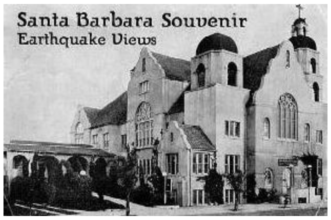


4th IASPEI / IAEE International Symposium:

Effects of Surface Geology on Seismic Motion

August 23–26, 2011 · University of California Santa Barbara

RELEVANCE OF GROUND MOTION NUMERICAL SIMULATIONS: WHAT HAVE WE LEARNED SINCE THE ESG' 2006 BENCHMARK?

Emmanuel Chaljub[1], Peter Moczo[2,3], Jozef Kristek[2,3], Pierre-Yves Bard[1] and Fabrice Hollender[1,4]

1: Institut des Sciences de la Terre
Joseph Fourier University Grenoble I
BP 53, 38041 Grenoble Cedex 9
France

2: Faculty of Mathematics, Physics and Informatics
Comenius University Bratislava
Mlynska dolina F1
842 48 Bratislava, Slovakia

4: CEA Cadarache
13108 St Paul lez Durance Cedex
France

3: Geophysical Institute
Slovak Academy of Sciences
Dubravska cesta 9
845 28 Bratislava, Slovakia

ABSTRACT

In parallel to the acquisition of field data and on-site observations, the theoretical understanding of site effects and the corollary development of numerical simulation are essential. This is particularly true in areas of low seismicity, where limited available data must be supplemented with numerical simulations. Before applying these approaches to the civil engineering design purposes, it is necessary to evaluate their reliability. The ESG 2006 simulation benchmark concluded that: "The way [*was*] still long towards a routine, debugged used of numerical simulation […], including new benchmarking exercises; the results and lessons drawn […] constitute a few, solid, forward steps in that direction". The logical and necessary continuation to the ESG 2006 exercise is the "EuroseisTest Verification and Validation Project (E2VP)". The E2VP focuses on the Volvi Mygdonian basin (Greece) for which a detailed 3D model and local earthquake recordings are available. It involves numerical-modeling teams from Europe, Japan and USA employing a wide range of different numerical methods – finite-difference, finite-element, global pseudospectral, spectral-element, discrete-element and discontinuous Galerkin. The problem configurations include elastic and visco-elastic rheologies, different basin velocity models and different source scenarios. The characteristics of the site - basin size of tens of kilometers, shear wave velocities as low as 200 m/s with VP/VS ratios as high as 7.5 and frequencies in the range [0-4 Hz] - make the E2VP an unprecedented effort in assessing the reliability of 3D numerical simulation to model earthquake ground motion in realistic configurations. The results achieved so far show that a proper method and implementation of a continuous and discontinuous material heterogeneity, large Poisson's ratios, attenuation, non-reflecting boundary and free-surface condition are the key elements of a reasonable numerical simulation. The project confirms that still some important methodological questions remain to be addressed and answered before the methods are confronted with data, and highlights the necessity of a continuing methodology development of the traditional and new methods in their application to the complex realistic models.

INTRODUCTION

During the last decades, an important effort has been dedicated to develop accurate and computationally efficient numerical methods to predict earthquake ground motion (EGM) in heterogeneous 3D media. The progress in methods and the increasing capability of computers have made it technically feasible to calculate realistic seismograms for frequencies of interest in seismic design applications. In order to foster the use of numerical simulation in practical prediction, it is important to (1) evaluate the accuracy of current numerical methods when applied to realistic 3D applications where no reference solution exists (verification) and (2) quantify the agreement between recorded and numerically simulated earthquake ground motion (validation).

Following what had been so far a tradition of ESG symposia, the ESG2006 held in Grenoble gave the opportunity to organize a verification exercise for numerical simulation of EGM in alpine valleys (Chaljub *et al*., 2006). The organization of the exercise at that time left little room for inter-comparisons and revealed that the 3D numerical simulation of EGM was far from being a "press-button approach". It was only after a few more years of collaborative work that four teams succeeded in getting close predictions, which were analyzed with objective quantitative misfit criteria (Tsuno *et al*., 2006; Chaljub *et al*., 2010). Among the lessons learned during this process it was clear that several predictions by different numerical methods were needed in realistic situations where no reference solution exists, and that no single method could be considered as best for all important medium-wavefield configurations in terms of accuracy and computational efficiency.

With the aim of extending this pioneer work on verification and to advance the validation process, it was decided in 2008 to launch 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 target of the project is the Mygdonian basin located in Northern Greece, close to Thessaloniki (see Fig. 1), in the epicentral area of a M6.5 event that occurred in 1978. 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 Fig. 2 and Manakou *et al*., 2007). The project involves more than 10 international teams from Europe, Japan and USA (see Table 1), eight of which employ the Finite-Difference Method (FDM), the Finite-Element Method (FEM), the Global Pseudospectral Method (PSM), the Spectral-Element Method (SEM), the Discontinuous Galerkin Method (DGM) and the Discrete-Element Method (DEM) in three dimensions (see Table 2). The numerical simulations by different methods are compared for a sequence of structural basin models ranging from the simplest up to the most complex. The models include laterally homogeneous sediments with a vertical gradient, 3 irregular homogenous sediment layers, and 3 irregular constant-gradient layers. Elastic and viscoelastic rheologies as well as low and large VP/VS ratios are also considered. Numerical predictions are compared using quantitative time-frequency envelope and phase goodness-of-fit criteria estimated at 288 receivers. Solutions are also compared with respect to model, wavefield and computational aspects of simulations.

In this article, we present a few results of the verification part of the E2VP project. The comparative analysis presented hereafter identifies non-planar material interfaces, free surface and contact of the free surface with the interfaces as key factors affecting the accuracy of simulations, and, in particular, the generation and propagation of diffracted surface waves.

MYGDONIAN BASIN

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). It is located 30 km ENE of Thessaloniki in North-Eastern Greece, and 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 Fig. 1), including a vertical array with 6 sensors over 200m depth at the central TST site.

The velocity structure of the basin is well constrained along a 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). 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 Fig. 2).

Several velocity models have been considered in the E2VP. The first one (hereafter referred to as model A) is made of homogeneous layers with laterally varying thickness and is detailed in Table 3. The letters A-F in the definition of the model 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. The second model (B) is a globally continuous model obtained by piecewise linear variations within the original three-layer model (see Table 4). Note that model B is only a very crude smoothed version of model A, no effort has been done yet to define a physically acceptable homogenization of model A. Other models have been considered in the E2VP (for example a laterally homogeneous model with a vertical gradient) but will not be discussed here. Outside the basin, the regional 1D velocity model of Papazachos [1998] is used.

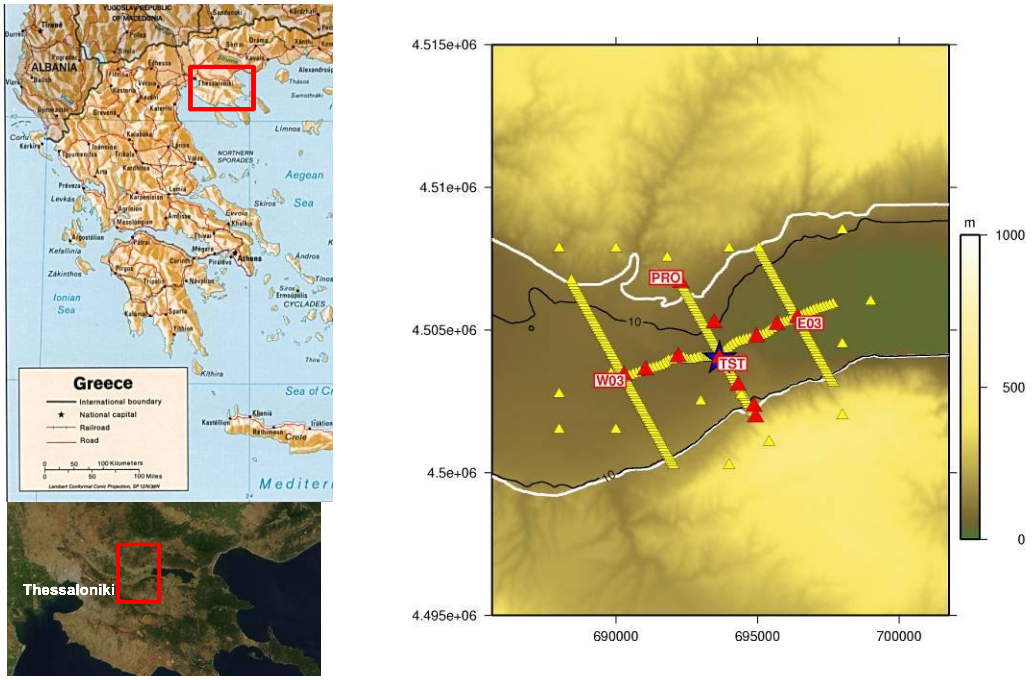


Figure 1. Location of the Mygdonian basin in the NE Greece with a detailed view of the Euroseistest accelerometric network (red triangles) and additional receivers (yellow triangles) used to compare numerical solutions. The white line denotes the basin edge and the black line is the location where the sediment thickness equals 10m.The blue star is the epicenter of a virtual seismic event considered in the numerical simulations.

Table 1. Teams and institutions contributing to the E2VP project with 3D simulations.

CUB **3D01**	FDM	Comenius Univ. Bratislava	Bratislava	Slovakia
UJF **3D02**	SEM	Université Joseph Fourier	Grenoble	France
DPRI **3D03**	FDM	Disaster Prevention Res. Inst.	Kyoto	Japan
OGS **3D04**	PSM	Istituto Nazionale di Oceanografia e Geofisica Sperimentale	Trieste	Italy
NIED **3D05**	FDM	Natl. Res. Inst. for Earth Science and Disaster Prevention	Tsukuba	Japan
CEA **3D06**	DEM	Commissariat à l´Energie Atomique et aux Energies Alternatives	Bruyères Le Chatel	France
CMU **3D07**	FEM	Carnegie Melon Univ.	Pittsburgh	USA
UNICE **3D09**	DGM	Université de Nice Sophia Antipolis	Valbonne	France

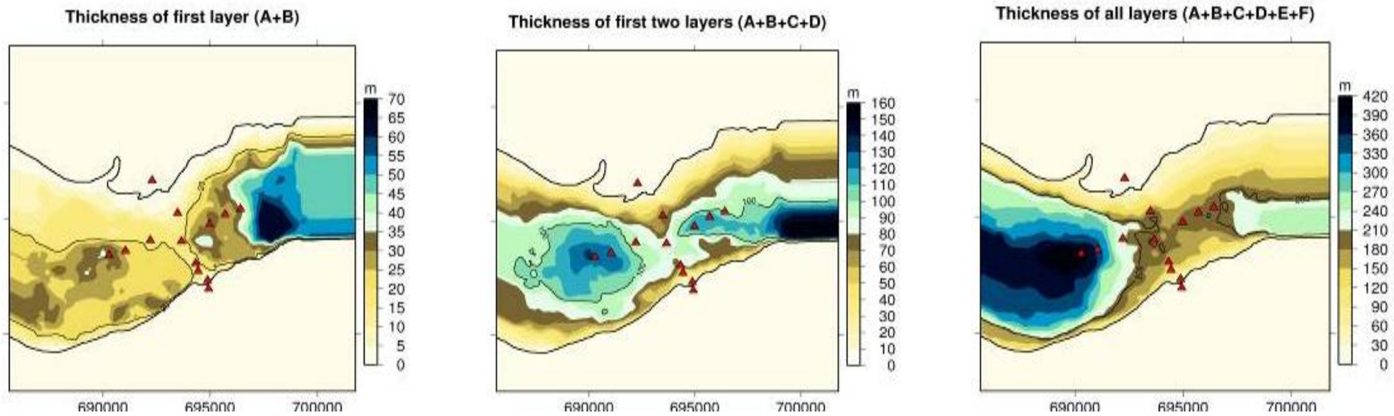


Figure 2. Sediment thickness in the 3D Mygdonian basin model A: first (left), first two (middle) and all layers (right). Note the strong lateral variations and the asymmetries between the northern and southern edges, as well as between the western and eastern sides. The central TST site appears as a saddle-point: a maximum in the NS direction and a minimum in the EW direction.

Table 2. Applied 3D methods used by the participants of the E2VP. All are 2nd order in time. GZB stands for Generalized Zener Body.

		Characterization	**Attenuation**	**Absorbing BC**
CUB	FDM	finite-difference, 4th-order velocity-stress volume arithmetic and harmonic averages of density and moduli, respectively arbitrary discontinuous staggered grid	GZB 4 rel. mechanisms	CPML
UJF	SEM	spectral-element, Legendre 4th-order polynomial Gauss-Lobatto-Legendre integration	GZB 3 rel. mechanisms	Lysmer & Kuhlemeyer
DPRI	FDM	finite-difference, 4th-order velocity-stress non-uniform staggered grid	linear Q(f) $f_0 = 2$ Hz	Clayton & Engquist A1 + Cerjan
OGS	PSM	Fourier pseudospectral, vertically stretching staggered grid	GZB 3 rel. mechanisms	CPML
NIED	FDM	finite-difference, 4th-order velocity-stress discontinuous staggered grid	linear Q(f) $f_0 = 2$ Hz	Clayton & Engquist A1 + Cerjan
CEA	DEM - SEM	hybrid discrete-element – spectral element, Voronoï particles (6 dof - 3 in translation, 3 in rotation), 2nd-order	hysteretic damping	Lysmer & Kuhlemeyer
CMU	FEM	finite-element, tri-linear elements octree-based discontinuous mesh	Rayleigh att. in the bulk	Stacey
UNICE	DGM	discontinuous Galerkin, 2nd-order polynomial	n.a.	CPML

Table 3. Mechanical properties of model A. 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	∞

Table 4. Mechanical properties of model B which is heterogeneous with no discontinuities within the sediments.

Layer	V_S (m/s)	V_P (m/s)	ρ (kg/m^3)	Q_S	Q_κ
A+B	200 - 250	1500 - 1600	2100	20 - 25	∞

C+D	350	1800	2200	35	∞
E+F	650	2500	2200	65	∞
Bedrock	2600	4500	2600	260	∞

C+D	250 - 500	1600 - 2200	2100 - 2130	25 - 50	∞
E+F	500 - 900	2200 - 2800	2130 - 2250	50 - 90	∞
Bedrock	2600	4500	2600	260	∞

COMPARISON OF NUMERICAL SIMULATIONS

In what follows, we compare different numerical simulations of the ground motion in the Volvi basin models, caused by a virtual M1.3 event, approximated by a double-couple point-source located 5 km beneath the TST central site. For each source-model configuration, the teams were required to compute 30 seconds of ground motion at 288 receivers.

Visco-elastic simulations in the three-layer model A

Figure 3 shows the peak ground velocity maps computed by four teams for the three-layer model A, when intrinsic attenuation is included (this case is referred to as 'I2b' in the E2VP). All maps show similar distributions of peak values, the largest being located on the northern side of the basin where the sediment cover is the shallowest and the slope of the basin edge varies most. The time-series of ground velocity at the central site TST computed by 7 teams are shown in Fig. 4 (team 3D09 did not contribute to this case as attenuation was not implemented in its code at the time when the exercise was performed). Note the good agreement between most of the predictions for early arrivals (less than 6 s) – especially on the vertical component – and the (sometimes large) differences both in phase and amplitude seen on late arrivals. Some of those differences, in particular in amplitude, can be attributed to the fact that two teams (3D03, 3D05) imposed a linear dependence of the quality factor on frequency, instead of the required constant (see Table 2).

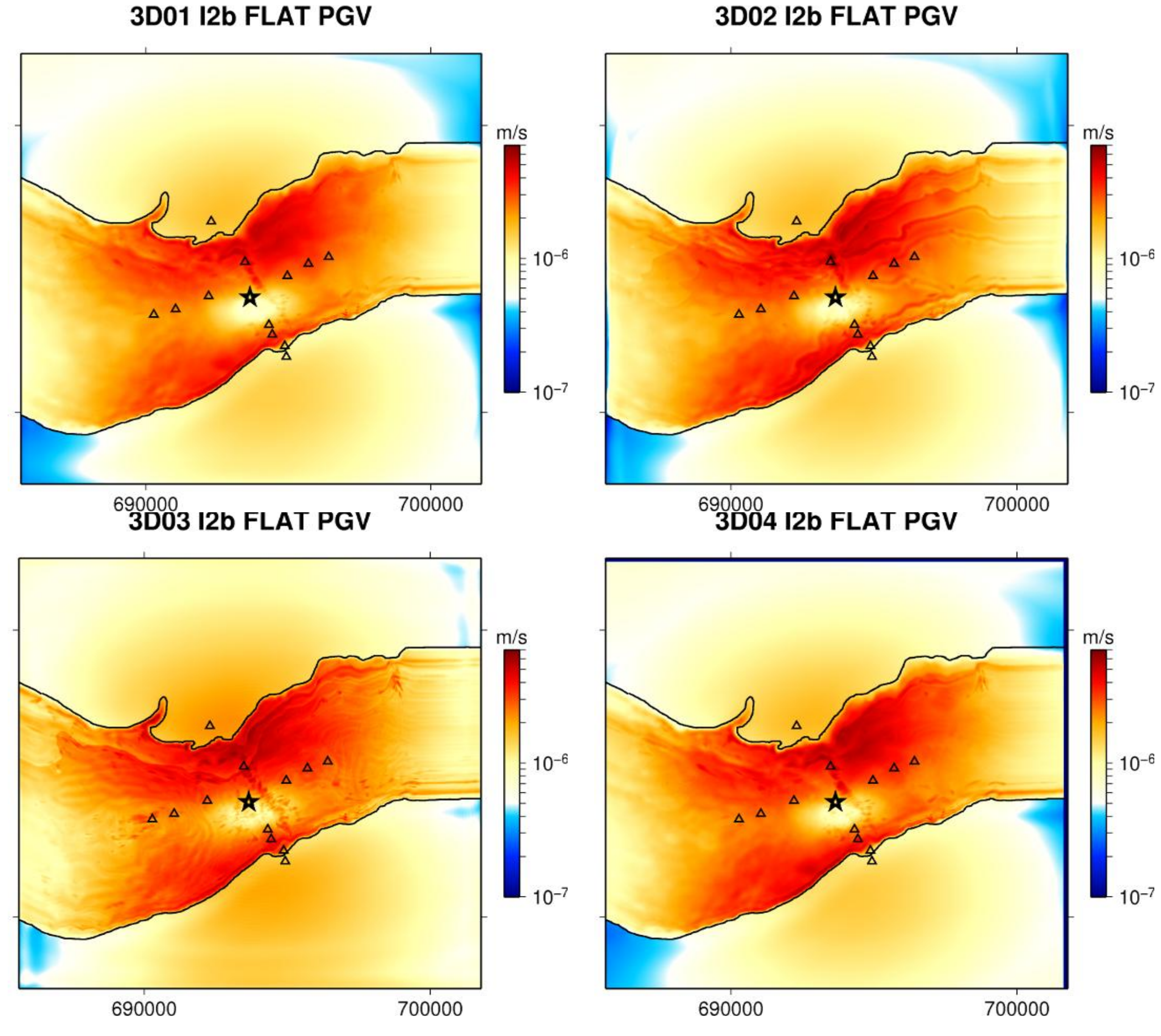
In order to get a more global and quantitative picture of the differences between numerical predictions, we applied the time-frequency misfit and goodness-of-fit criteria proposed by Kristeková *et al.* (2009) and recalled in Fig. 5. From the time-frequency representation of two signals, an envelope and phase misfits are computed, which are further averaged in time and frequency to give a single number. This misfit value is then converted into a goodness-of-fit (gof) score comprised between 0 (total misfit) and 10 (perfect fit) through a non-linear scaling (Fig. 5, right). Figure 6 shows the average of the phase and amplitude gof values computed at the 288 receivers. Each colored dot corresponds to a weighted average over the three components of ground velocity in the frequency range of the simulation ([0-4Hz]). These maps are very useful to track differences between predictions, which can be further investigated by inspecting individual (phase or amplitude) gof maps in separate frequency bands. Figure 6 shows that the results obtained by teams 3D01, 3D02 and 3D04 are the most similar, with mean gof values comprised between 7.4 and 8. The larger misfit seen between 3D01 and 3D03 is partly due to differences in implementing attenuation. Not shown in Fig. 6 are the gof maps for the other predictions which are all lower than the ones presented here, for reasons specific to each team: 3D05 did not implement the imposed visco-elastic rheology (the level of gof between 3D01 and 3D05 is similar with the one between 3D03 and 3D01), 3D06 is still working on the development of its code, and 3D07 implemented a different attenuation mechanism and imposed a maximum VP/VS ratio of 3 due to limitations of computational resources.

Elastic simulations in the three-layer model A

To cancel the effect of different implementations of attenuation in the misfits seen at late times, we have considered a case, referred to as 'I2c', with a pure elastic rheology. The PGV maps (computed by 5 teams) and the time series of ground velocity at TST (computed by 8 teams) are shown in Fig. 7 and 8, respectively. The I2c case, although completely non-physical, represents a numerical challenge since late arrivals, mainly very dispersive surface waves, are now dominating the time series. They also affect the maps of peak values with the presence of 'stripes' - their locations are very consistently reproduced by the different teams (see Fig. 7). Those peculiar features are caused by spatially localized surface wave packets diffracted off the basin edges and propagating towards the center of the basin without being attenuated. Figure 9 shows the maps of gof between the predictions of teams 3D01, 3D02, 3D04 and 3D09. The overall level of fit (wrt the result of 3D01) is generally lower than for the 'I2b' (attenuating) case, except for 3D03. The first impression that the two (finite-difference) predictions 3D01 and 3D03 are the closest does not resist a further analysis of gof maps in different frequency bands: it is rather seen that a reasonable fit (with global values around 7) is obtained between 3D01, 3D02, 3D04 and 3D09 for frequencies lower than 2 Hz, whereas the level of fit between 3D01 and 3D03 does not increase with decreasing frequency. Nonetheless, the higher part of the spectrum (above 2 Hz) appears extremely difficult to simulate consistently.

Elastic simulations in the smooth heterogeneous model B

Among the ingredients which make the previous cases ('I2b' and 'I2c') challenging for numerical simulation is the fact that model A contains discontinuities in the mechanical parameters. In the E2VP, we have also considered a few smooth models, laterally homogeneous or heterogeneous, which only contain first-order discontinuities (*i.e.* globally continuous, piecewise linear models). Figure 10 shows the time-series of ground velocity at the central station TST, computed in the continuous, laterally heterogeneous model B defined in Table 4, assuming a purely elastic rheology (this case is referred to as 'IV2' in E2VP). The similarity of the different predictions, including late arrivals, is striking. The gof maps wrt to the results obtained by team 3D01 are shown in Fig. 11. They clearly show that the level of agreement between most of the predictions is very good, with global average scores reaching values above 8. Note that the prediction by team 3D03 is the farthest from the result of team 3D01, although both teams use different variants of the FDM.


3D01 I2b FLAT PGV

3D02 I2b FLAT PGV

3D03 I2b FLAT PGV

3D04 I2b FLAT PGV

Fig. 3: Maps of peak ground velocity obtained by four different teams for the E2VP case 'I2b' which considers a viscoelastic rheology in the three-layer model A of the Mygdonian basin. The triangles denote the positions of the Euroseistest array and the star is the epicenter of the point-source used for verification purposes. Note the similarities in the displayed maps, and the asymmetries between the northern and southern edges, the largest peak values being obtained where the slope of the basin edge is the most gentle.

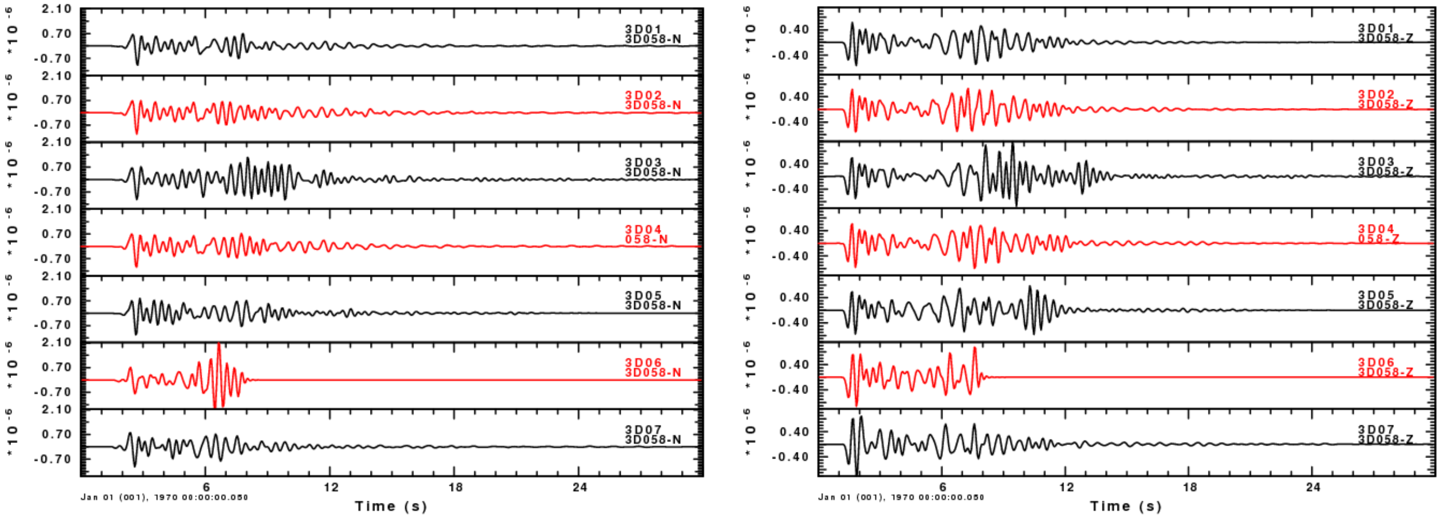


Fig. 4: N-S (left) and vertical (right) components of ground velocity at TST computed by 7 different teams for the I2b case. Most of the predictions are very consistent for the first 6 seconds, before the arrival of late phases, among which surface waves diffracted off the valley edges. Some predictions are very close (3D01, 3D02, 3D04) for the whole time window. Note that teams 3D03 and 3D05 did not implement the imposed constant-Q visco-elastic rheology, and that team 3D07 used a maximum VP/VS ratio of 3.

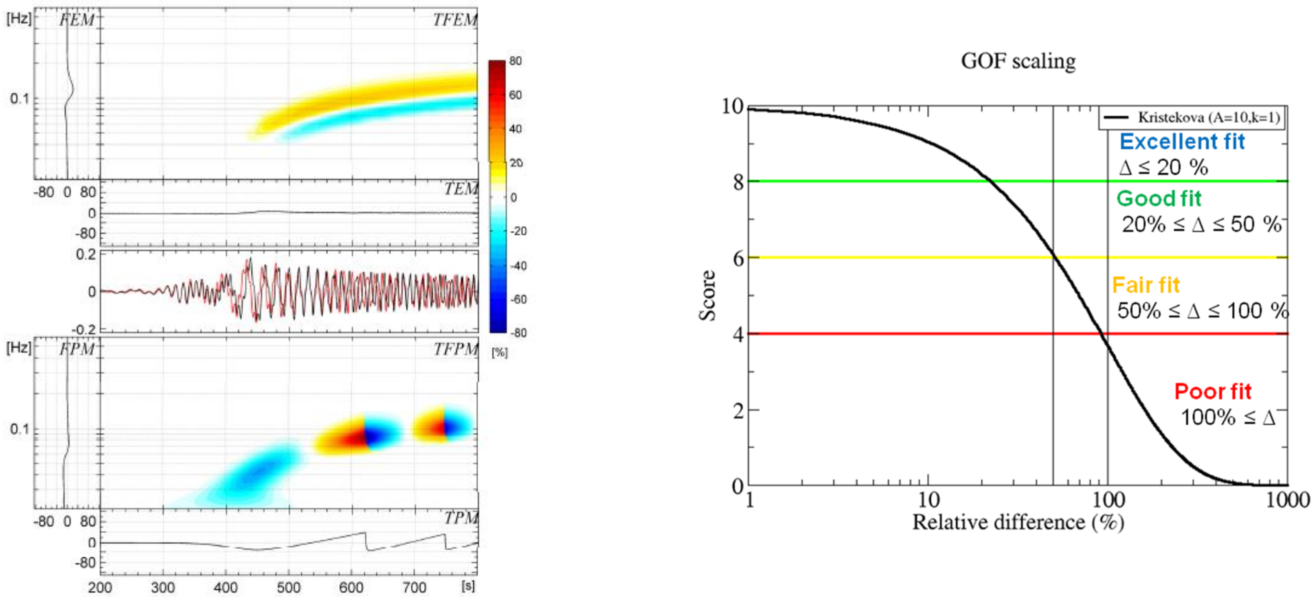


Fig. 5: Left: example of computation of the Time-Frequency Envelope and Phase misfits between two signals (after Kristeková et al.*, 2006). Right: non-linear scaling between the values of misfits and the values of goodness-of-fit used in this article. Following Anderson (2004) and Kristeková* et al. *(2009), a cruder verbal scale (poor-fair-good-excellent) is also used.*

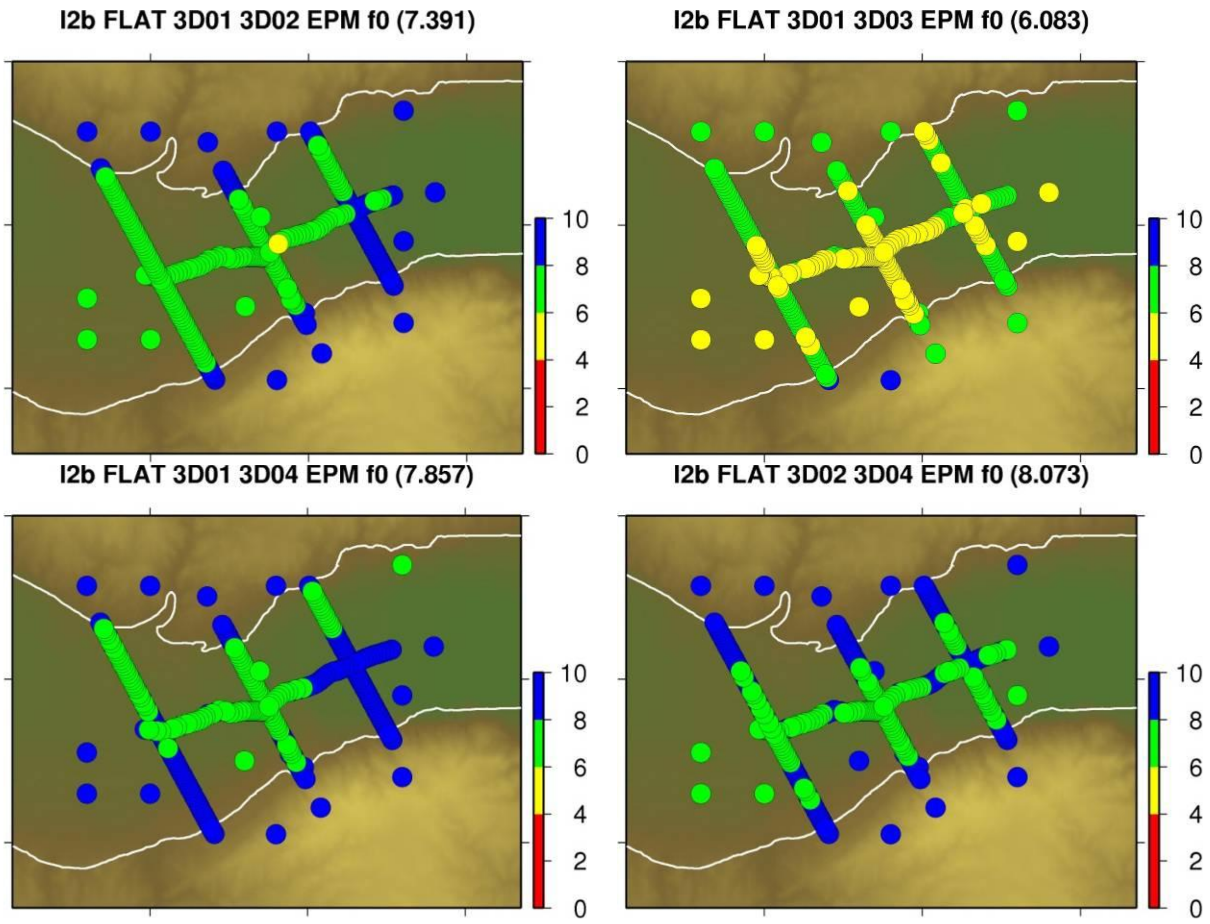
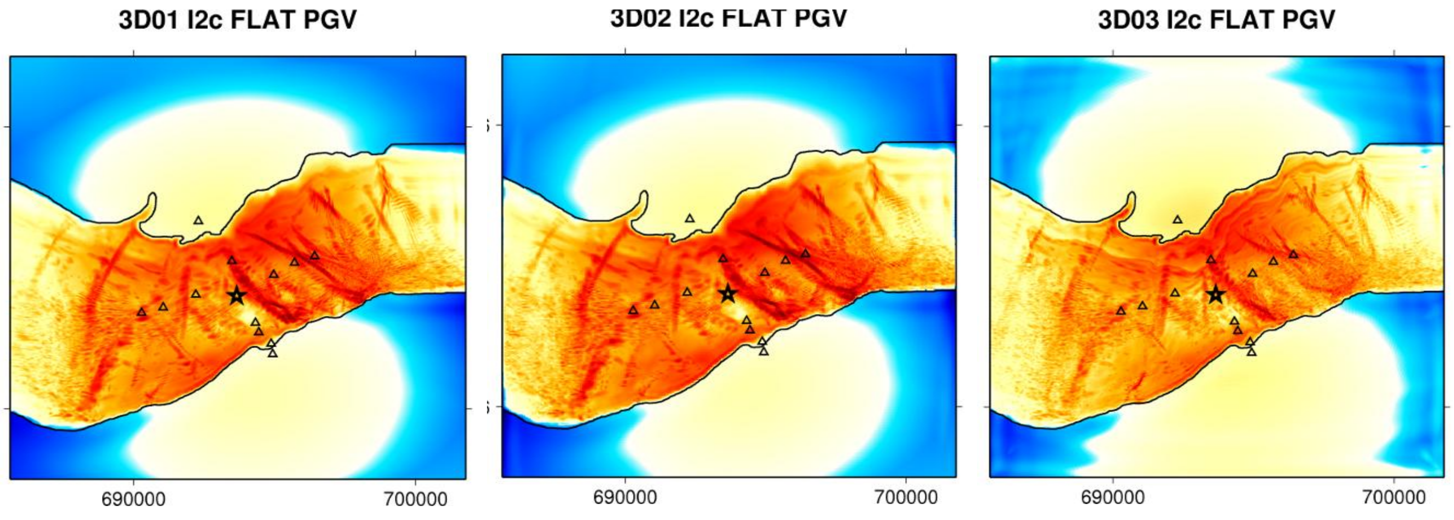


Fig. 6: Maps of goodness-of-fit computed for 4 different predictions (by teams 3D01, 3D02, 3D03, 3D04) of the E2VP case 'I2b' which considers a visco-elastic rheology in the three-layer model A of the Mygdonian basin. Each dot corresponds to the average of the amplitude and phase misfits computed for the three components of ground velocity in the whole frequency range [0-4Hz], and translated in terms of goodness-of-fit to get a number between 0 and 10 (perfect fit). The global average computed for the 288 receivers is given in the title of each image. The first prediction 3D01 has been used as a reference for the first three maps (top left, top right and bottom left) but changing the reference does not change the overall conclusion as can be seen in the bottom right map. The fit is generally found to be very good at rock sites and to decrease inside the basin. Note the good to excellent level of fit between the three predictions by teams 3D01, 3D02 and 3D04.



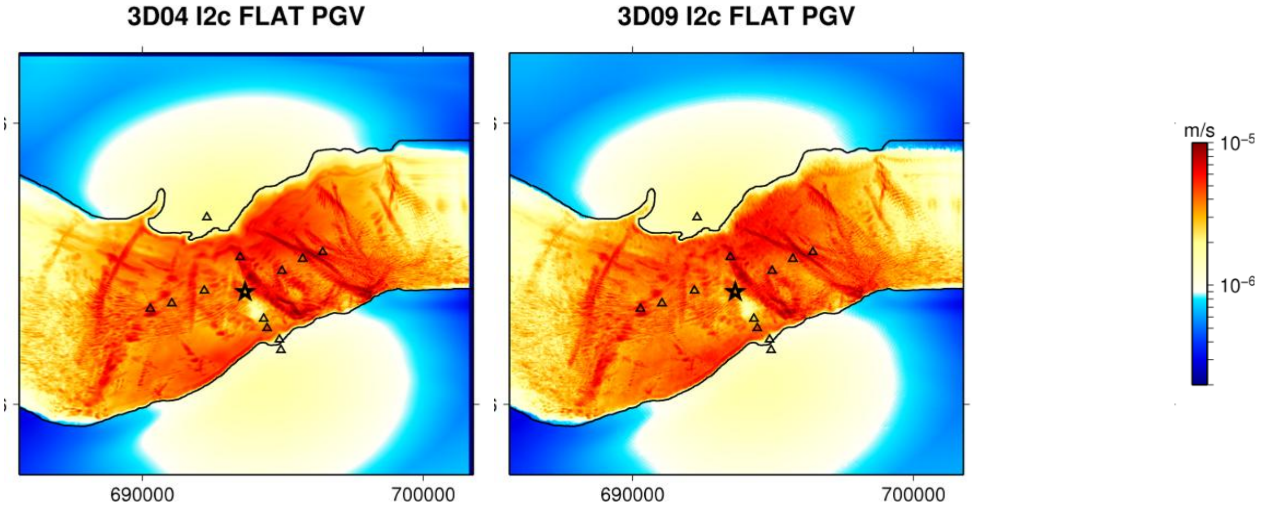


Fig. 7: Maps of peak ground velocity obtained by five different teams for the E2VP case 'I2c', which considers a purely elastic rheology in the three-layer model A of the Mygdonian basin. The triangles denote the positions of the Euroseistest array and the star is the epicenter of the point-source used for verification purposes. Note the presence of "stripes" which correspond to late interferences with surface waves diffracted off the edges and propagating towards the basin without being attenuated.

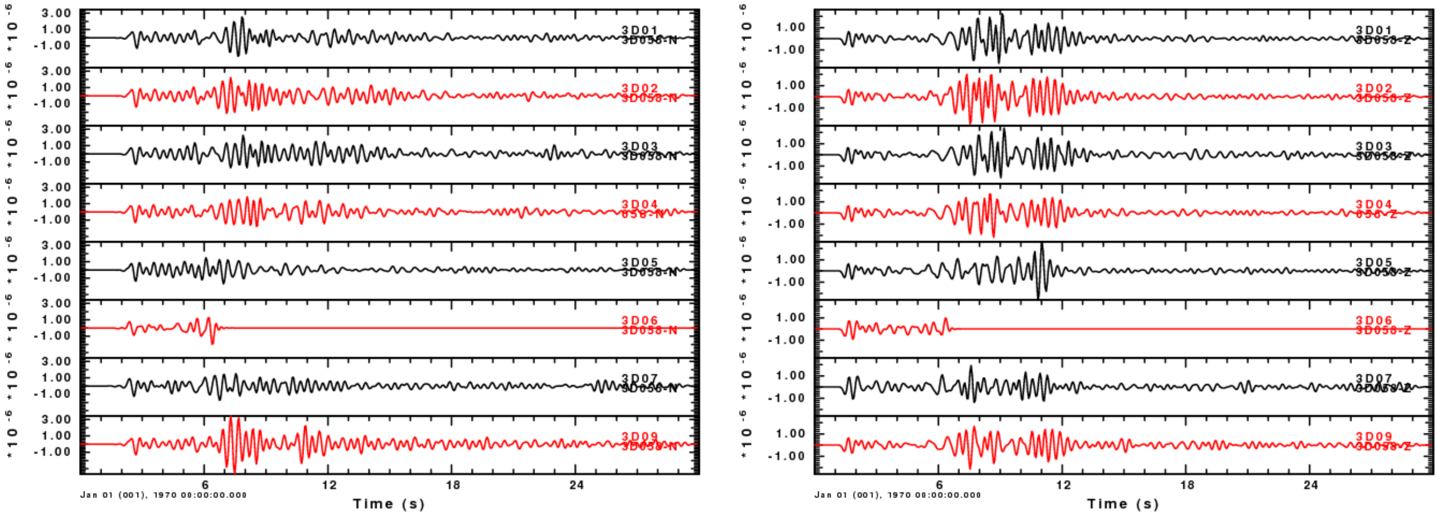


Fig. 8: N-S (left) and vertical (right) components of ground velocity at TST computed by eight different teams for the I2c case. Note the large differences (in phase and amplitude) for late arrivals (after 6 seconds), corresponding partly to surface waves diffracted off the valley edges and travelling towards the center of the basin without being attenuated.

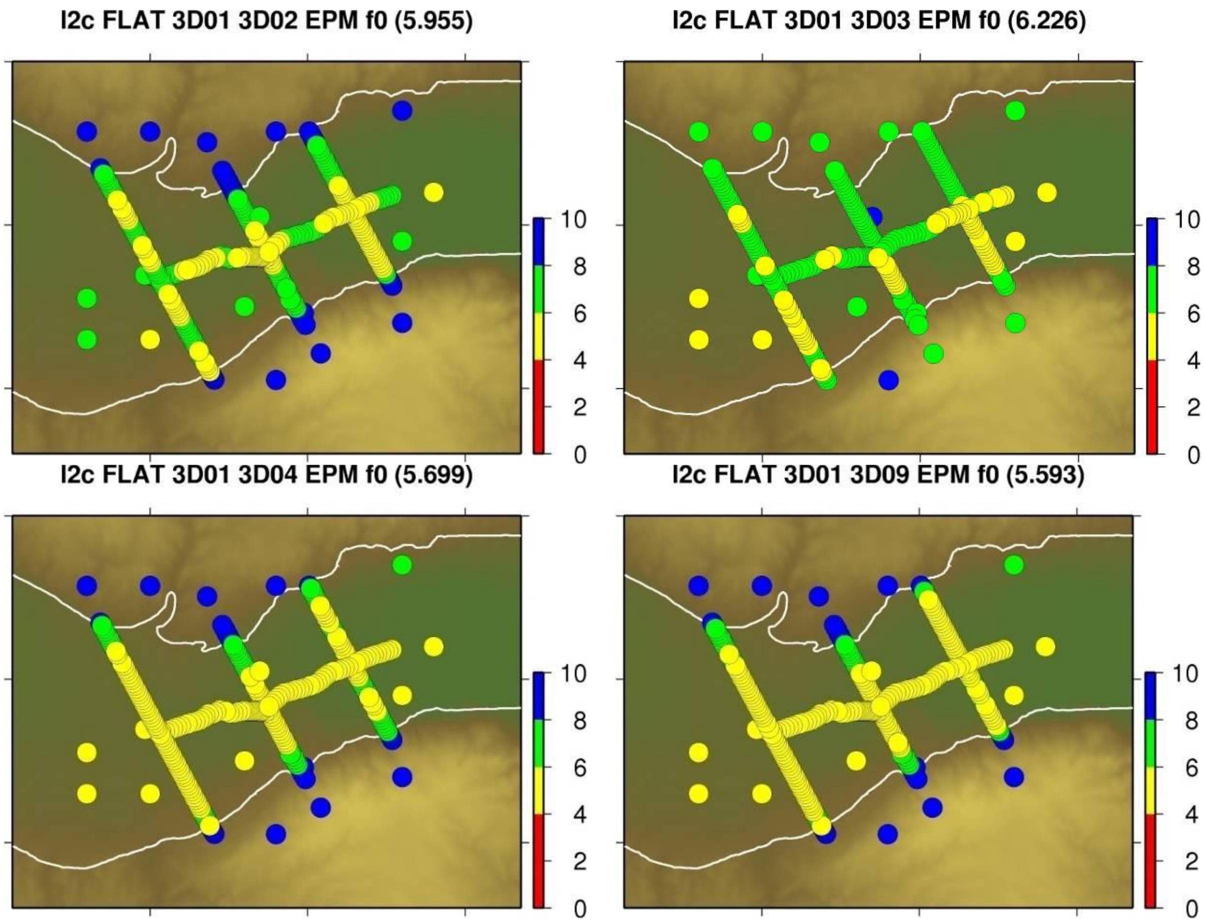


Fig. 9: Maps of goodness-of-fit computed for 5 different predictions (by teams 3D01, 3D02, 3D03, 3D04, 3D09) of the E2VP case 'I2c' which considers a purely elastic rheology in the three-layer model A of the Mygdonian basin. The first prediction 3D01 has been used as a reference for all maps but changing the reference does not affect the overall conclusion. Note the general decrease of fit between the predictions, mainly due to large differences in high-frequency late arrivals, which are undamped compared to the visco-elastic case I2b. The misfits are larger in phase than in amplitude (not shown here).

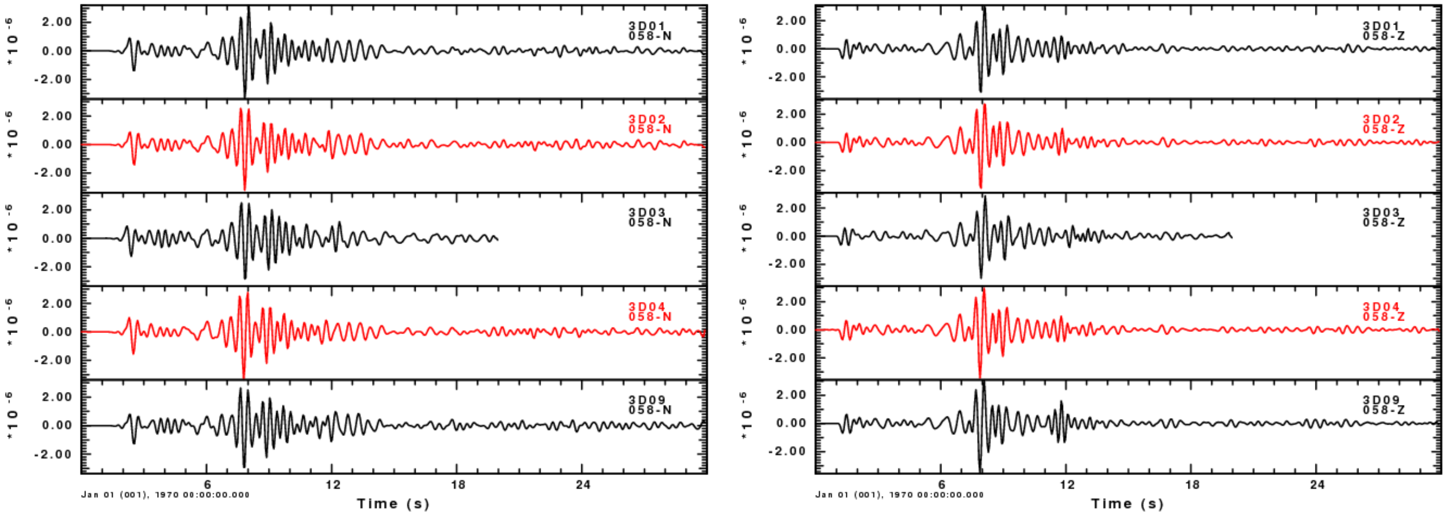


Fig. 10: N-S (left) and vertical (right) components of ground velocity at TST computed by four different teams (3D01, 3D02, 3D04, w3D09) for the IV2 case which considers a purely elastic rheology in the smooth heterogeneous model B of the Mygdonian basin. Note the excellent agreement between the predictions even for surface wave packets arriving at late times.

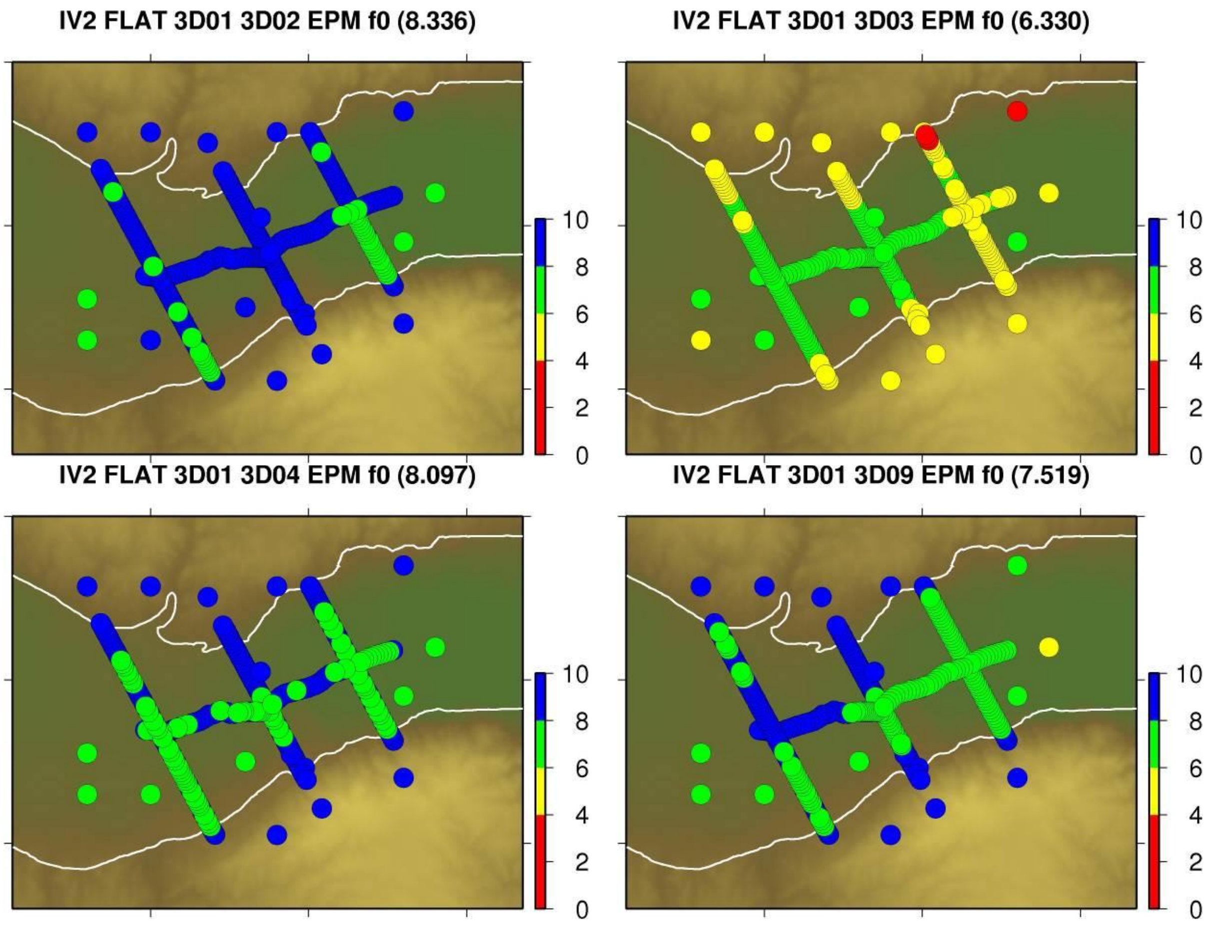


Fig. 11: Maps of goodness-of-fit computed for 5 different predictions (by teams 3D01, 3D02, 3D03, 3D04, 3D09) of the E2VP case 'IV2' which considers a purely elastic rheology in the smooth laterally heterogeneous model B of the Mygdonian basin. The first prediction 3D01 has been used as a reference for all maps. Note the very good level of fit between predictions by teams 3D01, 3D02, 3D04 and 3D09, even larger than when intrinsic damping is considered in the three-layer model A.

CONCLUSIONS

The analysis and comparison of numerical predictions for the different models within the verification part of the E2VP project confirms that, in general, the available numerical-simulation methods are not yet in a ”press-button” mode. Although an encouraging similarity among various simulations up to 4 Hz for relatively complex models has been achieved, it is very clear that a proper method and implementation of a continuous and discontinuous material heterogeneity, large Poisson's ratios, attenuation, non-reflecting boundary and free-surface condition are the key elements of a reasonable numerical simulation. The project confirms that still some important methodological questions remain to be addressed and answered before the methods are confronted with data, and highlights the necessity of a continuing methodology development of the traditional and new methods in their application to the complex realistic models.

ACKNOWLEDGMENTS

This study is conducted within the framework of the EuroseisTest Verification and Validation Project (E2VP), which is co-organized by AUTH (Aristotle University of Thessaloniki, Greece), ISTerre ("Institut des Sciences de la Terre", formerly LGIT "Laboratoire de Geophysique Interne et de Tectonophysique") of the Joseph Fourier University of Grenoble, France) and the Cashima research program (supported by the "Commissariat à l'Energie Atomique et aux Energies Alternatives"- CEA - and the "Institut Laue Langevin"- ILL -, France). We thank the participants of the project for contributing to this paper with their results: E. Priolo, P. Klin, T. Iwata, A. Iwaki, S. Aoi, F. Le Piver, C. Mariotti, J. Bielak, R. Taborda, H. Karaoglu, V. Etienne and J. Virieux.
This work was supported in part by the Slovak Research and Development Agency under the contract No. APVV-0435-07 (project OPTIMODE) and the Bilateral French-Slovak project SK-FR-0028-09. We also gratefully acknowledge the funding by the European Union through the Initial Training Network QUEST (grant agreement 238007), a Marie Curie Action within the 'People' Programme.

REFERENCES

Anderson, J. G. [2004], "Quantitative measure of the goodness-of-fit of synthetic seismograms", *13th World Conf. on Earthquake Engineering Conference Proc.*, Paper 243.

Chaljub, E., C. Cornou, and P.-Y. Bard [2006], "Numerical benchmark of 3D ground motion simulation in the valley of Grenoble, French alps", *Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, 30 August - 1 September 2006*, Paper Number: SB1, Volume 2.

Chaljub, E., P. Moczo, S. Tsuno, P.-Y. Bard, J. Kristek, M. Käser, M. Stupazzini, and M. Kristekova [2010], "Quantitative Comparison of Four Numerical Predictions of 3D Ground Motion in the Grenoble Valley, France", *Bulletin of the Seismological Society of America*, Vol. 100, No. 4, 2010, pp. 1427–1455.

Jongmans, D., K. Pitilakis, D. Demanet, D. Raptakis, J. Riepl, C. Horrent, K. Lontzetidis, and P.-Y. Bard [1998], "EURO-SEISTEST: Determination of the geological structure of the Volvi basin and validation of the basin response", *Bull. Seism. Soc. Am.*, Vol. 88 (2), pp. 473-487.

Kristeková, M., J. Kristek, P. Moczo, and S.M. Day [2006], "Misfit Criteria for Quantitative Comparison of Seismograms", *Bull. Seism. Soc. Am.* 96(5), 1836-1850, doi: 10.1785/0120060012.

Kristeková, M., J. Kristek, and P. Moczo [2009], "Time-frequency misfit and goodness-of-fit criteria for quantitative comparison of time signals", *Geophys. J. Int.* 178, 813-825, doi: 10.1111/j.1365-246X.2009.04177.x.

Manakou, M., D. Raptakis, P. Apostolidis, F. J. Chavez Garcia, and K. Pitilakis [2007], "The 3D geological structure of the Mygdonian sedimentary basin (Greece) ", *4th International Conference on Earthquake Geotechnical Engineering, June 25-28, 2007*, Paper No. 1686.

Papazachos, C. B. [1998], "Crustal *P*- and *S*-velocity structure of the Serbomacedonian Massif (Northern Greece) obtained by non-linear inversion of traveltimes", *Geophys. J. Int.*,134, 25-39, doi: 10.1046/j.1365-246x.1998.00558.x.

Pitilakis, K., G., Manos, D. Raptakis, A. Anastasiadis, K. Makra, and M. Manakou [2009], "The EUROSEISTEST Experimental Test Site in Greece", EGU General Assembly 2009, held 19-24 April, 2009 in Vienna.

Raptakis, D., F. J. Chavez-Garcia, K. Makra, and K. Pitilakis [2000], "Site effects at Euroseistest—I. Determination of the valley structure and confrontation of observations with 1D analysis", *Soil Dynamics and Earthquake Engineering*, 19, 2000, 1–22.

Raptakis, D., M. Manakou, F.J.Chavez-Garcia, K.Makra, and K. Pitilakis [2005], "3D Configuration of Mygdonian basin and preliminary estimate of its site response", *Soil Dynamics and Earthquake Engineering*, Vol. 25, pp. 871-887.

Tsuno, S., E. Chaljub, and P.-Y. Bard [2006], "Grenoble valley simulation benchmark: comparison of results and main learnings", *Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, 30 August - 1 September 2006*, Paper Number: SB2, Volume 2.