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ISTANBUL, TURKEY: VERIFICATION, VALIDATION AND SCENARIO SIMULATION BY MEANS OF PHYSICS-BASED NUMERICAL MODELLING.

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Abstract

At the present time Physics-Based Simulations are considered among the most advanced numerical approaches, capable to take into account region-, path- and site- specific effects related to the earthquake source, recording site conditions (e.g. complex site effects in case of large sedimentary basins) and source- to-site path. This methodology is particularly relevant in earthquake engineering as it seeks to achieve, within a certain frequency range, on the one hand, a clear and unambiguous explanation of the peculiarity and the variability of the ground motion observed (validation) and, on the other, a reliable prediction of the near-source shaking (scenario simulation), still nowadays poorly observed and understood.

In this contribution we want to present the verification/validation effort that has been undertaken regarding the area of Istanbul in Turkey. In order to accomplish the verification task, 3D physics-based elastodynamic simulations have been carried out by means of two different numerical approaches, as recommended by best practice. The synthetic seismograms produced by means of the spectral element discontinuos galerkin code SPEED [1] have been verified against the one simulated with the theoretical method proposed by Hisada and Bielak [2], based on Green's function and particularly suited for near-fault ground motions in layered half-spaces,

The validation was achieved taking advantage of the set of records publicly available, relative to the recent magnitude 5.8 earthquake occurring the 26th of September 2019 along the North-Anatolian Fault in the immediate proximity of the Marmara segment. By means of the two numerical approaches previously mentioned, synthetic seismograms are computed at specific sites and through quantitative misfit criteria, well accepted in the scientific community (e.g.: [3]), we propose here the preliminary outcomes of this validation exercise. Special attention is devoted to the comparison between SPEED simulations and the observed data available.

The results of this benchmark are extensively discussed especially in light of the final goal of this work that aims at producing a certified large set of scenarios occurring along the North Anatolian Fault, Marmara Segments, capable to bridge the gap of presently used standard approaches like Ground Motion Prediction Equation.

Keywords: Istanbul, Physics-Based Simulations, Ground Motion Verification, Validation.

1. Introduction

In recent years, stimulated by the increasing availability of computational resources, physics-based numerical simulations of earthquake ground motion including a full 3D seismic wave propagation model from the source to the site, have gained an increasing attention worldwide (see e.g. [4-7]). The deterministic numerical approach allows one to model within a single computational domain all factors that affect earthquake ground motion, i.e.: the features of the seismic fault rupture, the propagation path in heterogeneous Earth media, directivity of seismic waves, complex site effects due to localized topographic and geologic irregularities, variability/specificity of soil properties at a regional and local scale. For this reason, they are expected to become, in near future, the most promising tool to generate ground shaking scenarios from future realistic earthquakes and to promote an advanced characterization of seismic hazard.

The most appealing features of the 3D numerical approach are: (i) modelling of the full wavefield from the extended fault rupture to the site of interest; (ii) description of the 3D variability of the dynamic properties of soils, having an impact on the spatial variability of ground motion; (iii) modelling of complex interaction of source effects (directivity, focal mechanism, etc..) and localized soil irregularities; (iv) possibility to generate realistic scenarios from future earthquakes of concern for the seismic hazard at the site. On the other hand, the main drawbacks of such an approach are: (i) frequency limitation of deterministic simulations, hardly larger than 2-3 Hz approximately; (ii) computational cost; (iii) level of detail of input geological and geotechnical data.

In the perspective of promoting tools for an advanced seismic hazard characterization, Munich RE funded a research activity with Politecnico di Milano, having a twofold objective: on one side, the release of a certified computer code to execute numerical simulations of seismic wave propagation in complex large-scale models using high-performance computing architectures, and, on the other side, the development of an advanced integrated probabilistic/deterministic procedure for seismic hazard assessment in large urban areas, making use of Physics-Based ground shaking Scenarios, referred to hereinafter as PBS, obtained by 3D numerical modelling [8]. In fact, the Istanbul area has been selected as pilot case study in the frame of the afore mentioned project, for the application of the integrated probabilistic/deterministic seismic risk assessment approach.

In this framework the reliability of the synthetic scenarios play a crucial role and therefore the objective of this paper is to present the verification/validation effort that has been undertaken regarding the area of Istanbul in Turkey. In order to accomplish the verification task, 3D physics-based elastodynamic simulations have been accomplished using two different numerical approaches: the spectral element discontinuos galerkin code SPEED [1] and the theoretical method proposed by Hisada and Bielak [2], based on Green's function, particularly suited to compute near-fault ground motions in layered half-spaces.

Furthermore a validation exercise was undertaken, thanks to the set of seismograms, publicly available, and recorded during the recent magnitude 5.8 earthquake occurring the 26th of September 2019 along the North-Anatolian Fault in the immediate proximity of the Marmara segment. By means of the two numerical approaches previously mentioned, synthetic seismograms are computed at specific sites and through quantitative misfit criteria, well accepted in the scientific community (e.g.: [3]), we validated the SPEED simulations against the observed data available.

The area of Istanbul has been selected as one of the areas with the highest seismic risk worldwide. After showing an overview of the seismotectonic context of the Istanbul area and the main motivation behind the selection of this case study, the computational approach and relevant tools will be presented. Then, the main features of the 3D numerical model will be illustrated with emphasis on the geologic, topography and bathymetry setup. An overview of the main verification and validation results will be presented.

2. Why the Istanbul area?

The Istanbul-Marmara region of northwestern Turkey with a population of more than 15 millions, faces an high probability (62 +/- 15 %, ref [8]) for the occurrence of an earthquake of magnitude 7 or more. The cause can be found in the seismic gap beneath the Sea of Marmara, some five miles west of Istanbul: since the disastrous 1939 Erzincan earthquake (Magnitude 7.9), major earthquakes have occurred along the North Anatolian Fault (NAF) in a roughly domino-like fashion, breaking sequentially from east to west. The chain of earthquakes along the North Anatolian fault presents a gap at south of Istanbul as shown in Fig. 1 (from [8]).

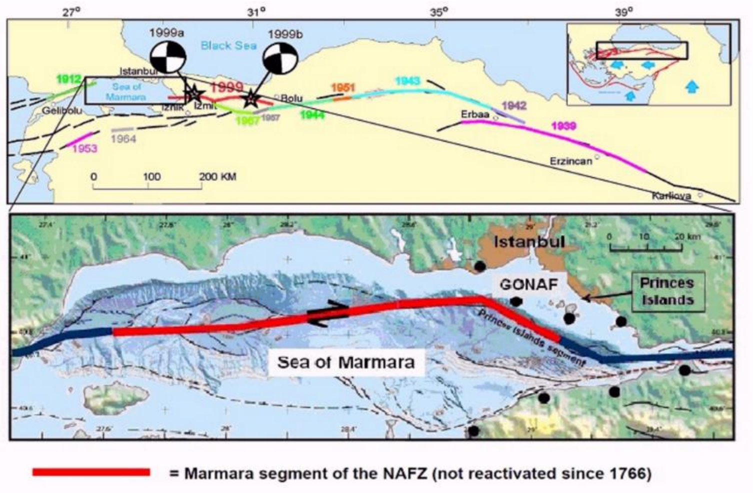


Fig. 1 – Top panel: sites and the length of the fractures of the NFA; bottom panel: seismic gap at the Marmara sea, the red segment of the NAFZ has been not reactivated since 1766. From [8].

Separate groups of authors have advocated different models to explain the origin of this seismic gap because of poor seismic coverage and insufficient use of available earthquake data. Each model has significant different implications for the seismic hazard at Istanbul: depending on the model, the Marmara seismic gap could be ruptured either by a single large earthquake or multiple smaller earthquakes with large differences in the resulting ground shaking and damage.

The expected earthquakes in this region represent an extreme danger for the Turkish megacity. Istanbul is, in fact, one of the world´s most populous cities and many buildings or constructions are very old and not built to the highest modern standards compared to other seismic areas of the world. A big earthquake could cause many victims and economics damages and this explain why the large interest in a detailed study for this area.

3. The computational approach

This section aims at illustrating the computational approach which has been used to generate the 3D PBSs in the Istanbul area. This involves three main tools: (1) the computer code SPEED running on parallel computer architectures; (ii) a pre-processing tool, i.e. a rupture generator, to produce a set of kinematic slip models along a given fault within a prescribed magnitude; (iii) a post-processing tool to generate broadband (BB) ground motions starting from the results of SPEED, applicable only to the low frequency range.

The open-source software package SPEED (*SPectral Element in Elastodynamics with Discontinuous Galerkin*: http://speed.mox.polimi.it/) is designed for the simulation of large-scale seismic wave propagation problems including the coupled effects of a seismic fault rupture, the propagation path through Earth’s layers, localized geological irregularities, such as alluvial basins, and soil-structure interaction problems (see e.g. [1]). Based on a discontinuous version of the classical spectral element (SE) method, as explained in [10], 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. SPEED is designed for multi-core computers or large clusters (e.g., Fermi BlueGene/Q at CINECA), taking advantage of the hybrid MPI-OpenMP parallel programming.

A pre-processing tool has been devised, in order to automatically construct physically constrained slip distributions for a given fault and a given earthquake magnitude, taking into account joint probability distributions of the main kinematic parameters. Furthermore a Post-processing tool capable to overcome the frequency limitation of the numerical simulations was devised: a novel approach was proposed to generate broadband ground motions (referred to as BB hereinafter), with realistic features in the entire frequency range of interest for engineering applications (say between 0 and 25 Hz), using Artificial Neural Networks (ANN) combined with spectral matching techniques [11].

4. Setup of the 3D numerical model

The 3D numerical model was constructed by combining the following features: (i) the topography and bathymetry model; (ii) the kinematic seismic fault model; (iii) the 3D velocity model. In the following details of these aspects will be provided and, finally, the resulting hexahedral mesh will be described.

4.1 Topography and bathymetry

For the elevation model, freely-available digital elevation dataset of CGIAR-CSI for the Tracia region has been extracted and downloaded from the website http://www.cgiar-csi.org (with a precision of roughly 70 x 90 m, for east-west and north-south directions around Istanbul city), while the bathymetry model has been derived from the MATLAB digitalization of the map proposed by Özsoy et al. 2000 [12]. Hence elevation and bathymetry models, both in a numerical format, have been assembled together in MATLAB environment obtaining the top surface of the computational domain, as illustrated in Fig. 2.

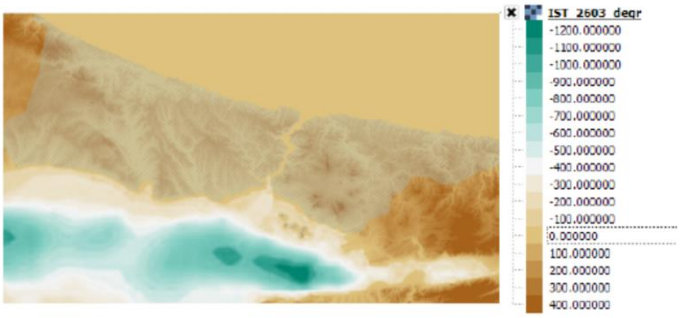


Fig. 2 – Combined digital elevation/bathymetry model.

4.2 Seismic fault

The seismic fault considered consists of the Central Marmara Basin (CMB) and North Boundary Fault (NBF), part of the NAF, located about 20-30 km south-west and south of Istanbul respectively, as shown in Fig. 3. The source is a vertical segmented fault, consisting of three main segments with different strike angles. The total length of the fault is around 98 km, capable of producing a M_W 7.4 event. The geometric parameters of the NBF, as implemented in the numerical model, are reported in Table 1.

Table 1 – Geometric parameters of the North Boundary Fault (NBF).

Segment	Strike (deg)	Dip (deg)	Rake (deg)	L_{max} (m)	W_{max} (m)	Fault Origin* (Lon [°N];Lat [°E])	Top depth (m)
1	81.5	90	0	58000	30000	28.12;40.81	836.5
2	99.6	90	0	10400	30000	28.79;40.88	655.7
3	119.3	90	0	30000	30000	28.91;40.86	543.8

**Fault Origin is defined as the point of the fault at zero strike and zero dip*

4.3 Soil characterization (3D velocity model)

In order to define the 3D soil model a three-step procedure has been adopted according to the geotechnical site characterization provided by Özgül (2011) (see [13]). First the digitalization of the maps presented by Özgül (2011) has been performed to obtain the map of $V_{S,30}$ and rock/soil information for the whole Istanbul region. Second, by making use of three sets of data, namely $V_{S,30}$, rock/soil map and slope information (extrapolated by QGIS, www.qgis.org), different site classes have been assigned ranging from $V_{S,30}$ = 250 m/s to $V_{S,30}$ = 1350 m/s, see colored map in Fig. 3 (left). Third, the model has been improved for the Avcılar zone, characterized by very soft sediments, where significant soil effects occurred during the 1999 Kocaeli Earthquake (see [14]), by reassigning the soil class as the softest. Finally, six homogeneous V_S profiles have been considered in the first layer (0 to 5 km depth) with a prescribed gradient, as shown in Fig.3 (right). The properties of the underlying bedrock layers (depth > 5 km) have been obtained by the interpretation of seismic profiles presented in Cotton et al. (2006) (see [15]) and Gurbuz et al. (2000) (see [16]). The quality factor Q is derived directly by the V_S values and is assumed to be proportional to frequency as $Q = Q_0 \cdot f$, with Q_0 set for the target value $Q = V_S/10$ to be obtained at f = 1 Hz. The 3D velocity model is summarized in the table on the right hand side of Fig.3.

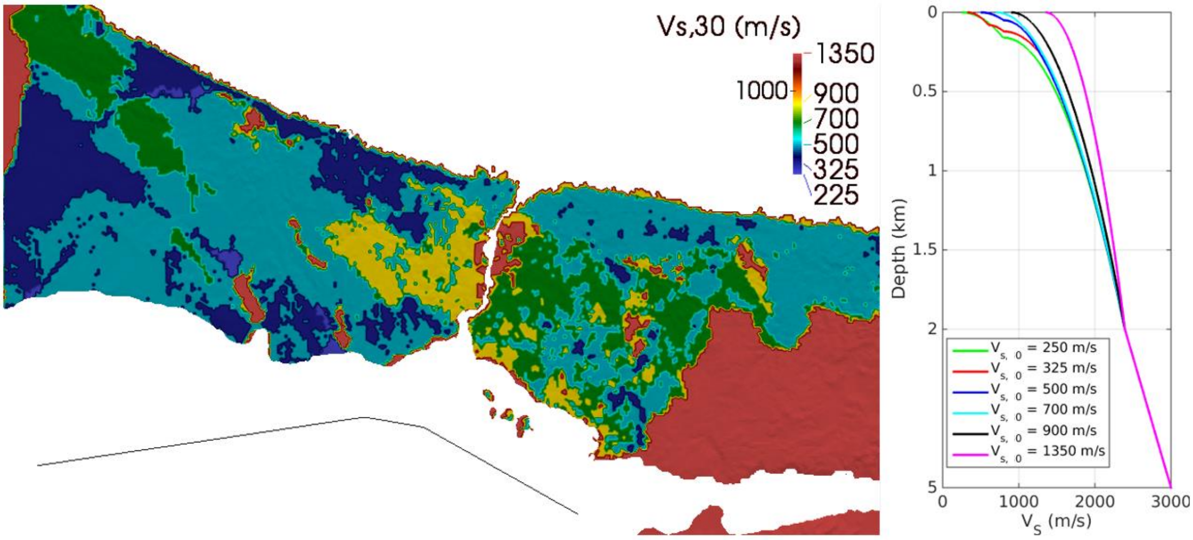
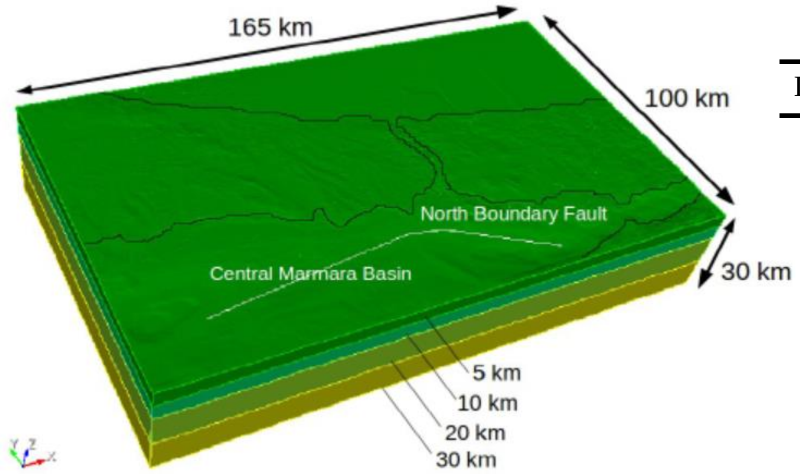


Fig. 3 - $V_{S,0}$ classes defined according to Özgül, 2011 (left). V_S, profiles adopted in the present work for the six soil classes considered in the first layer (0 to 5 km depth) of the computational domain (see also Fig.4).

4.4 Mesh

The computational domain, which extends over an area of 165x100x30 km^3 down to 30 km depth (see Fig.), has been built combining all the information previously described. Considering a rule of thumb of 5 grid points per minimum wavelength for non-dispersive wave propagation in heterogeneous media by the SE approach (see [1]), and considering a maximum frequency f_{max} = 1.5 Hz, the model consists of 2,257,482 hexahedral elements, resulting in approximately 475 million of degrees of freedom, using a fourth order polynomial approximation degree. The conforming mesh has a size varying from a minimum of 180 m, on the top surface, up to 600 m at 2 km depth and reaching 1800 m in the underlying layers.



Horizontally stratified crustal model

Depth (km)	V_S (m/s)	V_P (m/s)
0-5	See Fig.3	-
5-10	3490	5770
10-20	3500	6390
20-30	3920	6790

$Q_S = V_S/10$

Fig. 4 - Computational domain of the Istanbul region adopted in the present work. Fault system (CMB and NBF) included in the domain as well as topography and bathymetry model.

3. Verification

Prior to the massive computation of the PBSs in the area, as best practice recommends, it was decided to verify SPEED simulations against an independent solution. For this purpose, we considered the Hisada and Bielak 2003 [2] approach for a simplified case study consisting of homogeneous rock properties throughout the model (VS = 3000 km/s) and a homogeneous slip distribution (δ) on the fault. A very satisfactory agreement between the two numerical methods is obtained, as shown for two representative sites in Figure 5 with reference to a scenario of MW7.0 (top, segment #1 in Table 1 and δ = 2.1 m) and a scenario of MW7.4 (bottom, segment #1,2,3 in Table 1 and δ = 3.9 m).

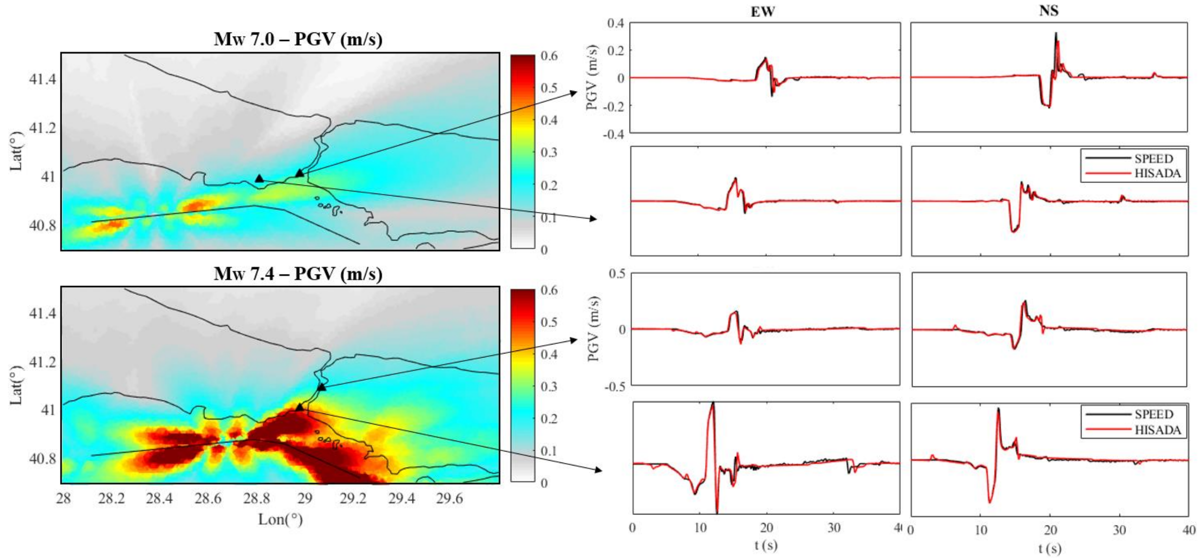


Fig. 5 - Left: PGV Maps obtained with SPEED for homogeneous soil conditions and homogeneous slip distribution for a MW7.0 (top) and a MW7.4 (bottom) scenario. Right: Hisada vs. SPEED comparison in terms of velocity time histories (EW and NS components) for two sites considering a MW7.0 (top) and a MW7.4 (bottom) scenario.

4. The 26.09.2019 Mw5.8 event

On September 26 2019 a powerful magnitude 5.8 earthquake shook Istanbul, causing panic across the city. The Disaster and Emergency Management Presidency (AFAD, https://deprem.afad.gov.tr/) localized the shallow quake on the southwest of Istanbul in the Marmara Sea. Epicentral coordinates and depth have been determined by AFAD Seismological Network as 40.8818N, 28.21400E and 7.97km. Marmara Sea Earthquake was recorded by 165 accelerometer stations belonging to AFAD National Strong Motion Network (TR-NSMN) with an epicentral distances (Repi) ranging from 22 to 456km (see Fig.6). The maximum peak ground acceleration (PGA) has been recorded at Silivri (Station Id: 3408) and B.Çekmece (Station Id: 3412) Stations. The damages reported were quite limited: the minaret of a mosque in Avcılar, a district closer to Silivri, partially collapsed while a residential building tilted by the strong tremor was evacuated. Two buildings in the Sultangazi and Eyüpsultan districts were damaged. In the aftermath of the event, the moment tensor solution was provided by different institutions (e.g.: KOERI and USGS) as presented in Fig.7.

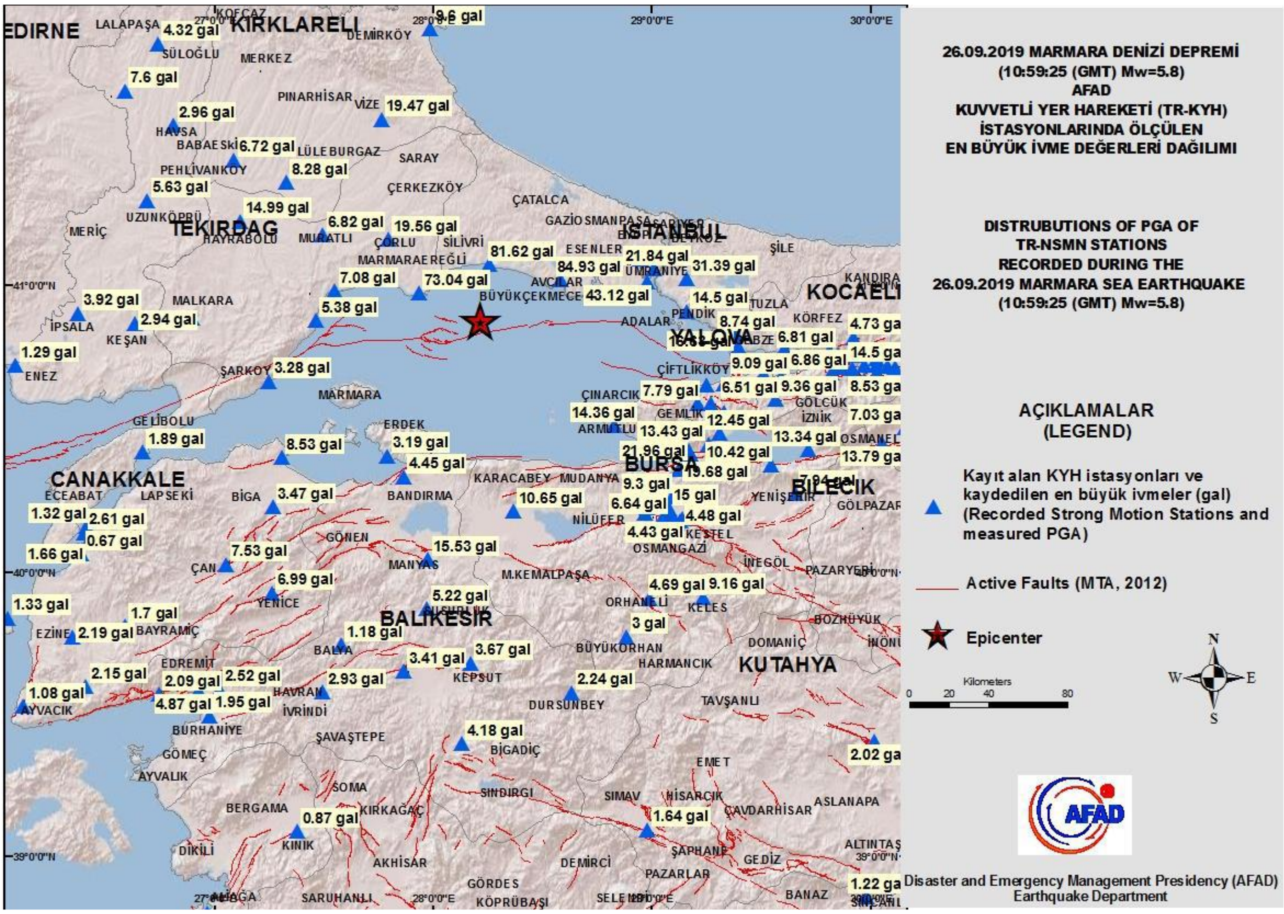
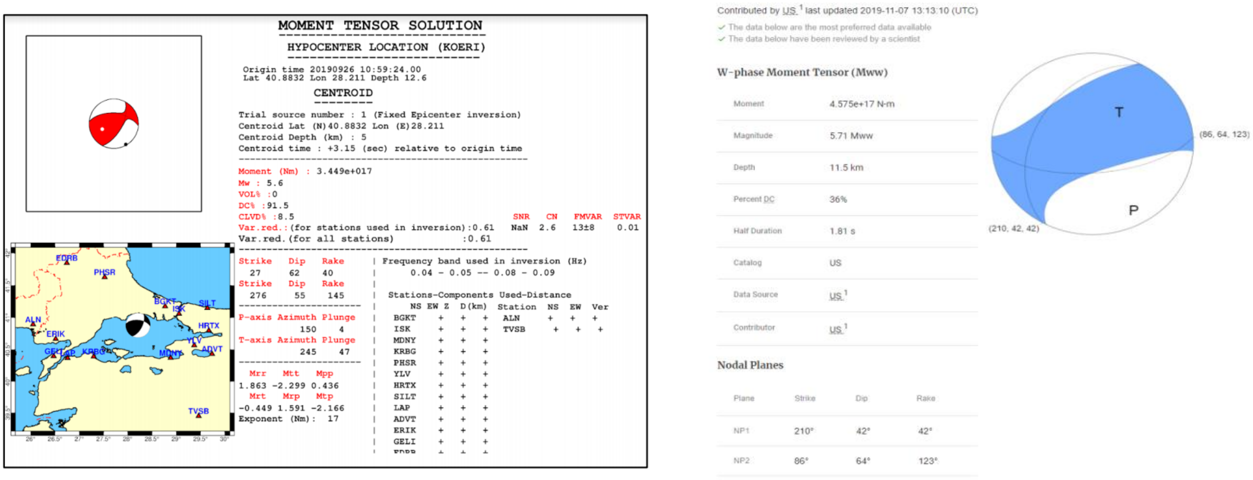


Fig. 6 – Distribution of PGA of TR-NSMN stations during the 26.09.2019 Marmara Sea earthquake.



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MOMENT TENSOR SOLUTION
----------------------------
HYPOCENTER LOCATION (KOERI)
---------------------------
Origin time 20190926 10:59:24.00
Lat 40.8832 Lon 28.211 Depth 12.6
CENTROID
--------
Trial source number : 1 (Fixed Epicenter inversion)
Centroid Lat (N)40.8832 Lon (E)28.211
Centroid Depth (km) : 5
Centroid time : +3.15 (sec) relative to origin time
----------------------------------------------------
Moment (Nm) : 3.449e+017
Mw : 5.6
VOL% :0
DC% :91.5
CLVD% :8.5                                           SNR   CN   FMVAR  STVAR
Var.red.:(for stations used in inversion):0.61       NaN  2.6   13±8    0.01
Var.red.(for all stations)             :0.61
----------------------------------------------------
Strike   Dip   Rake       | Frequency band used in inversion (Hz)
  27      62    40        |     0.04 - 0.05 -- 0.08 - 0.09
Strike   Dip   Rake       |
  276     55    145       |  Stations-Components Used-Distance
----------------------    |     NS EW Z  D(km) Station  NS  EW  Ver
P-axis Azimuth Plunge     |  BGKT   +   +   +  ALN      +   +   +
           150      4     |  ISK    +   +   +  TVSB      +   +   +
T-axis Azimuth Plunge     |  MDNY   +   +   +
           245     47     |  KRBG   +   +   +
----------------------    |  PHSR   +   +   +
  Mrr    Mtt    Mpp       |  YLV    +   +   +
1.863 -2.299 0.436        |  HRTX   +   +   +
  Mrt    Mrp    Mtp       |  SILT   +   +   +
-0.449 1.591 -2.166       |  LAP    +   +   +
Exponent (Nm):  17        |  ADVT   +   +   +
                          |  ERIK   +   +   +
                          |  GELI   +   +   +
```

Contributed by US [1] last updated 2019-11-07 13:13:10 (UTC)
✓ The data below are the most preferred data available
✓ The data below have been reviewed by a scientist

W-phase Moment Tensor (Mww)

Moment	4.575e+17 N-m
Magnitude	5.71 Mww
Depth	11.5 km
Percent DC	36%
Half Duration	1.81 s
Catalog	US
Data Source	US [1]
Contributor	US [1]

Nodal Planes

Plane	Strike	Dip	Rake
NP1	210°	42°	42°
NP2	86°	64°	123°

Fig. 7 – Moment tensor solution provided by KOERI (left-hand side) and USGS (right-hand side).

5. Validation of the 3D model

Thanks to the large set of publicly available records it was possible to undertake a rigorous validation of the 3D numerical model previously described. In the following are presented some selected results obtained both with the Hisada and Bielak approach [2] and with SPEED [1]. As already mentioned, the former is characterized by a relatively simple layer cake velocity model, without topography or soft soil, while the latter includes a full 3D layered velocity model for the deep geology, the topography and the uppermost soft soil presents different thickness and different Vs profiles (see Fig.3 right-hand side).

In Fig.8 a comparison between the mean of four selected Anderson criteria, namely ED (Energy Duration), PGV (Peak Ground Velocity), PGD (Peak Ground Displacement) and RS (Response Spectra). On the left-hand side “records vs Hisada” and on the right-hand side “records vs SPEED”; the overall improvement of the score, adopting the more sophisticated SPEED 3D model, is remarkable.

Among the different stations, 12 of them are located inside the boundary of the 3D model and are ranging within 20 and 100 km distance from the epicenter. Fig. 9 shows the comparison of recorded (black) against synthetic (red, SPEED) seismograms for all the station located within the 3D model. Data have been filtered between 0.05-1.5Hz. Fig. 10 shows the same comparison but in terms of Fourier amplitude Spectrum.

The overall agreement of recorded and synthetic SPEED seismograms it is definitely satisfactory, especially on the station located on stiff soil deposits. Only two stations, namely 3412 and 3416, are poorly performing: the amplification and the duration of the signal suggest strong local site effects that the present SPEED 3D model seems uncapable to reproduce. These findings lead us to think that the presented preliminary model of the region offers a very robust reference for the researchers that want to challenge the capability of Physics-Based Simulation in the Istanbul area. The commitment of the team that proposed this work is to grant the full accessibility, through the SPEED web site to the (i) code, (ii) model and (iii) data, aiming at promoting a further development of the regional velocity model and therefore the predictive capabilities of PBS.

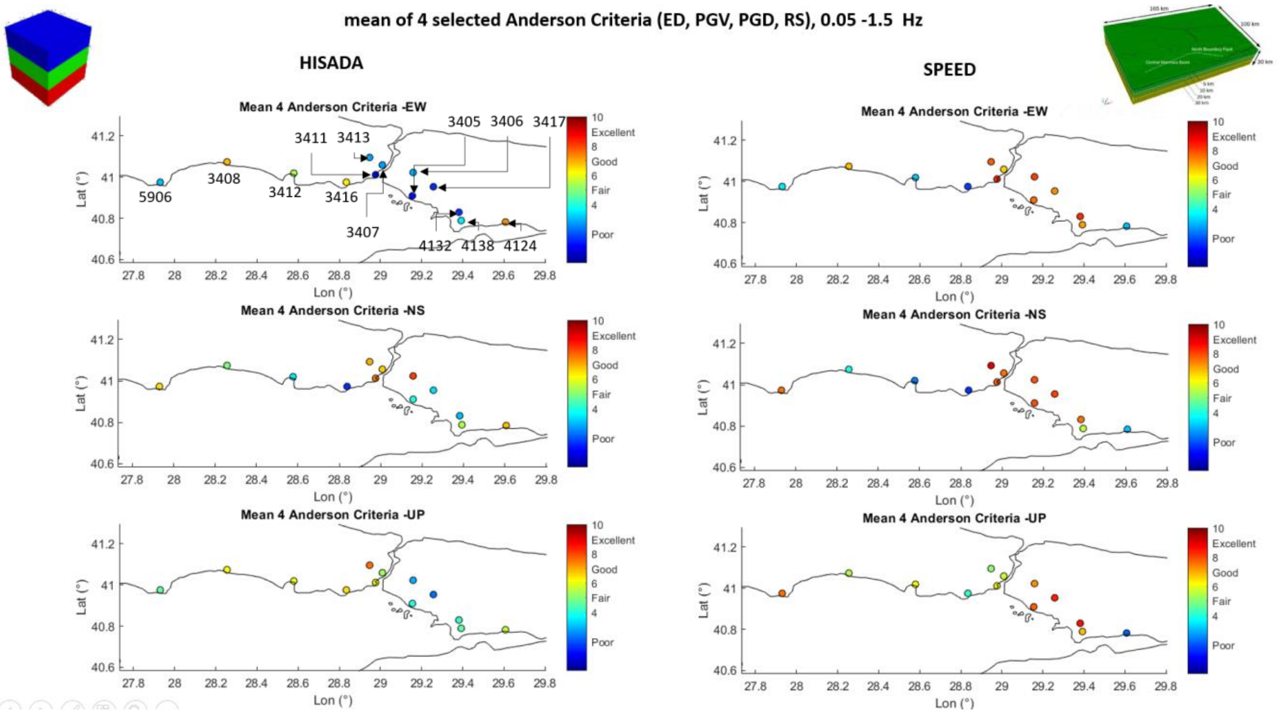

Fig. 8 – Mean of four selected Anderson criteria, namely ED (Energy Duration), PGV (Peak Ground Velocity), PGD (Peak Ground Displacement) and RS (Response Spectra). Left-hand side “records vs Hisada” and right-hand side “records vs SPEED”.

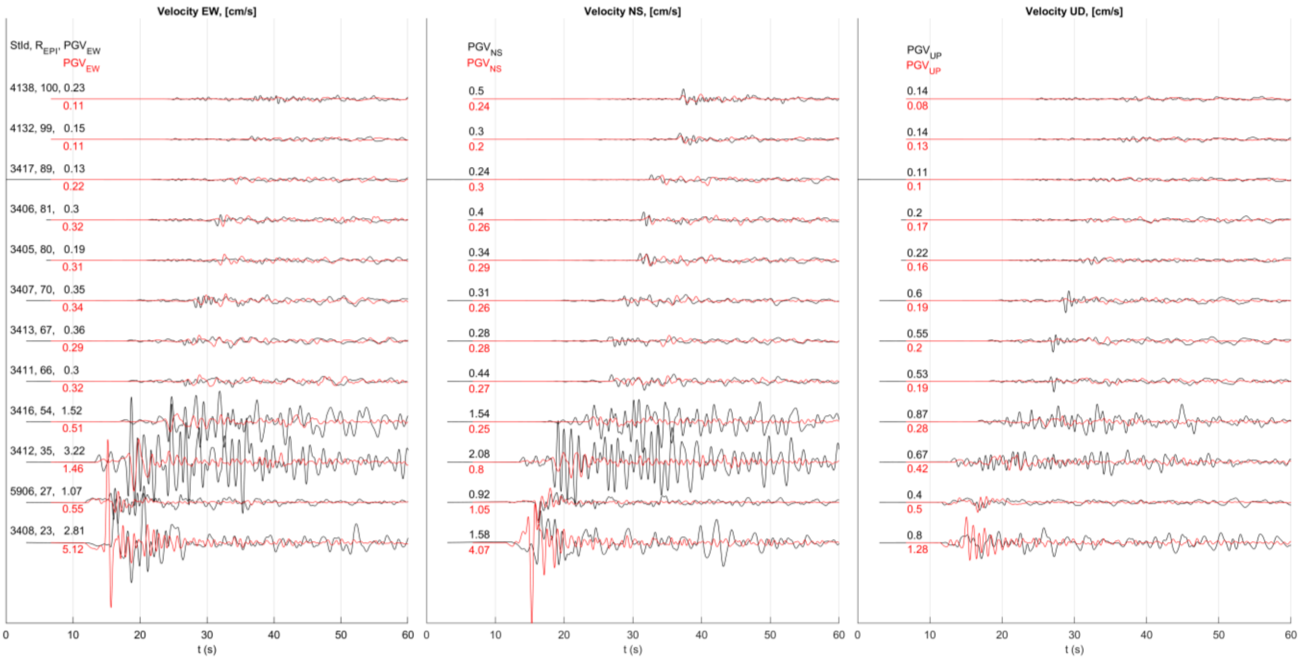

Fig. 9 – Comparison between the recorded (black) and the synthetic (SPEED) seismograms for all the station located within the 3D model. Data have been filtered between 0.05-1.5Hz. The Id of the station, the Repi [km] and the peak ground velocity [cm/s] of each component are also provided.

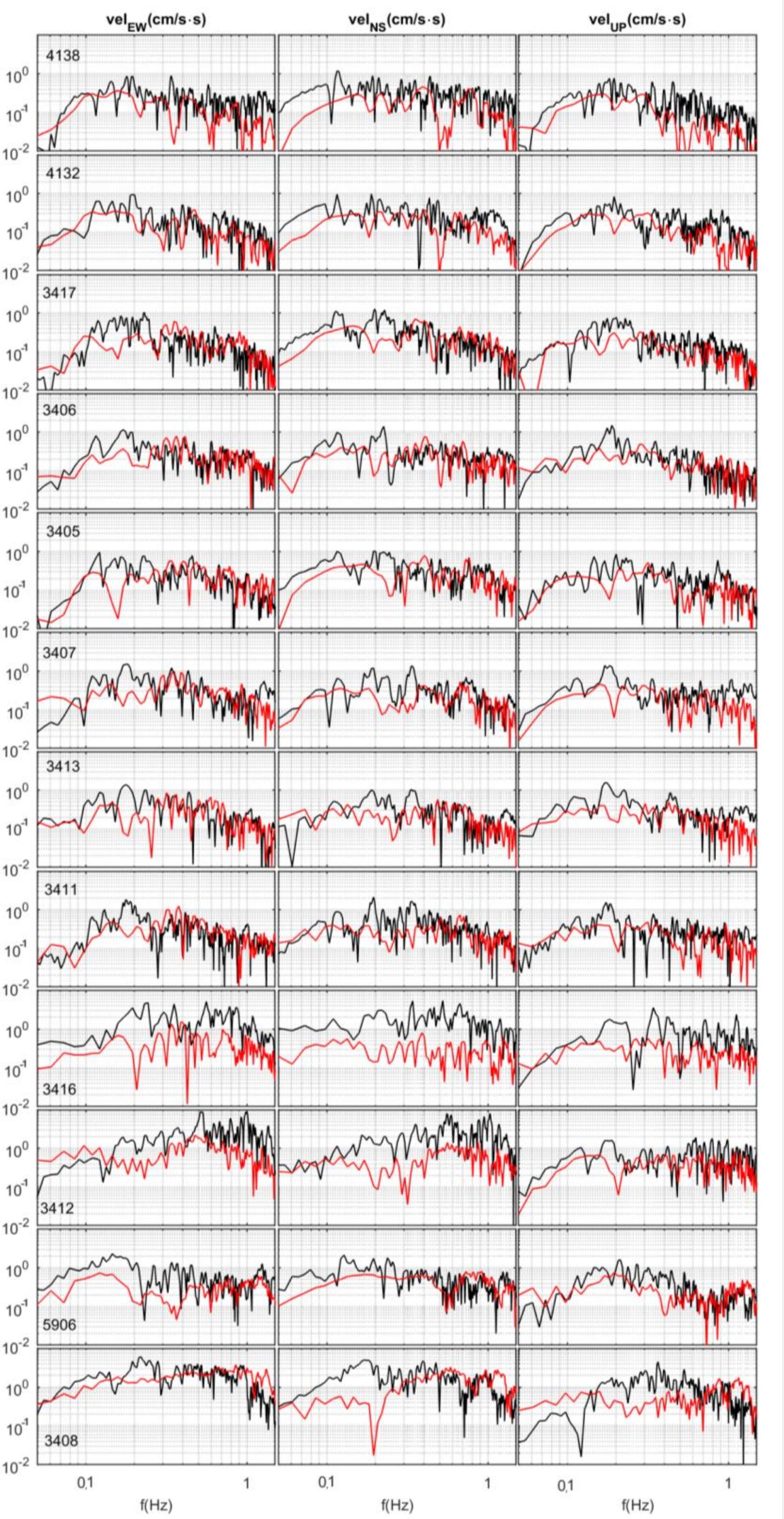

Fig. 10 – Comparison between the recorded (black) and the synthetic (SPEED) Fourier amplitude spectrum for all the station located within the 3D model. Data have been filtered between 0.05-1.5Hz.

6. Conclusions

In this contribution we presented the verification/validation effort that has been undertaken regarding the area of Istanbul in Turkey. In order to accomplish the verification task, 3D physics-based elastodynamic simulations have been accomplished using two different numerical approaches: the spectral element discontinuos galerkin code SPEED [1] and the theoretical method proposed by Hisada and Bielak [2], based on Green's function, particularly suited to compute near-fault ground motions in layered half-spaces.

The validation of the previous 3D models was accomplished thanks to the seismograms recorded during the recent magnitude 5.8 earthquake occurring the 26th of September 2019 along the North-Anatolian Fault in the immediate proximity of the Marmara segment. The Anderson criteria allowed us to quantitively prove the validity of the SPEED Physics-Based Simulation and the 12 stations show an overall good agreement between records and synthetic.

Obviously the model requires important improvements in order to capture local specific effects, nevertheless it already (i) offers a solid reference for future researches in the region and clearly (ii) strengthen the validity of physics-based simulation especially in regions where a large event is likely to occur.

7. Acknowledgments

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