Seismic Response of Statistically Varied Soil Column Profiles for SSI Analyses

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ABSTRACT

This paper presents a statistical approach to develop the soil column profiles and surface seismic response spectra for soil-structure interaction (SSI) analyses of structures founded on layered soil sites. The soil profile is developed using the statistical mean value of measured in-situ soil properties as determined from site boreholes and soil testing. The individual randomized soil profiles are input into a separate iterative soil column seismic analysis program to develop the seismic strain compatible soil profiles and surface acceleration response spectra consistent with the site design basis earthquake hazard.

The median and median plus one standard deviation of the statistically developed surface response spectra developed using the results of thirty randomized soil columns are presented to demonstrate the influence of variation in soil properties and layer geometry. The development of median design response spectra based on the mean seismic hazard established for the site is recommended by the US Department of Energy [1, Section 2.3] for the design and evaluation of structures, systems and components. The statistically developed spectra are compared with spectra developed using soil profiles based on ASCE 4-98 soil modulus uncertainty factors [2, Section 3.3.1.7]. The USNRC NUREG-0800 provides similar specific guidance regarding the variation in soil properties [3, 3.7.2]. A layered site having three different soil types overlying bedrock is used as an example.

Statistically derived soil profiles and response spectra (or acceleration time histories) in an SSI analysis utilize available soils information while avoiding designing for extreme site subsoil conditions which have a low probability of occurrence and provide a means to select an appropriate level of seismic risk. Additionally, the use of statistically derived soil profiles are appropriate to develop Uniform Hazard Spectra (UHS) at the surface given a UHS defined at bedrock.

INTRODUCTION

Seismic evaluations of important structures in moderate to high seismic zones founded on soil need to consider the uncertainties associated with the variability of soil materials and layering in order to adequately develop seismic strain compatible soil profiles and seismic responses. Soil test data can include, in part, characterizations of soil types, layer depths and thickness, depth to bedrock, and in-situ measurements of soil shear wave velocities. For each soil layer, the measured shear wave velocities (V_s) are used to calculate the site "low-strain" soil shear moduli (Gls) using the soil density (w):

$$Gls = \frac{w}{g} \times Vs^2 \tag{1}$$

Soil properties, such as the shear modulus and damping, are strain dependent. This means that soil properties developed based on the relatively low strains involved with shear wave velocity testing will be changed when subjected to the relatively high strains that can be expected during a large earthquake. At higher strain levels, soil shear modulus is reduced while the soil material damping is increased. This strain dependency is usually presented in the form shear modulus (also damping) strain degradation curves determined for each soil type by additional testing or comparison with generically available curves when appropriate. In order to estimate the higher strain level "seismic strain compatible" properties, an analysis is conducted which passes the site design seismic motion through a one dimensional model of the soil column constructed using the low strain properties. The analysis uses an equivalent non-linear iterative time history procedure along with the soil strain degradation curves to develop the soil properties corresponding to strains that can be expected to occur during the earthquake. The resultant strain compatible properties become the basis of the soil model used in the SSI analyses. This analysis also calculates the corresponding strain compatible acceleration response spectra (and associated acceleration time histories) that define the SSI analysis seismic input motion. Thus, it is seen that variability and uncertainty associated with the measured low strain soil properties would also affect the results of SSI analyses using strain compatible properties.

ASCE 4-98, Section 3.3.1.7 and NUREG-0800, Section 3.7.2, provide guidance to account for these uncertainties in the seismic analyses. Three sets of low strain soil properties are developed including the "best estimate" properties. "Upper bound" and "lower bound" properties are developed by multiplying and dividing the best estimate properties by the uncertainty factor 1 + Cv. The uncertainty factor is dependent upon the amount of soils data available. Cv can be directly calculated by statistically evaluating the soils test data. At a minimum, Cv should not be less than 0.5 [2]. If sufficient soil data is not available, Cv = 1.0 should be used [2], [3]. ASCE 4-98 recommends conducting analyses that range the low strain properties between the upper and lower bound properties. In practice, three analyses are often conducted [2], corresponding to the upper bound, lower bound and best estimate properties to obtain three sets of properties and surface response spectra (or comparable acceleration time histories) to be used in three corresponding SSI analyses.

The approach presented herein analyzes thirty sets of low strain soil columns and develops thirty sets of corresponding strain compatible soil properties and response spectra. The thirty low strain soil columns are developed by randomly sampling the log-normal distributions of the individual soil layer shear modulus developed from the soil test reports for the site. The resultant thirty acceleration response spectra are statistically analyzed as being log-normally distributed and the median and median plus one standard deviation (one sigma) spectra compared with the spectra developed using the ASCE 4-98 and NUREG-0800 approaches.

In addition to sampling the measured soil properties, the variation in soil layer thickness is also randomly sampled using a uniform distribution when developing the thirty low strain soil columns.

SUBGRADE SOIL PROFILE

The site soil profile used consists of three soil layers underlain by basalt bedrock as shown in Figure 1. The soil layer materials are representative of sandy gravel (12.5 feet thick), gravel (34.75 feet thick) and clay (5 feet thick). Figure 1 also shows the average measured depths to the top of the soil layers and bedrock along with the depth measurement variation.

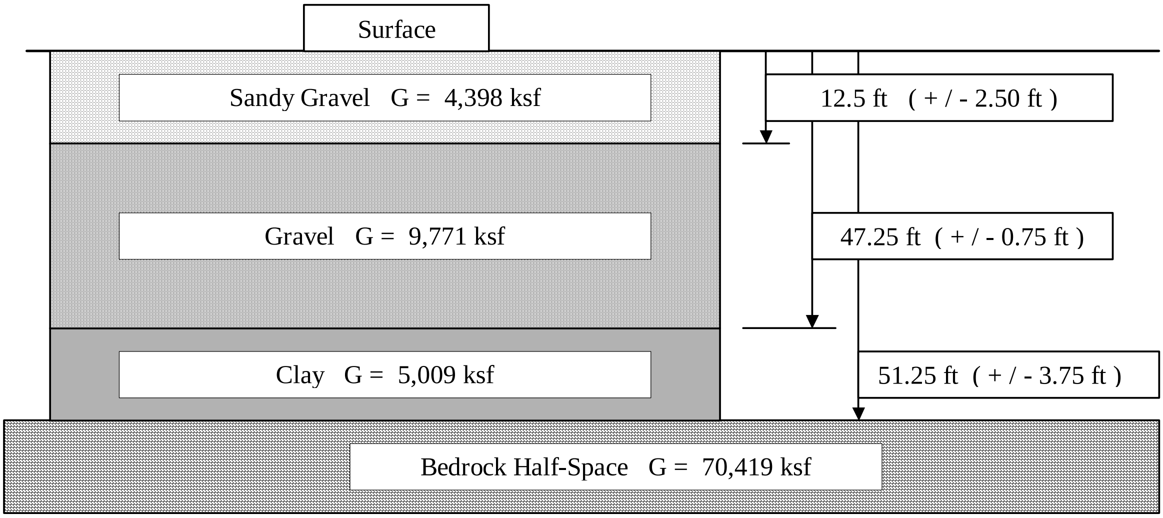

Figure 1 Site Soil Profile Showing Soil Layers and Layer Depths

A uniform distribution is used to sample the soil layer depth variation. The total depth variations of the soil layer depths are constrained to fit within the bedrock depth variation.

Table 1 lists the soil profile low strain material properties. For each soil layer, the best estimate soil shear modulus is the median shear modulus as obtained from the available soils data sample and using Eq. 1. The upper and lower bound soil moduli represent the median value plus and minus one standard deviation as determined from the log-normal distribution of the test sample. Cv, in the last column of Table 1, described in ASCE 4-98 as the coefficient of variation, correlates with the coefficient of variation in the log-normal distribution and is used to develop the upper and lower bound shear moduli.

$$G(\text{upper bound}) = G(\text{best estimate}) \times (1 + Cv) \tag{2}$$

$$G(\text{lower bound}) = G(\text{best estimate}) / (1 + Cv) \tag{3}$$

The corresponding upper and lower bound shear wave velocities are determined from the shear moduli and density using Eq. 1. Table 1 also lists the soil layer densities, Poisson's ratios and shear wave velocities for the site profile.

For the sandy gravel layer, the ASCE 4-98 coefficient of variation is determined to be 1.81 based on the statistical sampling of the available data. The gravel layer test data showed very little variation and resulted in a Cv that was less than 0.5. Accordingly, a Cv of 0.5 is assigned to meet the minimum ASCE 4-98 recommendation. The clay layer test data sample size is not sufficient to develop a reliable Cv. Therefore, a Cv of 2.0 was assigned, again following the ASCE 4-98 recommendation.

Table 1 Summary of Soil Profile Low Strain Material Properties

Layer	Property Variation	Density (kcf)	Poisson's Ratio (v)	Vs (ft/sec)	G (ksf)	ASCE 4-98 C_v
Sandy Gravel	Lower Bound (L.B.)			785	2,431	1.81
	Best Estimate (B.E.)	0.127	0.25	1,056	4,398	1.00
	Upper Bound (U.B.)			1,420	7,957	1.81
Gravel	L.B.			1,285	6,514	1.50
	B.E.	0.127	0.3	1,574	9,771	1.00
	U.B.			1,928	14,657	1.50
Clay	L.B.			898	2,505	2.00
	B.E.	0.100	0.25	1,270	5,009	1.00
	U.B.			1,796	10,018	2.00
Basalt	L.B.			3,020	42,495	1.66
	B.E.	0.150	0.34	3,888	70,419	1.00
	U.B.			5,005	116,691	1.66

SEISMIC INPUT

The seismic input for the site is defined for the bedrock level. This spectrum represents the mean seismic hazard for the site when considering the performance requirements of the structure [1]. The site seismic hazard dynamic characteristics are expressed as the design acceleration response spectrum shown in Figure 2. The spectrum of the acceleration time history used in the soil column analyses to develop strain compatible soil properties is also shown in Figure 2. The seismic hazard spectrum is based on 5% of critical damping and has a zero period acceleration (zpa) of 0.125 g and amplified plateau of 0.293 g. The acceleration time history of the spectrum shown in Figure 2, is used as input to the soil column analyses to develop strain compatible soil properties and the surface response spectra.

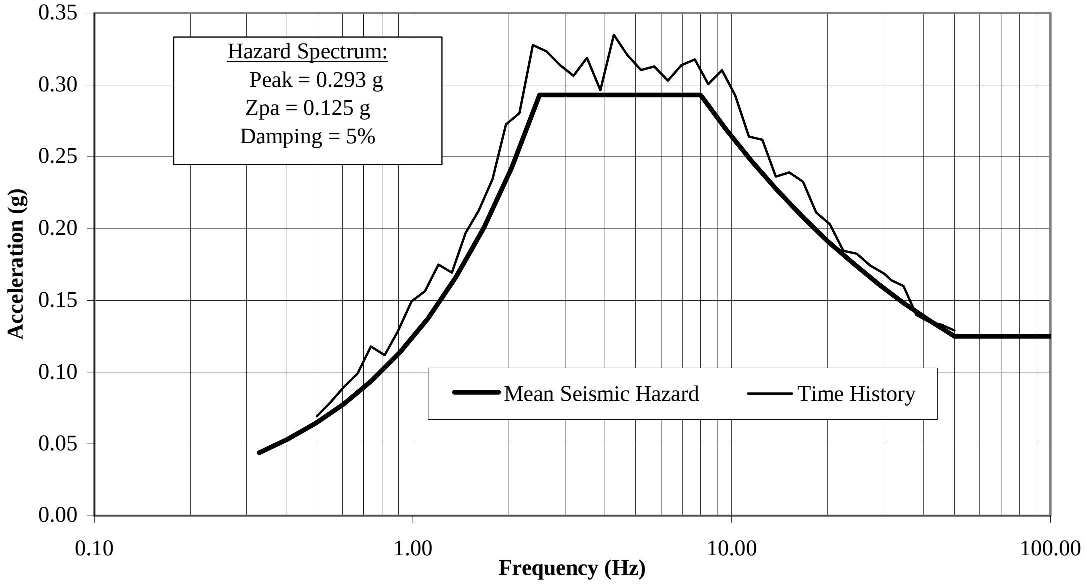

Figure 2 Site Mean Seismic Hazard

SURFACE RESPONSE SPECTRA

ASCE 4-98 Approach

Following the ASCE 4-98 and NUREG-0800 recommendations, three low-strain soil columns seismic were developed using the best estimate, upper bound and lower bound properties listed in Table 1. The three low-strain soil columns were analyzed using the acceleration time history for the bedrock spectrum shown in Figure 2. The analyses were conducted using the SHAKE91 [4] computer program. The SHAKE91 program has the capability to develop the soil column strain compatible soil properties and generate acceleration time histories and response spectra at soil layers within the site profile. For the analyses of each soil column used, the horizontal acceleration response spectrum at the soil column surface is generated. The surface spectra show how the bedrock seismic motion is amplified as the shear wave passes upward through the soil column. The resulting surface best estimate, upper bound and lower bound response spectra define the seismic motion to be used in subsequent SSI analyses. The three spectra, based on 5% damping, are shown in Figure 3.

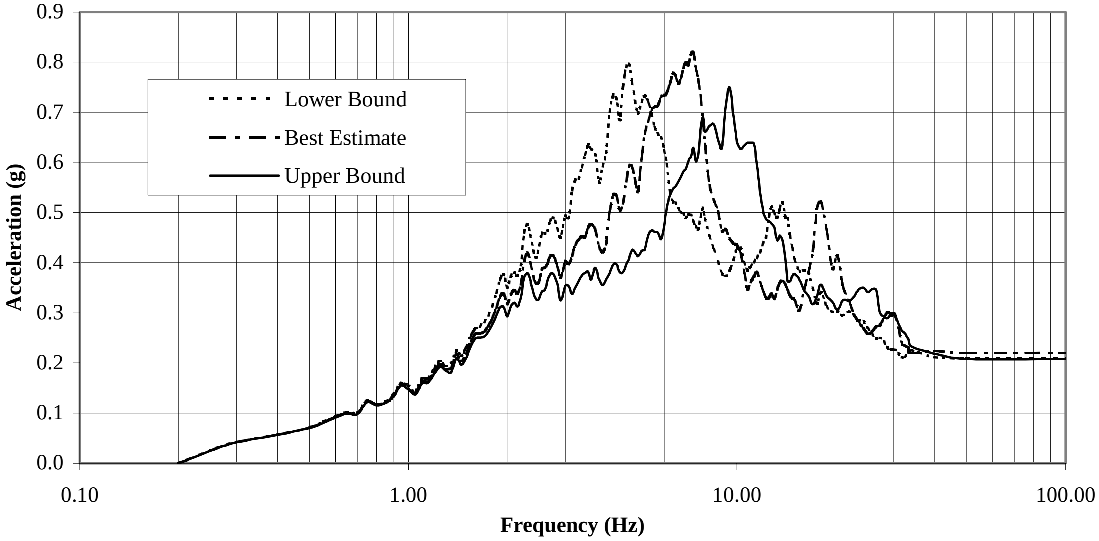

Figure 3 Surface Response Spectra using Lower Bound, Best Estimate, and Upper Bound Soil Properties

Statistical Approach

In using the statistical approach, thirty low strain soil column samples were developed. The columns represent the expected variability in soil stiffness and layer thickness. In each soil column, the shear modulus for each layer and the bedrock was picked using a Monte Carlo simulation of the log-normal distribution of the soil layer test data within three standard deviations of the median (best estimate) shear modulus. In addition to developing random soil properties, random soil layer depths are also generated. The random selection of soil layer depth (or layer thickness) is based on a uniform distribution of the measured depths variation shown on Figure 1.

By considering variations in both the material and geometric attributes, a better representation of the available soils data that directly affect the seismic response of supported structures is utilized. Because of the extensive and repetitive work involved in generating a large number of soil columns and resulting acceleration spectra, the computer program SPRand [5] was developed to automate the process. The program calculates the randomized soil properties and layer depths for the soil columns and formats the properties into SHAKE91 input files. The corresponding SHAKE91 analyses and results (strain compatible soil profiles and acceleration response spectra) are collected and processed.

The thirty response spectra generated from the SHAKE91 analyses correspond to the range of soil profile material and geometry variation that extends over three standard deviations from the best estimate values. Figure 4 shows the thirty acceleration response spectra.

At this time there is no formal regulatory requirement regarding the number of soil columns necessary to obtain the median spectrum. Using more or fewer columns may change the median response. The authors’ experience for several sites is that thirty columns are sufficient to achieve a reasonably stable median. However, this number should be confirmed on a site specific basis, especially when highly variable soil conditions exist. Regulatory guidance regarding this statistical approach and the number of soil column analyses is expected in the near future.

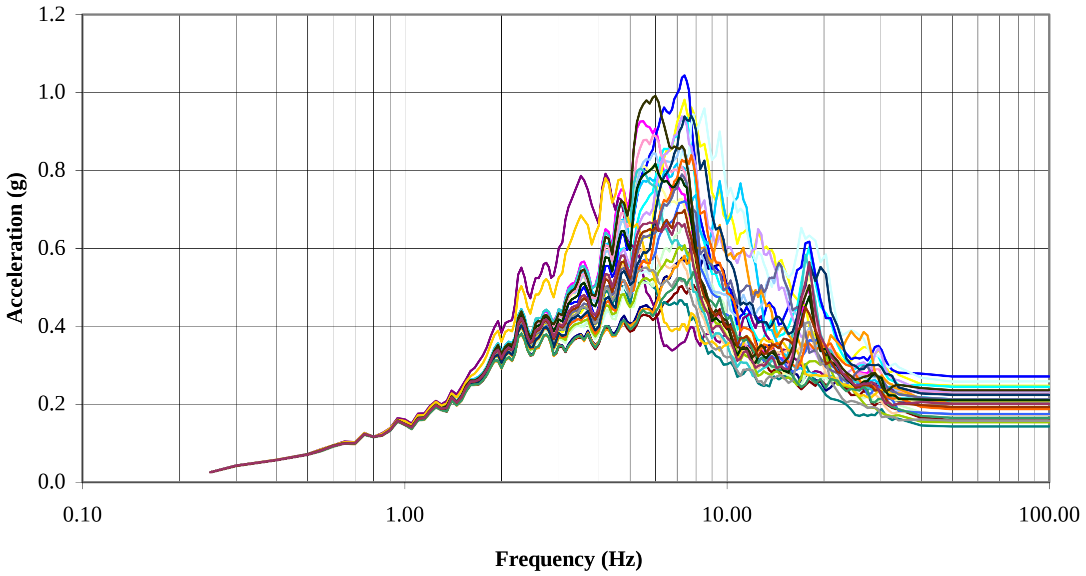

Figure 4 Surface Response Spectra from 30 Randomly Generated Soil Profiles

MEDIAN SURFACE RESPONSE SPECTRA

The median surface spectrum and the median plus one sigma spectrum are obtained from the thirty spectra shown in Figure 4 based on a log-normal distribution of the spectral accelerations at each frequency used to compute the spectrum. The resulting spectra are shown in Figure 5. The acceleration time history at bedrock is also shown to facilitate an estimate of the spectral amplification.

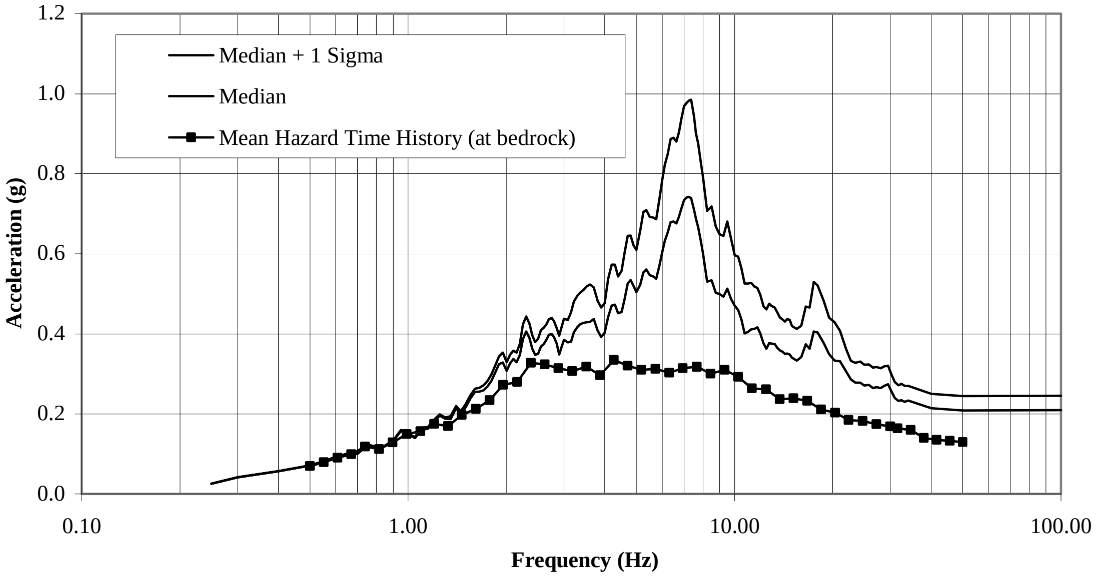

Figure 5 Surface Response Spectra using 30 Random soil Columns

COMPARISON OF METHODS

Figure 6 compares the response spectra developed using the two methods. The three spectra developed by analyzing the soil columns developed using the ASCE 4-98 uncertainty factor (1 + Cv) are enveloped and compared with the probabilistically developed median and median plus one sigma spectra. Enveloping the spectra fills out the frequency range used in the subsequent SSI analyses. Generally, three SSI analyses (u. b., b. e. and l. b.) would be conducted, each using a time history compatible with the applicable surface spectrum, and the resulting design information (forces, stresses, etc.) would be enveloped. Alternatively, a time history fit to the surface envelope spectrum could be used. When using the probabilistically developed median spectrum, three SSI analyses would also be conducted. These are used to vary the soil properties, and thus, the frequencies of response for the structure. However, each analysis would use the same time history compatible with the median spectrum.

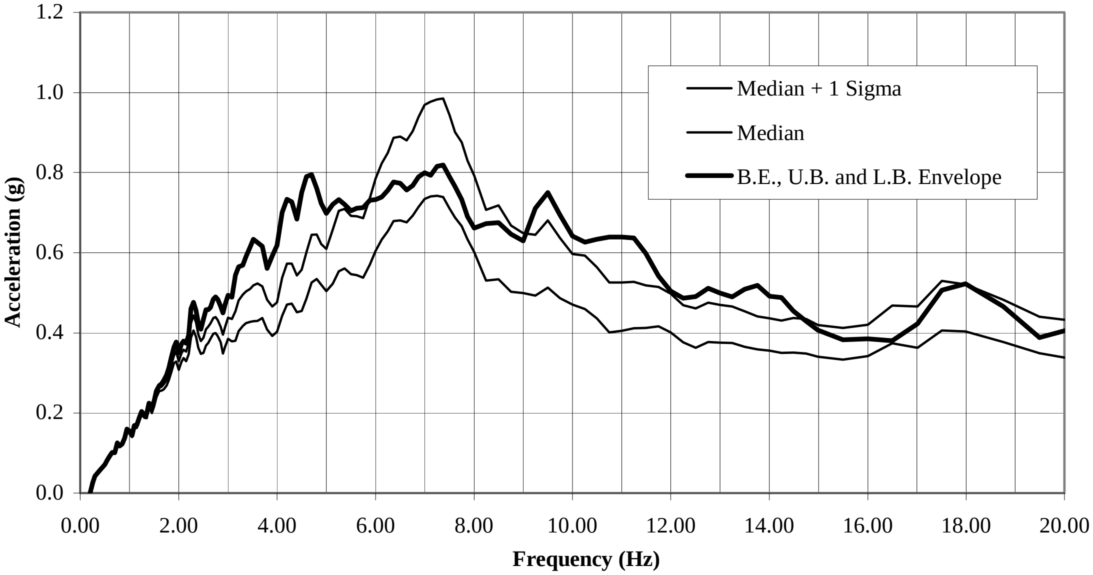

Figure 6 Surface Response Spectra Comparison

DISCUSSION OF RESULTS

Figure 6 clearly shows differences in the two approaches. The median spectrum represents the UHS at the surface. The envelope spectrum developed using the ASCE 4-98 methodology completely envelops the median spectrum and much of the median plus one sigma spectrum as well. Use of the ASCE 4-98 and NUREG-0800 approaches increases the structural demands non-uniformly, thus skewing the intended goal [1] of incorporating the UHS into the design. The greatest differences between the approaches occur at the upper and lower bound spectral contributions while the smallest difference occurs for the best estimate condition spectrum.

CONCLUSIONS

Conducting multiple (30 or more) statistically developed soil column response analyses provides a comprehensive dynamic characterization of the site soil data.

Conducting multiple site response analyses would:

a) Consider full variability of soil material properties inherent in the test data,
b) Consider full soil/bedrock layering variability
c) Maintain a consistent UHS for the surface.
d) Remove conservatism when evaluating existing structures.

When analyzed using seismic motions having known hazard levels (e. g. a uniform mean hazard level, as prescribed for DOE sites) statistically developed responses (e. g. spectra, strain compatible soil properties) provide a means of providing consistent input to subsequent SSI analyses which will maintain the UHS used in the seismic design. The median surface spectrum maintains the same seismic hazard level at the soil surface as, in the case of this site, is represented by the seismic hazard level prescribed for bedrock. Additional conservatism can be introduced in a controlled manner by using the median plus one sigma spectrum, for example.

The use of the three soil profiles, following the ASCE approach provides conservative input for subsequent SSI analyses and design. However, the level of additional conservatism above a prescribed hazard goal is uncertain.

REFERENCES

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