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3D NUMERICAL MODELLING OF THE SEISMIC RESPONSE OF THE THESSALONIKI URBAN AREA: THE CASE OF THE 1978 VOLVI EARTHQUAKE

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Abstract

This study aims at showing the numerical modelling of earthquake ground motion in the Thessaloniki urban area, using a 3D spectral element approach. The availability of detailed geotechnical/geophysical data together with the seismological information regarding the relevant fault sources allowed us to construct a large-scale 3D numerical model suitable for generating physics-based ground shaking scenarios within the city of Thessaloniki up to maximum frequencies of about 2 Hz. Results of the numerical simulation of the destructive M_W6.5 1978 Volvi earthquake are addressed, showing that realistic estimates can be obtained. Shaking maps in terms of ground motion parameters such as PGV are used to discuss the main seismic wave propagation effects at a wide scale.

Keywords: *deterministic seismic hazard, seismic wave propagation, Spectral Element Method.*

Περίληψη

Αντικείμενο της παρούσας μελέτης είναι η αριθμητική προσομοίωση της σεισμικής εδαφικής κίνησης στην αστική περιοχή της Θεσσαλονίκης με τη χρήση της μεθόδου των φασματικών στοιχείων. Η διαθεσιμότητα λεπτομερών γεωτεχνικών/γεωφυσικών δεδομένων, καθώς και σεισμολογικών πληροφοριών για τα ρήγματα που επηρεάζουν την περιοχή, μας επέτρεψε την κατασκευή ενός τρισδιάστατου αριθμητικού προσομοιώματος μεγάλης κλίμακας, κατάλληλου για την παραγωγή σεναρίων εδαφικής κίνησης για την πόλη της Θεσσαλονίκης και για μέγιστη συχνότητα 2 Hz. Στη μελέτη αυτή παρουσιάζονται αποτελέσματα της αριθμητικής προσομοίωσης του καταστροφικού σεισμού της Βόλβης του 1978, μεγέθους Mw6.5, καταδεικνύοντας τη δυνατότητα επίτευξης ρεαλιστικών εκτιμήσεων. Τέλος, χρησιμοποιούνται χάρτες εδαφικής ταλάντωσης σε όρους παραμέτρων εδαφικής κίνησης όπως PGV για τη μελέτη των κύριων φαινομένων διάδοσης σεισμικών κυμάτων σε μεγάλη κλίμακα.

Λέξεις κλειδιά: *ντετερμινιστική σεισμική επικινδυνότητα, προέλαση σεισμικών κυμάτων, Μέθοδος Φασματικών Στοιχείων.*

1. Introduction

Thessaloniki, the second largest city in Greece after Athens, is located in the Axios-Vardar zone, which is adjacent to the Servomacedonian massif (see Figure 1), extending from the Yugoslavia-Bulgaria border up to the North Aegean Trough. The Servomacedonian massif is one of the most seismotectonically active zone in Europe; a large portion of its seismicity is associated to the Mygdonia graben, around 25 km northeast of Thessaloniki, where on 20 June 1978 a destructive earthquake with moment magnitude M_W 6.5 occurred. The 1978 earthquake caused extensive damage to many villages located close to the epicentral area (Stivos, Scholari, Peristeronas, Gerakarou), as well as in Thessaloniki, where the death toll reached the value of 45 people. It is considered as the first earthquake with a serious impact on a big modern urban centre in Greece.

The earthquake attracted the attention of many researchers and marked the beginning of several studies, extending from the analysis of the seismological features of the largest events as well as of the aftershocks of the seismic sequence (see thorough overview in Roumelioti *et al*., 2007), to microzonation studies and researches related to the quantification of the local site effects (e.g., Lachet *et al*., 1996; Triantafyllidis *et al*., 2004a, b; Raptakis *et al*., 2004a,b), up to the construction of a 3D geotechnical/geophysical model for the sedimentary and bedrock formations within the city of Thessaloniki (Anastasiadis *et al*., 2001; Apostolidis *et al*., 2004).

The aim of this study is to present a numerical study on the prediction of earthquake ground motions in the Thessaloniki urban area, based on a full 3D model both of the seismic fault rupture and of the source-to-site propagation path, with reference, in particular, to the M_W 6.5 1978 earthquake. Numerical simulations were carried out using a high-performance code, namely SPEED, based on the Discontinuous Galerkin Spectral Elements Method (DGSEM). The comparison between synthetics and observations at the only available strong motion station will be addressed together with the comparison with Ground Motion Prediction Equations (GMPEs) and the generation of ground shaking maps at a broad scale.

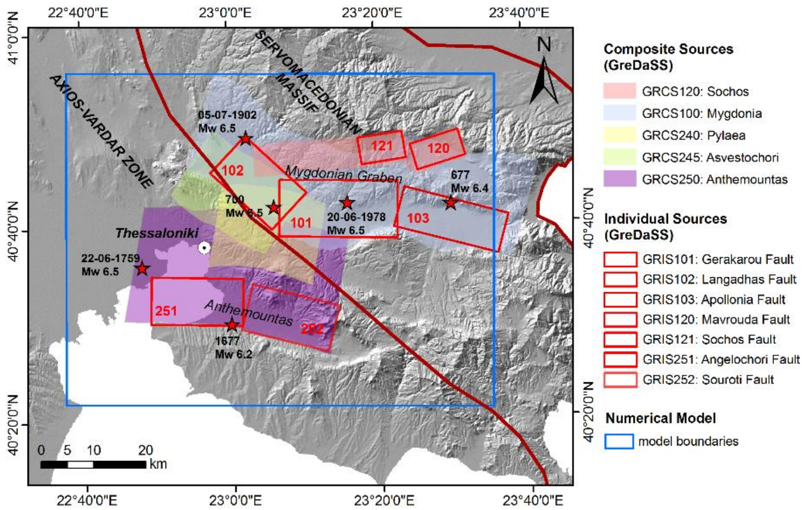


Figure 1 – Seismic sources for the broader Thessaloniki area, as provided by the GreDASS database, and distribution of the epicentres (denoted by the stars) of the historical earthquakes with M_W > 6. The blue box indicates the extent of the 3D model.

2. Seismotectonic and Geologic Context

The broader Thessaloniki area lies in Central Macedonia, an area characterised by extensive NW-SE and E-W-trending continental-type basins and grabens, filled with Neogene and Quaternary sediments, which formed as a result of Miocene to present extensive brittle extensional deformation that mainly related to high-angle normal faults (Tranos *et al*., 2003). Among them, the Mygdonian graben is the largest basin in the area (see Figure 1) and its continuous seismic activity poses a serious threat to the city of Thessaloniki. The tectonic regime of the broader area is characterised by extensional deformation associated mostly with E-W, NW-SE or NE-SW striking faults (Tranos *et al*., 2003; Paradisopoulou *et al*., 2006). The E-W trending faults are mainly normal dip-slip, while the NW-SE and ENE-WSW ones occasionally show strike-slip components of movement. The fault system bounding the southern boundaries of the Mygdonia graben (Gerakarou fault) was responsible of the destructive 20 June 1978 earthquake.

Figure 1 points out the main seismic sources of the broader Thessaloniki area, as provided by the Greek Database of Seismogenic Sources (GreDaSS: http://gredass.unife.it/; Caputo *et al*., 2012), a repository of geological, tectonic and active fault data for the Greek territory, together with the epicentres of the historical events with moment magnitude M_W>6 (events within the computational domain are selected). Data about the historical events are taken from Papazachos *et al*. (2000; 2010) and, specifically for the 1978 Volvi earthquake, from Roumelioti *et al*. (2007). The study area is characterised by an intense seismic activity with strong historical earthquakes, associated mainly to the Mygdonia Basin and the Anthemountas fault zone, with magnitude up to M_W=6.8. The boundary of the computational model, described in the following sections, is also indicated, as denoted by the superimposed blue box.

From a geological point of view, the Thessaloniki urban area is characterised by three main macro geological structures oriented in the NW-SE direction. Starting from the deepest one, these formations can be summarised as follows: (1) metamorphic substratum consisting of crystalline rocks (gneiss, epigneiss and green shists), which outcrops at the N-NE border of the city and reaches a depth larger than 500 m near the coastline in the W-WS direction; (2) sedimentary deposits, mainly of Neogene period, dominated by the red silty clay series, covering the bedrock basement beneath the city; (3) recent deposits consisting of clays, sands and pebbles of Holocene period. The definition of 3D thematic maps of these geologic formations together with their characterisation in terms of main geotechnical/geophysical properties have been addressed, first, by Anastasiadis *et al*. (2001) and, subsequently, by Apostolidis *et al*. (2004). In this work reference has been made to the 3D model produced by Apostolidis *et al*. (2004).

3. The Numerical Simulation Method

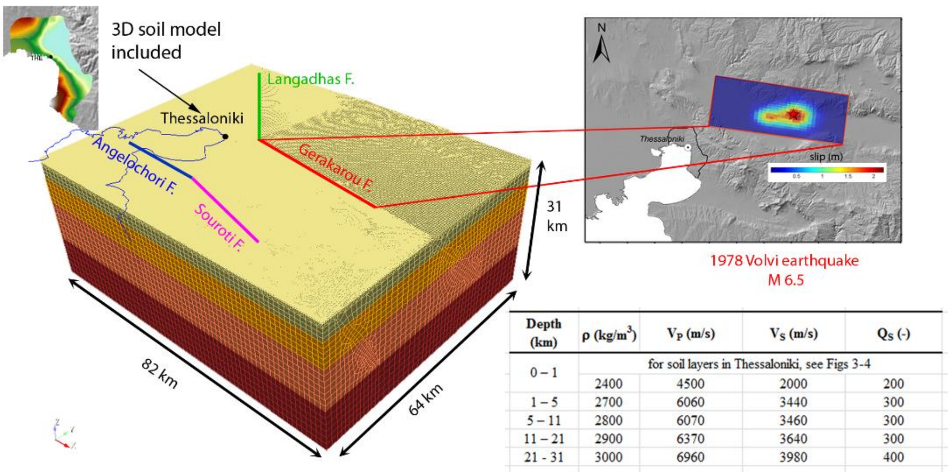
3D numerical simulations of seismic wave propagation have been performed using the Discontinuous Galerkin Spectral Elements Method (DGSEM) implemented in the open-source computer package called SPEED, SPectral Element in Elastodynamics with Discontinuous Galerkin (http://speed.mox.polimi.it/; Mazzieri *et al*., 2013). SPEED can handle the simulation of large-scale seismic wave propagation problems including the coupled effect of a seismic fault rupture, the propagation path through Earth’s layers and localised geological irregularities, such as alluvial valleys. Based on a discontinuous version of the classical spectral element (SE) method, as explained in Antonietti *et al*. (2012), SPEED is naturally oriented to solve multi-scale numerical problems, allowing one to use non-conforming meshes (*h*-adaptivity) and different polynomial approximation degrees (*N*-adaptivity) in the numerical model. The code has been optimised to run on multi-core computers and large clusters (e.g., Fermi BlueGene/Q at CINECA), taking advantage of the hybrid MPI-OpenMP parallel programming. The present version of SPEED includes the following features: i) different seismic excitation modes, including kinematic finite-fault seismic ruptures models; ii) both linear and non-linear visco-elastic soil materials; iii) different attenuation models with frequency proportional quality factor (Stupazzini *et al*., 2009) or frequency constant quality factor (Mozco *et al*., 2014); (iv) paraxial absorbing boundary conditions (Stacey, 1988); (v) time integration by either the second order accurate explicit leap-frog scheme or the fourth order accurate explicit Runge-Kutta scheme. Note that the current version SPEED cannot account for coupled fluid-soil seismic wave propagation analyses.

4. Computational Model for the Thessaloniki Urban Area

Based on the available data regarding both the characterisation of the seismic sources and geological, geotechnical and geophysical aspects, a large-scale 3D spectral element model (see Figure 2) has been constructed, including the following features, as key ingredients:

- ground topography as retrieved from 90 m SRTM DEM (http://srtm.csi.cgiar.org/);
- four seismogenic fault sources posing a hazard to the city of Thessaloniki, specifically, Gerakarou-GRIS101 (i.e., the fault responsible of the 1978 Volvi earthquake), Langadhas-GRIS102, Angelochori-GRIS251, and Souroti-GRIS252 (the latter two being part of the Anthemountas fault zone);
- horizontally layered crustal model for deep rock materials (from Ameri *et al*., 2008);
- 3D subsoil model of the Thessaloniki urban area, based on the detailed microzonation geotechnical studies (Anastasiadis *et al*., 2001) combined with extensive geophysical analyses (Apostolidis *et al*., 2004). Further details about the 3D subsoil model are given below.

As depicted in Figure 2, the mesh extends over a volume of about 82 km x 64 km x 31 km and is discretised using an unstructured hexahedral conforming mesh with characteristic element size ranging from a minimum of about ~150 m at the surface to ~1500 m at the bottom of the model. The model consists of 753’211 spectral elements, resulting in approximately 60 million of total degrees of freedom, with a third order polynomial approximation degree. Considering a rule of thumb of four grid points per minimum wavelength for non-dispersive wave propagation in heterogeneous media by the SE approach (Faccioli *et al*., 1997), this model can propagate frequencies up to about 2 Hz. Provided that the mesh honours the geometry of different faults, as highlighted in Figure 2, this model can be used for generating ground motion scenarios in the city of Thessaloniki, resulting from fault ruptures involving either a portion or the entire length of any of these seismogenic sources.



Depth (km)	ρ (kg/m³)	V_P (m/s)	V_S (m/s)	Q_S (-)
0 – 1	for soil layers in Thessaloniki, see Figs 3-4			
	2400	4500	2000	200
1 – 5	2700	6060	3440	300
5 – 11	2800	6070	3460	300
11 – 21	2900	6370	3640	300
21 - 31	3000	6960	3980	400

Figure 2 – 3D spectral element mesh for the broader Thessaloniki area. The crustal model, the faults included in the model and the slip distribution for the 1978 Volvi earthquake are also shown.

Regarding the 3D basin model, the following assumptions were made: (i) the 3D geometry of the geologic bedrock basement, as published in Apostolidis *et al.* (2004), was implemented in the numerical model (see Figure 3, left panel); (ii) two generic soil profiles with linear visco-elastic behavior were defined for the alluvial deposits overlying the bedrock for two ground categories, i.e. Eurocode 8 (EC8) soil B (V_{S30} = 360-800 m/s) and C (V_{S30} = 180-360 m/s), following the soil classification mapped in Figure 3 (right panel, from Pitilakis *et al*., 2015).

• The soil profiles in terms of S- and P- wave velocity (V_S and V_P, respectively), soil density (ρ) and quality factor (Q_S), are given in Figure 4. The functional form for the V_S gradient, $V_S(z) = V_{S,l} + (V_{S,m} - V_{S,l}) \cdot (z/h)^{0.70}$, with $V_{S,l}$ = 300 m/s and $V_{S,m}$ = 2000 m/s being the lower and upper V_S at ground surface and top of geologic bedrock, respectively, and h = 1000 m, was defined according to the recent findings achieved in the framework of NERA project, based on empirical data from SHARE-AUTH database (Pitilakis *et al*., 2014). Note that a minimum shear wave velocity of 300 m/s was assumed due to computational reasons, even though it overestimates the actual values especially along the shoreline. A frequency proportional quality factor is assumed using a reference frequency of 0.67 Hz.

• Note that, although well constrained data were available only for the Thessaloniki urban area, it was necessary to extend arbitrarily the basin model to the west/south-west (Axios basin and Thermaikos gulf) and to the south-southeast (Anthemountas basin). To this end, the shape of the bedrock-alluvial interface along the NW-SE edge of the model by Apostolidis *et al*. (2004) was replicated along these directions to follow roughly the general geomorphologic features of the area. Several preliminary simulations tests were performed to check the impact of this extrapolation procedure, pointing out that results are affected only to a minor extent.

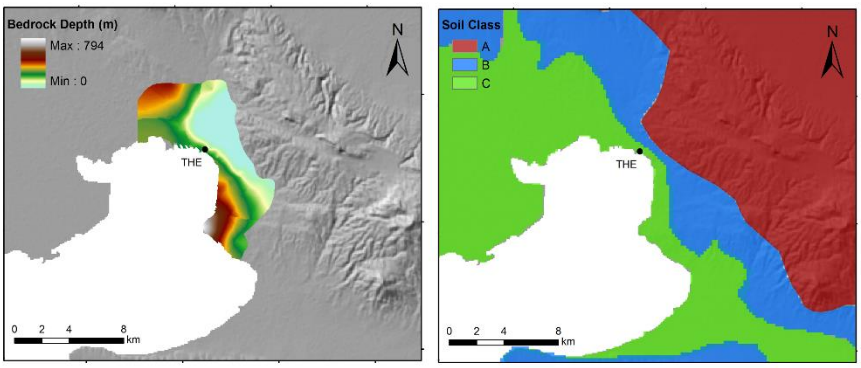


Figure 3 – Left: 3D map showing the depth of geologic bedrock (after Apostolidis et al., 2004) within the city of Thessaloniki; Right: EC8 soil classification (based on Pitilakis *et al.*, 2015).

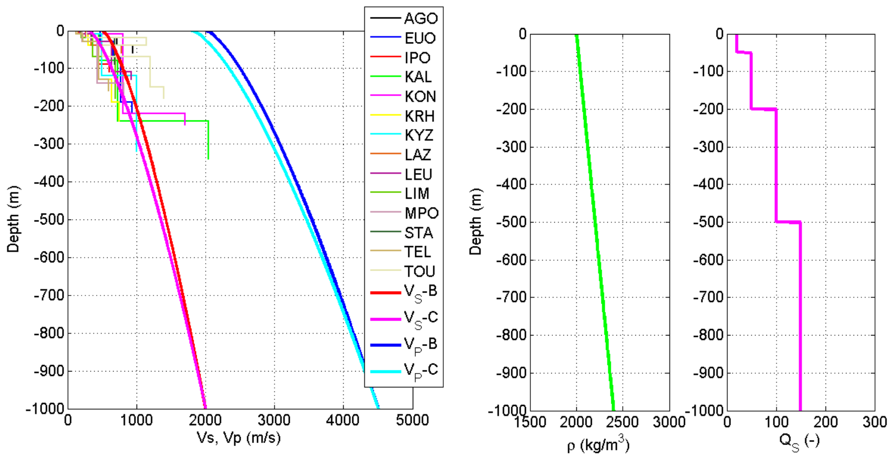


Figure 4– Calibration of average soil profiles in terms of V_S, V_P, ρ and Q_S (at a reference frequency f_0 = 0.67 Hz) for the 3D model, based on the available 1D data.

5. Numerical Simulation of the 20 June 1978 Volvi Earthquake

As a case study, the M_W 6.5 June 20 1978 Volvi earthquake was simulated by SPEED. Even though there was only one strong motion station in operation during the earthquake and the quality of the available recordings is rather low, it is interesting to analyse the main features of the predicted ground motion during this major event.

To simulate the Volvi earthquake, in addition to the features illustrated in the previous section, a kinematic source model along the Gerakarou fault was considered. Reference was made to the recent work by Roumelioti *et al*. (2007), who investigated the rupture process of the 1978 earthquake from the analysis of teleseismic waveforms, recorded in the distance range 21º to 37º, combined with near-fault levelling data. The main kinematic source parameters are listed in Table 1 while the slip distribution is shown in Figure 2. Based on the results of preliminary comparisons between synthetics and observations using the Hisada code (Hisada and Bielak, 2003), the following modifications were made with respect to the model published by Roumelioti *et al*. (2007): (i) the top depth of rupture as assumed at 1 km to avoid super-shear effects (V_S in the top layer is, in fact, 2 km/s); (ii) for the slip distribution, we used a k^2 slip model (Herrero and Bernard, 1994), with location and size of the main slip asperities resembling the ones in the original model.

It was, in fact, found that the application of the original finite-fault solution, characterised by a significant slip asperity at ground surface (as inferred from levelling data), in conjunction with the assumed crustal model, may induce unrealistic ground motion amplitudes towards the city of Thessaloniki owing to excessive amplification effects at the resonance frequency of the first layer of the crustal model, i.e. at 0.5 Hz, where the source radiates much energy. To clarify these effects, Figure 4 shows the results (velocity histories and corresponding Fourier Amplitude Spectra, FAS) at the accelerometric station THE-City Hotel (see location in Figure 3) for the kinematic slip model by Roumelioti *et al*. (2007) under two hypotheses regarding the crustal model, i.e., with or without the top layer of 2000 m/s. It is apparent that the case with the top layer produces excessive energy in the frequency range between 0.5-1 Hz, especially on the EW and UP component.

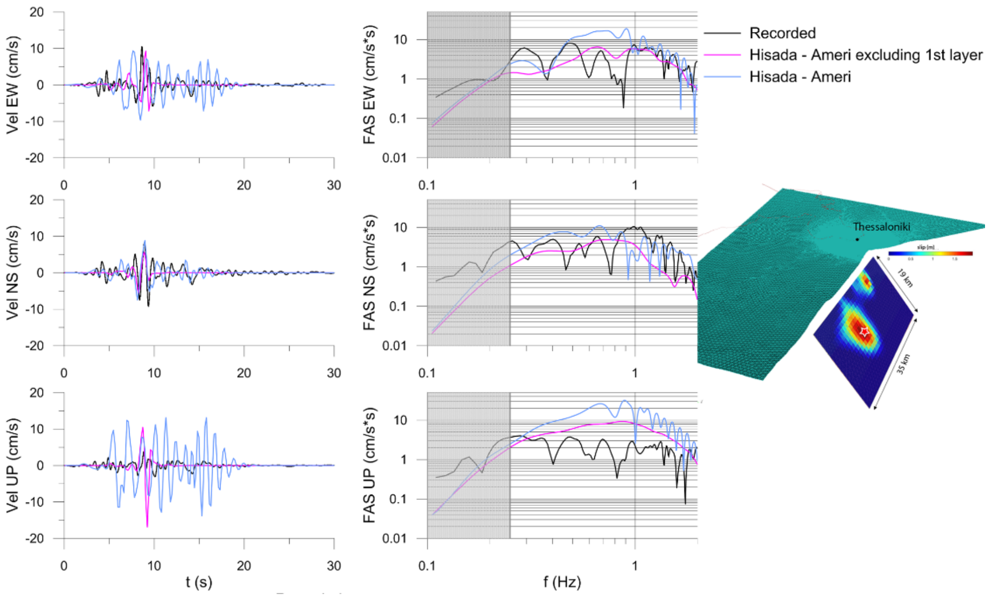


Figure 5 – Effect of the crustal model and kinematic slip distribution. Results refer to the THE-City Hotel station (see location in Figure 3) in the range 0.25-2 Hz.

Figure 5 shows the comparison between synthetics and ground motion observations at the accelerometric station THE-City Hotel in terms of velocity waveforms and FAS. Recorded motions were downloaded from ITSAK database (http://www.itsak.gr/). Both simulated and recorded data are band-pass filtered between 0.25 and 2 Hz, the former being the minimum usable frequency of the analog record and the latter being the frequency limit of the numerical simulation. A satisfactory agreement is found especially for the horizontal components, especially the NS one, while vertical component tend be overestimated, due to the assumptions regarding the assumed focal mechanism.

Table 1 - Summary of main source parameters for the 1978 Volvi earthquake.

Hypocentre (°N, °E)	Depth (km)	L x W (km^2)	Z_{top} (km)	Strike/Dip/Rake (°)	Rup. Vel. (km/s)	Rise Time (s)
(40.705, 23.266)	7.5	35 x 19	1	278/46/-70	2.6	0.6

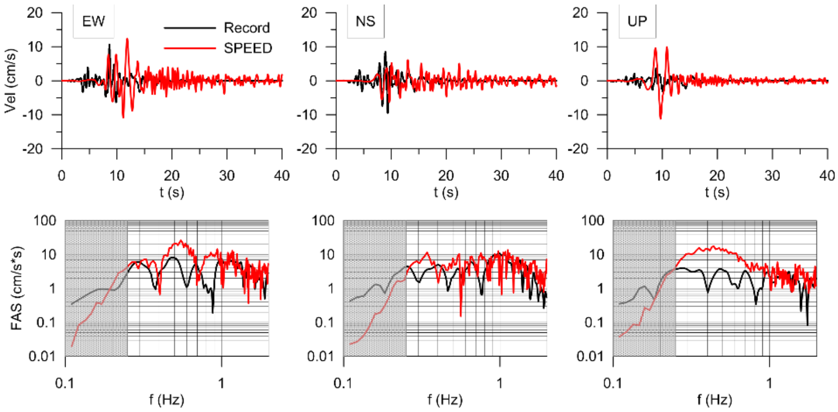


Figure 6 – Comparison between synthetics and recordings at the THE-City Hotel station: three component velocity time histories (top) and FAS (bottom) in the range 0.25-2 Hz.

Finally, as a further check on the results of the numerical simulations on a broad scale, Figure 5 illustrates the comparison with the GMPE by Skarlatoudis *et al*. (2003, 2007), SK07, developed specifically for shallow earthquakes in the broader Aegean area, in terms of geometric mean of PGV, considering a set of uniformly spaced sites on rock (left) and basin (right) conditions. A satisfactory comparison is found especially for rock and stiff soil sites, while at soft basin sites (EC8 class C) larger differences are found probably due to the inability of the empirical models to account for the specificity of local site conditions.

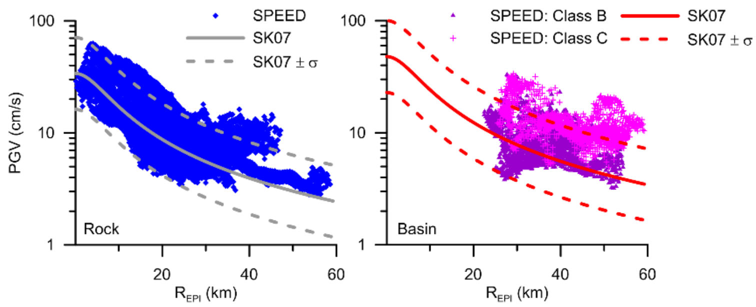


Figure 7 – Comparison between simulated results and the GMPE of Skarlatoudis et al. (2003, 2007), SK07, for both rock (left) and basin (right) sites.

6. Ground Shaking Maps

Interesting outputs of 3D numerical simulations are the ground shaking maps at a broad scale in terms of different ground motion intensity measures, such as Peak Ground Velocity (PGV), Peak Ground Displacement (PGD) or response spectral acceleration (SA). In Figure 6 the spatial distribution of PGV (filtered in the range 0.05-2 Hz) is shown for the three components of ground motion: normal to the fault strike (Fault Normal, FN), parallel to the fault strike (Fault Parallel, FP) and vertical (UP). For comparison purposes, the same colour scale has been adopted for the three maps. It is found that maximum PGV values of about 1.15 m/s are found on the hangingwall of the fault on the FN component, while the FP ground motions tend to be significant lower in the near field. However, at larger distances, differences between the FN and FP tends to decrease significantly. Vertical motion can be larger than the horizontal FP motion in the near-source region, in agreement with the evidence of larger vertical to horizontal ratios in the proximity of the source (see e.g. Ambraseys and Douglas, 2003). From both maps it is found that maximum ground motion amplitudes are found in the region, south-east of the epicentre owing to focal mechanism effects. At larger distances, amplification of ground motion due to the presence of the soft sedimentary deposits is also apparent.

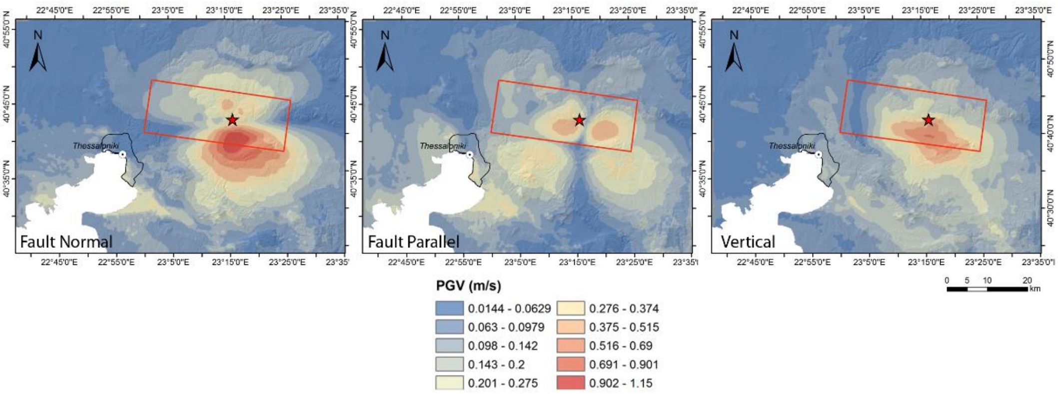


Figure 8 – Map of Peak Ground Velocity (PGV) on the Fault Normal (FN, left), Fault Parallel (FP, centre) and vertical (UP, right) component.

7. Conclusions

In this paper 3D numerical modelling of earthquake ground motion in the Thessaloniki urban area has been addressed with emphasis on the simulation of the destructive M_W 6.5 20 June 1978 earthquake, who affected seriously the city. The model covers a wide area of size 82 km x 64 km and includes the 3D subsoil structure of the urban area, as retrieved from the available geotechnical and geophysical studies, as well as the fault sources posing a serious threat to the city of Thessaloniki.

The first efforts to study 3D seismic wave propagation effects within the Thessaloniki urban area at a wide scale were made by Skarlatoudis *et al*. (2010, 2011, 2012), who adopted a finite-difference numerical approach. Compared to these numerical studies, in our modelling extended finite-fault rupture models have been addressed rather than point-source representations. However, a more simplified description of the subsoil structure has been adopted herein owing to computational reasons.

The available strong motion data, i.e., only one rather poor record at the basement of a high rise building, are not sufficient to carry out a comprehensive validation study. The comparison between recordings and synthetics at this strong motion station points out some discrepancies especially in the EW and UP components, probably due to the assumptions regarding the kinematic source model (focal mechanism and slip distribution). However, in this study, emphasis is given to the complex modeling of 3D seismic wave propagation, including a variety of factors, from the extended fault rupture to local site effects in Thessaloniki, to prove that this kind of analysis is now feasible and can reproduce in a satisfactory way the general features of spatial variability of ground motion at broad scale. Comparison with GMPEs is addressed and ground shaking maps in terms of PGV are provided to shed light on the most significant wave propagation effects (near-fault, focal mechanism and site effects). The model presented in this study may be used for generating various ground shaking scenarios from future earthquakes originating from the Gerakarou, Langadhas or Anthemountas seismogenic sources of potential major impact on the city of Thessaloniki.

8. Acknowledgments

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