Argostoli site, from site test to numerical model: a holistic approach

S. TOUHAMI[1], F. LOPEZ_CABALLERO[1], F. GATTI[1], F. HOLLENDER[2], M. CUSHING[3]

[1]MSSMat, CNRS, CentraleSupélec, Gif-sur-Yvette, France

[2]CEA Cadarache, St Paul-lez-Durance, France

[3]IRSN, Fontenay-aux-Roses, France

sara.touhami@centralesupelec.fr

Abstract: This work aims to study numerically the effect of both topography and bathymetry on ground motion prediction at a regional scale. For this purpose, a 3D model was developed using a numerical code (i.e. SEM3D) that permit to carry out such studies. This code is based on the spectral element method allowing solving of waves-propagation problems in three-dimensional solid media. The seismic phenomenon is simulated in its entirety: from the seismic source to the site using a representative model of the complexity of the wave path. In order to validate the proposed numerical model, several recorded earthquakes issued from the accelerometers array database are compared with the numerical simulated ones. The first obtained results show the importance of the in-situ measures on the regional scale simulations. Concerning the studied site, the Argostoli city located at Kefalonia Island was selected. This site was chosen because of geological reconnaissance and geophysical acquisition missions were carried out in the framework of SINAPS@ project and the NERA European research program among others.

Key Words: 3D numerical modeling, Ground motion prediction, Regional model, Spectral Element Method.

1. INTRODUCTION

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. Accordingly, accurate of ground motion prediction should face several difficulties. As far as prediction of the seismic motion is concerned, source propagation and site effects have been extensively studied these last two decades (Chávez-García 2000, Faccioli et at. 2002, Gatti et al. 2017). Moreover, recent numerical methods such as the Spectral Element Method or the Discontinuous Galerkin Method (Paolucci et al. 2015) combined with massively parallel computers have proved to be very effective to modeling the propagation of seismic waves from the source to the site even in complex tri-dimensional geological environments (Liu 2006, Göddeke et al. 2014).

However, the accuracy of such predictions remains limited due to large uncertainties on the data to be introduced in the model, ranging from the geometric and kinematic or dynamic characterization of the seismic source, to the detailed numerical model of the source-to-site propagation path, including possible non-linear response. Even very extensive geophysical surveys fail at reducing the resulting uncertainties on the predicted ground motion. As well, such large-scale surveys cannot be conducted for all practical cases. This is why the construction of a regional model that simulates the seismic phenomenon from the source to the structure would make it possible to better analyze the simulated signals. Indeed, the geological structure of the ground, nonlinear behavior or heterogeneity can have a significant influence on the site response.

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, 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)).

In this paper, the effect of topography as well as bathymetry on predicted ground motion is studied numerically via the simulation of some seismic events recorded at the site test installed at Kefalonia Island. Thus, the accuracy of the proposed numerical model is studied by the comparison of simulated signals with the recorded ones where the survey arrays are placed. For the construction of this numerical model, in addition to a mesh, it is necessary to have two types of data: the characteristics of the seismic source and the geology of the site. For this study, the size of the considered computational model is 67 × 50 × 50 km and it can resolve wave propagation up to 10 Hz. The simulation concerns a Mw4.6 earthquake of the June, 04th 2016 which can be compared with the available database.

The present work places itself within the framework of the French research project SINAPS (Séismes et Installations Nucléaires, Améliorer et Préserver la Sûreté). This project has been initiated by the members of the institute SEISM 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".

2. NUMERICAL TOOLS

The physics-based simulation of realistic earthquake scenarios requires a reliable estimation of several different parameters to reduce uncertainties, related to the source mechanism, geological configuration and mechanical properties of soil. Due to the scale of the considered problem, the degree of uncertainty associated to the whole earthquake process (from fault to site) is extremely high. This is why, it appears necessary to build up a multi-tool virtual laboratory to construct and calibrate the seismological model (FIG.1). In this work, the 3D Spectral Elements Method (Patera 1984, Mayday et al. 1989) code SEM3D was used to 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. To carry out these types of simulations, several issues must be tackled:

- meshing the domain of interest, its geological conformation (bedrock to sediment geological surfaces), the topographical surface and the bathymetry (if present).
- representation the material rheology, heterogeneity of the soil properties.
- describtion the triggering of the seismic source.

To deal with the problem of simulations of seismic scenarios at large scale (~ 10-100 km), an efficient meshing tool must tackle the following difficulties:

- meshing the topographical surface and eventually the coastline and the sea bottom;
- consider geological discontinuities (typically sedimentary basins, folded geological strata, fault segments);
- reach a sufficient refinement close the topographical surface, where slower soil strata are naturally found, so to preserve the maximum frequency propagated by the numerical model.

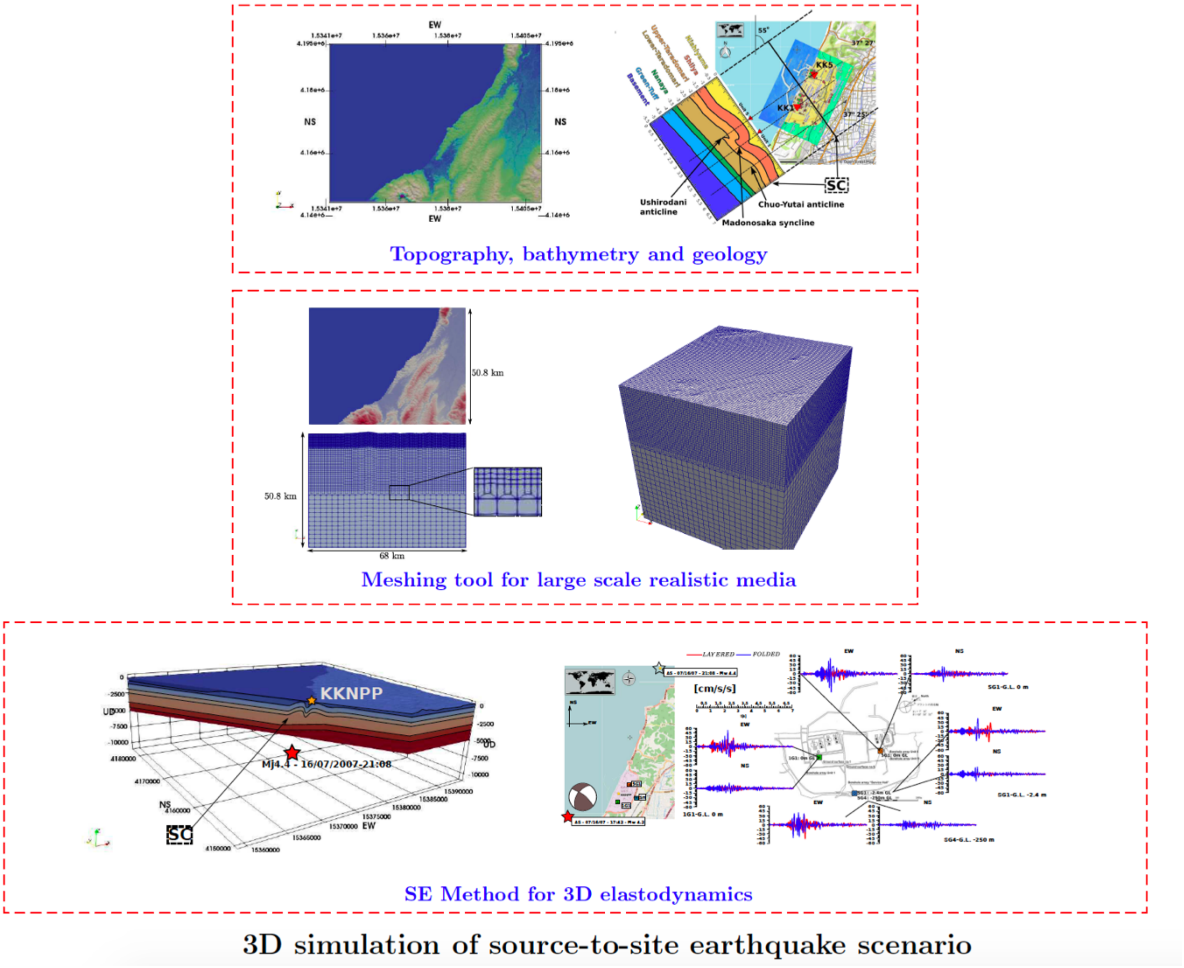

FIG.1. Construction steps of a 3D numerical model to simulate earthquakes scenarios from the source to the site using the SEM3D code (Gatti et al.2017).

3. STUDIED SITE AND GEOTECHNICAL MODEL DESCRIPTION

The Argostoli test site located at Kefalonia Island was selected for this study. It is a site of high seismicity which is due to the proximity of the Kefalonia Transform Fault (Hasslinger 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 (Sebaa 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. 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 (Caushing 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 analyzed.

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. Thus, a numerical model of the sedimentary basin is under construction in order to study the site effects, possible non-linearity of soil behavior and spatial variability.

3.1 Shear wave velocity profiles

So as to propagate the waves from the source to the site using a regional scale, it is necessary to define the crust velocity mode. In this work, the used model is adopted for the study of this region is the 1D profile proposed by Hasslinger et al. (1999) (FIG.2). This profile was obtained by wave-form inversion procedures, centered on the main phase of P-wave. Indeed, local events observed at several stations have been used to calculate a minimum 1D velocity profile which was verified by several tests (for P and S velocity model). Concerning the local scale, a more refined geological model has been obtained by Hollender et al. (2015) using in situ measurements. This profile modifies the model proposed by Hasslinger et al. (1999) near the ground surface (i.e. from the ground surface to a 5km depth). The velocity profile proposed by Hollender et al. (2015) will be used in a further work for the area of the sedimentary basin in order to evaluate the effect of local geology on ground motion prediction.

3.2.Mesh construction

In this study, in order to consider the real topography and bathymetry of the studied site, a mesh tool (HexMesh) was used to generate the Argostoli model (FIG.3). It is a software tailored to extrude a given Digital Elevation Model (DEM) down to a certain depth so to obtain an unstructured hexahedral mesh. HexMesh[1] is a hexahedral mesh generator for large domains based on octree and 27-tree structures. It allows for consideration of topography, bathymetry and coastlines, as well as water bodies and basins for geophysical applications.

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[1] Source : https://github.com/jcamata/HexMesh.git

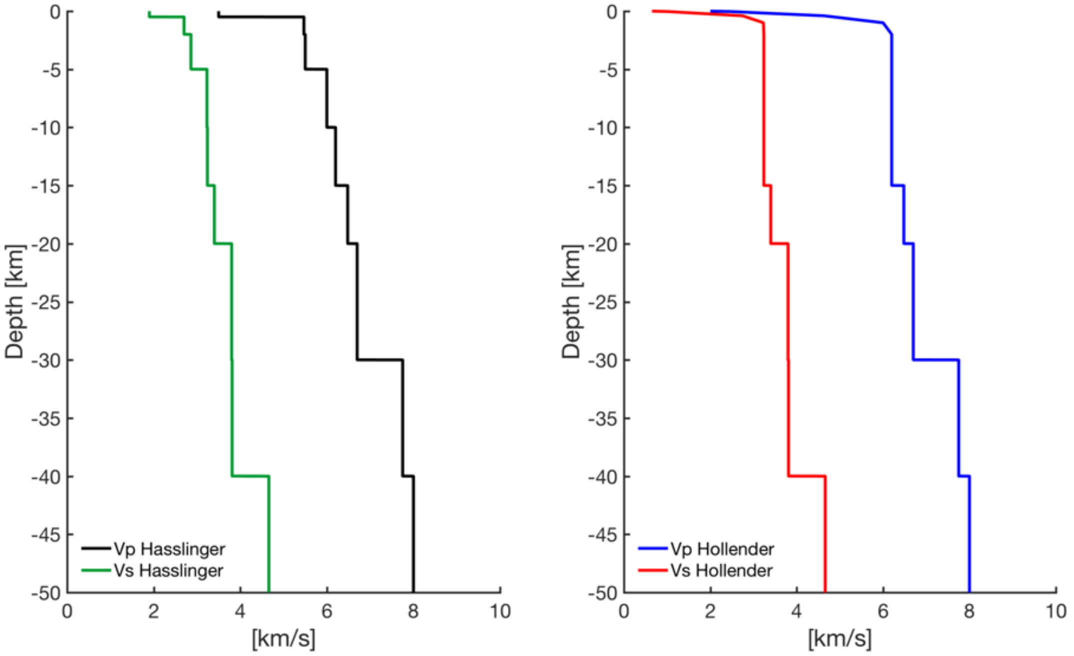

FIG. 2. Velocity models proposed by Hasslinger et al. (1999) for Ionian region and Hollender et al. (2015) for the sedimentary basin of Koutavos.

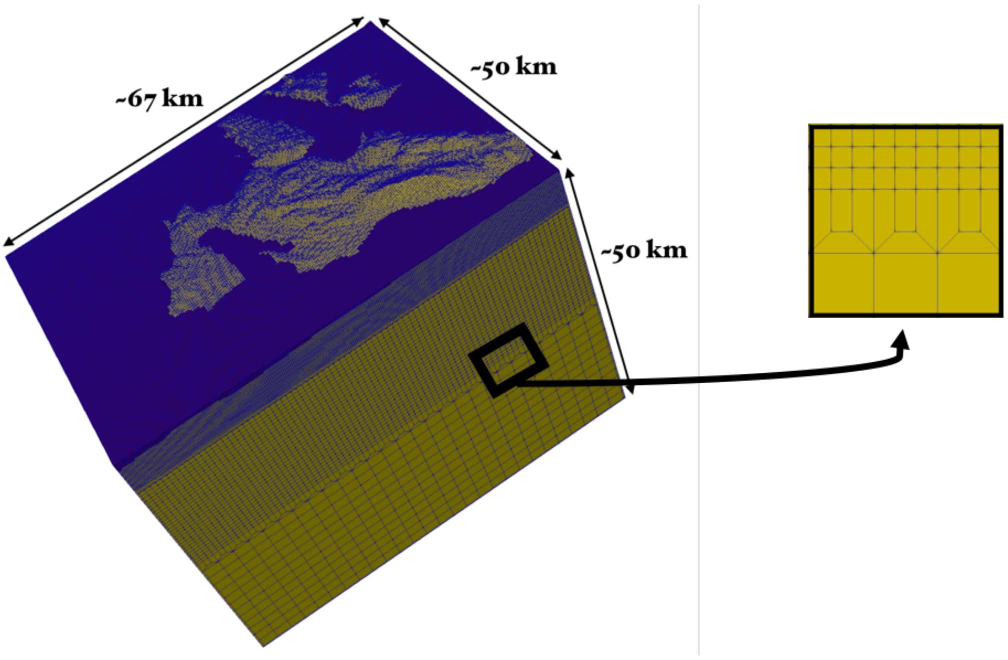

FIG. 3. Sketch of large scale mesh generated by 27-tree algorithm, for the Kefalonia region, Greece.

4. DATABASE DESCRIPTION

The experimental campaigns on the Argostoli site started in 2013 as part of the SINAPS @ project. The studies carried out on this site follow a European project called NERA which had already been the subject of a number of geophysical investigations. This project aimed to, i) characterize the structure and filling of the plio-quaternary basin of d'Argostoli and ii) to carry out a vertical seismic measurement network (ARGONET[2] network) to study the nonlinearities in the geological medium.

In September 2013, a first geological and geophysical survey was conducted. It leaded to a new geological map and 2D cross-section (FIG.4.), estimation of Vs profiles (obtained with surface wave based non-invasive methods), and a 3D overview of the basin through H/V measurements.

On the 26th January 2014, a Mw=6.2 earthquake shook the island. It was decided to launch a post-seismic survey with two main objectives:

- install temporary accelerometers in anticipation to the installation of the definitive permanent array in order to record possible strong after-shocks.
- install some dense sensors in order to get a database to study spatial short-scale variably.

Then, in 2015 a drilling campaign took place to install the vertical network. Three boreholes were drilled at 85, 40 and 15 m. As part of this work, the database resulting from these measurements makes it possible to compare the numerical simulations with the measures carried out on the site (FIG.5.).

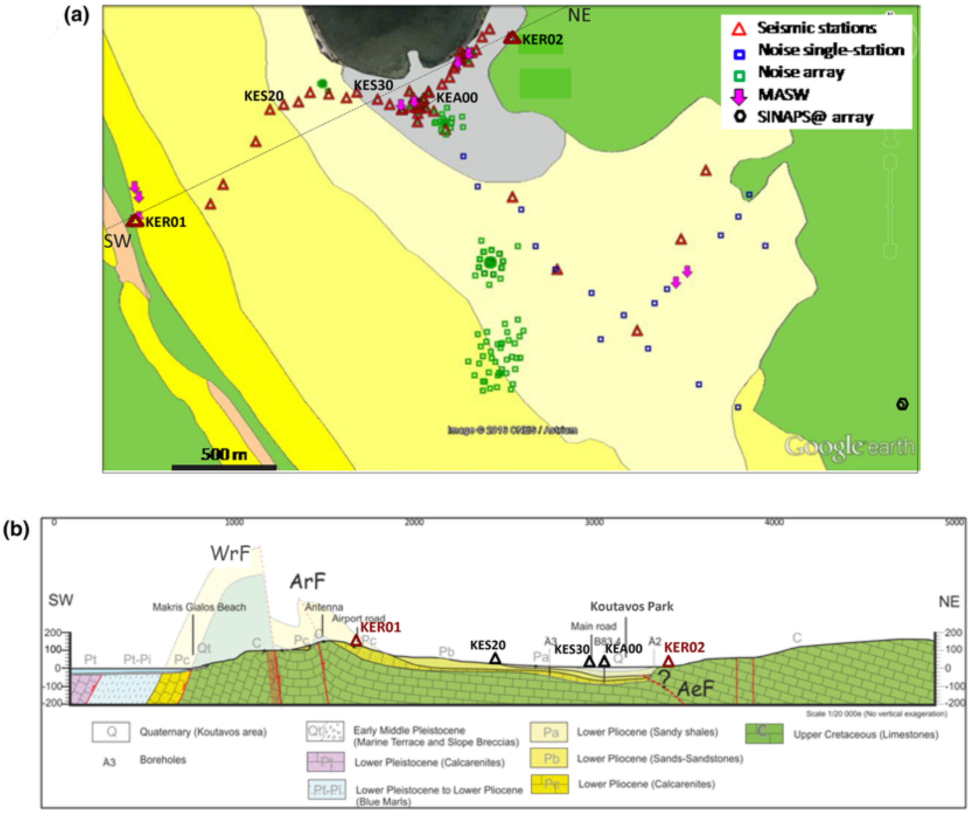

FIG. 4. (a) Plan view of the Argostoli basin together with the seismic array configuration. Contour lines of the geological map correspond to Quaternary (grey), Calcarenites (yellow), Sands-Sandstones (light yellow), Limestones (green), Miocene formation (pink) and they have been constrained using field data (NERA Deliverable D11.3). (b) geological cross-section across the basin (Hollender et al. 2015).

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[2] Source : https://www.institut-seism.fr/wp-content/uploads/2017/09/PresentationArgonetKefalonia.mp4?_=

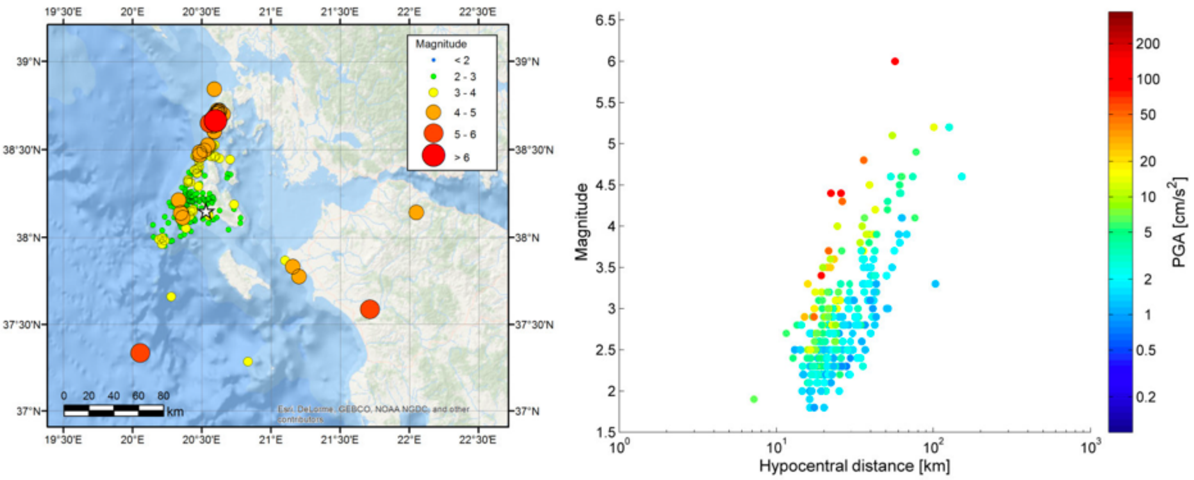

FIG. 5. Epicenters of aftershocks recorded by the Argostoli rock-site dense array and used in the present study. Colors indicate magnitude values. The white star represents the location of array.

5. RESULTS

The characterization and consideration of site's effects, related to soil conditions, are essential for the evaluation of seismic risk. Topographic features are part of these observed site effects. This work focuses on this type of local effect. In order to quantify the influence that the consideration of real topography and bathymetry of the site could have on its seismic response, three numerical models have been studied and compared. The models have the same size: 67 × 50 × 50 km. The first case is a layered model that does not take into account topography or bathymetry (FIG.6 a). There are analytical methods for modelling strong ground motion using Green's function (O'Connell et al. 1984). The numerical code used in this study to perform numerical simulations was validated with a semi-analytical method (Hisada, 1994, 1995, 2008) using Green's functions for semi-infinite stratified half-space (Gatti 2017). The size of the elements constituting the mesh is 320 × 320 m in the horizontal directions (EW and NS) and 250m vertically in the first layer of soil. The size of the elements in the vertical direction is adapted to propagate the desired frequency band according to the properties of the soil layers. The total number of elements of this model is 1789040. The second case is built with the same velocity profile (i.e. stratigraphy) but it takes into account the topography of the site (FIG.6 b). The third model include the real geometry of the soil surface: topography and bathymetry (FIG.6 c). The presence of seawater is also taken into account by modeling it with a fluid with a density of 1.03 g/cm3 and a P wave propagation velocity equal to 1.5 km/s. The size of elements for this case is 280 × 200 × 207 m. The total number of elements for this model is 2047945. Compared signals were filtered at 8 Hz. The seismic source was modeled by point-wise double-couple located at 14 km depth (FIG 7). It represents a magnitude Mw4.6 with Strike=163°, Dip=39°, Slip=92°. More detailed information about the data used to model the point source (orientation, magnitude…) are available through the GEOFON Program website:

https://geofon.gfz-potsdam.de/data/alerts/2016/gfz2016kylx/mt.txt

FIG.8 shows the study site as well as the locations where the sensors (numerical) were placed. In order to highlight the influence of topography and bathymetry on the prediction of ground motion, a comparison of accelerograms was carried out at the four stations highlighted by their altitude in this figure.

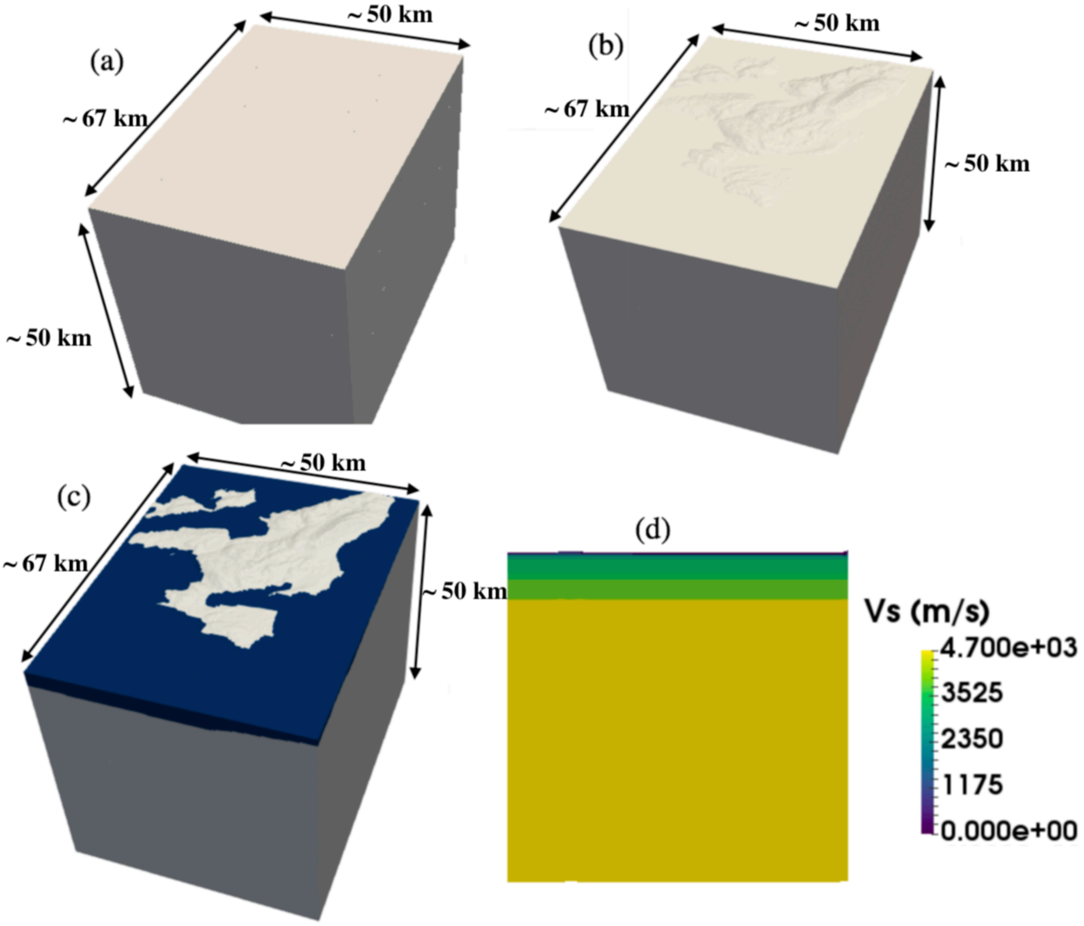

FIG. 6. Studied cases: (a) Layered model. (b) Model including stratigraphy, topography. (c) Model including stratigraphy, topography and bathymetry. (d) Velocity profile used for all studied models.

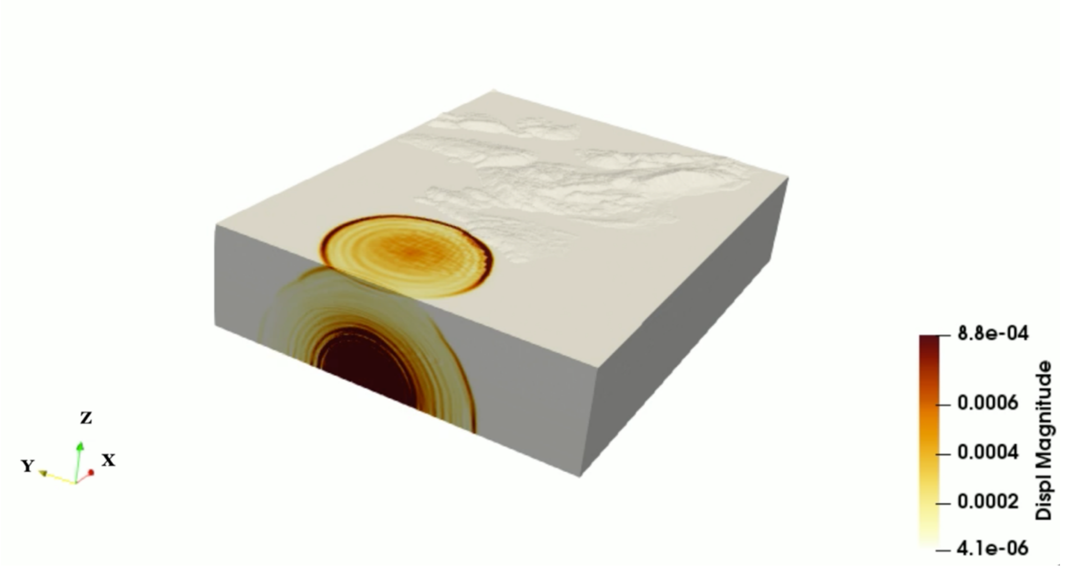

FIG. 7. Seismic source modeled by a point-wise double-couple of a magnitude M_w*4.6 located at 14 km depth.*

5.1.Topography effect

Several theoretical and numerical studies have been conducted to better understand the influence of topography on the propagation of seismic waves (Bouchon 1985; Geli et al. 1988; Koumatitsh et al. 1998; Zhou et al. 2006). It is generally observed that the recorded movements at the summits of the reliefs are greater than those recorded at their base. This amplification corresponds to a concentration of energy related to the reflection of the incident waves towards the interior of the structure. The theoretical and experimental results are generally in good agreement on the qualitative, but the level of the calculated amplifications underestimates the amplifications observed. Different explanations have been put forward to explain such differences (Bard, 1985; Bouchon et al. 1996). 2D modeling may initially be too limited for the evaluation of such effects generated by a very irregular topography or involving a combination of hills. Experiments at the site where strong accelerations were recorded during the Northridge earthquake revealed the 3D nature of the seismic response of the hill (Spudich et al. 1996). Numerical simulations taking into account 3D structures have shown particularly important directional effects (Bouchon et al. 1996; Bouchon and Baker 1996; Koumatitsh and Vilotte 1998).

Figure 9 shows the comparison between simulated signals at different points at different altitudes for the model considering topography (magenta line) and accelerograms obtained at the ground level for the other one (green line). A slightly shifted wave arrival is noted when the topography is taken into account. De-amplification more or less important depending on the location of the sensors is also observed for the model with topography. Indeed, for the three simulated signals at the top of the hill, a difference with the case without topography is noticed, nevertheless it could be neglected. On the other hand, the comparison of the two models at the ground level (a point at the surface with the coordinates to the one for the layered model) shows a big difference: the presence of the topography de-amplifies widely the site response. These results are overall in good agreement with existing works except for the case at 1060 m altitude where we expected to have more amplification than other cases. However, these amplification phenomena can present a great spatial variability, according to the irregularity of the topography and the incident wave.

Indeed, it has been found that the maximum amplification can occur in a concentrated area near the summit, or can take place at the halfway up the hill while the summit has a de-amplification (Koumatitsh et al. 1998). This highlights the complexity of this purely geometric phenomenon which can reveal interactions between the waves propagation and the irregularities of the surface relief.

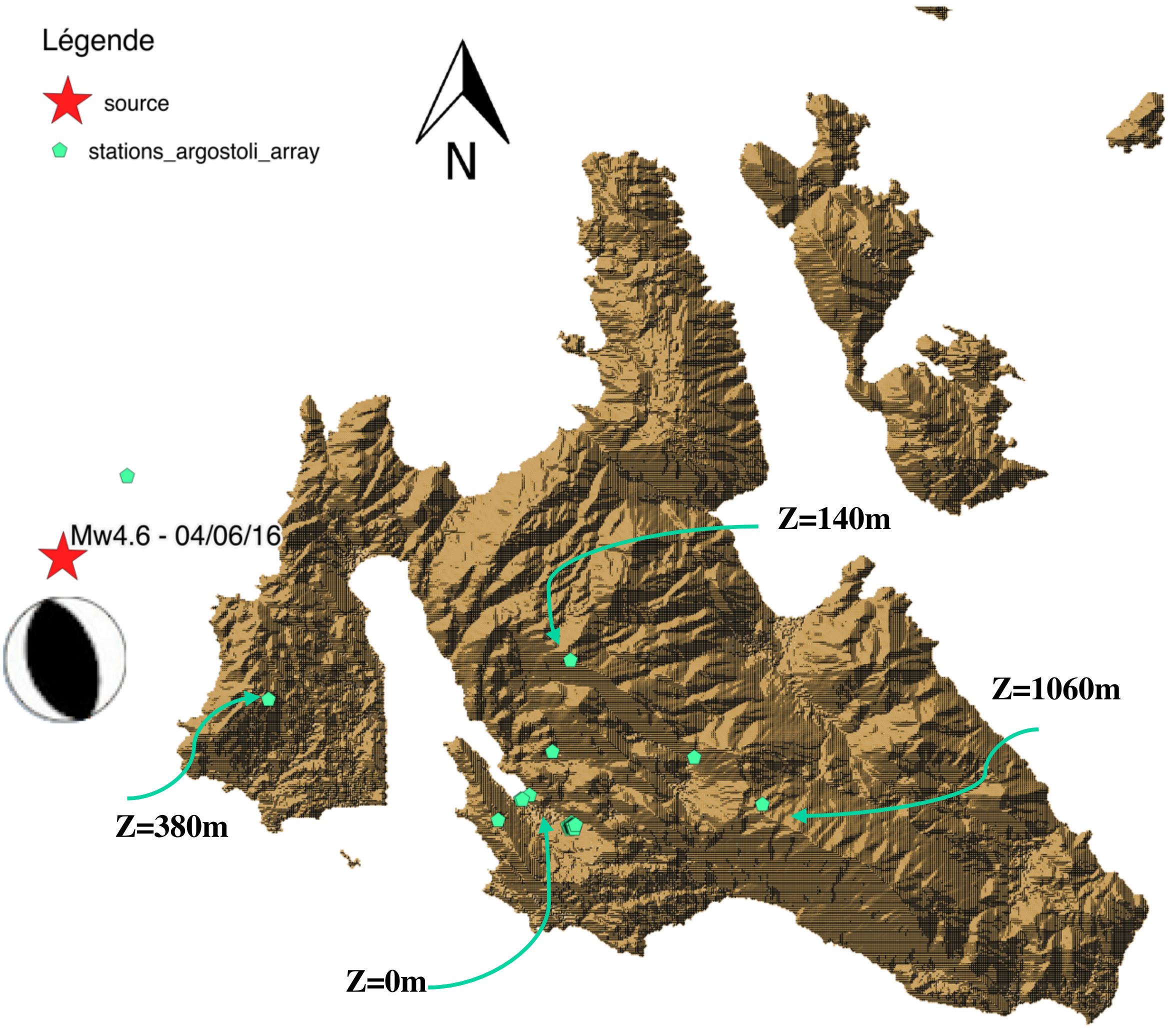

FIG. 8. Studied area. The green points correspond to the location of the sensors in the numerical models.

5.2.Bathymetry effect

The analysis here is focused mainly on the difference between the model including topography only and that including topography as well as bathymetry. Figure 10 shows the comparison of the time history acceleration and the Fourier spectra of the three case studies at the same previous stations.

It is noted that for stations located far from the sea at high altitudes (380 and 1060 m), the seismic response of the soil is the same for both models including topography. As expected, the closer sensors are to the coast, the more the presence of bathymetry affects the seismic response of the soil. On the other hand, these graphs show that the consideration of the bathymetry especially has the impact of amplifying the ground motion.

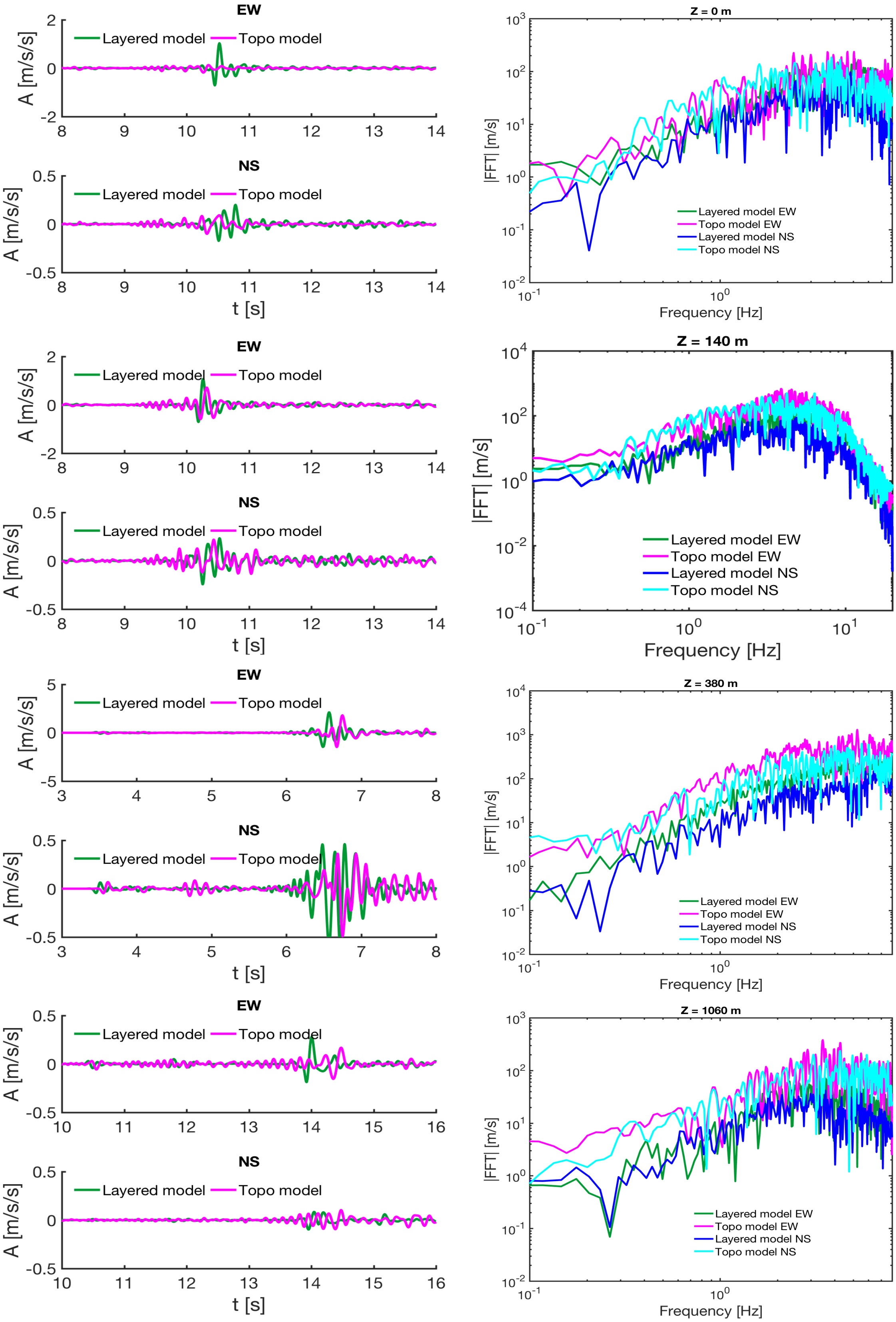

FIG. 9. Comparison of time history acceleration and Fourier spectra of the layered model and model including topography.

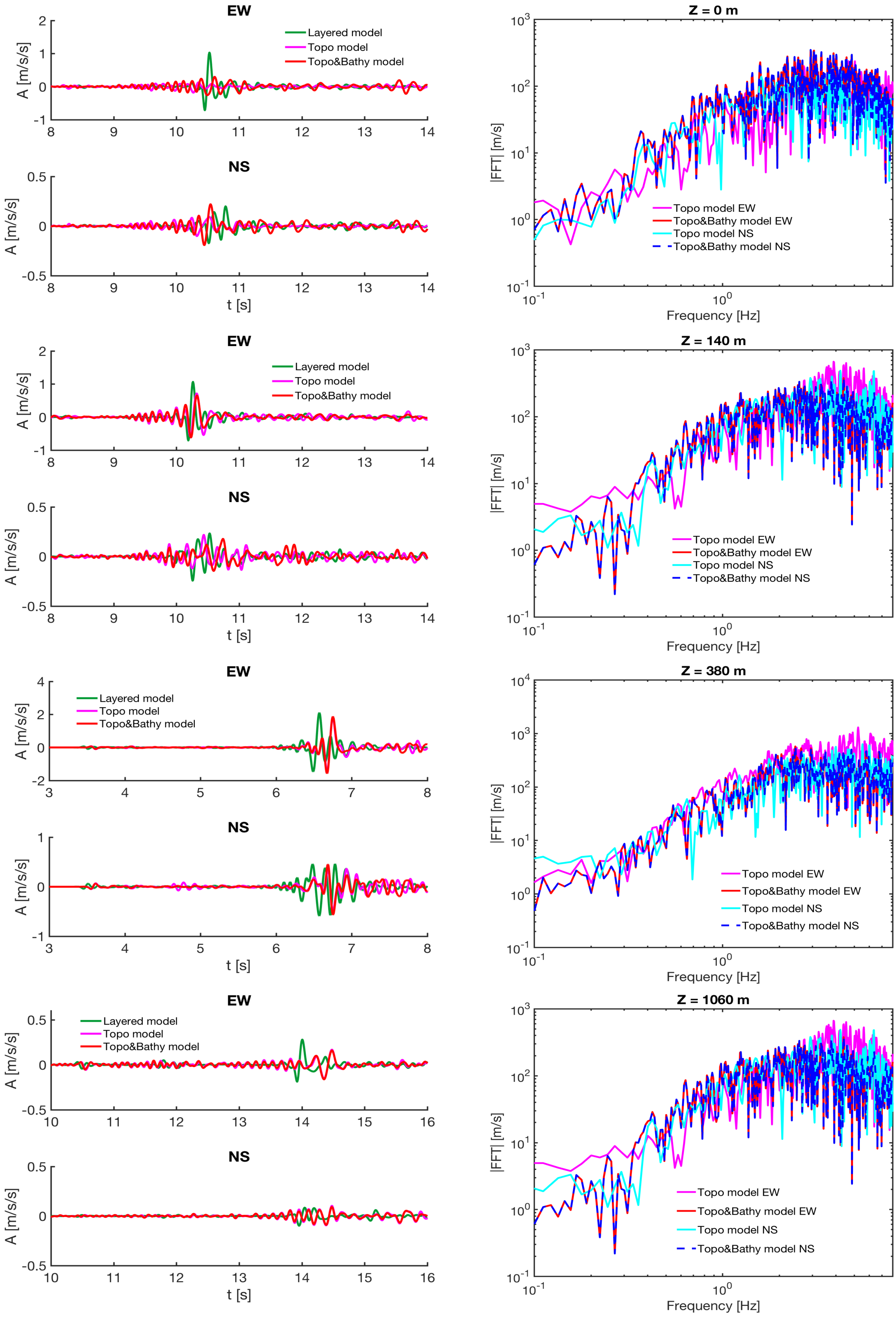

FIG. 10. Comparison of time history acceleration and Fourier spectra of the layered model, model including topography and the model including topography and bathymetry at four stations.

5.3.Comparison with recorded data

In this section, a comparison between simulated accelerograms for the three numerical models and those recorded take place (FIG.11). The comparison was carried out at four stations situated at the same location but at different depths (83, 40, 15 and 0 meters deep). These sensors are located in the sedimentary basin.

The consideration of the topography and the bathymetry has the effect of de-amplifying the movement in depth compared to the case where they are not present, especially in the EW direction that is parallel to the wave propagation direction. Moreover, the accelerogram obtained (topography & bathymetry case) looks like the recorded signal far from the coast. On the other hand, on the surface of the ground, the movement is greater than that simulated in the presence of the topography and bathymetry. This may be due to the fact that the sedimentary formations have not been modeled and therefore the site effects have been neglected. On the other hand, it is noted that the response of the layered case is close to measurements at the surface of the ground in terms of amplification level.

It leads to the conclusion that layered modeling is too simplistic because there is always an area at lower wave propagation velocity (as is the case for Argostoli) whose effect can be combined with the topographic effect to create more important amplifications. It is well known that soil effects play a major role in the level of amplification of the seismic response. This is why modeling the sedimentary basin and considering spatial variability would allow to carry out more complete analyzes.

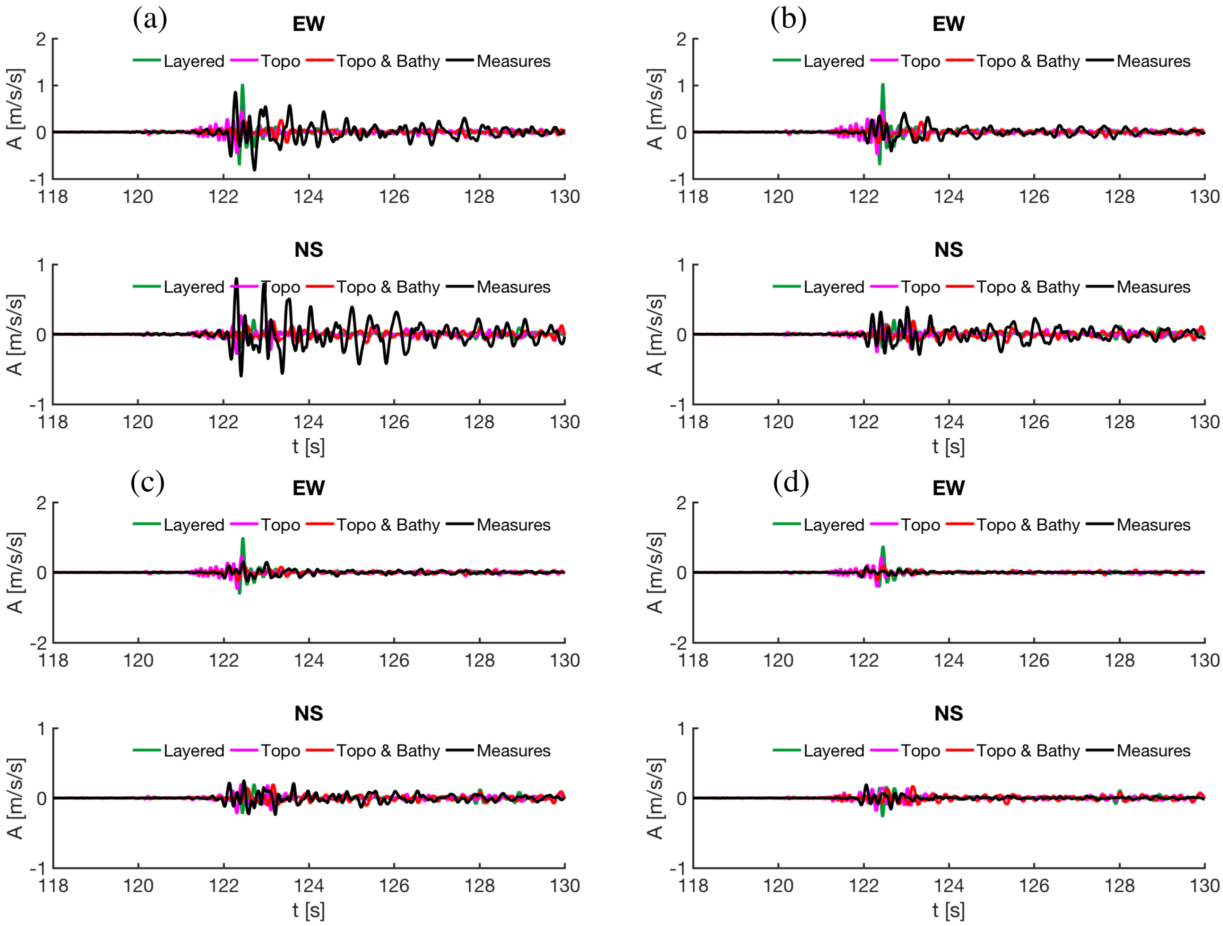

FIG. 11. Comparison of time history all studied numerical models with the recorded data at four stations: (a) at the surface, (b) at 15 m depth, (c) at 40 m depth and (d) at 83 m depth.

6. CONCLUSIONS

In this paper, numerical tools used to carry out the 3D physics-based analysis are presented. The study highlights the influence of both topography and bathymetry structure consideration on the ground motion prediction. It has been shown that it is difficult to develop quantitative rules to include the effect of topography in assessing the prediction of soil movement. The presence of a relief can greatly influence the seismic response at a given site, even relatively far from the topographic and bathymetric formations. The presence of this structures in the studied site requires a specific analysis that takes into account both the 3D structure and the soil conditions in order to capture local effects that may be particularly disastrous. Hence, further works include modeling of the Koutavos sedimentary basin will be carried out in order to quantify the effect of topographic and bathymetric reliefs combined with that of sedimentary fillings on ground motion.

7. ACKNOWLEDGMENTS

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