GENERATING BROADBAND GROUND MOTIONS FROM PHYSICS-BASED NUMERICAL SIMULATIONS USING ARTIFICIAL NEURAL NETWORKS

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ABSTRACT

Physics-based numerical simulations (PBS) are fast becoming a more and more reliable tool for earthquake ground motion prediction for those conditions, such as near-source and complex geologies, that are not well documented by strong motion records. However, the range of frequencies that PBS can encompass is still limited, because both of computational restraints and of insufficient detail of the geological model description at small spatial scales. In this paper an update of a technique that was recently introduced to overcome such limitation is presented. The technique relies on Artificial Neural Networks (ANN) in order to provide a correlation between long and short period spectral ordinates trained on strong motion records. The ANN is then applied to the PBS results, in order to extend their range of validity to the short period range. Finally, an application of this technique is shown, with reference to PBS of the Kumamoto earthquake sequence, carried out by the SPEED spectral element code in the framework of the ESG6 blind prediction test.

Keywords: Physics-based numerical simulations of earthquake ground motion; Broadband ground motions; Artificial neural networks; Kumamoto seismic sequence.

INTRODUCTION

Physics-based numerical simulations (PBS) rely on the rigorous numerical solution of the seismic wave propagation problem, based on 3D models both of the seismic source (either kinematic or dynamic) and of the source-to-site propagation path. However, the accuracy of the PBS is limited to the long period range $T \geq T^*$, with T^* being typically in the range of 0.5 - 1 s, mainly due to the lack of knowledge about the Earth crust and earthquake rupture process at short-wavelength and partially due to the computational cost of large and fine grids.
Several hybrid techniques were developed in order to use results from PBS for low frequencies, mostly relying on stochastic approaches to generate high frequency content of waveforms (Graves and Pitarka, 2010). Some of these approaches can be found in SCEC broadband platform (Maechling et al., 2015). However, such hybrid techniques may not produce simulated ground motions having the proper spatial correlation and coherence at high-frequencies, that is a fundamental requirement if PBS results are used for seismic risk evaluations at urban scale, or as input motions for spatially extended structures.
For these reasons, Paolucci et al. (2018) developed an approach to produce broadband ground motions from PBS, denoted by ANN2BB, that was found to overcome the previous limitations and to produce accelerograms with the proper correlation between short and long period components as well as with a spatial variability reasonably approaching that of recorded ground motions. The proposed ANN2BB procedure is summarized below (see Figure 1):

(1) an artificial neural network (ANN) is trained based on a strong motion records dataset to predict short period spectral ordinates ($T<T^*$) based on long period ones ($T \geq T^*$), T^* being the minimum period of the numerical model. The recording dataset may be selected by the user among the ones available in the literature, such as SIMBAD (Smerzini et al. 2014) or NGA-West 2 (Ancheta et al. 2013). Separate ANNs are trained on the geometric mean of the horizontal components and on the vertical components to allow the prediction of three-component ground motions;

(2) for each simulated waveform, a response spectrum is computed (ANN2BB spectrum), the spectral ordinates of which, for T≥T*, coincide with the simulated ones, while, for T<T*, they are obtained from the ANN (for both horizontal and vertical components);
(3) the simulated low-frequency waveform is enriched in the high-frequency by a stochastic contribution, characterized by the magnitude and source-to-site distance of the scenario earthquake under consideration;
(4) the hybrid PBS-stochastic waveform is iteratively modified in the frequency domain, with no phase change, until its response spectrum matches the target ANN2BB spectrum.

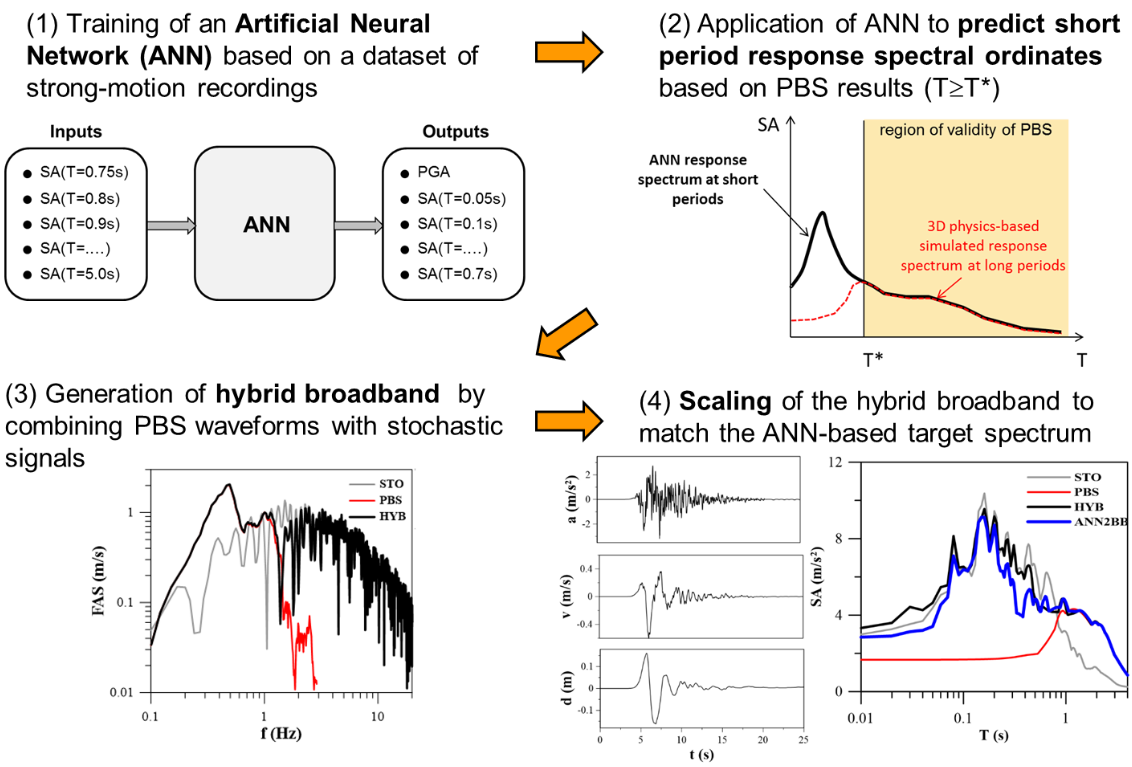

Figure 1. Flowchart of the ANN2BB approach for the generation of BB waveforms from physics-based numerical simulations.

UPDATE OF THE ANN2BB PROCEDURE

With respect to the procedure originally proposed by Paolucci et al. (2018), a revision of steps (3) and (4) above was made necessary to make the ANN2BB approach suitable for semi-automatic application to large sets of PBS results. The main revision to the procedure is that the iterative scaling of the hybrid stochastic-PBS waveform in the frequency domain is not done any more (step 4). Instead, the stochastic ground motion is linearly scaled in the response spectrum domain to fit the target ANN spectrum at short periods.

A weight vector is used to control the fit to the target ANN2BB spectrum. The recommended weight vector is to assign weight of w_i=2 to the spectrum ordinate at the merging period (which is set to be equal to the PBS spectrum), w_i=1 to spectrum ordinates at periods smaller than the merging period (i.e., high-frequency content), and w_i=0 for periods larger than the merging frequency (as the PBS spectrum is used for this range). The weight vector is normalized as $\sum w_i$=1. Misfit of the candidate ground motion to the target spectrum is calculated based on the following equation:

$$r^{\,nsim} = \sum_{i=1}^{N_{IM_i}} w_i \left[\frac{lnIM_i^{nsim} - lnIM_i^{Target}}{\sigma_{lnIM_i|Rup}}\right]^2 \qquad (1)$$

where IM_i^{nsim} is the i^{th} intensity measure (IM) value of the $nsim^{th}$ random realization; IM_i^{Target} is the i^{th} IM value of the target; $\sigma_{lnIM_i|Rup}$ is the standard deviation of $lnIM_i$; w_i is the weight-vector component emphasizing the importance of the IM_i; and r_m^{nsim} is the residual of the $nsim^{th}$ prospective ground motion. In order to rank the appropriateness of a prospective ground motion and identify the most suitable ground motion, the calculated residual for each prospective ground motion is minimized with respect to the applied amplitude scale factor. The prospective ground motion with the least misfit is finally chosen.
To summarize, the steps (3) and (4) of revised ANN2BB procedure are as follows (see Figure 2):

(3)* the stochastic ground motion is linearly scaled in the response spectrum domain to fit the target ANN2BB spectrum at short periods;
(4)* the scaled stochastic waveforms and low-frequency PBS are combined in the frequency domain based on a standard hybrid approach.

The comparison of results between the original and revised ANN2BB procedures have pointed out two main improvements:
a- Distinct troughs in the acceleration Fourier amplitude in the original code results that may occur (for some cases) due to the modification of the candidate ground motions in the frequency domain to fit the ANN target is resolved. As a matter of fact, the new code applies amplitude scaling in the response spectrum domain which does not change the initial frequency content of the simulated high-frequency ground motion.
b- The original code (for most cases) results in an excessive large high-frequency content due to the frequency modifications applied for the purpose of closer fit for the target peak ground acceleration (PGA). The amplitude scaling in the response spectrum domain ensures an appropriate fit to the target ANN (hence no frequency domain scaling is needed).

Such improvements of the ANN2BB procedure were implemented in the post-processing tools of SPEED (Mazzieri et al., 2013; https://speed.mox.polimi.it), a numerical code based on spectral elements for elastodynamics, that was successfully applied to a number of validation case studies, including earthquakes in Italy (Smerzini and Villani, 2012; Paolucci et al., 2015; Paolucci et al., 2016; Evangelista et al., 2017; Ozcebe et al., 2019), in Greece (Smerzini and Pitilakis, 2017), in New Zealand (Guidotti et al., 2011), induced seismicity in the Netherlands (Paolucci et al., 2021) and seismic hazard and risk assessment in Istanbul (Infantino et al., 2020; Stupazzini et al., 2021). Thanks to the implementation of the improved ANN2BB procedure, the SPEED post-processing workflow was made capable of conducting broadband ground motion generation for a large number of receivers with no manual interventions, facilitating time-efficient yet reliable outputs.

APPLICATION OF THE ANN2BB PROCEDURE TO PHYSICS BASED SIMULATIONS OF THE 2016 KUMAMOTO EARTHQUAKE SEQUENCE

The ANN2BB procedure was applied to the PBS of the 2016 Kumamoto earthquake sequence, performed using SPEED (Sangaraju et al., 2021). Figure 3 shows the typical output obtained by the procedure at 4 KiK-net borehole (BH) stations considered as a benchmark for the PBS, for the M_w7.0 mainshock. We focused on BH stations alone because, as explained by Sangaraju et al. (2021), the 3D modelling detail was not sufficient to capture the detail of the shallow surface layers. In such shallow layers, standard 1D ground response analyses (by DEEPSOIL) were carried out considering as vertical plane wave the broadband input motion generated by the ANN2BB approach starting from SPEED simulations.
Note in Figure 3 that PBS results predict well the recorded fling-step ground motions at KMMH16, with about 1 m permanent displacement, as well as the pulse-like feature of the velocity time history. It is clear from the figure that the ANN2BB procedure does not affect the low-frequency portion of ground motion, while it significantly enriches the high-frequency portion.

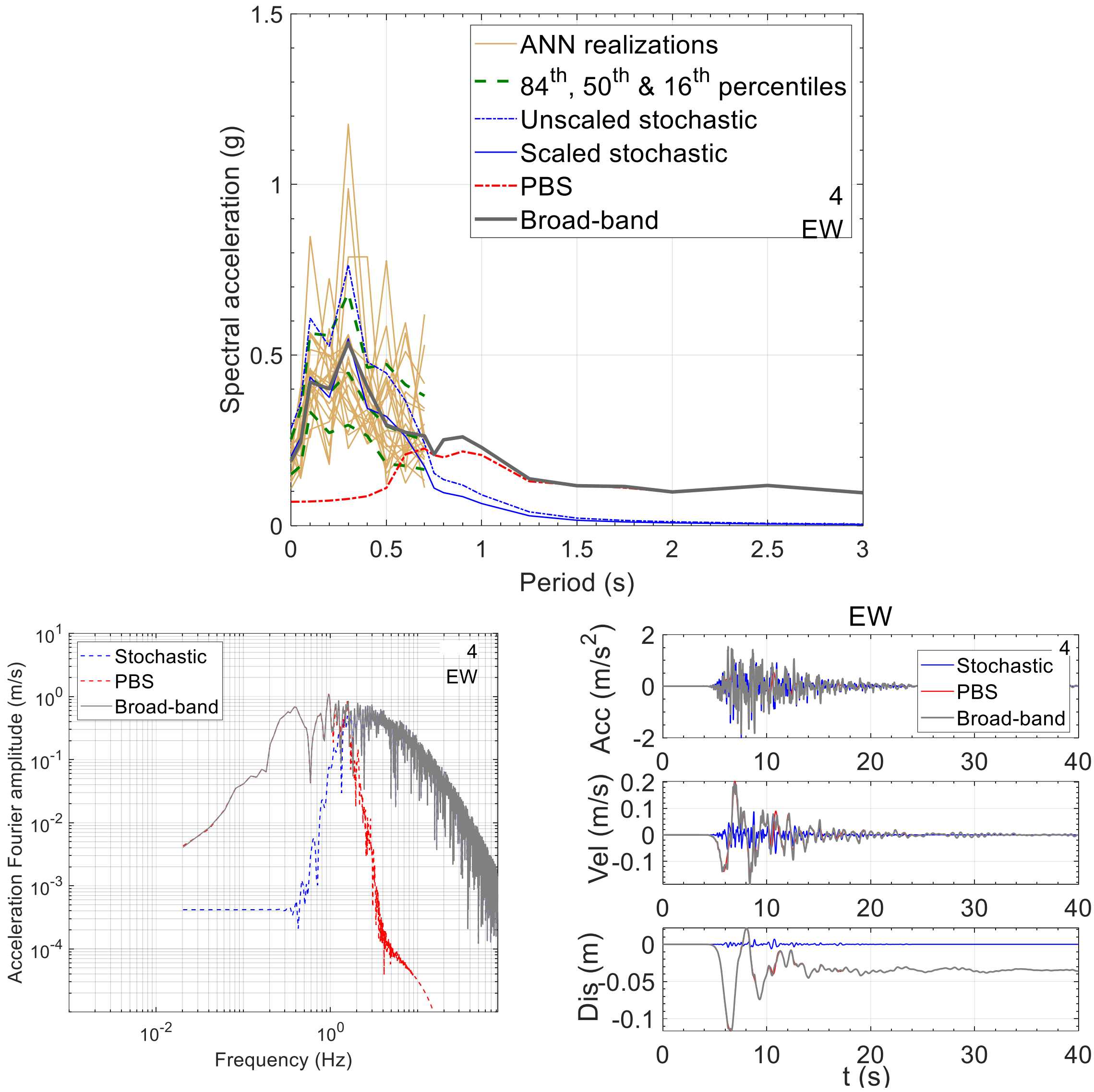

Figure 2. Revised steps (3) and (4) of ANN2BB procedure. Top: linear scaling of stochastic motion to fit the target ANN2BB response spectrum; bottom: combination of stochastic and PBs signals in the frequency domain (left) and corresponding acceleration, velocity and displacement time histories (right).

Figures 4 and 5 show the comparison of recordings Versus simulations in terms of both acceleration (left) and displacement (right) response spectra for both the M_w7.0 mainshock and M_w6.1 foreshock, respectively. The vertical line denotes the corner period (T*) beyond which the spectral ordinates are based on PBS and below which they are based on the ANN2BB. It should be noted that a different T* was applied for the two events, in order to optimize the results. Selection of T* typically depends on two main factors: first, the accuracy of the numerical mesh that, using the spectral element approach, is typically designed for the minimum wavelength to be sampled by around 4 grid nodes; second, the complexity that is achieved in the seismic source description, the model of which should be suitable to excite a realistically wide frequency range. Looking at the PBS response spectra in Figures 4 and 5, it is apparent that the spectral ordinates for the M_w7.0 event tend to decay below T*=0.5 s (Figure 4), while for the M_w6.1 event the decay at short periods starts at around T*=0.75s (Figure 5). The larger value of T* used in the latter case is most likely related to a smoother description of the source model.

With this selection, the overall agreement of the ANN2BB spectra with the recorded ones is found to be reasonably good. However, it can also be clearly seen that, as expected, the performance of the short period prediction is dependent on that of the long period one, obtained by PBS: the better is PBS prediction, especially in the vicinity of the corner period, the better is also the short period prediction through the ANN2BB.

In Figure 6 one of the main outcomes of PBS is shown in terms of maps of PGV (m/s, left) and PGA (m/s^2, right) for the considered area, for the three selected events of the 2016 Kumamoto seismic sequence. Compared to standard maps from empirical Ground Motion Prediction Equations (GMPE), these maps have the enormous advantage of providing a realistic region- and fault-specific spatial distribution of ground motion, that may enhance the accuracy of seismic risk evaluations in large urban areas (Stupazzini et al., 2021). As previously explained, the main advantage of the ANN2BB approach is that it provides a realistic spatial variability of ground motion in terms of spatial correlation, also at high frequencies (Schiappapietra et al. 2021). Referring to Infantino et al. (2021) for further details, Figure 7 illustrates, for the 2012 May 29 Po Plain earthquake (Mw6.0), the semivariograms for both PGA and SA1.0s (NS component), computed from both recordings (in triangles and dashed lines) and ANN2BB simulated ground motions (in dots and solid lines), using the same set of receivers. Note that the simulated SA for $T \geq 0.75$ s are derived entirely from the PBS, while for $T < 0.75$ s they are the result of the ANN2BB procedure. A very good agreement is found between the semivariograms from records and synthetics across all periods. Besides spatial correlation, also the spatial coherency of simulated motions (i.e. the variability of ground motion waveforms) appears to be properly captured, although more systematic analyses are in progress.

CONCLUSIONS

Although PBS are fast becoming a more and more reliable tool for earthquake ground motion prediction in those conditions, such as near-source and complex geologies, that are not well documented by strong motion records, the range of frequencies that they can encompass is still limited, because both of computational restraints and of insufficient detail of the geological model description at small spatial scales. The ANN2BB procedure illustrated in this paper seems to provide a promising approach to overcome some of these limitations, in that it allows to construct broad-band ground motions with a suitable correlation of short and long periods. Besides, it was also shown that the resulting spatial variability complies with realistic features of spatial correlation and coherency also at short periods.
However, this technique should not be considered as a *panacea*, because it does not overcome the still existing problem of the missing modelling of the high-frequency physical components of ground motion. This may be relevant in PBS both to model small-scale spatial discontinuities, as well as non-linear soil response, that typically shows itself especially with increasing damping effects on motion at high frequencies.
Keeping these limitations in mind, the application of the ANN2BB procedure to the PBS of the main events of the Kumamoto 2016 seismic sequence has shown the potential advantages of such techniques, not only to provide accelerograms with a realistic broadband frequency content, but also to produce realistic maps of earthquake ground motions, also at high frequency, that may be relevant for seismic risk applications in large urban areas.

ACKNOWLEDGMENTS

The first author wish to thank the organization committee of the ESG6 conference for inviting him to this lecture and Karim Tarbali for his contribution in the development of updated ANN2BB procedure. The research activity on advanced physics-based numerical approach for the production of broadband earthquake ground motion has been supported by the Department of Civil Protection within the DPC-ReLUIS projects and by swissnuclear (Switzerland).

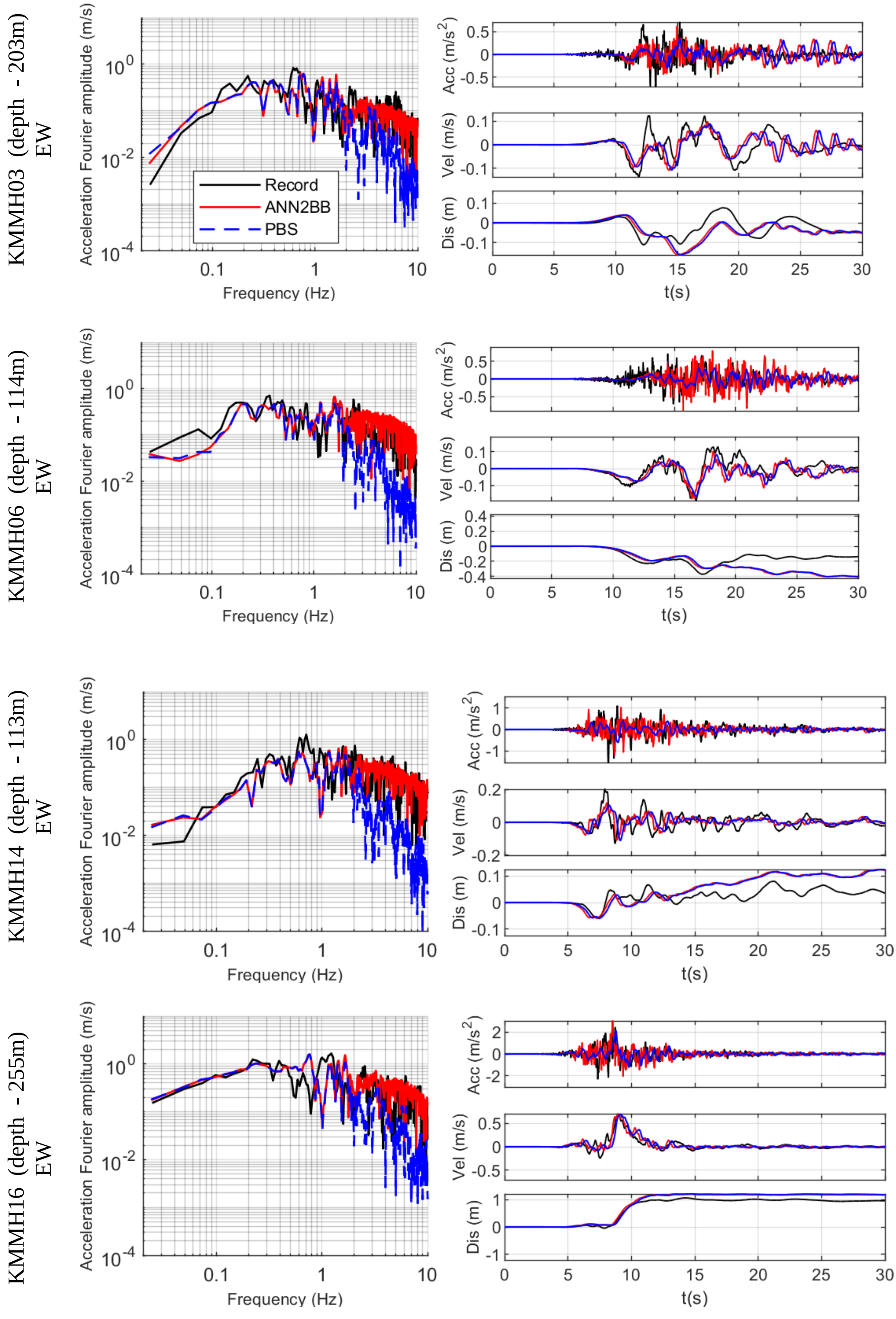

Figure 3. M_w7.0 Mainshock - Comparison of recorded ground motions (black) at borehole sensors of KiK-net with result of PBS (blue) and ANN2BB broadband ground motion (red), in terms of acceleration, velocity and displacement waveforms (right) and Fourier acceleration spectra (left). The ANN2BB procedure is applied in this case with T*=0.5s.

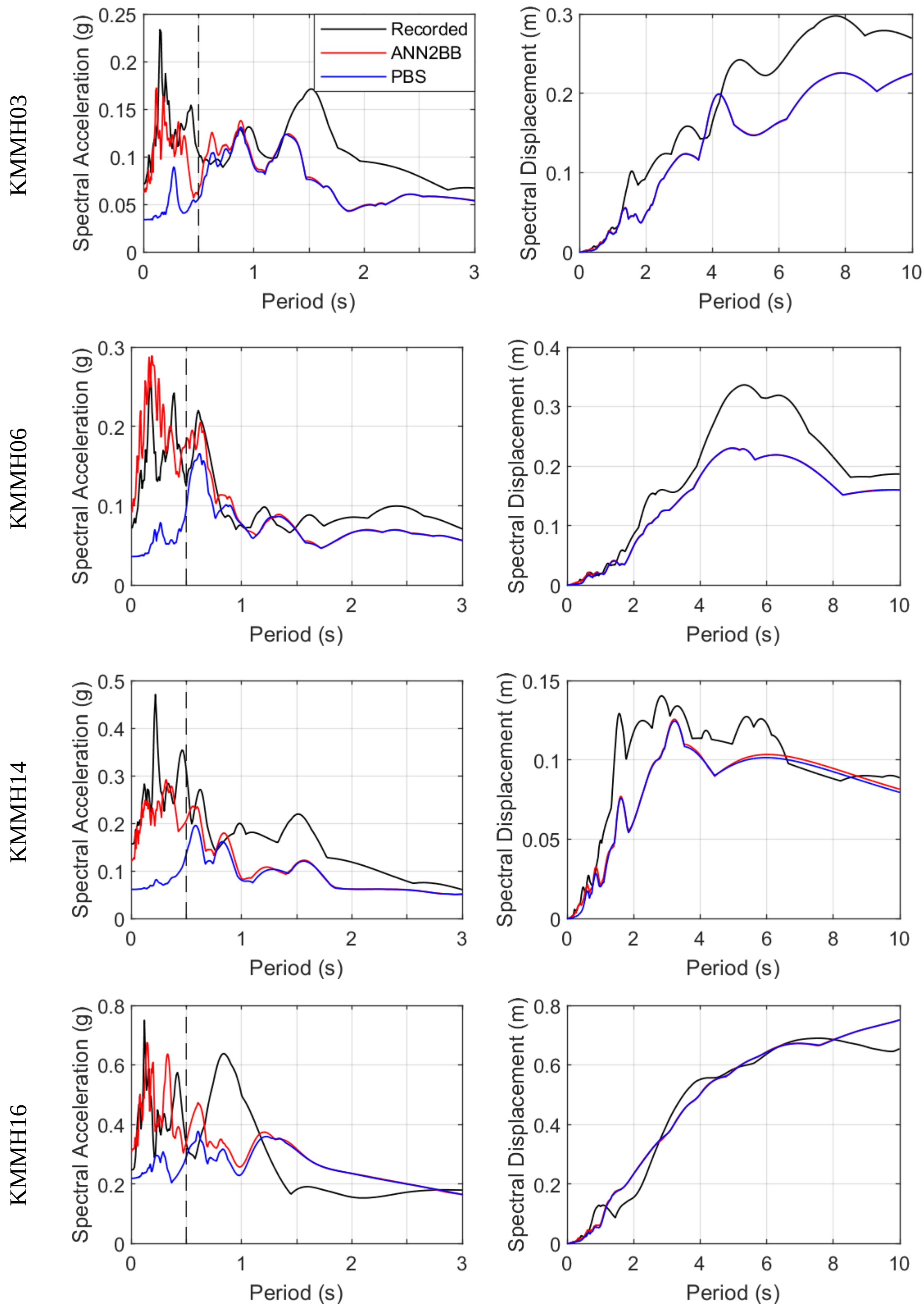

Figure 4. M_w7.0 Mainshock - Comparison of spectral accelerations (left panels) and spectral displacements (right panels) of recorded ground motions (black) at borehole sensors of KiK-net with result of PBS (blue) and ANN2BB broadband ground motions (red). The vertical line corresponds to T* = 0.5 s.

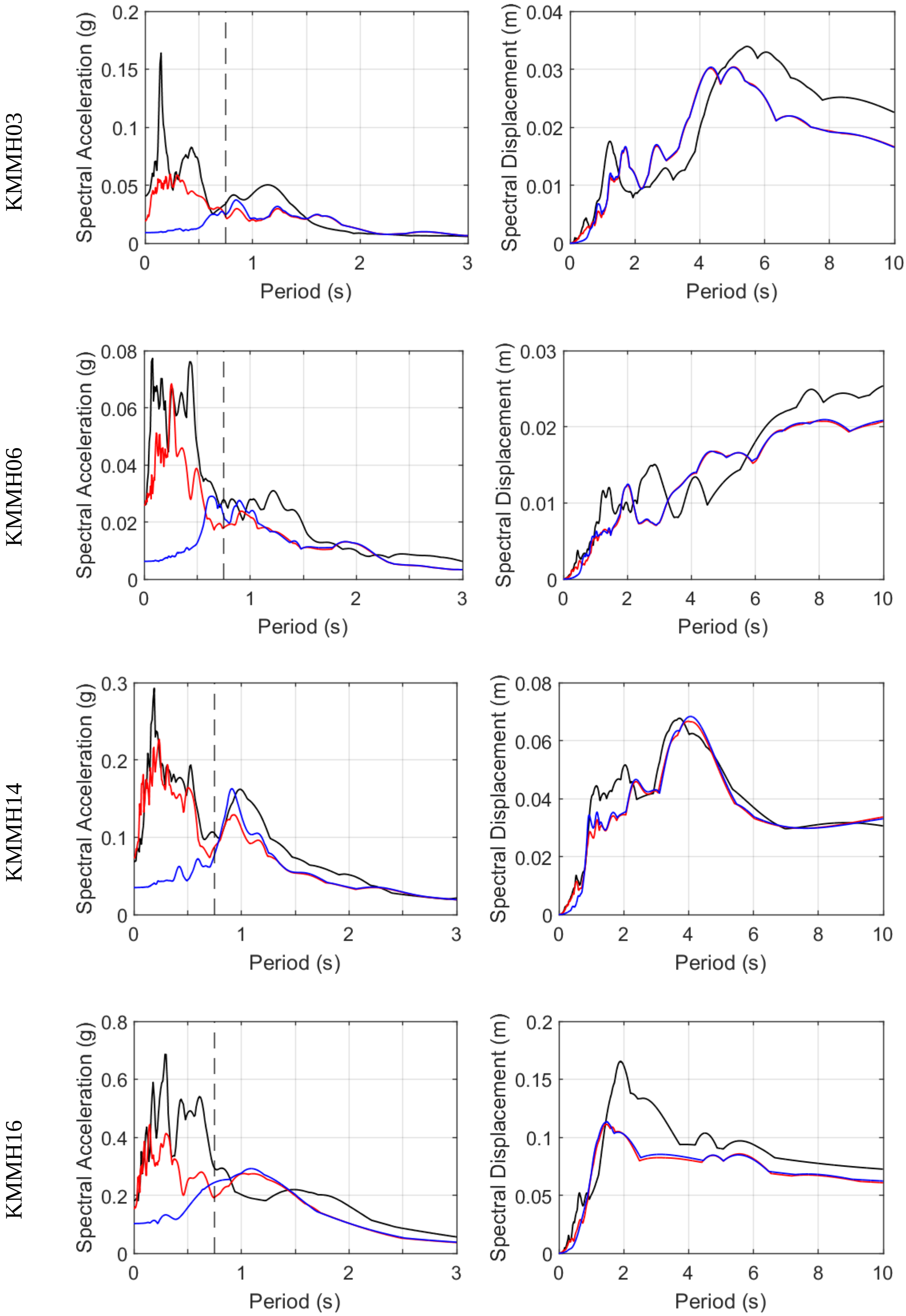

Figure 5. As Figure 4, but for the M_w6.1 Foreshock. The vertical line corresponds to T* = 0.75 s.

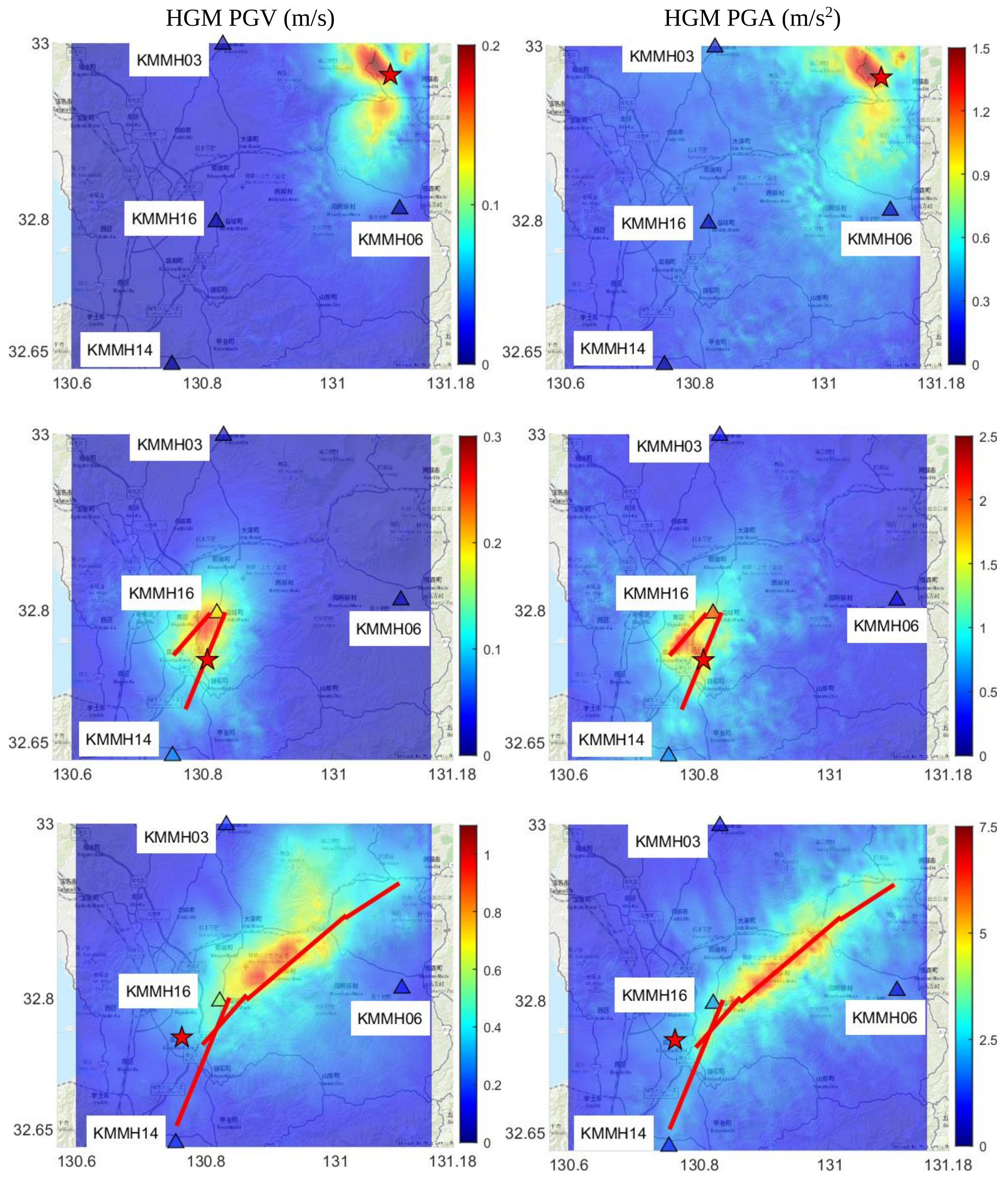

Figure 6. Peak ground motions of M_w5.5 (top), M_w6.1 (middle) and M_w7.0 (bottom) events: PGV (left) and PGA (right), horizontal geometric mean (HGM) component. Red lines indicate trace of fault segments, star represents epicenter of respective event. Since SPEED simulations do not account for the amplification related to shallow layers, triangle colours refer to the peak values of the borehole KiK-net stations. T*=0.75s was used for the M_w5.5 and M_w6.1 events, while T*=0.5s for the M_w7.0 mainshock.

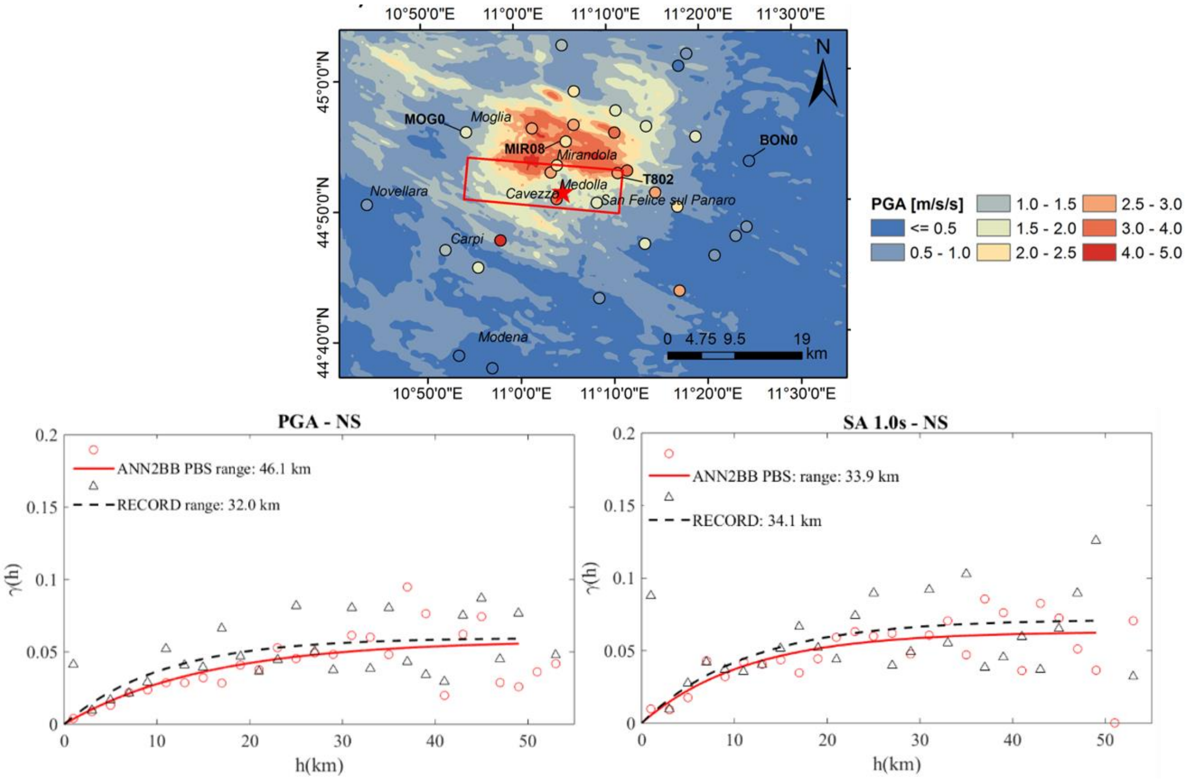

Figure 7. ANN2BB simulation of the 2012 May 29 Po Plain earthquake. Top: map of PGA (NS component), in comparison with recorded values (superimposed dots). Bottom: comparison between the semi-variogram computed from recordings (black) and from ANN2BB PBS (red) for both PGA (left) and SA(1.0s), NS component. Modified from Infantino et al., (2021).

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