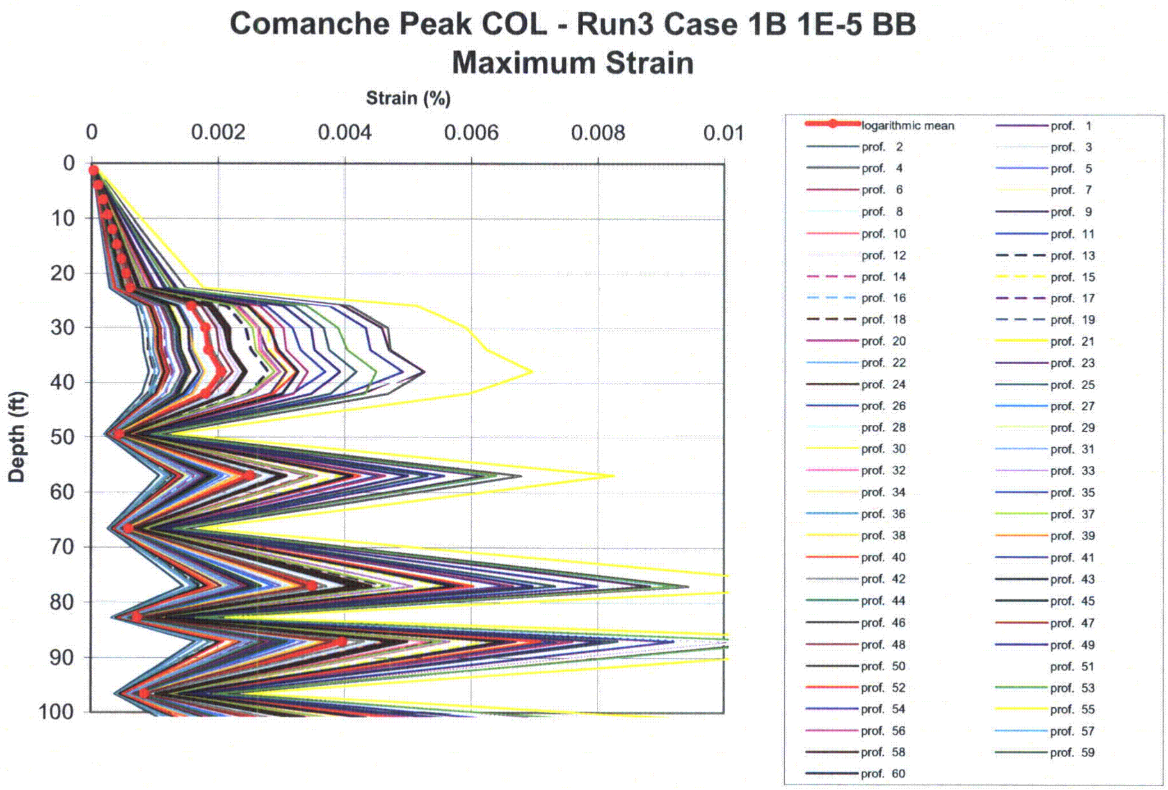


Figure A3-8. Peak strains for all 60 synthetic profiles considered in Run 3, Case 1a (only the top 100 feet of the soil column are shown).



FigureA3-9. Peak strains for all 60 synthetic profiles considered in Run 3, Case 1b (only the top 100 feet of the soil column are shown).

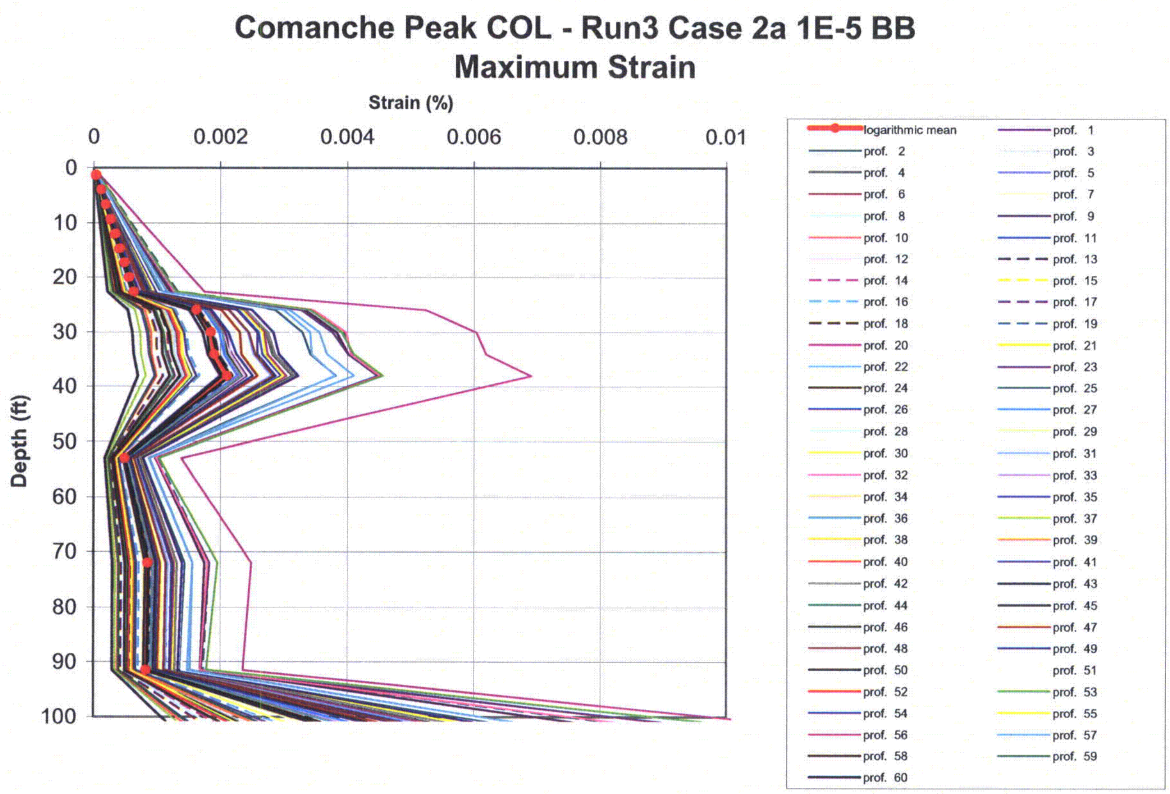


Figure A3-10. Peak strains for all 60 synthetic profiles considered in Run 3, Case 2a (only the top 100 feet of the soil column are shown).

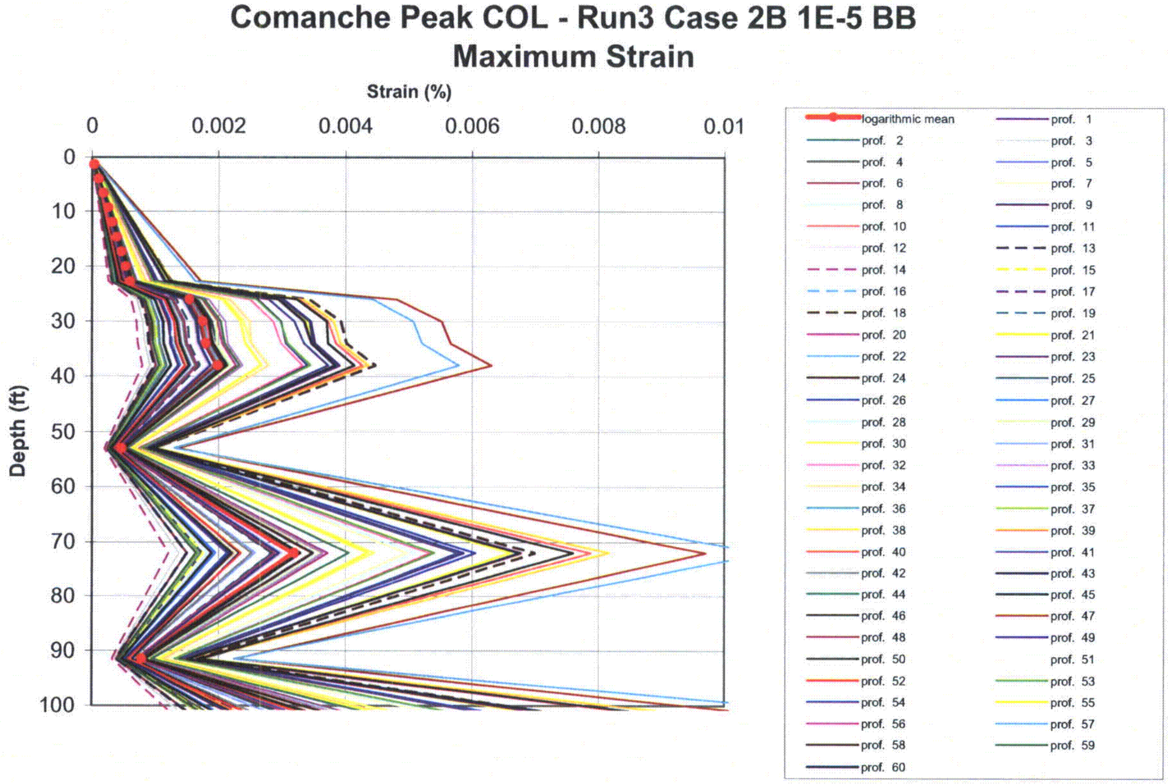


Figure A3-11. Peak strains for all 60 synthetic profiles considered in Run 3, Case 2b (only the top 100 feet of the soil column are shown).

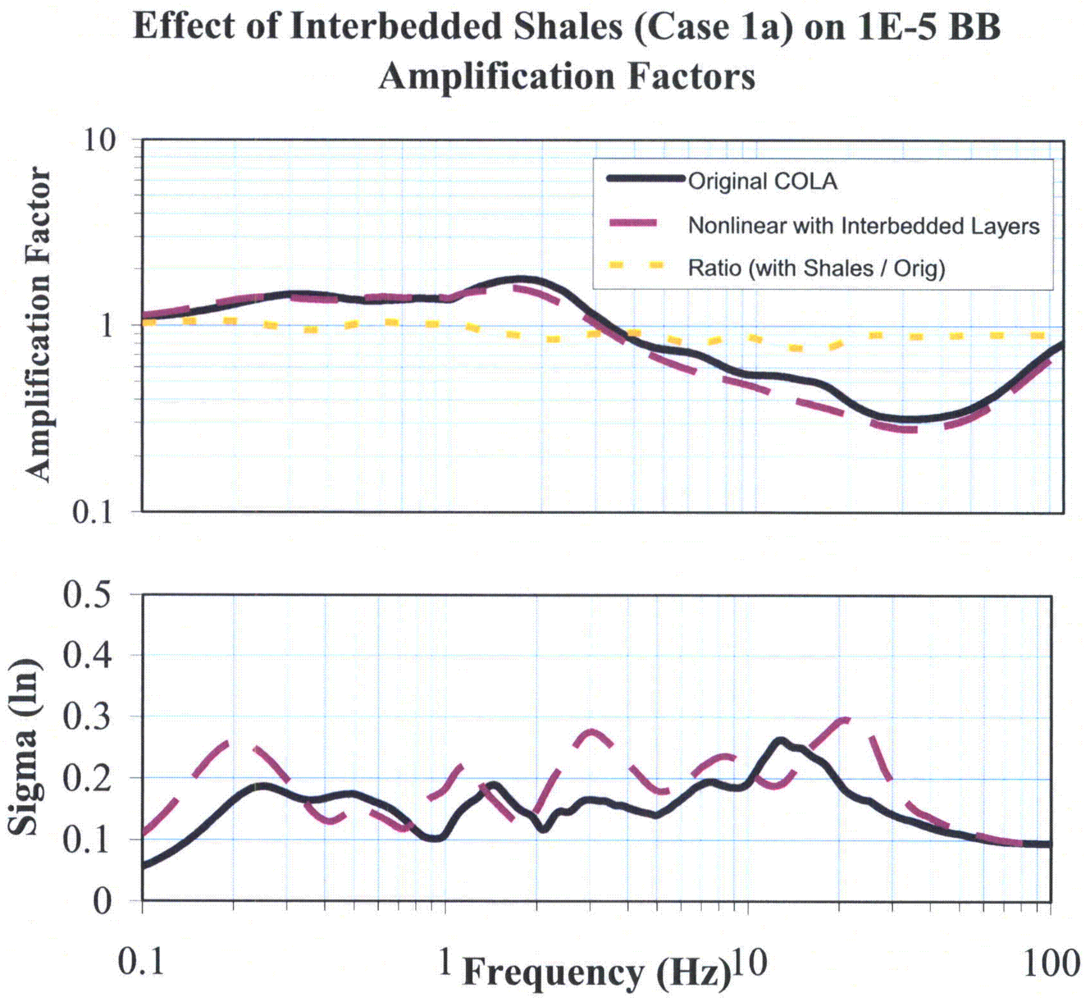


Figure A3-12. Comparison of amplification factors in Section 2.5 (original COLA) to those obtained using interbedded shale layers within Layer C (case 1a). Top, logarithmic-mean amplification factors; bottom, logarithmic standard deviations.

Effect of Interbedded Shales (Case 1b) on 1E-5 BB Amplification Factors

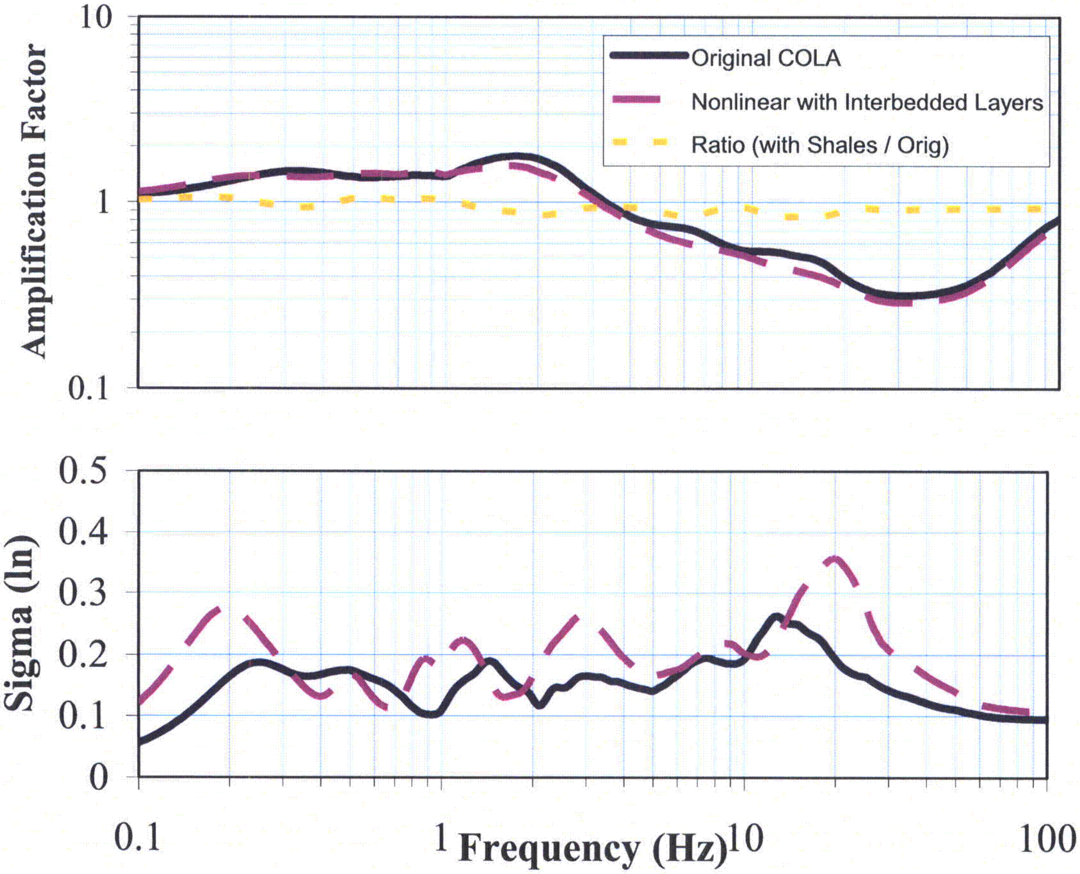


Figure A3-13. Comparison of amplification factors in Section 2.5 (original COLA) to those obtained using interbedded shale layers within Layer C (case 1b). Top, logarithmic-mean amplification factors; bottom, logarithmic standard deviations.

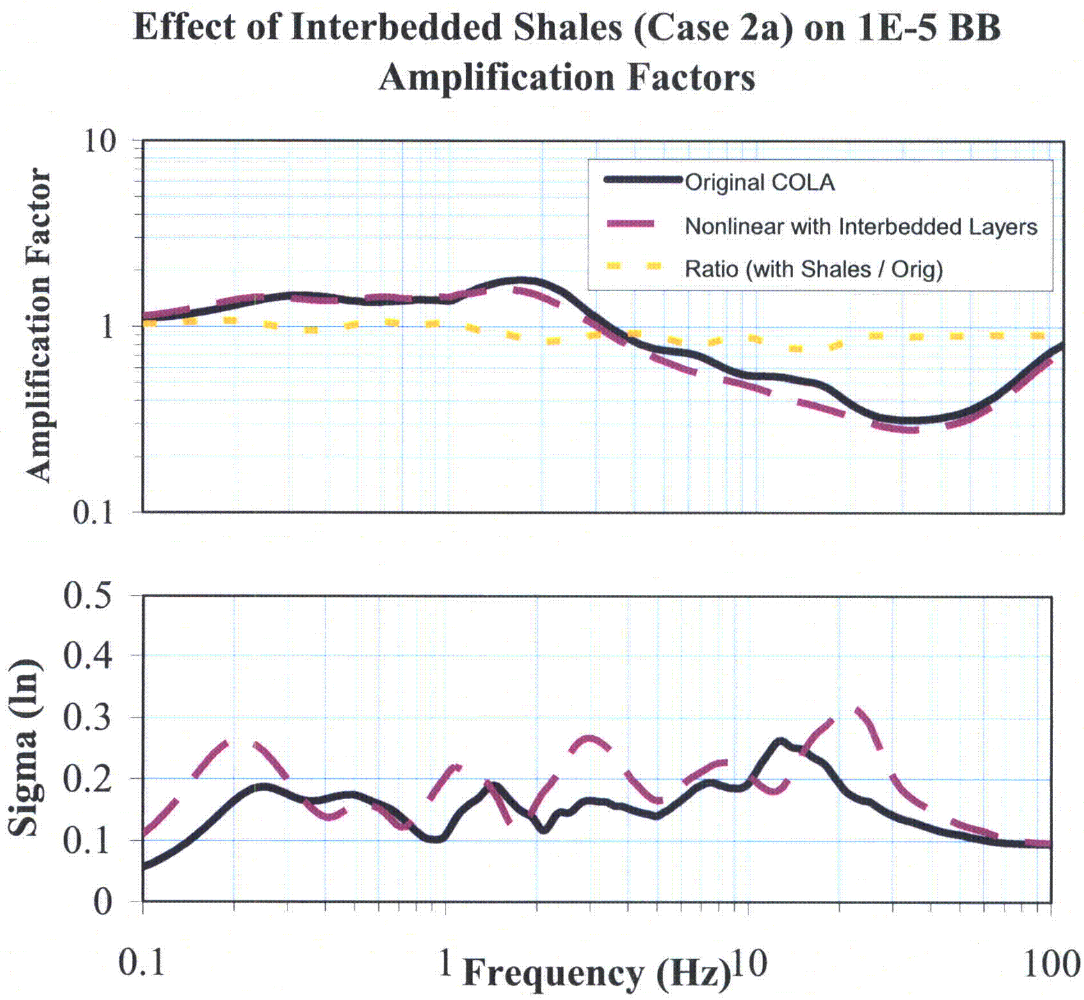


Figure A3-14. Comparison of amplification factors in Section 2.5 (original COLA) to those obtained using interbedded shale layers within Layer C (case 2a). Top, logarithmic-mean amplification factors; bottom, logarithmic standard deviations.

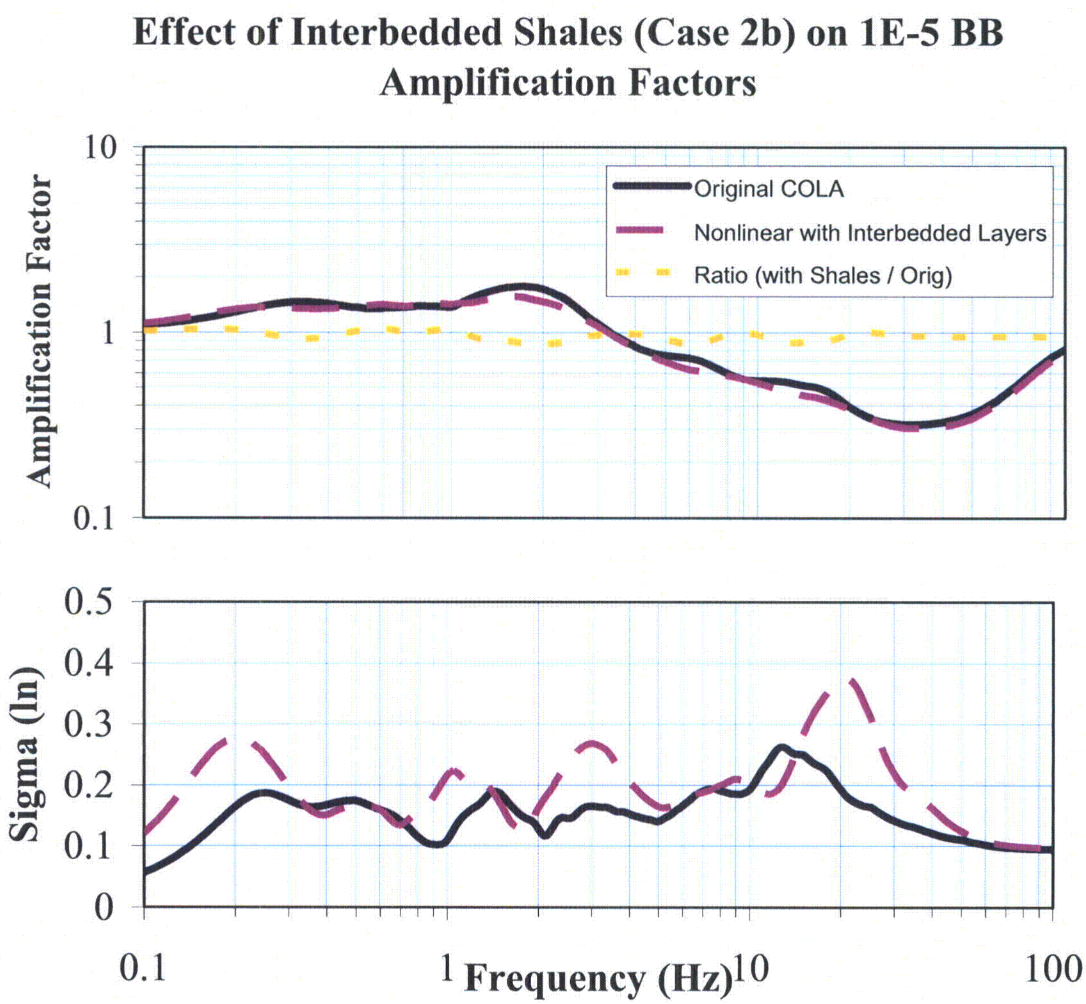


Figure A3-15. Comparison of amplification factors in Section 2.5 (original COLA) to those obtained using interbedded shale layers within Layer C (case 2b). Top, logarithmic-mean amplification factors; bottom, logarithmic standard deviations.