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CAN SITE RESPONSE BE PREDICTED?

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Large modifications of seismic waves are produced by variations of material properties near the Earth's surface and by both surface and buried topography. These modifications, usually referred to as "site response", in general lead to larger motions on soil sites than on rock-like sites. Because the soil amplifications can be as large as a factor of ten, they are important in engineering applications that require the quantitative specification of ground motions. This has been recognised for years by both seismologists and engineers, and it is hard to open an earthquake journal these days without finding an article on site response. What is often missing in these studies, however, are discussions of the uncertainty of the predicted response. A number of purely observational studies demonstrate that ground motions have large site-to-site variability for a single earthquake and large earthquake-location-dependent variability for a single site. This variability makes site-specific, earthquake-specific predictions of site response quite uncertain, even if detailed geotechnical and geological information is available near the site. Predictions of site response for average classes of sites exposed to the motions from many earthquakes can be made with much greater certainty if sufficient empirical observations are available.

Keywords: Site response; amplification; transfer functions; ground motion; variability; prediction.

1. Introduction

The importance of site response is well known, and few would question the assertion that the motion on soil is usually greater than on rock, all other things being equal — at least for motions whose amplitudes are not so great as to produce significant nonlinear soil response (Fig. 1 shows one example of the difference between rock and soil motions). But such a vague prediction is of little use. Reliable quantitative predictions of site response are needed for engineering design — thus the question posed in the title: "Can site response be predicted?". I think that many in the field would answer "yes", but I think that the answer to the title question is: "it depends". It depends on what kind of site response is being predicted and what accuracy is needed in the prediction. The main message of this paper is that variability in ground motions is large, making it difficult to predict site-specific, earthquake-specific site response accurately. That is unfortunate, because it is just that situation that is of importance for critical structures. On the other hand,

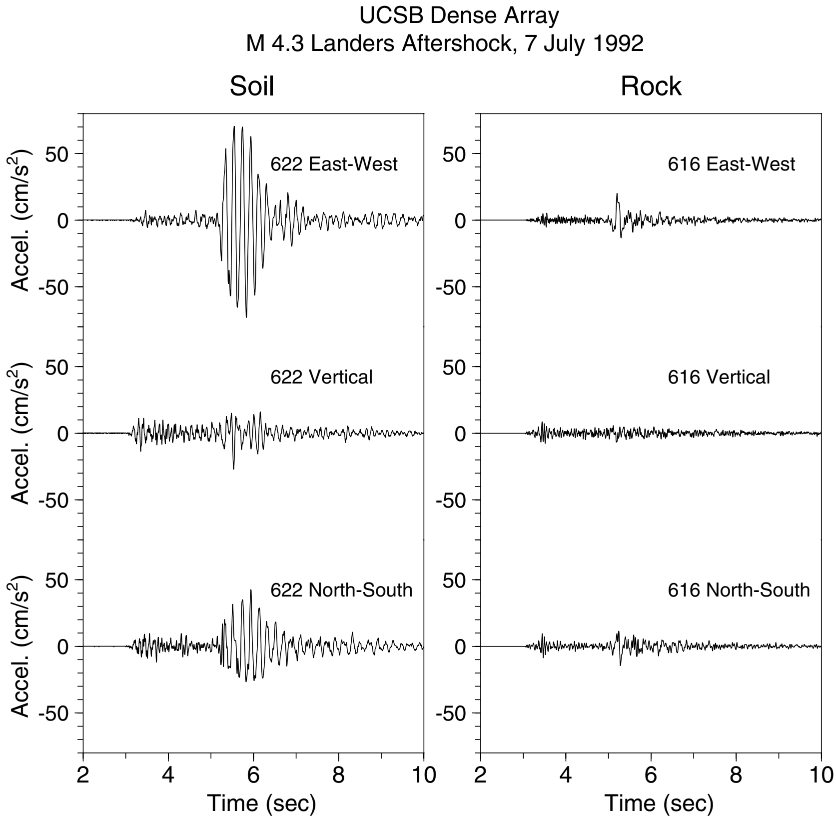

Fig. 1. Three-component ground motions on a soil (left) and a rock site (right). The two sites are about the same distance from the source (approximately 14 km), as indicated by the similar S–P times. "616" and "622" are station numbers [modified from Steidl, 1993].

predictions of mean amplifications for many events and a group of sites sharing somewhat similar geologic conditions can be done with some accuracy.

Before discussing predictions of site response, I should define the term "site response". This is difficult to do, because there is no single definition of "site response". Site response can be the ratio of some measure of ground motion (usually the response or Fourier spectrum) at a particular site (call it "A") to that at another site ("B") for a single earthquake or multiple earthquakes (the specification of motion at site "B" usually involves an empirical prediction). Another site-specific site response is a prediction of the motion at the surface site "A" relative to input motion at some depth below "A" (usually this would be a theoretical prediction). It can also be the difference in median motions for sites placed into different groups (call them "C" and "D") based on subsurface geological or geotechnical properties underlying the sites, after removing the effects of magnitude and distance by regression analysis of a large quantity of data. Common to any site response is a reference condition: Site response is always relative to something. In the first example just given, the reference is the motion at site "B", while in the second example it is the motion at the surface relative to the input motion at depth (not the total motion at depth, which is composed of upgoing and downgoing waves), and in the third example site response is the average of the motions at site group "D" relative to average of those in group "C", for a given magnitude and distance. This may seem pedantic, but it is essential that the reference condition must be considered in ground-motion predictions that account for site response. For example, it would not be correct to use observed motion at "B" as input to the material beneath "A" in a theoretical prediction of motion, because the motion at "B" can have its own site response, and the motion recorded at "B" is not necessarily the same as the input motion below "A" (even after correcting for the effect of the free surface) [Steidl *et al.*, 1996, 1997; Boore and Joyner, 1997].

Of course, other things can affect the ground motion at a site. Usually the physical process is broken into source-path-site (Fig. 2), and the assumption is that the site response is only due to the latter term. But this is an artificial, although often useful, distinction. For example, if not accounted for directly the effects of source directivity can be mapped into site response in equations based on regression analysis. Another example is basin waves. These are surface waves usually produced by the conversion of body waves at the edge of a basin into surface waves that propagate across the basin [Joyner, 2000]. Because of dispersion, these waves arrive

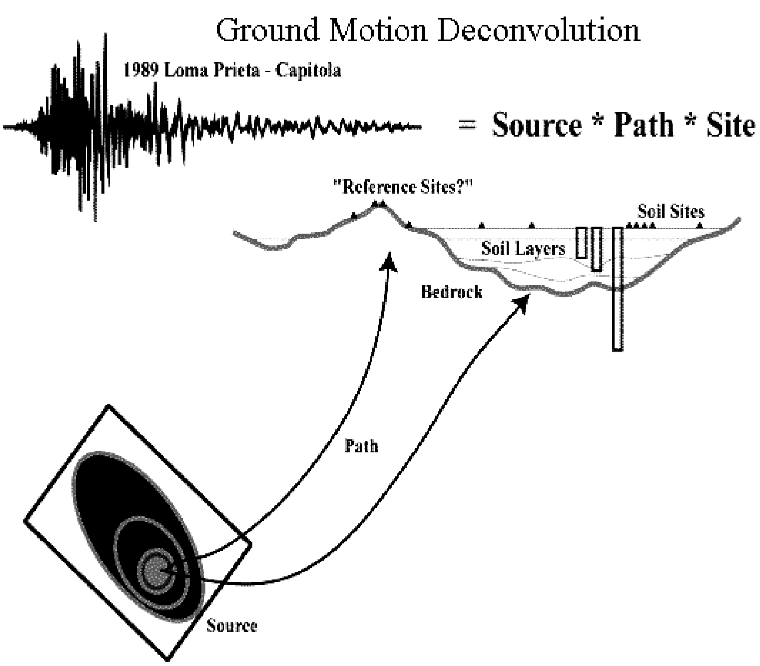

Fig. 2. Cartoon showing how the ground motion at a site can be considered as made up of contributions from the source, the path, and the site [from Steidl, *personal commun.*, 2003].

later than the body waves, and because of differences in geometrical spreading and damping they are usually larger than the body waves, at least when the basin is deep enough that the dominant period of the waves is relatively long and thus the waves are not strongly scattered by geologic complexities. A good example of these basin waves is shown in Fig. 3, which shows the acceleration time series recorded 74 km from a magnitude 5.6 earthquake in southern California. The path to the site traverses part of the Los Angeles basin (see Boore, 1999). The figure also shows the velocity and displacement time series derived from the recorded acceleration. While hardly visible on the acceleration time series, the displacements are dominated by

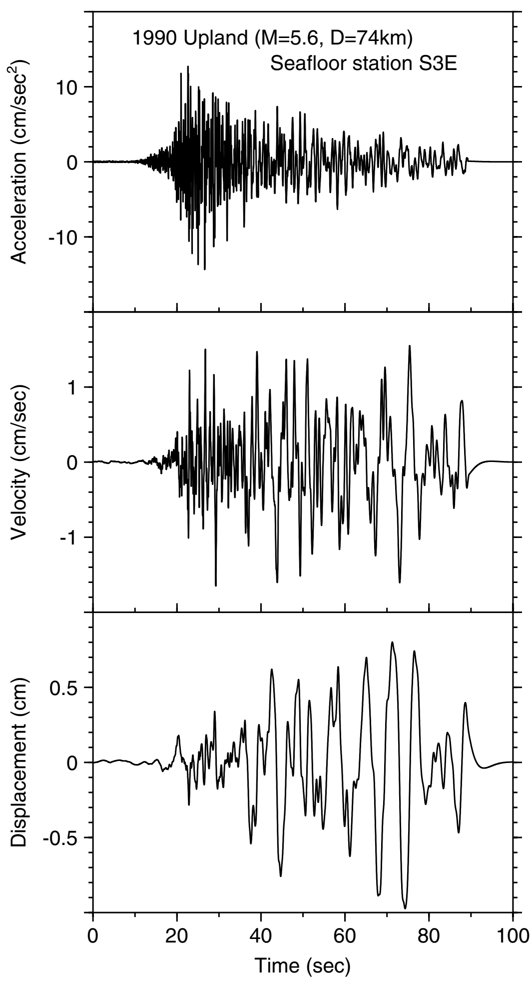

Fig. 3. Acceleration, velocity, and displacement time series for one horizontal component of a recording of the 1990 Upland earthquake. The waves travelling to the station have traversed part of the Los Angeles basin, and therefore large surface waves are present on the displacement time series [modified from Boore, 1999].

later arriving waves with periods of about 6 sec — these are basin waves. These waves are very similar to the waves recorded for other earthquakes whose paths have crossed the Los Angeles basin (not shown here). The effect of these waves on the response spectrum is remarkable, as shown in Fig. 4. The solid curve is the response spectrum for the complete acceleration time series, while the dashed curve was computed from only the S-wave portion of the time series. The basin waves produce an amplification of the response spectrum by over a factor of 10 at long periods. But is the amplification produced by these basin waves a path or a site effect? The waves are due to propagation along a significant portion of the path, and yet are controlled by geologic structure extending to only a few kilometres in depth. Furthermore, theoretical studies suggest that the amplification varies for different locations in the basin and is a function of location of the source [Olsen, 2000] — features that are often observed in studies of site response.

The literature on site response is huge and is growing: Almost every issue of a seismological journal contains one or several articles on site response — a good sign that the field is alive and well. A thorough review of only a small fraction of the literature on site response would be an enormous undertaking and is not the

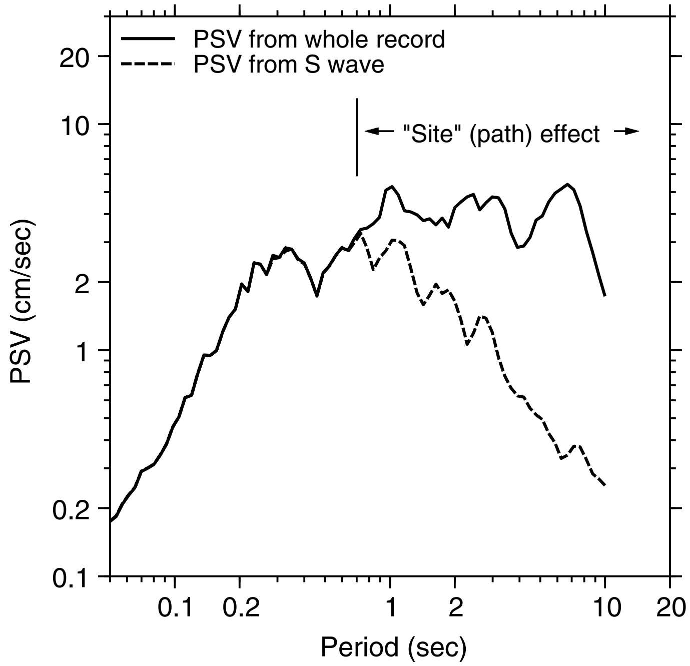

Fig. 4. 5%-damped response spectra for motion in previous figure, computed using the whole record and using only the portion up to about 35 sec in the previous figure (before the basin wave arrivals). The previous figure showed one horizontal component of motion, but the spectra in this figure were computed as the geometric mean of the spectra from both horizontal components [modified from Boore, 1999].

objective of this paper. The paper does not even pretend to be a thorough review of the field, and even for the topics covered here I know that seminal contributions have not been included. For this I apologize in advance to those whose work does not appear here; I have not intentionally ignored any work, and I am sure that there are better examples to illustrate each of my points. Recent reviews that are more complete and balanced than this paper include [Aki, 1988; Bard and Riepl-Thomas, 2000; Kawase, 2003].

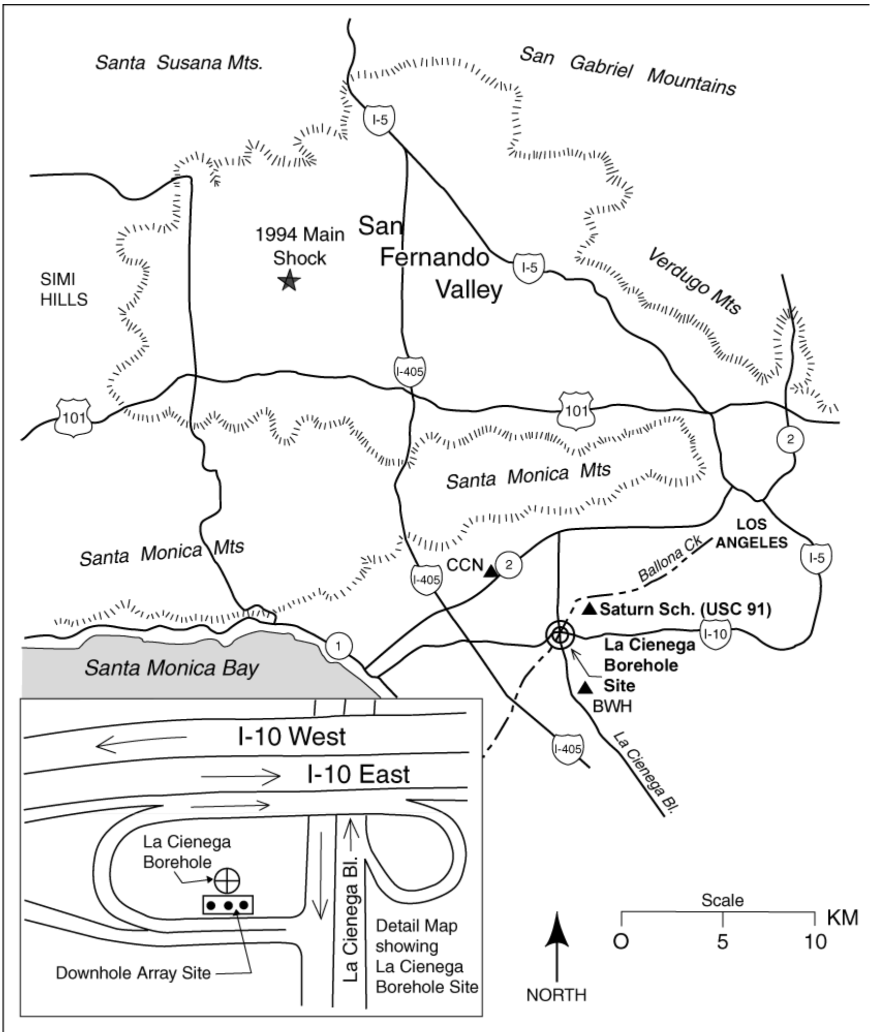

Fig. 5. Location of the bridge collapse at Interstate 10 and La Cienega Boulevard (nested circles) relative to the 1994 Northridge earthquake epicenter (star). The borehole is located at 34.0364N and 118.3780W (NAD83 datum). The Saturn Street School site (SAT) and two other sites (BWH and CCN) from which data are used in this paper are indicated by the triangles [from Boore *et al.*, 2003].

The paper starts with an example of a prediction of ground motion using relative site response. I then discuss empirical evidence for the variability of ground motions. This is followed by a section on prediction of site response, with subsections on predictions for (i) multiple sites and multiple earthquakes, (ii) single sites and multiple earthquakes, and (iii) single sites and single earthquakes. I have not discussed nonlinear response in a separate section, but both the empirical data and a number of the theoretical predictions shown in the paper include the effects of nonlinear soil response.

The theme running through this the paper is that ground motions are highly variable, both site-to-site and earthquake-to-earthquake (after removing effects of magnitude and distance). Because of this variability, I conclude that predictions of site-specific and earthquake-specific site response are very uncertain.

2. Predicting Site Response: An Example

During the 1994 Northridge earthquake a bridge collapsed at the intersection of Interstate Highway 10 and La Cienega Boulevard (Fig. 5). For brevity, I refer to this site as "I10". No ground motion was recorded at the site of the collapse, but good recordings were obtained 2.3 km away at Saturn Street School (SAT). Subsequent to the earthquake, boreholes were drilled and logged for geotechnical properties at both sites. The measured slownesses [the inverse of velocity, see Brown *et al.*, 2002, for a discussion of the advantages of slowness over velocity for use in engi-

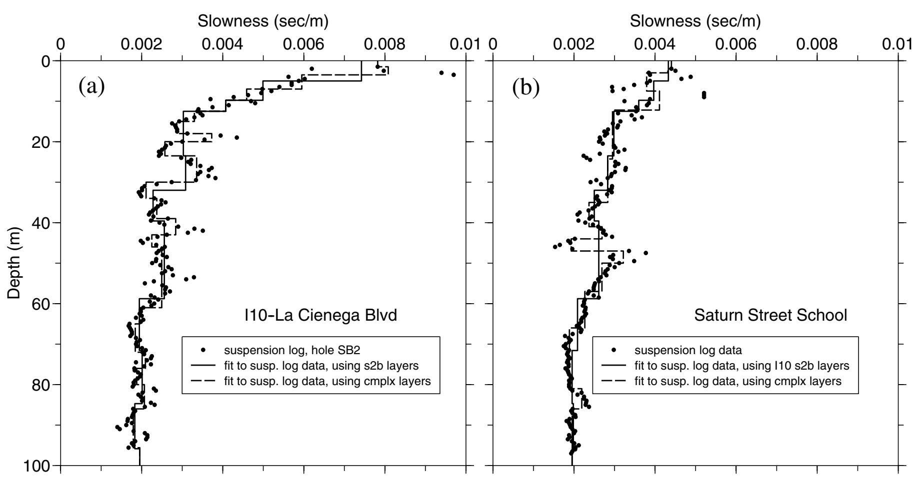

Fig. 6. Slowness from suspension log data, compared to layered models fit to that data in two ways: "s2b" (= **s**urface-to-**b**orehole) uses the layering derived from the analysis of the surface-to-borehole logging of a borehole at I10, and "cmplx" uses more detailed layering guided by the suspension log data. (a) I10-La Cienega data models and (b) Saturn Street School data and models. Models have the same depth interfaces below 100 m. The suspension log data were obtained from http://geoinfo.usc.edu/rosrine and from [C. Roblee, *written commun.*, 1999]; [from Boore *et al.*, 2003].

neering seismology] were clearly greater at the I10 site in the upper 12 m (Fig. 6), suggesting increased amplification at I10 relative to SAT. Boore *et al.* [2003] used the recorded motion at SAT to estimate the motion at the site of the bridge collapse. We deconvolved the recorded motion at SAT to obtain the input beneath SAT at a depth of 250 m and then used that motion as input to the sediments beneath I10. We considered uncertainties in the measured velocities at both sites and used linear and equivalent-linear calculations to estimate the motions at I10. The ratios of response spectra and the estimated motions at I10 are shown in Figs. 7 and 8, respectively. Although there is significant variability in the derived motions, there is clearly amplified motion at I10 over a broad period range, including the range of

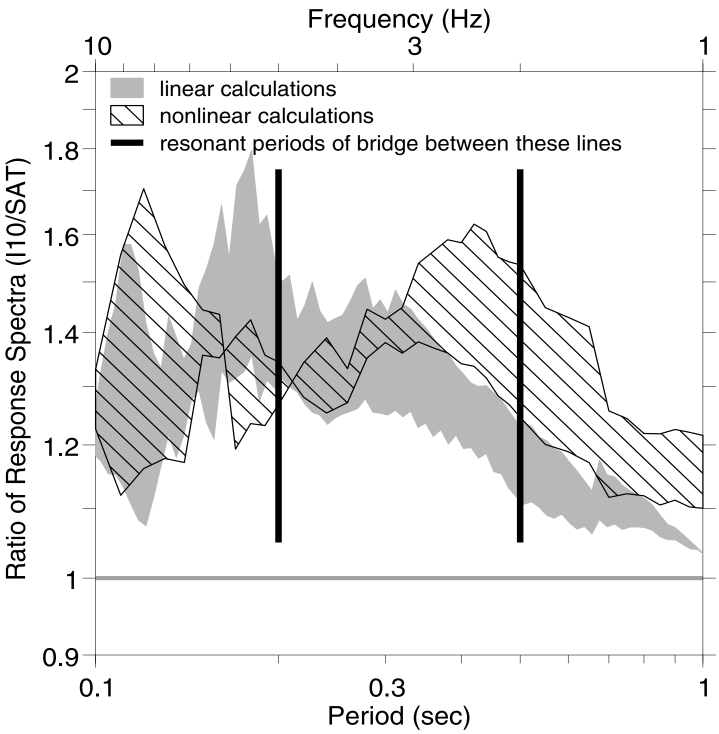

Fig. 7. Ratio of 5%-damped pseudo relative velocity response spectra from the ground motions at the I10 site, derived using both linear wave propagation and the linear approximation of nonlinear wave propagation for the site response (the so-called "equivalent-linear method"), and the response spectrum from the recorded motion at the Saturn Street School site. The hatched and gray areas indicate the range of ratios; the areas are generally bounded by models in which the I10 slowness is from the surface-source downhole-receiver (s2b) model (bottom of hatched and gray areas) and from the suspension log data (top of hatched and gray areas). As shown in Fig. 6, the suspension logging slownesses are higher than the s2b slownesses near the surface, and that is why the ratio of site response is higher for the I10 model based on the suspension logging data. In all cases the response at the I10 site is systematically higher than that at the Saturn Street School (SAT) site for periods between 0.1 and 1 sec. The resonant period of the bridge structure at I10–La Cienega is estimated to lie between the vertical black lines [C. Roblee, *written commun.*, 1997]; [from Boore *et al.*, 2003].

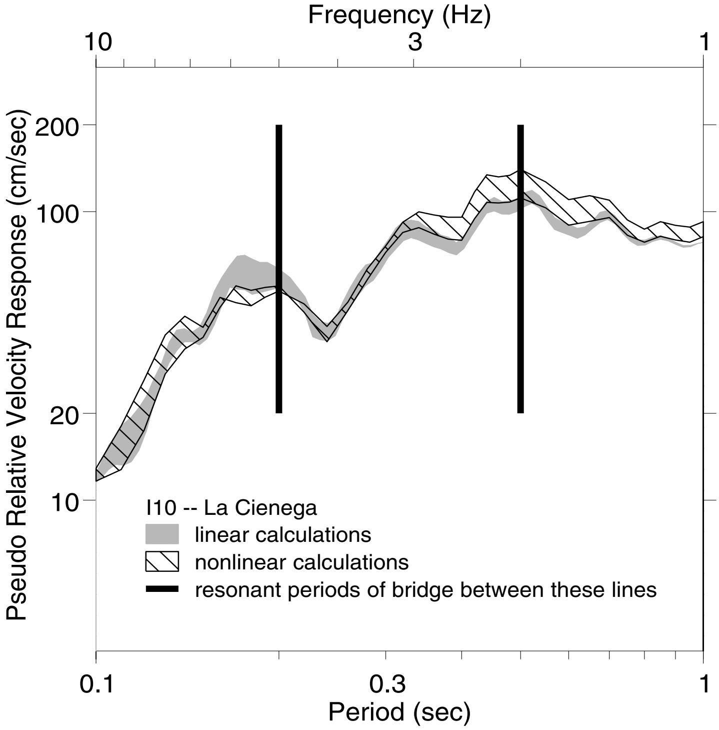

Fig. 8. 5%-damped pseudo relative velocity response spectra for ground motions at the I10 site derived using both linear wave propagation and the linear approximation of nonlinear wave propagation for the site response. The hatched and gray areas indicate the range of site response; the areas are generally bounded by models in which the I10 slowness is from the surface-source downhole-receiver (s2b) model (bottom of hatched and gray areas) and from the suspension log data (top of hatched and gray areas). The resonant period of the bridge structure at I10–La Cienega is estimated to lie between the vertical black lines [C. Roblee, *written commun.*, 1997]; [from Boore *et al.*, 2003].

periods judged to include the resonant periods of the bridge structure. This seems like a very straightforward exercise. What is wrong with this picture? One of the reviewers asked a simple question: Are you sure that the input motion beneath I10 is the same as that beneath SAT? Given the distance from the earthquake and the similar azimuths (Fig. 5), as well as the nearly identical slowness at the two sites below 12 m, we thought that the motions at depth would likely be very similar. But then we looked for the next nearest recordings from the event, and found two sites 3.4 and 4.8 km from I10 (Fig. 5) within the same NEHRP site class (Class D; NEHRP site classes are defined in terms of V_{30}: Greater than 1500, between 1500 and 760, between 760 and 360, between 360 and 180, and less than 180, all velocities in metres per second, corresponding to NEHRP classes A, B, C, D, and E, respectively). To our surprise, the response spectra for these sites are quite different from that at SAT, even after correcting for differences in geometrical spreading (a minor correction) (Fig. 9). Because of this variability, it is possible that the input motion

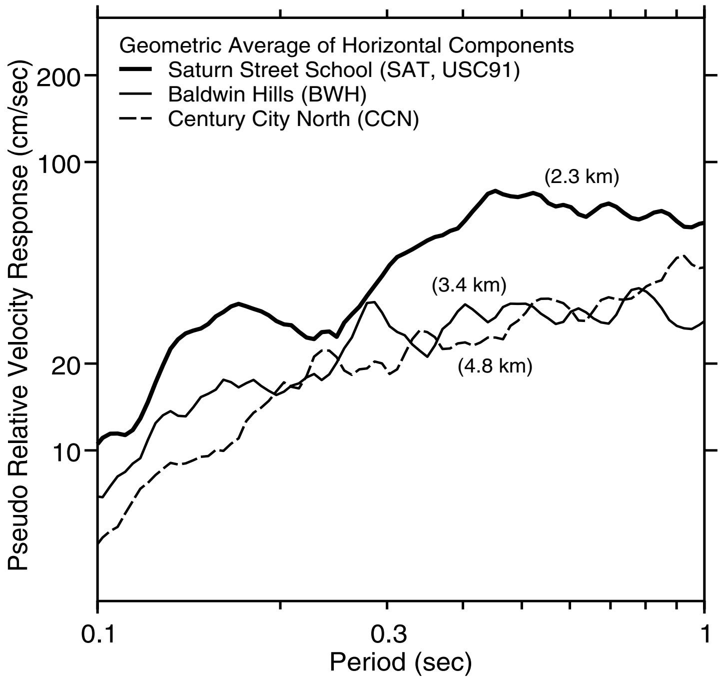

Fig. 9. 5%-damped pseudo relative velocity response spectra for ground motions at Saturn Street School, Baldwin Hills, and Century City North. The latter two sites have been corrected for geometrical spreading to the distance to Saturn Street School, using the equations of Boore *et al.* [1997]. (The Baldwin Hills station is in an area of low relief — the site is about 110 m above the I10 and Saturn sites — and the slowness at the site is intermediate between those at I10 and Saturn.) Shown are the geometrical means of the two horizontal components of the spectra computed from the motions recorded at each station. The distance from each station to the I10 — La Cienega site is given in parenthesis [Boore *et al.*, 2003].

at I10 was so small that even with amplification, the ground motions could be lower than those at SAT. This led me to look into the amount of spatial variability in ground motion to better assess the likelihood of that possibility.

3. Spatial Variability: Path and Site Effects

It is not hard to find examples of the spatial variability of ground motion. Indeed, this was recognised as early as 1898:

> "It is an easy matter to select two stations within 1000 feet of each other where the average range of horizontal motion at the one station shall be five times, and even ten times, greater than it is at the other." [Milne, 1898, p. 81].

In this section I refer to a few of the many examples of variability. I consider spatial variability for single earthquakes and spatial variability for earthquakes in different locations.

3.1. *Spatial variability for single earthquakes*

The 1994 Northridge, California, earthquake was recorded at a large number of sites. I studied the variability of peak accelerations as a function of station spacing, without accounting for site effects [Boore, 1997; Boore *et al.*, 2003]. When combined with other studies of variability for various interstation spacing, the results (Fig. 10) show a rapid increase from no variability for very closely spaced sites to essentially random variability for stations separated by 10 km. The results indicate a factor of 1.5 uncertainty for the I10–SAT separation of 2.3 km.

A second example of spatial variability for a single event comes from dense arrays of seismometers, as reported by Steidl [1993]. The stations were generally within a little over 100 m from one another, but in spite of this close spacing significant variations occur in waveforms and peak amplitudes (Fig. 11) as well as the Fourier spectra of the motions (Fig. 12). Many other examples can be found in the literature.

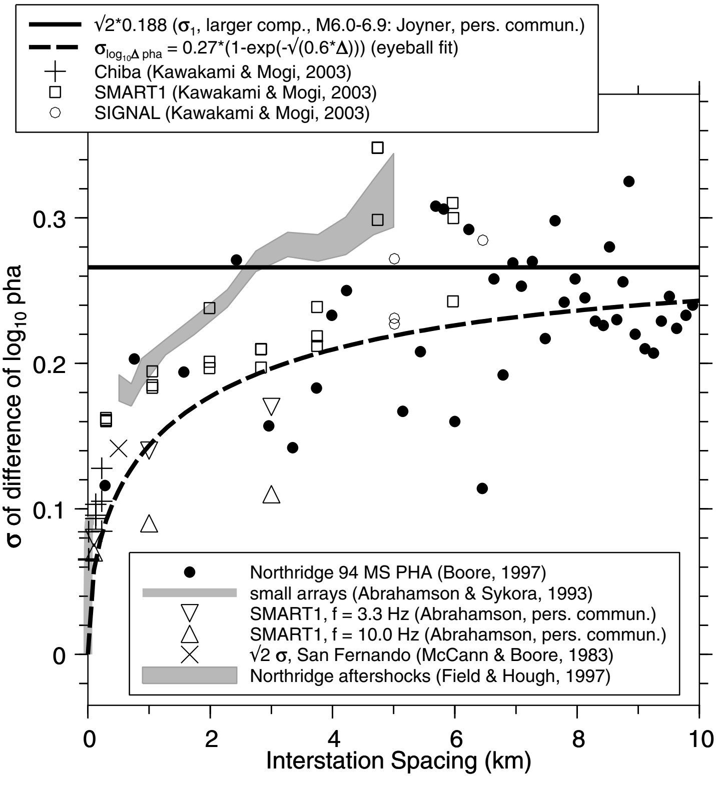

Fig. 10. Standard deviation of difference of log of the larger peak horizontal acceleration as a function of interstation spacing [for details, see Boore *et al.*, 2003].

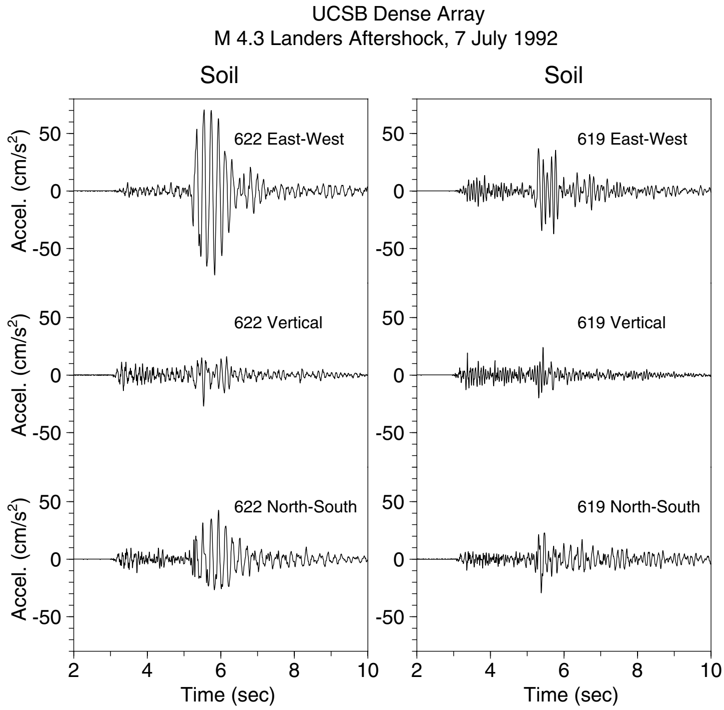

Fig. 11. Ground motions from two soil sites 115 m apart [modified from Steidl, 1993].

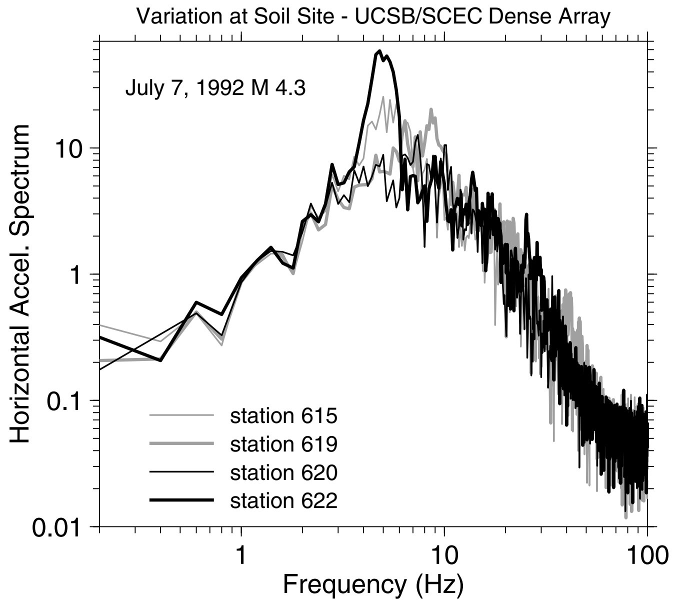

Fig. 12. Fourier acceleration spectra for four soil sites within about 110 m of each other [modified from Steidl, 1993].

3.2. *Spatial variability as a function of earthquake location*

Concentrated damage was caused in the city of Santa Monica, California, by the 1994 Northridge earthquake, at an unexpectedly large distance from the fault. Studies of aftershocks on temporary stations deployed after the earthquake indicated that the ground motions are highly variable spatially, and that the pattern of amplification is a sensitive function of the travel path from the earthquake to the station [Gao *et al.*, 1996; Davis *et al.*, 2000]. The authors of the reports just cited hypothesized that the variability and amplification are due to focusing by structure several kilometres below the region. To test this in more detail, Baher *et al.* [2002] studied recordings on a dense array of stations in Santa Monica. The sources of the recorded motions were aftershocks from various regions and also explosions (at distances and azimuths designed to duplicate the travel paths from the Northridge aftershocks to Santa Monica; the distances to the explosions were greater than to the aftershocks, such that the rays traversed through the hypocentral regions of the aftershocks). Baher *et al.*'s results are a good illustration of both spatial variability of ground motions from single events, as well as the dependence of that spatial

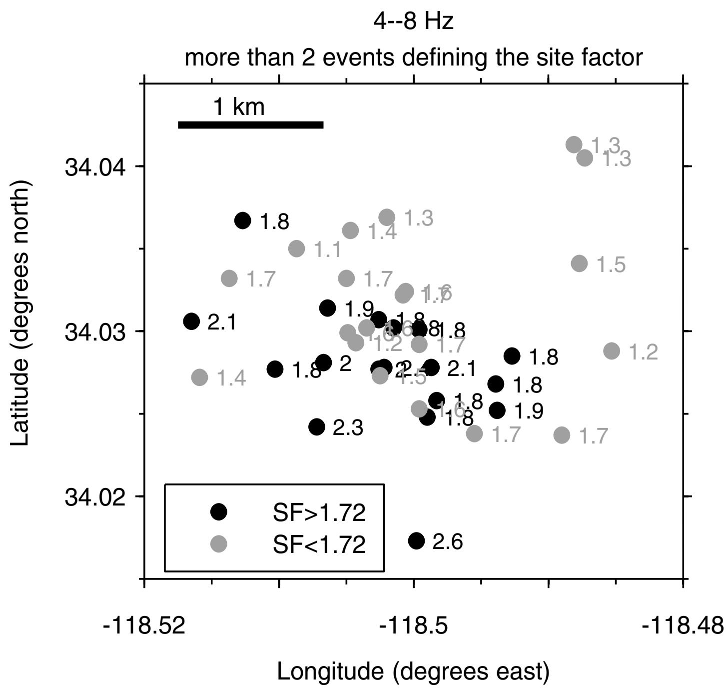

Fig. 13. Site factors (SF) from coda waves, relative to stations in the foothills of the Santa Monica Mountains, to the north of the Santa Monica fault, for ground motions in the range of 4 to 8 Hz [Baher *et al.*, 2002]. These site factors are intended to represent the contribution to site response from shallow structure [see Baher *et al.*, 2002, for a discussion]. The SF of 1.72 is the mean for this group of sites, and different symbols are shown for factors on either side of the mean for ease in assessing the spatial variability.

variability on the location of events. In their analysis they wanted to focus on sources of site amplification due to geologic complexity below the shallow layers. In order to do this, they used site response determined from coda waves, which are presumably made up primarily of scattered surface waves and are thus controlled by shallow structure and represent an average over all azimuths and angles of incidence. They then corrected the actual site response for this near-surface contribution to reveal how much of the site response is due to deeper structure. Baher *et al.*'s Fig. 9 gives the results for the near-surface amplifications in the form of a coloured-shaded contour map, but it is difficult to see the detailed variations for small regions. For this reason I made a map of the site factors (Fig. 13) using the site factors in Table 2 of Baher *et al.* [2002]; shown in Fig. 13 are the individual site factors, as well as symbols indicating whether the site factor is less than or greater than the mean factor of 1.72 (relative to an average of a number of sites in the foothills of the Santa Monica Mountains, to the north of the Santa Monica fault). It is clear that there is significant variability in a small region (note the kilometer scale).

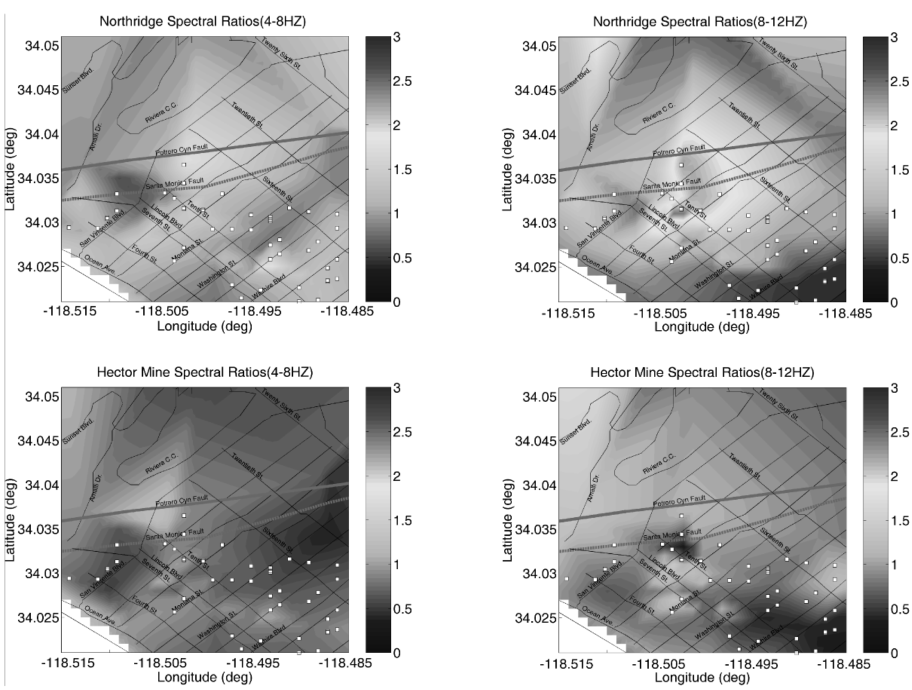

Fig. 14. Site response due to deeper structure (site response from shallower structure, determined from relative amplitudes of coda waves, has been removed) for earthquakes occurring in the region of the 1994 Northridge and 1999 Hector Mine mainshocks, relative to stations in the foothills of the Santa Monica Mountains, to the north of the Santa Monica fault. Site response is shown for two frequency bands, 4–8 Hz and 8–12 Hz. The white squares show buildings damaged enough by ground shaking during the 1994 Northridge mainshock to require red tags (unsafe for human occupancy, with entry prohibited). (From Baher *et al.*, 2002; the original version is in color and shows the site response much better than does this gray-scale version.)

The site response due to deeper structure is given in Fig. 14 for two frequency bands and for aftershocks of the 1994 Northridge and the 1999 Hector Mine earthquakes (the azimuths and distances from Santa Monica to these earthquakes differ greatly, as shown in Fig. 5 of Baher *et al.*, 2002). Although hard to see from these

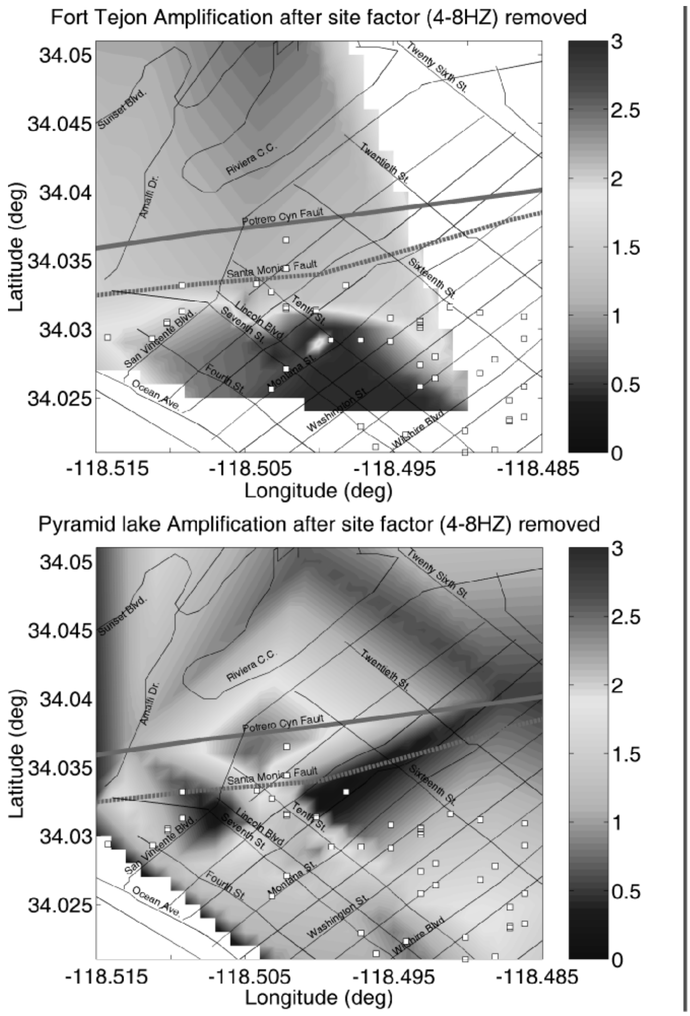

Fig. 15. Site response for explosions located so that ray paths near Santa Monica are similar to those travelled by rays from aftershocks of the 1994 Northridge earthquake, relative to stations in the foothills of the Santa Monica Mountains, to the north of the Santa Monica fault. The site response due to shallow layers has been removed to emphasize the site response due to deeper structure. The azimuths to the two explosions differ by only 3.7°, and yet the site response is completely different. Site response is shown for the frequency bands 4–8 Hz. The white squares show buildings damaged enough by ground shaking during the 1994 Northridge mainshock to require red tags (unsafe for human occupancy, with entry prohibited). (From Baher *et al.*, 2002; the original version is in color and shows the site response much better than does this gray-scale version.)

gray-scale plots, the amplifications differ significantly for sources in the two regions, with large amplifications in the 8–12 Hz band for Northridge aftershocks, but no amplification or even deamplification for the Hector Mine aftershocks. A further indication of the highly-source-specific amplifications is shown in Fig. 15, which compares the amplifications of P-waves from two explosions differing in azimuth by only 3.7° (at distances of 69 km and 91 km, the distances and azimuths chosen so that the travel paths in the Santa Monica vicinity are close to those of aftershocks of the 1994 Northridge earthquake), after removing the near-surface amplifications. Both the pattern and the size of the amplifications are completely different for the two explosions. This variability must be due to something other than the near-surface sediments. One explanation is the focusing of rays from the deeper structure (due to the juxtaposition of materials of very different velocities as the result of faulting along the Santa Monica fault). The ray diagram in Fig. 16 for a structural model determined from boreholes and tomographic inversion indicates the complexity in surface ground motions that can be produced by this deeper structure; three-dimensional ray tracing produces concentrations of ray arrivals that roughly correspond both to the areas of increased motion from the aftershock studies and to the damage distribution from the mainshock. Others, such as Meremonte *et al.* [1996], have suggested focusing by deeper structure to explain localised, azimuth- and angle-of-incident-dependent damage.

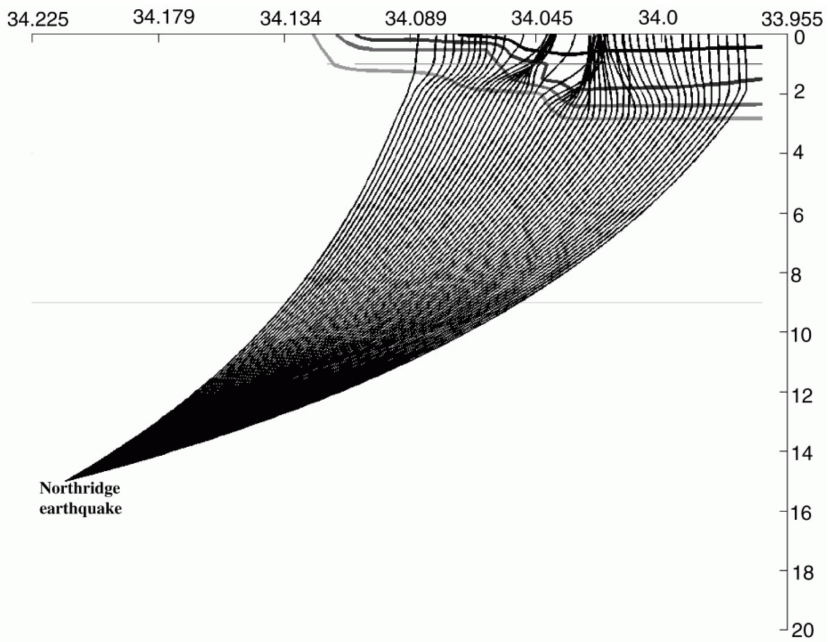

Fig. 16. Ray diagram for cross-section of structure beneath Santa Monica, California, showing focusing of rays due to geometrical complexity [from Baher *et al.*, 2002].

4. Predictions of Site Response

I now turn to several examples of predicting site response using both empirical observations and theoretical calculations. I have divided this part of the paper into two main sections: (i) predictions for multiple sites (invariably involving multiple earthquakes) and (ii) predictions for single sites. The single-site predictions are further divided into predictions involving multiple earthquakes and predictions for single earthquakes.

4.1. *Multiple sites*

The observations given so far show that ground motion can be highly variable, even over small inter-site distances. These basic observations suggest that predictions of ground motions may be very uncertain, particularly site- and earthquake-specific predictions. The situation is more hopeful for the type of prediction based on recordings of many earthquakes, where the site response is an average for a broadly-defined site class, relative to motions for another site class. A good example of the use of such site classes is given by the ground-motion prediction equations published by a number of authors in Issue 1, Volume 68 of *Seismological Research Letters*, for which sites are classified in one of three ways: Rock/soil, NEHRP class (based on the average shear-wave velocity over the upper 30 m, V_{30}) or directly using V_{30} as a continuous variable.

4.1.1. *Are site classes meaningful?: Ground motions in Anchorage, Alaska*

Several studies show that NEHRP site class is useful in distinguishing between site amplifications on different materials [e.g. Stewart *et al.*, 2003]. Here I show another example, using recordings in Anchorage, Alaska, from the 2002 **M** 7.9 Denali earthquake. This earthquake was about 280 km from Anchorage, and the direction of the rays travelling to Anchorage was approximately normal to the direction of fault rupture, a neutral direction for directivity. The distribution of stations for various site classes (including an intermediate class C/D) is shown in Fig. 17. As seen there, the site classes lie within geographic bands (because of the nature of the deposition of the sediments). Response spectra for the east-west component of displacement (essentially transverse, or SH, motion) are shown in Fig. 18, using various line types and gray scales to indicate the three site classes. The figure clearly indicates a separation between class D (higher motions) and class C (lower motions), with the intermediate class C/D actually having intermediate motions on average. The separation according to site class exists from short periods up to periods of about 10 sec (note that site response predictions published previously concentrated on periods less than 1 to 2 sec [e.g. Dutta *et al.*, 2001; Martirosyan *et al.*, 2002; Nath *et al.*, 2002]). For periods longer than about 10 sec the spectra merge with one another, indicating no site effect for these periods.

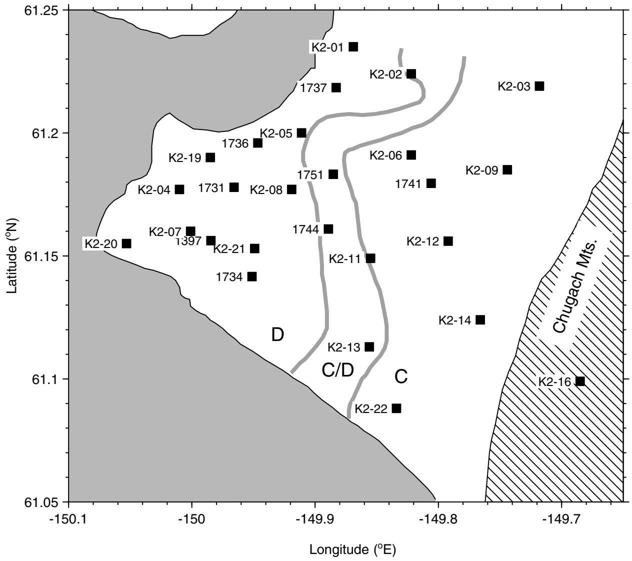

Fig. 17. Location of stations and NEHRP site classes (site classes and base map from Fig. 12 in Martirosyan *et al.*, 2002). The C/D class is intermediate between NEHRP classes C and D, and is defined by Martirosyan *et al.* [2002] by the average shear wave velocity to 30 m being between 320 and 410 m/sec [from Boore, 2004].

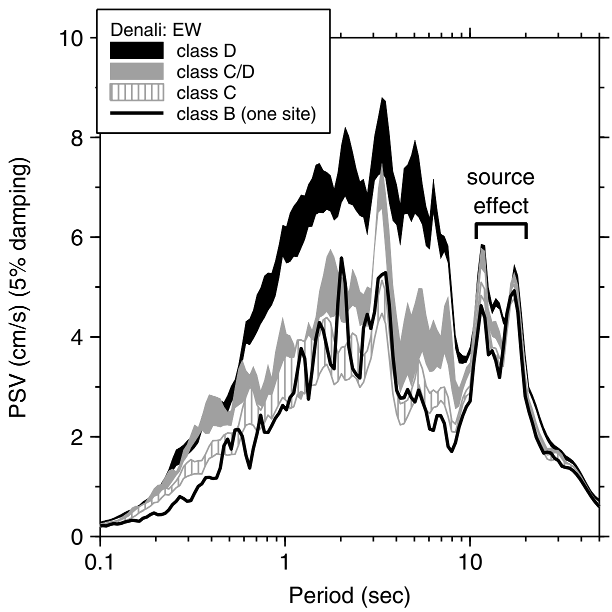

Fig. 18. 5%-damped, pseudo-velocity response spectra for the Anchorage recordings of the 2002 Denali, Alaska, earthquake, with NEHRP site class indicated by line type. Note that the various site classes are clearly separated for periods less than about 10 sec, but coalesce for longer periods. The increase in spectral amplitude between 10 and 15 sec is due to pulses radiated from the source and has nothing to do with site response [after Boore, 2004].

The peaks in the response spectra between about 10 and 15 sec deserve comment, as displacement-based design is making spectra at these periods of increasing engineering interest. I have just shown that these peaks are probably not a site effect, and the geometry of the propagation path and the source is such that they are not a "fault normal" or directivity effect, factors often invoked to explain enhanced long-period spectral motion. The peaks are most likely due to pulses radiated by the source, similar to the long-period pulse observed during the 1999 Hector Mine, California, earthquake [Boore *et al.*, 2002]. The displacement traces derived from the accelerations are shown in Fig. 19, arranged by site class. I have shifted the traces horizontally so that the displacement peaks line up. The presence of two displacement pulses is very clear, and it is these pulses that produce the peaks in the response spectra.

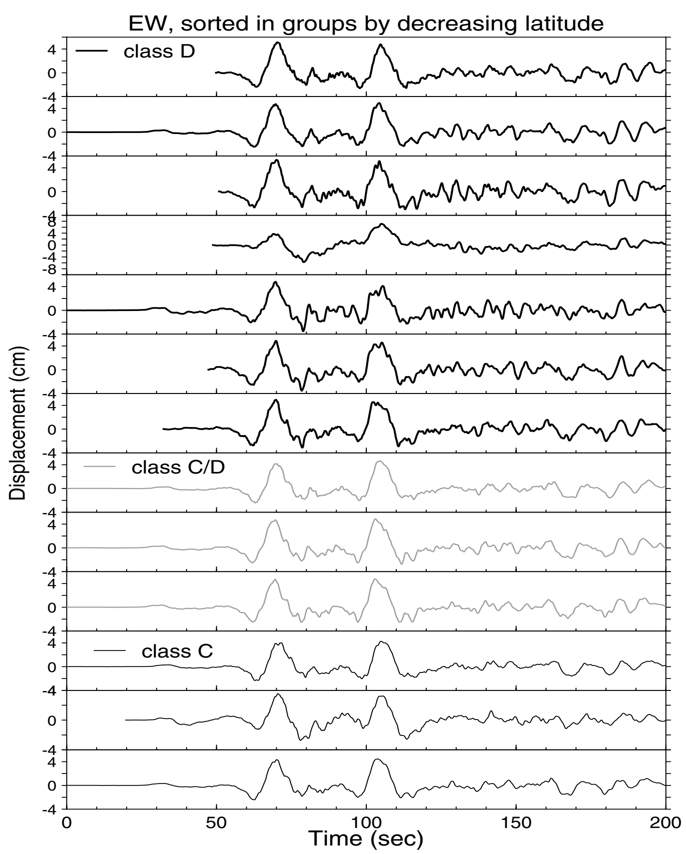

Fig. 19. Displacement ground motions in the E-W direction for the Anchorage recordings of the 2002 Denali, Alaska, earthquake, with NEHPR site class indicated by line type. Note the double pulses and relative independence of the ground motions (at the long periods that dominate the displacements) on site class. The pulses are radiated from the source and have nothing to do with site response; they also have nothing to do with directivity or fault normal motions [after Boore, 2004].

4.1.2. *Site classifications and variance of ground motion*

Figures 20, 21, and 22 show how the proper choice of site classification can remove systematic trends in the data, yet produce little reduction in the overall variance. The three figures are based on residuals for a 2.0 sec oscillator, a period chosen because longer periods have a greater site effect than do shorter periods, at least to a period of 2.0 sec. The residuals are the observed motions corrected for magnitude and distance using the Boore *et al.* [1997] equations and corrected for site effect as indicated below. The data are for a subset of the recordings used by Boore *et al.*, for which velocities to at least 30 m are available from colocated boreholes. The residuals for all graphs are plotted against continuous V_{30}, and rock and soil sites are distinguished by different symbols (the classification into "rock" and "soil"

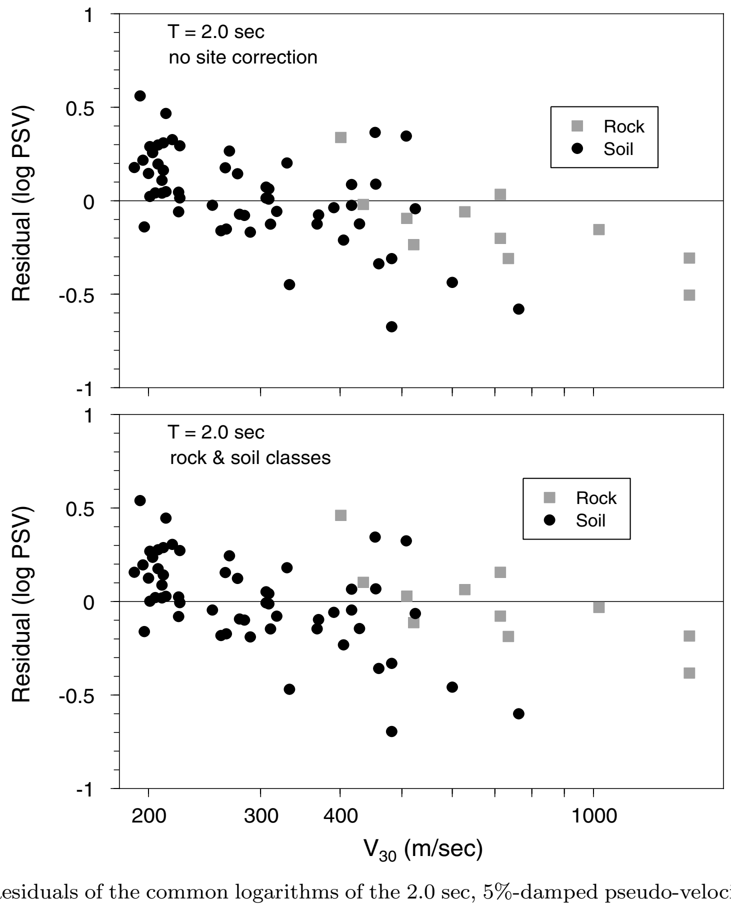

Fig. 20. Residuals of the common logarithms of the 2.0 sec, 5%-damped pseudo-velocity response spectral amplitudes, after removing magnitude and distance dependence using the equations of Boore *et al.* [1997], versus the average velocity to 30 m (V_{30}) at each site (the mean of all residuals was also removed). In the upper figure no site effect term was included; in the lower figure a rock/soil term was included in the regression. Note the trends with V_{30}, even after removing the rock/soil variation.

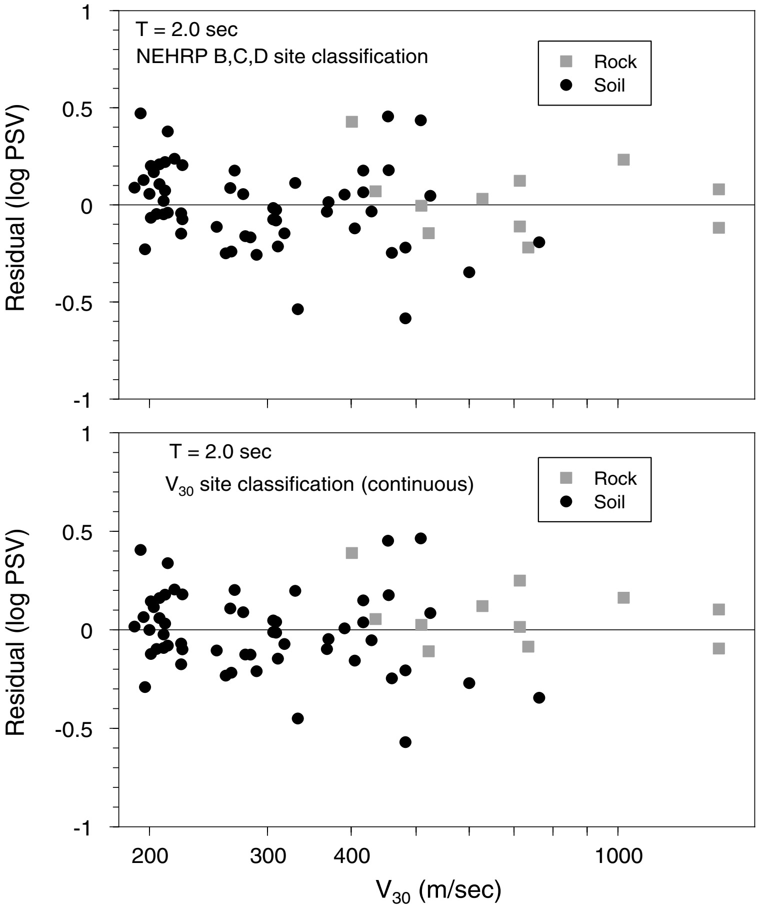

Fig. 21. Residuals of the common logarithms of the 2.0 sec, 5%-damped pseudo-velocity response spectral amplitudes, after removing magnitude and distance dependence using the equations of Boore *et al.* [1997], versus the average velocity to 30 m (V_{30}) at each site (the mean of all residuals was also removed). In the upper figure NEHRP site classes were used in the regression; in the lower figure the continuous variable V_{30} was used to represent the site response. Note that considerable scatter remains after using these various ways of representing the site response.

classes is based on surficial geology, as discussed in Joyner and Boore, 1981; there is an overlap in values of V_{30} for rock and soil sites classified in this way).

In the top graph of Fig. 20 no consideration has been given to site class and a clear dependence of both the rock and the soil sites on V_{30} is obvious. Although harder to see, the soil motions are larger than the rock motions on average. Solving for a rock/soil term in the regression equations and correcting the data for this term leads to the bottom graph of Fig. 20. Now the difference between rock and soil has been removed, but the trend with V_{30} remains. The next logical step in improving site class is to use the NEHRP classes, defined in terms of V_{30}. The result of doing so is shown in the top graph of Fig. 21.

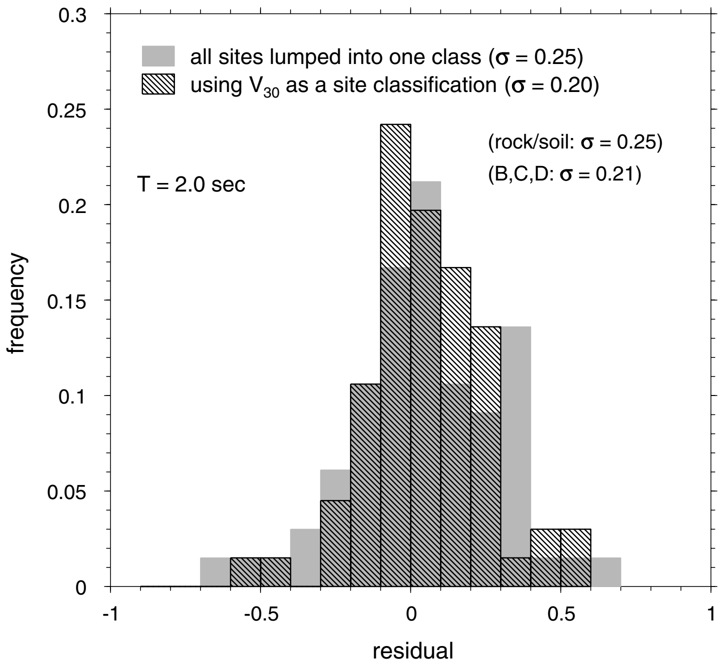

Fig. 22. Histograms of residuals for the two extreme cases of accounting for site response: (i) ignoring site response; (ii) using the continuous variable V_{30}. Also included are the standard deviations of the residuals after accounting for the site response in the four ways considered here (the mean of all residuals was removed in computing the standard deviations). The standard deviations are for log base 10 of the ground motions, so that $\sigma = 0.25$ corresponds to a factor of 1.8 in ground motion. A significant reduction in the variance is obtained in going from rock/soil to NEHRP site class, but little reduction is obtained going from NEHRP class to continuous V_{30}.

The trend with V_{30} has been largely removed. The final step in the logical progression is to use V_{30} as a continuous variable. The result of removing the site effect after doing this is shown in the bottom graph of Fig. 21. The difference between rock and soil has been removed, as has the trend with V_{30}, but a large scatter remains.

To study the changes in scatter due to various site classification schemes, Fig. 22 shows a histogram of residuals for the two end member cases: (i) site class is not considered (the residuals have been centered around 0.0), and (ii) continuous V_{30} is used to classify the site. It is hard to see much improvement in the scatter for the more detailed way of classifying a site. To be more quantitative, the graph also shows the standard deviation that remains after accounting for site class (these are the standard deviations of the log base 10 of the motions and have been computed after removing the mean of all residuals for each way of accounting for site geology). Going from no consideration of site class to a rock/soil classification produces no change in the standard deviation to two decimal places, whereas going from rock/soil classes to NEHRP classes produces a reduction from 0.25 to 0.21. Using continuous V_{30} only leads to a minor reduction in the standard deviation — from 0.21 to 0.20.

The results in Figs. 20, 21, and 22 suggest that although systematic trends exist and can be removed by using NEHRP site classes, the use of V_{30} as a predictive variable may not be worth the additional effort (and the dataset available to do so is reduced, because it is often possible to place a site into a NEHRP class even if a site-specific value of V_{30} is not available); on the other hand, if continuous V_{30} is used the difficulty of deciding what class to put a site into when V_{30} is near a class boundary is eliminated; it was precisely this situation that led Wills *et al.* [2000] to introduce transition site classes such as the C/D class used in the Anchorage case shown earlier. The other important conclusion is that the variability of individual motions is not reduced significantly by using site classes. This is just another expression of the site-to-site and earthquake-to-earthquake variability described earlier.

The regression equations that account for site amplification by binning sites into classes based on V_{30} can be combined with maps of V_{30} to produce maps of site amplification (as usual, these amplifications are relative to something, the "something" in this case being the motion predicted from the regression equations, setting V_{30} equal to 760 m/sec). An example from a major study performed by the Southern California Earthquake Center (SCEC) is shown in Fig. 23 (calculating the amplifications in this map also required basin depths, for which a model was developed as part of the SCEC study; for a collection of papers on the study see the *Bulletin of the Seismological Society of America*, Volume 90, Issue 6B).

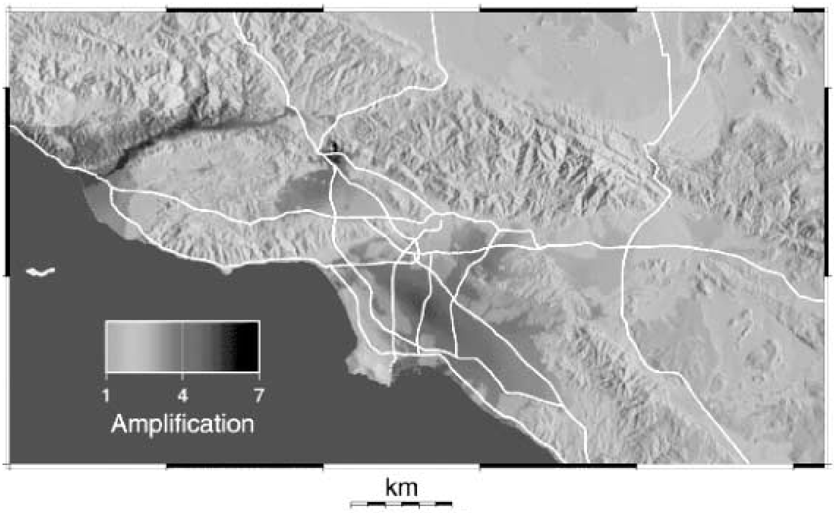

Fig. 23. Site amplification for southern California, based on average velocity to 30 m and on basin depth. (From Field, 2001; the original version is in color and shows the site amplification much better than does this gray-scale version.)

4.2. *Single sites*

The site-response predictions considered in the previous section were entirely empirical and were directed toward defining the mean site response for a large number of stations that primarily fall within a few site classes encompassing a wide range of geologic and geotechnical properties. Such site-response predictions are useful for hazard mapping, land-use planning, setting insurance rates, and so on, but they are of limited use for site-specific situations. By their nature, multiple-sites predictions are broad-brush and cannot capture site-specific details such as resonant peaks. But it is these site-specific situations that are often of the most interest, where ground motions must be provided for the engineering design of specific structures. I split the predictions at a single site into two cases: Predictions for the average of a number of earthquakes, and predictions for a single earthquake.

4.2.1. *Predictions at single sites, for an average of multiple earthquakes*

In this case the predictions are often based on empirical data. Theoretical calculations are also used, particularly if adequate observational data are not available or if strong shaking is expected, for which soil nonlinearity might produce significant modifications to linear site response.

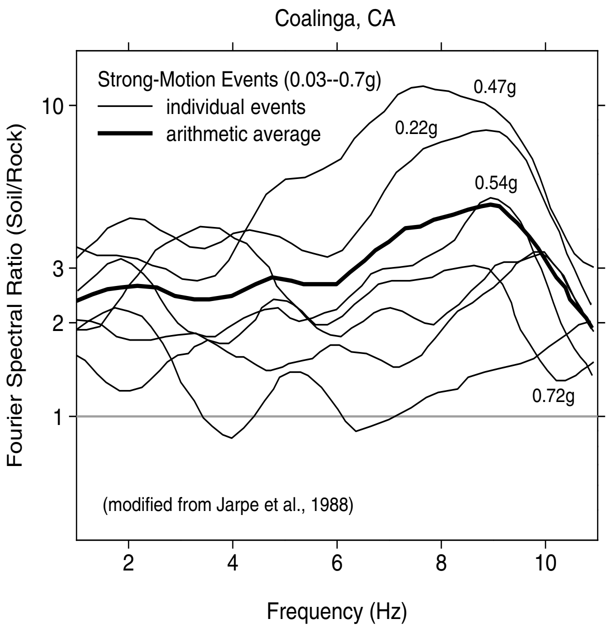

Fig. 24. Soil/rock ratio for strong motions recorded in Coalinga, California. The peak accelerations at the soil site were 0.03, 0.06, 0.18, 0.22, 0.47, 0.54, and 0.72 g; the figure from which this one was taken only labelled the curves corresponding to the four largest peak accelerations. The heavy curve is the arithmetic mean of the individual curves. The soil site is about 6 km from the rock site [modified from Jarpe *et al.*, 1988].

4.2.1.1. *Soil/rock ratios at Coalinga, California*

As the first example, I show in Fig. 24 ratios of Fourier spectra obtained for various aftershocks of the 1983 Coalinga, California, earthquake [Jarpe *et al.*, 1988]; also shown is the arithmetic mean of the ratios. The motions were obtained from permanent strong-motion instruments installed at a soil site in the city and a rock site 6 km away. The peak accelerations at the soil site range from 0.03 g to 0.7 g. The figure shows that the soil motions are almost all greater than the rock motions, as generally expected, but the variability is very large and does not seem correlated with the amplitude of the peak acceleration on the soil site (the curves corresponding to the larger peak accelerations are labeled). This is an example of earthquake-to-earthquake variability at a single site, and the results raise the question of whether the site response for any one of the earthquakes could have been predicted accurately in advance. With enough recordings, the mean ratio is relatively well determined, but the ratio for any single event is very uncertain. This point has been made by others, including Field *et al.* [1992].

What is producing this variability? A clue is given by other results shown by Jarpe *et al.* [1988], using measurements from portable weak-motion recorders colocated with the strong-motion instruments. These instruments, installed after the 1983 Coalinga mainshock, recorded a number of earthquakes, including a cluster in Mammoth, California, some 200 km away, as well as weak-motion events at closer distances but widely distributed spatially (azimuths from the soil site to the earthquakes spanned a range of about 150°, with the azimuths to the subset of events that produced the strong-motion recordings spanning a range of 90°). The ± 1 standard deviation band about the mean of Fourier spectral ratios calculated from recordings on the soil and rock sites from the regional events was much smaller than for either the local or strong-motion events, and the means for the latter two were similar (suggesting little nonlinear soil response). These results suggest that the ratios are repeatable if the earthquakes are located in the same place, but they make it clear that two- and three-dimensional effects (lateral refraction, focusing, scattering, conversion of wave types, etc.) are important; calculations assuming one-dimensional wave propagation in flat-lying models could not explain the results.

4.2.1.2. *Soil/rock ratios at Parkway, New Zealand*

The rock reference site in the previous example was 6 km from the soil site. This is a great enough distance to raise the question of whether both sites are being illuminated by the same wavefield. The answer to this question is not important if the application is based on purely empirical estimates of site response, always using the same soil and rock stations. But the answer to the question is very important if theoretical calculations are used to estimate site response. An informative recent study by Yu and Haines (2003) illustrates the importance of the choice of reference site. In that study, spectral ratios of motion at soil sites in a narrow valley in New Zealand were computed relative to motions recorded at various rock sites (Fig. 25).

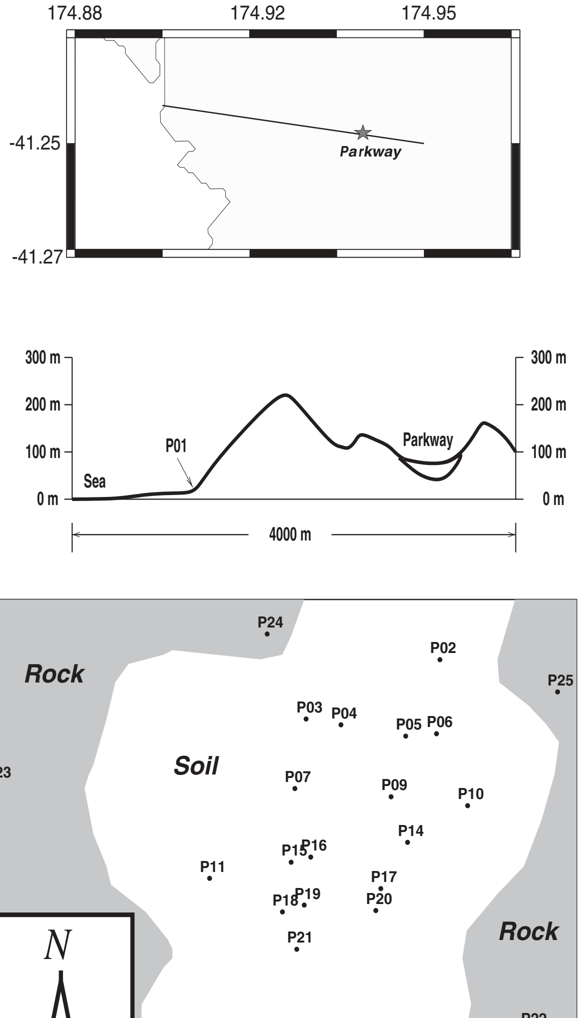

Fig. 25. Map of stations used in analysis by Yu and Haines [2003] of the choice of reference site in calculations of site response. The line in the top graph shows the location of the profile given in the middle graph; the lower graph shows detailed locations of stations in and around the Parkway valley [modified from Yu and Haines, 2003].

Note in Fig. 25 the station P01, 2 km from the valley and on the other side of the ridge bounding the valley. That site had been used as a reference in some previous studies of site response, and those studies found significant variability of the ratio with respect to earthquake location (Fig. 26, bottom graph). When either single rock sites closer to the valley, or an average of those rock sites, is used as the reference, the ratios are much more stable with respect to earthquake location

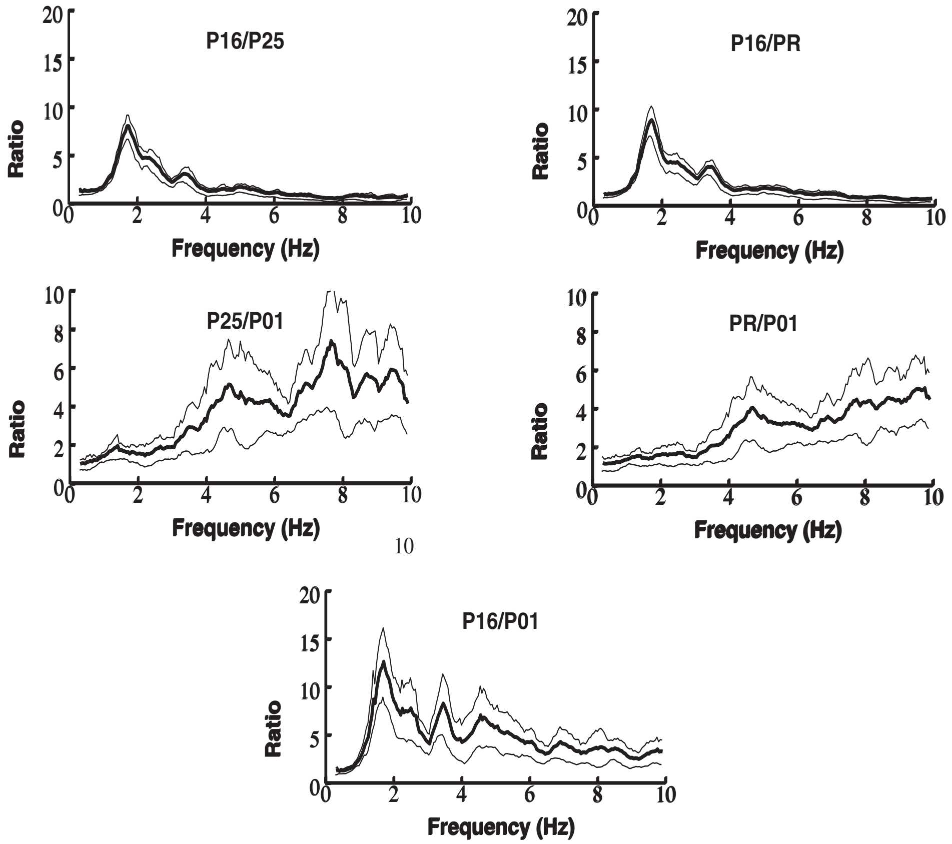

Fig. 26. Spectral ratios using various reference conditions. Station P16 is within the alluvial-filled valley, P25 is a rock station, PR is an average of four rock stations, and P01 is a rock station about 2 km from the valley (see previous figure). The heavy line is the average ratio, and the light lines are plus and minus the single-event standard deviations [from Yu and Haines, 2003].

(Fig. 26, top two graphs). (An extreme example of a rock reference site being far from the soil sites is in the paper by Finn *et al.*, 2003, who used a reference site 62 km from the soil sites.) Yu and Haines [2003] also find that irrespective of the earthquake-to-earthquake variability, the rock sites near the valley have a site response relative to the rock site P01 (Fig. 26, middle two plots). This is consistent with studies that make the point that the site response at reference sites must be considered — not all rock sites are created equal [e.g. Steidl *et al.*, 1996, 1997; Boore and Joyner, 1997; Chávez-Garcia *et al.*, 2002]. This point will come up in the next example.

4.2.1.3. *Soil/rock ratios at the Euroseistest Strong-Motion Array, Greece*

The Euroseistest Strong-Motion Array is a natural laboratory for investigating site response. It is in a valley about 2.5 km wide near Thessaloniki, Greece, and consists of a series of stations in a profile across the valley, with stations on rock on either side of the valley. The sediments in the valley have a maximum thickness of about 200 m [Makra *et al.*, 2001]. Many studies have been conducted to determine geological and geotechnical properties of the valley and adjacent rock sites, and a number of papers have been published comparing empirical and theoretical site response [Dimitriu *et al.*, 1998; Raptakis *et al.*, 1998; Riepl *et al.*, 1998; Makra *et al.*, 2001; Chávez-Garcia *et al.*, 2000; Raptakis *et al.*, 2000; Chávez-Garcia *et al.*, 2002]. Here I will show the results of an early study [Raptakis *et al.*, 1998] in which the average spectral ratio for the station at the center of the valley (TST) relative to the rock site to the north of the valley (PRO) was computed from recordings of 36 earthquakes, widely distributed in space. The maximum recorded peak acceleration was 0.05 *g*. Before discussing the average ratio, I show in Fig. 27 the standard deviation of the individual ratios normalised by the average value of the ratio. As in previous examples, this figure shows that there is a large earthquake-to-earthquake variability in the ratios (much larger than indicated in the Parkway, New Zealand study), making predictions of earthquake-specific site response very uncertain, at least using one-dimensional models.

The average spectral ratio is shown in Fig. 28. Clearly the motions in the valley center are much larger on the average than those at the rock site, and there is an

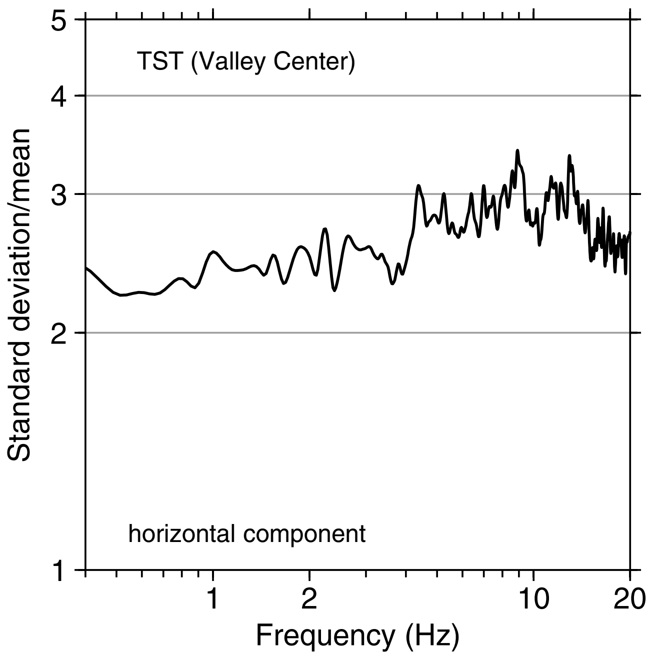

Fig. 27. Standard deviation divided by mean for the TST/PRO spectral ratio, from recordings of 36 earthquakes on the Euroseistest Strong-Motion Array near Thessaloniki, Greece. This figure shows that there is a large variability in the ratio of a single event about the mean ratio [from Raptakis *et al.*, 1998].

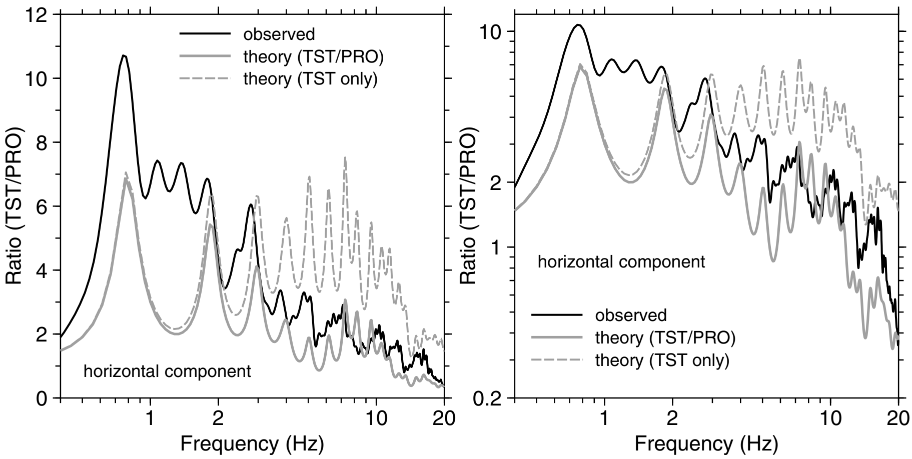

Fig. 28. Averaged ratio of Fourier spectra of motion recorded on the Euroseistest array at the valley centre (station TST) and the rock site to the north of the valley (PRO). Also shown are theoretical one-dimensional calculations, both for the TST site relative to input below the site, and the ratio of the site responses at TST and PRO (this is the proper theoretical site response to compare with the data, because the site response at PRO was not removed from the observations when the observed ratios were computed). Both linear and log scaling for the ordinate are used to emphasize how the form of the plot can alter the perception of the comparison between observations and data (see text). (From Raptakis *et al.*, 1998. In order to show the effect of the structure beneath the reference site, I redid the theoretical calculations using vertically incident SH waves and velocity-density-Q models for TST and PRO provided by N. Theodulidos, *written commun.*, 2003; my results are similar to those in Raptakis *et al.*, 1998, although they differ in detail.)

indication of resonant peaks in the response. The ratio seems to be filled in to a large extent between the peaks, however, making the ratio overall a broadband amplification. Also included in the figure are theoretical calculations, assuming vertically incident shear-waves. The same information is in the two plots, but the lefthand plot uses a linear scale for the ordinate whereas the righthand plot uses a logarithmic scale. I have done this to illustrate how the choice of scale can influence the perception of how well two curves compare with one another. Before getting into that, however, I should explain the theoretical curves. I computed the theoretical curves using the program NRATTLE (written by C. Mueller, with modifications by R. Herrmann). The velocity-density-Q models were provided by N. Theodulidis [*written commun.*, 2003], who assures me that the models were determined independently of the observed spectral ratios. The dashed curve represents the transfer function for the TST site alone, while the solid curve is the ratio of the transfer functions using the TST and the PRO models. The transfer function for each site alone is relative to an equivalent bedrock outcrop consisting of the lowest layer in the velocity model for each site. The ratio of the TST and PRO transfer functions is the proper quantity to use in comparing observed and theoretical ratios, because the observed motions at PRO used in determining the TST/PRO ratio were not corrected for the site response at PRO and thus include that response. The results in Fig. 28 clearly show the importance of including the site response of the reference site, at least at higher frequencies (but still frequencies of concern in earthquake engineering). At low frequencies (less than about 2 Hz), the PRO transfer function approaches unity and thus has only a small influence on the TST/PRO ratio. The solid gray curve in Fig. 28 is similar to the theoretical site response published in Raptakis *et al.* [1998], but the response at PRO was not used in computing the theoretical response [D. Raptakis, *personal communication*]! That must mean that the attenuation in the model for TST was modified to produce a fit to the observed ratio — the Q values cannot be as high as those in the model provided to me. Regardless of the reason for the differences in the theoretical calculations, both my calculations and those shown in Raptakis *et al.* [1998] show the observed ratio to be generally underpredicted by the theory. This is where the two plots come in. If plotted using a linear scale for the ordinate, the underprediction near the peak response (at about 0.8 Hz) seems quite large, whereas that at higher frequencies seems less important. In terms of ratios of observed to predicted site response, however, the mismatch at the fundamental mode resonant peak (a factor of 1.6) is significantly smaller than that at higher frequencies (as much as a factor of 3.5, with a factor of 2 being common). The ratios of observed to theory are best judged from the plot using logarithmic scaling.

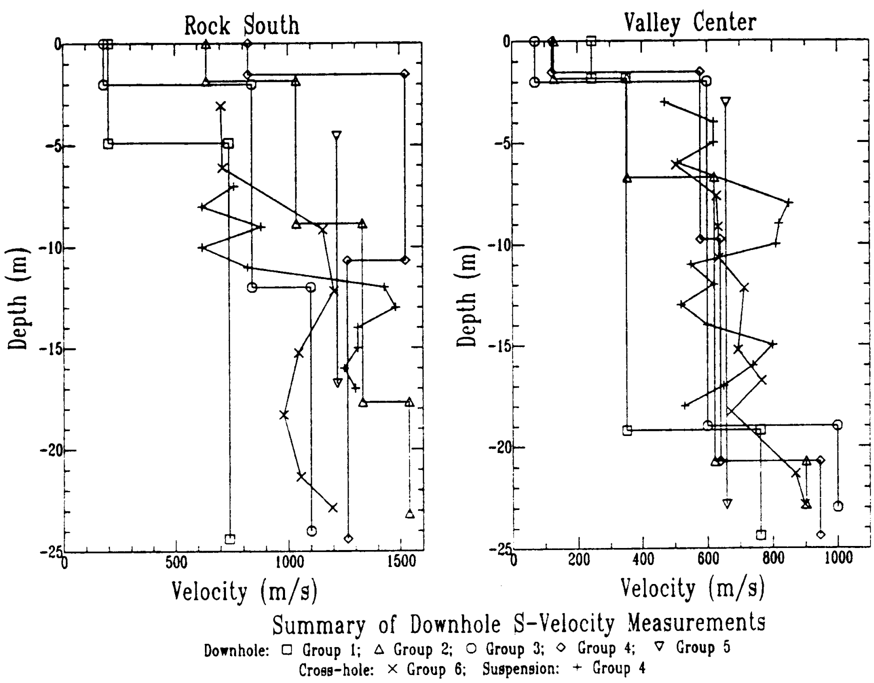

Fig. 29. Velocity profiles measured by different groups, using downhole, crosshole, and suspension logging methods, at Turkey Flat, California, as part of the weak-motion prediction study [modified from Real and Cramer, 1992].

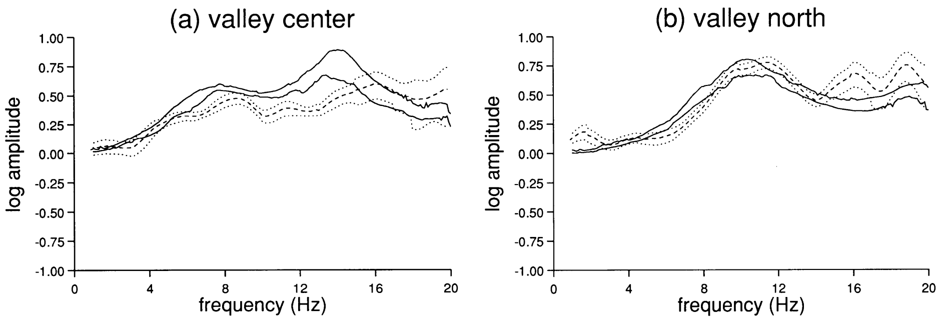

Fig. 30. Spectral ratios for valley centre and valley north relative to the south rock site. Shown are observed mean plus and minus one standard deviation (dashed) and the first and third quartiles of the blind predictions (solid) [modified from Field and Jacob, 1993, based on Real and Cramer, 1992].

4.2.1.4. *Blind weak-motion prediction experiment: Turkey Flat, California*

The comparison of observed and theory in the Euroseistest example was "blind" in the sense that the models were obtained independently of the observations and were not modified to fit the observations. Blind predictions have also been made in two intensive studies involving many groups. The first was conducted in the vicinity of a small valley (Turkey Flat) near Parkfield, California. Many groups were invited to determine geotechnical models from a number of geophysical and geotechnical measurements made at the site, and a consensus geotechnical model was then used in making predictions of motions at several soil sites, given the motion at a rock site south of the valley. All motions were weak motions. Figure 29 shows the range of velocity models determined by the different groups. There is a surprising amount of uncertainty, particularly for the rock site. The results of the predictions are summarised in Fig. 30, which compares the observed motion from 33 weak-motion events at two soil sites (with the standard deviation of the observations) with the first and third quartiles of the predicted motions. While the differences may not seem large as plotted, in fact the mismatch exceeds a factor of 1.5 for a wide frequency range, particularly for the valley center site. Field and Jacob [1993] summarise it best:

> "However, the theoretical predictions are not very precise.... 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.... 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."

4.2.1.5. *Site-specific response predictions for many sites in California*

In a comprehensive study, Baturay and Stewart [2003] made site response predictions at 68 sites in California for which shear-wave velocity models were available from co-located or nearby borehole measurements; they used an equivalent-linear model to approximate nonlinear wave propagation effects. The site response is relative to ground motion on firm rocks, as given by a modification of the equations of Abrahamson and Silva [1997]. Directivity effects and event-specific corrections were included in the predicted motions. (The event-specific corrections account for the propensity of all motions from any given earthquake to be high or low relative to the motions averaged over many events of the same magnitude.) The authors considered predictions based on empirical regression equations using only a rock/soil classification, these same equations with site effects according to NEHRP classes, and the site-specific predictions based on ground response analyses, just described. The authors showed site-specific predictions at three sites, and the observed spectra were poorly predicted at those sites. Considering all sites, the authors concluded "... ground response analyses are beneficial for [response spectral] predictions at soft sites [e.g. NEHRP class E], but generally provide no identifiable benefit for typical stiff soil or rock sites". They found that the site-specific response calculations could not remove systematic differences between observed and predicted spectra and did not significantly reduce the variance in the scatter, compared to predictions based on the empirically-based regression equations.

4.2.2. *Single sites, single earthquakes*

For critical facilities, site-specific, earthquake-specific predictions are sometimes made in the hope that more reliable estimates of ground motion will be obtained than by evaluating ground-motion prediction equations for a generic site condition. A number of such predictions have been made (often only available in engineering consulting reports), but I found relatively few comparing observed site response with predicted site response, particularly blind predictions and cases where I am certain that the velocity models were not adjusted to fit the data. I discuss here two of those studies.

4.2.2.1. *Blind strong-motion prediction experiment: Ashigara Valley, Japan*

The only example of a blind site-specific, earthquake-specific prediction experiment that I could find was conducted in the Ashigara Valley of Japan. And this blind experiment was not really the same as many applied cases, because observed motion was available at a rock site near the soil sites at which the motions were predicted. In applications, usually the reference motion is specified from empirically-based prediction equations or from simulated motions, thus introducing another element of uncertainty in the predictions.

Like the Turkey Flat experiment, many groups made predictions of the motion at soil sites, given motion at a rock site and the geotechnical models at the sites.

The individual predictions are shown in Fig. 31, with the observed motion barely discernable as a thicker line buried in the mass of predicted motions. The variability in the predicted motions is very large. The results are summarised in Fig. 32, which compares the observed motion and the first, second, and third quartiles of the predicted motion. As in the Turkey Flat results, the differences do not seem large until looked at in detail. The differences vary systematically with period and exceed a factor of 1.5 in many places (as Midorikawa, 1992, delicately puts it: "Although overall shape of predicted response spectra tend to reproduce observed ones, discrepancy between predicted spectral ratios and observed ones is not negligible"). It is not comforting that such large differences exist, given the effort that went into defining

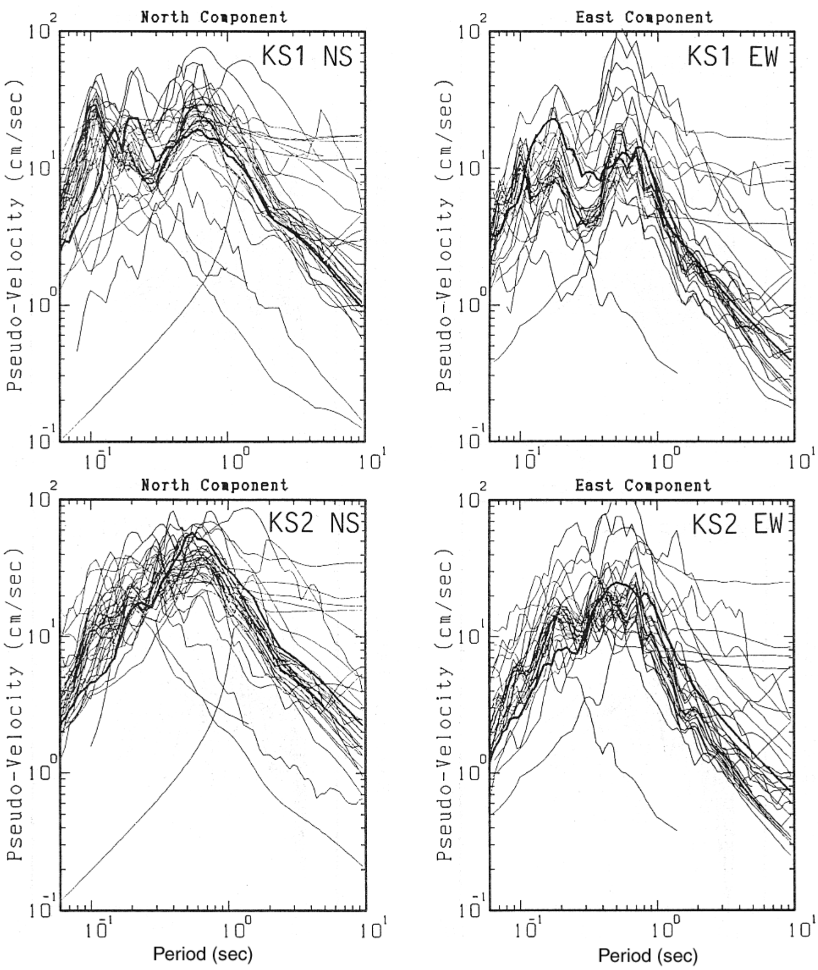

Fig. 31. Response spectra for two soil sites from the Ashigara Valley strong-motion prediction experiment. The thin lines are predictions from many teams; the thick lines (barely discernable) are observations [modified from Midorikawa, 1992].

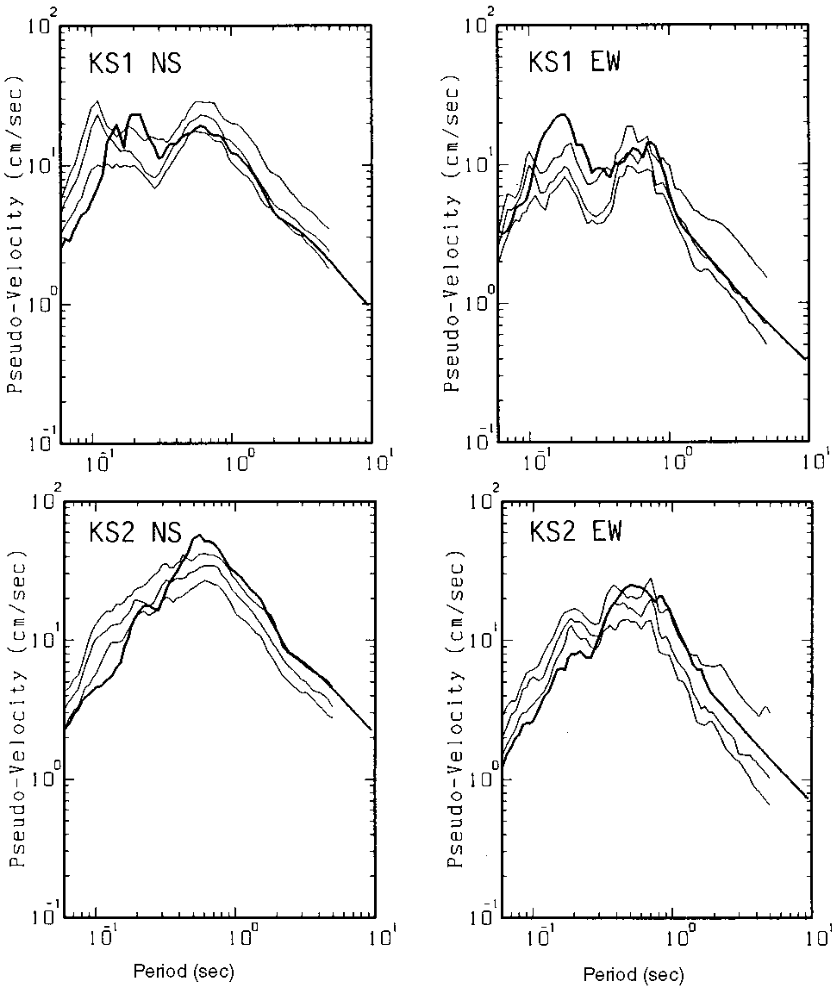

Fig. 32. Response spectra for a soil site from the Ashigara Valley prediction experiment. The thin lines are the first, middle, and third quartiles of the predictions; the thick line is the mean of the observed response spectra [modified from Midorikawa, 1992].

the geotechnical properties of the sites, including three dimensional characteristics. Scherbaum *et al.* [1994] revisited the predictions, refining the geotechnical model to better match the observed motions (a procedure not usually available in practice). But even with the refined model, the predictions were systematically different than the observations over a wide range of frequencies.

4.2.2.2. *Predictions of motions observed at two sites during the 1994 Northridge earthquake*

The final examples come from Chang *et al.* [1996] who compared response spectra at two free-field sites from the 1994 Northridge, California, earthquake with

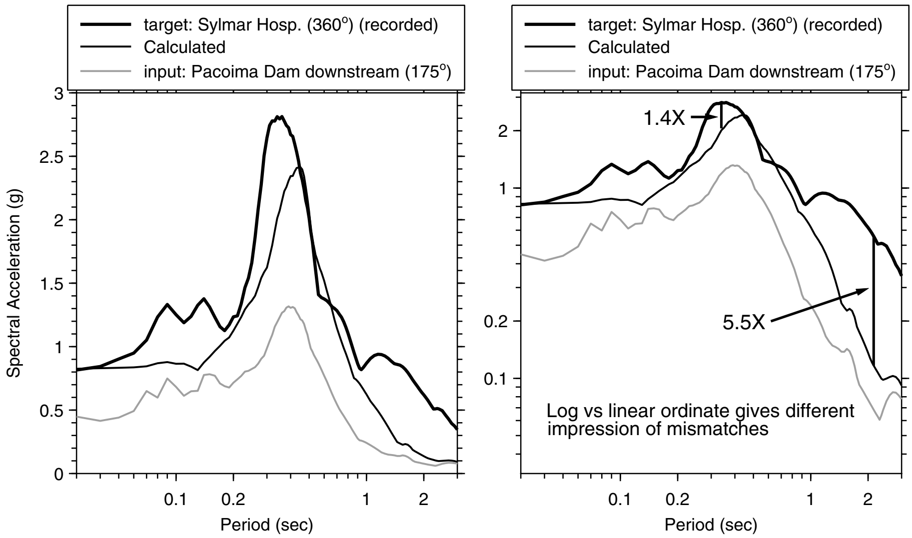

Fig. 33. Observed and calculated horizontal-component response spectra at Sylmar Hospital free-field station, 1994 Northridge mainshock, plotted using linear and log scales for the ordinate. The input for the site response was motion recorded at the Pacoima Dam downstream station, 4.3 km from the Sylmar Hospital station. The notation "1.4X" and "5.5X" denotes the multiplicative factors separating the curves [modified from Chang *et al.*, 1996].

predictions made using several methods (linear, equivalent linear, and fully non-linear calculations) and a variety of input motions. Velocity models were available for both sites. Figure 33 shows the observed and predicted spectra at the Sylmar Hospital free-field site, using as input the recording at the Pacoima downstream site (4.3 km from the Sylmar site). As before, I have plotted the results using both linear and log scaling to illustrate the different perceptions of the comparison resulting from the two displays. The apparently large difference near the peak in the linear plot corresponds to a factor of only 1.4, whereas the seemingly smaller differences at longer periods exceed a factor of 5. Not all structures will have their resonant period near that of the peak in the spectra for this recording, and the factor of 5 mismatch could represent a significant error in specification of design motions for some structures. The second example is the motion at the Hollywood Storage Building free-field site from the Northridge earthquake (Fig. 34). In this case, a number of different input motions were used, including observed motions at two sites 4.8 km and 9.2 km from the Hollywood Storage Building (upper left) and synthetic seismograms using a model of the source and path derived from a number of rock-like sites that recorded the earthquake (this type of reference motion has also been used by Atkinson and Cassidy, 2000, in their study of site response in the Fraser River delta, Canada). Chang *et al.* [1996] used several models for the velocities beneath the site; the results for the original velocity model for the site and for a velocity model with 20% higher values are shown in the lower part of

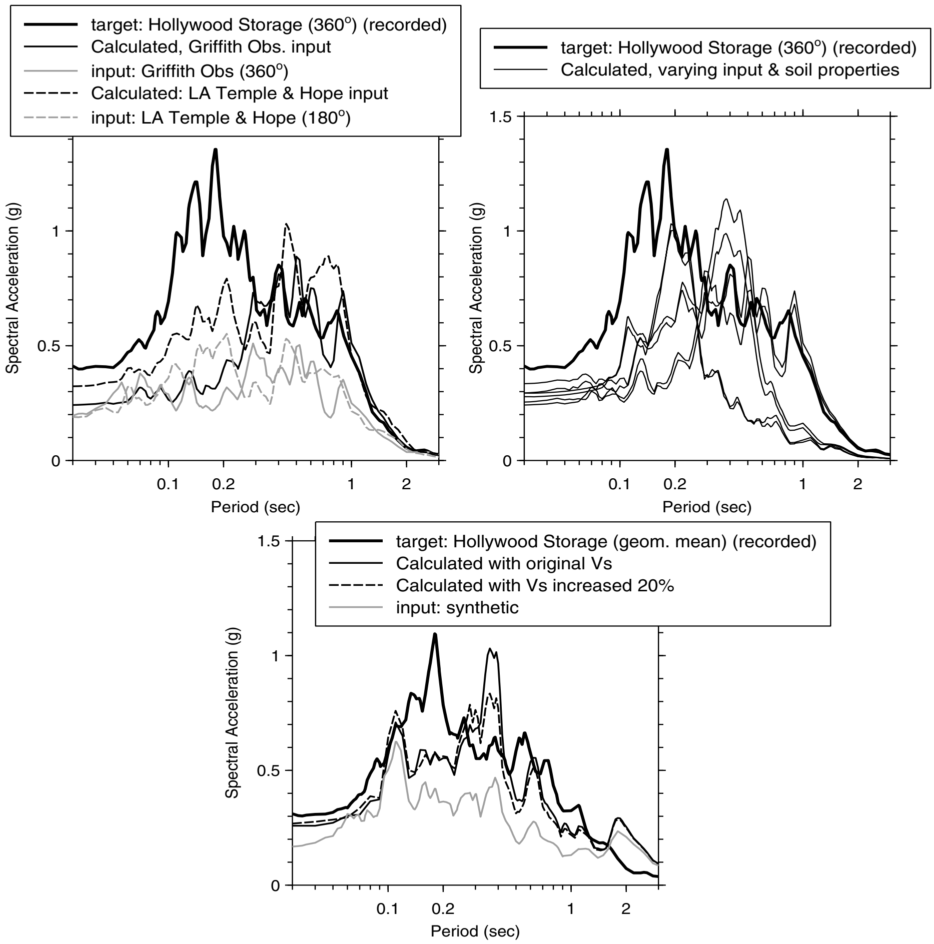

Fig. 34. Observed and calculated horizontal-component response spectra at Hollywood Storage Building free-field station, 1994 Northridge mainshock, for a variety of input motions (a single record, multiple records, and synthetic motions based on a model fit to ground motions at other, more rock-like, stations). The calculated spectra are from accelerations that used a linear approximation of nonlinear wave propagation (the so-called "equivalent-linear" method) to account for site response. Griffith Observatory and LA Temple are 4.8 km and 9.2 km from the Hollywood Storage Building, respectively [modified from Chang *et al.*, 1996].

Fig. 34. Finally, the upper right graph of Fig. 34 shows the results from a number of different inputs and for variations in the soil properties. None of the predictions come close to matching the observed peak in the response spectrum around 0.2 sec.

5. Discussion and Conclusions

Using observed ground motions, I have shown that there is a large amount of variability in ground motions, both site-to-site variability for a given earthquake and earthquake-to-earthquake variability for a given site. These variations imply that site-specific, earthquake-specific predictions of site response, either empirical or theoretical, cannot be made with much accuracy, at least currently. A blind prediction experiment supports this conclusion. If the engineering need is for site-specific, earthquake-specific ground motion (e.g. if a time series is needed for structural analysis), the potential for a more physically realistic estimate of ground motion for a site-specific prediction must be balanced against the possibly increased uncertainty in the estimate. The alternative is a mean site response for a class of sites and for many earthquakes, which can probably be determined with as much accuracy as desired, given enough sites and enough earthquakes. But again the scatter of individual site responses will be large.

To come full circle, let's go back to the task of estimating the ground motions at the I10–La Cienega bridge collapse site. Given what I have shown, it is clear that the input beneath I10 may not be the same as that beneath SAT. I think that they are the same is the best assumption if forced to choose only a single input

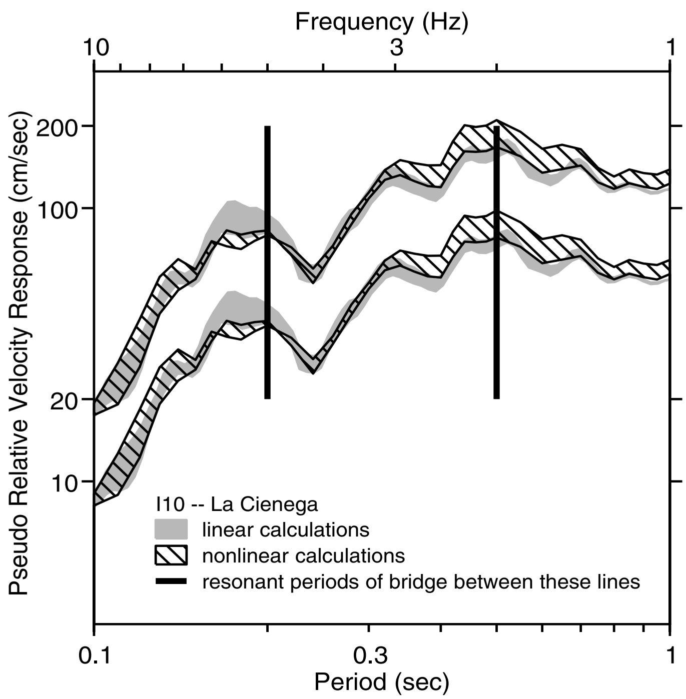

Fig. 35. 5%-damped pseudo relative response spectra for ground motions at the I10 site derived using both linear wave propagation and the linear approximation of nonlinear wave propagation for the site response (the so-called "equivalent-linear method"), showing a range of estimates obtained by considering plus and minus one standard deviation of the amplitude of the input motion beneath I10–La Cienega derived from the Saturn Street School recording. Within the context of this model and assumptions, the upper and lower sets of curves span the range within which there is roughly a 68% chance that the actual ground motion would be included. See the caption to Fig. 8 for other details [from Boore *et al.*, 2003].

motion, but the spatial variability in ground motions should be considered. This leads to a range of estimated motions at the collapse site, as shown in Fig. 35. So site response predictions are inherently probabilistic in nature, and some indication of the probability distribution should be given in all estimates of site response.

It is easy to be pessimistic about the chance that this scatter can be reduced. But nature has not rescinded the laws of wave propagation, and site response potentially should be predictable with sufficient accuracy to be useful for engineering purposes. There is great research potential here, but progress will require detailed studies of geologic structures and material properties at scales of kilometres, not just tenths of a kilometre as is currently done. This may require rethinking the traditional source-path-site trichotomy, blending path and site effects together.

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References

Abrahamson, N. A. and Silva W. J. [1997] "Empirical response spectral attenuation relations for shallow crustal earthquakes," *Seism. Res. Lett.* **68**, 94–127.

Aki, K. (1988). Local site effects on strong ground motion, in *Earthquake Engineering and Soil Dynamics II, Proc. Am. Soc. Civil Eng. Geotech. Eng. Div. Specialty Conf.*, June 27–30, 1988, Park City, Utah, pp. 103–155.

Atkinson, G. M. and Cassidy J. F. [2000] "Integrated use of seismograph and strong-motion data to determine soil amplification: Response of the Fraser River Delta to the Duvall and Georgia Strait earthquakes," *Bull. Seism. Soc. Am.* **90**, 1028–1040.

Baher, S., Davis, P. M. and Fuis G. [2002] "Separation of site effects and structural focusing in Santa Monica, California: A study of high-frequency weak motions from earthquakes and blasts recorded during the Los Angeles Region Seismic Experiment," *Bull. Seism. Soc. Am.* **92**, 3134–3151.

Bard, P.-Y. and Riepl-Thomas J. [2000] "Wave propagation in complex geological structures and their effects on strong ground motion," in *Wave Motion in Earthquake Engineering*, E. Kausel and G. Manolis (Editors), WIT Press, Southampton, Great Britain, pp. 37–95.

Baturay, M. B. and Stewart J. P. [2003] "Uncertainty and bias in ground-motion estimates from ground response analyses," *Bull. Seism. Soc. Am.* **93**, 2025–2042.

Boore, D. M. [1997] "Estimates of average spectral amplitudes at FOAKE sites, Appendix C in Bandyopadhyay, K. K., Kana, D. D., Kennedy, R. P. and Schiff, A. J. "An evaluation of methodology for seismic qualification of equipment, cable trays and ducts in ALWR plants by use of experience data," NUREG/CR-6464 and BNL-NUREG-52500, C-1–C-69.

Boore, D. M. [1999] "Basin waves on a seafloor recording of the 1990 Upland, California, earthquake: Implications for ground motions from a larger earthquake," *Bull. Seism. Soc. Am.* **89**, 317–324.

Boore, D. M. [2004] "Ground motion in Anchorage, Alaska, from the 2002 Denali fault earthquake: Site response and displacement pulses," *Bull. Seism. Soc. Am.* **94**, in press.

Boore, D. M. and Joyner, W. B. [1997] "Site amplifications for generic rock sites," *Bull. Seism. Soc. Am.* **87**, 327–341.

Boore, D. M., Joyner, W. B. and Fumal, T. E. [1997] "Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work," *Seism. Res. Lett.* **68**, 128–153.

Boore, D. M., Stephens, C. D. and Joyner, W. B. [2002] "Comments on baseline correction of digital strong-motion data: Examples from the 1999 Hector Mine, California, earthquake," *Bull. Seism. Soc. Am.* **92**, 1543–1560.

Boore, D. M., Gibbs, J. F., Joyner, W. B., Tinsley, J. C. and Ponti, D. J. [2003] "Estimated ground motion from the 1994 Northridge, California, earthquake at the site of the interstate 10 and La Cienega Boulevard bridge collapse, west Los Angeles, California," *Bull. Seism. Soc. Am.* **93**, 2737–2751.

Brown, L. T., Boore, D. M. and Stokoe, K. H. II [2002] Comparison of shear-wave slowness profiles at ten strong-motion sites from noninvasive SASW measurements and measurements made in boreholes, *Bull. Seism. Soc. Am.* **92**, 3116–3133.

Chang, S. W., Bray, J. D. and Seed, R. B. [1996] "Engineering implications of ground motions from the Northridge earthquake," *Bull. Seism. Soc. Am.* **86**, S270–S288.

Chávez-Garcia F., Raptakis, D. G., Makra, K. A. and Pitilakis, K. D. [2000] "Site effects at Euroseistest-II. Results from 2D numerical modelling and comparison with observations," *Soil Dyn. Earthq. Eng.* **19**, 23–39.

Chávez-Garcia F., Raptakis, D., Makra, K. and Pitilakis, K. [2002] "The importance of the reference station in modelling site effects up to larger frequencies. The case of Euroseistest," *Proc. 12th European Conf. on Earthquake Engineering*, (CDROM — paper 589), Elsevier Science, Ltd.

Davis, P. M., Rubenstein, J., Liu, K. H., Gao, S. S. and Knopoff, L. [2000] "Northridge earthquake damage caused by geologic focusing of seismic waves," *Science* **289**, 1746–1750.

Dimitriu, P. P., Papaioannou, Ch. A. and Theodulidis, N. P. [1998] "EURO-SEISTEST strong-motion array near Thessaloniki, northern Greece: A study of site effects," *Bull. Seism. Soc. Am.* **88**, 862–873.

Dutta, U., Martirosyan, A., Biswas, N., Papageorgiou, A. and Combellick, R. [2001] "Estimation of *S*-wave site response in Anchorage, Alaska, from weak-motion data using generalized inversion method," *Bull. Seism. Soc. Am.* **91** 335–346.

Field, E. H. [2001] "Earthquake ground-motion amplification in southern California," *US Geol. Surv. Open-File Rept. 01-164* http://geopubs.wr.usgs.gov/open-file/of01-164/).

Field, E. H. and Jacobm, K. H. [1993] "Monte-Carlo simulation of the theoretical site response variability at Turkey Flat, California, given the uncertainty in the geotechnically derived input parameters," *Earthquake Spectra* **9**, 669–701.

Field, E. H., Jacob, K. H. and Hough, S. E. [1992] "Earthquake site response estimation: A weak-motion case study," *Bull. Seism. Soc. Am.* **82**, 2283–2307.

Finn, W. D. L., Zhai, E., Thavaraj, T., Hao, X.-S. and Ventura, C. E. [2003] "1D and 2D analyses of weak motion data in Fraser Delta from 1966 [sic; should be "1996"] Duvall earthquake," *Soil Dyn. Earthq. Eng.* **23**, 323–329.

Gao, S., Liu, H., Davis, P. M. and Knopoff, L. [1996] "Localized amplification of seismic waves and correlation with damage due to the Northridge earthquake," *Bull. Seism. Soc. Am.* **86**, S209–S230.

Jarpe, S. P., Cramer, C. H., Tucker, B. E. and Shakal, A. F. [1988] "A comparison of observations of ground response to weak and strong ground motion at Coalinga, California," *Bull. Seism. Soc. Am.* **78**, 421–435.

Joyner, W. B. [2000] "Strong motion from surface waves in deep sedimentary basins," *Bull. Seism. Soc. Am.* **90**, S95–S112.

Joyner, W. B. and Boore, D. M. [1981] "Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake," *Bull. Seism. Soc. Am.* **71**, 2011–2038.

Kawase, H. [2003] "Site effects on strong ground motions," in *International Handbook of Earthquake and Engineering Seismology*, (edited by W. H. K. Lee, Kanamori, H., Jennings, P. C. and Kisslinger, C.), Chapter 61, Academic Press, pp. 1013–1030.

Makra, K., Raptakis, D., Chávez-Garcia, F. J. and Pitilakis, K. [2001] "Site effects and design provisions: The case of EUROSEISTEST," *Pure and Applied Geophy.* **158**, 2349–2367.

Martirosyan, A., Dutta, U., Biswas, N., Papageorgiou, A. and Combellick, R. [2002] "Determination of site response in Anchorage, Alaska, on the basis of spectral ratio methods," *Earthquake Spectra* **18**, 85–104.

Meremonte, M., Frankel, A., Cranswick, E., Carver, D. and Worley, D. [1996] "Urban seismology — Northridge aftershocks recorded by multiscale arrays of portable digital seismographs," *Bull. Seism. Soc. Am.* **86**, 1350–1363.

Midorikawa, S. [1992] "A statistical analysis of submitted predictions for the Ashigara Valley blind prediction test," *Proc. Int. Symposium on the Effects of Surface Geology on Seismic Motion*, March 25–27, 1992, Odawara, Japan, pub. by Assoc. for Earthquake Disaster Prevention, Tokyo, Japan, **II**, pp. 65–77.

Milne, J. [1898] *Seismology*, Kegan Paul, Trench, Trübner, & Co., London, 1st ed., pp. 320.

Nath, S. K., Biswas, N. N., Dravinski, M. and Papageorgiou, A. S. [2002] "Determination of *S*-wave site response in Anchorage, Alaska in the 1–9 Hz frequency band," *Pure and Applied Geophy.* **159**, 2673–2698.

Olsen, K. B. [2000] "Site amplification in the Los Angeles basin from three-dimensional modeling of ground motion," *Bull. Seism. Soc. Am.* **90**, S77-S94.

Raptakis, D., Theodulidis, N. and Pitilakis, K. [1998] "Data analysis of the Euroseistest strong motion array in Volvi (Greece): Standard and horizontal-to-vertical spectral ratio techniques," *Earthquake Spectra* **14**, 203–224.

Raptakis, D. G., Chávez-Garcia, F., Makra, K. A. and Pitilakis, K. D. [2000] "Site effects at Euroseistest-I. 2D determination of the valley structure and confrontation of the observations with 1D analysis," *Soil Dyn. Earthq.* **19**, 1–22.

Real, C. R. and Cramer, C. H. [1992] "Site characterization and standard geotechnical model for the Turkey Flat, USA site effects test area near Parkfield, California," *Proc. Int. Symposium on the Effects of Surface Geology on Seismic Motion*, March 25–27, 1992, Odawara, Japan, pub. by Assoc. for Earthquake Disaster Prevention, Tokyo, Japan, **II**, pp. 9–14.

Riepl, J., Bard, P.-Y., Hatzfeld, D., Papaioannou, C. and Nechstein, S. [1998] "Detailed evaluation of site-response estimation methods across and along the sedimentary valley of Volvi (EURO-SEISTEST)," *Bull. Seism. Soc. Am.* **88**, 488–502.

Scherbaum, F., Palme, C. and Langer, H. [1994] "Model parameter optimization for site-dependent simulation of ground motion by simulated annealing — reevaluation of the Ashigara valley prediction experiment," *Natural Hazards* **10**, 275–296.

Steidl, J. H. [1993] "Variation of site response at the UCSB dense array of portable accelerometers," *Earthquake Spectra* **9**, 289–302.

Steidl, J. H., Tumarkin, A. G. and Archuleta, R. J. [1996] "What is a reference site?" *Bull. Seism. Soc. Am.* **86**, 1733–1748.

Steidl, J. H., Tumarkin, A. G. and Archuleta, R. J. [1997] "Erratum for "What is a reference site?" *Bull. Seism. Soc. Am.* **87**, 516.

Stewart, J. P., Liu, A. H. and Choi, Y. [2003] "Amplification factors for spectral acceleration in tectonically active regions," *Bull. Seism. Soc. Am.* **93**, 332–352.

Wills, C. J., Petersen, M., Bryant, W. A., Reichle, M., Saucedo, G. J., Tan, S., Taylor, G. and Treiman, J. [2000] "A site-conditions map for California based on geology and shear-wave velocity," *Bull. Seism. Soc. Am.* **90**, S187–S208.

Yu, J. and Haines, J. [2003] "The choice of reference sites for seismic ground amplification analyses: Case study at Parkway, New Zealand," *Bull. Seism. Soc. Am.* **93**, 713–723.