13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Numerical analysis of local geology effects on ground motion prediction

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ABSTRACT: It is well known that to better characterize the seismic phenomenon several parameters such as site effects have to be considered. Indeed, during the wave propagation process, the soil near the surface can have an effect of amplification or de-amplification on the ground motion. This may be related to soil type (soft), geology or soil heterogeneity among others. This work aims to study numerically the effect of local geology on ground motion prediction at a regional scale. The studied site is located at Kefalonia Island (Greece). This site is well characterized and instrumented by several sensors placed in such a way that allow to measure the effect of spatial variability on the recorded signals.

1. INTRODUCTION

The seismic hazard is influenced by different effects, from the emission of waves during an earthquake to the studied site. This hazard depends on the heterogeneities of the fracture process at different scales, the wave propagation path and the site effects. At the regional level, the mechanisms of radiation during the rupture and its propagation in the earth's crust characterizing the hazard involve the determination of attenuation laws. On the other hand, at the local scale, the geomorphological conditions of a site can considerably intensify the strength of an earthquake by the amplification of the movement of the ground (Cruz-Atienza et al., 2016). The characterization and the consideration of these site effects, related to the soil conditions, are essential for the evaluation of the seismic risk. Site effects are related to the geometric structure of the soil and subsoil. Two types of structures are responsible for the main observed effects: the topography and the sedimentary fillings (e.g. during the 1985 Mexico City and 1995 Kobe earthquake (Pitarka et al., 1996).

The importance of these local soil effects is well established, especially the effects of relief and sedimentary failures, which can generate large amplifications and significant spatial variations of ground motion and thus strongly influence long-term structures, such as large-scale bridges. At first, the 1D models made it possible to explain certain amplification effects. By their extreme simplicity of implementation and application, they are widely used in earthquake engineering (soil/structure interaction). But this 1D modelling is very limited, especially for the consideration of surface waves that can significantly amplify and lengthen the signals. 2D simulations have thus made it possible to highlight surface-wave reflection effects at the edge of a basin (Kawase, 1996), as well as amplification effects related to a 2D mode resonance (Bard and Bouchon, 1985). Numerous studies have shown the influence of the 3D basin structure on the seismic response, characterized by larger amplitudes and higher frequencies than the 1D and 2D responses. Predicting physics-based ground motion in a region characterized by complex geology is a challenge.

The simulation of ground motion created by an earthquake involves the numerical resolution of the equations of elastodynamics. Numerous numerical methods exist to simulate the wave propagation and have been developed lately. However, despite a good understanding of the physics and mathematics underlying the problem of ground motion simulation in complex geological framework, such simulations represent a real challenge. Three-dimensional simulations that consider realistic models and cover the complete frequency band of interest are not yet sufficiently developed. Indeed, such studies imply the necessity to consider several aspects of the problem: large spatial expanses (allowing to capture all the phenomena of structural origin and those related to the source), a good resolution, constitutive laws capable of modelling the soil effects, seismic source modelling and many scenarios for a better characterization of the seismic hazard.

In this paper, the effect of local geology on predicted ground motion is studied numerically via the simulation of some seismic events recorded in the site test installed at Kefalonia Island. For this study, the size of the considered computational model is 27 × 30 × 50 km and it can resolve wave propagation up to 5 Hz. The simulation concerns a Mw4.6 earthquake of the June, 04th 2016 which can be compared with the available database.

2. METHODOLOGY

2.1. *The studied site characterization*

The Argostoli test site located at Kefalonia Island was selected for this study (Fig. 1). It is a site of high seismicity which is due to the proximity of the Kefalonia Transform Fault (Haslinger et al., 1999; Sokos et al., 2016). In fact, this fault is a connection boundary close to the island of two subduction troughs: Hellenic Arc in the south and the Adriatic Fault Zone (Louvari et al., 1999). This site was chosen to carry out geological reconnaissance and geophysical acquisition missions in the framework of SINAPS@ project and the NERA European research program among others (Cultrera et al., 2014). Different site characteristics have motivated this choice, i) the significant seismicity which allows to collect strong movements in a reduced time (Sbaa et al., 2017) and ii) the geological configuration of this area, namely the presence of sedimentary basin which is favorable to the occurrence of site's effects (Fig. 2). The sedimentary basin (Koutavos) is located south of the capital of the island (Argostoli). It is located at the bottom of a lagoon and filled with quaternary and Pliocene detritic deposits (Cushing et al., 2016). In addition, according to the works of Svay et al. (2017) and Imtiaz et al. (2017), a spatial variability was obtained when the records of installed dense network were analysed.

Figure 1: Location of measurement site on Cephalonia island in Greece.

One of the goals of this site is to allow the validation of 3D computational codes by comparing their prediction to real data through the installation of a permanent accelerometric vertical network.

Concerning the geological model, in this work, the crustal velocity model adopted for the study of this region is the 1D profile proposed by Haslinger et al. (1999) (Tab. 1). Concerning the local scale, a more refined geological model that has been obtained by Hollender et al. (2015) using in situ measurements is used (Tab. 2).

2.2. *Numerical model*

The 3D Spectral Elements Method (Patera, 1984; Mayday et al., 1989) code SEM3D was used to

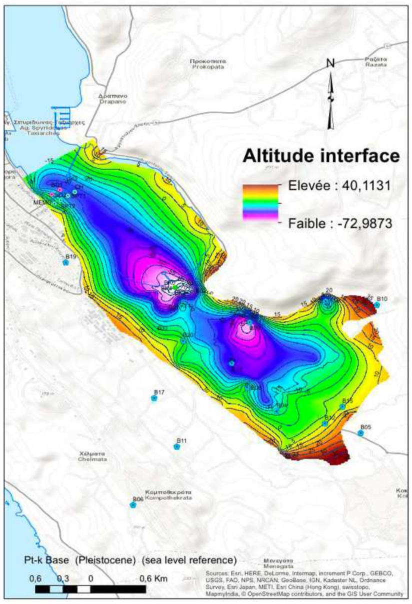


Figure 2: 3D refined geological model of Argostoli region proposed by [Cushing et al., in prep.].

Table 1: Values for 1D Crustal model proposed by Haslinger et al. (1999) for Ionian region.

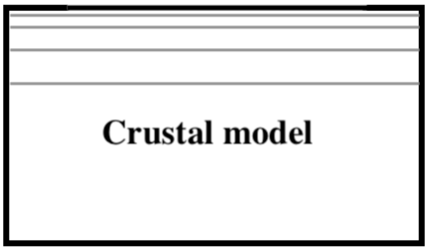
Depth (km)	V_p (km/s)	V_s (km/s)	Q_p	Q_s
0.5	5.5	2.7	300	150
2.0	5.5	2.9	300	150
5.0	6.0	3.2	300	150
10.0	6.2	3.2	300	150
15.0	6.5	3.4	300	150
20.0	6.7	3.8	300	150
30.0	6.8	3.8	300	150
40.0	8.0	4.7	1000	500

Table 2: Values for velocity model proposed by Hollender et al. (2015) for Argostoli Area.

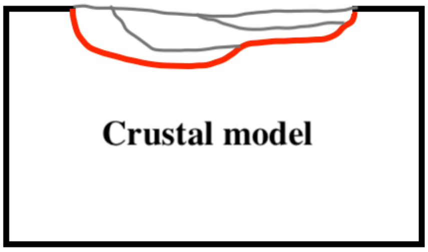
Depth (km)	V_p (km/s)	V_s (km/s)	Q_p	Q_s
0.0	2.0	0.6	300	150
0.03	2.4	1.0	300	150
0.4	4.6	2.7	300	150
1.0	6.0	3.2	300	150
2.0	6.2	3.2	300	150

compute numerically the propagation of elastic waves in the medium (solid or fluid). Among the advantages of SEM3D, its efficient and cost-effective massively parallel implementation (by Message Passing Interface, MPI) on large super-computers and its ability to accurately take into account 3D discontinuities such as the sediment-rock interface. The original core of the SEM3D software allowed to solve the wave propagation problem in any velocity model, including anisotropy and intrinsic attenuation.

In order to evaluate the effect of the presence of a sedimentary basin on ground motion two different cases was studied and compared. The first case is a layered model using the velocity model proposed by Haslinger et al. (1999) (for upper layers). However, this model does not allow to see the local effects. In order to take into account the geological characteristics of the site, a more refined model (second case) was studied considering the reel geometry of the sedimentary failures (Fig. 3). The two models have the size of : 27 × 30 × 50 km (Fig. 4). The size of the elements constituting the mesh is 130 × 130 m in the horizontal directions (EW and NS). For the vertical direction the size of the elements is adapted according to the properties of each layer. Figure 5 shows a plan view and a cross section of the constructed numerical model.



(a) Layered model



(b) Basin Model

Figure 3: Studied cases to evaluate basin effect on seismic ground motion. (a) The first model est a layered one. (b) The second studied model takes into account the reel local geology of the studied site.

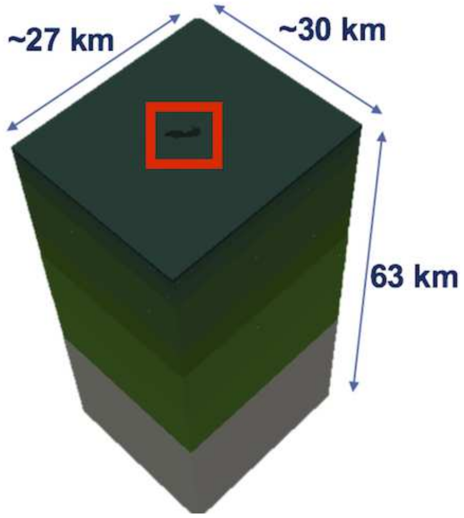


Figure 4: Sketch of the studied Argostoli area including basin model.

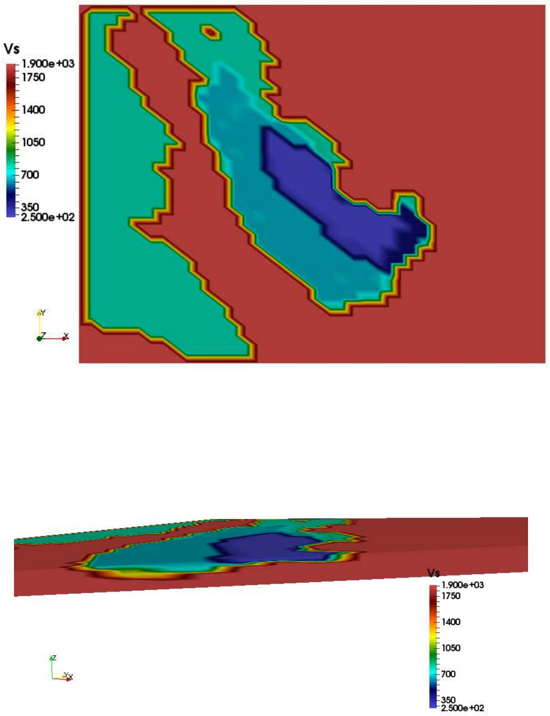


Figure 5: Plan view and cross section of the studied Argostoli area including basin model.

3. NUMERICAL RESULTS

The basins have complex structures in which amplifications are generally due to the interference between the geometrical shape and the surface waves. Wave propagation is analysed here in a realistic model of the Argostoli Basin. The dimensions of the basin are about 2.0 km × 0.6 km. The waves are generated by a source located 14 km deep in the rock modelled by point-wise double-couple. It represents a magnitude M_w4.6 with Strike=163°, Dip=39°, Slip=92°. A series of receivers is placed on the surface. The influence of the basin is estimated by the amplification function calculated between a point inside the basin and another point located outside the basin at the reference rock. In order to take into account the surface waves, the vertical displacement as a function of the horizontal displacement is calculated. Figure 6 shows that the consideration of a realistic geometry of the basin (Basin model) generates a stronger displacement than the simplified case (Layered model). This indicates the appearance of surface waves due to the presence of the basin.

Figure 7 shows the amplification between the sensor inside the basin and the one outside the basin. It should be noted that in the case of the stratified model there is no peak in the NS directions and the appearance of very small peaks in the EW direction. On the other hand, in the case of the basin model the peaks appear in both directions. Theses peaks are approximately at 1.8 HZ, 2.9 Hz and 4 Hz.

Figure 8 shows that the presence of the sedimentary basin amplifies the response of the soil, especially in East-West direction and shifts it slightly towards the high frequencies.

Figure 9 shows the signal elongation as a function of time of the two models studied compared to the two reference points. It is noted that for both studied models the elongation is greater in the East-West direction and is even more important for the point within the sedimentary basin.

4. CONCLUSIONS

In this paper, a 3D physics-based earthquake scenario is presented. The selected case study is the Argostoli basin, in Greece. A 3D numerical model of the shallow sedimentary basin is constructed, by means of a SEM model. The 3D analyses are accurate up to 5 Hz.

The effect of the basin is studied in terms of time histories displacement recorded at the surface and

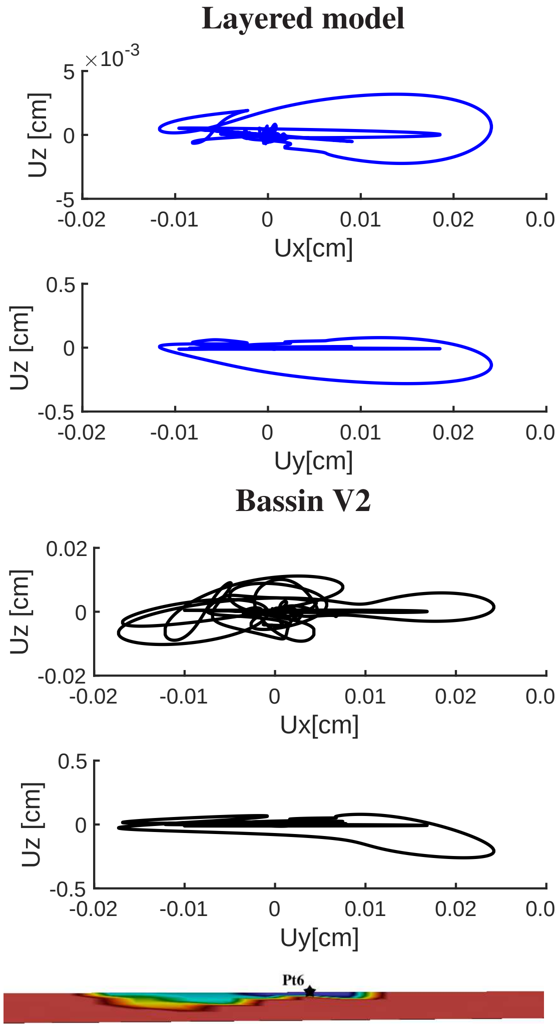


Figure 6: Comparison of sensors displacement at the point 6 located inside the basin.

amplification functions by comparing tow models. In this case the basin has the effect of amplifying the ground motion at particular frequencies and also generating surface waves.

These results highlight the influence of the presence of sedimentary basin on the seismic response of the study site. These effects are very important to be considered in particular for the construction of the Ground Motion Prediction Equations in order to introduce site's effects.

As future developments, the construction of a model including the geological reality (consideration of the topography and bathymetry and the sedimentary basin) of the site is envisaged with an increased frequency range.

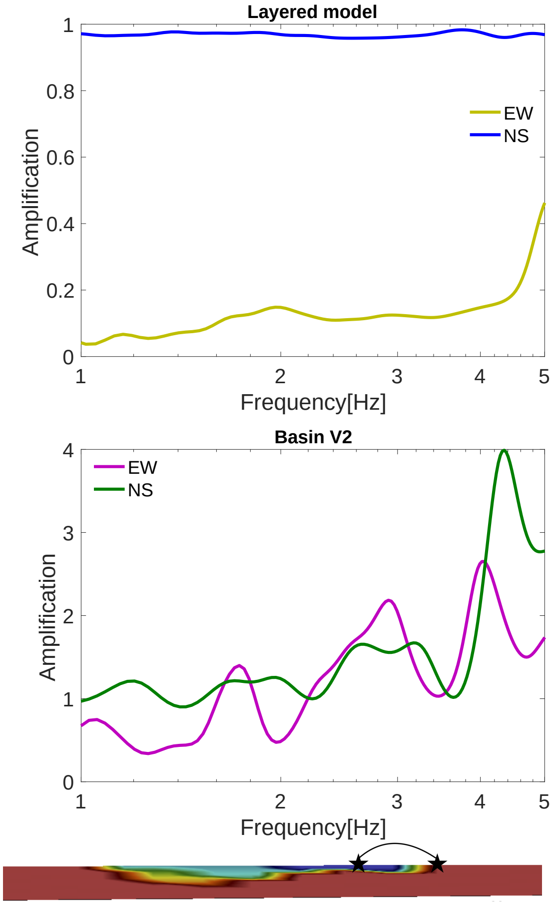


Figure 7: Comparison of the amplification functions of the studied models in EW and NS directions

Acknowledgements The present work places itself within the framework of the French research project SINAPS (Séismes et Installations Nucléaires, Améliorer et Préserver la Sûreté) managed by the National Research Agency under the program Future Investments (SINAPS@ reference No.ANR-11-RSNR-0022). This project has been initiated by the members of the institute SEISM (`https://www.institut-seism.fr/en/`) after the nuclear disaster of Fukushima (Japan, 2011). It aims to enhance the scientific background in the area of the nuclear safety and radiation protection. The project contains different work packages. Our present work is part of the work package "Non-Linear Sites Effects and Soil-Structure Interaction".

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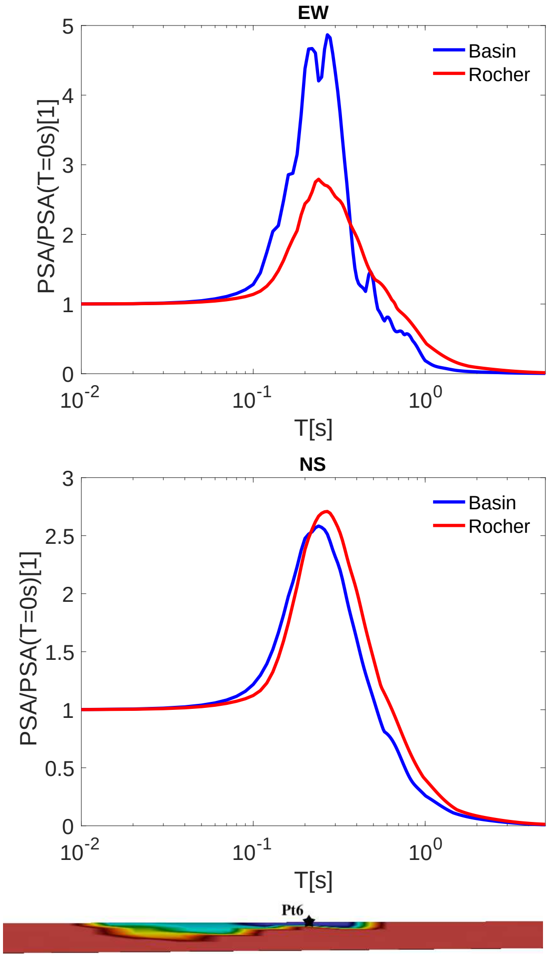

Figure 8: Comparison of the spectrum response for the basin model in EW and NS directions at point 6 located inside basin (Pt6) and at point 7 located outside the basin (Pt7).

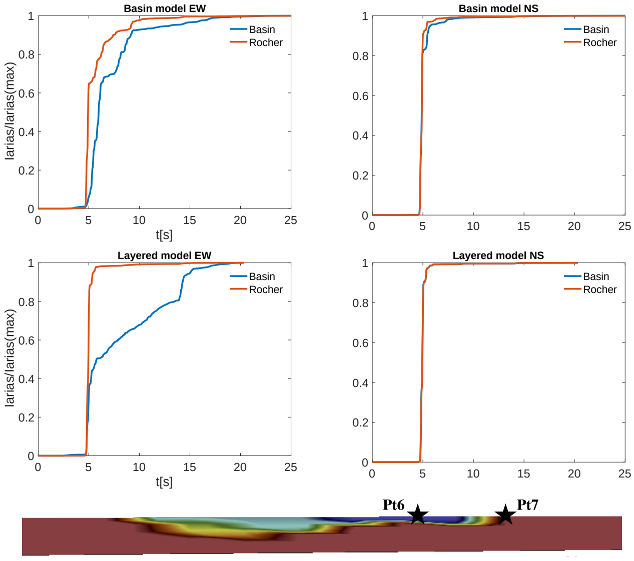

Figure 9: Comparison of the signal elongation of the two studied models in EW and NS directions at point 6 located inside basin (Pt6) and at point 7 located outside the basin (Pt7).

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