Validated physics-based numerical simulations of earthquake ground motion in the Thessaloniki area

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Abstract: A realistic prediction of earthquake ground motion and of its spatial variability is one of the key components in the chain of seismic risk assessment of spatially distributed portfolios or infrastructural systems in large urban areas. In this work, a large-scale 3D numerical model is developed to generate physics-based ground shaking scenarios in the city of Thessaloniki in Northern Greece using the computer code SPEED (http://speed.mox.polimi.it) as input for seismic risk studies. The numerical model accounts for kinematic finite-fault sources, a 3D model of the propagation path and local site response conditions. The case study of Thessaloniki is addressed due to the detailed knowledge on its geologic, seismotectonic context as well as on up-to-date exposure and vulnerability models which are key ingredients for future seismic risk analyses. To validate the numerical model, simulated motions are compared against the recordings of a real small-magnitude (Mw4.4) earthquake, and with predictions from conventional approach based on Ground Motion Prediction Equations for historical 1978th Mw6.5 earthquake whose spatial correlation is analysed.

Keywords: earthquake ground motion, 3D physics-based numerical approach, seismic risk, spatial correlation

1. Introduction

A reliable estimation of earthquake ground motion and of its spatial variability is one of the key components for seismic risk analysis especially for spatially distributed structures or infrastructural systems such as pipelines in large urban area. Due to the developments of computational ability and enrichment of seismology-related resources, numerical simulations have gradually played a promising role as an alternative in predicting earthquake ground motion intensities.

A 3D physics-based numerical simulation approach (3D PBS) whose computation code is SPEED (Spectral Element in Elastodynamics with Discontinuous, http://speed.mox.polimi.it/) that could handle different seismology aspects such as seismic faults rupture, seismic wave propagation, localized site irregularities, soil-structure interactions, attracts attention of seismologist and earthquake engineers. SPEED is an open-source software package, developing by cooperation between Department of Mathematics and Department of Civil and Environmental Engineering at Politecnico di Milano, that successfully applied and verified in worldwide regions such as Grenoble in France from Chaljub et al. (2010), L'Aquila, Po Plain in Italy check from Smerzini et al. (2012), Paolucci et al. (2015), Christchurch in New Zealand from Guidotti et al. (2011) and so on.

As the second-largest city in Northern Greece, Thessaloniki possess over million population in its historical centre and metropolitan area, considered to be a major economic, industrial, commercial, and political centre. Since medieval times, Thessaloniki was hit by strong earthquakes, notably in 1759, 1902, 1978 and 1995, among which the destructive one occurred on June 20th 1978 with Magnitude = 6.5 causing a series of considerable damages in the instrumental era. This 1978 earthquake, therefore, attracted significant interest from seismologists and engineers as the first earthquake with a serious impact on a big modern urban centre like the city of Thessaloniki. This stimulated a set of fruitful investigations that led to a detailed knowledge of geological, geophysical and geotechnical information, seismotectonic features, micro zonation studies, vulnerability and exposure analyses for the Thessaloniki area to better constrain seismic hazard and risk assessment studies (Pitilakis et al. 2015).

In this work, a three-dimensional numerical model of Thessaloniki area was updated by integrating the detailed information on seismotectonic, geological and geophysical context as a necessary component for 3D physics-based numerical approach. The results from simulations were compared with recordings of a real earthquake event with magnitude = 4.4 for validation purpose. Then a comparison between simulated strong motions and Ground Motion Prediction Equations (GMPEs) from 1978th 06.20 earthquake (Mw=6.5) is analysed and the spatial correlation of spectral acceleration is computed and discussed.

2. An updated 3D numerical model of the study area

Due to the level of available information regarding Thessaloniki area, a large-scale 3D numerical model is developed in this work by taking advantage of a pre-existing spectral element model, as presented by Smerzini et al. (2017). Fig. 1 provides an overview of the 3D numerical model with volume size equal to 82 x 64 x 31 km^3 indicating 4 seismic faults and a zoom to point out mesh refinement on the top layer. Considering a third order spectral degree, the numerical model consists of 98,297,229 degrees of freedom and it is capable to propagate accurately frequencies up to 1.5 Hz. The mechanical properties associated to the 3D numerical model are indicated in Table 1.

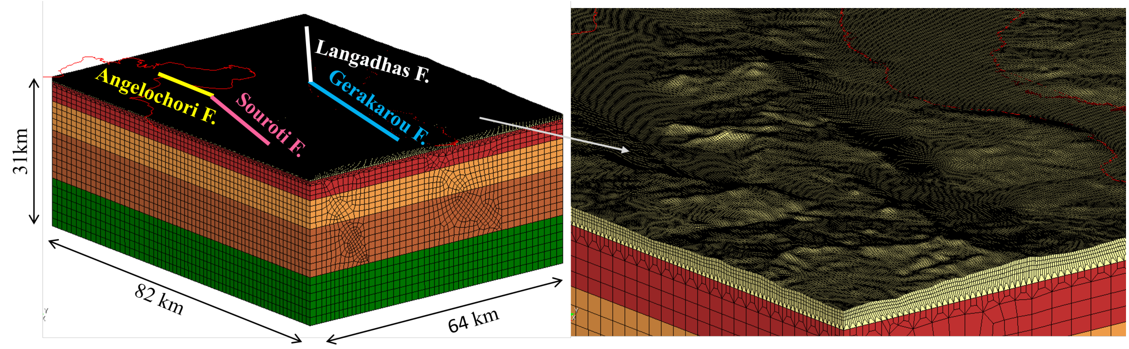

Fig. 1 – Mesh of the 3D numerical model

Table 1. *Mechanical property of 3D numerical model*

Material		**Thickness (m)**	**V_S (m/s)**	**V_P (m/s)**	**ρ (kg/m$_3$)**	**Q_S**	**Q_P**
Bas-in	Thessaloniki	0-800	Soft: $300+13.5*z^{0.7}$ Stiff: $500+11.9*z^{0.7}$	Soft: $1800+21.4*z^{0.7}$ Stiff: $2000+19.8*z^{0.7}$	2000+0.4*z	Note below	2Qs
	Mygdonia	0-450	$200+15*z^{0.63}$	$1500+32.8*z^{0.63}$	2075+0.55*z	0.1*Vs	2Qs
Crust 1 🟨		1000	Cotton et al. (2006)	2.25*Vs	Cotton et al. (2006)	0.1*Vs	2Qs
Crust 2 🟥		4000	3440	6060	2700	300	600
Crust 3 🟧		6000	3460	6070	2800	300	600
Crust 4 🟫		10000	3640	6370	2900	300	600
Crust 5 🟩		10000	3980	6960	3000	400	800

Note: Q_s=20; z<=200, Q_s=50; z<=500, Q_s=100; z<=1000, Q_s=150 (z=depth from ground surface)

The 3D model includes the following key features:

- ground topography as retrieved from 90 m SRTM Digital Elevation Model (http://srtm.csi.cgiar.org/), covering the broader Thessaloniki area;
- four main seismogenic sources posing a hazard to the city of Thessaloniki, namely, (i) the Gerakarou Fault (i.e., the fault responsible of the Mw6.5 1978 Volvi earthquake), (ii) the Langadhas Fault, (iii) the Angelochori Fault, and (iv) the Souroti fault. The location and geometry of these faults were retrieved from the GreDaSS database (http://gredass.unife.it/). The first two faults are segments of a larger fault zone (Mygdonia Composite Source according to GreDaSS database) that bounds the southern margins of the Mygdonia Basin, while the Angelochori and Souroti faults constitute the Anthemountas fault system, southward of the city of Thessaloniki;
- crustal model for deep rock materials (see Table 1), adapted from Ameri et al. (2015) and with the modifications explained below;
- 3D models of both Thessaloniki and Mygdonia basins.

The main improvements with respect to the existing model are outlined below.

2.1. Geological model: inclusion of Thessaloniki and Mygdonia basin

Efforts were devoted to the construction of a large-scale 3D geological model including, in the same computational domain, both the Thessaloniki basin and the Mygdonia basin. While the Thessaloniki basin model was taken from Smerzini et al. (2017), the 3D shape of the Mygdonia basin is taken from Maufroy et al. (2016).

The 3D shape of both Thessaloniki basin and the Mygdonian basin is shown in Fig. 2.

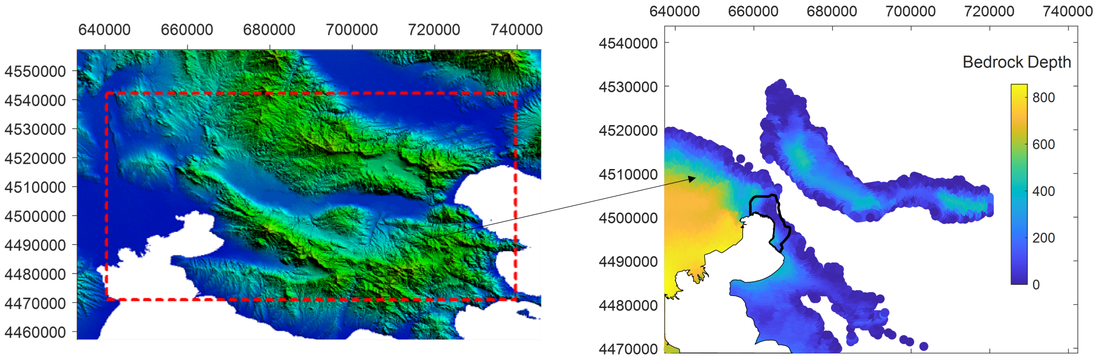

Fig. 2 - Geological context of study area and depth of bedrock in Thessaloniki and Mygdonia basins

2.2. Updating of the shallow crustal model

The velocity of the uppermost layer of the crustal model was modified to provide a more realistic velocity profile of the outcropping bedrock in the area under study. With respect to Smerzini et al. (2017), where the outcropping bedrock layer consists of very hard rock with constant shear wave velocity $V_S = 2000$ m/s, the updated crustal model features a first layer (see Crust 1 in Table 1) with a gradient of V_S from a minimum value of 1150 m/s up to a value of 3440 m/s at 1000 m depth from the topographical surface. The gradient of this velocity profile was calibrated based on the studies conducted by Cotton et al. (2006) on rock velocity profiles.

3. Validation with M4.4 event

After a set of preliminary numerical tests, the numerical model was applied to simulate a real small-magnitude (Mw4.4) earthquake event occurred on 12th, September 2005 near the Mygdonia basin for validation purpose by comparing the results from simulations with the recordings. Owing to the small magnitude, the finiteness of the fault rupture area is neglected and a point-source was considered. This M4.4 event is selected because the accuracy of simulations was controlled by uncertainties in the source properties, propagation path and shallow layer structure, it is therefore recommended to prefer deep event (depth > 8-10 km) for validation performance from Maufroy et al. (2016). Following is the Table 2 with source parameters for Mw4.4 earthquake:

Table 2. *Source information for Mw4.4 earthquake*

Date	Lat. (°)	Long. (°)	Depth(km)	Mw	Strike (°)	Dip (°)	Rake (°)
2005/09/12	40.7255	23.3408	10	4.4	281	52	-98

The earthquake was recorded by several stations (http://euroseisdb.civil.auth.gr/events), and herein E03 station (Latitude: 40.6762, Longitude: 23.3241) is selected for comparison between simulated and recorded ground motions.

Fig. 3 is the comparison of velocity waveforms and corresponding Fourier Amplitude Spectra (FAS) in terms of three components (horizontal components (EW, NS) and vertical component (UD)) between simulations (red) and the recordings (black) at E03 station. Both are filtered below 1.5 Hz satisfying frequency-limitation of numerical simulation.

It is found that velocity waveform histories from NS component and vertical components shows well agreement, especially for the starting time and maximum amplitudes, and corresponding FAS also show general good agreement. On the other hand, for EW component, SPEED tends to underestimate observations probably because of inaccuracies in the source model and shallow layer properties.

The comparison herein is not only for a satisfactory level of validation of reliable numerical model, but also indicate the potentiality of the numerical parameters in predicting ground motions for future earthquakes.

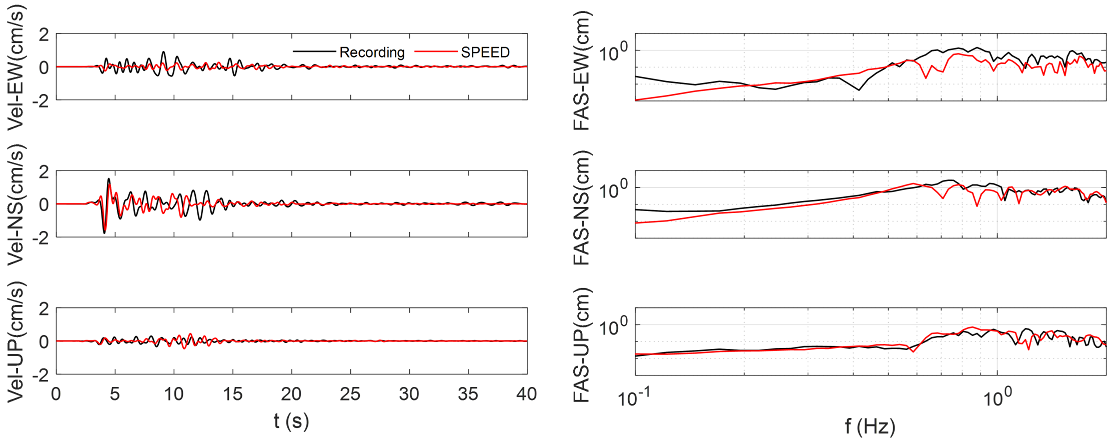

Fig. 3 - Comparison of velocity waveforms and corresponding Fourier Amplitude Spectra

4. Earthquake ground motion for the historical Mw6.5 1978 earthquake

The 1978 Thessaloniki earthquake with a normal focal mechanism (magnitude 6.5) is regarded as the first destructive seismic activity in historical recording generation. The earthquake is associated with EW trending Gerakarou fault at the southern area of the Mygdonia graben according to Papazachos et al. (1979) and Mountrakis et al. (1983). This section aims at providing a general overview of the estimated ground motion by comparing the simulated results with the Ground Motion Prediction Equations (GMPEs) and by computing the spatial correlation of horizontal PGA, SA (0.2s, 0.5s, 1.0s, 3.0s).

4.1. Comparison with Ground Motion Prediction Equations (GMPEs)

Fig. 4 shows the ground shaking map from 3D PBS in terms of peak ground velocity (PGV), geometry mean of horizontal components (GMH). As we can see, maximum PGV-GMH, up to 1.2 m/s, is found within Mygdonia graben because of the coupling of source effects with basin amplification effect. It is worth to note that roughly 0.2 m/s is found along the coastline in the Thessaloniki urban area.

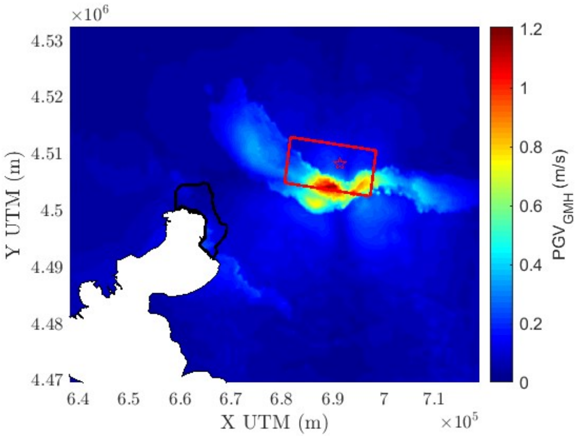

Fig. 4 – PGV (GMH) from 3D PBS method

In order to check the overall consistency of the simulation, the decay of simulated PGV(GMH) with distance (R_{rup}: rupture distance) is compared with the one from the empirical model by Cauzzi et al. (2015), referred to as CEA15, as illustrated in Fig. 5. Comparison is shown for three site categories (Site A, B, C) according to EC8 site classification. The dark grey, red, and blue dots in Fig. 5 represent results from 3D PBS for site A, B and C. Correspondingly, the black, red, blue lines denote PGV(GMH) values from GMPE for site A, B and C. A general satisfactory agreement is found between simulations and empirical predictions, especially in terms of site A (rock site) and Site C (soft site), which are the predominant sedimentary deposit under broader Thessaloniki region.

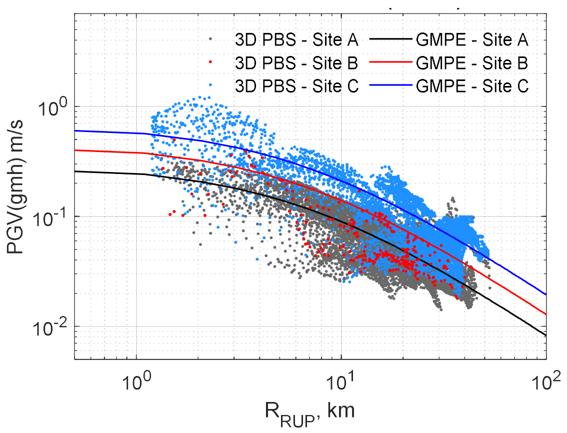

Fig. 5 – Comparison of PGV(GMH) as a function of Rrup between 3D PBS and GMPE by Cauzzi et al. (2015), referred to as CEA15

4.2. Overview of spatial correlation

One of the key components in the seismic risk assessment chain is spatial correlation of earthquake ground motions, especially for spatially distributed structures. This work employs a multi-stage approach by calculating and fitting semi-variogram, which is a geostatistical tool that is commonly used in seismology field. We refer to Infantino et al. (2021) for further details regarding the adopted methodology.

Fig. 6 shows the range as a function of period for the 1978 Mw6.5 earthquake in broader Thessaloniki region on the left, and indicates the sample semi-variogram (grey dots) and its fitting (black line) with respect to h (distance) for spectral acceleration at 2 second on the right. Range means the separation distance at which the data can be considered fully uncorrelated, which is the maximum correlated distance. As we could see from the figure, as expected, the range shows an increasing trend as a function of period up to around 1 s where a maximum range around 64 km is found. Beyond this period, range values drop to around 20 km.

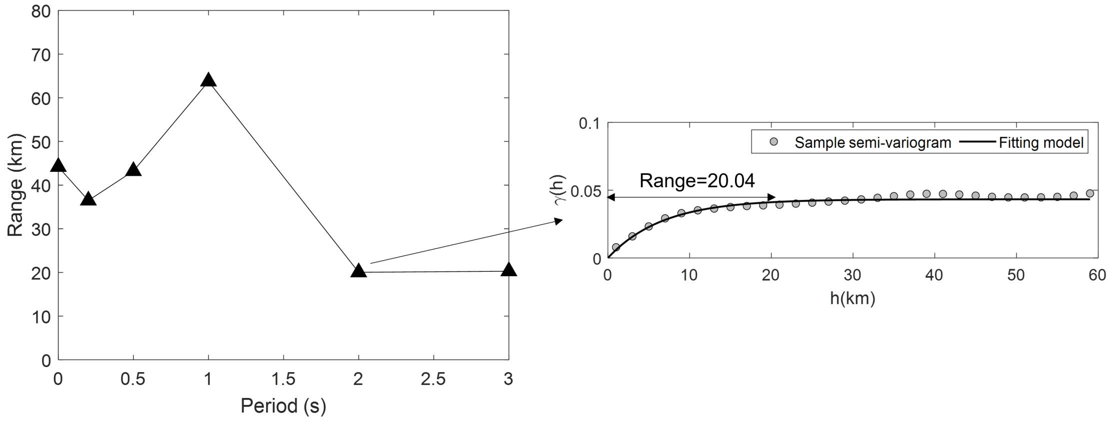

Fig. 6 – Range of semi-variogram of spectral acceleration (GMH) across different periods and the semi-variogram for SA (2s)

5. Conclusions

In this research, a 3D numerical model of the broader Thessaloniki region is constructed by including new features with respect to the pre-existing model. Specifically, the 3D seismic wave propagation model was updated by including the Mygdonia basin, in addition to the Thessaloniki basin, and by modifying the velocity of the outcropping bedrock of the crustal model. The 3D model is applied to the simulation of two real earthquakes, a small Mw4.4 event and the historical Mw6.5 1978 earthquake, both originating from the faults bordering the Mygodnian basin, for validation purposes. The validation is conducted at two levels, first by comparing the simulated velocities with the recordings (for the M4.4 event) and with the empirical ground motion models (for the M6.5 event) and, second, by computing the spatial correlation structure of spectral accelerations. These comparisons prove a successful validation of the 3D physics-based approach, making them suitable to compute realistic ground motion scenarios for application in seismic risk studies.

Acknowledgements

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