Uncertainties related to large-scale earthquake simulations in the Pointe-à-Pitre Region

E. Foerster, F. De Martin, E. Bourdon, G. Courrioux, T. Ulrich, J. Abad, A. Lemoine & A. Roullé
BRGM, France

SUMMARY:
This paper aims at evaluating the impact of uncertainties in the simulation process performed for risk assessment purposes, considering earthquake scenarios of magnitude Mw 6, related to the Gosier fault located at South-East of Pointe-à-Pitre city (Guadeloupe). A local model (size: 7x7x0.1km^3) was built from the geological, geotechnical and geophysical data available in the urban zone. It was included into a regional model (size: 40x30x30km^3) with 4 main geological formations. In this study, different results have been compared, deriving from: 1) 3D viscoelastic regional simulations using a mesh grid valid up to 5 Hz and including topography; 2) 1D viscoelastic or elastoplastic "grid" simulations using columns either derived from the 3D regional model (maximum of 4 layers over bedrock) or with detailed geology (up to 7 layers) provided by existing geotechnical data (e.g. borehole data) and microzoning studies. In this paper, only the results obtained with 4 layers are presented.

Keywords: seismic site effects, large-scale simulations, uncertainties

1. INTRODUCTION

Quantitative risk assessment at urban scale is a challenging task, which requires assessing the seismic response of soils and potential damages on the built environment. For this purpose, deterministic simulations at regional scale (e.g. wave propagation from the seismic source to the target zone), as well as at the local scale (e.g. nonlinear site effects and soil-structure interactions), are to be performed, using some accurate three-dimensional (3D) models built from the available deep and surficial geological, geotechnical and geophysical data. However, in order for such simulations to be relevant for damage evaluation of structures and infrastructures at local scale, dispersion in the computed ground motion (e.g. amplitude, frequency content) is to be minimized, which implies to increase the spatial resolution, even at the regional scale, and hence, to dispose of high-performance computation codes, with accurate numerical methods. Thanks to the recent developments in parallel computation and improvements made for a decade regarding the numerical methods used in seismology (e.g. Finite Difference Method – FDM -, Spectral Element Method – SEM -, etc.), synthetic (i.e. computed) seismograms are now able to reproduce with good accuracy, observed seismograms in many sedimentary basins , as soon as a realistic velocity and attenuation model is available for the modeled geological medium (e.g. see Graves, 1996 ; Pitarka et al., 1998 ; Wald and Graves, 1998 ; Kawase and Matsushima, 1998 ; Satoh et al., 2001 ; Komatitsch et al., 2004).

In this study, one of the objectives was to quantify the linear and nonlinear site effects in the region of Pointe-à-Pitre city (Guadeloupe), as well as the related uncertainties, considering different earthquake scenarios of magnitude Mw 6, related to the Gosier fault located at South-East of Pointe-à-Pitre. For this purpose, first step has consisted in building a 3D detailed model corresponding to the urban zone of Pointe-à-Pitre. The local geology of this urban zone has then been included into a 3D regional model. Further details are given in section 2.

Then, 3D viscoelastic spectral-element (SEM) simulations have been performed, in order to assess linear site effects at the regional scale, using a mesh grid valid up to 5 Hz (horizontal/vertical spacing: 10m and 1m respectively). Finally, two sets of 1D "grid" simulations have also been performed, using columns derived from the 3D geological model and considering as input motion, the wave motion computed at bedrock within the 3D SEM model. The first set was based on a gross modeling at regional scale (4 geological formations and grid spacing as in the 3D SEM model). The second set was based on a refined modeling at urban scale (horizontal/vertical spacing: 5m and 0.5m respectively), including a detailed geology (up to 7 layers) provided by existing geotechnical data (e.g. borehole data) and microzoning studies. In this case, either a viscoelastic or an elastoplastic constitutive behavior is assumed for the 1D soil layers. In the section 3 of this paper, we present the regional viscoelastic site effect simulations and we assess related uncertainties by comparing the 3D and 1D simulation results, in terms of PGA maps on the entire domain, as well as the time history and response spectra in accelerations computed at specific receivers, such as high stake facilities of Pointe-à-Pitre (e.g. city council, airport, hospital, etc.).

2. THE 3D GEOLOGICAL MODEL AND VELOCITY STRUCTURE

Making a 3D geological model of the Pointe-à-Pitre urban region was a real challenging task, due to: (1) the lack of a homogeneous geological map over the target zone, which is at the junction between the volcanic domain of Basse-Terre and the calcareous one of Grande-Terre; (2) the important spatial and qualitative heterogeneity of available borehole data; (3) a broad urbanization with large infill areas, mainly composed of calcareous tuffs and dating from 1950s'.

The data used for building the 3D detailed model (size ~ 8 x 7 x 0.1 km^3) with the geological editor software (brgm Geomodeler©), was collected from:

- 2 geological maps available at 1/50,000 scale, from which content has been homogenized: the geological map of Basse-Terre dating from 1966 and which needs to be updated, and the one of Grande-Terre dating from 1988;
- IGN maps at 1/25,000 scale dating from 1950 and 2004, which helped determining the extent of infill zones;
- the French database for soils BSS (1,500 data points) and 143 geotechnical and geophysical investigation points collected by brgm in 2006 for liquefaction studies (see Fig. 1).

The detailed model is constituted of four main geological formations: a weathered limestone substratum, red clays, silty muds and ballast (which form soft sedimentary basins). The local model was then inserted into a regional model (size ~ 40 x 30 x 30 km^3) built from the 1D structure proposed by Dorel (1979) and including topography derived from a 40 m DTM. Table 2.1 gives the S- and P-wave velocities and quality factors derived within each formation, from the existing geophysical campaigns (e.g. SASW, cross-hole, H/V, etc.) and preliminary studies (Monge et al., 1998). Figure 2 presents both the extent of the 3D regional model with regards to the Guadeloupe Island, as well as a view of the detailed geological model.

Table 2.1. Elastic and viscoelastic features of the geological formations of the local and regional 3D models

Geological formations	Vs (m/sec)	Vp (m/sec)	Bulk density (kg/m^3)	Qs	Qp
Ballast	250	800	1600	10	30
Silty muds	200	1000	1500	10	30
Red Clays	350	1000	1700	10	30
Weathered Limestone	1000	2000	2000	25	75
Bedrock 1 *(0-3km)*	1500	3500	2500	50	150
Bedrock 2 *(3-12km)*	3410	6000	2500	50	150
Bedrock 3 *(12-15km)*	3980	7000	2500	50	150
Bedrock 4 *(15-50km)*	4550	8000	2500	50	150

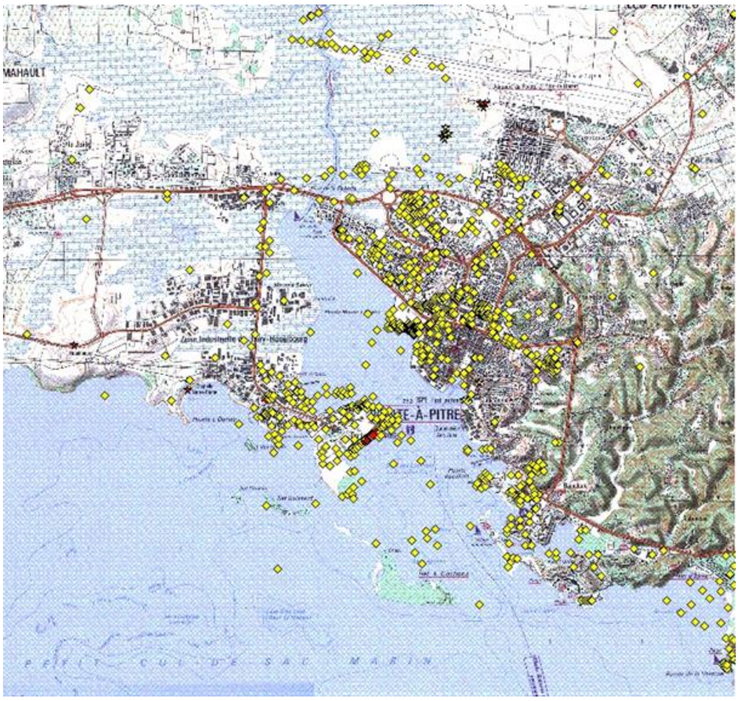

Figure 1. Data points (French database for soils BSS), used to build the 3D detailed model of Pointe-à-Pitre.

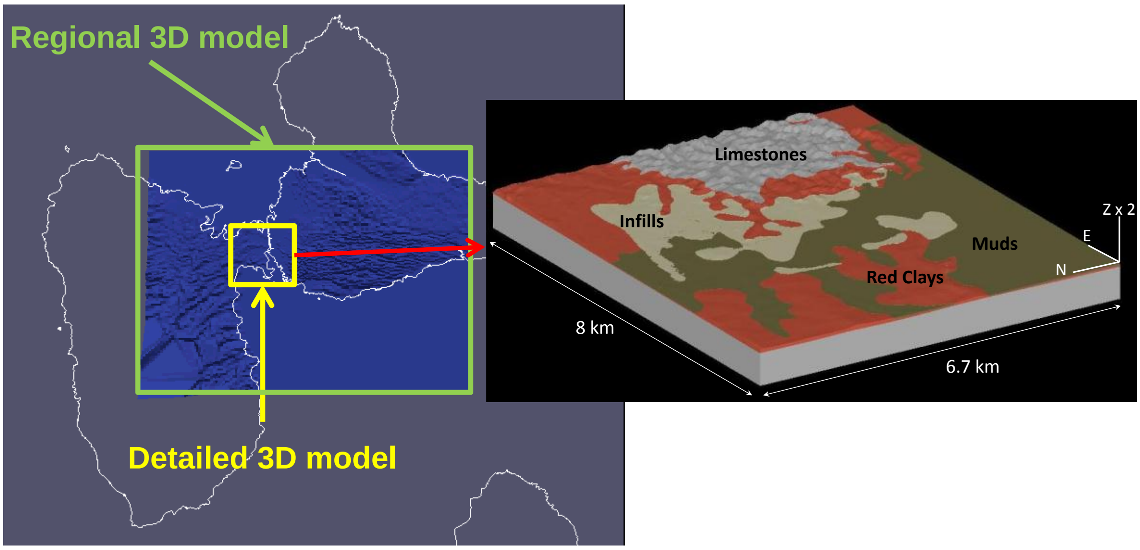

Figure 2. 3D local and regional models used for site effects simulations

3. QUANTIFYING SITE EFFECT UNCERTAINTIES AT REGIONAL SCALE

3.1. Description of the seismic scenarios

In this study, we have considered earthquakes possibly occurring on the Gosier fault, lying at South-East of Pointe-à-Pitre (see Fig. 3). The fault is assumed to be plane with 90° azimuth (fault strike direction with respect to North), 70° dip and a slip direction (rake) of -90° (Terrier et al., 2002). Two magnitude Mw=6.0 intra-plate shallow earthquake scenarios have been considered, assuming a kinematic rupture with heterogeneous slippage. This type of earthquakes is potentially very damaging (same type as the 1897 earthquake). The slip distributions of the finite-fault have been generated according to the spatial random field model developed by Mai & Beroza (2002). The fault plane (size:

10 x 5 km^2) has been divided into 7,881 segments, in order to reach a good accuracy for asperities. Two earthquake scenarios have been considered in this paper (see Fig. 4): the earthquake scenario “a” assumes an asperity located near the west edge of the fault (i.e. near Pointe-à-Pitre), whereas the scenario “b” assumes an asperity located near the east edge (i.e. far from the city).

Allowing to the double couple theory (e.g. see Aki & Richards, 2002), the body-force equivalent to shear faulting is a double-couple, corresponding to the energy radiated from the earthquake and defined by the seismic moment value M_0, which is expressed as a function of the average slip, rupture surface and shear resistance of each fault segment. In this paper, each fault segment contains a double-couple source point and we use the following relationship between the seismic moment and magnitude Mw (see Aki & Richards, 2002):

$$\log_{10} M_0 = 1.5M_w + 9.1 \tag{3.1}$$

Finally, the displacement source function is a hyperbolic tangent written as:

$$s(t) = 0.5\left(1 + \tanh\left(\frac{t-t_0}{\tau/5}\right)\right) \tag{3.2}$$

with τ, the rising time (fixed for each source point) and t0, the delay time, chosen as variable to simulate the propagation of a circular rupture). Results in this paper are shown for scenarios “a” and “b”, and for $\tau = 0.3$ sec.

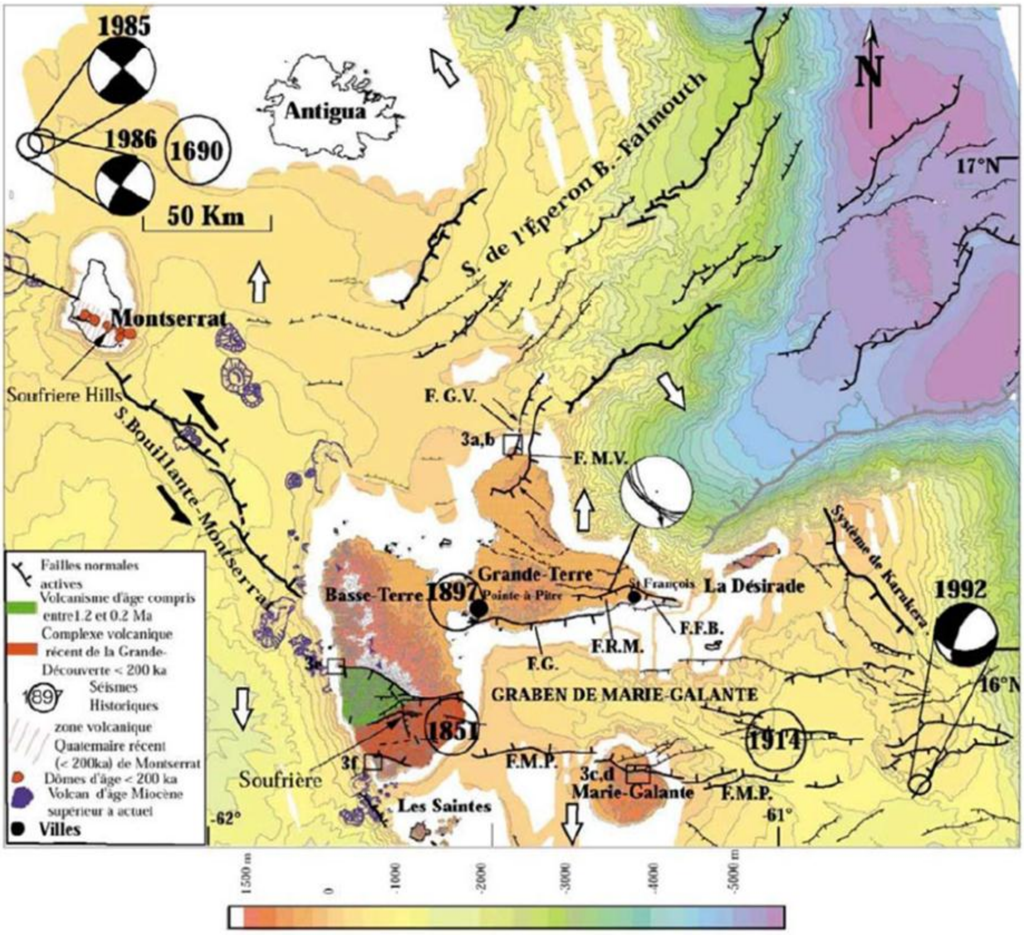

Figure 3. Normal faults of Guadeloupe archipelago (after Feuillet et al., 2001), with Gosier fault denoted as F.G (near Pointe-à-Pitre).

3.2. Numerical features of the 3D simulations

The 3D viscoelastic simulations at regional scale have been performed with EFISPEC3D, a brgm software based on the Spectral Element Method (SEM). It is a FORTRAN90 code, parallelized with MPI ("Message Passing Interface") and verified on the viscoelastic LOH.3 test from the "Southern California Earthquake Center" (cf. De Martin, 2010&2011).

In order to perform simulations valid up to 5 Hz, we have built a Scottish-type mesh (see Fig. 5), where the sedimentary basin zone of Pointe-à-Pitre is refined (horizontal/vertical spacing: 10m and 1m respectively). The final mesh, generated with GiD software (http://gid.cimne.upc.es/), is composed of 8,341,190 nodes and 8,205,084 hexahedral 8-node elements. 195,612 additional quadrangles have been used to discretize the absorbing boundaries (paraxial approximation P1, after Stacey, 1988). Shape functions of the spectral elements are 4^{th} – order polynomials.

An explicit time integration scheme has been used, which implies to choose a very small time-step for stability considerations. In this case, the time step value has been fixed to $2.5\ 10^{-5}$ sec, for simulated earthquake durations of 30 sec (120,000 time-steps per simulation).

The total number of kinematic degrees of freedom is 1,705,228,632. To solve the matricial system, the simulation domain has been distributed over 224 processing units (CPUs). Moreover, we use 8 memory variables for the viscoelastic behavior law (Liu and Archuleta, 2006), which requires to have about 440 Go of available memory for each simulation.

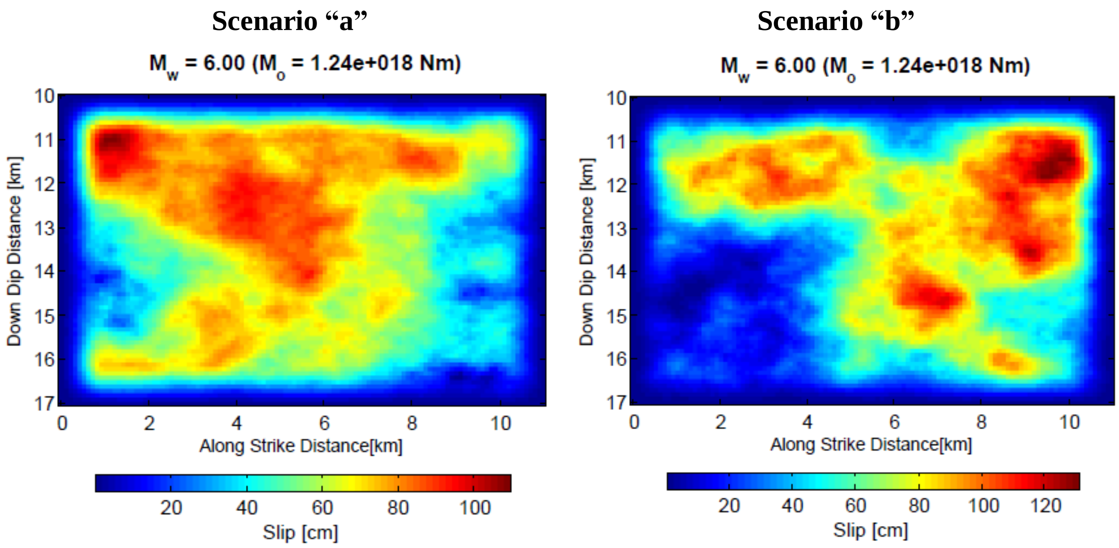

Figure 4. Slip distribution on the Gosier fault, for 2 scenario earthquakes "a" and "b" of magnitude Mw = 6.0 (after Mai & Beroza, 2002).

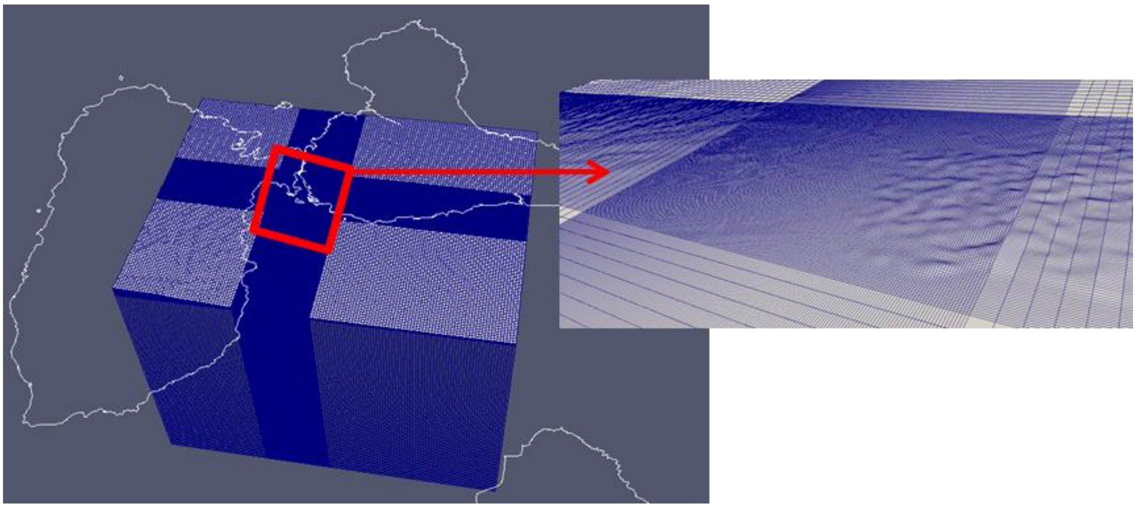

Figure 5. Scottish-type hexahedral mesh used for regional viscoelastic simulations (left) and zoom over the Pointe-à-Pitre region (right).

3.3. Results of the 3D simulations

Fig. 6 presents the velocity magnitudes computed every second during the wave propagation for the scenario “a” earthquake (see section 3.1 and Fig. 4). A site effect due to the sedimentary basin can be clearly seen on the Pointe-à-Pitre region at 8 and 9 seconds (black circles). Similar results are obtained for the scenario “b” earthquake and they will not be presented in this paper.

In Fig. 7, we compare the PGA (Peak Ground Acceleration) computed for both earthquake scenarios (“a” and “b”). We see that scenario “a” generally leads to higher PGA. Moreover, we observe that the most affected region is located at sea. This is due to the Gosier fault orientation and to the rupture mechanism.

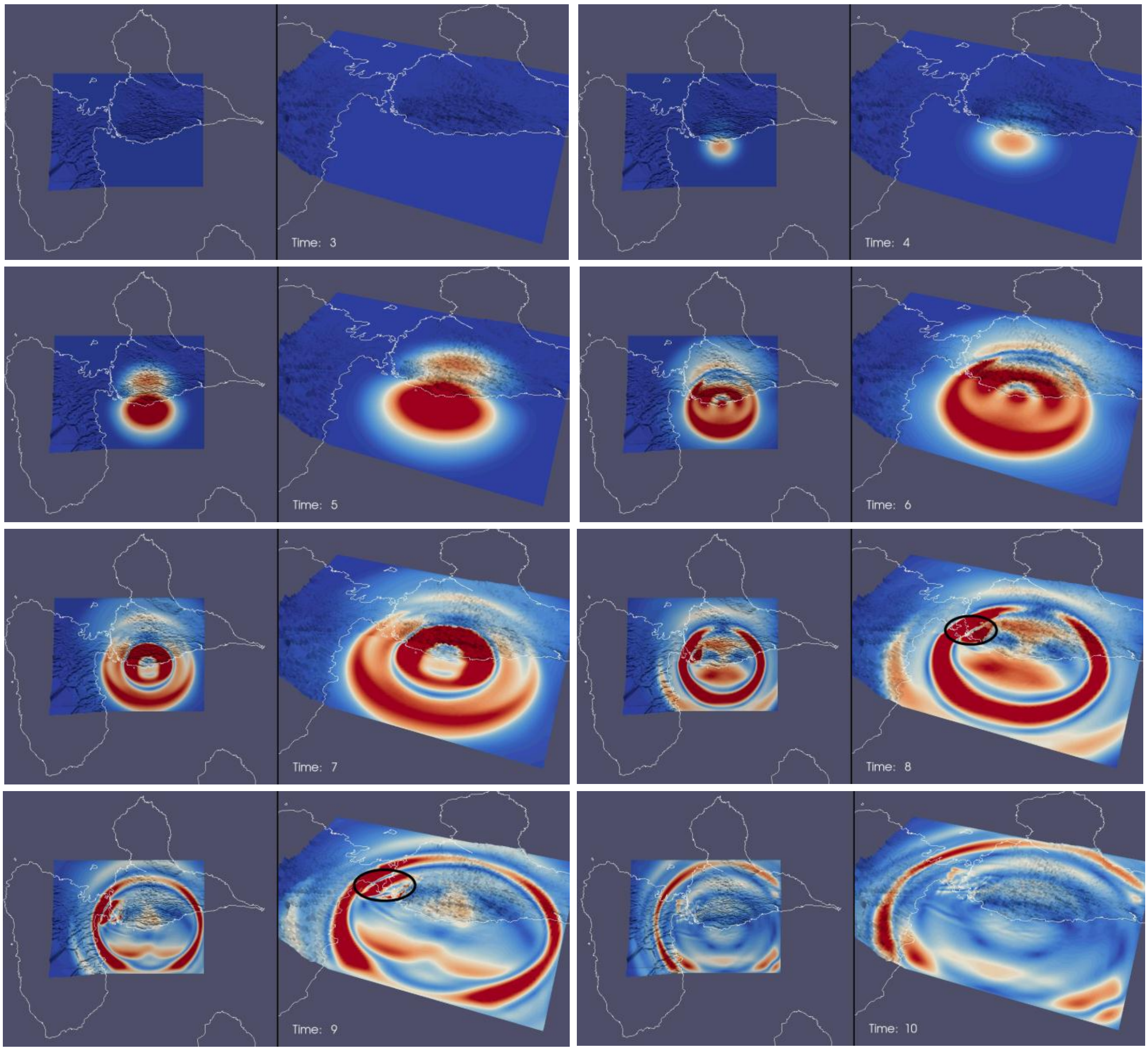

Figure 6. 3D regional simulation for the earthquake scenario "a": each snapshot shows the velocity magnitudes computed every second (plane representation on left and isometric view on right).

3.4. Comparing 3D and 1D viscoelastic simulation results

In order to assess uncertainties related to site effect simulations, a set of 1D "grid" viscoelastic simulations has been performed at regional scale, using 5,508 columns derived from the 3D geological model and considering as input motion, the wave motion (EW, NS and UP) computed at bedrock within the 3D SEM model. This 1D set is hence based on a gross modeling (4 geological formations and grid spacing as in the 3D SEM model).

The 3D and 1D site effect simulation results have been compared for the earthquake scenario "a", by looking at PGA maps on the entire domain (see Fig. 8), as well as the seismic response computed at specific receivers, such as high stake facilities of Pointe-à-Pitre (e.g. city council, airport, hospital, etc.). Fig. 9 and Fig. 10 present the time history and response spectra in accelerations computed with the 3D and 1D models near the city council of Pointe-à-Pitre.

First, we note that the computed NS accelerations are much higher than the EW ones, due to the normal fault mechanism. Then, we observe that 1D simulations underestimate both motion duration and computed amplitudes or PGA. This is due to the fact that 1D simulations can neither account for lithological and topographic site effects, nor for surface waves trapped within the sedimentary basin.

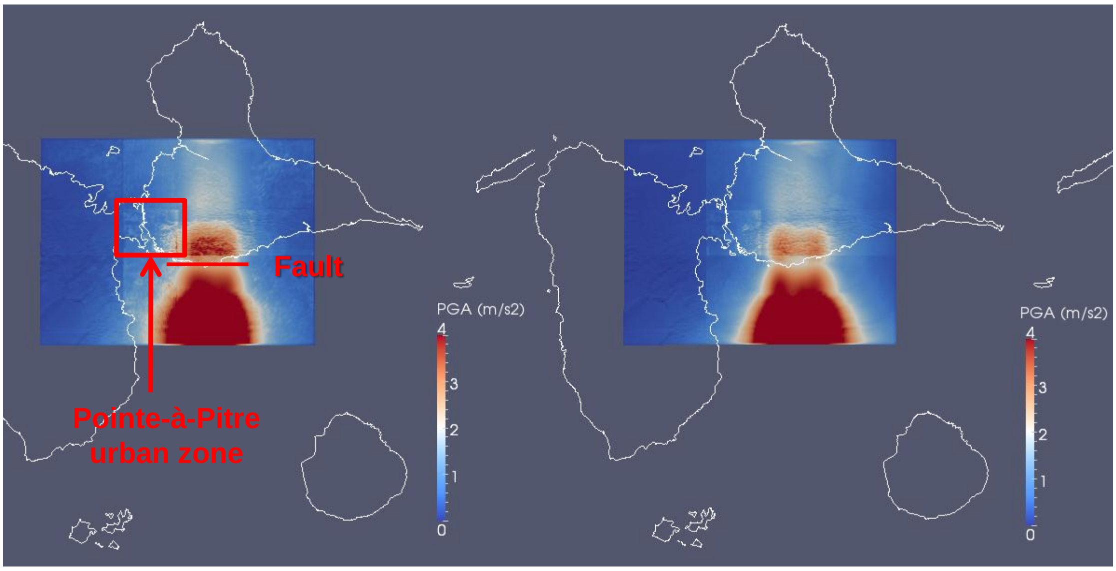

Figure 7. Comparison of PGA maps computed for the earthquake scenarios "a" (left) and "b" (right).

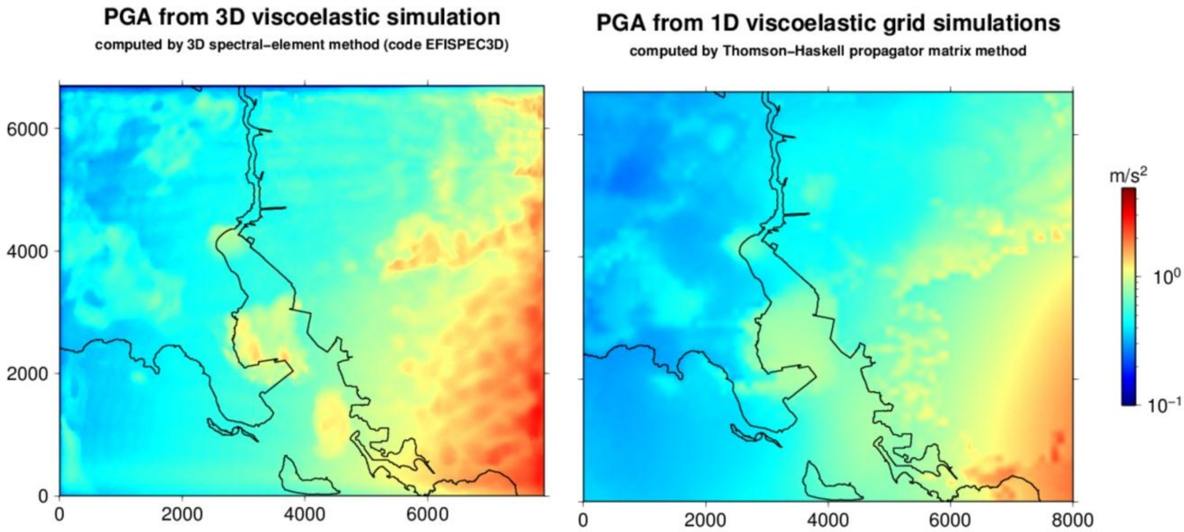

Figure 8. Regional PGA maps computed with the 3D (left) and 1D (right) models (earthquake scenario "a").

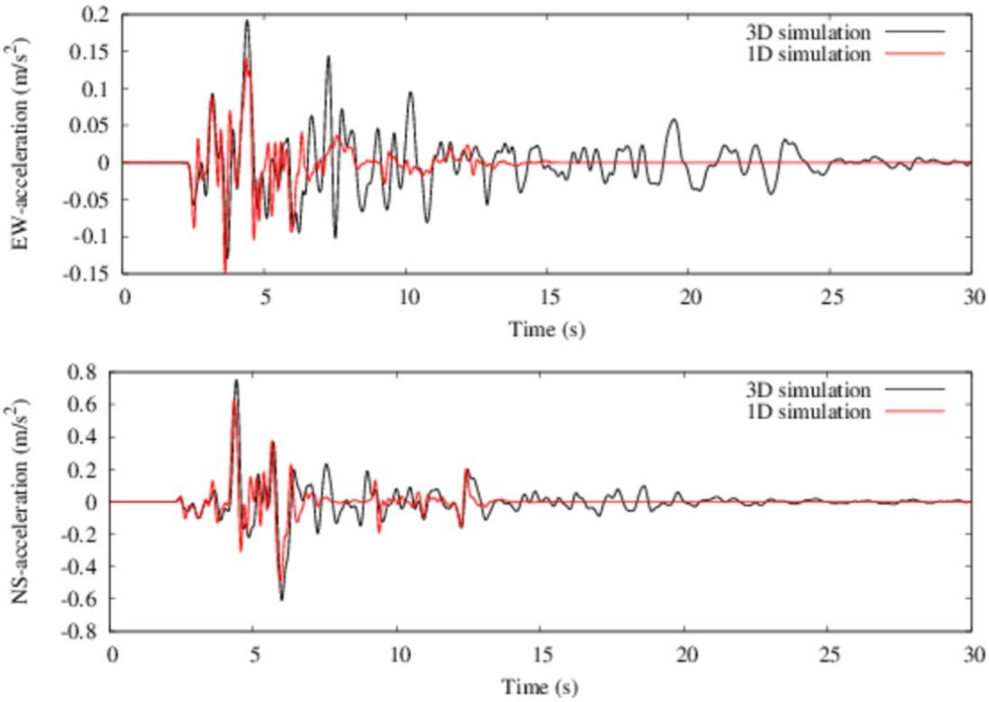

Figure 9. Time-history accelerations computed with the 3D (black) and 1D (red) models near the city council of Pointe-à-Pitre (earthquake scenario “a”).

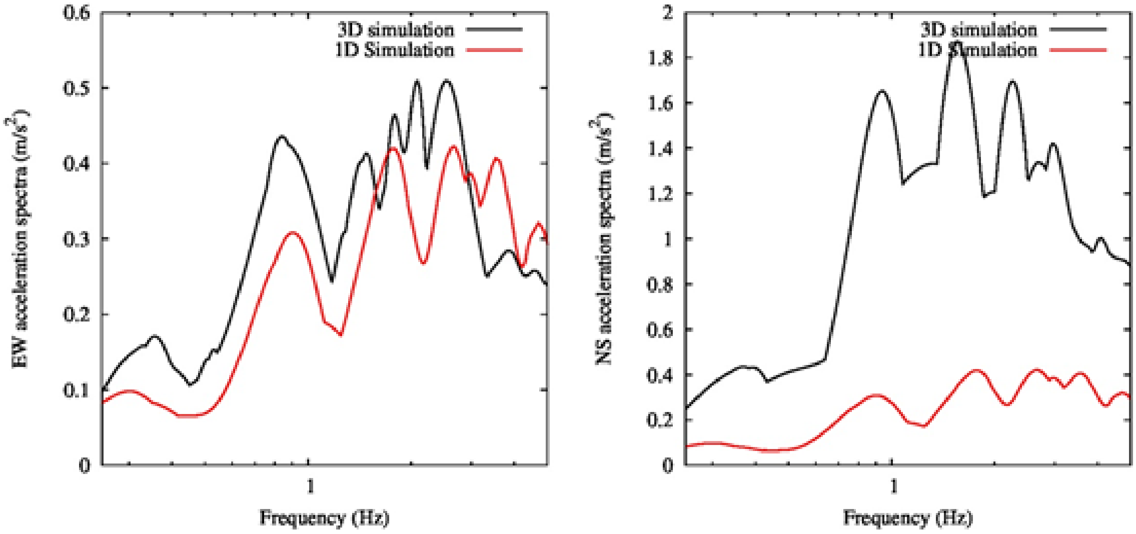

Figure 10. Response spectra in accelerations computed with the 3D (black) and 1D (red) models near the city council of Pointe-à-Pitre (earthquake scenario “a”).

4. CONCLUSIONS

The evaluation of uncertainties related to linear site effect simulation process has been performed by comparing the viscoelastic 1D (standard method used for seismic hazard assessment) and 3D (method proposed in this study) response in terms of time-history accelerations, response spectra in and PGA, computed near different high-stake facilities of the Pointe-à-Pitre region (e.g. city council, airport, etc.). For this purpose, a 3D regional model (size ~ 40 x 30 x 30 km^3) has been built, which is composed of 4 geological formations (weathered limestone, red clays, silty muds and ballast) within the first 100 m and 4 bedrock types underneath. Moreover, two intra-plate shallow earthquake scenarios (magnitude Mw=6), have been considered for analysis, with seismic source located along the Gosier fault.

The comparisons between 1D and 3D results show that 1D simulations globally underestimate the seismic aggression in terms of motion duration and computed PGA. In fact, contrary to 3D simulations, 1D approaches are not able to account for lithological and topographic site effects, nor for surface waves potentially trapped within the sedimentary basin.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support of PAP3D research project ‘‘Three-dimensional model for quantitative seismic analysis of site effects and soil-structure interactions at Pointe-à-Pitre/Jarry (Guadeloupe)’’, financed by the Guadeloupe Region and BRGM.

REFERENCES

Aki, K., and Richards, P. G. (2002). Quantitative Seismology. 2nd ed., University Science Books, ISBN 0-935702-96-2.

De Martin, F. (2010). Influence of the Nonlinear Behavior of Soft Soils on Strong Ground Motions. *Ph. D. thesis*, Ecole Centrale Paris, Paris, France.

De Martin, F. (2011). Verification of a Spectral-Element Code for the Southern California Earthquake Centre LOH.3 Viscoelastic Case. *Bull. Seism. Soc. Am.*, **101:6**, doi: 10.1785/0120100305.

Dorel, J. (1979). Seismicité et structure de l'arc des Petites Antilles et du Bassin Atlantique, *Ph. D. thesis*, University of Paris VI, France (in French).

Feuillet N. (2000). Sismotectonique des Petites Antilles. Liaison entre activité sismique et volcanique, *Ph. D. thesis*, University of Paris VII, France (in French).

Graves, R. W. (1996). Simulating realistic earthquake ground motions in regions of deep sedimentary basins. *Proc. of the 11th World Conference on Earthquake Engineering*. **CD-ROM No. 1932**.

Kawase, H. and Matsushima, S. (1998). Strong motion simulation in Kobe during the Hyogo-ken Nanbu earthquake of 1995 based on a three-dimensional basin structure. *J. Struct. Constr. Eng. Trans. Architectural Inst.*, **514**, 111–118 (in Japanese with English abstract).

Komatitsch, D., Liu, Q. Tromp, J., Suss, P., Stidham, C. and Shaw, J. H. (2004). Simulations of Ground Motion in the Los Angeles Basin Based upon the Spectral-Element Method. *Bull. Seism. Soc. Am.*, **94**, 187–206.

Liu, P. and R. Archuleta (2006). Efficient modeling of Q for 3D numerical simulation of wave propagation. *Bull. Seism. Soc. Am.*, **96**, 1352–1358.

Mai, P. M., and G. C. Beroza (2002). A spatial random field model to characterize complexity in earthquake slip. *J. Geophys.*, **107:B11**, 2308.

Monge, O., Vermeersch, F., Martin, C. (1998). Microzonage sismique de l’agglomération pontoise : extension aux communes des Abymes et du Gosier et homogénéisation. *Report BRGM/R 39213* (in French).

Pitarka, A., Irikura, K., Iwata, T., and Sekiguchi, H. (1998). Three-dimensional simulation of the near-fault ground motion for the 1995 Hyogo-Ken Nanbu (Kobe), Japan, earthquake. *Bull. Seism. Soc. Am.*, **88**, 428–440.

Satoh, T., Kawase, H., Sato, T., and Pitarka, A. (2001). Three-Dimensional Finite-Difference Waveform Modeling of Strong Motions Observed in the Sendai Basin, Japan. *Bull. Seism. Soc. Am.*, **91**, 812–825.

Stacey, R. (1988). Improved transparent boundary formulations for the elastic wave equation. *Bull. Seism. Soc. Am.*, **78**, 2089–2097.

Terrier, M., Combes, P., Carbon, D., Grellet, B., Sedan, O. (2002). Failles actives et évaluation de l'aléa sismique: prise en compte des failles actives dans l'aménagement du territoire aux Antilles (Martinique et Guadeloupe). Partie 1 : Identification des systèmes de failles actives dans l'archipel de la Guadeloupe. *Report BRGM/RP-51258-FR* (in French).

Wald, D. J. and Graves, R. W. (1998). The seismic response of the Los Angeles basin, California. *Bull. Seism. Soc. Am.*, **88**, 337–356.