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Monte-Carlo Simulation of the Theoretical Site Response Variability at Turkey Flat, California, Given the Uncertainty in the Geotechnically Derived Input Parameters

Edward H. Field, M.EERI, and Klaus H. Jacob, M.EERI

In the weak-motion phase of the Turkey Flat blind-prediction effort, it was found that given a particular physical model of each sediment site, various theoretical techniques give similar estimates of the site response. However, it remained to be determined how uncertainties in the physical model parameters influence the theoretical predictions. We have studied this question by propagating the physical parameter uncertainties into the theoretical site-response predictions using monte-carlo simulations. The input-parameter uncertainties were estimated directly from the results of several independent geotechnical studies performed at Turkey Flat. While the computed results generally agree with empirical site-response estimates (average spectral ratios of earthquake recordings), we found that the uncertainties lead to a high degree of variability in the theoretical predictions. Most of this variability comes from poor constraints on the shear-wave velocity and thickness of a thin (~2m) surface layer, and on the attenuation of the sediments. Our results suggest that in site-response studies which rely exclusively on geotechnically based theoretical predictions, it will be important that the variability resulting from input-parameter uncertainties is recognized and accounted for.

INTRODUCTION

In 1984 the Committee on Earthquake Hazard Assessment of the International Association of Seismology and Physics of the Earth's Interior established a working group to investigate the effects of surface geology on seismic ground motion. The goal of this working group was to make a quantitative comparison of the different techniques used to estimate site response. This effort was motivated by the recognition that site conditions can significantly enhance the level of earthquake ground motions. A good review of this phenomenon has been given by Aki (1988).

After being joined by members of the International Association of Earthquake Engineering, the working group established two locations where different site-response estimation techniques are currently being tested. The first is the Turkey Flat sediment-filled valley near Parkfield, California, and the second is the Ahigara sediment-filled valley near Odawara, Japan. Since part of the effort is to address the long-standing question of nonlinear site response, these two sites were chosen because they are both expected to experience strong ground motion from earthquakes in the near future.

Both at the Lamont-Doherty Earth Observatory of Columbia Univ., Palisades, NY 10964

The comparison of the various site-response estimation techniques is in the form of a blind prediction experiment. After extensive geotechnical analyses of the sites were conducted, "standard" physical models of the valleys were developed which represent a consensus among a committee of experts (Real, 1988). These models were then distributed to professionals around the world who were asked to predict various aspects of the site response. Only after all submissions had been made was anyone allowed to examine actual earthquake data (thus, the blind aspect of the prediction). This effort represents traditional science in the sense that theoretical predictions are being tested by comparison with empirical earthquake data. This contrasts with the commonly used inverse approach where observations are fit with a model, a procedure which often yields a nonunique solution. In this paper we concentrate on the site response at Turkey Flat, however our discussion and conclusions will also be relevant to other site-response studies including the Ashigara Valley, Japan, prediction experiment.

Turkey Flat is located about halfway between Los Angeles and San Francisco, California, near the Parkfield section of the San Andreas Fault (Figure 1a). It is classified as a shallow stiff-soil site. Twelve industry, academic, and government organizations form the U.S. and Japan conducted independent geotechnical site-characterization studies at Turkey Flat. Hundreds of thousands of dollars were spent on this effort, and with respect to site response estimation,Turkey Flat may well be the most extensively studied sediment filled valley in the world. A compilation and summary of the data gathered in these geotechnical analyses has been given by Real (1988). The standard physical models established for the two valley sites, valley-center and valley-north shown in Figure 1b, are reproduce here in Table 1. Again, these models were reached by consensus among a committee of experts who reviewed all the geotechnical data (Real, 1988). Profiles of the boundary layer topographies across the valley were also provided by Real for those interested in modeling multi-dimensional effects.

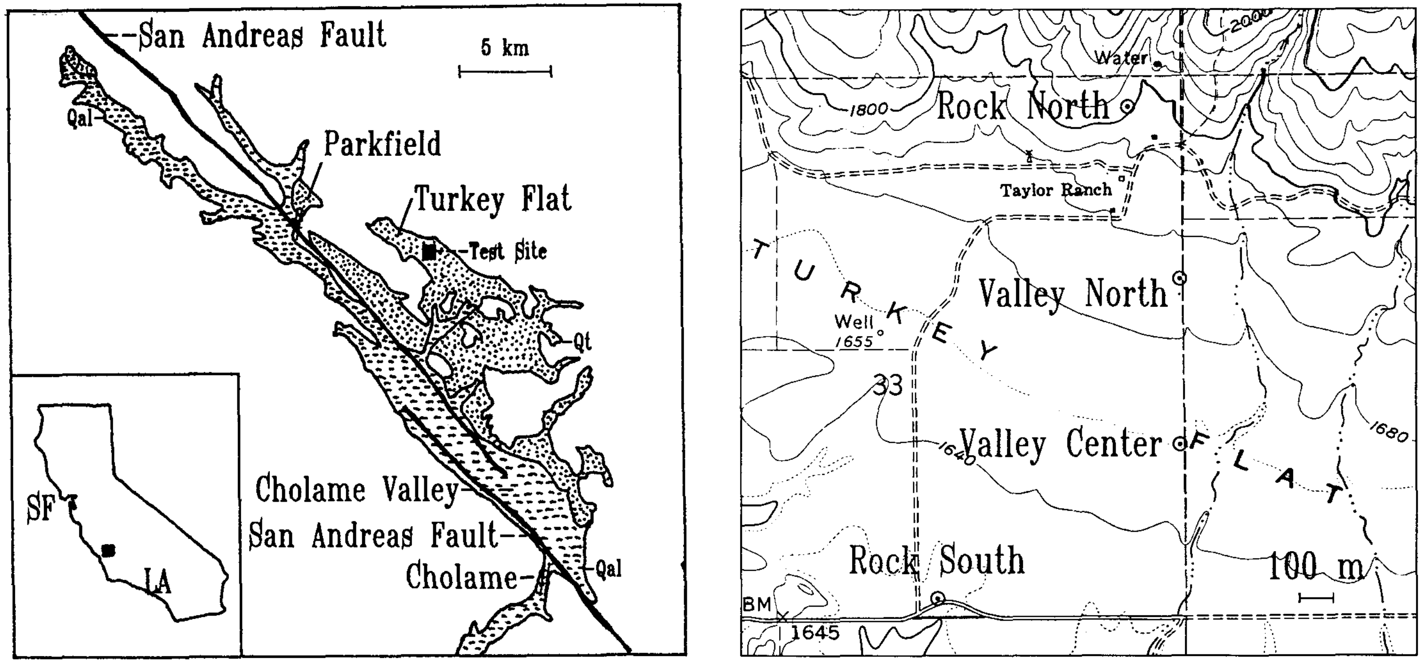
TABLE 1

a) Valley Center Standard Model (From Real , 1988)

layer	depth range (m)	shear wave velocity (m/s)	density (gm/cm^3)	quality factor
1	0 - 2.4	135	1.50	33
2	2.4 - 7.6	460	1.80	33
3	7.6 - 21.3	610	1.90	33
halfspace	21.3 - inf	1340	2.20	---

b) Valley North Standard Model (From Real , 1988)

layer	depth range (m)	shear wave velocity (m/s)	density (gm/cm^3)	quality factor
1	0 - 2.1	150	1.55	33
2	2.1 - 5.5	275	1.75	33
3	5.5 - 11.0	610	1.90	33
halfspace	11.0 - inf	1340	2.20	---



(a) (b)

Figure 1 (a) Location map for the Turkey Flat Site Effects Test Area. Insert shows the location of the test area in Central California relative to San Francisco (SF) and Los Angeles (LA). The main map shows the location relative to Parkfield and the San Andreas Fault. Qal (dashed area) represents Quaternary alluvial deposits and Qt (dotted areas) represents Quaternary Terrace deposits. (b) Topographic map of Turkey Flat Site Effects Test Area showing the location of ground motion recording sites and seismic response prediction sites. Both figures and captions are from Cramer and Real (1990) and are reproduced here with permission.

Based on these standard physical models, predictions of various attributes of weak-motion site response were solicited from the participants (the strong-motion phase of the experiment awaits the next Parkfield earthquake). Submissions were made by 28 individuals and groups from 10 different countries. A main component of the prediction was an estimate of the shear-wave transfer function (amplitude as a function of frequency) at the valley-center and valley-north sites. From the submissions, Cramer and Real (1990) found that the transfer-function predictions tend to group together despite the variety of theoretical methods used (based on one-, two-, or three-dimensional geometries, and linear, equivalent linear, or nonlinear soil rheologies). This observation is reproduced in Figure 2 where the two solid lines represent the first and third quartiles of submitted predictions (i.e. the middle 50% of the predictions fall between these lines).

The agreement among the various theoretical methods, each involving different assumptions and approximations, gives us confidence in their applicability (at least at Turkey Flat). However, in terms of predicting the true site response, the output from such calculations can only be as good as the input parameters. In fact, Cramer and Real (1990, p. 55) have concluded that "...the accuracy of the geotechnical model used to characterize the site is more important than the particular method used to calculate the response". Included in Figure 2 are empirical estimates of the site response at each site (Cramer and Real, 1990). These were determined from actual earthquake data by averaging spectral ratios of sediment versus bedrock site recordings. The dashed line represents the mean and the dotted lines define the 95 percent confidence limits ($\pm$ two standard deviations of the mean). At valley north (Fig. 2b) there is general agreement between the observations and predictions. However, at the valley center site there is up to a factor of three discrepancy between the two. In order to know whether the theoretical calculations successfully predict the observations, it is necessary to determine whether this discrepancy is significant.

While the standard model at each site was reached by consensus among a committee of experienced professionals, it is but one model among several that might be consistent with the geotechnical data. In other words, the values of the parameters that go into the theoretical calculations have some uncertainty, and the question remains as to how this uncertainty maps into the theoretical predictions. Therefore, one of the goals of this study has been to determine the uncertainty in the theoretical response at each site (a study of error propagation), given the best estimate and uncertainty (mean and standard deviation of the mean) of each of the input parameters. From this we can determine whether differences between the average spectral ratios and the theoretical predictions are significant, and thereby conclude the scientific test of determining whether theory has successfully predicted the empirical observations.

Another goal of this paper is to answer the related question: If an additional geotechnical study were performed at Turkey Flat, or if only one study had been performed in the first place, where would the theoretical site response function based on this study likely fall? In other words, what is the variability in the theoretical site response given the scatter in the parameter-value estimates seen among the different geotechnical studies. As described below, for this case we use standard deviations of the input parameters rather than standard deviations of the means.

During the blind prediction effort, participants were invited to submit, in addition to the required standard-model prediction, theoretical predictions based on a "preferred" physical model (determined from their own interpretation of the geotechnical data). While this, in principle, could have provided an indication of the theoretical site response variability resulting from the range of parameter values that are consistent with the geotechnical data, only six such preferred-model predictions were submitted which is probably too few to span the range of possible values.

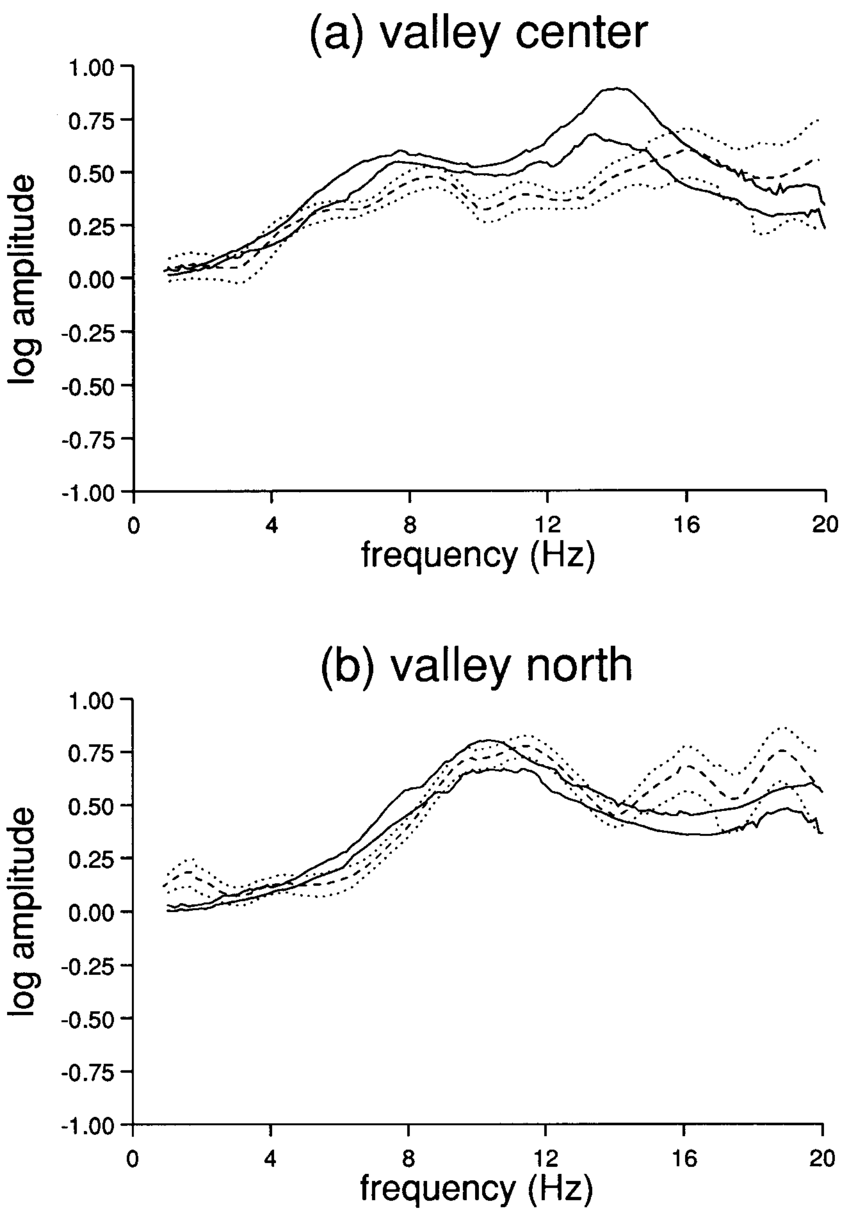


Figure 2 Solid lines represent the first and third quartiles of the submitted site-response predictions. The dashed line represents the mean and the dotted lines delineate the 95% confidence limits (±2 standard deviations of the mean) of average spectral ratios of earthquake recordings. This data was provided by Cramer (personal communication).

Cramer (1991) conducted a study in which the input parameters for the theoretical site response at Turkey Flat were adjusted until a best fit with empirical estimates (average spectral ratios) was found. This was done on a trial and error basis where the sediment shear-wave velocities were varied (all by the same amount) to fit the peak frequencies, and the quality factors were adjusted to match the amplitudes. A significant improvement in fit between the observations and theory was obtained. However, as Cramer points out, the solution is nonunique and so it is difficult to determine how well it represents reality at Turkey Flat.

We feel that the present error-propagation study is warranted, if not demanded, given the amount of time, money, and effort that has been put into the Turkey Flat experiment. Since the theoretical site response is a complicated and nonlinear function of the input parameters, the analysis must be done using monte-carlo simulations where response functions are computed for several thousand sets of input parameters that vary in a statistically specified way (discussed more below). A vaguely similar probabilistic approach to assessing the theoretical response variability, given input parameter uncertainties, was proposed and shown to by useful by Seed et al. (1988). In defining the statistics of the parameter values used in the present study, we have sought to adhere strictly to what the geotechnical data dictate, and to not be influenced by the standard model, the empirical estimates (spectral ratios), or any personal biases.

MODEL PARAMETER STATISTICS

As mentioned previously, a compilation and summary of the data collected during the site characterization effort has been given by Real (1988). The twelve geotechnical studies were performed by Leroy Crandall Assoc., Dames and Moore, Woodward Clyde Consultants, Quest Consultants, Harding Lawson Associates, Pitcher Drilling Company, Lawrence Livermore Nat. Labs., California's Dept. of Conservation / Division of Mines and Geology, OYO Corporation, Kajima Corporation, Tokyo University, and Kyoto University. When discussing the results of these studies here, the particular groups associated with the various data sets shall remain anonymous.

In setting up the monte-carlo simulations, it is necessary to construct a physical model of the valley sites and to determine the statistics (e.g. mean and standard deviation) of the input parameters. There are an infinite number of ways this problem could be set up. Since several thousand response functions must be computed in the monte-carlo simulations, it is desirable to make the model as simple as possible. In the blind prediction experiment, two- and three-dimensional models did not give significantly different results from the one-dimensional models (Cramer and Real, 1990). In addition, we are concerned here with the weak-motion response. Therefore, we have used the one-dimensional linear-viscoelastic method of Kennett and Kerry (1979) for the site response calculations. There are also several ways one could go about determining the input parameter statistics (e.g. what statistical distributions are assumed). In what follows, we have made every attempt to make these decisions in a reasonable fashion.

At the valley center site, 14 different estimates were made of the shear-wave velocity profile using a variety of techniques (downhole, crosshole, and suspension logging). One of these profiles was removed from consideration since it was determined, by the contributor, to be in error. The remaining 13 profile estimates are shown in Figure 3a. Only three shear-wave velocity profile estimates were made at the valley-north site, and these are shown in Figure 3b. Since shear-wave velocities cannot have negative values, we have assumed that these estimates are log-normally distributed. Shown in Figure 4 are the statistics of this profile data (computed from logarithmic values and converted back for plotting purposes). The dashed line represents the mean (or median in the log-normal distribution), the dotted lines are

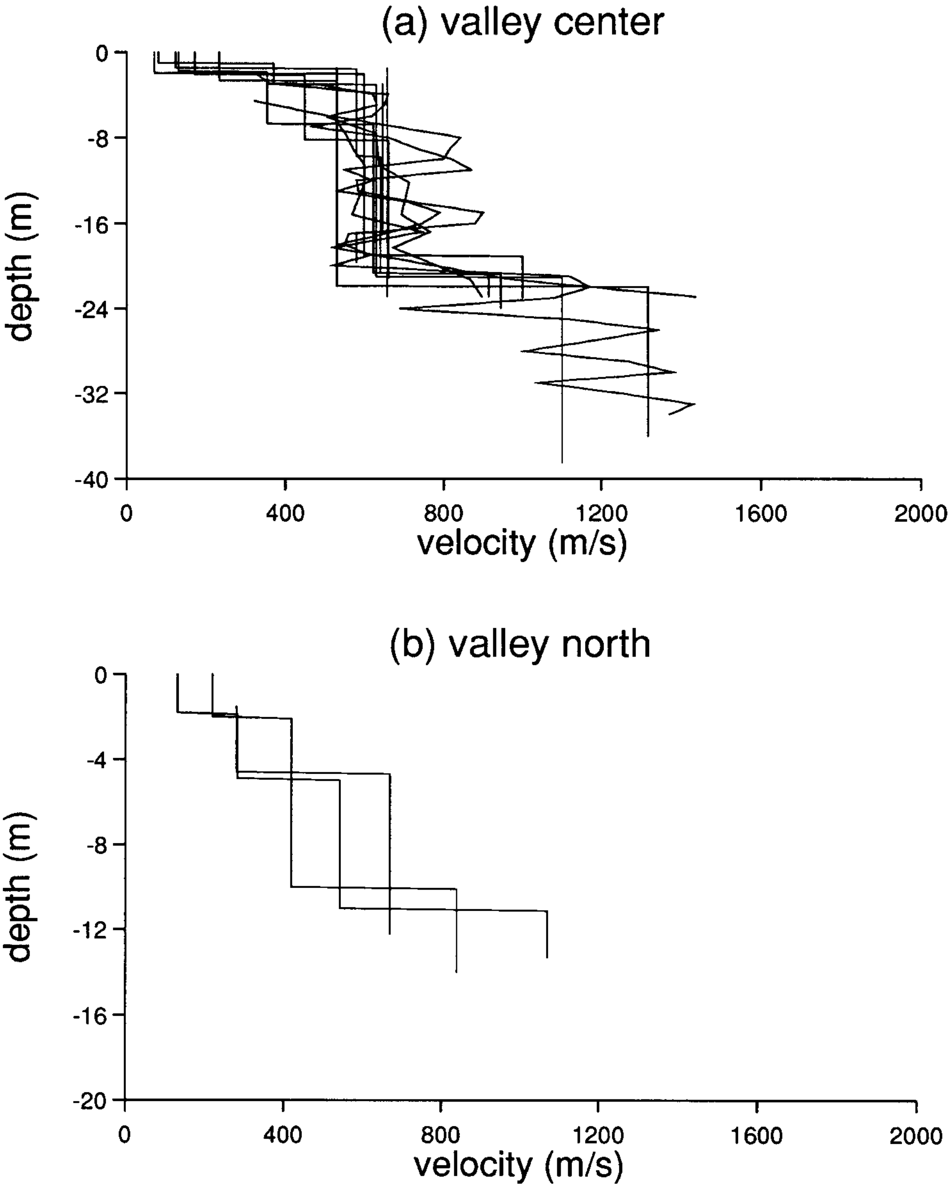


Figure 3 (a) The 13 shear-wave velocity profile estimates made at valley-center during the geotechnical site characterization effort. (b) The 3 shear-wave velocity profile estimates available for valley-north.

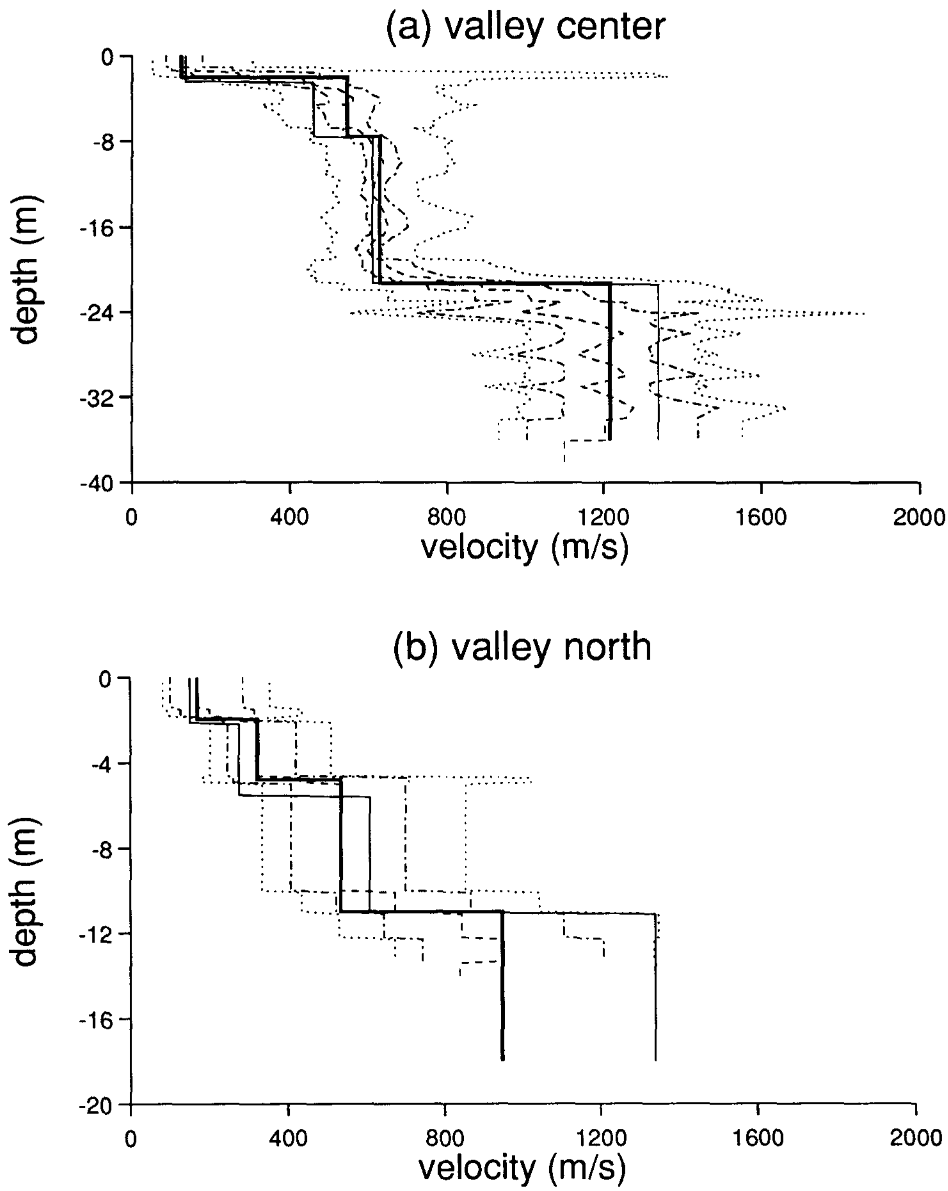


Figure 4 The statistics of the shear-wave velocity profile estimates made at valley-center (a) and valley-north (b). These were computed for log-velocity values and converted back for plotting purposes. The dashed lines represent the means, the dotted lines are the ±2 standard deviation intervals, and the dot-dashed lines represent ±2 standard deviations of the means. The solid lines are the standard-model profiles used in the blind prediction experiment, and the bold line represents the profile median and discretization used in the monte-carlo simulations.

the ±2 standard deviation intervals (defining the region where a future estimate has 95% likelihood of landing), and the dot-dashed lines represent ±2 standard deviations of the mean (defining the region in which the true mean has 95% likelihood of residing). Also shown by thin solid lines are the standard-model profiles used in the blind prediction experiment. The bold lines in Figure 4 represent our choice of median velocity profile used in the monte-carlo simulations. Like the standard model, we have chosen to approximate the sites with three homogeneous layers over a half-space. Our basis for determining these profile approximations was to include distinct layers only where warranted by the geotechnical data (given the uncertainties). There remains the question of whether the apparent velocity transition zones seen in the average profiles near our discrete layer boundaries are real. We found that if these transition zones are represented by some number of intermediate homogeneous layers, the observed range in response values is similar to that obtained by allowing uncertainty in the boundary layer depths instead. Therefore, our 3-layer model is probably a fair approximation of the true velocity profile, provided that uncertainties in the layer boundaries are accounted for.

The physical model and parameter statistics used in the monte-carlo simulations are given in Table 2. The layer-velocity means (β_m), standard deviations (σ), and standard deviations of the means (σ_m) were computed, and are listed, for logarithmic values (since log-normal distributions were assumed). Included are median values (inverse-log of β_m) and 95-percent confidence limits (inverse-log of $\beta_m \pm 2\sigma_m$) of the log-normally distributed layer velocities. These shear wave velocity statistics were determined after first discretizing the individual profiles with the three-layer model (the transition zones were not included in determining the homogeneous layer velocities). The standard deviations of the layer thicknesses were somewhat arbitrarily set as one-sixth the width of the lower transition zone, and a normal distribution has been assumed since a log-normal distribution does not give significantly different results. The densities listed in Table 2 are the same as those used in the standard models. These are assumed to be exact since we found that their uncertainties do not significantly influence the theoretical site response.

Both laboratory and in situ measurements of the sedimentary-layer shear-wave quality factors (Q) were made during the site characterization effort. The former, based on two-stage dynamic triaxial tests, gave consistently higher values than the latter, which were based on spectral ratios and peak amplitude decay of artificial-source borehole recordings (Real, 1988). While the reason for this discrepancy is still not certain, it may be due to the fact that laboratory values do not include the effects of scattering. Resisting the temptation to exclude data, we decided to separate the data into three categories: laboratory values, in situ values, and both. The statistics of the frequency-independent shear-wave quality factors used in the monte-carlo simulations are given in Table 3. Log-normal distributions have been assumed since negative values are not possible. No systematic variations between sites, or with respect to depth, were found so the same quality factor statistics apply to all the sedimentary layers (as in the standard models).

Comparing Tables 2 and 3 with Table 1, or comparing the solid and bold lines in Figure 4, it can be seen that differences exist between the median values chosen for our study and those chosen by the committee for the standard-model predictions. There is apparently no official record of how the committee reached consensus on the standard model. However, it is known that personal experience and opinions lead to rejections of some of the geotechnical data. This is especially true of the shear-wave quality factor where a value of 33 was adopted for the standard model, which is significantly higher than the values suggested by the geotechnical studies (15.4, 4.2, or 6.7 for the laboratory, in situ, and combined data, respectively) . As stated previously, we have sought here to adhere strictly to what the geotechnical data warrants. All of the groups that conducted geotechnical studies at Turkey Flat were known to be experienced and qualified, and given the nature of the experiment, they

TABLE 2

a) Statistics for the Valley Center monte-carlo simulations

layer	mean thickness (m)	σ of thickness (m)	σ_m of thickness (m)	β_m: mean of $\log_{10}(\beta)$	σ of $\log_{10}(\beta)$	σ_m of $\log_{10}(\beta)$	median β (10^{β_m}) (m/s)	95% conf. of β ($10^{\beta_m \pm 2\sigma_m}$)	density (gm/cm^3)
1	2.0	0.38	0.15	2.091	0.196	0.080	123	85 - 178	1.50
2	5.6	0.25	0.07	2.735	0.075	0.021	544	493 - 598	1.80
3	13.7	1.1	0.64	2.798	0.039	0.011	628	597 - 660	1.90
halfspace	inf	---	---	3.085	0.040	0.023	1216	1094-1352	2.20

b) Statistics for the Valley North monte-carlo simulations

layer	mean thickness (m)	σ of thickness (m)	σ_m of thickness (m)	β_m: mean of $\log_{10}(\beta)$	σ of $\log_{10}(\beta)$	σ_m of $\log_{10}(\beta)$	median β (10^{β_m}) (m/s)	95% conf. of β ($10^{\beta_m \pm 2\sigma_m}$)	density (gm/cm^3)
1	1.95	0.12	0.08	2.230	0.159	0.11	170	102 - 282	1.55
2	2.85	0.07	0.05	2.507	0.100	0.06	321	244 - 424	1.75
3	6.2	0.38	0.27	2.728	0.102	0.06	535	405 - 705	1.90
halfspace	inf	---	---	2.977	0.074	0.05	948	753 - 1194	2.20

(Note: σ and σ_m represent the standard deviation and the standard deviation of the mean, respectively) were likely performing some of their most careful work. In a typical practical application, only one geotechnical study is performed and this is commonly regarded as accurate and sufficient. Therefore, we do not wish to exclude any of the geotechnical data unless the contributor had retracted them before any comparisons were made.

TABLE 3

Quality factor (Q) statistics used in the monte-carlo simulations

data type	Q_m: mean of $\log_{10}(Q)$	σ of $\log_{10}(Q)$	σ_m of $\log_{10}(Q)$	median Q (10^{Q_m})	95% conf. ($10^{Q_m \pm 2\sigma_m}$)
laboratory	1.186	0.151	0.053	15.4	12.0 - 19.6
in situ	0.625	0.250	0.067	4.2	3.1 - 5.7
both	0.829	0.350	0.075	6.7	4.8 - 9.5

(Note: σ and σ_m represent the standard deviation and the standard deviation of the mean, respectively)

MONTE-CARLO SIMULATIONS

The monte-carlo simulations proceeded by computing the theoretical site response for several thousand sets of model parameters, where the values were selected using a random number generator from the previously defined distributions. The distributions from which the layer velocities were taken are shown in Figure 5. The dotted lines represent the distribution of the velocity estimates (based on standard deviations) and the dashed lines represent the distribution of the *mean* velocity estimates (based on standard deviations of the means). Figure 6 shows the distributions from which the quality-factor values were taken. The dotted, dashed, and solid line pairs are for the laboratory, in situ, and combined data, respectively. The narrower/higher-amplitude curve in each pair represents the distribution of *mean* estimates, whereas the wider curve represents the distribution of the measured values. Since the valley-center site was studied more extensively during the site characterization effort, the parameter statistics for this site are presumably more accurate than those for valley north. Therefore, a more comprehensive set of monte-carlo simulations was performed for the valley-center site.

Variability In The Theoretical Site Response Given The *Variability* In The Input-Parameter Estimates:

We shall first show the variability in the theoretical site response that results from the variability in parameter estimates observed among the different geotechnical studies. This analysis was done by selecting the parameter values from distributions with the observed means and standard deviations (dotted lines in Figure 5, and wider curves in Figure 6). The standard deviations represent the natural spread in the geotechnical parameter estimates. This analysis will give us an idea of where the theoretical response, based on any other geotechnical studies, would likely fall. To demonstrate how the various parameters influence the response, results where only one parameter was varied at a time are shown first. These are followed by results obtained when all the parameters were allowed to vary simultaneously. The site response calculations were made for vertically incident shear waves.

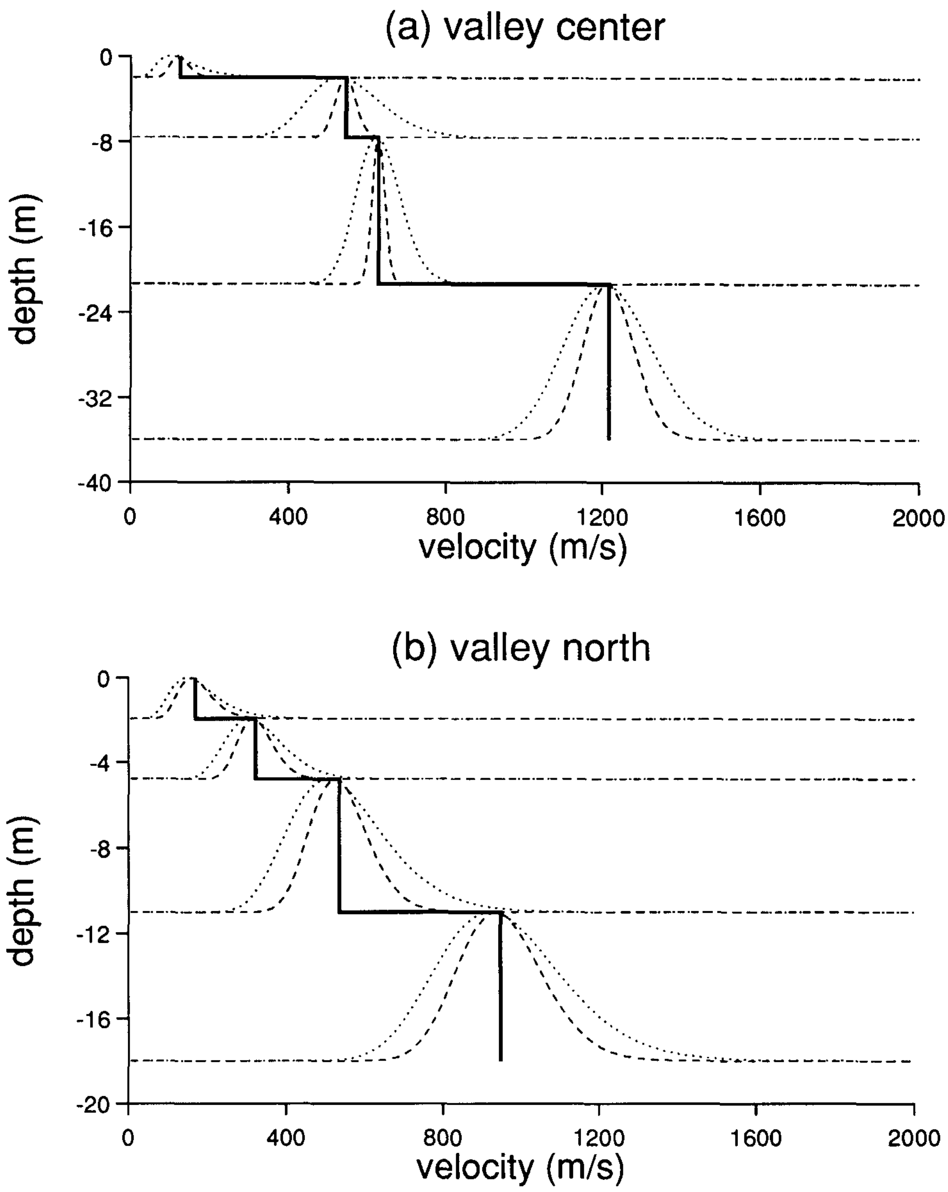


Figure 5 The shear-wave velocity distributions used in the monte-carlo simulations for (a) valley-center, and (b) valley-north. The bold lines represent the median value in each layer, the dotted lines represent the distribution of velocity estimates in each layer, and the dashed lines represent the distribution of the mean velocity estimates in each layer.

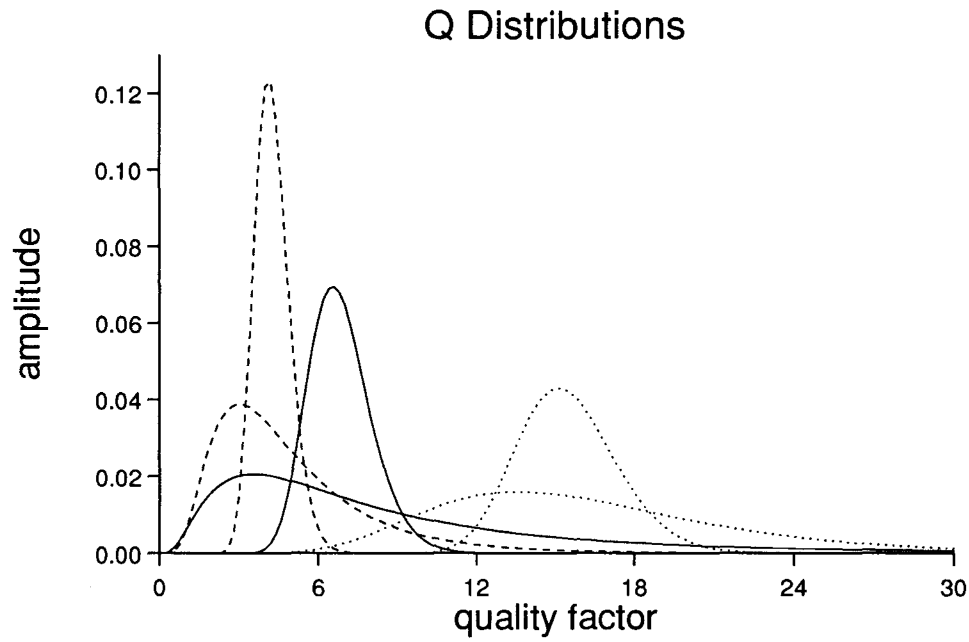


Figure 6 The distributions of the shear-wave quality factors used in the monte-carlo simulations. The dotted lines are for the laboratory values, the dashed lines are for the in situ values, and the solid lines are for the combined data. The lower-amplitude/wider curve in each pair represents the distribution of measured values, and the narrower/higher-amplitude curve represents the distribution of the mean quality factor estimates.

Shown in Figure 7 are the valley-center monte-carlo results for the case where only the shear-wave velocities were varied. A total of 5000 site response estimates were computed in these simulations. The quality factors were set at 6.7, which is the median value of the combined laboratory and in situ data. Figures 7a, 7b, 7c, and 7d correspond to a variable shear-wave velocity in layer 1, layer 2, layer 3, and the half-space, respectively. The bold lines represent the response for the median parameter values, the solid lines represent the median response of the monte-carlo simulation, the dashed lines define the region where the central 50 percent of the response amplitudes occurred (the first and third quartiles), and the dotted lines represent the area where the central 90 percent of the values landed. The dot-dashed line represents the response for the standard model specified in the blind prediction experiment. This figure shows that most of the amplitude scatter results from the variability observed in the layer-1 velocity estimates. At 15 Hz, the difference between the third and first quartiles is 93 percent of the median value. It is interesting to note that in Figure 7a, near 17 Hz, the response of the median parameter values (bold line) is not near the median response of the monte-carlo simulation (solid line), but lies just above the 90 percent range of the monte-carlo simulation. This occurs because the site response amplitude near 17 Hz, as a function of the layer-1 velocity, has a maximum near the median value of 123 m/s. Figure 8 demonstrates this effect by showing the site-response amplitude as a function of the layer-1 velocity. At 17 Hz, an amplitude maximum is clearly seen near the the median shear-wave velocity of 123 m/s. The case where all shear-wave velocities were allowed to vary simultaneously (not shown) is indistinguishable from the case where only the layer-1 velocity is varied (Figure 1a).

Figure 9 shows the results obtained when only the layer thicknesses were allowed to vary. Again, the quality factors were set at 6.7, and 5000 response functions were calculated for each of the simulations. The plotting convention is the same as that in Figure 7. Figures 9a, 9b, and 9c correspond to a variable thickness in layer-1, layer-2, and layer-3, respectively. Figure 9d represents the result where all three layer thicknesses were varied simultaneously. These plots show that most of the site-response amplitude scatter comes from the variability in the layer-1 thickness (at 20 Hz the difference between the third and first quartiles is 62 percent of the median value). The layer-3 thickness has considerably less, and the layer-2 thickness has a negligible influence on the amplitude variability. Again, near 17 Hz the response of the median parameter values (bold line) is not near the median response of the monte-carlo simulation (solid line). Figure 10, which shows the amplitude as a function of the layer-1 thickness, demonstrates that this also results from a maximum in amplitude (at 17 Hz) near the median thickness of ~2m.

Figure 11, computed and plotted in the same way as Figures 7 and 9, shows the results obtained when only the frequency-independent quality-factor values were varied (11a, 11b, and 11c correspond to the cases for the laboratory, in situ, and combined data, respectively. The distributions from which the quality factors were taken are represented by the wider distribution curves in Figure 6, and the value in each layer was varied independently. These plots demonstrate that the variability in quality-factor estimates leads to a substantial variability in the site response amplitude (e.g. near 16 Hz, the difference between the third and first quartiles is 23, 65, and 73 percent of the median value for the laboratory, in situ, and combined data, respectively). To further elucidate the influence of this parameter, Figure 12 shows the theoretical site response amplitude as a function of the shear-wave quality factor where the same value was used in all layers.

Shown in Figure 13 are the results obtained when all parameters were allowed to vary simultaneously. This was done separately for the three quality factor categories. In each simulation, 20,000 site response functions were calculated. These plots show that the variability in parameter estimates, seen among the geotechnical studies, produced a very large degree of variability in the theoretical site response. For example, near 15 Hz the difference between the third and first quartiles is 105, 70, and 82 percent of the median value for the

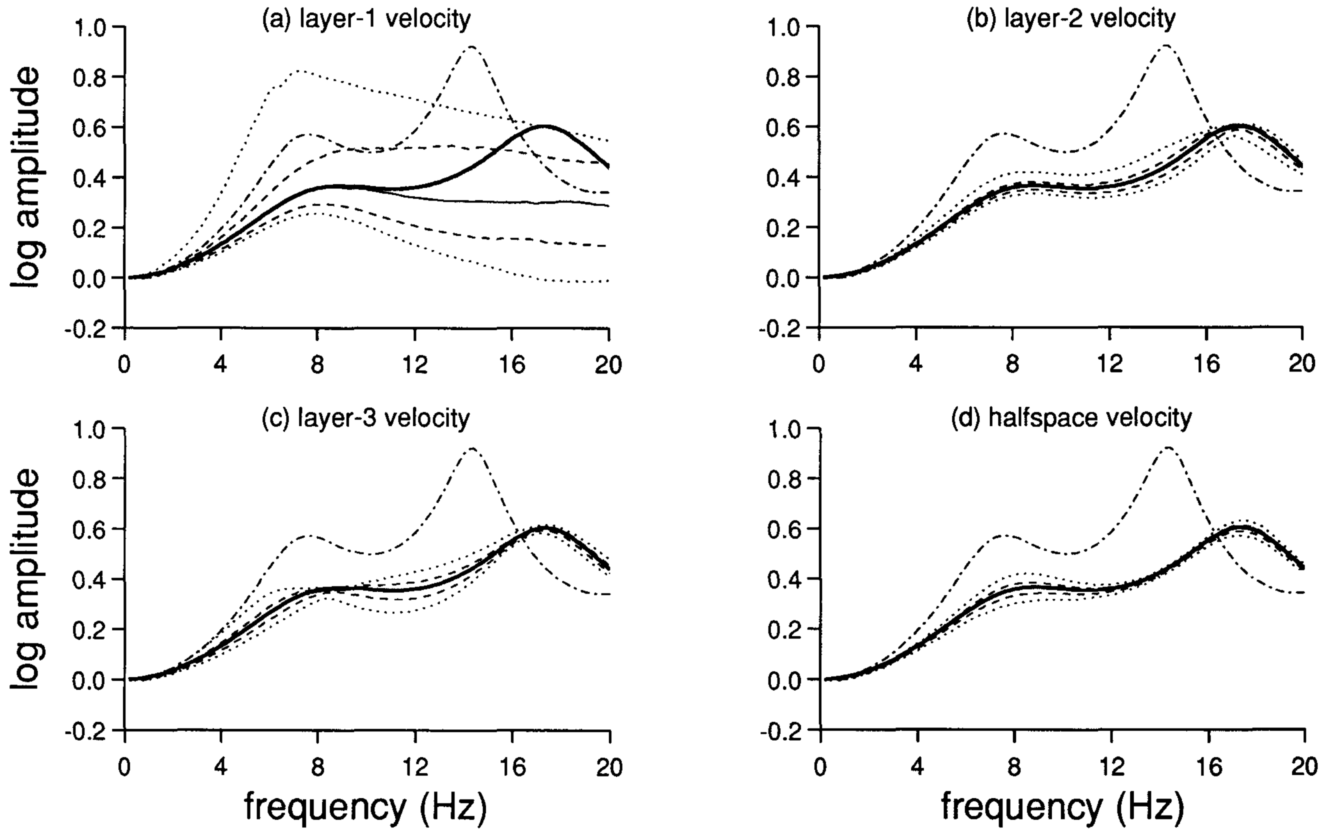


Figure 7 Valley-center monte-carlo simulation results for the case where only shear-wave velocities were varied in (a) layer-1, (b) layer-2, (c) layer-3, and (d) the half-space. The bold lines represent the response to the median parameter values (given in table 2a). The solid lines represent the median response of the 5000 estimates computed in the monte-carlo simulations, the dashed lines define the region where the central 50-percent occurred (the first and third quartiles), and the dotted lines represent the area where the central 90 percent of the estimates landed. The dot-dashed line represents the response for the standard model specified in the blind prediction experiment (given in Table 1a).

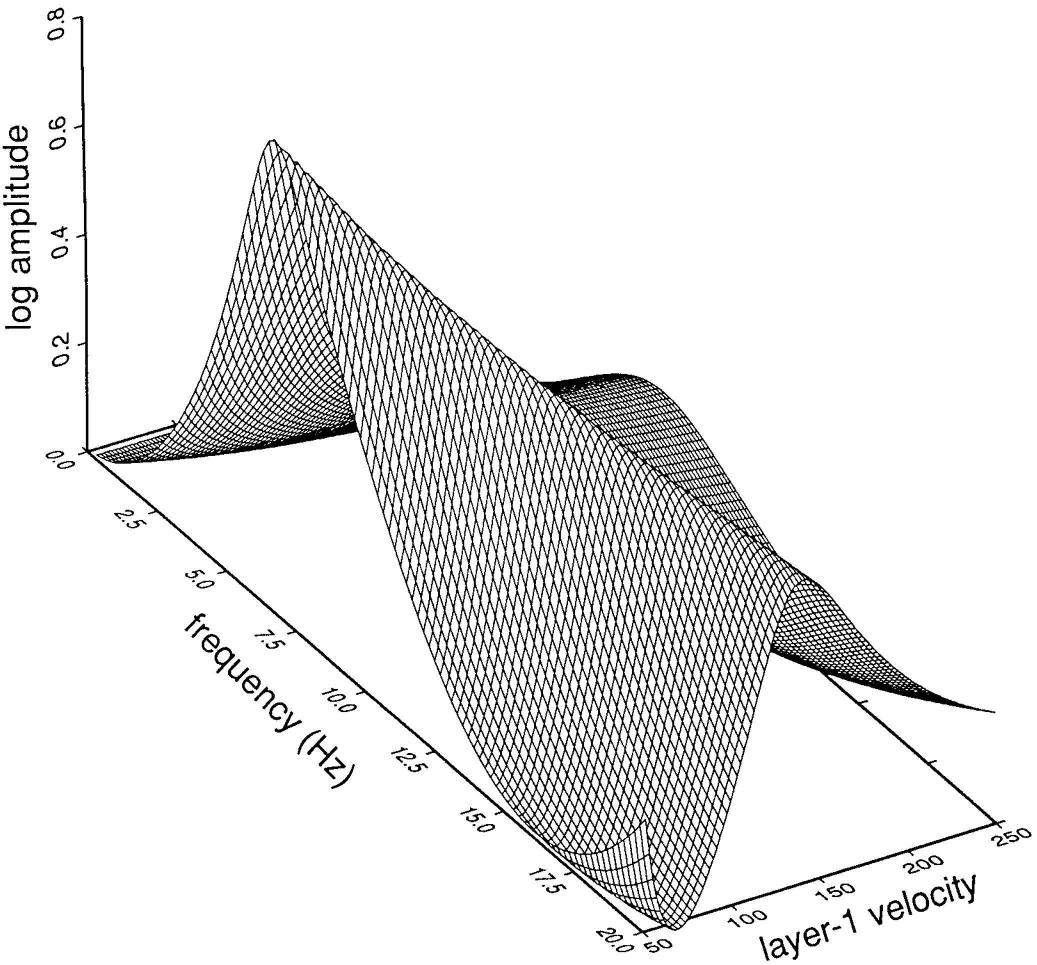


Figure 8 The valley-center theoretical site response amplitude as a function of the layer-1 velocity (all other input-parameters were set to the median values).

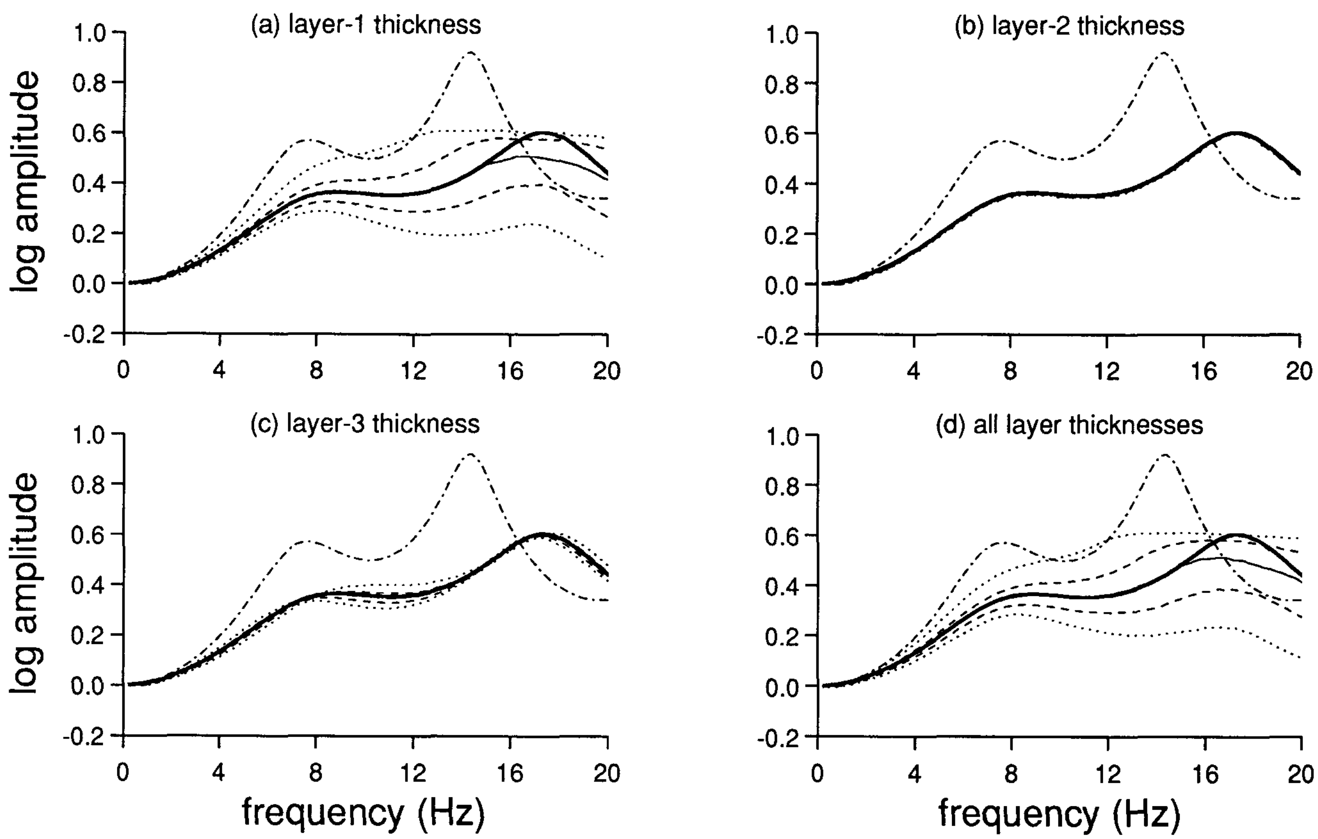


Figure 9 Valley-center monte-carlo simulation results for the case where only layer-thicknesses were varied. (a), (b), (c), and (d) correspond to variability in layer-1, layer-2, layer-3, and in all 3 layers, respectively. The plotting convention is the same as in Figure 7.

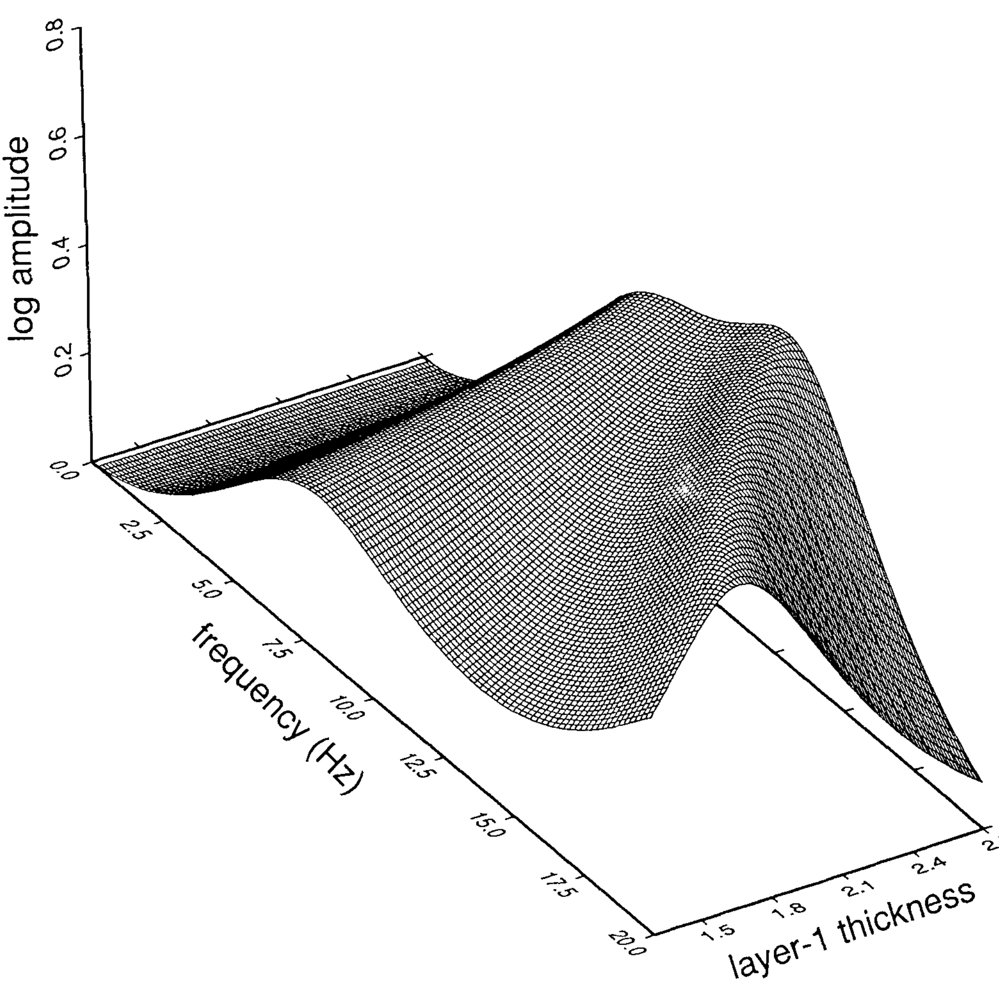


Figure 10 The valley-center theoretical site response amplitude as a function of the layer-1 thickness (all other input-parameters were set to the median values).

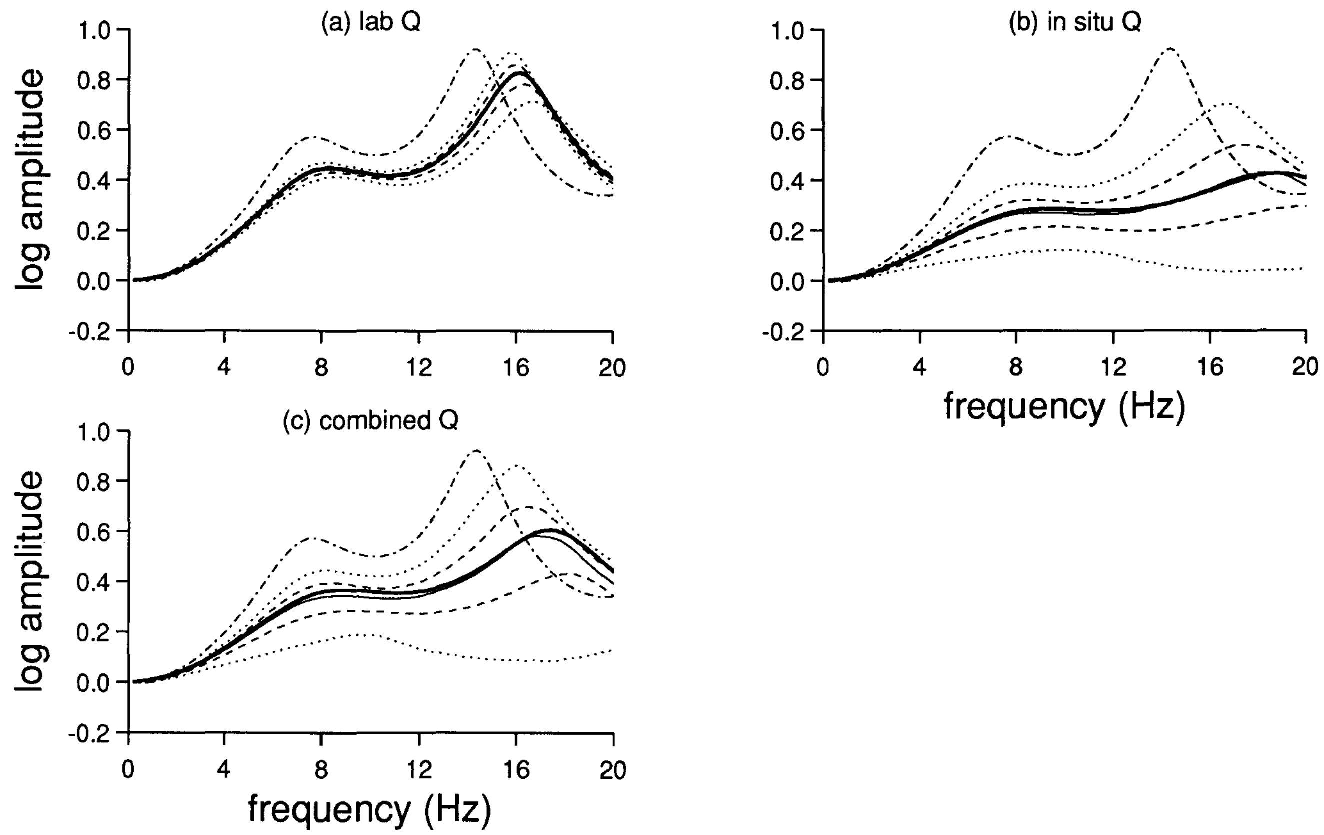


Figure 11 Valley-center monte-carlo simulation results for the case where only the shear-wave quality factors were varied. (a), (b), and (c) correspond to the results for laboratory, in situ, and combined data, respectively. The plotting convention is the same as in Figure 7.

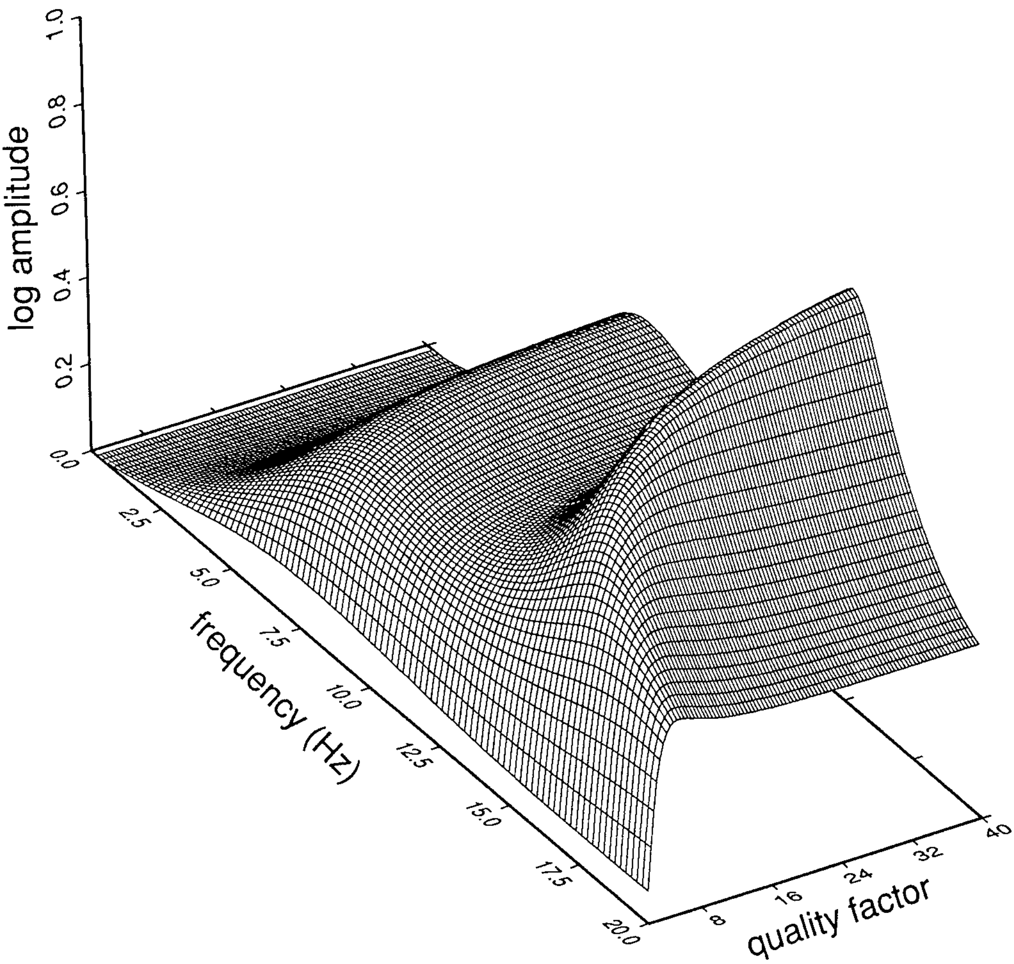


Figure 12 The valley-center theoretical site response amplitude as a function of the sediment shear-wave quality factor (all other input-parameters were set to the median values).

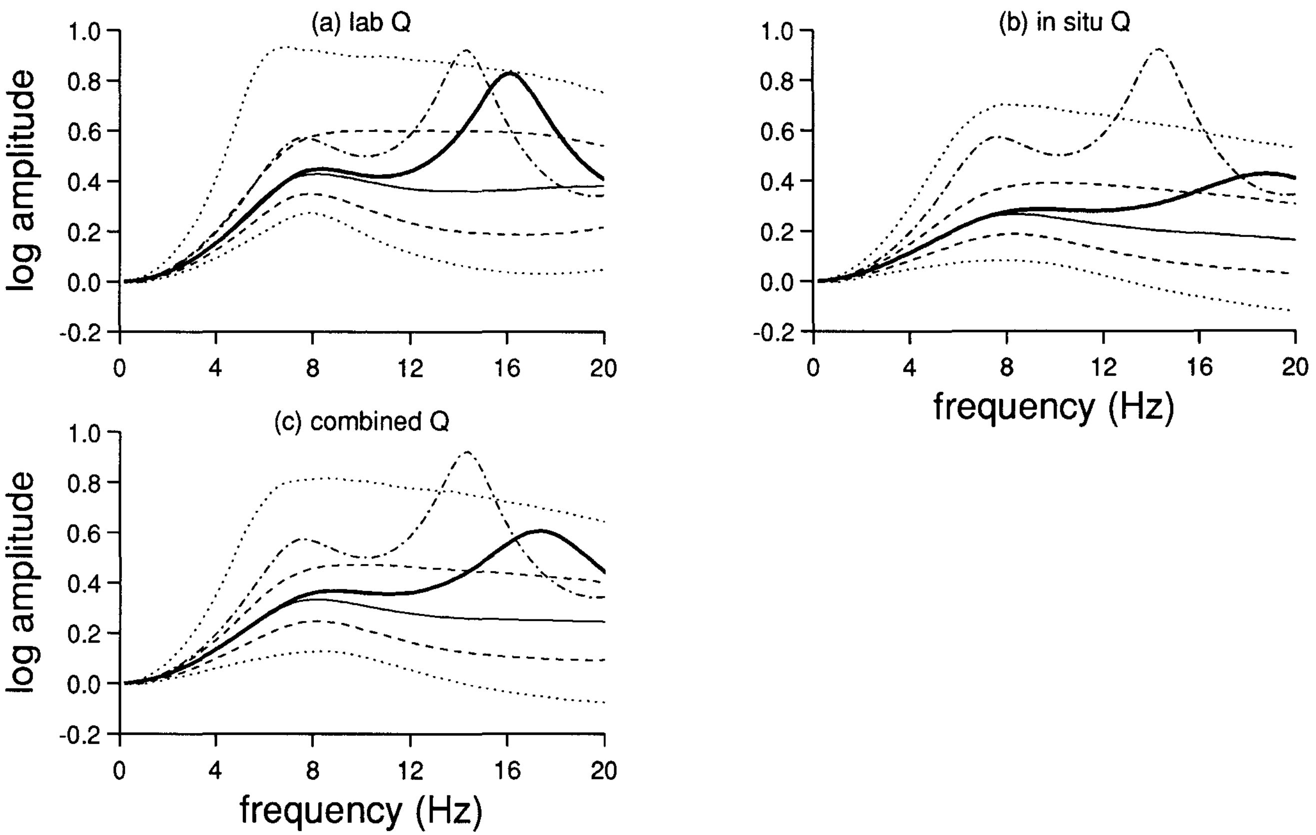


Figure 13 Valley-center monte-carlo simulation results for the case where all input parameters (except density) were allowed to vary. (a), (b), and (c) correspond to the results for the laboratory, in situ, and the combined quality-factor data, respectively. The plotting convention is the same as in Figure 7.

laboratory, in situ, and combined data, respectively. This result suggests that the theoretical site-response functions based on individual geotechnical studies would vary widely for this site.

Shown in Figure 14 are similar plots for the valley-north site (computed in the same way as for Figure 13) where all parameters were allowed to vary simultaneously. While one could argue that the three velocity profile estimates available for this site are not enough to provide accurate estimates of the parameter statistics, we show the result nonetheless. The amplitude scatter is somewhat less than in the valley-center result. However, the variability is still rather large. Near 11 Hz, the difference between the third and first quartiles is 52, 45 , and 51 percent of the median value for the laboratory, in situ, and combined data, respectively. This implies that site-response predictions based on individual geotechnical studies would vary widely for this site as well.

Variability In The Theoretical Site Response Given The *Uncertainty* In The Parameter Estimates:

In this section we present results that address the question of how well the theoretical site response can be constrained, given our best estimates and uncertainties of the input parameters. For this case, the parameter values were selected from the distributions of the means (the dashed lines in Figure 5, and the more sharply peaked curves in Figure 6). The standard deviation (σ) represents the scatter observed among estimates of a given parameter. In principle, σ should not change as more estimates of that parameter become available. In contrast, the standard deviation of the mean (σ_m) represents the uncertainty in the mean, given all the available estimates, and it tends toward smaller values (less uncertainty) as the number of estimates increases. Therefore, this analysis should give us an idea of how well the theoretical site response can be constrained given the parameter uncertainties determined from all the geotechnical data combined. This result can then be compared with the empirical observations (spectral ratios) to conclude the scientific test.

These simulations have been performed only for the case where all parameters are varied simultaneously. The results for the valley-center site are shown in Figure 15, where 15a, 15b, and 15c correspond to the laboratory, in situ, and combined data respectively. A total of 20,000 response functions were computed in each simulation. The solid, dashed, and dotted lines represent the median, 50 percent, and 90 percent bounds respectively. The bold line represents the response of the median values, and the dot-dashed line is the response for the standard model. In Figure 16, these results are compared with the empirical weak-motion site-response estimate for this site (based on average spectral ratios). The solid lines are the 95 percent confidence limits of this empirical estimate. The dashed lines correspond to the central 50 percent region for the monte-carlo simulations, the bold line is the response for the median parameter values, and the dot-dashed line is the response for the standard model.

Since the empirical estimates are ratios of sediment- and bedrock-site spectra, they should be regarded as a relative site response. We examined geotechnical data collected at the bedrock reference site (rock-south) and found that it implies a negligible site response. Therefore, the average spectral ratios should not be influenced by any site response at the reference site. Another consideration is that the observations presumably include shear-waves with nonzero incidence angles, whereas the monte-carlo simulations were computed only for vertical incidence angles. Figure 17 shows the theoretical site-response amplitude as a function of incidence angle. This plot suggests that up to about 40 degrees, incidence angle has a negligible influence on the site response. Monte-carlo simulations performed for the case where the incidence angle is allowed to vary also show this to be a minor effect.

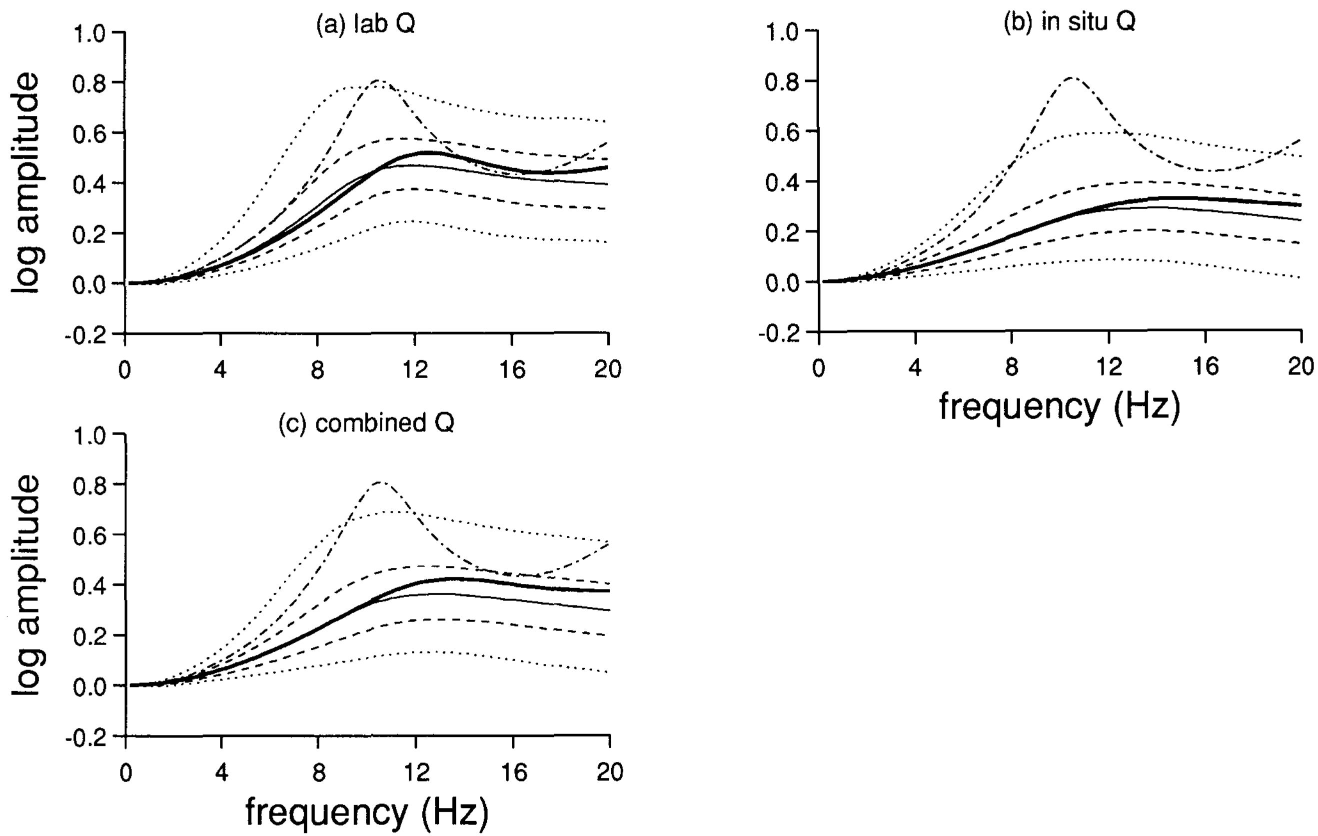


Figure 14 The valley-north monte-carlo simulation results for the case where all input parameters (except density) were allowed to vary. (a), (b), and (c) correspond to the results for the laboratory, in situ, and the combined quality-factor data, respectively. The plotting convention is the same as in Figure 7, except that the bold lines represent the response to the median parameter values for valley-north (given in Table 2b).

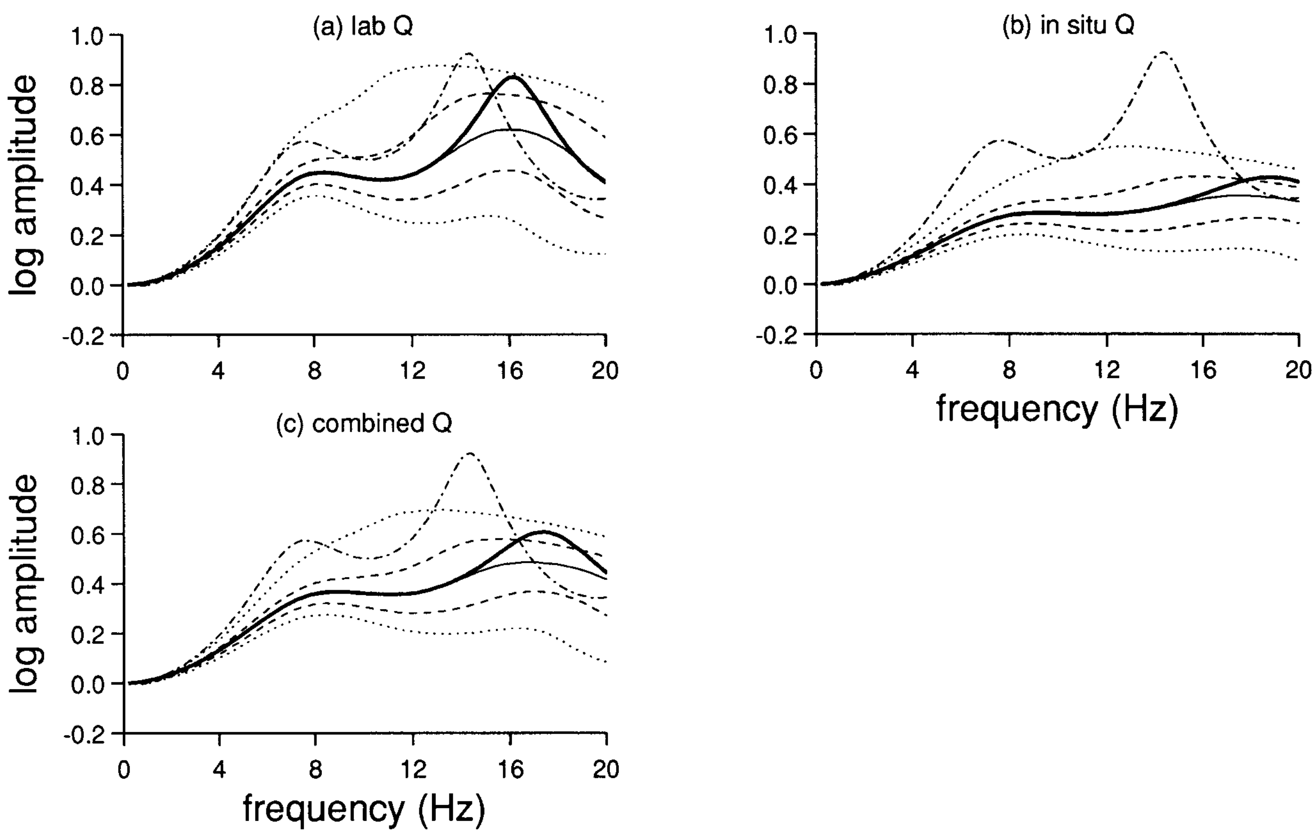


Figure 15 Valley-center monte-carlo simulation results for the case where all input parameters (except density) were allowed to vary, and where the distributions of the parameter-value means were used rather than the distributions of the parameter values. (a), (b), and (c) correspond to the results for the laboratory, in situ, and the combined quality-factor data, respectively. The plotting convention is the same as in Figure 7.

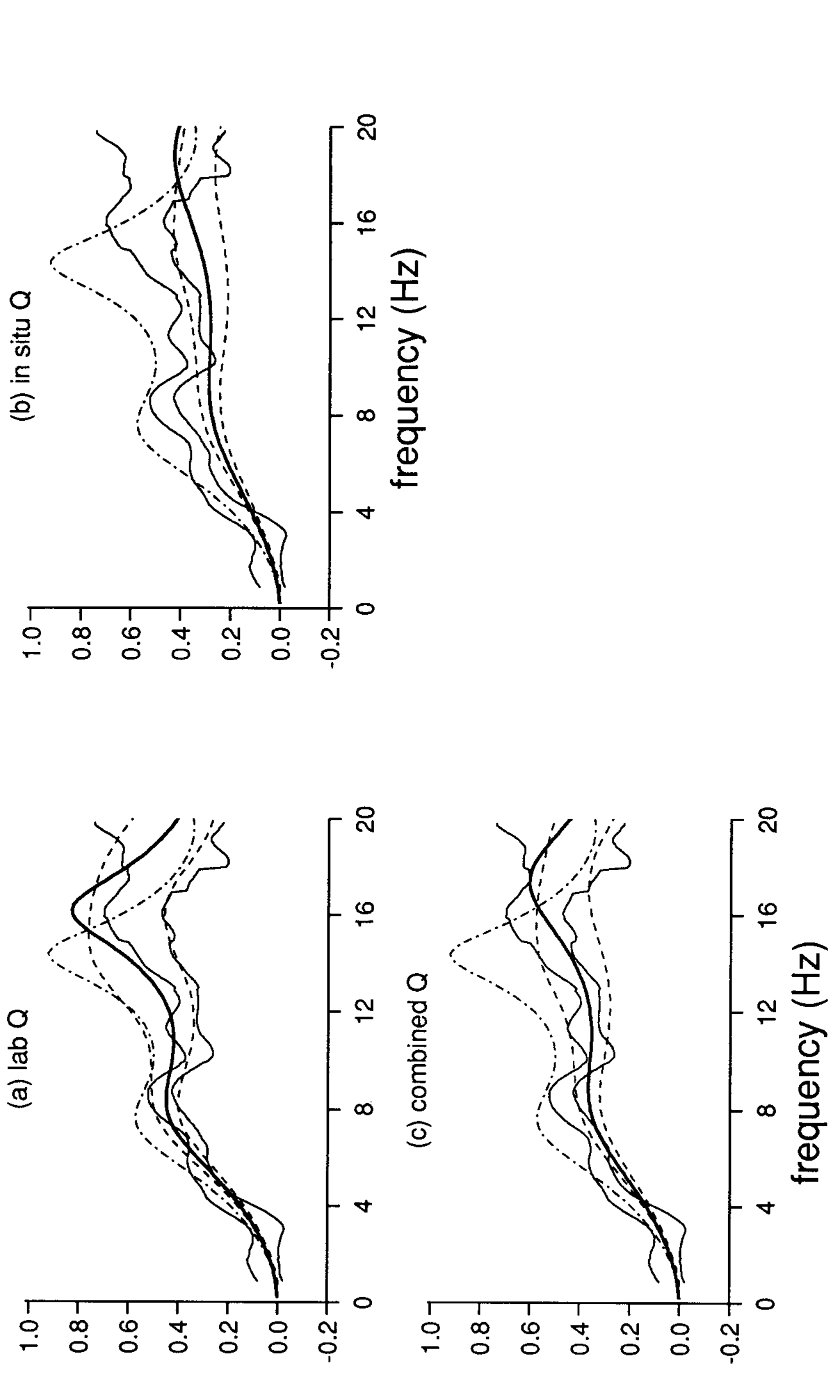


Figure 16 Comparison of the results shown in figure 15 with the empirical site response estimate (average spectral ratios) for valley-center. The solid lines are the 95-percent confidence limits of the empirical estimate, the bold lines are the response for the median parameter values (given in Table 2a), the dashed lines delineate the central 50-percent region for the monte-carlo simulations, and the dot-dashed lines are the response for the standard model (given in Table 1a). (a), (b), and (c) correspond to the results for the laboratory, in situ, and the combined quality-factor data, respectively.

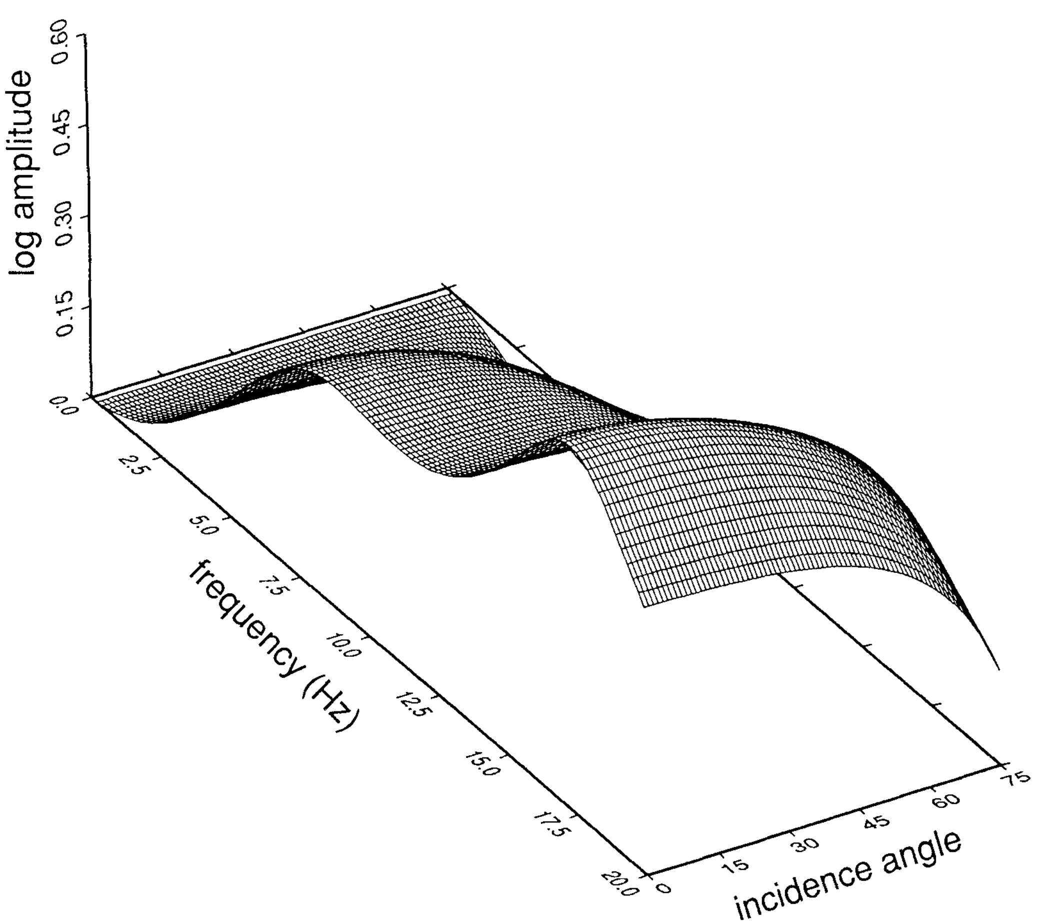


Figure 17 The valley-center theoretical site response amplitude as a function of the incidence angle (all other input-parameters were set to the median values).

Returning to the comparison in Figure 16, the site response predicted by the monte-carlo simulations generally agree with the empirical observations, except, perhaps, for the in situ quality-factor data (Figure 16b). In addition, the agreement is better than that for the standard-model prediction, which suggests that the committee in charge of developing this model would have done better if it had followed the geotechnical data more closely.

Results for valley-north are given in Figures 18 and 19, which have the same plotting scheme, and were computed in a similar fashion, as Figures 15 and 16, respectively. Again, the input-parameter uncertainties give rise to much scatter in the theoretical site response. However, in contrast to the valley-center case, the standard model for valley-north provides a better match to the empirical estimate than do the models based exclusively on the geotechnical data. As mentioned previously, the few number of velocity profile estimates available for valley-north may preclude an accurate estimation of the shear-wave velocity and layer-thickness statistics. In this situation, the opinions of the committee members were apparently a better guide than adhering exclusively to the geotechnical data.

Examining the valley-north velocity data in Figure 3b, it can be seen that one of the profiles completely lacks a discontinuity seen in the other two profiles near 4.8 m depth. If we use this fact as a basis for rejecting this profile, we can adopt an alternative valley-north model based on the other two profiles. The parameter statistics for this alternative model are given in Table 4. Since only one estimate remains for the layer-1 velocity, the uncertainty in this parameter was arbitrarily set at the value used in the valley-center simulations. Since it could be argued that the valley-north profiles did not penetrate far enough to get accurate estimates of the bedrock velocity, the statistics of this parameter were also taken from the valley-center data. The monte-carlo simulation results obtained using this alternative model are shown in Figure 20, which has the same plotting convention as Figures 17 and 19. Better agreement with the observations is found for this alternative model, especially for the case using laboratory quality-factor data. However, one might argue that the agreement is still not as good as that for the standard model prediction.

DISCUSSION AND CONCLUSIONS

When the uncertainties in the geotechnically derived input parameters are accounted for, the theoretically predicted site response at the two valley sites generally agrees with the empirical observations (average spectral ratios). Therefore, one can claim a positive result from the scientific test. However, the theoretical predictions are not very precise since the difference between the third and first quartiles tends to be a large percent of the median value (e.g. 84, 47, and 61 percent near 14 Hz at the valley center site, for the laboratory, in situ, and combined quality-factor data, respectively). This is somewhat disheartening given the fact that Turkey Flat constitutes one of the most thoroughly studied sediment-filled valleys in the world. Even worse is the range of amplitude values that is apparently spanned by predictions based on individual geotechnical studies (Figures 13 and 14). This means that a site-response prediction based on only one geotechnical study would not have a high likelihood of being near the observed values.

One might reasonably ask whether our study was in some way flawed. For example, erroneous choices for the parameter distributions could have been made. Unfortunately, there was generally not enough data to conduct a Chi-square test of the assumed distributions. However, we feel that the distributions adopted are probably fair approximations, and that the results based on any other reasonable distributions would not be significantly different.

From the simulations performed where only one parameter was allowed to vary, it was found that most of the uncertainty results from poor constraints on the shear-wave velocity and

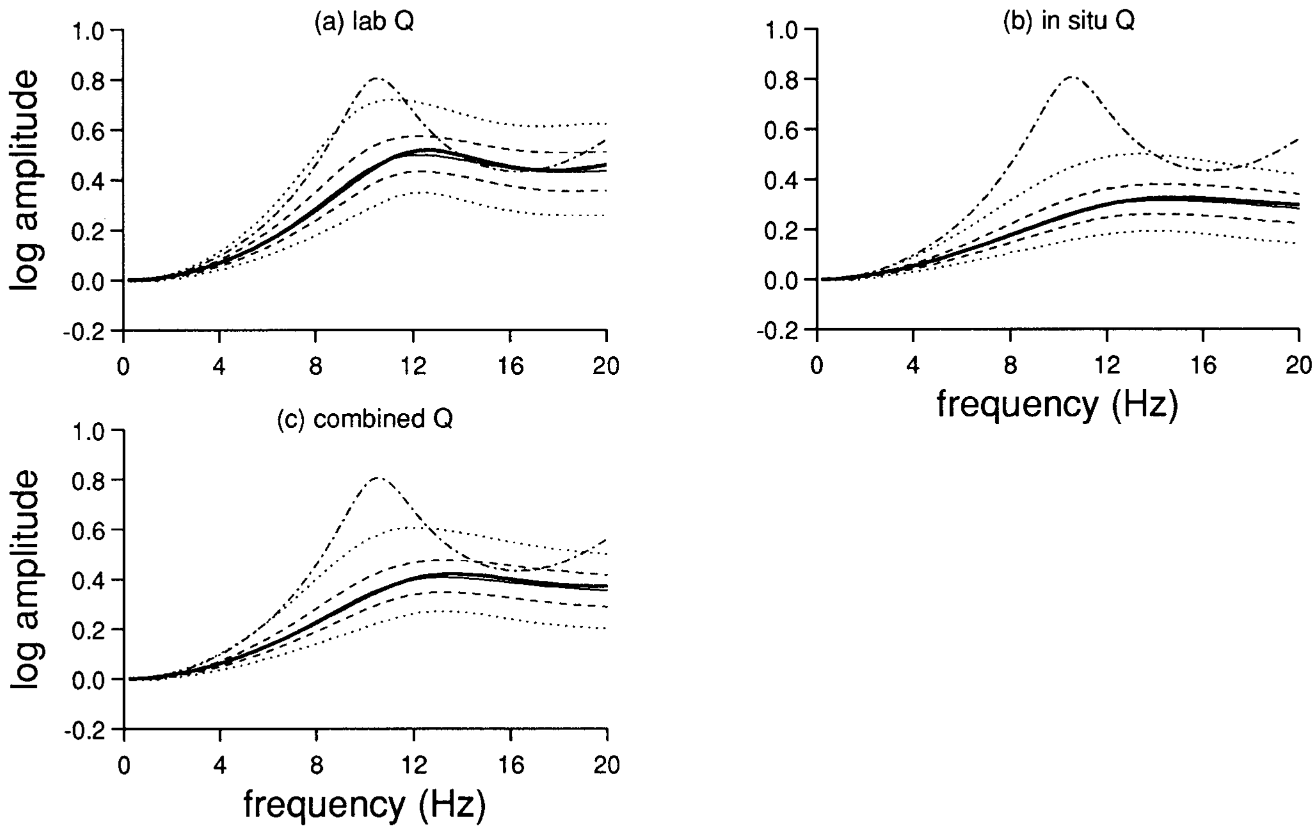


Figure 18 Valley-north monte-carlo simulation results for the case where all input parameters (except density) were allowed to vary, and where the distributions of the parameter-value means were used rather than the distributions of the parameter values. The plotting convention is the same as in Figure 7, except that the bold lines represent the response to the valley north median parameter values (given in table 2b). (a), (b), and (c) correspond to the results for the laboratory, in situ, and the combined quality-factor data, respectively.

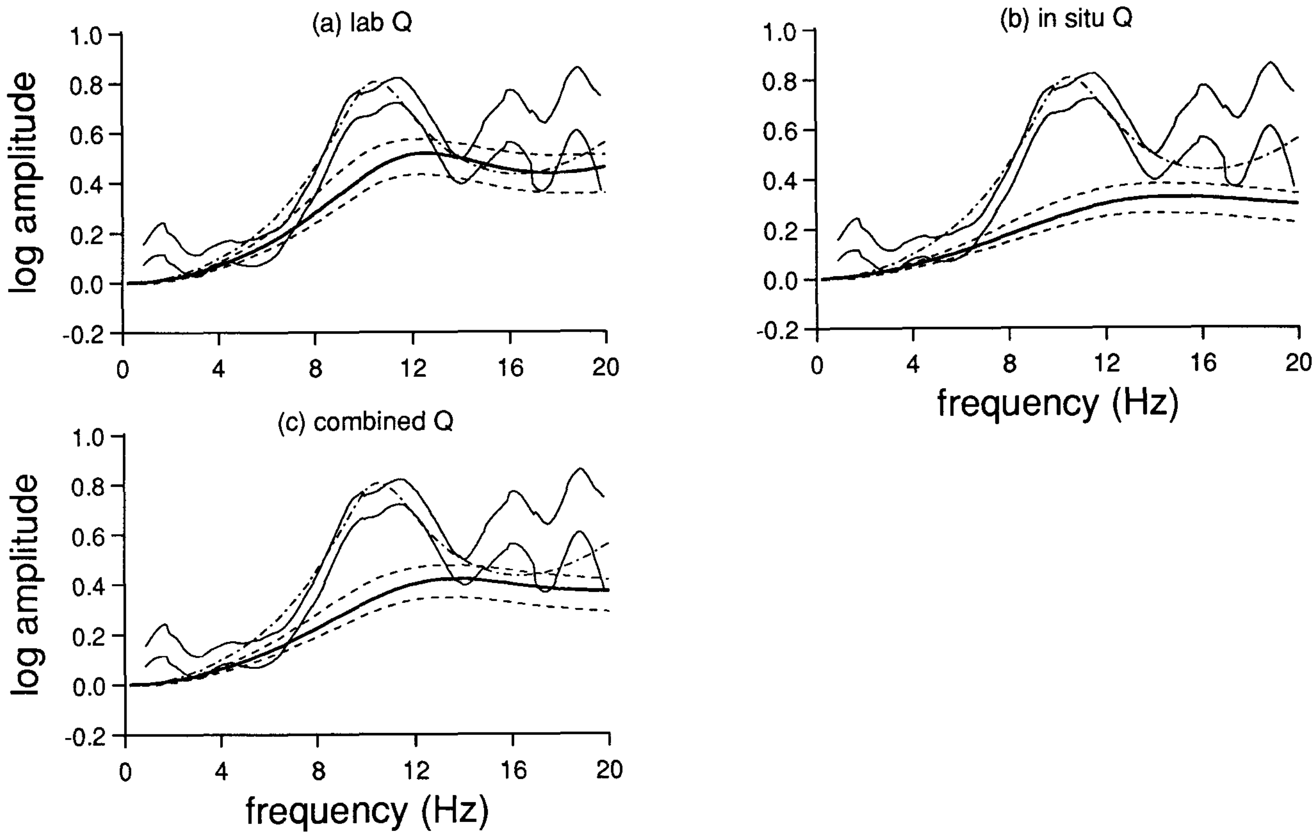


Figure 19 Comparison of the results shown in figure 18 with the empirical site response estimate (average spectral ratios) for valley-center. Again, (a), (b), and (c) correspond to the results for the laboratory, in situ, and the combined quality-factor data, respectively. The solid lines are the 95-percent confidence limits of the empirical estimate, the bold lines are the response for the median parameter values (given in Table 2b), the dashed lines delineate the central 50-percent region for the monte-carlo simulations, and the dot-dashed lines are the response for the standard model (given in Table 1b).

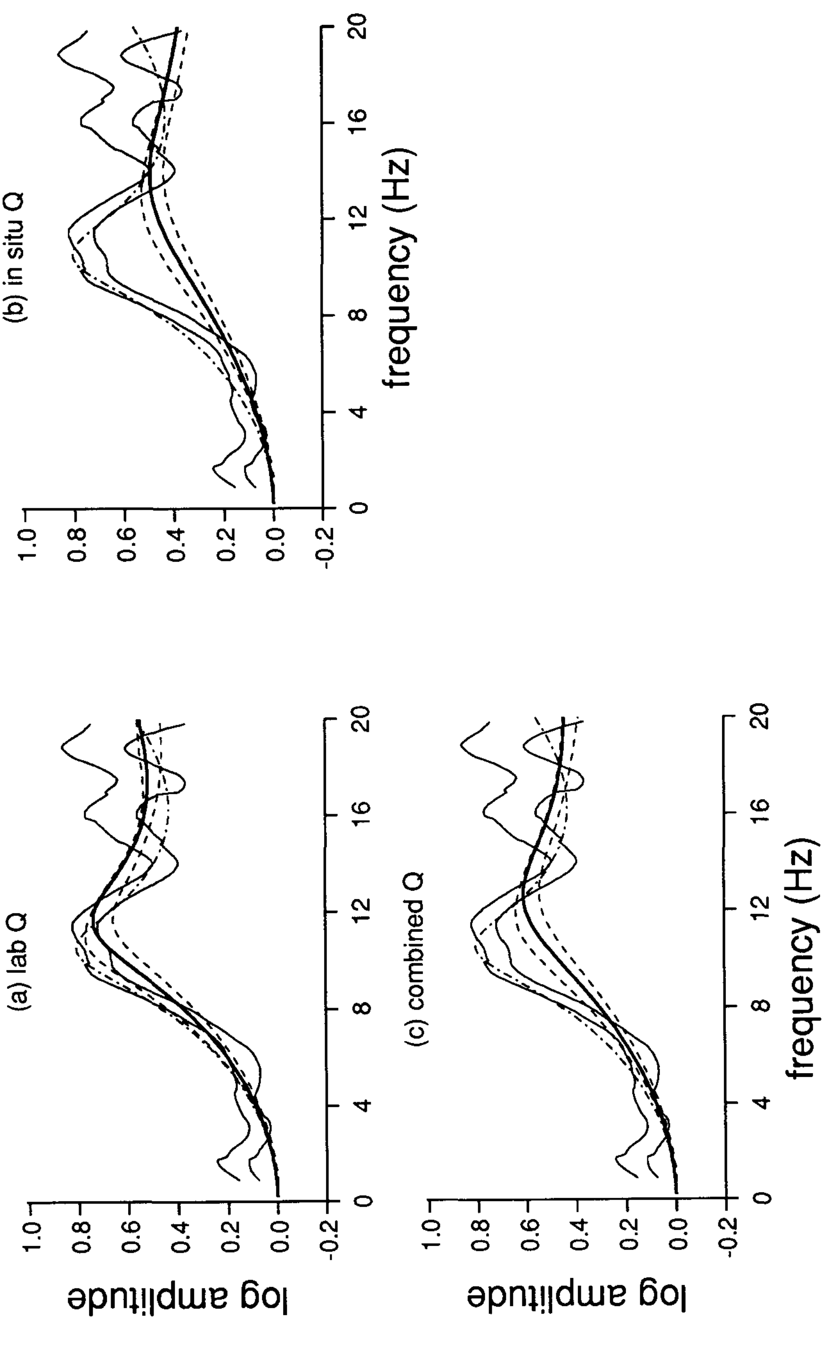


Figure 20 Same as Figure 19, but where the alternative valley-north model (given in Table 4) was used in the monte-carlo simulations.

TABLE 4

Statistics for the Valley North alternative model

layer	mean thickness (m)	σ of thickness (m)	σ_m of thickness (m)	β_m: mean of $\log_{10}(\beta)$	σ of $\log_{10}(\beta)$	σ_m of $\log_{10}(\beta)$	median β (10^{β_m}) (m/s)	95% conf. of β ($10^{\beta_m \pm 2\sigma_m}$)	density (gm/cm^3)
1	1.95	0.12	0.08	2.117	0.196	0.080	131	91 - 189	1.55
2	2.85	0.07	0.05	2.449	0.003	0.002	281	279 - 284	1.75
3	6.2	0.38	0.27	2.781	0.065	0.046	604	489 - 746	1.90
halfspace	inf	---	---	3.085	0.040	0.023	1216	1094-1352	2.20

(Note: σ and σ_m represent the standard deviation and the standard deviation of the mean, respectively) thickness of layer-1, and on the quality factor of the sediments. Since the first layer is only a couple of meters thick, it is possible that either the velocity profiling techniques are not accurate, or that the technicians did not realize the need for accurate values, at such shallow depths. It is clear in retrospect, however, that obtaining more accurate constraints on the velocity profile in the first few meters would substantially improve the theoretical predictions at Turkey Flat.

An important question is whether this high site-response sensitivity to velocity profile uncertainties is unique to Turkey Flat, or whether it is a general problem. In the only other probabilistic site-response uncertainty study that we know of, conducted for sites in Mexico City, it was shown that a "... very small change in shear wave velocity over a very limited depth leads to a very significant change in the spectra for the computed motions at the ground surface" (Seed et al., 1988, p. 716). Therefore, it would appear that this may be a common problem. The strong influence of the shallowest layer observed here is probably not a general result, and exactly which regions of a profile influence the site response most will vary from site to site. Perhaps the best approach in practice would be an iterative one in which a geotechnical study is made, a sensitivity analysis based on the resulting model is performed, and additional investigations are then conducted to obtain better constraints on the more influential parameters.

The influence of the poorly constrained quality factors is also a problem. The discrepancy between laboratory and in situ values, as well as with the opinions reflected in the standard model, must clearly be reconciled. As mentioned previously, the first discrepancy may be due to the fact that in situ measurements include the effects of scattering while the laboratory measurements do not. However, the median value of 4.2 for the in situ measurements seems surprisingly low. As indicated by the standard-model quality factor of 33, it would appear that the committee of experts found the median laboratory value of 15.4 to be unacceptably low as well. In the monte-carlo simulations for valley-center, the best match with spectral ratios was found for the combined quality-factor value of 6.7 (bold line in Figure 16c). For valley-north, however, a better match was found for the laboratory median value of 15.4. A similar observation was found in the trial and error modeling of Cramer (1991). It is possible that this discrepancy in "best fit" quality factors between the two sites is real. However, the geotechnical data does not suggest such a difference. This uncertainty in weak-motion quality-factor values naturally brings into question the strain dependent values used to predict nonlinear site response. Clearly more research, and/or the development of new analysis techniques, is needed so that better constraints can be placed on the important influence of sediment damping values. A contribution toward this end was recently made by Trampert et al. (1992). They show from SH propagator matrix theory that the elastic and anelastic properties between borehole measurement locations can be decoupled (and thereby determined independently) by inverse transforming complex spectral ratios back to the time domain. The advantage is that this quality factor estimation technique is not corrupted by near-surface resonances, which have limited the validity of traditional spectral ratio slope analysis methods to higher frequencies. It will be interesting to see if this new approach can provide more precise and accurate quality factor estimates.

Based on our study, it would appear that the average spectral ratios of earthquake recordings provide a better estimate of the weak-motion site response at Turkey Flat than do theoretical predictions (when uncertainties in the input-parameter values are accounted for). A similar conclusion was reached by Cramer (1991) in stating that "... accurate and consistent prediction of weak motion may not be possible when based on field geotechnical measurements alone". Again, one might ask whether this result is unique to the Turkey Flat site. The superiority of empirical observations was also suggested by Seed et al. (1988, p. 719) in stating that "... it is desirable to refine direct measurements of shear wave velocities with data that may be obtained from actual earthquake records". Unfortunately, it is not possible in practice to collect earthquake records at all sites of engineering concern. Therefore, some studies will be forced to rely on geotechnically based theoretical predictions. When incorporating these results into assessments of probabilistic hazard, it will be important that the variability resulting from input parameter uncertainties is recognized and accounted for.

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