VARIABILITY OF ONE-DIMENSIONAL SOIL AMPLIFICATION ESTIMATES AT FOUR SITES OF THE FRENCH PERMANENT ACCELEROMETER NETWORK (RAP)

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ABSTRACT :

In this study, we compute site amplification estimates and response spectral ratios for different acceleration time histories scaled to different PGA's by propagating them through 1D soil models with stochastic variation of their mechanical properties. We use three models of wave propagation: the widely known equivalent linear model (EQL) (Schnabel et al., 1972), the frequency-dependent equivalent linear model (AKEQL) (Kausel and Assimaki, 2002), and the elastoplastic nonlinear model (NL) developed by Iwan (1967). We have selected four sites from the French permanent accelerometer network (RAP) deployed in the city of Nice, which is characterized by local strong site amplification due to alluvial filling. A sensitivity study on the numerical methods shows that purely nonlinear analysis greatly depends on the input motion whatever the rock input PGA (PGA_r) is; whereas equivalent linear analyses have less dependency with respect to PGA_r. We present then the variability of amplification estimates among the wave propagation models. We found that frequency-dependent equivalent linear results are close to those from the traditional equivalent linear model for PGA's larger than 0.7g. Conversely, for intermediate PGA_r values, the first model de-amplifies the high frequencies much lower than the second one. Furthermore, the standard deviation of amplification estimates increases as PGA and frequency increase regardless of the utilized wave propagation model. Using the previous results, the response spectral ratio as a function of PGA_r has been computed and inserted in simplified site-specific probabilistic seismic hazard assessment (Cramer, 2003). Finally, a comparison with experimental data shows that 1D modeling is a first order approximation of site effects in Nice.

KEYWORDS: Soil variability, wave propagation, nonlinear site amplification, Nice.

1. INTRODUCTION

It is widely known that the earthquake ground motion can be significantly affected by the local subsurface geology and morphology. Soil amplification associated to this phenomenon can be represented by either the so-called transfer function (TF) or the response spectral ratio (RSR). The transfer function can be evaluated empirically analyzing the recordings of earthquakes with or without reference site (Meneroud et al., 1993; Field and Jacob, 1995; Bonilla et al., 1997). In moderate seismicity zones, this methodology is expensive, time consuming, and the results are limited to weak motion. Another way of specifying soil amplification is either by using correlation with specific soil parameters (Vs30) or by the mean of calibrated numerical models.

Usually, in numerical simulations, only the mean value of the site amplification is calculated. Nevertheless, to evaluate the reliability of the results, the estimation of uncertainties is essential. The uncertainties come from the input parameters (shear wave velocity, density, quality factor, thickness, shear modulus degradation and damping curves, and the input acceleration time series) as well as from the numerical model itself.

This study aims at showing a way of quantifying site amplification and the associated uncertainties related to both soil profile and input ground motion. In each site, the site-specific amplification factor is computed for different earthquake excitation levels. Four different numerical methods are used: linear Haskell-Thompson model, the widely known equivalent linear model (EQL) (Schnabel et al., 1972), the frequency-dependent equivalent linear model (AKEQL) (Kausel and Assimaki, 2002), and the elastoplastic nonlinear model (NL) developed by Iwan (1967). The site amplification functions resulting from the numerical simulations will be described by two functions: the transfer function of the site and from an engineering point of view, the response spectral ratio.

The methodology will be applied to four RAP (French permanent accelerometer network) sites in the city of Nice. The regional seismicity of Nice (located in the south eastern of France) is moderate but not negligible. The RAP (Nals, NLib, NPor, NRoc, yellow points on figure 1) stations are located in the quaternary sedimentary basin, where experimental measurements of site effects (Duval et al., 1994, 1996), which used microtremors and earthquakes recordings, clearly indicated that site amplification occurs in Nice (figure 1).

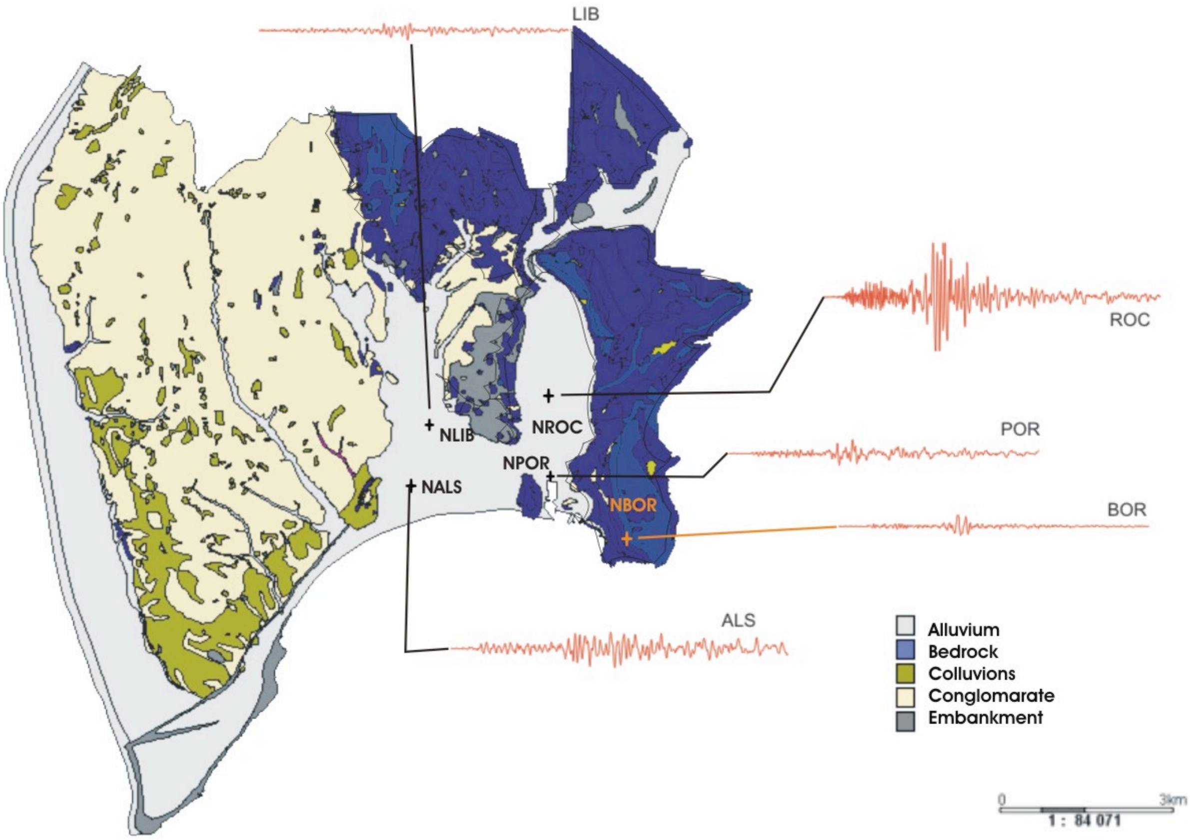

Figure 1: Map of Nice of accelerometer station locations and records for the 1999 first of September earthquake. The yellow points give the position of the permanent accelerometer station. This map put the light on the fact that site effects are present in Nice (Huge amplification at NROC, NALS compare to the record at NBOR).

2. METHODOLOGY

2.1. Overall methodology

In each RAP station site, four wave propagation models are used. For each numerical method, 19 ground motion levels are investigated (from 0.005g to 2g with an increasing multiplicative factor of 1.4). In addition, to integrate aleatory and epistemic uncertainties, 29 acceleration time series from the European database (Ambraseys et al, 2004) and 20 random soil profiles at each site are used, respectively. A Monte Carlo exploration is used to combine all input parameters at each site. The velocity profile is assumed to have a lognormal distribution with a coefficient of variation of 0.2, and the rest of soil parameters (density, thickness and quality factor) are supposed to follow a uniform distribution. For each trial, the acceleration time histories at the surface, its response spectrum, and the corresponding transfer function are obtained. The ensemble of results provides a statistical distribution that can be characterized by the mean and percentiles. In this study, we compute the standard deviation as a measure of the uncertainty of simulations, therefore, the uncertainty on the site response.

2.2. Numerical models

2.2.1. Traditional equivalent linear model

The first site response formulation considered the code TREMORN (Hartzell et al, 2004), which is based on the original code by Schnabel et al. (1972). Due to its simple formulation, limited data, and numerical robustness, the equivalent linear approach has been widely used. With this method, the shear modulus, G, and damping, η, are iterated to find their values compatible to the level of strain induced in the soil layer.

2.2.2. Frequency dependent equivalent linear model (Kausel and Assimaki, 2002)

Recognizing the overdamping that occurs with the traditional equivalent linear approach, Kausel and Assimaki (2002) have recently advanced a formulation with frequency-dependent moduli and damping. The process is iterated in the same way as TREMORN to obtain internally consistent soil parameters. This method is implemented in the code TREMORKA.

2.2.3. Non linear model

The NOAH_SH_IWAN program is a second-order, staggered-grid finite difference code that implements Iwan (1967) model. The advantage of this rheology is the direct use of laboratory shear modulus reduction curve. Thus, the same data are used in the equivalent linear methods and this truly nonlinear analysis. This code operates in the time domain by tracking the earthquake load through stress-strain space. Time and space discretization in the finite difference considered a maximum frequency of 10 Hz of resolution.

3. APLLICATION TO NICE

3.1. Data used

The soil data, which will be used for the simulations, come from the 3D geotechnical model. This model has been created in Nice during the program GEM-GEP (GEM-GEP phase 1, 2000) and has been updated in 2007 (CETE). For each site a soil column under the RAP stations has been extracted. The mean soil parameters needed for the numerical methods are the shear wave velocity, the thickness, the density, the quality factor and the shear modulus degradation and damping curves in each layer. 29 input motions have been extracted from the European ground motion database. The selection criterions were a minimum magnitude of 5 maximum hypocentral distance of 30 km, and rock site conditions, which corresponds to the characteristics of the reference earthquake defined in GEMGEP.

3.2. Sensitivity study

An essential task of this study was to know the influence of each input parameters in the numerical result. This knowledge permits organize hierarchically their importance. The sensitive analysis in this work is based on the effect of the input parameters on the fundamental frequency as shown in figure 2 and amplitude at station Lib.

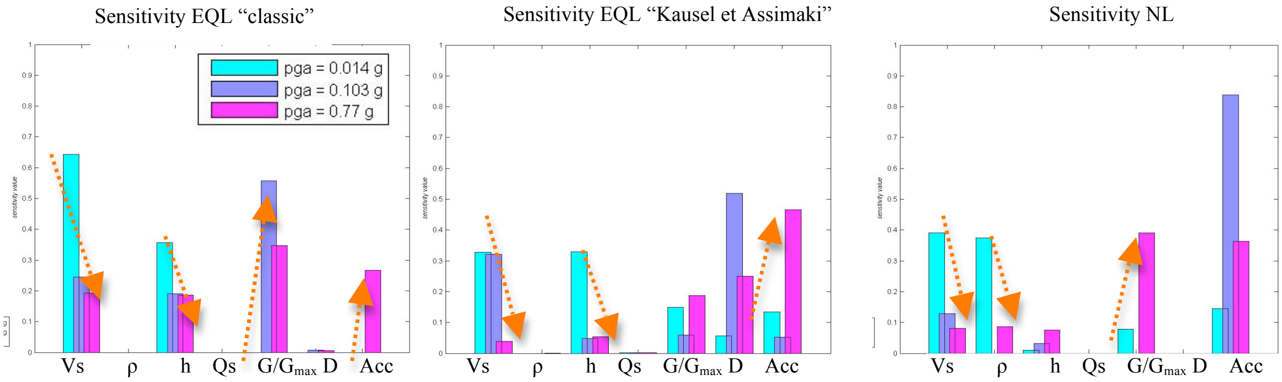

Figure 2: Sensitivity analysis based on the effect of the input parameters on the fundamental frequency for station LIB

Generally speaking, for all methods, as the PGA$_r$ increases, the influence of Vs and H decreases in favor of G/G$_{max}$, damping curves and input acceleration. The orange arrows represent this general tendency. The difference between the equivalent linear and nonlinear models is the large influence of the input motion (results for the three PGA$_r$s in figure 2). Nonlinear model results are widely dependant on the acceleration time series. For this reason, for a correct computation one should select several input motions to have a representative result.

3.3. Data processing

Given the large amount of simulations (around 11000 simulations at each site), we suppose the results follow a Gaussian distribution, thus by computing the mean and standard deviation we also suppose that the mean response and its uncertainty are characterized through these values.
The distribution of the transfer function coming from the traditional equivalent linear model through variations of the soil parameters (20 soil models) and input acceleration time series (29 input ground motions) is illustrated in figure 3. The distribution is exposed for a low value of PGA$_r$ (linear case) in the left figure and for an intermediate PGA$_r$ in the right one. The yellow curves represent the individual results for each simulation; the red curves are the mean and the 68% confidence limits. This figure suggests that in the case of weak motion, low PGA$_r$, the higher modes are sensitive to the knowledge of the soil structure. However, in the case of higher PGA$_r$ values, the responses of the higher modes are flattened due to the nonlinear deamplification effect.

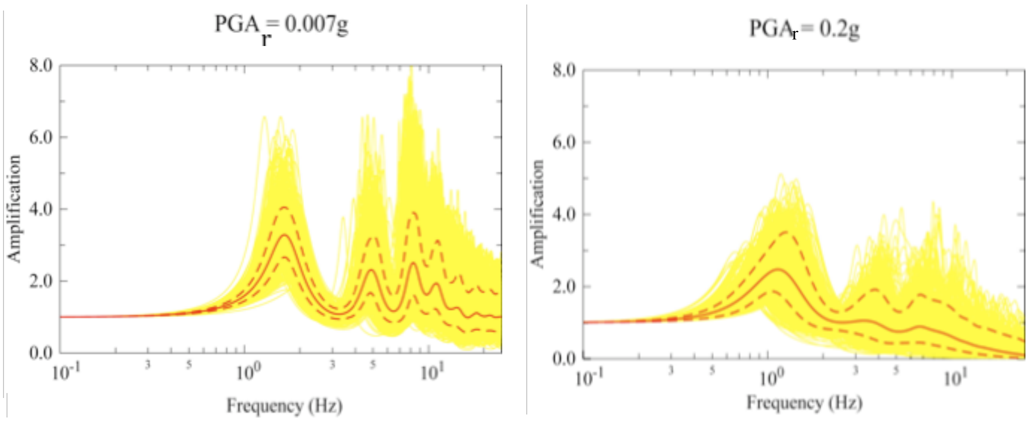

Figure 3: Individual results of simulations (yellow curves) and 68% confidence limits (red curves) for the transfer function. The left graph illustrates the distribution of the transfer function through variations of the soil and input acceleration time series scaled to 0.007g. The second graph illustrates the same results for a PGA$_r$ of 0.2g.

3.4. *Variability of the results*

In this section, we compare the results (TF and SRS) coming from the three different numerical models, in term of mean value and standard deviation. In particular, the influence of the rock input PGA is investigated. The RAP station NPor has been chosen to illustrate the purposes, figures 4 and 5.

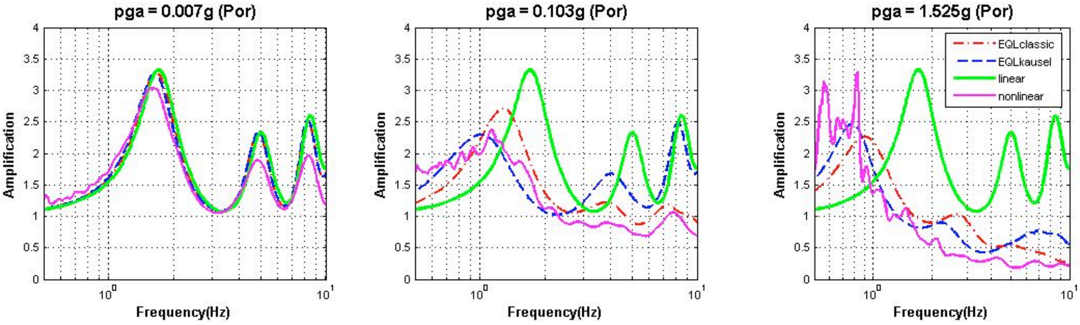

Figure 4: Comparison of the mean of the transfer functions for three input time series levels.

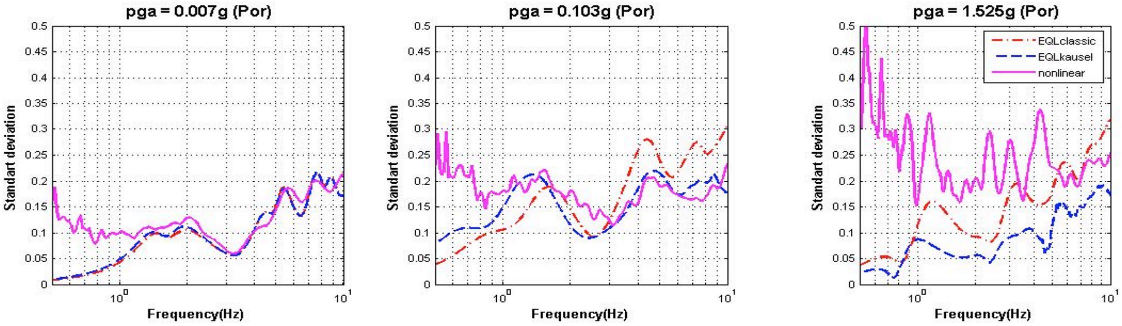

Figure 5 Comparison of the standard deviation of the transfer functions for three input time series levels.

The general tendency of non-linear behaviour of the soil is, for all the methods, a de-amplification and a shift of the energy of the signal at low frequencies.

As the NL method is concerned, we can see in figure 4 and 5 that the soil response is amplified at low frequencies compared to the equivalent linear methods, the variability is also stronger at such frequencies. Hence, the reliability of the amplification estimate is weak for low frequencies. One of the source of the high variability level can be due to low signal to noise ratio at low frequencies. This result shows how important is to select good quality acceleration time series in particular for non-linear computations and high input excitation level.

As the equivalent linear methods are concerned, the variability of the transfer function increases with frequency. All models give similar results for both very low PGA_r (linear case) and very high PGA_r (non linear behavior). Nevertheless, for intermediate values of PGA_r, which is the order of magnitude for a big event in the south of France, the transfer functions are quite different. Indeed, KAEQL method does not deamplify the high frequencies as much as the traditional equivalent linear method. This suggests that the model chosen for the computations of the amplification function at one site has an important impact on the results.

3.5. *Application to site specific Probabilistic Seismic Hazard Assessment (PSHA)*

The principal outcome of this work is the uncertainty estimation when computing site effect amplification. In PSHA, site amplification is defined by a deterministic factor. Nevertheless, to have a truly probabilistic study one should take into account all the uncertainties in the whole calculation. Cramer (2003) proposes to use response spectral ratios (as a function of PGA_r) for a given site in order to consider the variability of the amplification in PSHA computations. In the following, an example of the combination of empirical Ground Motion Prediction Equation (GMPE) with the amplification distribution found above is shown. PSHA computes the exceedance of a given acceleration threshold produced by a given event of magnitude M and located at a distance R (Cornell, 1968).

$$P(A_s > A_0/M,R) = 1 - \int_{Ar} \underbrace{P(A_s \le A_0/A_r)}_{\text{Come from the study}} \underbrace{P(A_r/M,R)}_{\text{Come from the GMPE}} dA_r \qquad (3.1)$$

Where A_s: soil acceleration, A_r rock acceleration, A_o threshold acceleration

The results of the previous study are given in tables for two different periods of the RSR, in this example we have selected T= 0 s (PGA) and T= 1 s. In order to show the effect of soil amplification in the probability of exceeding a threshold acceleration, we use the precedent formulation (eq 3.1) with the results of the present study and using Boore et al (1997) GMPE to compute the probability of exceeding A_0 for a rock and soil condition at "NPor" RAP station.

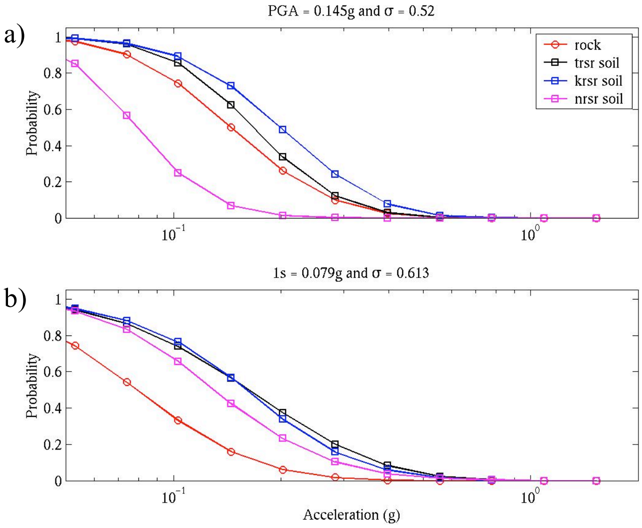

Figure 6: Comparison of the probability of exceeding the threshold acceleration indicated in the abscise axis for an event of magnitude 6 located at 10 km on rock site conditions (red curve) and soil site conditions. The soil conditions are obtained from the traditional equivalent linear model (black curve), the Kausel and Assimaki equivalent linear model (blue curve), and the nonlinear model (purple curve).

Figure 6(a) shows the probability that the spectral acceleration at 0 sec period (PGA) exceeds the threshold acceleration given in the abscise axis. Figure 6(b) gives the same information but for a spectral acceleration corresponding to a period of 1s. In figure 6(a), one can notice that the two equivalent linear models are above the rock curve, meaning soil amplification. Conversely, the truly nonlinear results are under the red curve, meaning soil deamplification. As for figure 6(b), all methods are above the red curve, thus showing soil amplification. Indeed, at 1s period, the acceleration given by the attenuation relation is very low and nonlinear effects are small to inexistent.

3.1. Comparison with experimental data

The comparison with experimental data is important to check the reliability of the numerical methods and a way to improve them. In this study, we have computed site/reference spectral ratios for all sites from 11 small events around Nice. Station NBor is the reference station located on rock (Mount Boron). Due to the small input PGA_r of these data, we expect only linear soil behavior.

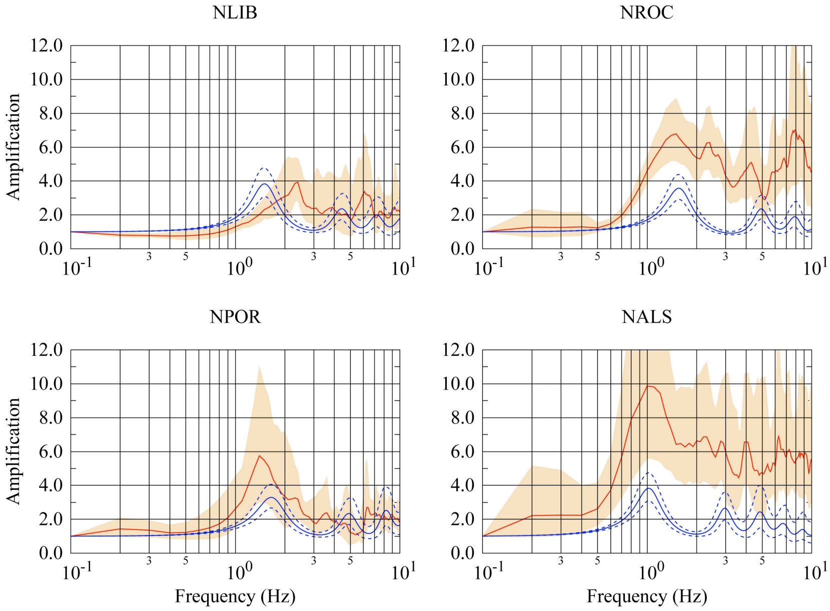

Figure 7: Empirical transfer functions for all four RAP stations. The red line is the mean value and the dashed area corresponds to the 68% confidence limits. The blue lines are the mean and the 68% confident limits for the ensemble of simulations.

Figure 7 shows the empirical transfer function for all four RAP stations. We can observe that the fundamental frequency has been well captured by the numerical models in all sites. Stations NLib and NPor can be approximated by 1D soil response. On the contrary, stations NAls and NRoc show that 2D/3D effects may be present. Semblat et al (2000) and Gélis et al (2008) have shown that 2D modeling produce closer results to the observed data. Thus 1D modeling cannot be used to correctly asses the seismic hazard in these two stations.

4. CONCLUSION

In this study, we have computed site-specific soil amplification factors for different earthquake excitation levels at four RAP sites in Nice. This methodology permits the computation of site effects from linear to nonlinear response and the quantification of uncertainties related to both the soil profile and the input ground motion. In addition, we have tested different wave propagation methods in order to see the difference in the resulting site response analysis. All these computations assumed 1D vertically-incident wave propagation.

The variability of the soil model and the input ground motion affect the total uncertainty of the computed transfer function. We see an increasing uncertainty for increasing input PGA_r values and for increasing frequency. We interpret this result by the fact that higher frequencies are largely affected by the lack of knowledge of the fine details of the local structure. This is, in addition, exacerbated for the nonlinear case due to the shear modulus reduction dependency of the shear strain.

Seismologists use the transfer function to study soil amplification effects. Conversely, engineers use the response spectra as a measure of the ground motion. Thus, we also computed the response spectral ratio as an engineering proxy for the transfer function. Note, however, this is not true because the response spectra depend on the damping of the oscillator. The computed response spectral ratios have been grouped according to the input PGA level, and for different frequencies of the response spectra. These results can directly be used to correct deterministic seismic hazard analyses that use empirical ground motion prediction equations. Indeed, the output of these equations is the response spectra on rock. Thus, by adding the soil effect (response spectral ratio), one obtains site-specific response spectra on soil. We can go further by doing a complete probabilistic seismic hazard as suggested by Cramer (2003) and explained in the corresponding section of this work.

This result, however, has to be handled with care since a simple nonlinear modeling has been done (total stress analysis). In the presence of water pressure, liquefaction and cyclic mobility may strongly change these results. In addition, 2D or 3D effects may be important. This might be the case for the four sites since empirical transfer functions have a much stronger amplification values than the computed ones.

Although 2D methods are closer from the empirical transfer functions the cost of these methods prevent from applying the whole methodology describes in this study. The results of the 1D numerical simulations are a first approximation of site effects in Nice.

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