Quantitative estimation of PGA in the French Riviera

by Víctor M. Cruz-Atienza[1,2*], Jean Virieux[1,2], Carine Kohrs-Sansorny[1,2], Olivier Sardou[2], Stéphane Gaffet[1] and Martin Vallée[1]

1 Géosciences Azur, CNRS, Sophia-Antipolis, France
2 GIS CURARE, Sophia Antipolis, France
* now at Department of Geological Sciences, San Diego State University, USA

SUMMARY: We have developed a finite difference technique for the simulation of seismic waves in elastic media with attenuation. The method is based on a numerical stencil on a rotated grid, stencil which provides stable and accurate results when considering complex topographies as well as waves encounter interfaces between solid and liquid. Double couple sources have been implemented allowing us a complete deterministic estimation of the ground motion once the medium properties have been established for a specified punctual sources.

This tool is quite adapted for area as the French Riviera where a strong continental topography is extended under the sea as a quite steep bathymetry. Both contribute to make the seismic signal quite complex when estimated along the sea shore. We have been able to perform seismic numerical modelling upto frequencies 1.5 Hz using a standalone computer for a medium of 40 km by 40 km by 30 km. We have considered various models as half-space with and without water zone although new models are now available with sediments. In spite of a quite simple initial model, the water layer induces amplification factor for the acceleration by a factor of five with respect to a simulation without water at sea bottom. As frequencies increase, the Peak Ground Acceleration (PGA) could be reduced by a factor of 0.8, which could be important for the possibility of triggering a submarine landslide. All these simulations have been performed with an earthquake of magnitude 4.5 at a deptb of 6.5 km and at a distance of 10 km from St-Jean Cap Ferrat peninsula towards the South.

MOTS-CLÉS : séisme, source ponctuelle, moment sismique, propagation des ondes, lois d'atténuation, amplification locale,

KEYWORDS: earthquakes, punctual source, seismic moment, wave propagation, attenuation law, local amplification.

1. Introduction

During this half-period of the QSHA project, a tool has been designed for simulating seismic wave propagation in 3D structures including water layer. While many softwares exist for seismic wave propagation, few can handle with fair precision both the solid and liquid areas with interaction and feedback. This is the purpose of the development of this tool.

The estimation of the ground motion is the key target of the seismologist for estimating seismic hazard. This is essential to provide the most accurate and quantitative estimation to engineers for building designs in order to sustain this ground motion and to reduce effects of the ground shaking by earthquakes. In order to do so, this estimation could envelop any expected ground motion the area may suffer. Up to now, this estimation is based on quite simple attenuation laws related to geometrical spreading in simple propagating media. These laws are calibrated for each selected zone and will depend on the geological context of the zone. As seismic records increase because of new earthquakes, variability of amplifications observed during seismic crisis could not be explained easily by these simple laws (Berge et al, 2003). We must improve our estimation of the propagation effects aside the improvement of source estimation by combining different approaches. The statistical approach is based on probabilistic arguments always necessary as our knowledge of the medium will always be limited. The deterministic approach we are very concerned about in this work and related to effects of topography, sedimentary layers, basin amplifications (Virieux et al, 2007) will require the definition of the medium as well as the specification of the source. The third approach is based on empirical methodology with already recorded signals for small earthquakes which could be used for the estimation of ground motion for a bigger earthquake without knowing the medium properties.

As the information about the medium increases with better constrains for the underground properties, it is possible to perform numerical simulations which allows an appreciation of amplifications and attenuations of the seismic ground motion for a specified earthquake. This approach starts to attract interest and to provide pertinent information, as for California with the Los Angeles Basin (e.g. Komatitsch et al., 2004; Cotton et al., 1998; Wald and Graves, 1998; Bielak et al., 1999; Olsen et al, 1999). The upper frequency is of the order of 1 Hz to 2 hz for propagations over few hundreds of kilometres, frequency limitation related to our incomplete knowledge of the medium where waves propagate.

It is possible to perform simulations as well for more local structures as those encountered in the French Riviera zone which encounter a seismic activity quite permanent for an area away from tectonic boundaries with high contrasts in topography and bathymetry. This shape of the solid interface is related to a complex tectonic which leads as well to depth and lateral variations of the seismic velocities. The seismic activity is related to the Alpin Arc and to the Ligurian Sea. We shall focus our interest on the ground motion estimation around the Nice city as its seismic records show that various earthquakes have occurred in the past with epicentral intensity (MSK) between VII and VIII in the last centuries (Lambert et Levret, 1996).

2. Model definition and repeated discretisation through a geomodel tool.

Thanks to different geophysical data collected through various scientific initiatives, we may have an idea about the geological structure beneath the French Riviera. From passive seismic experiments (Courboulex et al, 2003), from data integration over years (Calais et al., 2000; Rollet et al, 2002) and from files of log profiles and microseismic zonations (Duval, 1994), a crustal model of the Nice area could be built with various degrees of precision. As we expect that the information will increase in the future (Debran-Passard et al., 1984; Larroque et al, 2001), we have to collect this information in such a way that the updating will be easy and that new simulations could be performed, thanks to the collaboration between Géosciences Azur and BRGM. In relation with the WP1, we have designed a protocol for recovering the medium properties and for improving our model structure. Three scales have been considered: the regional scale where the tectonic information is th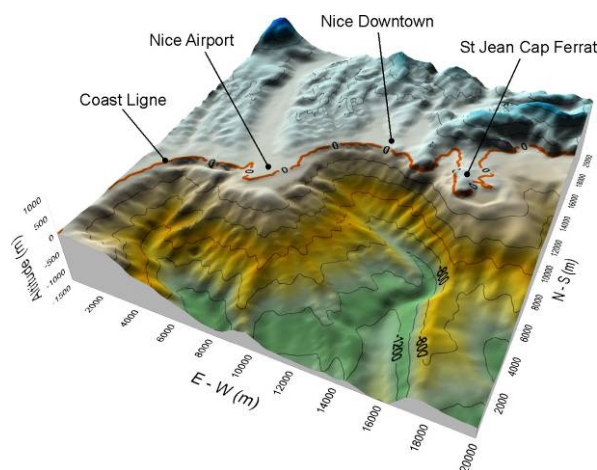e driven information canal, the local scale where local geophysical data will help refining the structure and the superficial scale where logs provide critical information.

Figure 1. *Geographical frame of the local structure of the area of Nice showing horizontal dimensions in numerical simulations.*

We have extracted, for example, a local model enough large for analysing effects of both topography and bathymetry and the presence of sea water around the city Nice (Figure 1). Up to now, we have considered a structural model quite simple just to emphasize effects coming from these features although they should be combined with other geological informations as alluvial sediments which can be quite unconsolidated especially at the sea floor.

Our current model of propagation is defined as an isotropic elastic half-space limited by the realistic topography and the sea flat interface. The only internal interface is, therefore, the interface solid-fluid between the crust and the sea as defined by the bathymetry (Figure 1). Mechanical properties of the medium are as follows: Vp = 5.7 km/s, Vs = 3.3 km/s and ρ = 2.6 gr/cm^3 for the solid part and Vp = 1.53 km/s, Vs = 0 km/s and ρ = 1.03 g/cm^3 for the fluid part where quantities Vp, Vs et ρ are respectively the velocity of seismic P waves, of seismic S waves and the density.

The quantities at the interface have been estimated when necessary using an heterogeneous formulation by an harmonic mean in order to better smooth out sharp diffractors (see Cruz-Atienza (2006) for more details).

The strategy is such that these informations are identified in a blocky model where a label defines each bloc: values inside each bloc will vary for different simulations. Blocs are specified in a grid with a uniform grid size which is 50 m in both three directions in our specific case. Domain decomposition which allows various grid steps will not be considered as we want a quite versatile numerical tool for easy use. Other strategies as unstructured meshing related to finite volume methods for example have been selected (see presentation of INRIA/CERMICS). Therefore, we have focus our attention to the simplicity of the computer code to be used in our collaborative strategy.
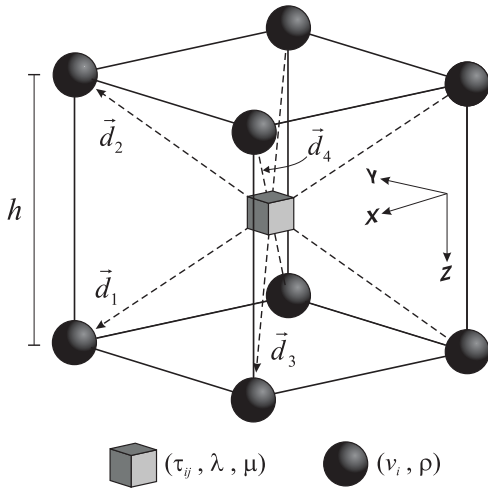
Consequently, the superficial scale will not be considered using this FDTD tool. We shall consider either the regional scale in this work.

Figure 2. *Spatial stencil in the PSG appraoch for a second-ordre accuracy. The stress field derivative has to be estimated from the velocity components. Please note that simple discretisation of Lamé coefficients and density.*

3. Partiel Differential equations of elastodynamics.

Let us consider a 3D linear elastic and isotropic media: wave propagation will be completely described by using Lamé coefficients λ and μ, et the density ρ. Following Madariaga (1976), away from areas where act body forces, the elastodynamic equations will describe the time evolution of the particle velocity v_i and the stress tensor τ_{ij} through the following first-order hyperbolic system:

$$\rho \frac{\partial v_i}{\partial t} = \tau_{ij,j}$$

$$\rho \frac{\partial \tau_{ij}}{\partial t} = \lambda v_{k,k} \delta_{ij} + \mu(v_{i,j} + v_{j,i}). \tag{1}$$

The system (1) is composed of nine equations which can be solved numerically on a grid discretized regularly by an element square cell over the entire domain. This grid connected to the finite difference technique we are going to use is a partially staggered grid (PSG) as particle velocities and stress components are defined into two sub-grids shifted along the main diagonal as a centered face cubic crystallographic structure as shown in Figure 2. The numerical estimation of the spatial derivative along the x axis at the centre of a square will use

eight values of the field (Saenger et al., 2000). This spatial discretisation shares the same efficiency as the standard staggered grid (SSG) (Madariaga, 1976 ; Virieux, 1986) where each component of velocity field or stress field are spred over different numerical points of the grid. In the PSG method, we estimate all components of each field in a single grid point while retaining nice features of the SSG method as the stability of the stencil at solid/liquid interfaces. Moreover, as shown by Saenger and Bohlen (2004) and Bohlen and Saenger (2006), this approach allows accurate modelling of surface waves when excited. The limitation will come from the discretisation of t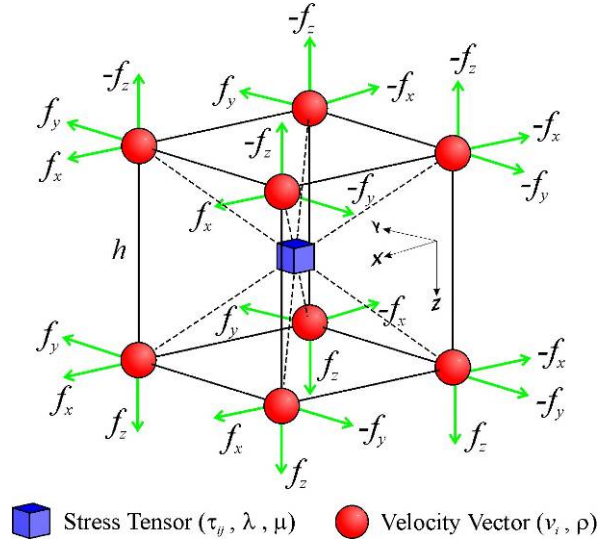he free surface using a staircase approximation requiring a significant number of points per wavelength of the order of 30 points per wavelength. The time integration is performed using simple leap-frog integration where velocity and stress are known at two different half-step times. Let us remark an additional feature with a less restrictive CFL condition (Cruz-Atienza, 2006) where a Von Neumann analysis of the stability shows that the time stepping is 1.7 times higher for the PSG approache than for the SSG approach. This will reduce the number of time iterations by 40 % for the simulations inside the same grid.

Figure 3. *Discrétisation d'une source ponctuelle dans la grille différences finies partiellement en quinconce, décrite par l'ensemble de forces $(f_i).v_i$, τ_{ij} et ρ étant respectivement le vecteur de vitesse, le tenseur de contraintes et la masse volumique ; et λ et μ le coefficients de Lamé.*
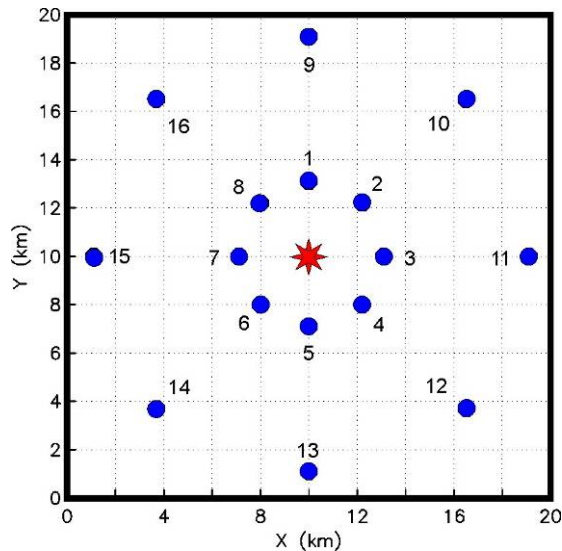

Figure 4. *Sensor (blue) network description around the epicenter (triangle) used for the validation of the excitation by a earthquake source in a 1D medium as described by table 1.*

We have implemented absorbing boundary conditions PML (Perfectly Matched Layer) for the simulation of an infinite medium (Berenger, 1994 ; Collino et Tsogka, 2001) using requested artifical splitting of fields only in the PML zones, making a significant reduction in the memory requirement (Marcinkovich and Olsen, 2003).

This dedicated development has been performed into a sequential computer code in FORTRAN 90 which has been distributed among participants of QSHA project (Cruz-Atienza, 2006). This computer code has been denoted "SHAKE3D" and is going to be used through the QSHA project.

4. Numerical implementation of a ponctual seismic source

We are interested in the excitation of seismic waves by ponctual sources representing an earthquake, where are best described using a moment tensor. The source excitation is taken as a combination of equivalent body forces to be added to the inertial equations. These combinations

could describe the desired radiation pattern as an isotropic radiation, a double-couple radiation or any combined radiations. These forces applied to velocity nodes are described in the figure 3 and display three dipoles and six couples related to the seismic moment tensor description M_{ij}. The body forces averaged over a cell are simply related to the tensor components in the following way

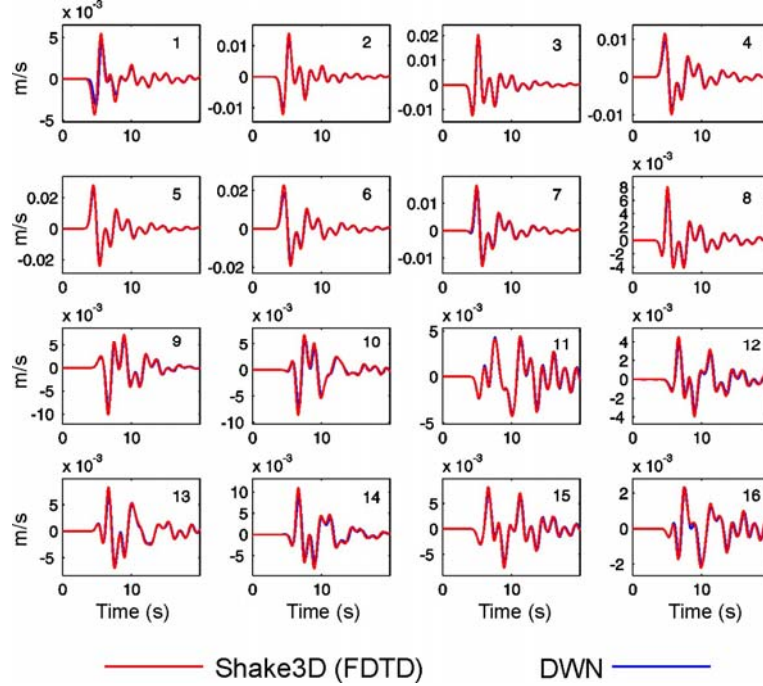$$f_i(t) = \frac{M_{ij}(t)}{4h \cdot h^3} \qquad (2)$$

Figure 5. *Quantitative comparison of vertical components of the velocity field at the free surface using the SHAKE3D code (in red) and the DWN code (in blue) in the 16 sensors shown in the figure 4.*

where the spatial step is denoted by h. The force is scaled down by the size of the volume (h^3) defined by the eight velocity nodes (red dots, Figure 3). In the equation (2), the components of the stress are described by the product of the seismic moment M_0, le radiation pattern $R(\phi, \delta, \lambda)$ where angles define the position of the fault (strike and dip angles) and the direction of slip (rake angle) on the fault and the integral of the normalized Source Time Function (STF), namely f(t):

$$M_{ij}(t) = M_0 \cdot R(\phi, \delta, \lambda) \cdot f(t) \qquad (3)$$

In order to preserve the accuracy of the numerical scheme during the excitation of the medium, these external forces have spread over few cells with a Gaussian weighting with a standard deviation of $2h$. By doing so, we prevent the patchwork related to different excitations between odd and even points depending on which nodes forces are applied.

In order to validate the implementation of the source excitation as well as the implicit discretisation of water interfaces, we have compared seismograms computed with the SHAKE3D code with synthetics seismograms computed by a spectral element method as the Discrete Wave Number (DWN) approach on sixteen sensors well distributed around the

epicentre (Figure 4). We have selected a stratified medium with four layers. The superficial layer is the sea water. Physical parameters are given in the table 1. The source lies at a depth of 5 km and the source time function is described by a Gaussian of time duration of ~2 s (i.e. a standard deviation of 0.5 s). The simulated earthquake has a moment magnitude of 4.9 and a focal mechanism with an azimuth angle ϕ =142°, a dip angle δ = 74° and a rake angle λ = 215° with a grid step of h = 100 m.

Model	Thickness	Vp velocity (m/s)	Vs velocity (m/s)	Density (km/m3)
Layer 1	2100 m	1530	0	1030
Layer 2	3000 m	5400	3100	2500
Layer 3	7000 m	5700	3300	2600
Layer 4	Half-space	6400	3700	2800

Table 1 : Layered structure of the model for comparison between finite difference method and discrete wave numbers method.
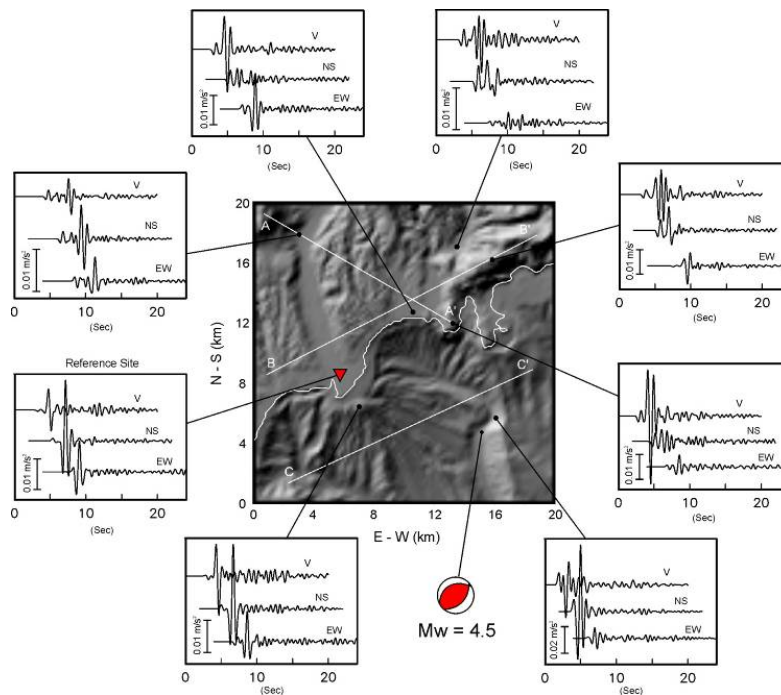

Figure 6. *Seismograms for an earthquake of magnitude 4.5 located at 10 km South the Saint-Jean Cap-Ferrat position and at a depth of 6.5 km. This earthquake is used a the reference earthquake for an hypothetical scenario for computing maximal accelerations. The reference site is taken as the airport position.*

The comparison of vertical seismograms is presented in the Figure 5 and shows that indeed the computer program SHAKE3D handles quite accurately both free surface conditions and continuous conditions between two media as interfaces solid-solid and solid-fluid. The most important misfit comes probably from the grid approximation of the receiver positions as we extract signals from the nearest node and we do not perform an interpolation between the eight nodes of the cell inside which lies the sensor while the DWN method considers exact positions. If we consider that the frequency 0.5 Hz is the maximal frequency in the radiated wave field, we find that the minimal number of grid points per wavelength N_λ should be of the order of 30 for accurate simulations.
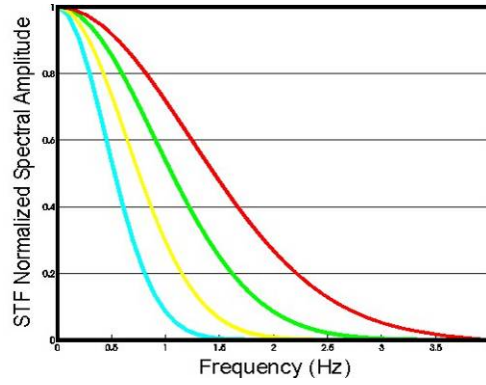
Figure 7. *Spectral estimation of source time functions used for site effect estimations.*

5. Simulation results and interpretation

In order to estimate site effects occurring in the local structure of the city Nice (Figure 1) and, more specifically the influence of the sea water in the propagation of seismic waves, we have realized few simulations with an explosive source located at the position defined in Figure 6 with four different source spectra (i.e. by adding dipoles of seismic moment tensors). These temporal source time functions are given by Gaussian functions with standard deviations of 0.5 s, 0.375 s, 0.25 s and 0.175 s (associated respectively with blue, yellow, green and red lines as shown in the Figure 7). The model has been discretized with spatial step size h of 50 m and the time stepping is 0.005 s. This leads to 48.10^6 degrees nodes (400 x 400 x 300) which correspond to a computer memory of 2.2 Go. Because we need about 30 points per wavelength in order to minimize the numerical dispersion at the free surface (Saenger and Bohlen, 2004) and (Bohlen and Saenger, 2006), wavelengths higher than 1500 m are resolved correctly by our simulations. This means that a maximal frequency of 1 Hz is considered inside the model. The table 2 gives a more precise value of maximal frequencies and the minimal wavelength propagated in the test case.

Site effects are determined through maximal values of ground accelerations (PGA) once they have been corrected of the geometrical decrease $1/r$ related to the expansion of the spherical wave front, where the distance r denotes the distance between the hypocenter and the observation point. These corrected PGA values have been normalized for each simulation with respect to those taken from the reference site at the Nice Airport (Figure 1).

	λ_{min}	f_{max}
Source 1	~8.3 km	~0.4 Hz
Source 2	~5.5 km	~0.6 Hz
Source 3	~3.6 km	~0.9 Hz
Source 4	~2.8 km	~1.2 Hz

Tableau 2*: Approximate characteristic wavelengths and associated frequencies for the four source time functions (Figure 7) used for the Figure 8.*

The Figure 8 shows that the amplification factors at the interface between the fluid layer and the solid layer using the procedure we have just described. The right panel is for results of simulation with sea water while the left panel is without the sea water. The contour line in yellow corresponds to an amplification factor of one (i.e. without amplification with respect to the geometrical expansion in the reference site at the airport). Each horizontal picture is for
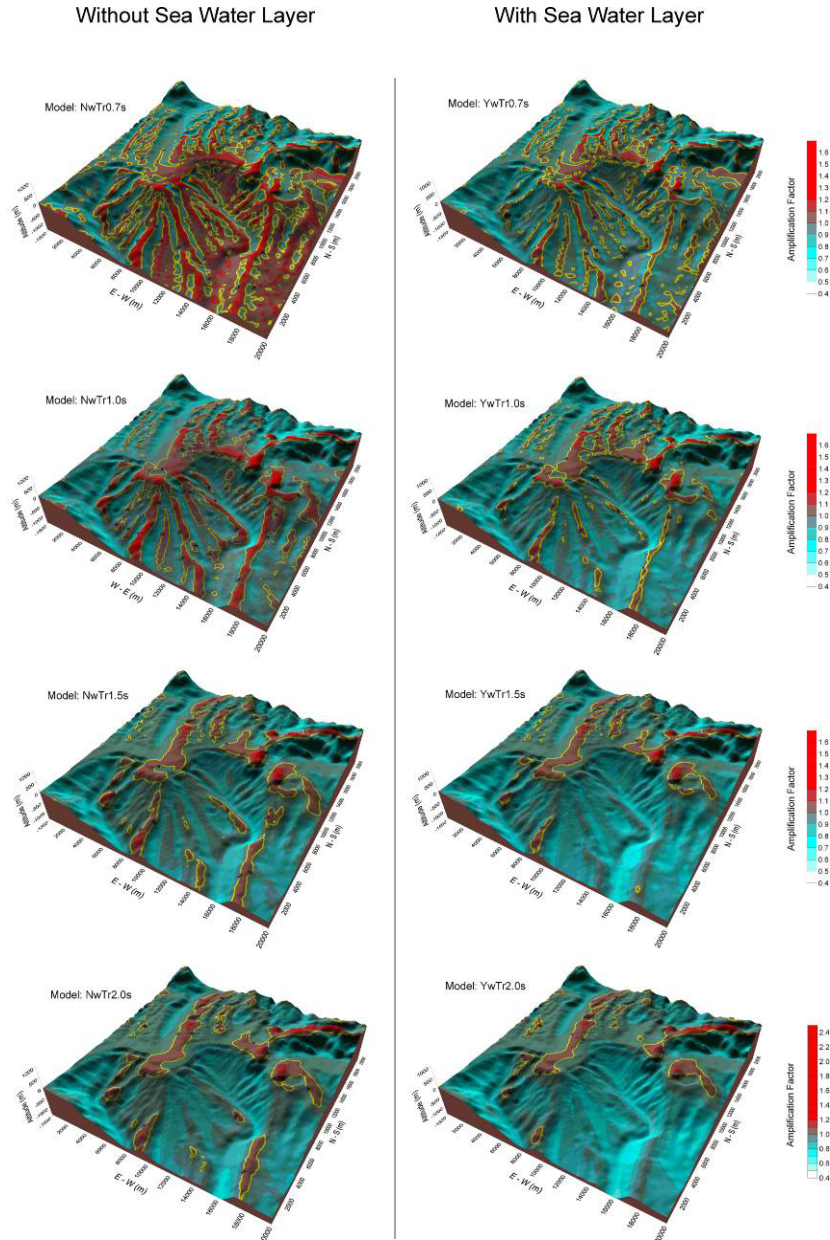
Figure 8 : *Amplification factor at the solid-fluid interface with a water column (right panel) and without water column (left panel) for different excitations with spectra given in Figure 7.*

different frequency content of the source from low frequencies (blue line of the Figure 7). One can see the influence of the frequency and the topography on the amplification modulation. The water influence has a quite noticeable effect at low frequencies.

It is possible as well to perform quantitative estimations of felt accelerations leading to PGA maps for a selected earthquake (Figure 9). By performing a quite important number of simulations, it might be possible to have a statistical analysis of these PGA values and, therefore, to induce characteristic features related to the propagation inside the chosen medium than to the source itself. This will provide bridges with the probabilistic approach. Of course, in case of a real earthquake, these estimated maps could be compared to maps deduced from quantitative observation if the station density is enough for the next earthquake as it has been the case for Chichi earthquake (1999) in Taiwan.

6. Conclusion

The deterministic approach allows us to build different scenarii with site effects leading to amplification factor above 2 which can reach sometimes a factor of 5 because of topographic effects. This amplification is related to the wave frequency content and is quite significant at high frequencies (above 2 Hz). The water column attenuates these amplifications essentially at the sea bottom but the mechanical energy stored in this water volume is sent back inside the solid medium increasing the time length of the seismogram. The simulation we have performed for our analysis of site effects is not related to any already defined scenario of earthquakes in the area of the city of Nice and we can not draw quantitative features for seismic hazard estimation in the French Riviera. Further work is required once more precise scenarii have been defined for this geographical zone.
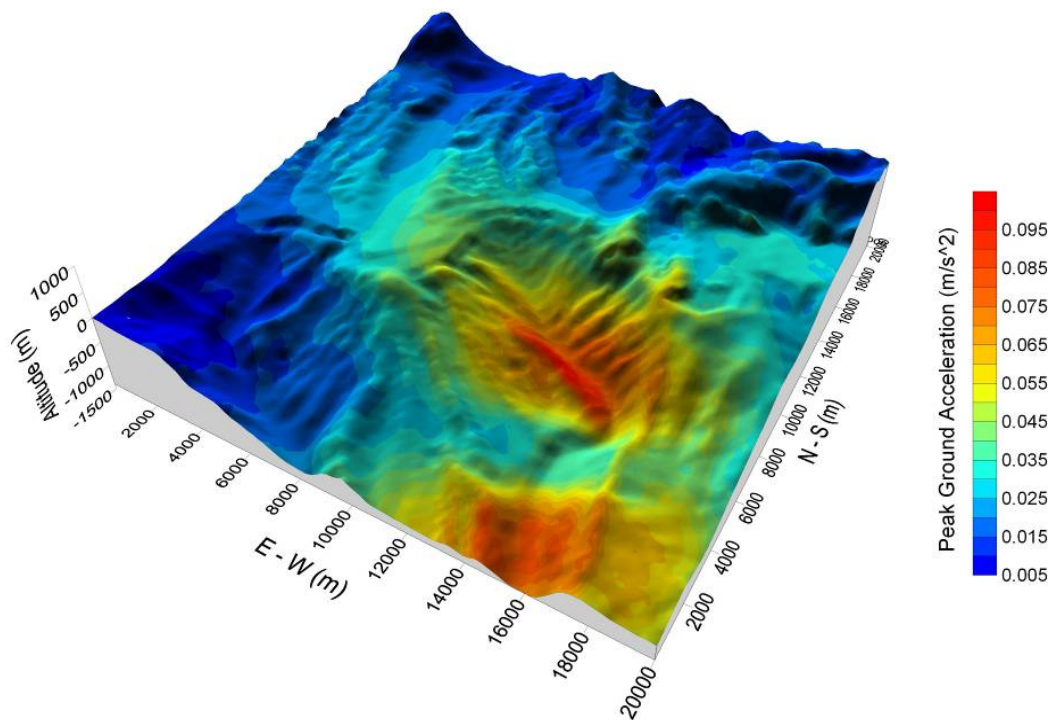

Figure 8. *PGA estimation for the scenario of Figure 5 with an earthquake nearby Saint-Jean Cap-Ferrat.*

Acknowledgements

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