Site response analysis including earthquake input ground motion and soil dynamic properties variability

F. Lopez-Caballero
Ecole Centrale de Paris, France

C. Gelis
Institut de Radioprotection et de Surete Nucleaire, France

J. Regnier
CETE-Mediterrannee, France

L.F. Bonilla
Universite Paris Est - IFSTTAR, France

SUMMARY
Earthquake engineering analyses often concentrate on the variability of soil properties when computing site-specific ground motion. Conversely, the earthquake source is modelled as a simple modulated noise that fits a target response spectrum. In this study we propose to evaluate the site-specific ground-motion variability including the overall effect of the input ground motion as well as the dynamic parameters of the soil column. In this case, we show that including realistic input ground motions may strongly control the total variability of soil response and computed ground motion. This is very important when assessing site-specific probabilistic seismic hazard studies where rock uniform hazard spectra (UHS) estimates are usually computed. Such studies have an inherent uncertainty related to all possible scenarios that contribute to the seismic hazard, which should be taken into account.

Keywords: Site response, soil variability, nonlinear soil behaviour

INTRODUCTION

Local site effects have long been recognized as an important factor contributing to variations in strong ground motions. Their study is one of the most important goals of earthquake engineering. Seismic hazard evaluations are calculated over broad geographical areas; however, as more ground motion data are collected, the local geology condition is emerging as one of the dominant factors controlling the variation in ground motion and determination of the site-specific seismic hazard for a given earthquake.

Site response analyses are usually performed in a deterministic way. This means that soil elastic and dynamic properties remain constant through the analysis. At most, several input ground motions are used when computing nonlinear soil computations to assess the variability of the obtained time histories. This is because the soil dynamic properties play an important role, especially when the material enters into a nonlinear regime. Recorded data generally show high frequency de-amplification and a shift of the soil resonant frequency to lower frequencies.
In this paper, we study the effect of input motion and soil parameters variability on numerical site response evaluation. In particular, we show the effect of nonlinear soil response on the dispersion of computed ground motion.

2. NUMERICAL SIMULATIONS METHOD

2.1. Probabilistic soil column properties

It is well known that the shear-wave velocity profile and the nonlinear modulus reduction and damping curves have a significant impact on the soil behaviour subjected to cyclic loading. Furthermore, the estimation of the soil profile layout, the corresponding properties (e.g. Vs, density, shear modulus) and their evaluation in situ and in the laboratory exhibits some degree of uncertainty. Recently some authors (Koutsourelakis et al., 2002; Popescu et al. 2006; Rathje et al. 2010) among others propose to adopt probabilistic approaches in practical earthquake engineering applications. In this way, the variability in soil properties can be incorporated in site response analysis through a Monte Carlo simulation. This method allows estimating the statistical response of a model by computing their response for different input parameters values. Two main sampling procedures can be used to generate these parameters: simple random sampling and Latin hypercube sampling (Xu et al. 2005; Helton et al., 2006). According to Xu et al. (2005) several studies point out that Latin hypercube sampling (LHS) can more exhaustively explore model parameter space than simple random sampling with a smaller sample size.

In this work, the relevant input parameters are the shear wave velocity profile and the shear modulus reduction curves. The studied response parameters concern both the acceleration level and spectral response at free field. According to Griffiths and Fenton (2001), Popescu et al. (2006) among others, there is no clear evidence pointing to any specific model for the probability density function (pdf) of soil properties. However, they proposed to use non-negative functions as Beta, Gamma or lognormal for many material properties. The probabilistic shear-wave velocity profiles generated for Latin hypercube simulations are based on a baseline shear-wave velocity profile. The baseline shear-wave velocity profile used in this study is based on the model proposed for the IWTH08 KiK-net station (see section 3) and it is assumed to be characterized statistically by a lognormal distribution at any given depth. The baseline shear-wave velocity profile defines the mean values of Vs and in order to take into account the uncertainty several values of the coefficient of variation (CV) varying from 10 to 30% are used. Figure 1 displays one of the obtained uncertainty shear-wave profile for CV_{Vs}=20%. In this figure, the median, the ± one standard deviation and the range of Vs profiles determined by Latin hypercube sampling are showed. These summarized curves involve 100 sample computations. The range of Vs profiles represents the limits of the probabilistic profiles. It is important to note that the median response obtained is in agreement with the baseline shear-wave velocity profile, meaning that the statistical model converge at least at first order.

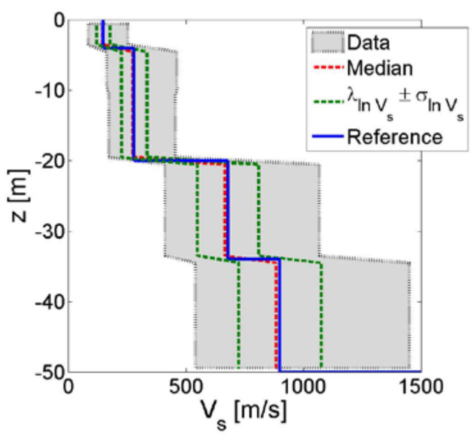

Figure 1. Simulated probabilistic shear-wave velocity profiles (CV=20%)

Concerning the probabilistic shear modulus degradation (i.e. G-γ) curves, according to the used backbone stress-strain model (i.e. the hyperbolic model) the nonlinear relation is controlled by the γ_{ref} parameter following the hyperbolic model (Konder and Zelasko, 1963). Thus the randomness in the dynamic properties of the soil is introduced through this parameter. It is assumed that γ_{ref} is characterized statistically by a lognormal distribution with a coefficient of variation (CV) varying from 20 to 30%. Figure 2a shows the mean, the ± one standard deviation and the range of G/G_{max} curves determined by LHS. The choice of simulation (i.e. only one random parameter) implies a variation of the CV of G/G_{max} for each γ level. It means that for lower γ values the randomness of these curves is due principally to Vs dispersion and for higher strain levels the randomness is a combination of both Vs and γ dispersion.

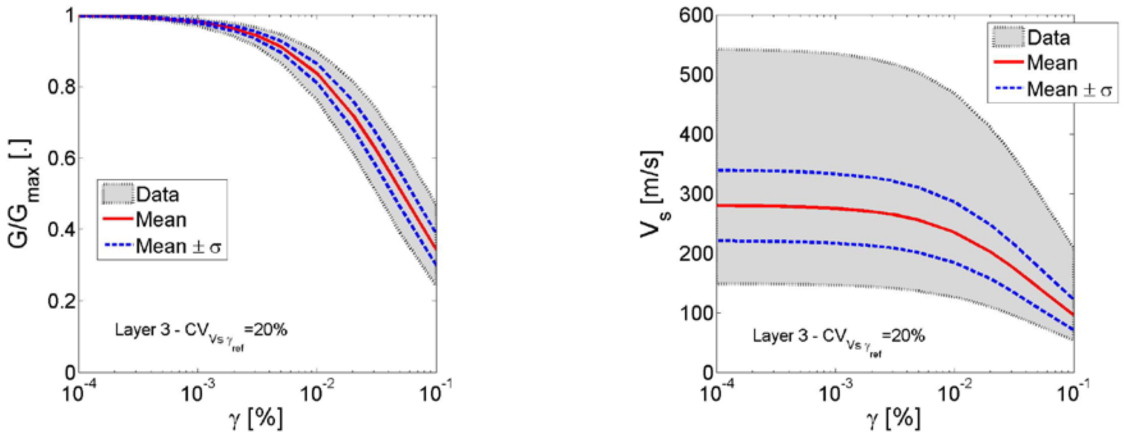

Figure 2. Simulated probabilistic a) G/G_{max}–γ and b) Vs–γ

2.2. Shear-wave propagation in soil columns

When waves are propagating through a medium, part of the energy is converted to heat and is lost during the propagation. This phenomenon called intrinsic attenuation is thought not to depend on frequency or on shear deformation level. To model the wave propagation in a viscoelastic model, we follow the technique of Liu and Archuleta (2006) based on a generalized Maxwell model (Day and Bradley, 2001). In this technique, energy is dissipated through the use of memory variables that allow to implementing constant attenuation between 0.1 and 50 Hz through quality factors ranging between 5 and 5000.

In the case of strong motion propagating on soft soils, the shear strain becomes significant and nonlinear soil behavior may take place (Iai et al., 1995; Ishihara, 1996). In this study, we adopted the nonlinear soil rheology proposed by Towhata and Ishihara (1985) and Iai et al. (1990). This is a plane strain model that is relatively easy to implement and needs only the angle of friction and the cohesion when pore pressure is not taken into account, which is the case in this paper. The material strength is computed following a Coulomb's criterion, and the stress-strain relation follows the hyperbolic model. Bonilla et al. (2005) modified the nonlinear constitutive model of Towhata and Ishihara (1985) and Iai et al. (1990) so that hysteresis cycles are assured by applying the Generalized Masing Rules operator. In order to take into account low strains damping (viscoelastic part) and hysterestic attenuation (nonlinear part), we follow Assimaki et al. (2010) approach where the total energy dissipated in the soil is equal to the sum of attenuation related to small shear strain damping modeled with the technique of Liu and Archuleta (2006) and hysteretic damping accounted for through the nonlinear constitutive model.

3. CASE STUDY: IWTH08 KIK-NET STATION

3.1. Selection of the studied site

To evaluate empirically the site response, the common way is to perform spectral ratio between signals recorded simultaneously on sediments and a nearby reference site, usually a rock site. When applying this technique, the main issue to be overcome is the selection of a reference site. The reference site must not amplify seismic waves and should be close enough to the studied site so as the travelling path from the seismic source remains equivalent for both sites. Vertical array of accelerometers, with a borehole reference site, overcome this issue. We selected the site among the Kiban-Kyoshin Network (KiK-net) in Japan that is characterized by sites with borehole and surface stations. For most of the sites, shear and compressive waves velocity profiles are available. These velocity profiles are obtained from downhole PS logging measurements down to the borehole stations depth generally located between 100 and 200 m.

We calculated for each site the empirical linear borehole response (namely the Fourier spectral ratio between the surface and the borehole). We use earthquake data with PGA at depth lower than 10 gals. For each recording at each site we select the signal (beginning of the P-waves arrivals until the end of the coda wave) along with the pre-event noise. We calculate the Fourier transform of the recordings at depth and at the surface for the 3 components of motion and compute the quadratic mean of the horizontal spectral ratio of the surface to depth spectrum (Régnier et al, 2012). Then for each site the mean and 95% confidence limit of the borehole spectral ratio were computed. We choose a given site that accomplishes the following criteria:

1. The empirical linear site response is close to the 1D configuration.
2. The linear site response variability is weak (the variability correspond to the inter-events variability)
3. The station has also recorded strong events and has non-negligible nonlinear soil behavior.

The station IWTH08 fulfils all the requirements previously defined. As displayed in figure 3, this station is characterized by a strong amplification at 2.9 Hz associated to the velocity contrast located at 50 m depth and having broadband amplification from 6Hz up to 12Hz. The H/V curve and the empirical borehole site response indicate the same first peak and the same trend for the broadband amplification which suggest that the down going wave field did not pollute significantly the borehole recording. Furthermore, the numerical simulation is in very good agreement with the empirical evaluation indicating that the shear wave velocity profile at this station is valid and the site configuration is 1D. Finally, the empirical linear site response has a very low inter-event variability, which was already highlighted by Baise et al (2011). Three events with surface PGA higher than 100 gals were recorded at this station. The comparison between linear and nonlinear site response showed in figure 3 indicates that there is significant difference (at 95% probability level) between linear and non-linear site response evaluation suggesting that the soil behaves nonlinearly at this station.

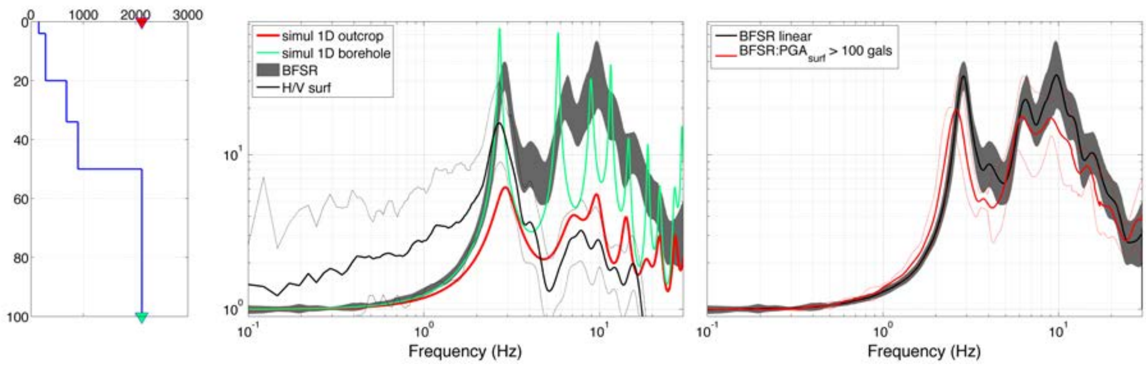

Figure 3 : Left : shear wave velocity profile of the station IWTH08. The triangles indicate the location of the stations used to compute the borehole site response . Middle : Comparison of site response curves calculated empirically (earthquake) and numerically (Haskell-Thopsom). The red curve displays the numerical outcrop site response. The green curve displays the numerical borehole site response curve. The gray area represents the 95% confidence limit of the empirical linear borehole site response. The black plain and dashed curves represent the mean and 95% confidence limit of the H/V curve at the surface. Right : Comparison of the site response curve obtained from weak motion (PGA at depth lower than 20 gals) and the one from strong motion (PGA at surface greater than 100 gals). The black curve represents the mean and the gray area the 95% confidence limit.

3.2. Selection of input motion

We selected three sources of acceleration time series:

1. Iervolino and Cornell 2005 (hereafter called “T1_nh”),
2. Kayhan et al., 2011 (hereafter called “PS1a2”).
3. KiK-net recordings from IWTH17 site (hereafter called “acc”).

We choose IWTH17 that is located in the same districts as IWTH08, which is characterized by a high Vs30 (1270 m/s). Figure 4 shows the site response curves at IWTH17. The borehole spectral ratio (BFSR) is flat up to 10 Hz and the amplitude of the H/V curve is quite low (below 3) up to 30 Hz. This suggests negligible site effects for this station. Then we select 20 earthquakes having the strongest PGA and were recoded at this site (figure 5).

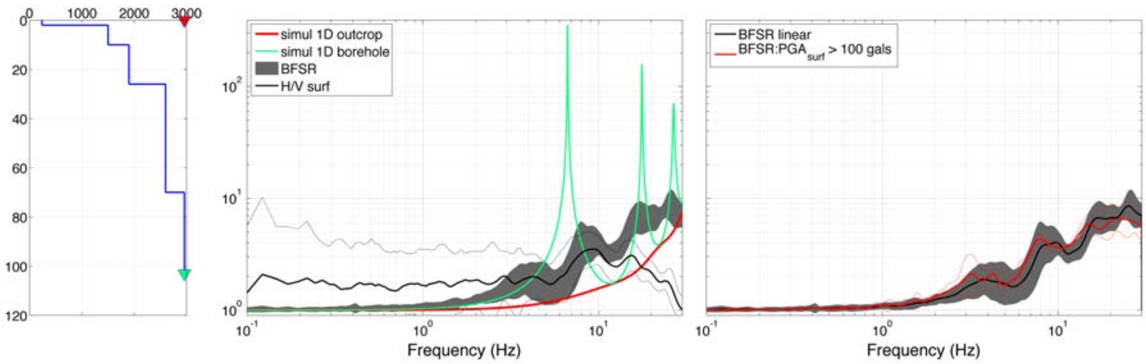

Figure 4 : Same as figure 3 for station IWTH17.

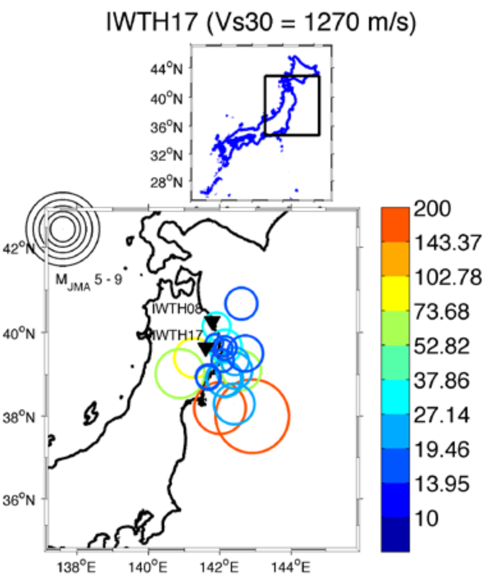

Figure 5: Location of the epicentre of the 20 greatest earthquakes recorded at the site IWTH17 according to their surface PGA.

In order to have more signals that increase the non linear behavior of the studied soil, 17 earthquake records proposed by Iervolino and Cornell (2005) and Kayhan et al., (2011) are also used. The events range in magnitude between 5.2 and 7.6 and the recordings are at site-to-source distances from 15 to 50km and dense-to-firm soil conditions (i.e. 360m/s < Vs 30m < 800m/s).

RESULTS

3.1. Probabilistic shear waves velocities

We compare the deterministic PGAs and the mean PGAs calculated with different coefficient of variation associated to the random generation of soil profiles. The shear wave velocity of each layer is first considered as random (figure 1) whereas the soil nonlinear properties are fixed. Figure 6 shows PGA values at the surface ground motion as a function of the PGA input motion (PHA). When PHAs are small, the ground motion is amplified in the soil column and computed PGA is predominantly greater than PHA. When the input increases, PGA increases more slowly due to soil nonlinearity (i.e. the soil damping increases affecting the higher frequencies). Above a PHA of 0.25g, PGA values at surface are lower than those at depth; nonlinear soil behavior deamplifies the input motion. This saturation effect is characteristic of nonlinear effects (e.g. Bonilla et al., 2011).

Moreover, deterministic PGAs at surface are most of the time greater than mean PGAs whatever the coefficient of variation (figure 6). Additionally, higher coefficients of variation lead to lower PGAs at surface as shown in figure 7. Figure 8 displays the PGA coefficients of variation at surface as a function of PHA. When PHA increases, the coefficient of variation for PGA also increases and becomes higher than the Vs profiles coefficients of variation.

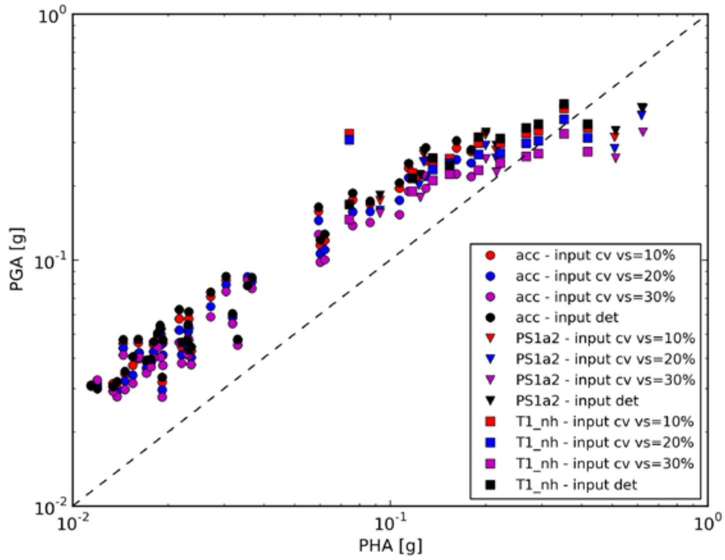

Figure 6: Deterministic PGA ("det") and mean PGA calculated with different coefficients of variation of the shear wave velocity (10%, 20%, 30%) for different input motion ("T1_nh" from Iervolino et al., 2005; "PS1a2" from Rayhan et al., 2010; "acc" recorded at station IWTH17)

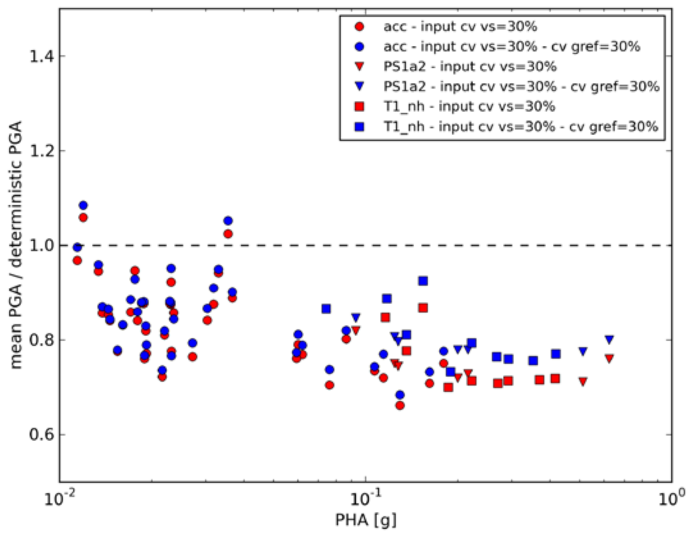

Figure 7: Ratio of mean PGA and deterministic PGA as a function of PHA for the different coefficients of variation of the shear wave velocity profiles and the different input motions.

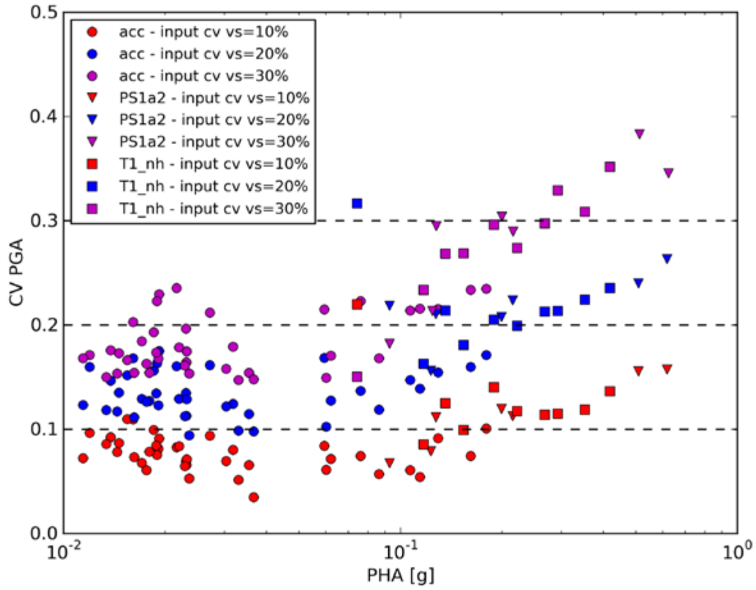

Figure 8: PGA coefficients of variation as a function of PHA for the different coefficients of variation of the shear wave velocity profiles and the different input motions.

Therefore, taking into account the shear waves velocity variability with constant nonlinear properties leads to a decrease of the mean PGA at surface while increasing the coefficient of variation. Rathje et al. (2010) obtained similar results with an equivalent-linear soil constitutive model.

As suggested by Idriss (2011), the presence of nonlinearity may be observed in real data by looking at the PGA as a function of PGV/Vs30 (PGV: Peak Ground Velocity) that roughly approximates the shear strain. We show in figure 9 the comparison between observed data at station IWTH08 and computed values with real accelerograms. When PGV/Vs30 increases, PGA increases more slowly and a saturation effect appears, showing the presence of nonlinearity.

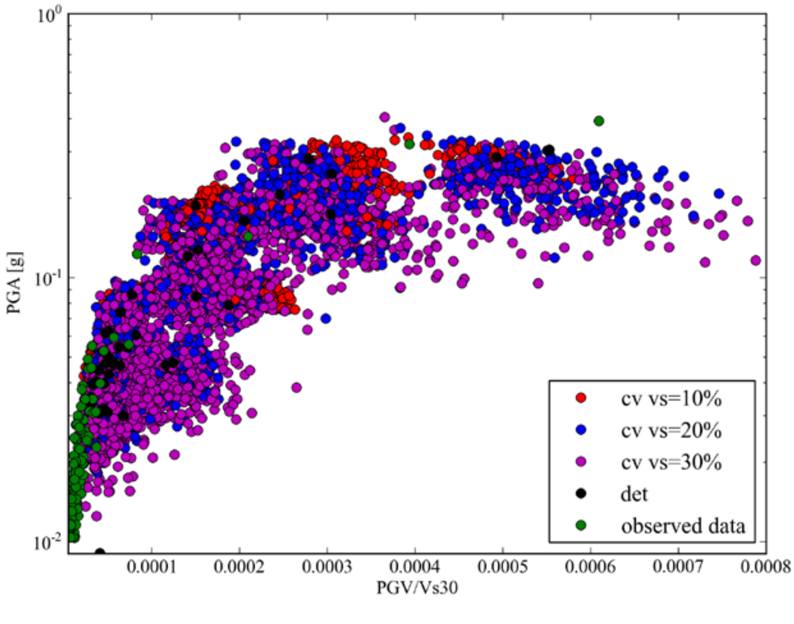

Figure 9: PGA as a function of PGV/Vs30.

3.2. Probabilistic shear wave velocities and soil nonlinear properties

We now consider the variability of shear wave velocity profile together with the soil nonlinear properties (figures 1 and 2). Figures 10 and 11 shows the mean PGA related coefficient of variation as a function of the PHA. Previous results are added for comparison. With the variability of both shear waves velocity profiles and soil nonlinear properties, mean PGA decrease is more pronounced than with the shear waves velocity variability only, whereas the coefficient of variation is higher.

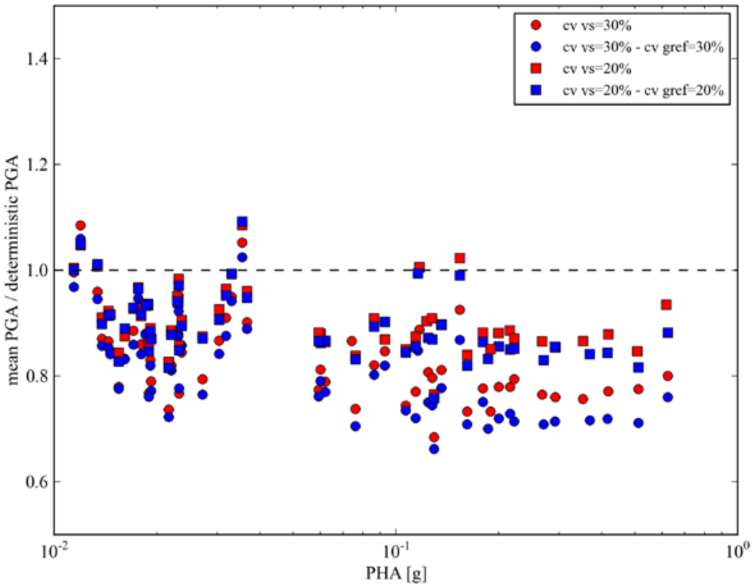

Figure 10: Ratio of mean PGA and deterministic PGA as a function of PHA for 20% and 30% coefficient of variation of the shear wave velocity profiles and the nonlinear properties for the different input motions.

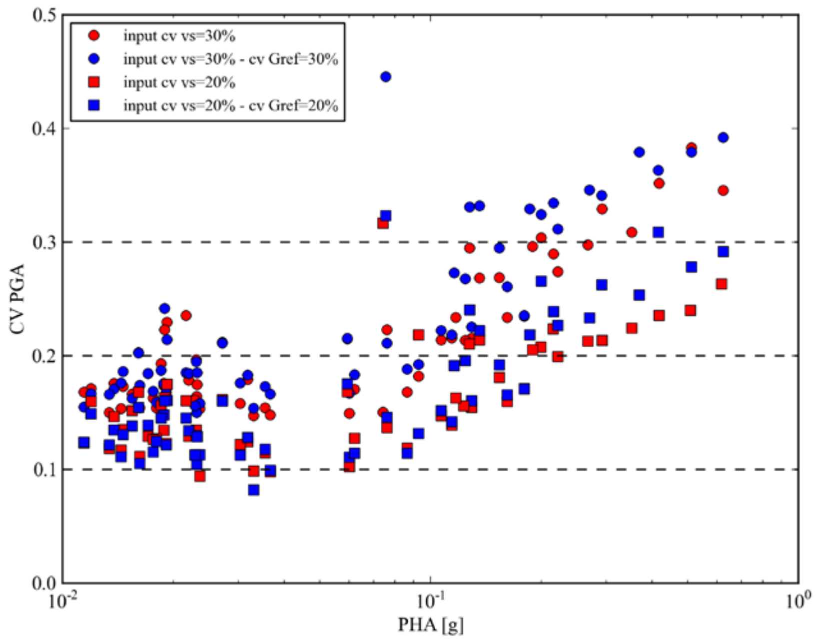

Figure 11: PGA coefficients of variation as a function of PHA for 20% and 30% coefficient of variation of the shear wave velocity profiles and the nonlinear properties for the different input motions.

CONCLUSIONS

This study shows that when adding variability to the soil profiles (shear waves velocity and soil nonlinear properties) the PGA generally increases its variability while decreasing its mean value as Rathje et al. (2010) previously noticed. This suggests that introduction of variability is not necessarily conservative. Therefore, when soil variability is introduced, the choice of the coefficient of variation must be carefully chosen and potentially assessed with data (i.e. Moss (2008) gives values of coefficients of variation associated with different methods of Vs30) helping the determination of realistic coefficients of variation to be used in earthquake response analyses.

AKCNOWLEDGEMENT

This research was partly funded by the 2012 GIS-RAP project entitled « Influence de la variabilité du milieu et de la sollicitation sismique sur l’évaluation des effets de site ».

REFERENCES

Baise, L.G., 2011. Complex Site Response - Does One-Dimensional Site Response Work? in 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion, August 23-26, 2011, University of Santa Barbara, 2011.

Bonilla L. F., Archuleta J. R. and Lavallee D., 2005. Hysteretic and dilatant behaviour of cohesionless soils and their effects on nonlinear site response : field data observation and modelling. *Bull. Seism. Soc. Am*., **95, 6**, 2373-2395.

Bonilla, L., C. Gelis, and J. Regnier, The challenge of nonlinear site response: field data observations and numerical simulations, in 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion, August 23-26, 2011, University of Santa Barbara, 2011.

Griffiths D. V. and Fenton G. A. (2001) Bearing capacity of spatially random soil: the undrained clay Prandtl problem revisited. *Géotechnique* **51:4**, 351-359.

Helton J. C., Johnson J. D., Sallaberry C. J. and Storlie C. B. (2006) Survey of sampling-based methods for uncertainty and sensitivity analysis. *Reliability Engineering and System Safety* **91:9-10**, 1175-1209.

Iai S., Matsunaga Y. and Kameoka T., 1990. Strain space plasticity model for cyclic mobility, *Report of the Port and Harbour Research Institute*, **Vol.29**, pp. 27 –56.

Idriss, E. 2011. Use of Vs30 to Represent Local Site Conditions, in 4th IASPEI/IAEE International Symposium: Effects of Surface Geology on Seismic Motion, August 23-26, 2011, University of Santa Barbara, 2011.

Iervolino I. and Cornell C.A., 2005. Record Selection for Nonlinear Seismic Analysis of Structures, *Earthquake Spectra*, Volume **21**, No. **3**, pages 685–713

Ishihara K., 1996. Soil Behaviour in Earthquake Geotechnics. Oxford engineering science series 46.Oxford science publications.

Kayhan A.H., Korkmaz K.A., Irfanoglu A. (2011). Selecting and scaling real ground motion records using harmony search algorithm. *Soil Dynamics and Earthquake Engineering*, **31,** 941–953

Konder, R.L., and J.S. Zelasko (1963). A hyperbolic stress-strain formulation for sands, in Proc. of 2nd Pan American Conference on Soil Mechanics and Foundation Engineering, Brazil, 289-324.

Koutsourelakis S., Prévost J. H. and Deodatis G. (2002) Risk Assessment of an interacting structure-soil system due to liquefaction. *Earthquake Engineering and Structural Dynamics* **31:4**, 851–879.

Liu P.C. and Archuleta J. R., 2006. Efficient modelling of Q for 3D numerical simulation of wave propagation. *Bull. Seism. Soc. Am*. **Vol. 96, No. 4A**, pp. 1352-1358.

Moss R.E.S. (2008). Quantifying Measurement Uncertainty of Thirty-Meter Shear-Wave Velocity. *Bulletin of the Seismological Society of America*, Vol. **98**, No. **3**, pp. 1399–1411, doi: 10.1785/0120070101

Popescu R., Prévost J. H., Deodatis G. and Chakrabortty P. (2006) Dynamics of nonlinear porous media with applications to soil liquefaction. *Soil Dynamics and Earthquake Engineering* **26:6-7**, 648-665.

Rathje E. M., Kottke A. R. and Trent W. L. (2010) Influence of Input Motion and Site Property Variabilities on Seismic Site Response Analysis. *Journal of Geotechnical and Geoenvironmental Engineering* **136:4**, 607-619.

Régnier, J. Cadet, H., Bonilla, F., Bertand, E., Semblat, J.F. (2012) Quantifying the effects of soil non-linear behavior on site response: Statistical analysis on KiK-net data, To be submitted.to BSSA

Towhata I. and K. Ishihara, 1985. Modeling soil behavior under principal axes rotation, *paper presented at the*

Fifth International Conference on Numerical Methods in Geomechanics, Nagoya, Japan. Pp 523–530.

Xu C., He H. S., Hu Y., Chang Y., Li X. and Bu R. (2005). Latin hypercube sampling and geostatistical modeling of spatial uncertainty in a spatially explicit forest landscape model simulation. *Ecological Modelling* **185:2-4**,255-269.