Validation of site-effect numerical predictions: New results from the Euroseistest Verification and Validation Project (E2VP)

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SUMMARY:
The capability of numerical methods to predict earthquake ground motion in realistic configurations and frequency range is investigated through the Euroseistest Verification and Validation Project (E2VP). E2VP focuses on the Mygdonian basin (Greece) which structure has been extensively investigated for more than two decades. A detailed 3D model of the basin as well as recordings of local earthquakes by the Euroseistest array provide a reasonable basis to validate numerical methods for frequencies up to 4 Hz. Simulations performed by more than 10 teams (Europe, USA, Japan, China) using different numerical methods (Finite Difference, Finite Element, Spectral Element, Discontinuous Galerkin, Pseudospectral) are compared to recordings of 6 local events with magnitude below 4.5. We present the detail of those comparisons and give some insight about the variability of simulated ground motion caused by 1) insufficient knowledge of the structural model (geometrical and material parameters), and 2) uncertainties in source parameters.

Keywords: numerical simulation, site response, goodness-of-fit

1. INTRODUCTION: THE EUROSEISTEST VERIFICATION & VALIDATION PROJECT

The estimation of site effects within the framework of a seismic hazard study can involve the use of different approaches, both empiric and numeric. However, in context of low or moderate seismicity, the use of empirical approaches may be difficult to implement due to the lack of representative earthquakes. In this context, the use of numerical tools becomes essential.
Before using the ground motion simulation codes within the framework of civil engineering design purposes, it was requisite to evaluate them. Previous “benchmark” exercises were already done, as for example the previous work for the ESG’2006 meeting that concerned the Grenoble basin (Chaljub *et al.*, 2006; Chaljub *et al.*, 2010). Nevertheless, this last work focused on comparisons between simulation (“verification procedure”) and not comparisons between simulation and real data (“validation procedure”).

Hence, it was necessary to continue the effort on a site where the validation could be possible. This was the motivation of the Euroseistest Verification and Validation Project (E2VP) – an ongoing international collaborative work, organized jointly by the Aristotle University of Thessaloniki, Greece, the Cashima research project (supported by the French nuclear agency, CEA, and the Laue-Langevin Institute, ILL, Grenoble), and the Joseph Fourier University, Grenoble, France.
The project involves more than 10 international teams from Europe, China, Japan and USA (see Table 1) using different numerical methods (Finite Difference, Finite Element, Spectral Element, Discontinuous Galerkin, Pseudospectral). The first phase of the E2VP was conducted between autumn 2007 (preparation tasks) and June 2010 (final meeting), and mainly applied on the verification part with the computation of realistic and canonical cases by several teams (see participants in Table 1 and http://www.sismowine.org). The second phase of E2VP was lunched on February 2012 (Kickoff meeting) and aims to proceed the validation work, especially to better access uncertainties and identify their origins.

Table 1. Teams and institutions contributing to the E2VP.

Institution	Country	Town	Team acronym
Comenius University of Bratislava	Slovakia	Bratislava	CUB
Université Joseph Fourier	France	Grenoble	UJF
Disaster Prevention Research Institute	Japan	Kyoto	DPRI
Istituto Nazionale di Oceanografia e Geofisica Sperimentale	Italy	Trieste	OGS
National Research Institute for Earth Science and Disaster Prevention	Japan	Tsukuba	NIED
Commissariat à l´Energie Atomique et aux Energies Alternatives	France	Bruyères le Chatel	LDG
Carnegie Melon University	U.S.A.	Pittsburgh	CMU
Politecnico di Milano	Italy	Milan	POLIMI
Université de Nice – Sophia-Antipolis	France	Valbonne	UNICE
Bureau de Recherches Géologiques et Minières	France	Orléans	BRGM
University of Science and Technology of China	China	Hefei	USTC
Institut de Radioprotection et de Sureté Nucléaire	France	Fontenay-aux-Roses	IRSN
Aristotle University of Thessaloniki	Greece	Thessaloniki	AUTH
Géodynamique et Structure	France	Bagneux	GdS

2. THE MYGDONIAN BASIN AND ITS 3D NUMERICAL MODEL

The target of the project is the Mygdonian basin located in North-Eastern Greece, 30 km ENE of Thessaloniki, in the epicentral area of a magnitude 6.5 event that occurred in 1978. This site has the advantage of a velocity model already available in both 2D (7-layers model derived from Raptakis *et al.*, 2000) and 3D (3-layers model derived from Manakou *et al.*, 2007, 2010). In addition, numerous accelerograms are available.

The Mygdonian basin is the place of the so-called "Euroseistest" test site which has been extensively investigated within the framework of various European projects (Euroseistest, Euroseismod, Euroseisrisk, Ismod) and is now maintained by ITSAK and AUTH (Pitilakis *et al.*, 2009). The basin has been shaped by NS extensive tectonics with EW trending normal faults on each side. It is now densely instrumented with surface accelerometers (red triangles in Figure 1), including a vertical array with 6 sensors over 200 m depth at the central TST site.

The project makes use of a new detailed 3D model of the Mygdonian basin about 5 km wide and 15 km long, with sediments thickness reaching about 400 m (see Figure 1 and Manakou *et al.*, 2007, 2010). The velocity structure of the basin is well constrained along a central NS profile crossing TST, from a large number of geophysical and geotechnical measurements (*e.g.* Jongmans *et al.*, 1998), surface and borehole seismic prospecting, electrical soundings and microtremor recordings. The sediment thickness is maximum along this profile at the TST site (197 m) and the velocity increases from 130 m/s at very shallow depth to about 650 m/s at large depth, with a large contrast with the underlying bedrock (2600 m/s, see Table 2). The 3D structure in the whole graben has then been extrapolated from this central profile, taking into account information from many single point microtremor measurements, a few array microtremor recordings, one EW refraction profile, and old deep boreholes drilled for water exploration purposes (Raptakis *et al.*, 2005). In the resulting 3D model, the TST site appears like a saddle-point, with the sediment thickness increasing both eastward and westward, off the central profile which actually corresponds to a buried pass between two thicker sub-basins (see Figure 1).

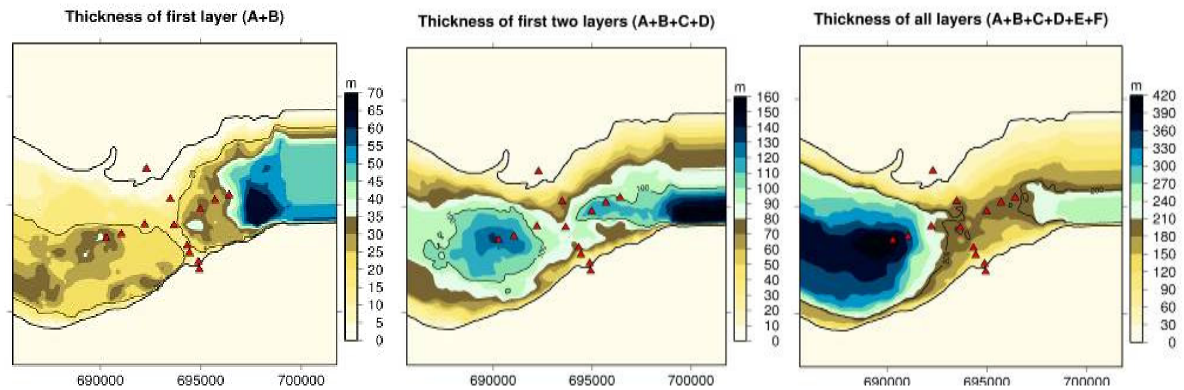

Figure 1. Sediment thickness in the 3D Mygdonian basin model: first (left), first two (middle) and all layers (right). Note the strong lateral variations and the asymmetries between the northern and southern edges, as well as between the western and eastern sides. The location of the accelerometric array is represented by the red triangles. The central TST site appears as a saddle-point: a maximum in the NS direction and a minimum in the EW direction. The letters A-F refer to the 6 sedimentary units used in the 2D model of Raptakis *et al.* (2000), which have been grouped into three main units in the E2VP 3D model (see Table 2).

Table 2. Mechanical properties of the Mygdonian basin model. Each layer has homogeneous properties but laterally varying thickness.

Layer	V_S (m/s)	V_P (m/s)	ρ (kg/m^3)	Q_S	Q_κ
A+B	200	1500	2100	20	∞
C+D	350	1800	2200	35	∞
E+F	650	2500	2200	65	∞
Bedrock	2600	4500	2600	260	∞

3. HOW TO EVALUATE THE ACCORDANCE BETWEEN REAL AND SYNTHETIC SIGNALS

It is not so simple to determine how to test the reliability of ground motion simulation tools. Of course, this will lead to compare signals between them (simulated signals to simulated signals within the "verification procedure" or real recorded signals to simulated signals within the "validation procedure"). But how to decide the criterion(s) of what is a good agreement or what is a poor agreement? The goal of E2VP is to evaluate the reliability of the simulation tools for civil engineering design purposes. However, even within the civil engineering design context, the choice of the right parameter (or a set of parameters) and the definition of an acceptable agreement threshold is not easy and is one task of its own in the project.

For the moment, in the validation part of E2VP, the synthetics are confronted to real data by comparing the values obtained on ten representative ground motion criteria: Arias duration, energy duration, Arias intensity, energy integral, PGA, PGV, PGD, response spectra, Fourier spectra and cross correlation (defined by Anderson, 2004). The match between the observed records and synthetics is then quantitatively scored by computing the goodness-of-fit (GOF) scores for each ground motion criterion comprised between 0 (total misfit) and 10 (perfect fit) through the following non-linear scaling (see also Figure 2):

$$\mathrm{GOF} = 10\ exp\ (-\mathrm{misfit}^2) \qquad (1)$$

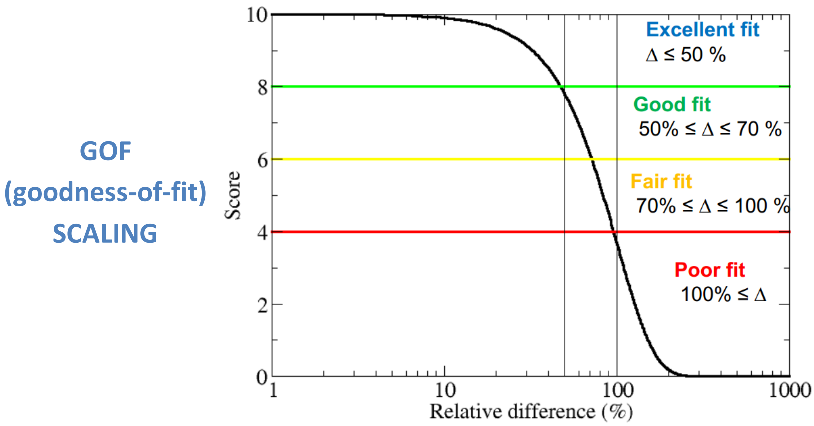

Figure 2. *Non-linear scaling recommended by Anderson (2004) between the values of misfits and the values of goodness-of-fit (GOF) computed on representative ground motion criteria used in the validation part of the E2VP. Following Anderson (2004), a cruder verbal scale (poor-fair-good-excellent) is also used.*

4. COMPARISON WITH LOCAL EARTHQUAKE RECORDINGS FOR VALIDATION OF THE 3D GROUND MOTION NUMERICAL PREDICTIONS

One of the validation steps consists in comparing numerical predictions with actual recordings up to 4 Hz. The exercise has been performed for 6 local, weak to moderate magnitude events, spanning various azimuths, depth and distances, and recorded by the local array of 19 surface and borehole accelerometers (see Figure 3 and Table 3).

In the following we only display the synthetics obtained by one of the numerical methods (Spectral Element by team UJF) since we have carefully checked in the verification phase of the project that they could be considered as a reference (Chaljub *et al.*, 2012).

The synthetics are computed in the 3D anelastic layered model of the Mygdonian basin (Figure 1 and Table 2). The simulations are accurate for frequencies up to 4 Hz and do not account for the surface topography.

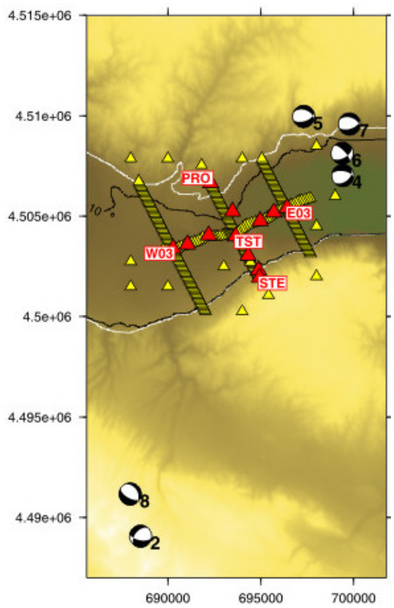

Figure 3. Detailed view of the Euroseistest accelerometric network (red triangles) that recorded 6 local events (beachballs with number ID). The additional virtual receivers (yellow triangles) were used in the 3D numerical simulations of these events. The white line denotes the basin edge and the black line is the location where the sediment thickness equals 10 m.

Table 3. Magnitude, depth and focal mechanism of 6 selected real events (see locations on Figure 3) which recordings by the Euroseistest array were compared to numerical predictions.

Event ID	Magnitude	Depth	Strike	Dip	Rake
2	2.8	6.9 km	100°	60°	-50°
4	4.4	5.0 km	53°	43°	-127°
5	3.1	6.0 km	72°	55°	-113°
6	3.9	6.0 km	61°	55°	-115°
7	3.4	5.0 km	72°	55°	-113°
8	3.8	10.0 km	329°	34°	-64°

The recorded ground motion of the largest event #4 (black curves) is compared with synthetics (red curves) at two stations: TST0 (surface soil site, Figure 4) and TST5 (borehole, 197 m depth, Figure 5). Additional comparisons are available at other stations but are not shown here for the sake of clarity. For each site, velocity time histories and acceleration response spectra are displayed for the 3 components of ground motion.

In general, while the detailed waveforms do not match, the overall amplitude, duration and response spectra exhibit a relatively satisfactory agreement. The detailed waveforms are indeed very sensitive to the source parameters (hypocenter location and focal mechanism), to the shape of the sediment-basement interface and to the internal sediment layering.

The highest level of agreement is found on the NS component of the TST0 station (see Figure 4). The fit is excellent for the PGA, the acceleration response spectra and the energy duration. The same NS component of the TST5 borehole station, located 197 m beneath the TST0 station, also exhibits an excellent fit for the acceleration response spectra (see Figure 5).

The level of agreement is less satisfactory at the other sites, with the ground motion at E03 being entirely overestimated by the synthetics. The fit at the rock sites (TST5, STE) is slightly better than at the soil sites (E03, W03), except at the central TST0 soil site that shows the best agreement between recordings and synthetics on the NS component of the ground motion. The velocity structure of the Mygdonian basin is precisely best constrained along a central NS profile crossing TST0. This illustrates how strongly the accuracy of the ground motion numerical predictions is dependent of the geological structure knowledge at the site of interest.

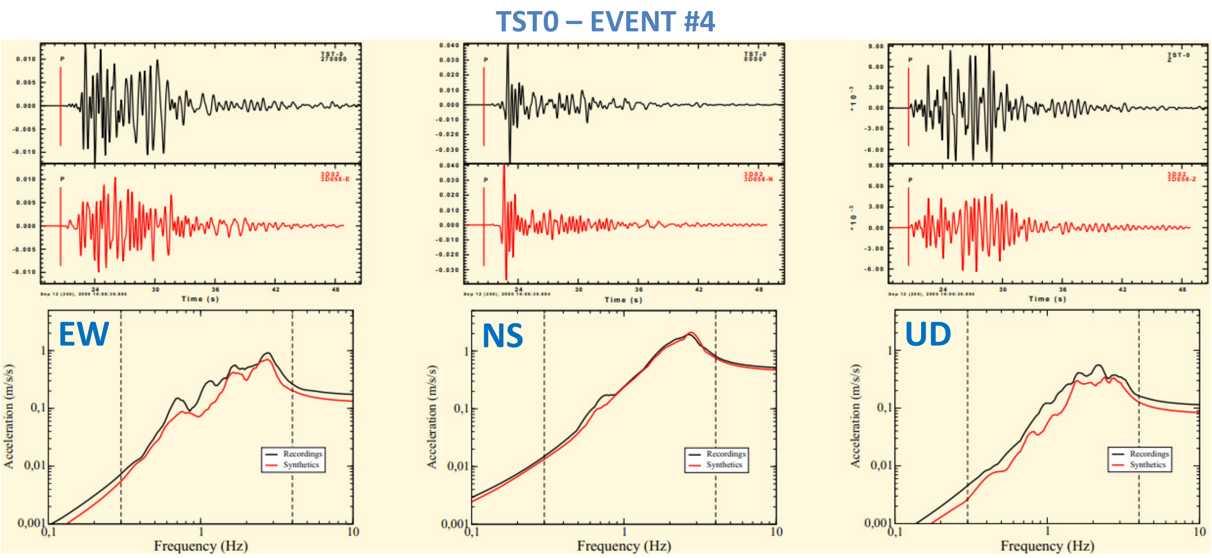

Figure 4. Comparison of recorded ground motion (black curves) with synthetics (red curves) at the station TST0 for event #4. Time histories (top) and acceleration response spectra (bottom) are displayed.

TST5 – EVENT #4

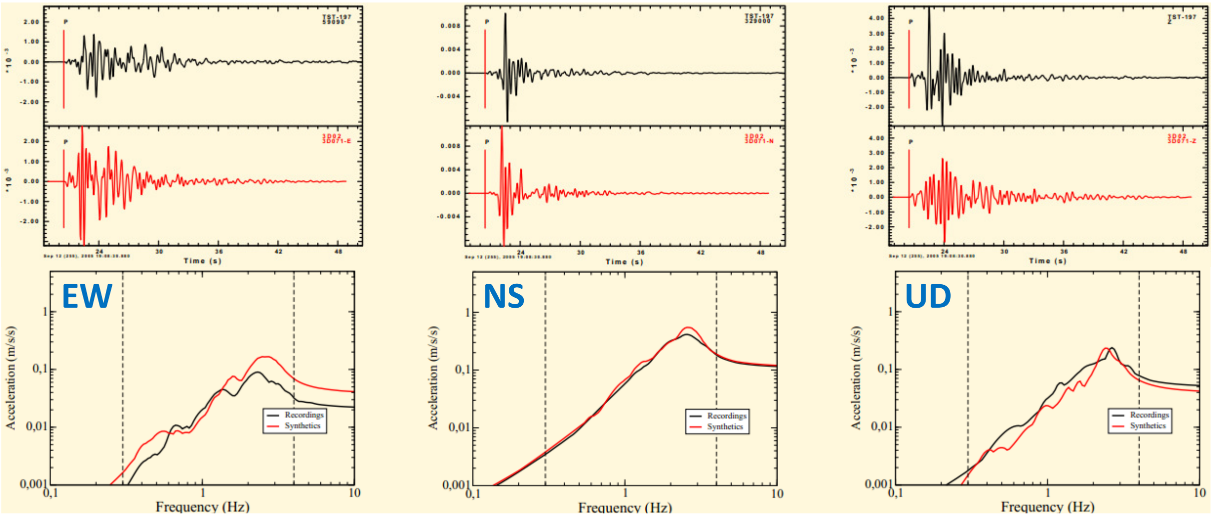

Figure 5. Comparison of recorded ground motion (black curves) with synthetics (red curves) at the station TST5 for event #4. Time histories (top) and acceleration response spectra (bottom) are displayed.

A global comparison is based upon the ground motion criteria defined by Anderson (2004) to quantitatively score how well the synthetics match the statistical characteristics of the observed records. The goodness-of-fit (GOF) scores on some representative ground motion criteria are given in Table 4 for all of the 6 selected local events shown in Figure 3 and simulated by team UJF in the Mygdonian basin model. Depending on the criterion, the event and the site, the scores are very variable. In general the best agreement between recordings and synthetics is unsurprisingly found at the TST0 site. However the agreement is strongly different from one event to the other, as a result of the combined uncertainties in the source parameters and the basin structure. The largest – and thus best known – event (#4) shows one of the best fits between recordings and synthetics. The two furthest events (#2 and #8) also exhibit a general good agreement: due to the higher distance between the sources and the receivers, the results are slightly less dependent of the source parameters.

Table 4. Anderson goodness-of-fit scores between recorded ground motion and synthetics computed by team UJF on 4 representative ground motion criteria (Arias intensity, energy duration, PGA and response spectra) for the 6 selected local events (see Figure 3 and Table 3) recorded at 5 different sites: TST0 (central soil site), TST5 (rock site, downhole, 197 m bellow TST0), E03 (soil site), W03 (soil site) and STE (rock site). The scores are averaged on the two horizontal components of ground motion. The average Anderson score (Anderson, 2004) is also given in the last column. The score and color scaling is described in part 3.

EVENT #2

site	Arias intensity	energy duration	PGA	response spectra	average Anderson score
TST0	8.8	7.7	9.3	7.4	7.5
TST5	2.5	8.1	6.8	5.7	5.6
E03	8.0	6.1	9.8	8.7	7.4
W03	3.4	7.3	7.0	7.4	5.6

EVENT #4

site	Arias intensity	energy duration	PGA	response spectra	average Anderson score
TST0	9.2	7.1	9.9	9.2	8.0
TST5	3.2	5.6	5.6	8.0	5.4
E03	0.7	5.2	4.3	3.9	4.0
W03	3.4	6.7	9.1	7.2	6.1
STE	5.1	3.1	7.8	7.3	5.6

Table 4 (continued)

EVENT #5					
TST0	9.7	7.1	9.8	8.9	8.0
TST5	5.9	8.1	8.6	7.6	7.3
E03	9.1	7.1	9.3	7.2	7.2
W03	0.2	7.0	2.7	2.8	3.0
STE	0.0	6.1	0.7	2.0	2.3
EVENT #6					
TST0	0.0	6.5	0.6	2.4	2.5
TST5	0.0	7.3	0.3	0.4	2.4
W03	0.0	6.8	2.5	2.4	2.8
STE	5.0	4.3	5.9	6.2	5.1
EVENT #7					
TST0	1.0	7.2	5.2	5.2	4.3
TST5	0.0	7.8	2.0	2.0	2.9
W03	0.1	7.5	4.1	1.6	3.3
STE	6.8	4.8	9.1	8.2	6.6
EVENT #8					
E03	8.7	6.4	4.4	5.1	4.4
W03	4.7	6.9	6.6	5.3	5.1
STE	5.9	6.7	9.4	7.0	7.0

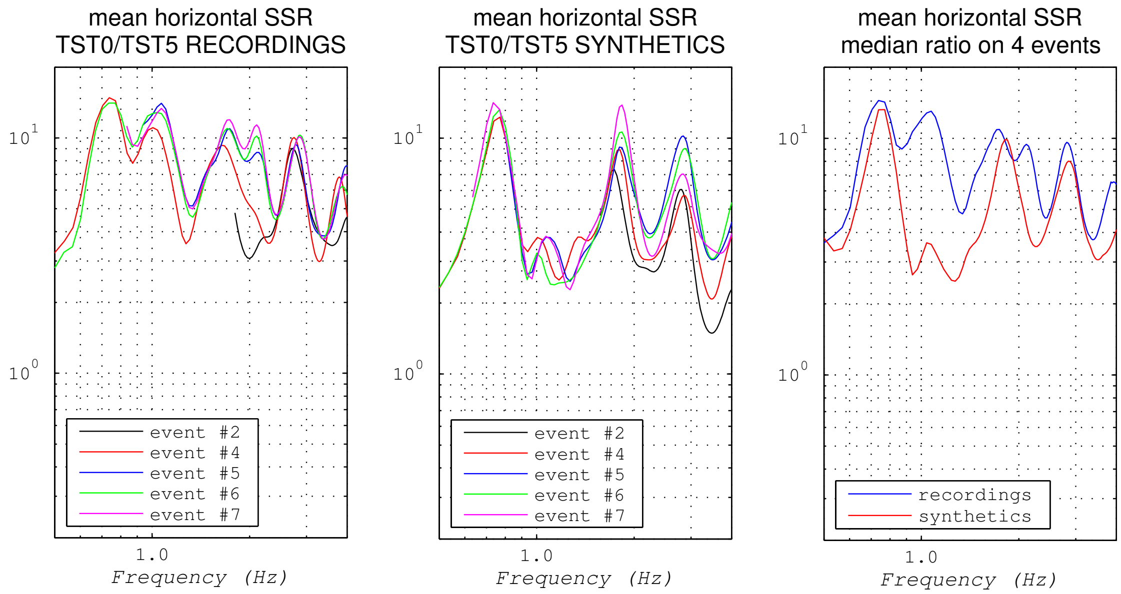

Figure 6. Standard spectral ratios of the mean horizontal component between stations TST0 (surface) and TST5 (borehole) for recordings (left) and synthetics (middle) of 5 local events (see Table 3). The event #8 was not recorded by TST5. The spectral ratios are plot only for frequencies where the signal-to-noise ratio is greater than 10. On the right panel, the median ratios for recordings (blue) and synthetics (red) are calculated on 4 events (#4, #5, #6 and #7). The event #2 is not included in the median ratio as its signal-to-noise ratio at TST is acceptable only above 2 Hz (this is both the furthest and lowest event).

In order to remove (some of) the errors due to source parameter uncertainties, another comparison was based upon the Fourier transfer functions from the downhole sensor (TST5) to the surface sensor (TST0) at the central vertical array. The instrumental site-to-reference spectral ratios derived from the available recordings were compared with those derived from 1D and 3D synthetics (see Figure 6 and Figure 7). The best fit is obtained for 3D simulations, which do account for both the broad band amplification due to lateral reverberations and the scatter due to the sensitivity of the diffraction

pattern to the source location. The theoretical 1D surface/downhole transfer function also overestimates the amplification at fundamental frequency, due to the systematic occurrence of destructive interferences at the sediment/basement interface at the fundamental frequency for vertically incident plane waves.
However, while the fundamental and overtones may be seen on each estimate, the amplification at intermediate frequencies, which proves to be large on observed SSR, witnesses further contribution of lateral reverberations and surface waves. There is a trend for underestimating the actual amplification in 3D simulations that could have several explanations: incorrect estimates of damping (too low Q values), incorrect internal sediment layering structure, mislocation of the buried pass just beneath the central profile, overestimation of hypocentral depth. Moreover, the increased standard deviation at intermediate frequencies for the observed SSR (when derived from many more events, see Figure 7) emphasizes the variability of the scattering/diffraction phenomena as a function of the source location. The derivation of the average synthetic SSR should thus take more events into account (6 events are definitely not sufficient).

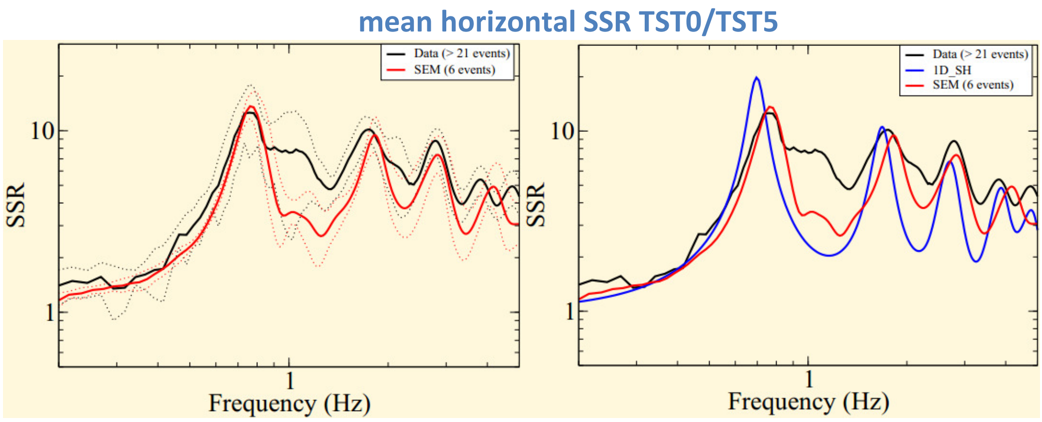

Figure 7. Standard spectral ratios of the mean horizontal component between stations TST0 (surface) and TST5 (borehole) for recordings (black curves), 3D synthetics (red curves) and 1D synthetics (blue curve). The left frame displays the average (plus/minus one standard deviation) spectral ratio derived from the available recordings (more than 21 events) and the synthetics (the 6 selected events), while the right frame compares these average SSR with the theoretical 1D SH transfer function.

5. SENSITIVITY STUDIES

Several sensitivity studies were performed in order to determine the impact of variations in model geometry, damping and velocity model on the computed ground motion in the Mygdonian basin. These studies help to better understand the differences between recorded and synthetic waveforms. Some of these studies were performed in 2D, others in 3D, and a few were performed both in 2D and 3D.
The results of all the sensitivity studies conducted until now are summarized in Table 5 in terms of engineering goodness-of-fit scores. Only the average values, taking into account all available components (*i.e.*, 2 or 3, respectively, for 2D and 3D results) and receivers, are considered. It indicates that the key ingredients most influencing the goodness-of-fit are a) the way damping is implemented in the simulation code, and b) the description of lateral heterogeneities within the sediments. As the corresponding engineering GOF scores are comparable to the previous validation scores (compare values in Table 4 and Table 5), the following issues should be considered as high priority whenever using the numerical simulation approach:
1/ using a code with a proper implementation of damping;
2/ having a detailed enough knowledge of the internal structure of the sediments and of their lateral variability.

Table 5. Wrap-up of sensitivity results. GOF stands for goodness-of-fit scores on Anderson's criteria.

Sensitivity topic		Resulting GOF	Comment
Model geometry	effect of surface topography	6-9	*affects waveforms in basin but not much peak values, affects amplitude mainly at rock sites*
Damping	implementation (constant value *vs* proportional to frequency)	6-8	*affects mainly total energy and duration, not so much peak values nor spectral acceleration*
	damping value (V_S/20 *vs* V_S/5)	7-8	
Velocity model in rock	effect of surface weathering in rock	9	*affects reference sites and relative amplification*
Velocity model in sediments	Poisson's ratio	8	*affects waveforms*
	homogeneous layers *vs* gradient layers, including lateral heterogeneities	7-8	*affects waveforms but not much peak values*
	without lateral heterogeneities within sediments (vertical gradient only)	6-8	*mainly affects waveforms, but also strongly impacts all criteria*

6. CONCLUSION AND PERSPECTIVES

Comparison with actual data (in-situ earthquake recordings), whenever possible, are always useful. Having sensitive in-situ instrumentation (continuously recording broad-band velocimeters or sensitive accelerometers) proves to be invaluable for checking the reliability of numerical simulation results.
The validation exercise had to be limited to local, weak-to-moderate magnitude events with significant high frequency contents since no stronger local event has occurred in recent years. The satisfactory match of 'overall' characteristics (amplitude, envelope, duration, response spectra) should be balanced by the large differences in the details of waveforms, especially for frequencies beyond 1-2 Hz. The source of the mismatches is not yet clearly identified. Are they linked to the intrinsic variability of ground motion? Are they linked to uncertainties in source parameters, or to an imperfect 3D description of the geological and geotechnical underground structure at short wavelength, including some badly known parameters such as material damping? E2VP phase 2 intends to tackle these questions.
One high-priority issue is the engineering importance of the local surface waves. What is the engineering added value of more reliable 3D predictions compared to 1D common practice? Up to which levels of accuracy should they be modelled/accounted for by 2D and 3D models? This question is important for (1) developers of numerical codes, since the canonical cases in the verification part of E2VP did show the much larger sensitivity to surface waves compared to body waves (Chaljub *et al.*, 2012), and (2) for geotechnical and geophysical surveys as well since the generation of surface waves is directly linked to geo-mechanical properties on valley/basin edges (underground slopes, heterogeneity wavelengths and velocity contrasts).
In the validation procedures, in order to better assess the uncertainties associated to the source parameters, sensitivity studies will be performed to determine the effect of source parameter uncertainties on the ground motion simulation by introducing changes in the source parameter values with the uncertainties domain.
Concerning the geological model, the results of recent surveys that were not valorised in the previous model will be considered. A few new surveys will also be done to extend the geological model toward the West and toward the East in order to get a larger model. A new model will then be proposed, associated to several other alternative models, different but plausible and compatible with available

data. Within the validation procedure, one can then evaluate the effect of reasonable changes in the geological model on the ground motion simulation results.
Finally, as already outlined, the small number of "candidate events" for validation is a typical situation of moderate/weak seismicity areas. Future validation events would certainly benefit from the possibility to include more distant events, which implies the use and/or the development of some "hybrid" numerical schemes coupling computations at different scales.

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