6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

Earthquake Ground Motion in the Mygdonian Basin, Greece: Latest Lessons from the E2VP Verification and Validation Project

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ABSTRACT

The Euroseistest Verification and Validation Project (E2VP) aimed at a quantitative analysis of accuracy of the current, most-advanced numerical methods applied to realistic 3D models of sedimentary basins (verification), and a quantitative comparison of the recorded and numerically-simulated ground motions (validation). The target site, located within the Mygdonian basin near Thessaloniki, Greece, has been thoroughly investigated for two decades and a detailed, realistic 3D model has been derived from geological, geophysical and geotechnical investigations, while a dedicated instrumentation provided a significant number of surface and borehole recordings. Verification and validation tests up to a frequency of 4 Hz, much beyond the 0.7 Hz fundamental frequency, have been performed for a set of local, small to moderate magnitude events. For careful and accurate enough computations, the model-to-model differences are smaller than the model-to-observations differences, controlled by uncertainties primarily in the crustal propagation model and source properties, and secondarily in the shallow structure.

Introduction

The rapid development of the simulation codes and computational facilities made the use of numerical-simulation tools for predicting seismic ground motion to be considered a valid option, especially for poorly instrumented or moderate-seismicity countries lacking representative earthquake recordings. However, such an approach requires a careful evaluation of the actual performance of the 3D simulation codes. This issue has been the topic of a few international studies, including blind prediction tests or comparative exercises, focused on various sites.

It started with the Turkey Flat, California (Cramer 1995), and Ashigara Valley, Japan (e.g., Bard 1992), blind tests focusing on effects of surface sediments, the results of which were presented during the first ESG conference in Odawara (1992). It was followed by the more comprehensive

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comparison exercises on the Osaka/Kobe basin area in Japan (Kawase and Iwata, 1998), and on the Southern California area within the SCEC framework (Day et al. 2001, 2003, 2005; Bielak et al. 2010), which also included the effects of extended sources and regional propagation in the low frequency range (f < 1 Hz). Each of these cases had its own specificities (for instance, very low frequencies for the Osaka and SCEC exercises). A request issued in late 2003 by the French Nuclear Authority (ASN) to perform a 3D, NL simulation of site response for specific sites, was the initial impetus for a dedicated R&D program funded by CEA Cadarache and ILL (Laue-Langevin Institute, an international research centre on neutron science based in Grenoble, and operating the most intense neutron source on Earth). It started with an international benchmarking exercise on the Grenoble basin (Chaljub et al., 2009; Tsuno et al., 2009; Chaljub et al., 2010), and was further deepened through the Euroseistest Verification and Validation Project (E2VP). Considering the lessons of the ESG2006 Grenoble benchmark, the E2VP project was launched in 2007 with two main objectives: (a) a quantitative analysis of accuracy of the current, most-advanced numerical methods applied to realistic 3D models of sedimentary basins (verification); (b) a quantitative comparison of the recorded and numerically-simulated ground motions (validation). The selected target site was an extensional graben located in the Mygdonian basin near Thessaloniki, Greece (Figure 1): a detailed, realistic 3D model of the medium had already been derived from a comprehensive set of geological, geophysical and geotechnical investigations, and the site instrumentation installed for about two decades provided a significant number of surface and borehole recordings.

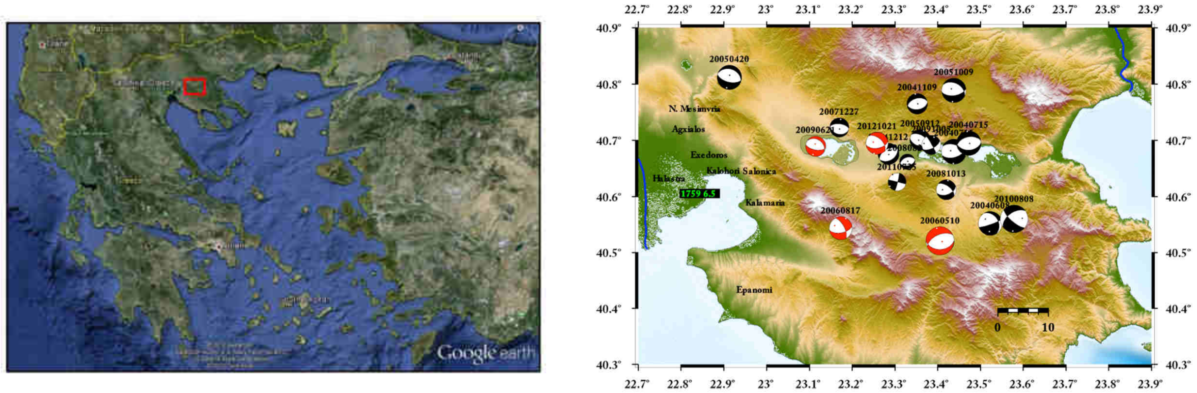

Figure 1 : Location of the Euroseistest site in between the Volvi and Langhada lakes in NorthEastern Greece, together with the location and focal mechanisms of the 19 events used for the validation phase.

This paper is intended to present a concise overview of the work accomplished since the launching of the E2VP project. This project has been organized in two phases, E2VP1 (2007-2010) and E2VP2 (2012 – 2014). As the main results of the first phase are reported in two recent papers (Chaljub et al., 2015; Maufroy et al., 2015), the present article puts more emphasis on the latest results, while reminding the overall process.

Moreover, this 3DL benchmarking exercise has been complemented with two other similar exercises, focusing on the comparison and the assessment of uncertainties associated with a) 1D non-linear simulation codes and b) non-invasive and invasive as well methods used to derive the seismic velocity profile or seismic parameters within the soil. As these exercises are presented in larger detail elsewhere, only their overall characteristics will be summarized here.

From E2VP1 to E2VP2: the Main Steps

Table 1 : Summary of main learnings from E2VP Phase 1.

Main lessons about verification and validation studies	• Careful verification requires time and often to "go back to basics", while careful validation requires high quality data, i.e., including rich and high quality metadata. • No ground-motion simulation code accounting for wave propagation in complex media can be considered as press-button, neither in the linear, 3D domain, nor in the non-linear 2D - or even 1D - cases. The most common case is that, without iterations and cross-checking, different codes provide significantly different results when applied to the same case study. • Too fast applications of existing codes may yield VERY wrong ground-motion estimates, potentially resulting in raising mistrust in end-users. • Some codes currently used in engineering applications would deserve some significant improvements, or strong warnings on stringent validity limits, while even state-of-the-art codes (predominantly in the "academic" field) deserve constant upgrading.
Main recommendations for a wise use of numerical simulation codes	• One should never be satisfied with only one computation from one single team, but should request several teams (at least two) with different numerical schemes to perform parallel computations of the same case. Results should be considered as reliable only if they agree beyond some quantitative goodness-of-fit threshold. • These goodness-of-fit criteria should definitely be agreed upon by the engineering community in order to reach an objective of transparent quantitative comparison, which should replace sentences such as "one can see the very good agreement on the figure"… • In the long run, it would be very valuable to assign a specific "quality label" to numerical codes and teams that did accept to run some of the now existing "canonical" cases with their own numerical code, which are freely available on web pages (http://www.sismowine.org/). Maintaining this kind of internet facility in the long run will be beneficial for the whole community. • External peer reviews are always useful in assessing the quality of results derived from highly sophisticated numerical codes. • 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.

In short, the basic ideas of the project were, on the example of the Euroseistest site, to (1) quantify the "distance" between results of independent models and numerical schemes, and as much as possible to reduce them to the lowest possible level through a careful understanding of the differences; and (2) to compare this "cross-computation distance" to their "distance" to actual measured data for as many real events as possible. The first phase E2VP1 (2007-2010) included a comprehensive series of cross-model verifications, with side computations on canonical models aimed at investigating the accuracy of numerical schemes under very stringent conditions – as detailed in Chaljub et al. (2015) -, and a first round of comparison between observations and simulations for a small number (6) of local events, as reported in Maufroy et al. (2015). The computations were performed up to a frequency of 4 Hz: this remains limited compared to the frequency range of interest in earthquake engineering, but this is higher than all previous similar exercises. It led to a number of lessons and recommendations on the use of the numerical-simulation approach, as listed in Table 1, but it also led to the identification of a few further issues that needed to be addressed in a second phase.

3D linear modeling

The main focus and success of E2VP1 was thus on the use of 3D, linear simulation. The main results are summarized in Figure 2. The code-to-code differences could be drastically reduced by the consideration of dedicated canonical models and stringent goodness-of-fit criteria comparing the waveforms in the time-frequency domain (Kristekova et al., 2009), leading to significant improvements in the numerical schemes (Chaljub et al., 2015). The simulation-to-observation differences could be quantified for only a limited number of events (6) because of the moderate seismicity and the limited extension of the 3D model. For those events, the simulated and observed waveforms remain so different that another metrics was adopted to quantify their distance, on the basis of "engineering" parameters. After a careful analysis of the original Anderson's criteria, five parameters (C1 to C5) were selected: pga, the spectral acceleration at intermediate and low frequencies (averages in the [1.5 – 3 Hz] and [0.375 – 0.75 Hz] ranges, respectively), an "energy" indicator (cumulative absolute velocity, CAV), and the Trifunac-Brady duration (RSD). The misfit was computed for each parameter in terms of relative increase or decrease compared to the measured values. Figure 2indicates that such an "engineering" distance is around 10-25 % between different simulations, while it is in the range 40% to 80% between observations and simulations. These numbers do vary depending on the considered receiver (rock or valley), on the considered event, and on the engineering parameter, but the overall trends are robust, and emphasize both the usefulness of the prior verification part and the difficulty to obtain satisfactory, unbiased numerical predictions of ground motion.

Only very few events could be used for the validation: this is a typical situation for moderate/weak seismicity areas. It was therefore considered useful to include more events, from 6 to 19, in the second phase of the validation exercise (those shown in Figure 1), which led to increase the size of the 3D model, as illustrated in Figure 3a. In addition, the significant distance between observations and simulations was shown to be partly due to uncertainties or errors in source parameters: the misfits on the sole site response component were found lower than those on absolute motion (Maufroy et al., 2015). It was thus decided first to improve as much as possible the location of the 19 selected events, and second to investigate through numerical simulation how the uncertainties in source parameters map on the variability of site-specific ground motion from local earthquakes.

Non-linear (NL) modeling

The first phase also included a comparison of 2D, NL simulations on a NS cross-section of Euroseistest. This attempt for a verification of NL codes proved however to be a failure, as code-to-code differences were too large with too many and too poorly identified origins. Yet, it is obvious that NL simulation codes deserve similar verification and validation efforts, especially as they are much more often used in engineering practice than 3D, linear simulation codes. The E2VP1 failure allowed to issue three main recommendations for future benchmarking exercises: a) NL verification should be performed on the simplest possible cases (1D soil columns); b) it should be performed on already instrumented sites having recorded large acceleration levels; c) it should be associated with careful in-situ surveys and lab tests designed in tight connection with the needs of the rheological models implemented in the various NL codes.

The second phase, E2VP2 (2012-2014) was thus designed to answer some of the identified issues related with 3D linear modeling, while the PRENOLIN project (Régnier et al., 2015a, b) was designed to start answering the issues about NL modeling according to the E2VP1 lessons.

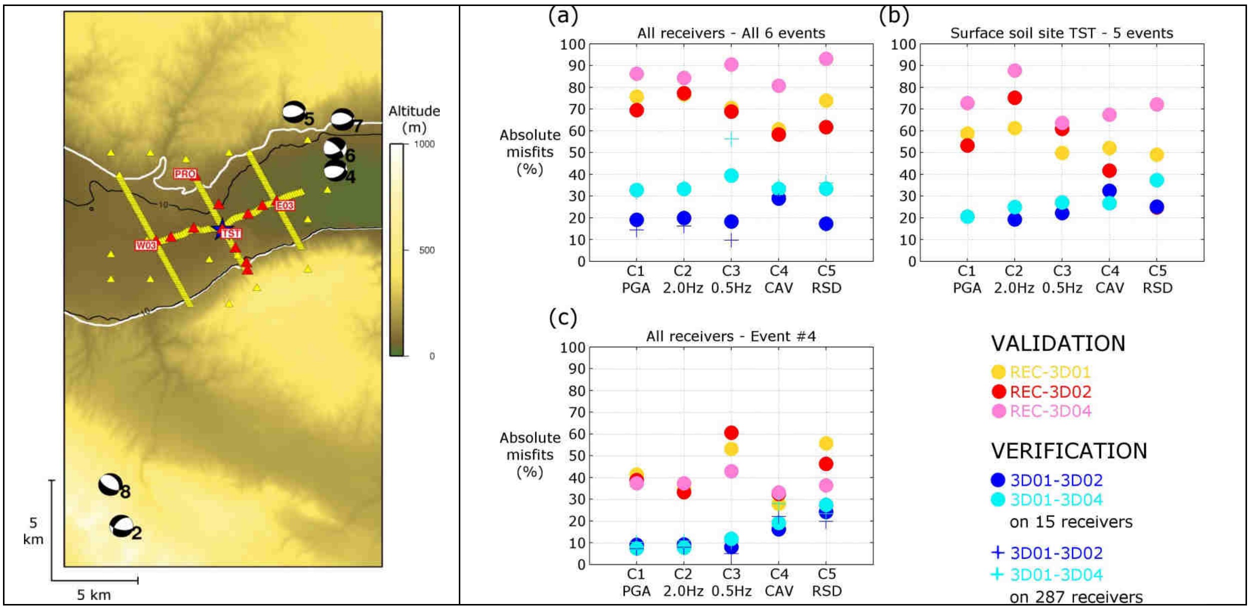

Figure 2 : Summary of horizontal absolute misfits obtained on the E2VP1 evaluation parameters C1 to C5 (see text for their definition) for the verification and validation exercises considering different configurations. Left: localization and focal mechanism of the 6 validation events (beachballs) and of the receivers used for the comparison (red and yellow triangles). Right : (a) average for the 6 selected events at all receivers; (b) average for the 5 events recorded at the central soil site TST; (c) average for the biggest event #4 at all receivers. Synthetics-to-synthetics misfits (verification, blue tones dots) are compared to recordings-to-synthetics misfits (validation, warm tones dots). The verification misfits are computed for either the real array of 15 surface receivers (red triangles, solid circles) or the complete virtual array of 287 receivers (yellow triangles, crosses). A single value per array is obtained by calculating the weighted average of the absolute misfits over the considered receivers (with weights proportional to the value of the corresponding ground-motion parameter).

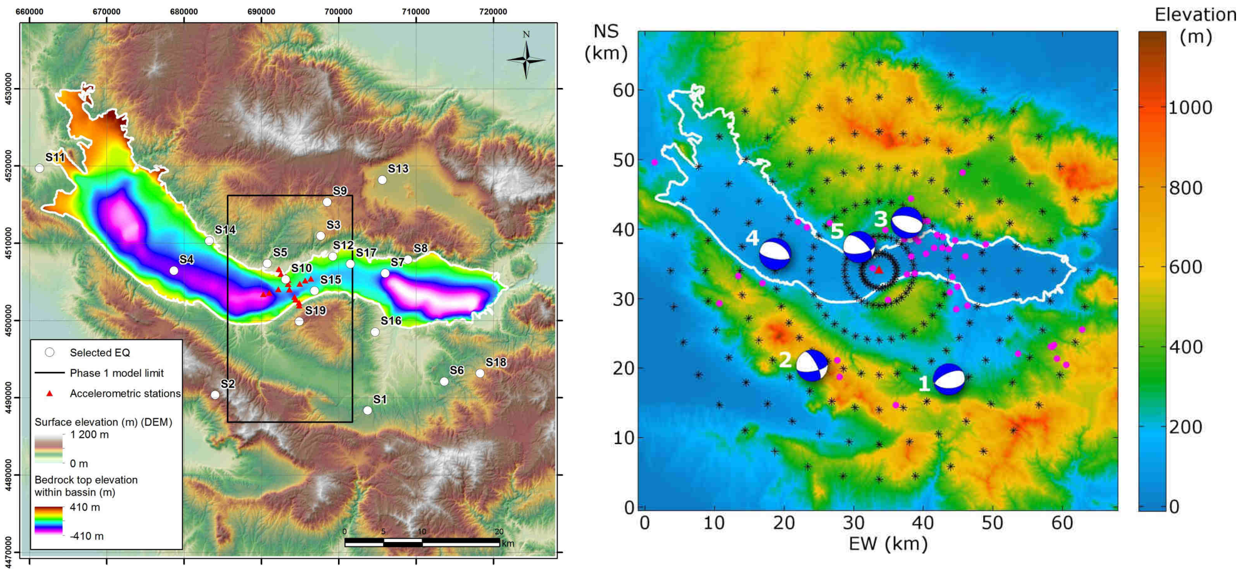

Figure 3: Left, a): Map of the whole model used for E2VP phase 2 modeling (box of 69 x 69 km), with the location of the area of the “phase 1” modeling box, accelerometric stations, modeled earthquakes, DEM et elevation of the top of the bedrock within the basin. Right, b): Location of the "virtual" seismic sources considered in the numerical study. The response of the Mygdonian basin (bold white line) is computed for five real events (beachballs) and 1260 sources (black circular crosses) at the central soil site TST indicated by the red triangle. The real catalog of local events is also shown by the magenta dots.

Example Results of the Second Phase E2VP2

E2VP2 scope and contents

The second phase of E2VP thus included the following steps:

- Improvement of source parameters for an increased number of local events (19)
- Update and extension of the 3D model of the whole Mygdonian basin using all available information (geology, hydrological and geotechnical boreholes, geophysical surveys: seismics, electric resistivity, magneto-telluric, microtremor H/V) to constrain the bedrock geometry, the sedimentary thickness and the seismic velocity. The new model is characterized by the absence of velocity jumps within the sediments, with velocity gradient from 130m/s at surface to 800 m/s at the bottom.
- Update of the 3D simulation model (Spectral Element method) with improved meshing and velocity homogeneization strategy, including surface topography and intrinsic attenuation. The meshing was tuned for a maximum frequency of 4 Hz and the associated wavelengths.
- Ground motion simulations for various sets of events and receivers:
    - The validation set consisting of the 19 selected events, with their actual, improved source parameters (magnitude range : 2.7 – 4.6; distance range : 0 – 30 km), computed at the 15 receivers

- A second set corresponding to 5 real events, taking into account the uncertainty in source location : 125 hypocentral positions were considered for each of the 5 events, by shifting the actual hypocenter by ± 1 km and ± 2 km in each X, Y and Z directions
- A large set of 7*36*5 =1260 virtual events arranged in 7 concentric circles from 2.5 to 30 km, 36 back-azimuths (10° step) and at 5 different depths from 1 to 15 km. The corresponding focal mechanisms were randomly generated following a Gaussian distribution around the "average" normal faulting parameters in the Mygdonian basin area : strike = 86°±18°, dip = 52°±15°, rake = -101°±51° The objective was to investigate the sensitivity of the site response to the source location in a fully 3D environment

The two latter sets were computed for the 15 receivers using the reciprocity theorem. The hypocenter location of the two latter sets are displayed in Figure 3b.

New validation results

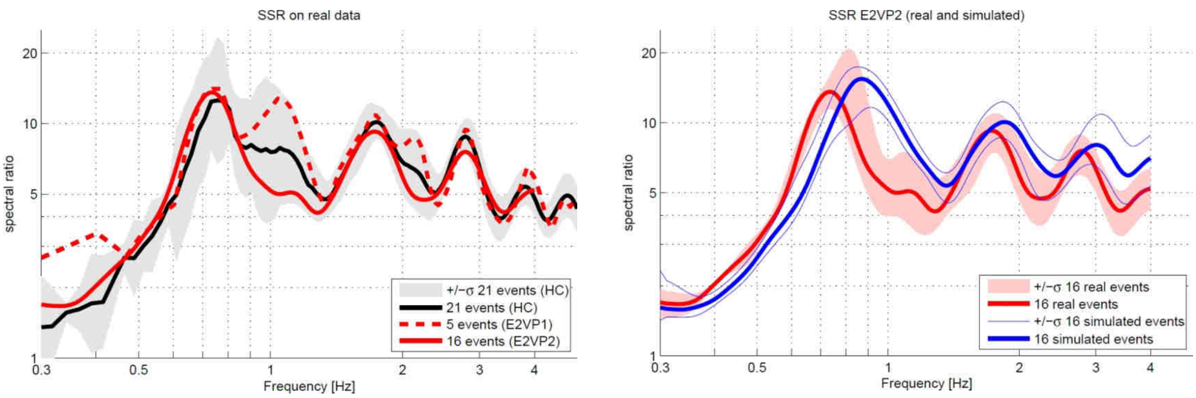

Figure 4: Left : Median of SSR (Standard Spectral Ratios) at TST0 with TST5 as the reference station, computed for the actual recordings of 21 events (black line, associated variability shown in gray), for the 5 events selected in E2VP1 (dashed red line) and for 16 events selected in E2VP2 (solid red line), that were recorded both at TST0 and TST5. Right: The same for the E2VP2 simulations (bold blue line, associated variability shown by thin blue lines) with comparison for the recordings of the same events (bold red line, associated variability in light red).

The comparison for the 19, relocated events has been found in average slightly improved for rock sites, and slightly deteriorated within the Mygdonian basin, with an overall trend for an overestimation. Results are summarized in Table 2 and Figure 4 for the case of the central site TST, in terms of absolute motion and relative TST0/TST5 amplification. It is found once again that the sole site response ("hybrids") is better estimated: the "hybrids" correspond to synthetics obtained with convolving the downhole actual recording ("TST5") with the Fourier transfer function TST0/TST5 computed for the same event. The significant overestimation in terms of signal amplitude (C1-C3, C4) thus comes mainly for the overestimation of the rock motion, also associated with an underestimation of signal duration (C5) : both may come from the absence of scattering in the considered crustal model. When considering all the real receivers, the overall E2VP2 misfit values range between +50 and +150%, to be compared with the +40-80 % of E2VP1 (on only 6 events), while the "site-response only" misfits now range around +20%, while they were around -40% for E2VP1. In short, the new validation phase highlighted once again a strong sensitivity of the validation scores to the source parameters and the associated uncertainties, and the importance of a higher number of rock sites (more than 1 or 2) for a proper "calibration" of the reference motion. The modifications in the basin model have slightly improved the site response estimate

Table 2: Values of average horizontal misfits on the five engineering parameters Ci between the actual recordings at central soil site TST0 and their numerical predictions. Values in % evaluate the predictions by full synthetics vs. hybrid time histories (i.e. site response only).

	FULL SYN.	HYBRIDS	FULL SYN.	HYBRIDS	FULL SYN.	HYBRIDS	FULL SYN.	HYBRIDS	FULL SYN.	HYBRIDS
	C1	**C1**	**C2**	**C2**	**C3**	**C3**	**C4**	**C4**	**C5**	**C5**
AVERAGE	143	19	129	16	45	-22	107	50	-69	27

Findings from the sensitivity study

Given the consistent indications of E2VP phases 1 and 2, the first objective was to evaluate the sensitivity of both the absolute motion and the site response to hypocentral uncertainties: the ± 2 km variability in each X, Y and Z direction is considered a reasonable and probably minimum estimate of the actual location uncertainty. The results are displayed on Figure 5 for the TST0/TST5 spectral ratios and the 5 considered events shown in Figure 3b. Significant differences appear between the 5 events: the largest variability is found for events S1 and S5, while it is very limited for events S2, S3 and S4. Event S5 turns out to be the shortest epicentral distance to the receiver (apicentral distance 4.5 km, a depth of 11 km), while event S1 is the most distant source, but the most shallow (depth = 5 km, epicentral distance = 18.5 km). Events S2, S3 and S4 have depths around 10km and epicentral distance in the range 8 – 16 km. Validation exercises are thus very difficult for very close events or very shallow, local events, because of the larger sensitivity of the site response in such cases (highly variable incidence and azimuth angles).

The results of the comprehensive set of 1260 virtual sources allowed to further quantify the variability of the site amplification and to compare it with the site specific residual and the associated within-event, single site variability as derived with a GMPE approach using the available catalog (a total of 52 events). As displayed in Figure 6, a preliminary analysis conducted for the central TST station confirms the slight, mean overestimation of the predicted amplification, while the predicted variability (i.e., within event, single site sigma) is significantly smaller than the empirically estimated one, especially around 1 Hz, where the observed response is quite complex and highly variable (see also Figure 4a). This very preliminary result, to be completed in the next months for other sites, does show that carefully verified simulation codes can be used not only to perform deterministic predictions of the ground motion for given scenarios, but also to investigate the structure of the aleatory variability (between-event / within event, single site components).

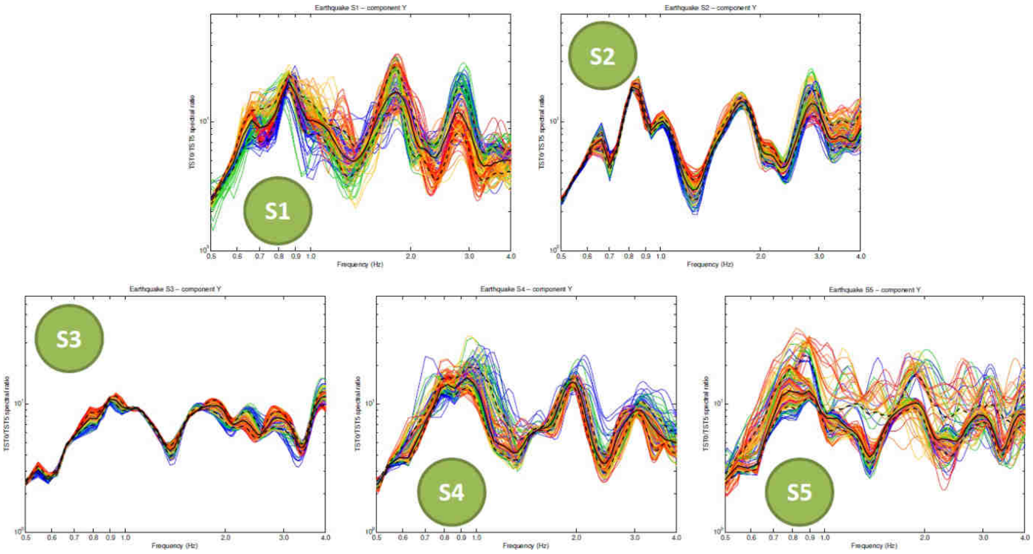

Figure 5: Standard Spectral Ratio TST0 / TST5, computed for the 5 selected real events shown by beachballs in Figure 3b. The variability of the spectral ratio due to hypocenter uncertainty is indicated by the colored lines, from blue for more shallow hypocenters to red for deeper hypocenters. The median ratio is given in each panel by the solid black line, surrounded by the upper (84%) and lower (16%) percentiles as dashed lines.

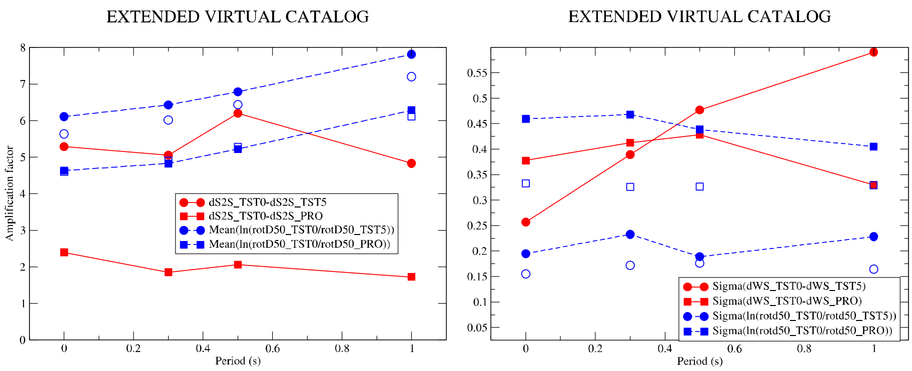

Figure 6 : Comparison of the mean (left) and standard deviation (right) of the observed (red) and simulated (blue) amplification factors at the surface station TST0. The reference station is either the downhole site TST5 (circles) or the outcropping rock site PRO (squares). The filled blue symbols correspond to the comprehensive set of 1260 virtual sources, the red symbols to the real catalog with 52 events, and the open blue symbols to the same simulated 52 events.

Conclusions

The main findings of E2VP1 were confirmed in E2VP2, for both verification and validation aspects:

- The use of numerical simulation codes, even after extremely careful testing and even with the most sophisticated and up-to-date numerical schemes, can still be subject to errors (especially related to the "human factor"): careful use and cross-checking still proves to be mandatory.
- There is no single numerical-modelling method that can be considered the best in terms of accuracy and computational efficiency for all structure-wavefield configurations.
- The very detailed investigations on canonical models allowed identifying the origin of inaccuracies (type of seismic waves vs velocity model smoothness). We thus go on with recommending that any numerical method and code that is intended to be applied for numerical prediction of earthquake ground motion in engineering projects, should be verified through stringent models that would make it possible to test the most important aspects of accuracy. The canonical cases developed within E2VP, and made freely available to the seismological community (http://www.sismowine.org), can serve this purpose.

Most of the new work achieved during E2VP2 was related to validation. The feasibility of such a validation up to the frequency limit considered here (4 Hz) is still a real challenge:

- The site response proves to be very sensitive to the exact position of the source – especially its depth and back azimuth – for very close events and for local, shallow events: as it is unrealistic to expect a precision on localization smaller than 2 km (especially for the depth), it is not recommended to select such events for validation.
- The distance between observations and numerical predictions remain significantly larger than the distance between carefully selected, up-to-date, and carefully implemented numerical simulation codes. For the prediction of ground motion for expected events with a priori defined source characteristics, the numerical-simulation approach is fully legitimate in the toolbox for site-specific ground-motion estimation.
- In addition, the predictions-to-observations differences are significantly lower when considering only the site amplification, especially when the reference is at depth within a vertical array. This emphasizes the added value of "hybrid" approaches made possible by the availability of down-hole recordings and the invaluable usefulness of in-situ recordings: it seems today very difficult to predict site effects in a complex geometry context with only geological, geophysical and geotechnical information.
- A comprehensive sensitivity study also showed also that, beyond the deterministic prediction of ground motion for a given earthquake scenario, numerical simulation proves also to be a useful tool for investigating the structure of the aleatory variability.

Acknowledgements

We thank A. Kiratzi, Z. Roumelioti from AUTH for their efficient help in relocating the events, and O. Ktenidou for her contribution about aleatory variability. The funding of this project is provided by CEA within the framework of the CASHIMA and SIGMA projects.

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