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SITE RESPONSE ANALYSIS INCORPORATED IN PROBABILISTIC SEISMIC HAZARD ASSESSMENTS

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ABSTRACT

It is now widely recognized that using a deterministic procedure to incorporate site effects in a probabilistic seismic hazard assessment results in the underestimation of surface ground motions and the prediction of motions with unknown frequency of exceedance. Therefore, this paper studies a fully probabilistic procedure, which incorporates site effects into the hazard calculations by transforming generic ground-motion prediction equations into site-specific ones. It explores the sensitivity of the mean amplification function, its standard deviation and the resulting surface hazard curve, to different methods of site response analysis and model input parameters. For the soft site investigated, it is shown that the choice of equivalent linear or nonlinear analysis with different constitutive model parameters has a large impact on the hazard results. The computed site-specific surface hazard curves are also compared with those obtained from a generic soil ground-motion prediction equation.

Introduction

Site-specific ground response analysis is often performed in an attempt to capture important features of the response of a site of interest. In many cases, engineers go to great lengths performing a very detailed and complex site response analysis using advanced constitutive models and nonlinear dynamic analyses. Similarly, engineers and seismologists go to great lengths to identify any uncertainties associated with the complex earthquake process and to take them into account when estimating the seismic hazard using rigorous probabilistic approaches. When combining the two, the effects of local ground conditions are often not given the necessary attention. Uncertainties associated with the site response analysis are often ignored and, as a result, when incorporated in the seismic hazard assessment, the surface hazard estimates are often severely underestimated and have unknown rates of exceedance (Bazzurro and Cornell, 2004; Goulet and Stewart, 2009). A number of methodologies have been developed towards the proper incorporation of site effects in probabilistic seismic hazard analyses (e.g. Baturay and Stewart, 2003; Bazzurro and Cornell, 2004). This paper focuses on an approach developed by Bazzurro and Cornell (2004) where a generic ground-motion prediction equation is transformed

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into a site-specific one. The sensitivity of the method and of the resulting surface hazard curve, to different site response analysis methodologies and input parameters is investigated.

Overview of the Bazzurro and Cornell (2004) approach

The methodology proposed by Bazzurro and Cornell (2004), aims to transform a traditional rock ground-motion equation to a soil-specific ground-motion prediction equation. Following the performance of a sufficient number of site response analyses, the site amplification function can be expressed in terms solely of the rock spectral acceleration, $S_a^r(f)$, as:

$$\ln AF(f) \approx c_o + c_1 \ln S_a^r(f) + \varepsilon_{\ln AF(f)} \sigma_{\ln AF(f)} \tag{1}$$

where c_o and c_1 are regression coefficients, $\varepsilon_{lnAF(f)}$ is the standard normal variable and $\sigma_{lnAF(f)}$ is the standard error of estimation resulting from the regression. Since the surface spectral acceleration can be computed from the product of the rock spectral acceleration and the site amplification, in the logarithmic space the surface acceleration is given by:

$$\ln S_a^s(f) = \ln S_a^r(f) + \ln AF(f) \tag{2}$$

where $lnS_a^r(f)$ is computed from a suitable rock ground-motion prediction equation and $lnAF(f)$ from the results of site response analyses and regression. Combining Eqs. (1) and (2) gives:

$$\begin{aligned} \ln S_a^s(f) = {} & \ln \widehat{S_a^r(f)} + \varepsilon_{\ln S_a^r(f)} \sigma_{\ln S_a^r(f)} \\ & + c_o + c_1 \left(\ln \widehat{S_a^r(f)} + \varepsilon_{\ln S_a^r(f)} \sigma_{\ln S_a^r(f)} \right) + \varepsilon_{\ln AF(f)} \sigma_{\ln AF(f)} \end{aligned} \tag{3}$$

where $\widehat{S_a^r(f)}$ is the median rock spectral acceleration. Rearranging Eq. (3) allows the separation of the median from the dispersion measure terms and thus the surface spectral acceleration can be calculated by modifying the median of an appropriate ground-motion prediction equation by:

$$\ln \widehat{S_a^s(f)} = c_o + (c_1 + 1) \ln \widehat{S_a^r(f)} \tag{4}$$

while the standard deviation is now computed using:

$$\sigma_{\ln S_a^s(f)} = \sqrt{(c_1 + 1)^2 \sigma^2_{\ln S_a^r(f)} + \sigma^2_{\ln AF(f)}} \tag{5}$$

Eqs. (4) and (5) allow the transformation of a generic rock ground-motion prediction equation into a site-specific one by coupling the existing rock equation with the site-specific regression. The result of the above transformation is that the uncertainty associated with the site response analysis is also taken into consideration when incorporating site effects in probabilistic seismic hazard analyses. Due to nonlinearity in soil behaviour, c_1 often takes negative values. Therefore, the standard deviation of the surface spectral acceleration can be reduced compared to that of the bedrock. The methodology presented by Bazzurro and Cornell (2004) is based on a linear regression of the amplification function on the rock spectral acceleration. However, a more complex functional form can also be used that accounts for the nonlinearity between the amplification and the input ground-motion. This is achieved by adding another regression coefficient, c_2 (Goulet et al., 2007). Thus, the amplification function is computed as:

$$\ln AF(f) \approx c_0 + c_1 \ln\left(S_a^r(f) + c_2\right) + \varepsilon_{\ln AF(f)}\sigma_{\ln AF(f)} \tag{6}$$

The performance of nonlinear regression results in a median surface spectral acceleration that is given by:

$$\ln \widehat{S_a^s(f)} = \ln \widehat{S_a^r(f)} + c_o + c_1 \ln\left(\widehat{S_a^r(f)} + c_2\right) \tag{7}$$

while its associated standard deviation is given by:

$$\sigma_{\ln S_a^s(f)} = \sqrt{\left(\frac{c_1 \cdot S_a^r(f)}{c_2 + S_a^r(f)} + 1\right)^2 \times \sigma^2_{\ln S_a^r(f)} + \sigma^2_{\ln AF(f)}} \tag{8}$$

The modified ground-motion prediction equation can subsequently be used directly for the estimation of the hazard at the site of interest. It is important that a sufficient number of records are used in the performance of the site response analysis, to allow a robust estimation of the amplification function and to capture the ground-motion variability.

Site Response Analysis

A recent study by Stewart et al. (2008) has explored several issues regarding the performance of nonlinear site response analysis. This study explores the sensitivity of the site amplification function and its standard deviation to a number of the model parameters and further compares nonlinear analysis results against those obtained from an equivalent linear analysis. The site response investigation is performed for a soft sandy site located in California, the Sylmar County Hospital (SCH) site, using a total of 120 ground-motion records from the PEER NGA database, both scaled and unscaled. The site consists entirely of alluvial layers, it is 91m deep and the water table is located 46m below the ground surface. The average shear-wave velocity in the upper 30m, V_{s30}, is approximately 280m/s and thus the site is classified as a NEHRP class D site. The site information and the shear wave velocity profile are after Kottke (2006). Fig.1 shows the site stratigraphy and the associated shear wave velocity profile together with the 5% damped acceleration response spectra for the records used in the site response analyses. It should be noted that the adopted records cover a wide range of acceleration levels, with the peak ground acceleration, *PGA*, varying from approximately 0.01 to 1.1g.

The equivalent linear analysis is performed using SHAKE91 (Idriss and Sun, 1992) and the Darendeli (2001) dynamic soil properties curves, which estimate the stiffness degradation and damping ratio as a function of the soil confining pressure, plasticity index, overconsolidation ratio, frequency of vibration and number of cycles. The same family of curves is also used in the nonlinear analysis as target curves against which the fitting parameters of the nonlinear model are selected. The nonlinear analysis is performed using the program DMOD2000 (Matasovic, 2007) which employs the modified hyperbolic model, MKZ (Matasovic and Vucetic, 1995). The analysis was performed using the total stress model and thus the pore water pressure effects are not taken into consideration.

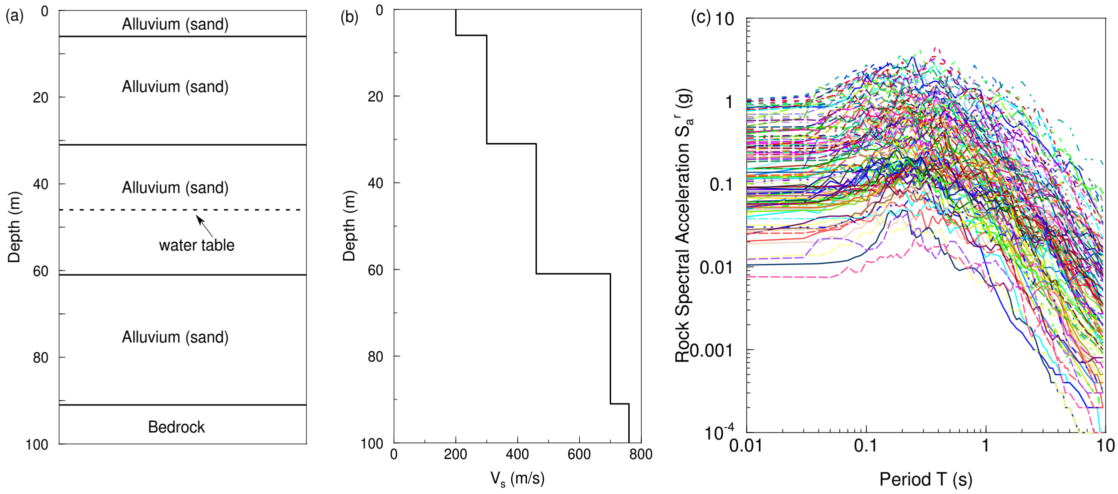

Figure 1. Site stratigraphy, shear-wave velocity profile and acceleration response spectra of the 120 rock records used in the ground response analysis.

The MKZ model implemented in DMOD2000, as well as in several other programs, suffers from two main, widely recognised, disadvantages. The use of the Masing rules to describe the loading and unloading curves leads to severe overestimation of damping in the large strain range. On the other hand, the model predicts zero damping in the very small strain range; a prediction that is in contradiction with laboratory tests, which have shown very small levels of damping even at strains less than 10^{-4}%. In order to resolve the issue in the small strain range, the program uses a viscous damping formulation, which estimates damping as a function of a target damping ratio and frequency. The viscous damping can be estimated either based on the full Rayleigh formulation or the simplified formulation (e.g. Hashash and Park, 2002), with the latter predicting significantly higher damping levels in the high-frequency range. This study uses both formulations, with a target damping ratio of 0.5%, in order to investigate its impact on the ground response prediction and on the amplification function.

The inability of the MKZ model to provide an equally good fit to both the stiffness degradation and damping curves has led to the development of two model calibration approaches. The model parameters are selected either in order to provide a perfect fit to the stiffness degradation curve, accepting any damping overestimation, or they are selected in a way that averages the error between the two fits (Kwok et al., 2007). Due to the use, in this study, of records whose rock *PGA* sometimes exceeds even 1g, the first approach was considered inappropriate since in the case of the more extreme records, which are also the most valuable in capturing the nonlinear soil behaviour, it would cause significant overdamping. In this study two parameter fits have been used, shown in Fig. 2 for one soil layer, which both try to limit the damping overestimation, one without significantly deteriorating the stiffness fitting (limiting the error in stiffness to less than 50% at each strain level) and the second one averaging the error between the two based on the guidelines suggested by Stewart et al. (2008).

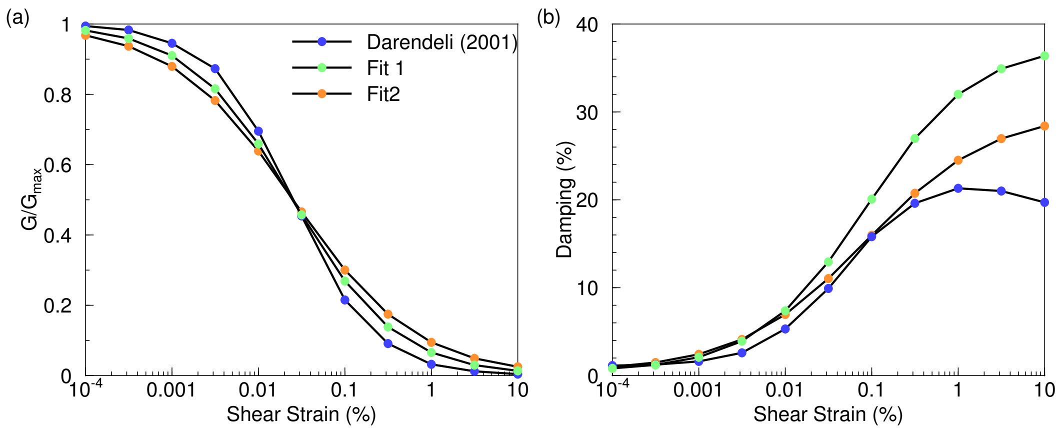

Figure 2. Different choices in fitting the modulus reduction and damping curves used in the analysis against the Darendeli (2001) curves.

One set of equivalent linear analyses (EQLIN) and three sets of nonlinear analyses were performed for the 120 records in the database; the first one employing the simplified Rayleigh damping formulation with parameter fit 1 (NON1-SR), the second one using the full Rayleigh damping formulation with parameter fit 1 (NON1-FR) and the third one employing the full Rayleigh damping formulation with parameter fit 2 (NON2-FR). The results for three records of variable intensities (*PGA* equal to 0.06g, 0.42g and 0.9g) are shown in Fig. 3.

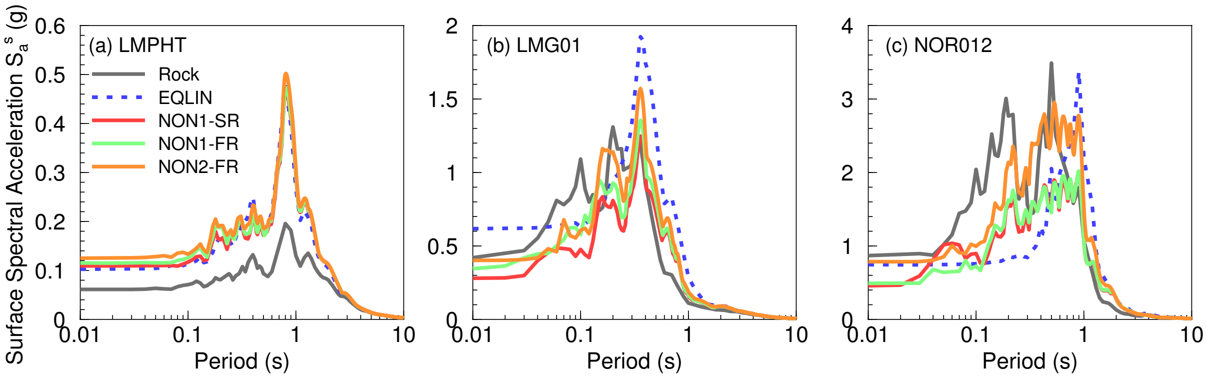

Figure 3. Comparison of surface acceleration spectra obtained from the 4 set of analyses.

It is noted that for the low intensity records (Fig.3a) the differences between the various parameter selection schemes and between the two site response analysis methodologies are fairly limited. In the higher intensity range, differences become more significant, with the equivalent linear analysis predicting generally higher levels of acceleration, while damping any high-frequency fluctuations of the input motion. On the other hand, the nonlinear analysis using the simplified Rayleigh formulation tends to damp more the high-frequency part of the motion, including the peak ground acceleration. Differences between the simplified and full Rayleigh damping formulations are limited to the short period range, up to about 0.2-0.3s. The differences between the two parameter fittings are evident across a wider range of periods, with the second fitting predicting significantly larger accelerations as a result of the use of lower damping and of a more linear stiffness degradation curve. The differences between the two fits are particularly evident for the highest intensity record shown in Fig (3c). At this level of shaking, the induced shear strains in the soil profile were in excess of 1% and at this strain level the differences between the two fits are significant (see Fig. 2). Another important issue that needs to be considered at this level of shaking arises from the inability of the equivalent linear analysis to converge to a solution for a number of cases, due to the highly nonlinear behaviour (i.e. very steep stiffness degradation) of the examined sandy soils. This strain level is already in excess of the strain range for which the equivalent linear analysis should be typically used. Consequently, and given the convergence issues, the equivalent linear methodology is considered to be unable to provide a robust estimate of the ground response at such high levels of shaking.

Site Amplification Functions

The site amplification function for each set of analyses was estimated using nonlinear regression and the functional form shown in Eq. (6). The amplification functions arising from the different methods of analyses and selected parameters are shown in Fig. 4 for a range of spectral periods of interest.

It is immediately noticeable that the differences are most pronounced in the shorter periods, with the NON1-SR analysis predicting significantly lower amplification across the entire acceleration range. It is interesting to note that in the short-period range the differences between the four sets of analyses are observed across almost the entire acceleration range, despite the observations made in Fig. (3a), where all analyses resulted in almost identical ground response estimates. At longer periods, all three sets of nonlinear analyses result in an almost identical amplification function in the small rock-acceleration range, with differences increasing as accelerations exceed 0.1g. As expected, the Rayleigh damping formulation has no impact on the amplification function for periods longer than 0.2s. The equivalent linear analysis generally results in the highest amplification, although at T=0.2s the amplification curves predicted by the analyses EQLIN and NON2-FR coincide. The exact match noted in Fig. 4b was not observed for other investigated sites (not presented in this paper), although in all cases the NON2-FR analysis gave amplification functions similar to those obtained from the EQLIN analysis.

Despite the similarities in the amplification functions obtained from the EQLIN and NON2-FR analyses, important limitations of the equivalent linear analysis make it unsuitable for the estimation of the amplification across the entire acceleration and period range. The inability of the equivalent linear analysis to converge to a solution for a number of the higher intensity records causes the unexpected upward shift of the amplification function at longer periods, which is particularly evident at T=1.0s. The predominant elastic period of vibration for the examined stratigraphy (based on an average shear wave velocity) is 0.75s, which during intense shaking shifts to periods close to 1.0-1.2s, depending on the strains induced in the soil. The records that cause the shift to this range of periods tend to have spectral acceleration levels at T=1.0s close to 0.3-0.4g and were in resonance with the elongated site period. Due to the inability of the method to converge, most of the higher intensity records had to be excluded prior to the regression. As a result, the increase in the amplification, observed due to the resonance in this range with the elongated site period, influences significantly the regression, as higher records that would be expected to be less amplified, or even deamplified, have now been removed from the dataset. The above observation highlights the importance of using records in the site response analysis which capture the entire range considered in the probabilistic seismic hazard assessment and gives an indication of the impact that the ground-motion selection has on the mean amplification function.

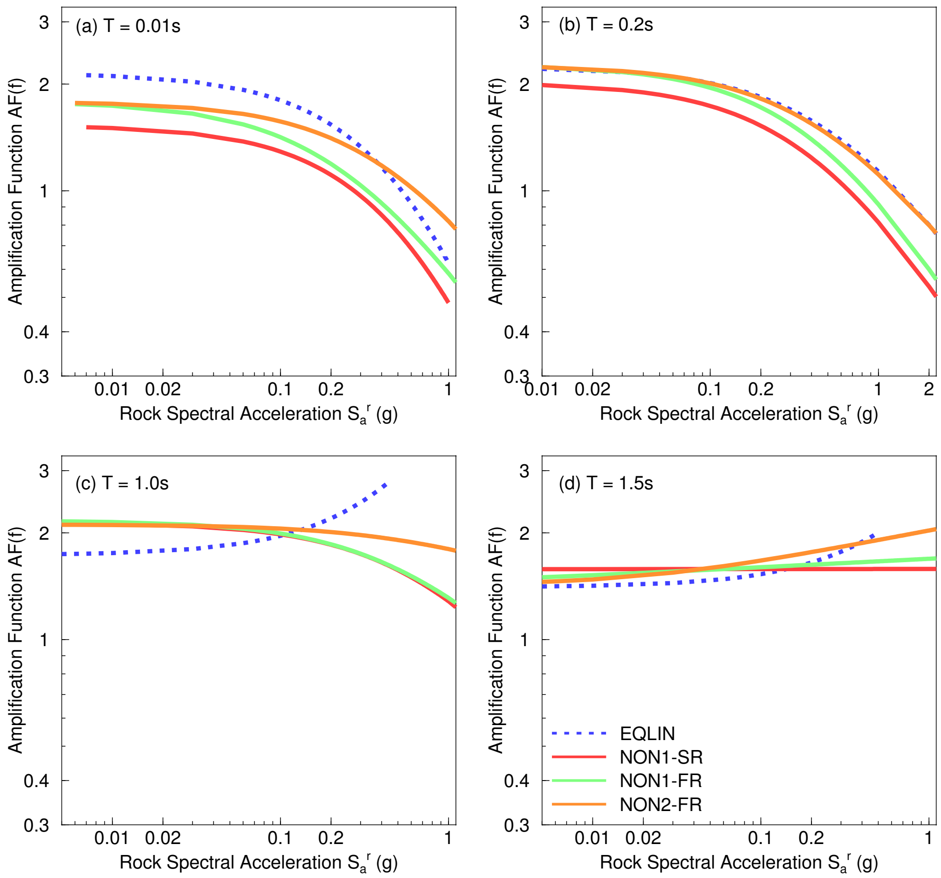

Figure 4. Mean amplification functions *AF(f)* for site SCH for a number of spectral periods.

Table 1 shows the standard deviation $\sigma_{lnAF(f)}$ obtained from the different sets of analyses for the four examined spectral periods. It is observed that differences among the four sets of analyses are relatively small in terms of the standard deviation, particularly between the nonlinear analyses results, indicating that the biggest impact on the surface hazard curve will be due to the variation in the mean amplification functions.

Table 1. Variation of the standard deviation, $\sigma_{lnAF(f)}$, for different site response analyses and periods

$\boldsymbol{\sigma_{lnAF(f)}}$	**T=0.01s**	**T=0.2s**	**T=1.0s**	**T=1.5s**
EQLIN	0.128	0.147	0.116	0.152
NON1-SR	0.175	0.187	0.167	0.166
NON1-FR	0.167	0.203	0.175	0.173
NON2-FR	0.173	0.190	0.163	0.167

Nevertheless, care needs to be taken that a sufficient number of records is employed in the performance of the site response analyses in order to ensure that the dispersion associated with the site response is properly captured. Use of too small a number of records can result in erroneous levels of dispersion that can be highly influenced by a single outlying record. The reduced standard deviation observed in the case of the equivalent linear analysis is associated to a large extent with the smaller number of ground-motion records remaining in the dataset after excluding those for which convergence was not achieved, highlighting once more the sensitivity of the methodology to the number of records used.

Probabilistic Seismic Hazard Analysis (PSHA)

The probabilistic seismic hazard analysis was performed using the open-source software OpenSHA (Field et al., 2003). In this program, the Bazzurro and Cornell (2004) methodology has been implemented on the Abrahamson and Silva (1997) rock ground-motion prediction equation. The surface spectral accelerations, as predicted by the modified ground-motion prediction equations, are shown against the distance from the rupture plane, r_{rup}, for two magnitude levels and periods in Fig. 5. Differences are larger for *PGA*, where, particularly for the larger magnitude, significant variability is noted across almost the entire distance range. At T=1.0s differences are only significant for the larger magnitude and only at relatively small distances, while the curves obtained from the two Rayleigh formulations are indistinguishable. For the performance of the hazard analysis the investigated sandy site is assumed to be located in LA Bulk Mail, the default location assumed by the program. The analysis was performed using the USGS/CGS (2002) earthquake rupture forecast, the fault model by Frankel et al. (2002) and assuming a time span of 1year.

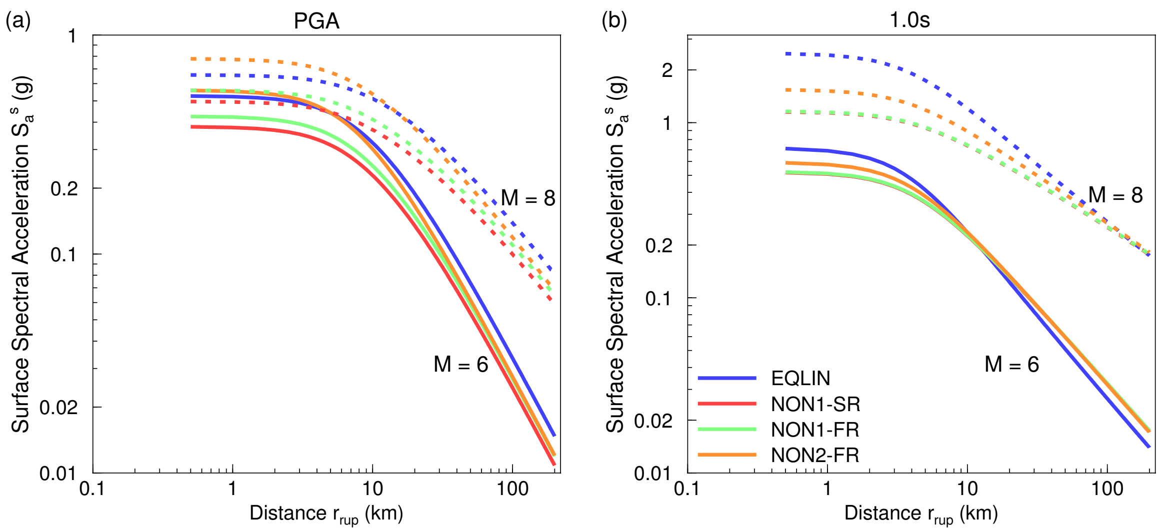

Figure 5. Modified Abrahamson and Silva (1997) equations using the Bazzurro and Cornell (2004) formulation shown for PGA and T=1.0s and two magnitude levels.

The results of the PSHA are shown in Fig. (6) for the peak ground acceleration and the 1.0s spectral acceleration. Fig. (6) also presents the results of the analysis when the rock and generic soil Abrahamson and Silva (1997) ground-motion prediction equations are used. Significant variability is observed in the results for both periods, particularly between the equivalent linear and nonlinear analyses. It is verified that the impact of the Rayleigh damping formulation on the surface hazard curve is minimal compared with the impact that the method of analysis and the nonlinear model parameters have. It is also noted that the equivalent linear analysis leads to a significantly larger amplification at T=1.0s than any of the nonlinear analyses. This is associated with the upward shift of the amplification function at this range of periods, as it was observed in Fig. 4 and discussed in the previous section.

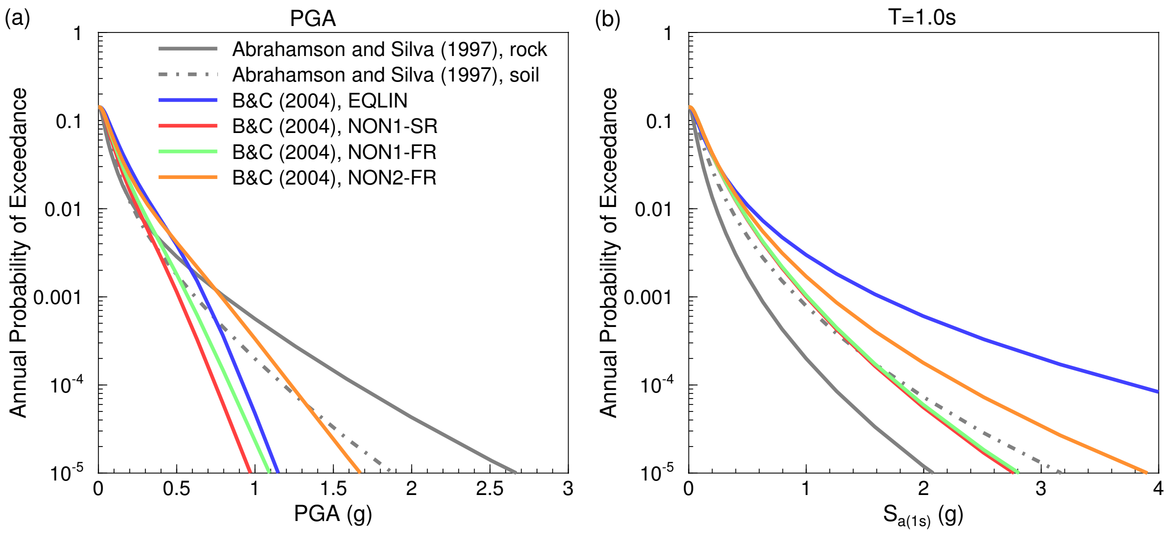

Figure 6. Hazard curves for Sylmar County Hospital for PGA and 1.0s spectral acceleration.

Finally, it is particularly interesting to note that, for the majority of probability of exceedance levels typically used in engineering design, all site-specific analyses predict a larger amplification at T=1.0s than the one predicted by the generic soil factors of the Abrahamson and Silva (1997) equation. This is attributed to the ability of the site response analysis to capture specific details of soil response, such as the higher soil amplification close to the predominant site period, an effect not captured by generic factors, and highlights the importance of site-specific analysis for critical structures.

Conclusions

This study explored the sensitivity of the Bazzurro and Cornell (2004) methodology for the transformation of a generic ground-motion prediction equation to a site-specific one to different methods of site response analysis and input parameters. The computed mean site amplification functions and their standard deviations were found to be sensitive to the examined site response analysis approaches, having in turn a significant impact on the probabilistic seismic hazard analysis. It was shown that the Rayleigh damping formulation, although influencing the short period ground response, has a minimal effect on the surface hazard curve, whereas the two investigated parameter fits were shown to affect the surface hazard curve more across all periods. An important limitation of the equivalent linear analysis, associated with its inability to converge to a solution for all records in the dataset, was identified and the impact of the number of ground-motion records used for the estimation of the amplification was briefly discussed. Further work regarding the sensitivity of the surface hazard curve to different suites of ground-motion records remains to be completed. Finally, in the present study, only total stress nonlinear analysis was performed and the sensitivity of the results to the inclusion in the modeling of the pore water pressure effects remains to be evaluated in future work.

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