Effects of earthquake magnitude and source distance on the response spectral amplification ratios of soft-soil sites

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ABSTRACT: We used a suite of rock site records from subduction slab earthquakes to evaluate the response spectral amplification ratio for soil sites using elastic and nonlinear modelling. The records are well distributed with respect to magnitude and source distance. Because a response spectrum is the peak of structural response to the excitation over a wide frequency range, response spectral amplification ratios of a soil site subjected two rock site records with an identical response spectral value at a given spectral period are not usually equal. Scatter of the amplification ratios is found to be considerable. Analyses of the scatter reveal that response spectral amplification ratios for an elastic soil site depend on both the earthquake magnitude and the source distance. It is also found that, at periods much shorter than or much longer than the site natural periods of the soil sites modelled as elastic, the amplification ratios decrease with increasing excitation, as does the scatter. The response spectral amplification ratios of a simple 2-dimensional nonlinear soil basin have similar characteristics to those of elastic sites. These findings have potential impact in establishing design spectra for soft soil sites using strong motion attenuation models or dynamic modelling.

1 INTRODUCTION

Ground response in earthquakes is often amplified by soft soil layers and the amplification can cause severe structural damage, such as in the cases of Mexico City and the Marina District, San Francisco. Much research has been done in assessing soil amplification, ranging from elastic response of 2- or 3-dimensional soil basins, with emphasis on the long duration of ground shaking, to surface waves induced by the basins, and the amplification of peak ground response. Nonlinear response of 1- or 2-dimentional soil sites has also been considered.

Amplification effects can be characterised by Fourier spectral ratios and response spectral ratios. Fourier spectral ratios, between the soil surface response and the excitation ground motion obtained from rock sites, are often used to characterize the elastic response of a soil site. The Fourier spectral amplification ratio for an elastic site is a function of the soil material properties and soil depth. The Fourier spectral ratios can be used to assess the dominant periods of the site and the extent of amplification at low levels of ground shaking. Fourier spectral ratios are not usually used to determine the amplification of nonlinear soil sites because both the dominant period of the site and the spectral ratios change significantly with the severity of ground shaking. Fourier spectral ratios are seldom used in engineering applications.

The response spectrum for a given ground motion is the peak response of single-degree-of-freedom structures as a function of their fundamental period and damping, and is therefore a design parameter for a given structure. Response spectral ratios are commonly used in assessing the amplification level of a particular site, or a group of soil sites from the same soil class in an attenuation model for response spectra. Response spectral ratios for soil sites are used directly in the design of engineering structures through site-class-dependent design spectra.

While a Fourier spectrum at a given frequency is the amplitude of the ground motion at this particular frequency, the response spectrum at a given spectral period is the structural response due to ground motion with energy from all periods. At a particular spectral period, the response spectra of two records that have identical Fourier spectral amplitudes at that period but have different values at the other periods can be significantly different. As a result, the scatter of response spectral amplification ratios at a given spectral period is moderately large (see Figure 3) while the Fourier spectral ratio is unique and independent of excitation spectra for an elastic site. The scatter of the response spectral ratios is largely a result of the different response spectral shapes of the excitation ground motion. Figure 1 shows the normalized pseudo-velocity spectra derived from an attenuation model by Takahashi et al (2004) for subduction slab events. Note that the spectral shape varies significantly with both magnitude and source distance.

In the present study, we investigate the effects of earthquake magnitude and source distance on the spectral amplification ratios of simple 1-dimensional soil layers on bedrock and a simple 2-dimensional nonlinear soft-soil basin.

2 STRONG MOTION DATA SET

To systematically investigate the possible dependence of response spectral amplification ratios on earthquake magnitude and source distance, a large number of records from rock or stiff soil (classified as rock in attenuation models for response spectra for Japan, such as the Takahashi et al. 2004 model) is required. The records should also be well distributed with respect to magnitude and source distance as well as of a consistent source type (i.e. crustal, subduction interface or slab earthquakes). In the present study, we selected strong motion records from subduction slab events in Japan. The reason for using Japanese data is that all records have been consistently processed and hypocenters for all events have been relocated by special studies (Takahashi et al 2004). Source distances for all large events are the shortest distances from the site to a known rupture plane, and hypocentral distances for smaller events. The magnitude-distance distribution of the data set is shown in Figure 2, with the data well distributed with respect to magnitude within a source distance of 180km. The data from Mw = 6.5 or larger events are well distributed across all source distance ranges. A subset of the data was used for nonlinear 2-D basin analyses. These data are all from SC I sites, i.e. for sites that have a dominant period less than or equal to 0.2s, with a large number of these stations having a thin layer of stiff soil overlying weathered bed rock. The corner frequency of the high-pass filter (used to eliminate low-frequency noise) is less than 0.25 Hz for majority of the records, so the comparison of response spectral ratios up to 4s period should not be severely affected by the high-pass filter.

3 RESPONSE SPECTRAL RATIO OF SINGLE LAYER ELASTIC SOIL SITES

The first group of sites are 1-D elastic soil sites with assumed natural periods of 0.5, 0.75, 1.0, 1.5 and 2.0s. Sites with long natural periods such as 1.5 and 2.0s are not common and these sites are used as comparison only. Material damping ratios of 5, 10, 15 and 20% of critical were used together with an equivalent damping ratio of 5% from energy leakage back to the underlying bedrock (Zhao 1996). The soil surface response was calculated from a frequency-domain analysis. Response spectral ratios of the soil-site surface motions with respect to the excitation ground motion were calculated (Figures 3 and 4). The geometric mean of spectral ratios, R_{mean}, and the residuals $\log_e(R_{SA}/ R_{mean})$, where R_{SA} is the spectral ratio for a particular record, were calculated for spectral periods of 0.0, 0.1, 0.2, 0.3, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0s. To investigate the possible dependence of spectral ratios on magnitude and source distance, these residuals are plotted against magnitude and source distance. If spectral ratios for a particular site at a particular period are independent of magnitude and source distance, the slope of a straight line fitted to the residuals should be close to zero (Figures 5 and 6). A linear function of magnitude and source distance was fitted to the residuals. The coefficients for the magnitude and source-distance terms of the fitted functions are also used to gauge the effect of the magnitude and source distance on the response spectral ratios.

Figures 3 and 4 show the response spectral ratio for peak ground acceleration (PGA) and 3.0s spectral period of a soil site with a natural period of 0.75s and a damping ratio of 5% for both material and radiation damping. The amplification ratios show a decrease with increasing excitation spectra. Note also that the scatter of the amplification ratio has an apparent reduction with increasing excitation spectra. The reduction of amplification ratio is moderate, from about 1.65 at 0.01g input ground motion to about 1.3 at a 0.7g excitation PGA.

The rate of reduction in amplification ratios with increasing excitation can be measured by parameter α which relates the amplification ratio to the excitation spectra by $R_{SA} = \chi S_{rock}^{\alpha}$ where S_{rock} is the excitation spectral acceleration. Parameter χ is a scale factor that can be eliminated by a suitable parameter comparison, see Equation 1. Parameter α is the average slope of the relationship between the amplification ratio and excitation spectral acceleration, with both plotted on logarithmic scales. For this site the reduction rate for PGA and long periods are similar while α is relatively small for other periods. Intuitively, amplification ratios should be independent of excitation spectra for a linear elastic system and the reduction must be a result of source and path parameters. To assess the effect of excitation-level dependent amplification ratios, an excitation bias factor μ is used, defined by,

$$\mu = \frac{R_{S2}}{R_{S1}} = \left(\frac{S_{Rock2}}{S_{Rock1}}\right)^{\alpha} \qquad (1)$$

where S denotes the excitation spectra. When μ is less than 1.0, the spectral ratio at an excitation spectrum S_{rock1} would over-estimate the amplification ratio at an excitation spectral value S_{rock2}.

Figures 5 and 6 show the distribution of residuals with respect to magnitude and source distance at 3s period for a soil site with a natural period of 0.75s and damping ratio of 5% for both material and radiation damping. The residuals are clearly biased with magnitude and also with distance at least in the 0-180 km range. Figure 5 suggests that the average amplification ratio from all data will under-estimate the amplification ratios from small magnitude events and over-estimate those from large events. The average amplification ratios from all data will under-estimate the amplification ratios of records with short source distance and over-estimate the amplification ratios of records with large distance, as shown in Figure 6. The distribution of residuals with focal depth is not biased even though attenuation models for subduction zone events suggest that short period spectra increase with increasing focal depth.

To examine the effects of magnitude and source distance, a linear function of magnitude and source distance is fitted to the residuals and the coefficients γ for magnitude and λ for source distance are used to represent the extent of the bias. A meaningful presentation of γ and λ should be the direct effect on the spectral ratio over a magnitude and a source distance range and they can be expressed as

$$\varphi = \frac{R_{M2}}{R_{M1}} = e^{\gamma(M2-M1)} \qquad (2a) \qquad\qquad \psi = \frac{R_{D2}}{R_{D1}} = e^{\lambda(D2-D1)} \qquad (2b)$$

where R stands for response spectral ratio between the soil surface and excitation ground motions, M stands for magnitude and D for source distance. Parameters φ and ψ are the relative difference of average amplification ratios at two magnitudes and two source distances, and are referred to as magnitude and source distance bias factors, respectively. Note that λ was obtained from those data within a source distance of 180km and γ was obtained from all records.

Figure 7 shows the excitation bias factor $R_{S=1.0}/R_{S=0.02}$ for five sites. Note that values for PGA are plotted at 0.02s period for all comparisons. The unit of the spectral value is not important and S=1.0 and S=0.02 indicates a factor of 50 in the magnitude of the excitation. At the natural periods of all sites, the amplification ratios are either independent of excitation spectra or increase with increasing excitation spectra while the excitation bias factors of all sites at the periods much less than their site natural periods are less than 1.0. . For example, for a very soft soil site with a natural period of 2.0s, the PGA amplification ratio derived from rock site records with an average PGA=1.0g will be just of 70% the PGA amplification ratio at an excitation PGA=0.02g. At the natural periods of a long period sites such as a 2.0s site, the amplification ratios estimated at 0.1g average excitation spectra will be just 1.3 times the amplification ratios estimated from 0.002g average excitation spectra. These results clearly suggest that using weak motion records to estimate response spectral ratios of strong motion records is not appropriate.

Figure 8 shows the magnitude bias factor $R_{Mw=7}/R_{Mw=5}$. For all sites the magnitude bias factor gently decreases from 1.1-1.3 for PGA to about 0.95-1.1 at 0.2s. The magnitude bias factors of the three sites with a natural period of 0.5, 0.75 and 1.0s decrease with increasing period from 1.1, at the period band of 0.2-0.8s, to a value of 0.7-0.8 at 4.0s period. Note that the magnitude bias changes from positive at periods less than site natural periods to negative at periods considerably longer than the site natural periods for sites with a natural periods of 0.5, 0.75 and 1.0s. For the 1.0s site, the PGA amplification ratio estimated by using records from magnitude 5 events on average will under-estimate the spectral amplification ratio from magnitude 7 events by as much as 20%, while at 4.0s period, the amplification ratio estimated by using records from magnitude 5 events on average will over-estimate the spectral amplification ratio from magnitude 7 events by as much as 30%. For 2 sites with a natural period of 1.5 and 2.0s, the magnitude bias factors over 1.0s are considerably larger than those for the other three sites. At 2.5s period for a 2.0s site, the magnitude bias factor is about 1.25, i.e., the spectral ratio estimated from earthquakes with Mw=7 would be on average 1.25 times those estimated from Mw=5.0 events.

Figure 9 shows the distance bias factor $R_{D=180}/R_{D=30.}$ Note that the distance bias changes from positive at shot period to negative at long periods for sites with a natural period of 0.5, 0.75 and 1.0s. The distance bias factor for PGA varies from 1.15 to 1.5, suggesting that PGA amplification ratios calculated from records obtained at 180km distance could be 1.15-1.45 times those from records at a source distance of 30km, on average. At long periods, amplification ratios at 180km source distance can be 0.75-0.8 times those estimated by using records at a source distance of 180km. The distance bias factor at the site natural periods for sites with 1.5 and 2.0s natural period are very large.

Figure 10 shows the standard deviation of the residuals for 5 elastic sites. For all site periods, the standard deviation as a function of spectral period is the largest for 0s (PGA). The PGA standard deviation increases with increasing site natural period, from 0.25 (a factor of about 1.3 in the amplification ratio) for 0.5s site to about 0.4 (a factor of about 1.5) for 2s site. In the period range of 0.2-1.5s all sites have similar standard deviations between 0.14-0.24 in a natural logarithm scale corresponding to factors of about 1.15 to 1.3. Beyond 0.2s period, the standard deviation for all sites increases moderately with increasing spectral periods.

We calculated the standard deviation of amplification ratios and the average excitation spectra in overlapping moving windows of excitation amplitude, with each window having about 100 records. Figures 11 and 12 show the variation in standard deviation with respect to the average excitation spectra in each data window for the 0.5s and 1.0s period sites for 4 spectral periods. The standard deviation is nearly constant at weak excitation. The range of excitation spectra in which the standard deviation is nearly constant is larger for the 1.0s period site than that for the 0.5s period site. The reduction of standard deviation is significant, ranging from 0.2-0.25 at weak motion to about 0.1 at strong ground motion using a natural logarithm scale. These results suggest that the estimate of soft soil site amplification ratios is more reliable for strong ground shaking than for weak motion at long periods. The reduction of standard deviation is negligible for the PGA and short periods.

The soil material damping ratio has little effect on most parameters evaluated here. The standard deviation of the amplification ratios increases slightly with increasing soil material damping.

4 AMPLIFICATION RATIOS OF A SIMPLE 2-DIMENSIONAL BASIN ACCOUNTING FOR NONLINEAR SOIL RESPONSE

For a simple 2-dimensional soil basin with an elastic period of about 0.7s approximately, see Figure 13, nonlinear soil response was evaluated by a finite difference method using the computer code by Joyner (1975) and modified by Larkin (personal communication). The nonlinear soil model used is shown in Figure 14 (an average model of those by Sun et al 1998). An excitation ground motion of vertically propagating SH waves was assumed and true nonlinear analyses were carried out. In this code, viscous damping was not accounted for and the radiation damping was approximately modelled by using dashpots at the boundaries of the soil site model shown in Figure 13. Because there is no viscous damping, weak motion excitation can lead to large amplification ratios that may be unrealistic. Experimental studies show that damping exists at very small shear strain, although the damping source and mechanism may not be certain. The exclusion of weak motion records leads to an ill-distributed dataset that would impair any systematic statistical analysis. Here results for the basin centre are presented without any detailed analysis. To compute the nonlinear response of a 2-D basin is very time consuming and many small records used in the 1-D analysis were not included.

70% records used for the nonlinear site analyses have a PGA of 0.05g or larger, and 55% of the records have a PGA of 0.1g or larger, with the smallest PGA being 0.007g. The records with PGA less than 0.05g were originally excluded from the data set and the examination of the response spectral amplifications suggests that these records can be used to constrain the function fitted to the amplification ratios at the low level of excitation. The results shown in Figures 15-18 include the response spectral amplification ratios for records with a PGA in a range of 0.007-0.05g. In the data set used for the 2-D nonlinear analyses, records from sites with a thin layer of soil were not included. The magnitude-source distribution of the data for 2-D analysis is shown in Figure 2 and the correlation between magnitude and source distance is strong. A number of records were scaled by a factor of two so that amplification ratios can be estimated for very strong ground shaking. Such large records were not available in our dataset. These scaled records were excluded in the plots of residuals with respect to magnitude and distance.

For nonlinear soil site response, amplification ratios should, intuitively, reduce with increasing excitation. Zhao et al (1999) used a function of the excitation spectra fitted to amplification ratios to illustrate the effect of nonlinear soil response. We took the same approach and fitted the amplification ratio to a two-segment curve for each period, as shown in Figures 15 and 16 for 0.2 and 2.0s period, much shorter and much longer than the site natural periods (estimated as about 0.7s) respectively. Note that the decrease of amplification ratios as the excitation increases may be the combined effects from soil nonlinear response and the decreasing amplification with increasing excitation inherited from elastic response of soil sites shown in Figures 3 and 4. The residuals $\log_e(R_{SA}/R_P)$, with R_{SA} being the amplification ratio of each record and R_P being the amplification ratio calculated from the fitted function accounting for the first order effect of soil nonlinear deformation, are shown in Figures 17 and 18. The residuals are only moderately biased with respect to magnitude but strongly biased with respect to source distance. Though it is possible that the bias with respect to source distance is partially a result of the correlation of magnitude and source distance of the excitation data set, the distribution of residuals for the records obtained from an Mw=7.03 event in a large distance range confirms the bias with respect to source distance (Figure 18).

5 IMPLICATION TO ENGINEERING APPLICATIONS AND CONCLUSIONS

The variability of response spectral amplifications for a single soil site is moderate, and the factor for calculating the mean plus one standard deviation for PGA amplification ratios is about 1.3-1.5 and about 1.15-1.3 for intermediate and long periods for elastic site response. The scatter reduces with increasing excitation level for long period and this suggests that amplification ratios can be better estimated for strong ground motion than for weak ground motion even for an elastic soil site. Response spectral amplification ratios depend not only on site soil properties but also on earthquake magnitude and source distance. The average amplification ratios obtained from a suite of records well distributed with respect to magnitude and source distance are not necessarily the correct values for records from small magnitude (Mw=5) or large magnitude (Mw=7+) events, and nor for records obtained from short or large source distances. The amplification ratios of a simple 2-D soil basin, accounting for soil nonlinear deformation, show very similar characteristics to those of the 1-D elastic sites and many aspects derived from elastic site analyses could apply to nonlinear soil sites. However, it is difficult to separate the effect of nonlinear soil deformation that tends to reduce the amplification ratios from the effect of magnitude- and source-distance-dependent amplification ratios shown for elastic sites.

Many attenuation models for response spectra have site class terms. The differences between the site class terms for soil and rock sites lead to soil site amplification ratios if spectral amplitude independent site class terms are used. Unfortunately, the majority of the strong-motion records from soil sites do not possess strong nonlinear soil response and the soil site class terms essentially reflect the average soil amplification of elastic/moderately nonlinear soil sites. When nonlinear soil site class terms are used, the reduction of mean amplification ratios present in the elastic response may have been inappropriately accounted for by the nonlinear soil class terms. For example, it is possible that many aspects examined in the present study could apply, to some extent, to the site class terms in a spectral attenuation model, and the same soil site class terms may not be appropriate for all magnitude and source distance ranges.

Also, the site terms in an attenuation model represent the response of a group of sites with a range of site natural periods, and any effects observed in the present study are likely to be included in the variability of the attenuation models. With the accumulation of strong motion records and detailed site information, variability of strong-motion attenuation models for response spectra may be reduced if some aspects raised in the present study can be accounted for. Caution needs to be exercised in assessing the site class terms for soft soil sites because of the apparent magnitude- and source distance-dependent site amplification ratios, as presented in the current study. These effects mean that the data set used in developing attenuation models needs to be a well balanced across a wide range of magnitudes and distances to obtain appropriate estimates of soil site terms. It is possible that an unbalanced dataset, for example, with strong correlation of magnitude and source distance, may lead to biased estimates of site class terms for soft soil sites, even though the development of attenuation models makes use of "random effects" (Abrahamson and Youngs 1992) model which is designed to tackle the correlation of magnitude and source distance.

The results presented in this study suggest that response spectral amplification ratios should not be used to assess possible site amplification using records from very small earthquakes. In performing a site specific nonlinear modelling, it is vitally important to select strong ground motion records from rock sites for nonlinear modelling of a specific soil site in an appropriate combination of magnitude and source distance ranges of the scenario earthquakes that a structure is designed for.

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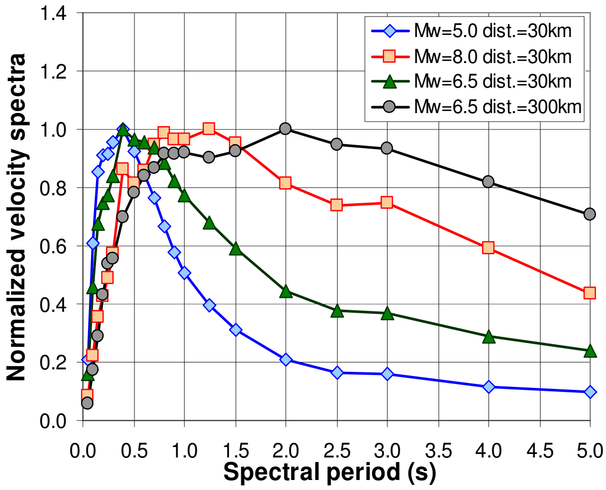

Figure 1 Spectral shape for different magnitude and source distance from an attenuation model

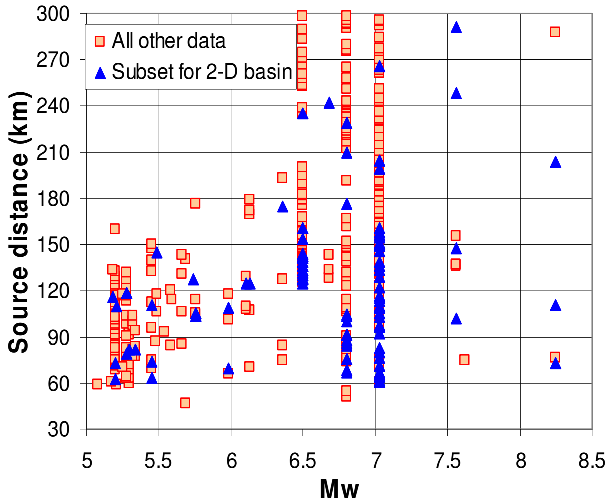

Figure 2 Magnitude-distance distribution of records from subduction slab earthquakes

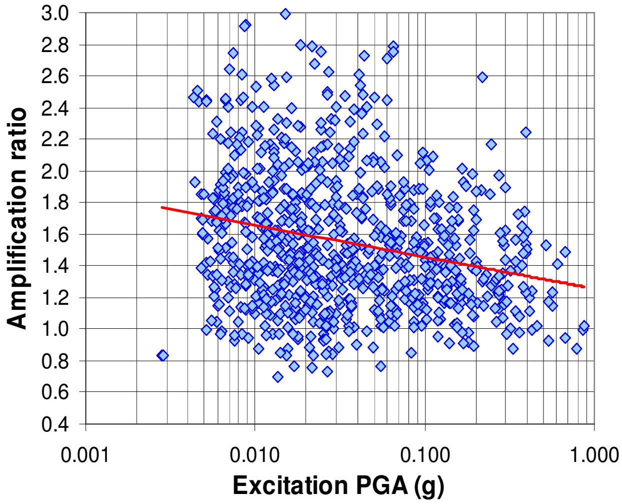

Figure 3 PGA amplification ratio of an 1-D elastic site with a 0.75s natural period.

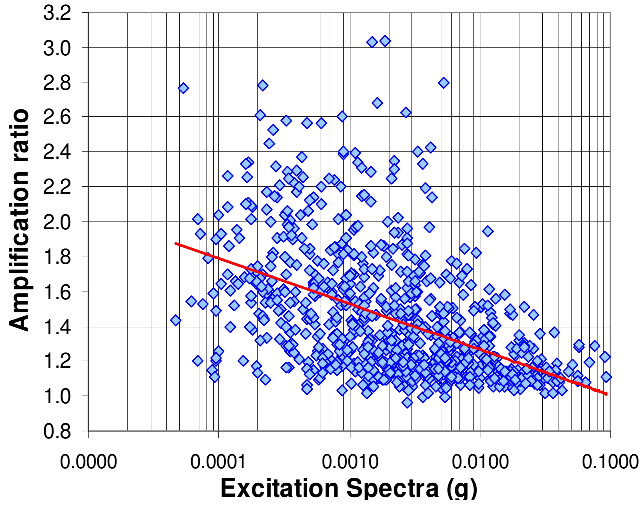

Figure 4 Response spectral amplification ratio at 3s period of an 1-D elastic site with a 0.75s natural period.

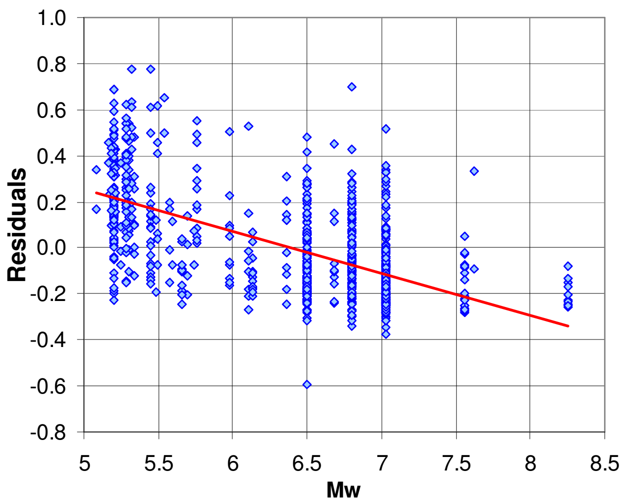

Figure 5 Residual distribution with respect to magnitude at 3s period for a 0.75s elastic 1-D soil

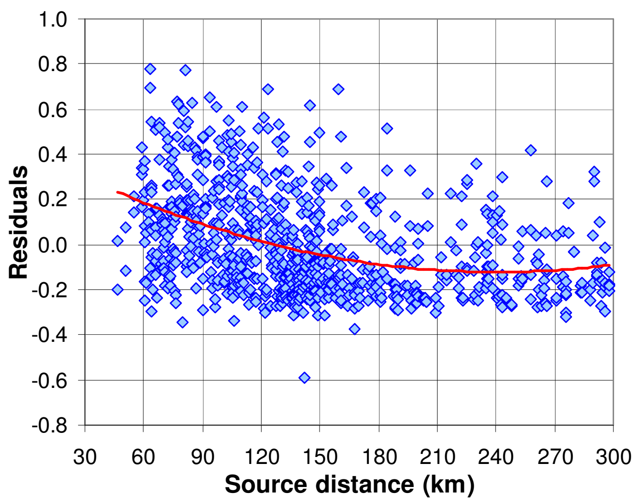

Figure 6 Residual distribution with respect to distance site. at 3s period for a 0.75s elastic 1-D soil site

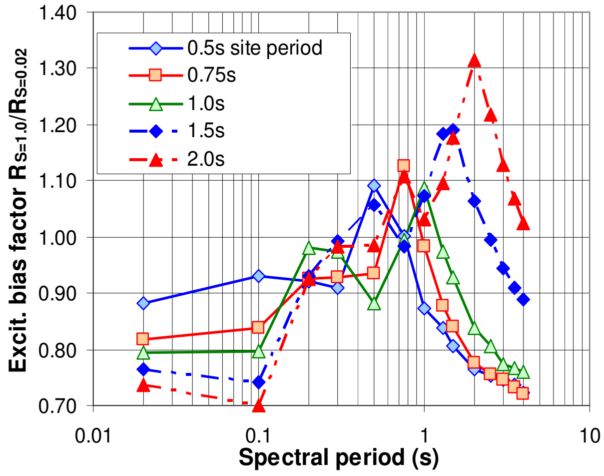

Figure 7 Excitation bias factor

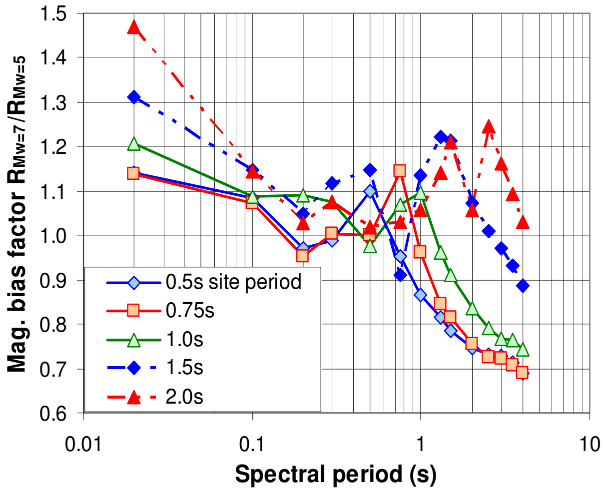

Figure 8 Magnitude bias factor

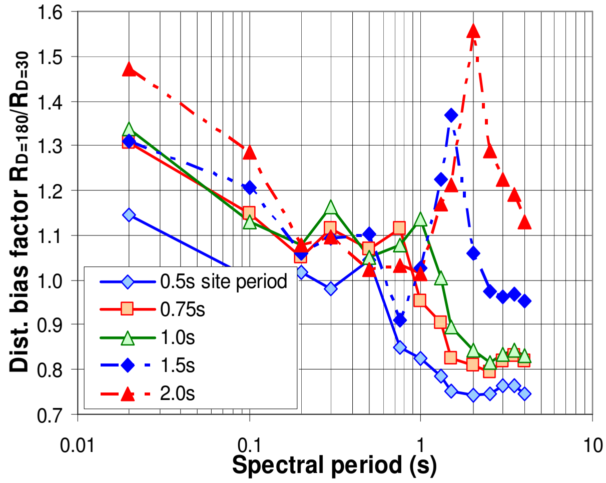

Figure 9 Distance bias factor

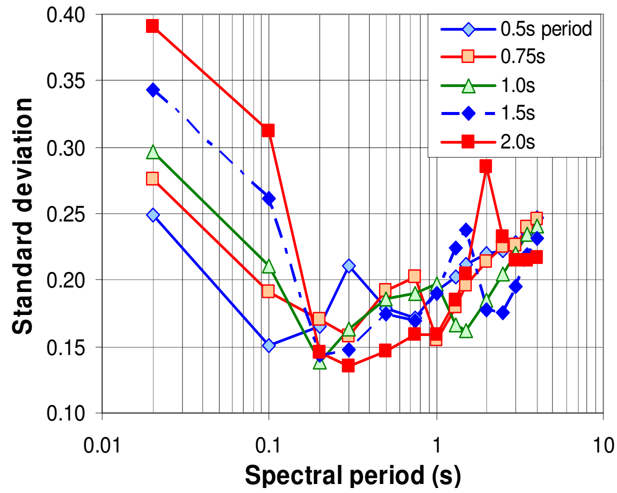

Figure 10 Standard deviation of amplification ratios

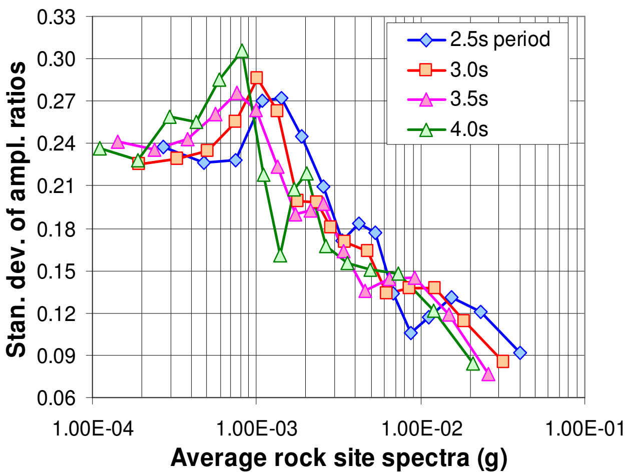

Figure 11 Standard deviation as a function of average excitation spectra evaluated in a series of moving windows for an elastic 1-D site with a natural period of 0.5s.

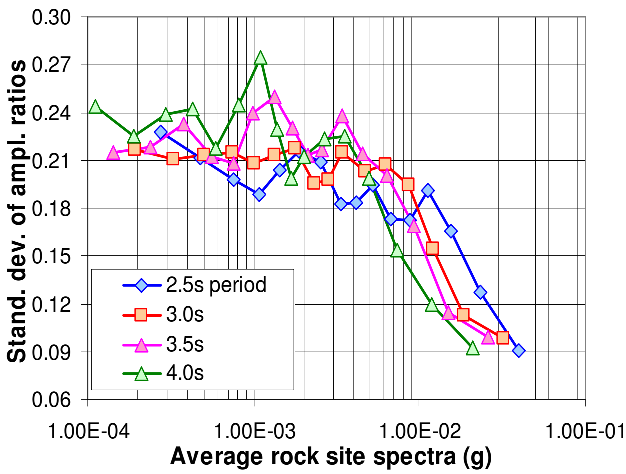

Figure 12 Standard deviation as a function of average excitation spectra for an elastic 1-D site with a natural period of 1.0s.

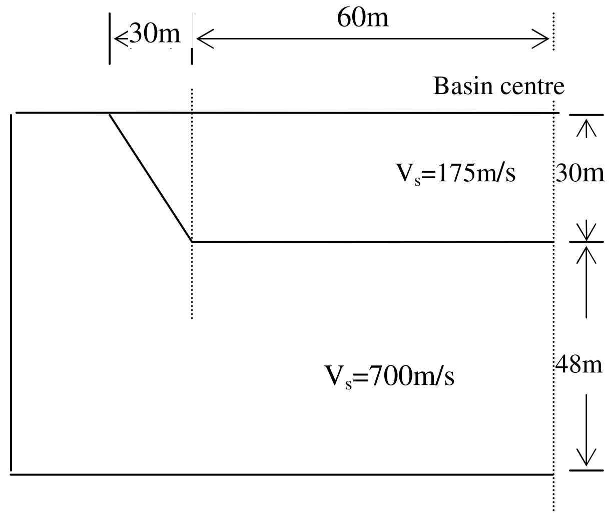

Figure 13 Geometry and material properties of a simple 2-D basins

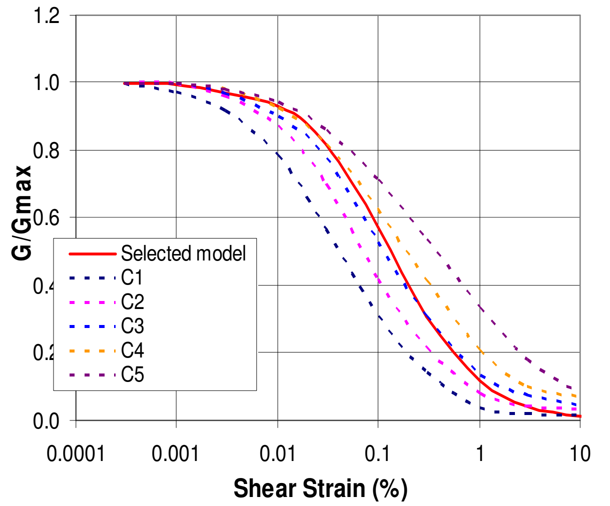

Figure 14 Nonlinear soil models for the 2-D soil basin

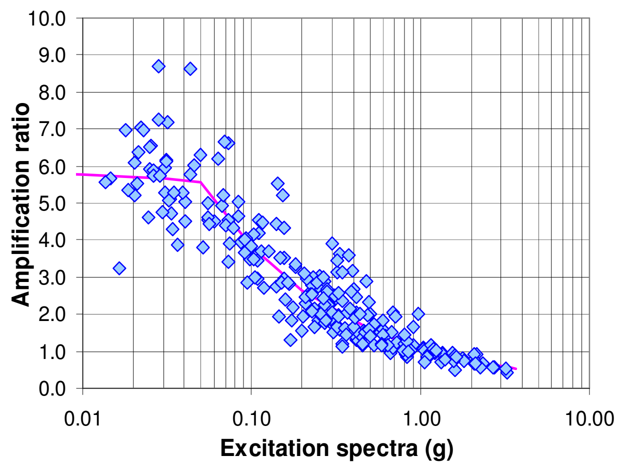

Figure 15 Amplification ratios for 0.2s period. The soil line is the fitted function of excitation spectra

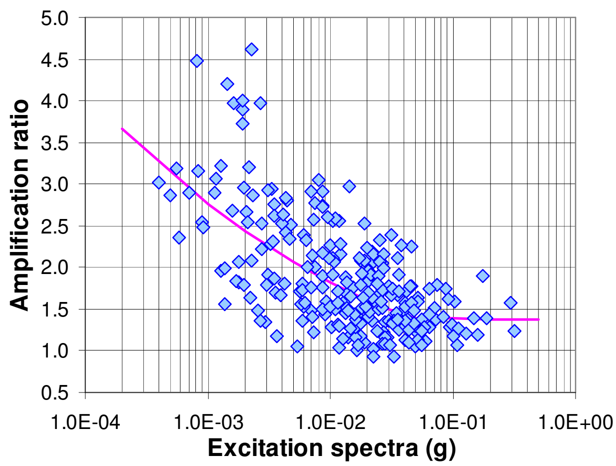

Figure 16 Amplification ratios for 2.0s period. The soil line is the fitted function of excitation spectra

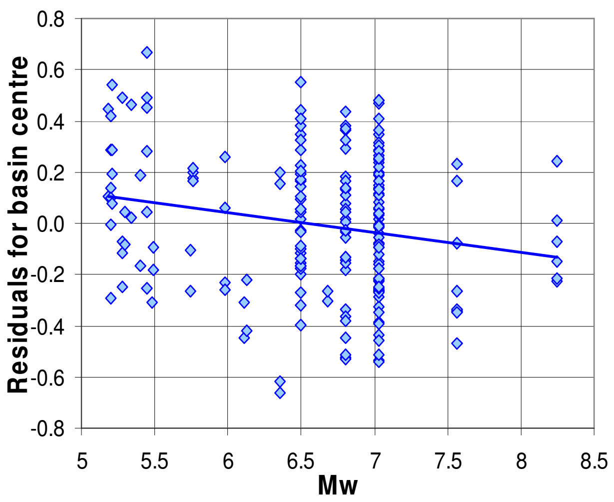

Figure 17 Distribution of residuals with respect to magnitude for basin centre

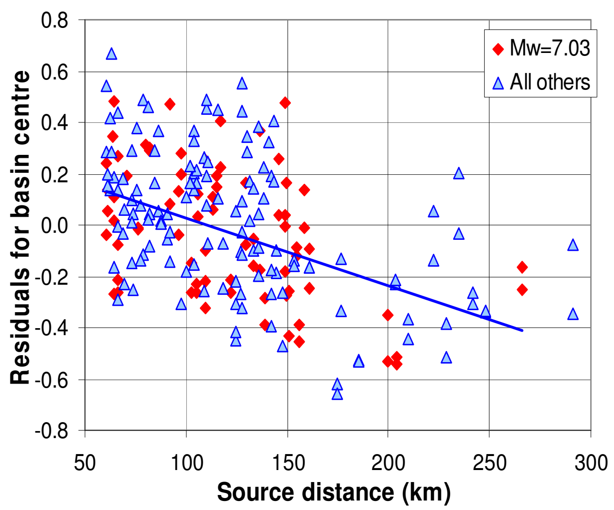

Figure 18 Distribution of residuals with respect to source distance for basin centre