BB-SPEEDset: a validated dataset of broadband near-source earthquake ground motions from 3D physics-based numerical simulations

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Abstract

This paper provides an overview of the BB-SPEEDset, a strong-motion dataset of near-source broadband earthquake ground motions from 3D physics-based numerical simulations, obtained by the spectral element code SPEED developed at Politecnico di Milano, Italy. Taking advantage of the earthquake ground motion scenarios produced so far by SPEED, in most cases validated against earthquake recordings, the main objective of this work is to construct and validate a dataset of simulated broadband waveforms to be used as a support for characterization and modelling of near-source earthquake ground motions. To pursue this objective, the following steps were necessary, namely: (i) the implementation of an effective workflow suitable to process in an homogeneous format various SPEED simulations; (ii) the generation of broadband time histories using a technique based on Artificial Neural Networks, trained on strong motion records; (iii) the creation of a flat-file collecting, for each simulated scenario, the most relevant metadata (fault rupture scenario, site response proxies, source-to-site distances) as well as a comprehensive set of ground motion intensity measures of the processed broadband waveforms (Peak Ground Acceleration, Velocity and Displacement, spectral ordinates, duration, pulse period, etc..). Finally, a comprehensive set of consistency checks is made to verify the absence of any systematic bias in the trend of the BB-SPEEDset results with respect to the NESS v2.0 near-source recorded ground motion dataset. Indeed, the main features of near-source ground motion in BB-SPEEDset, ranging from the statistical distributions of peak and integral measures both at short and long periods, the ground motion attenuation with distance, to the features of impulsive ground motions and directionality effects, are in substantial agreement with those from NESS.

Keywords

earthquake ground motions, near-source conditions, 3D physics-based numerical simulations,

simulated broadband waveforms dataset.

Introduction

It is well known that the characterization of earthquake ground motion in the near-source region is made difficult by the paucity of records that, in spite of their ever-growing number, cannot reliably describe yet neither the median values nor their variability, in the variety of source and site conditions typically present in the vicinity of the seismogenic fault.

As in most fields of science, when the laboratory investigations are either limited or prevented owing to the size of the prototype and to the difficulties to reproduce the in-field conditions, analytical and numerical modelling may be an alternative to complement in an ideal laboratory the information that is difficult to capture from nature.

In this perspective, the so-called physics-based numerical simulations (PBS) of earthquake ground motion aim at complementing the recorded data by providing simulated results in the source and site configurations that may resemble as closely as possible the real ones. In some cases, the role of PBS has been extended to provide realistic seismic scenarios of earthquake ground motions suitable to improve the approaches for seismic hazard and risk analysis (see e.g., Graves et al. 2011, Maeda et al. 2016, Smerzini and Pitilakis 2018, Bradley et al. 2017 and 2020, Stupazzini et al. 2021) and to provide input for seismic structural analyses (Galasso et al. 2013, Baker et al. 2021, Fayaz et al., 2021).

With this objective, several research groups worldwide (see e.g., amongst others, Graves and Pitarka 2010 and 2015; Irikura and Miyake 2011; Mazzieri et al. 2013; Komatitsch et al. 2013; Isbiliroglu et al. 2015; Paolucci et al. 2018; Lu et al. 2018; McCallen et al. 2020a and 2020b) have continuously contributed in the recent years to development of numerical tools that may become more and more suitable to produce, with a reasonable computational effort, realistic earthquake ground motions that may reliably complement the recorded ones in the near-source region and eventually coupled with engineering models for non-linear structural response.

Combining the computational burden with the difficulty to accurately reproduce details of the fault geometry, of the seismic slip distribution, and of the complex geology (typically 3D) of the area of interest, that may extend by tens of km, PBS are generally considered to be bounded within frequency limits hardly beyond about 2-3 Hz, although some successful examples of PBS extending up to 8-10 Hz in the presence of very detailed knowledge of local site conditions are also present, such as for the simulation of induced seismicity in the Groningen (Netherlands) area (Paolucci et al., 2021).

Some cross-verification activities of numerical tools for PBS were undertaken in the recent past (Chaljub et al. 2010; Bielak et al. 2010; Maufroy et al. 2015), that were seminal steps for the different research groups to solve the major issues arising when the numerical codes are applied to very complex configurations. However, relatively little effort was devoted up to now to comprehensive validations of PBS against strong motion records, especially in the near-source region (Taborda and Bielak 2013 and 2014, Paolucci et al. 2015, Imperatori and Gallovič 2017, Gatti et al. 2018, Pitarka et al. 2020, Paolucci et al. 2021). For this reason, a blind prediction experiment was set up in the framework of the 6th IASPEI/IAEE International Symposium - The Effects of Surface Geology on Seismic Motion (ESG6), with the objective to reproduce earthquake ground motions during the Kumamoto, Japan, seismic sequence of 2016, with a moment magnitude M_w7 mainshock.

With a long-lasting expertise gained (i) in the development of the open-source numerical code SPEED based on spectral elements (Mazzieri et al. 2013), (ii) in the advancement of techniques to enrich at high frequencies the PBS results (Paolucci et al. 2018), (iii) in the validation of PBS results against near-source ground motions recorded from different earthquakes in Italy and worldwide and in the application to several scenario case studies (see overview in Table 1), we have collected a large subset of our simulated results with a uniform processing procedure that will be illustrated in the sequel. In this way, we have constructed the BB-SPEEDset (v1.0), a dataset of broadband near-source ground motions aiming at providing a complementary tool for characterization of earthquake ground motions, in terms of their dependency on magnitude, distance and site conditions, such as the most common empirical ground motion models (GMM), with a complete and well constrained characterization in terms of seismic source and site conditions. Additionally, this dataset may also provide the basis to properly analyze the spatial variability of ground motion, with potential important implications to validate and improve the existing models for spatial correlation (e.g., Infantino et al., 2021b; Schiappapietra and Smerzini, 2021) and spatial coherency, that currently suffer from the lack of records from sufficiently densely spaced arrays of seismic stations (e.g. Smerzini 2018).

As introduced by D'Amico et al. (2017), the main advantage of a broadband ground motion dataset based on PBS is that all input source data are clearly identified, as well as the site conditions of recording stations, and ground shaking scenarios of the simulated earthquakes can easily be constructed. On the other side, it is difficult to prove that the available waveforms are not biased with respect to records, in terms of the different parameters of ground motion that are relevant for engineering applications, typically because of the limited detail of the input data of PBS in terms of seismic source and geological layering, and because of the computational limits of the numerical simulations.

To overcome such limitations, the novelty of this paper is to provide a comprehensive comparison of the BB-SPEEDset statistical distributions with those obtained by NESS2.0 (denoted in the following by NESS), a dataset of worldwide recorded near-source ground motions addressed in this special issue by Sgobba et al. (2021), updated after Pacor et al. (2018). Although the origin of the two datasets is completely different, BB-SPEEDset being based on relatively few earthquake scenarios, each with a large sample of simulated accelerograms, while NESS is based on a large number of real earthquakes, each with relatively few records, such comparison is a crucial step to assess whether a bias exists between the trend of simulated results in the BB-SPEEDset with respect to those of NESS. The absence of systematic differences will strongly support the effectiveness of the procedure to produce broadband waveforms from the SPEED physics-based numerical simulations as well as the potential use of the BB-SPEEDset to improve the available tools for the prediction of near-source earthquake ground motion and to provide input motions for earthquake engineering analyses.

This paper is organized as follows. After an introduction of the workflow for post-processing PBS results and for generating broadband waveforms by taking advantage of Artificial Neural Networks (ANN), the BB-SPEEDset is introduced with its current features, in terms of distribution of simulated waveforms according to magnitude, distance, site conditions. Subsequently, a comprehensive comparison of the BB-SPEEDset trends with respect to those of the NESS dataset is presented, involving the statistical distribution of various IMs, their attenuation with distance, and the main features of near-source ground motion such as directionality, vertical components and impulsive motions. Finally, an example of a query by earthquake scenario from the BB-SEEDset is introduced with reference to the 2009 L'Aquila earthquake, where one of the main advantages of a dataset based on PBS can be appreciated, in terms of generation of ground motion maps of a selected earthquake scenario.

Workflow for post-processing of SPEED results

A fundamental step for the construction of a database of PBS results is the definition of an optimized workflow for post-processing of results of SPEED simulations in a uniform and repeatable format. To this end, the SPEED kernel is supplemented by a set of Matlab routine packages that allow to post-process the raw waveforms computed by SPEED (typically, displacement time histories at receiver points) and generate outputs and metadata in a standard format. Note that, for the earthquake scenarios included in BB-SPEEDset, kinematic rupture models were introduced, consisting of heterogeneous slip functions across the fault. While for real earthquakes (validations in Tab. 1) the kinematic source parameters were calibrated based on the available seismic source inversions studies, for ideal scenario earthquakes the kinematic rupture generators proposed by Herrero and Bernard (1994) and Schmedes et al. (2012) are adopted. The generation of these fault slip distributions is handled by means of specific Matlab routines, implemented in the pre-processing tools of SPEED.

An overview of the post processing workflow is given in Figure 1 and it is organized in the following steps:

- *3PTOOL*: the code extracts and organizes the raw SPEED seismograms in a common format (output file: Matlab .mat file) including receiver coordinates, displacement time histories (unfiltered), low frequency (directly from SPEED) and broadband (from ANN2BB, see following Section) peak ground motion maps.
- *SITE RESPONSE PROXIES*: the routine computes from the velocity model the most relevant site response proxies, namely: H_{bed} – depth of the alluvial-bedrock interface included in the simulation model, H_{800} – depth at which the shear-wave velocity V_S is equal or higher than 800 m/s, V_{S30} – time averaged shear-wave velocity from the surface to a

depth of 30 meters, V_{Seq} – time averaged shear-wave velocity from the surface to H_{800} (if $H_{800} \leq 30$ m; if $H_{800} > 30$ m, then H_{800} =30m), see definition in the Italian Building Code (NTC 2018), V_{Sbed} – time averaged shear-wave velocity from the surface to H_{bed}, V_{S800} – time averaged shear-wave velocity from the surface to H_{800}; topography slope.

- *EFFECTIVE FAULT*: the code calculates the effective dimensions of the rupture fault area according to the procedure originally proposed by Mai and Beroza (2000), and extended by Thingbaijam and Mai (2016), see Figure 2. This step is particularly relevant to define metadata with unbiased source dimensions, as the fault implemented in the numerical grid (typically, the fault associated with a maximum magnitude to be simulated) may be different from the co-seismic rupture area associated with a given earthquake scenario. Effective source dimensions are based on the definition of autocorrelation width (Bracewell, 1986) of slip distributions, calculated in along-strike and down-dip directions. These slip functions are computed summing up the slip in columns (or rows) on the rectangular rupture plane. An iterative, trimming, process determines the largest dimensions that fit the autocorrelation width, according to the subfault size. The dependence of these effective measures on magnitude through scaling relationships has been verified (using e.g. Wells and Coppersmith 1994 or Leonard 2010).
- *SELECT RECEIVERS*: the code extracts subsets of receiver points according to prescribed sampling techniques. Since the simulated seismograms are generally obtained at tens of thousands of receivers, the computation of broadband time histories and of all corresponding intensity measures is limited to a subset of receivers to minimize the computational cost. In our processing for the BB-SPEEDset, the receiver selection was defined to achieve a higher density of receivers at lower distances from the source.

- *BROADBAND GENERATION*: at the selected receivers, the SPEED signals (typically reliable up to about 1.5-2 Hz, see Table 1) are enriched at high frequencies using a technique based on ANN trained on strong ground motion recordings (referred to as ANN2BB).
- *SPEED IDCards*: the routine produces an informative sheet (.pdf) summarizing the main features of the numerical model (e.g. mesh, wave velocity model), of the simulated fault rupture scenario (e.g. fault slip distribution, rise time, rupture times, etc..) and a selection of outputs (e.g. ground shaking maps).
- *FLAT-FILE GENERATION*: a flat-file is created in a format consistent with the one adopted in up-to-date strong motion databases (e.g. NESS) and populated with an exhaustive list of metadata (regarding the source, source-to-site distances, site response proxies, post-processing, etc..) and ground motion IMs.

Broadband generation

As well known, 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 (see maximum frequency in Table 1), 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. For this reason, the core of the post-processing workflow is the generation of broadband waveforms, where the low-frequency simulated waveforms are enriched in the high-frequency range to produce time histories with a realistically broad frequency content. This is an essential step to treat the simulated waveforms in the same way as recordings and, therefore, make them usable in earthquake engineering applications.

To this end, the ANN2BB approach (Paolucci et al. 2018), based on Artificial Neural Networks trained on strong ground motion recordings, is adopted. In this work, the ANN2BB technique has been enhanced with respect to the original version published in 2018 to make it suitable for massive post-processing of larger datasets in a semi-automated fashion and to improve the quality of generated waveforms.

Referring to Paolucci et al. (2018) for further details, the ANN2BB procedure is based on four main steps, as sketched in Figure 3:

(1) An ANN, consisting of two-layer feed-forward neural network with 30 hidden neurons, is trained on a dataset of strong motion records, such as SIMBAD v6 (Smerzini et al. 2014) or NGA-West 2 (Ancheta et al. 2013), to predict short period spectral ordinates ($T<T^*$) based on the long period ones ($T \geq T^*$). Different ANNs are trained separately on the geometric mean of the horizontal components and on the vertical components for prediction of three-component ground motions.

(2) For each simulated waveform, a target ANN2BB response spectrum is computed, the long spectral ordinates of which, for $T \geq T^*$, coincide with the simulated ones, while, for $T<T^*$, they are obtained from the ANN (separately for horizontal and vertical components). In our application, the corner period T^* is set depending on the frequency-limitation of the numerical mesh. To preserve variability of the ANN results, the target at short periods is built on the median value calculated over 20 ANN realizations.

(3) Once the ANN2BB target spectrum is defined for each waveform, the non-stationary stochastic approach by Sabetta and Pugliese (1996) is followed to generate the high frequency portion of the signal. Updates of this approach (see e.g. Pousse et al., 2006; Sabetta et al. 2021) will be implemented in the next releases of the BB-SPEEDset. More

specifically, 20 stochastic realizations are obtained, according to the simulated scenario (M_w) and receiver (distance, site conditions) and, out of these, a specific realization is selected based on the criteria illustrated in the sequel.

(4) The selected stochastic signal (HF) and the PBS waveform (LF), previously filtered in the high and low frequency range, respectively, are combined in the time domain. Phase matching between HF and LF is achieved by alignment of the two time histories according to the instant at 5% of normalized Arias intensity.

The scaling and selection of the stochastic signal of step (3) is based on a two-step procedure of minimization of the residuals with respect to the target ANN2BB spectrum. First, for each stochastic realization, a scaling factor *SF* that minimizes the residuals with respect to the target is calculated and, subsequently, among the different scaled stochastic signal the one with the minimum misfit is selected. The residuals are computed using the following equation:

$$\min_{nsim} r^{nsim} = \min_{nsim}\left(\min_{SF}\sum_{i=1}^{N_{periods}} w_i\left(\frac{lnANN_{median,i} - ln\left(SF*STOCH_i^{nsim}\right)}{\sigma_{lnANN,i}}\right)^2\right) \quad (1)$$

where SF is the scaling factor (typically in the range 0.5-2), $N_{periods}$ are the vibration periods of the target ANN spectrum, w_i is the weight-vector, $nsim$ = 20 is the total number of stochastic signal realizations (20 realizations are found to guarantee a satisfying final spectrum). $STOCH^{nsim}$ is the $nsim^{th}$ stochastic realization. Note that both median (ANN_{median}) and standard deviation (σ_{lnANN}) of the 20 ANN are used to calculate the misfit. The weight-vector w controls the fit to the target ANN spectrum. As the fit is actually performed only on the HF range, the weight vector takes the following values: w = 0 for T>T*; w =1 for T<T* and w = 2 for T=T*. These values were selected after appropriate sensitivity analyses and they ensure that at the end of the procedure, the final spectrum is 'as close as possible' to the PBS one in the LF range, including the merging

period.

The main differences with respect to the procedure introduced by Paolucci et al. (2018) are the following:

- step 2: the target ANN2BB in the high frequency range is computed as the median of 20 different ANN realizations, rather than the output of a single ANN, in order to achieve a greater stability of results and minimize overfitting issues;

- step 3: the frequency scaling of the stochastic signal is replaced by a linear scaling in the time domain to approach the target ANN2BB spectrum at short periods. This improvement overcomes some issues related to the unrealistic frequency content, that was sometimes introduced by the manipulation of Fourier spectra in the previous procedure. Furthermore, owing to its computational efficiency, it makes the broadband generation tool of SPEED suitable for massive computations over a very large number of receivers with no manual interventions, facilitating time-effective yet reliable outputs.

Finally, it is worth to remark two major advantages of the ANN2BB procedure with respect to other hybrid approaches to generate broadband signals based on PBS (see e.g., Mai and Beroza, 2003). First, since the resulting waveform is obtained based on the fit to a regular target response spectrum, it is possible to avoid the spurious discontinuities of the Fourier spectrum, that are the typical result of "glueing" around a cross-over frequency the physics-based (LF) signal with the stochastic one (HF). Second, as thoroughly discussed by Paolucci et al. (2018), in the ANN2BB procedure the LF and HF portions are not independent, as it is the case for most hybrid approaches, but their correlation is enforced by the records-trained ANN. This allows the BB-SPEEDset results to be used to produce realistic earthquake ground motion maps with the proper spatial correlation also at short periods, as it will be illustrated in the last section of this paper for the case of the

L'Aquila earthquake.

Overview of the BB-SPEEDset: metadata and intensity measures

For each scenario and each selected receiver, a list of source metadata, post-processing metadata, receiver metadata, site response proxies, source-to-site distances and IMs are computed and stored in a flat-file (see Table 2 for details). Note that the fields of the flat-file are consistent with the ones in the Engineering Strong-Motion (ESM) (Lanzano et al., 2018) and the NESS flat-files (Sgobba et al. 2021). However, when considering a database of PBS results, it is relevant to store information regarding the type of post-processing accomplished, such as ANN training database, ANN transition period, broadband procedure, as done in BB-SPEEDset.

Since directional effects may be significant in the near-source region, each IM is defined on different horizontal directions, besides the vertical one, namely: the fault normal (FN) and fault parallel (FP) components, calculated rotating the horizontal waveforms orthogonal and parallel to the strike of the fault, respectively; the horizontal geometric mean (HGM), computed using the two horizontal EW and NS components; the maximum (RotD100) and the median (RotD50) values of IMs over all orientations (Boore, 2010), denoted in the following by D100 or D50, respectively. In addition to standard peak IMs, such as Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV), Peak Ground Displacement (PGD) and response spectral accelerations (SA), a variety of integral and frequency-related IMs is included, such as the Housner Intensity (HI), the Cumulative Absolute Velocity (CAV), the Arias Intensity (IA), the IA-based durations (i.e., time interval between 5% and 95% of the total IA, Ds595, and between 5% and 75%, Ds575; see Trifunac and Brady, 1975, Bommer and Martinez-Pereira, 1999) and the mean period (Rathje et al. 1998). Furthermore, in the flat-file compilation, special care was given to the characterization of pulse-like waveforms, which are of particular interest in earthquake engineering applications owing to their increased damage potential. Impulsive ground motions reflect two main physical effects. First, in forward-directivity conditions, the constructive superimposition of waves generated by a propagating rupture in front of a site may yield double-sided velocity pulses. Second, the contribution of waves generated by a finite dislocation on the fault plane can produce a permanent displacement (i.e. fling step) which results in a one-sided velocity pulse. As further discussed in the following, it is worth underlining that PBS can provide accurate predictions of displacement waveforms, including static offsets, which are hardly retrieved from recordings, because of the baseline drifts associated with errors in instrument response at low frequencies. The identification of pulse-like waveforms and of pulse period (T_p) has been done relying on the algorithm proposed by Shahi and Baker (2014). A thorough discussion on impulsive ground motions will be provided later in the paper (see Section Analysis of impulsive ground motions).

The distribution of BB-SPEEDset data with respect to magnitude and distance is given in Figure 4. The dataset includes a total of 12058 three-component waveforms from earthquake scenarios with M_w from 5.5 to 7.4 and Joyner-Boore distances (R_{jb}) up to 80 km. Strike-slip, normal and thrust events are included in the dataset. Most records refer to normal (50%) and strike-slip (41%) focal mechanisms, while only 9% is from thrust earthquakes (i.e., only the 2012 Po Plain event, see Table 1). The dominance of normal and strike-slip faults is because, on one hand, normal events are typical of the seismicity in Central Italy (mostly represented within the BB-SPEEDset) and, on the other hand, a significant set of strike-slip events from the North Anatolian Fault (Istanbul case study, see Infantino et al. 2021a) and from the 2016 Kumamoto sequence (Sangaraju et al. 2021) is also included.

In the same figure, the distribution of the NESS dataset is illustrated for comparison. Although the

BB-SPEEDset does not cover yet earthquakes with $M_w \geq 7.5$ (and for this reason the comparisons shown hereafter will neglect this range), it can be seen that PBS allow to approach an ideally dense sampling at short distances, that cannot be obtained by the NESS recording stations.

The distribution of BB-SPEEDset with respect to site conditions, parametrized in terms of the V_{S30}, is shown in Figure 5. About 40% of data corresponds to soil conditions with $V_{S30} < 800$ m/s, and about 60% to rock conditions, with dominance for hard rock sites with V_{S30} larger than 1000 m/s. Within the soil classes, the majority of waveforms is on stiff soil with $V_{S30} > 400$ m/s, but an appreciable number of data is on very soft sites with V_{S30} as low as 150 m/s (Marsica case study). Figure 5 highlights another potential advantage of the simulated datasets: seismo-stratigraphic conditions are fully known in the PBS, so that each receiver may easily be associated to different proxies related to site response. Furthermore, site conditions that are typically poorly represented in the recorded datasets, such as rock and very soft sites, may be better sampled. This may provide further constraints, complementary to those from earthquake recordings, for the calibration of site amplification factors, especially in complex geological conditions.

As a final remark, note that, BB-SPEEDset should be considered as a dynamically growing dataset, the scenarios of which may increase in a short time by extending to the case studies listed in Table 1 and not processed yet. Furthermore, new scenarios may specifically be developed to fill in the magnitude, distance and site conditions gaps of the present version.

Statistical distributions of ground motion intensity measures

As remarked in the introductory section, a crucial step for the potential use of the BB-SPEEDset flat-file and signals for engineering applications is to compare the statistical distributions of different IMs, their attenuation with distance, the features of directional and impulsive near-source accelerograms, with those obtained from recorded ground motions, in order to verify the presence of potential biases and to identify their sources. For this purpose, since the SPEED results essentially refer to near-source conditions, we considered as a reference the NESS dataset introduced previously.

Figure 6 shows the cumulative distribution function of different IMs, namely, PGA, PGV, SA(1.0s), SA(3.0s), CAV, Ds595, IA and HI, as computed from the entire BB-SPEEDset flat-file. For all IMs, the D50 component is considered. To verify the consistency of our results against recordings, the statistical distributions derived from BB-SPEEDset are compared in Figure 6 with those obtained on the NESS dataset, within similar ranges of M_w and distances as covered by BB-SPEEDset. As a matter of fact, for this comparison, only records with $M_w<7.5$ are considered (corresponding to about 55% of NESS, see shaded region in Figure 4), consistently with BB-SPEEDset, but, at low magnitude, larger distances are covered by BB-SPEEDset. To emphasize the comparison between the two independent sets of data, the lognormal distributions, fitting the empirical ones, are also superimposed and the corresponding statistical moments are provided. Furthermore, for each IM distribution, the values of ground motion with a probability of exceedance less than 5% (i.e. 95th percentile of the related distributions) are highlighted on the graph. Overall, it is remarkable that a full consistency is found between BB-SPEEDset and NESS, as it should be, as the distribution of M_w and R_{jb} of the two datasets are also consistent (apart from slight differences, as commented above). Although the BB-SPEEDset tends to underestimate the recorded values of PGA by a factor of about 20%, probably owing to the difficulty of the ANN2BB approach to describe the short periods as accurately as the long periods, the statistical distributions of several IMs, from peak measures to integral ones, are noticeably similar both in terms of median and standard deviation (σ_{log10}). The agreement of PGV, SA(1.0s), CAV and HI is excellent. For

SA(3.0s), BB-SPEEDset tends to provide more severe ground motions, most likely because of the intrinsic higher coherency of waveforms simulated by means of numerical models which inevitably cannot account for the actual small-scale heterogeneities and complexities in the source, path and site. Referring to IA, some discrepancies are found especially at intensity values lower than the median values (median from BB-SPEEDset is lower than NESS of a factor of about 25%), but the agreement improves significantly above the median. As a matter of fact, the 95th percentiles from BB-SPEEDset and NESS differ of less than 10%. While in most cases the standard deviations from BB-SPEEDset and NESS are comparable, differences are found for the duration Ds595, being σ_{log10} from BB-SPEEDset lower (0.18) with respect to the one from NESS (0.25), suggesting that the level of waveform complexity achieved through SPEED simulations is still lower than reality.

As a further consistency check, the distribution of SA(0.1s) and SA(5.0s) obtained from BB-SPEEDset is compared with that from NESS (M_w<7.5) in Figure 7. It turns out that the correlation between long and short periods of BB-SPEEDset (the latter ones being a direct output of the ANN2BB procedure described previously) is consistent with the one from NESS, with few exceptions of NESS values having a combination of high short-period and low long-period spectral ordinates, not present in the simulated waveforms.

Ground motion attenuation with distance

Attenuation of ground motion IMs with distance for the BB-SPEEDset and NESS are compared in this section. Figure 8 shows PGA and SA(1s) as a function of R_{jb}, using D50 component, for different M_w ranges. No discrimination of soil conditions has been made. The agreement is reasonably good, with a similar trend of IMs with distance. As already mentioned, there is a tendency of PGAs of the BB-SPEEDset to lie on the lower side of recorded values, especially in the lower M_w range. Spectral ordinates at intermediate periods, SA(1s), show a better agreement with NESS, at any distance. A large but comparable scatter can be observed for the two datasets, slightly larger for SA(1s). The larger scatter for M_w around 7.0 and R_{jb} > 10km is related to the Istanbul simulations, that do not have receivers at shorter distances from the source. The high NESS spectral accelerations at 1s for M_w in the 6.3-6.7 range and R_{jb}>10km are mostly related to the1994 Northridge earthquake, while the lowest values (in the same M_w and R_{jb} ranges) are for the 2014 Aegean Sea earthquake of M_w 6.4. The very low SA(1s) values for M_w in the 6.8-7.2 range and R_{jb} >20km are related to the Japanese earthquake of 2008.

Figure 9 shows attenuation with R_{jb} for the Ds595 duration of ground motion. Again, an overall good agreement among the two datasets is noticeable, with NESS records showing a greater scatter probably because of their higher complexity than simulated waveforms, as previously noted. Except for this remark, simulated durations provide a consistent trend with magnitude and distance.

Directionality and vertical-to-horizontal motions

It is widely recognized that, in proximity of the source, earthquake ground motion may exhibit specific features (e.g., Stewart et al., 2001), including polarization related to the fault mechanism and large, short-period, vertical components exceeding, even significantly, the corresponding horizontal ones (Bommer et al. 2011, Gülerce and Abrahamson 2011). These aspects will be addressed in this section, with special care again to the comparison with recordings.

Figure 10 shows the median (±σ, shaded regions) FN/FP (top) and V/D50 (bottom) for PGA, PGV and SA(3s), as a function of R_{jb}, as obtained from BB-SPEEDset and NESS (M_w < 7.5). Note that, while long-period components of ground motion are directly related to the PBS results, short-period components, such as PGA, reflect the output of the ANN2BB procedure. Referring to the FN/FP distribution, an excellent agreement is found both in terms of median value and variability at different distances from the source. As expected, both datasets show that in near-source conditions the FN motion is stronger than the FP at intermediate and long periods and at very short distance, R_{jb}<5 km. At increasing distances, the FN polarization tends to vanish, in agreement with previous studies (Somerville et al. 1997, Pacor et al. 2018). On the other hand, at short periods, no polarization effects are found, with median FN/FP ratios equal to approximately one at all distances, both in the BB-SPEEDset and in NESS. Note that, especially at long periods, the variability across periods is rather large, meaning that directionality features are region- and scenario-specific. Here, the variability of simulated waveforms tends to be slightly larger but differences remain limited. Further insights on the physical reasons of such variability could be obtained by analyzing the dependence on the focal mechanism and the spatial distribution of such ratios for specific rupture scenarios.

As regards the V/D50 ratios, there is a good agreement in terms of PGA (median V/D50 ~ 0.6 for both datasets, but with larger variability for NESS), while for PGV and SA(3s) the BB-SPEEDset values at very short distance (median V/D50 ~ 0.6) are higher than NESS (median V/D50 ~ 0.4). More detailed studies are planned to investigate the dependence of such different ratios on the focal mechanism and site conditions.

Analysis of impulsive ground motions

This section focuses on the identification and comparison of pulse signals, together with the corresponding period T_p, tagged and stored in both BB-SPEEDset and NESS flat-files.

Figure 11 shows T_p values, calculated following the algorithm proposed by Shahi and Baker (2014), as a function of magnitude, for both BB-SPEEDset and NESS. T_p ranges from 1 to 12 s, with amplitudes tending to increase with magnitude (Mavroeidis and Papageorgiou, 2003; Somerville, 2003), but with the largest values probably related to coupling with deep basin conditions, such as for the earthquakes of Po Plain, M_w 6.0, and Marsica, M_w 6.7, that are poorly represented by the NESS dataset. With these limitations in mind in terms of comparison of datasets, the agreement of the T_p trends from the two datasets is remarkable.

Figure 12 shows the trend of T_p as a function of PGD/PGV, for NESS (left), and BB-SPEEDset (right). A reasonably good agreement between the two sets is found, within comparable magnitude ranges (i.e., M_w from 6.0 to 7.4). Note that, to improve the accuracy of the PGD estimations from the NESS dataset, T_p and peak values from the e-BASCO baseline corrected waveforms have been considered (see Sgobba et al. 2021 for details).

Closed-form analytical relationships between T_p and PGD/PGV ratios are also shown in Figure 12 , with thick black and grey lines, calculated based on simple functions that may approximate impulsive ground motion. These relationships are based on the analytical expressions of the Fourier spectra of the "Ricker wavelet" and of the "double-impulse" functional forms[1], for which the peak of the Fourier spectrum at $f_p=1/T_p$ can be identified and related to PGV and PGD, as shown in the top-right of Figure 12 . It is interesting to notice that most data from both sets fall between the two analytical relationships, suggesting that the variability of impulsive ground motions may roughly be represented by these two functional families.

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[1] The Ricker wavelet function is defined by $v(t)=\left(1-2\alpha^2t^2\right)e^{-\alpha^2t^2}$, with $\alpha=\pi f_p$. The double-impulse function is defined by $v(t)=2\pi f_p\sqrt{e}\,te^{-\alpha^2t^2}$, with $\alpha=\sqrt{2}\pi f_p$. f_p represents in both expressions the frequency corresponding to the peak of the Fourier spectrum. Both pulses are scaled to have unit peak amplitude.

Query by earthquake of the BB-SPEEDset: the L'Aquila example

In this Section we highlight the information that can be obtained from BB-SPEEDset by selecting a specific earthquake (*query by earthquake*) and extracting the corresponding waveforms and IMs. As an explanatory case study, the 2009 April 6 L'Aquila earthquake (M_w 6.2) is considered.

First, as a set of illustrative results of the ANN2BB procedure, Figure 13 shows the broadband three-component (EW, NS and UD) acceleration, velocity and displacement time histories at selected receivers, superimposed on the corresponding PGA, PGV and PGD maps. Referring to Smerzini and Villani (2012) and Evangelista et al. (2017) for a thorough comparison of recorded and simulated waveforms, it is noted herein that simulated time histories have realistic features in terms of duration, amplitudes and frequency content, with displacement waveforms showing permanent displacements related to the co-seismic slip on the fault. Furthermore, the spatial distribution of peak ground motion values at high frequency (PGA) turns out to be well correlated with the geological features of the basin (see areas of maximum amplitudes within the basin), supporting the effectiveness of the ANN2BB approach in establishing a correlation between long and short period ordinates and, thus, reproducing at short periods physics-based features that are simulated only at long periods. It is also interesting to note that, moving from maps related to short periods (PGA) to those related to long periods (PGD), the spatial correlation of ground motion appears to be characterized by increasing correlation length, as expected, at least from a qualitative point of view. Quantitative evaluations of spatial correlation of spectral accelerations from broadband numerical simulations can be found in Infantino et al. (2021b) and in Schiappapietra and Smerzini (2021).

To appreciate the richness of information included in BB-SPEEDset flat-file, Figure 14 shows, for the same case study of L'Aquila, the maps of different IMs, namely, PGV, CAV, IA, T_P, HI, Ds595. The FN component is shown for all IMs expect for T_p. In the latter case, the algorithm by Shahi and Baker (2014) provides as output the T_p along the orientation along which the pulse is the strongest.

Note that one of the main outcomes of BB-SPEEDset is related to the possibility of drawing maps and making quantitative evaluations of spatial correlation of a broad spectrum of IMs, for any orientation of ground motion, with a level of detail which could not be possible using recordings owing to their limited number. From the maps of Figure 14 the following comments can be made:

- areas of maximum intensity of PGV, CAV, HI and IA are concentrated on the surface projection of the fault and inside the alluvial basin, because of the coupling of site response with rupture propagation effects;
- lobes of maximum CAV correlate well with the shape of the basin, also at its South-Eastern edge;
- there is an overall similarity between the spatial patterns of PGV and HI, which is not obvious from their definitions: the former is an instantaneous measure of ground shaking, while the latter, defined as the area of the pseudo-velocity spectrum (5% damping in this case) between 0.1 and 2.5 s, is proportional to the maximum kinetic energy stored in an elastic structure;
- the areas of pulse-like ground motion occurrence are found typically close the top edge of the fault, mostly related to up-dip directivity effects, highlighting an interesting correlation between strong pulse-like motions with the areas of peak values for the FN component (see left panels of Figure 14);
- correspondingly to areas with impulsive motions, the lowest values of ground motion duration are found.

Although these comments may be considered to be specific for the L'Aquila earthquake case study, they convey the idea of the comprehensive picture of earthquake ground motion that can be obtained from PBS and of the potential outcomes that the analysis of the simulated waveforms may provide in terms of an improved characterization of near-source ground shaking. As a further example, Figure 15 shows the maps of permanent displacement, D_{perm}, computed from BB-SPEEDset for the L'Aquila case study, along the FP (left), FN (center) and UD (right) components. Note that, while the fling step is naturally reproduced by physics-based simulation of seismic wave propagation, the estimation of permanent displacement from earthquake recordings requires complex signal processing procedures (D'Amico et al. 2019), which are typically subject to high uncertainties. This points out one of the main advantages of numerical simulations, i.e. to provide an accurate and detailed picture of the long period components of earthquake ground motion, with relevant implications for the calibration of ground motion models for peak ground displacement and displacement spectral ordinates (Cauzzi et al. 2015).

Coherently with the normal focal mechanism of the Paganica fault, responsible of the L'Aquila earthquake, the ground has undergone a static maximum horizontal offset of around 10 cm (both on the footwall and hanging wall along the FN and FP directions, respectively) and a maximum subsidence of about 15 cm on the hanging wall. The latter is consistent with the maximum co-seismic vertical displacement obtained from both synthetic aperture radar (DInSAR) and GPS observations (D'Agostino et al. 2012).

Conclusions

In this paper we have presented the BB-SPEEDset, a new dataset of near-source broadband earthquake ground motions from 3D physics-based numerical simulations obtained by the spectral element computer code SPEED. This is expected to support research on the characterization of earthquake ground motions in the proximity of the seismic source and in complex geological conditions, that cannot be extensively documented based on available records.

To produce the dataset, an effective workflow has been devised to post-process raw PBS results in a homogeneous and repeatable format. The core of the workflow is the generation of broadband ground motions starting from PBS results, reliable only in the low frequency range, according to the ANN2BB procedure first proposed in Paolucci et al. (2018) and further improved in this work to make it suitable for massive processing of simulated waveforms.

At the present stage, BB-SPEEDset consists of a total number of 12058 three-component waveforms from worldwide earthquake scenarios, mostly validated against records, with M_w from 5.5 to 7.4 and R_{jb} up to 80 km. Besides source, receiver and post-processing metadata, the BB-SPEEDset flat-file can provide a large portfolio of ground motion intensity measures, from the standard peak and spectral measures to integral ones (e.g. HI, CAV, duration, IA), up to parameters related to impulsive ground motions (e.g. pulse period T_p) and long period components of ground motions, such as D_{perm}.

An extensive set of checks has been performed and documented in this paper to verify that the BB-SPEEDset provides peak values, integral intensity measures, ratios of long-to-short period spectral ordinates, features of impulsive ground motions and directionality effects, consistent on a statistical basis with NESS, a dataset of worldwide near-source records (Sgobba et al., 2021). The positive outcome of such consistency check was not obvious, because the BB-SPEEDset is the last step of a series of complex studies, starting from the construction of large scale 3D numerical models, the simulation of realistic fault rupture scenarios, the source-to-site propagation of seismic waves in complex geological media, and, finally, a smart post-processing of low-frequency signals to get broadband waveforms using ANN. Although reproducing exactly the recorded ground motions by PBS is not an objective within reach, this paper shows that it is possible to construct realistic earthquake ground motion scenarios, and that the resulting waveforms are consistent, in terms of peak values, duration and frequency content, with records obtained in near-source conditions.

Given this major outcome, we envisage that the BB-SPEEDset, either in the present version or in the following ones enriched by further simulated scenarios, will serve as the basis for several new achievements for an improved characterization and engineering usage of near-source earthquake ground motions, such as:

- to fill in the gaps, in terms of source-to-site conditions, focal mechanisms, variability of fault-slip distributions and directivity effects, complex geological conditions, that are present in the worldwide near-source records datasets and that are not expected to be easily covered in short time by additional records;
- in the conditions above, provide region- and site- specific input motions for non-linear structural analyses of engineered structures, that are presently often carried out using unrealistic scaling factors on recorded ground motions;
- to provide accurate predictions of long period components of ground motions, including peak ground displacements and static offsets, that are hardly retrieved from records because of the uncertainties associated with the post-processing procedures;
- to construct region-specific scenarios of earthquake ground shaking, suitable to improve empirical models of spatial correlation (Infantino et al. 2021b) and spatial coherency of ground motion (Smerzini 2018), taking advantage of the dense spacing of receivers that can be achieved in the numerical modelling;

- to support the development of non-ergodic models for ground shaking scenarios as a key tool for enhanced seismic hazard and seismic risk evaluations in large urban areas (Stupazzini et al., 2021).

Data and Resources

The NESS2.0 dataset has been downloaded at http://ness.mi.ingv.it/ (last accessed March 17th 2021). The BB-SPEEDset (v1.0) is available at the website http://speed.mox.polimi.it/BB-SPEEDset (last accessed May 18th 2021), where both the flat-file and corresponding broadband waveforms can be downloaded.

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Tables

Table 1 Numerical simulations performed by the code SPEED. M_w = moment magnitude, SoF = Style of Faulting (SS=Strike-Slip, NF=Normal Fault, TF=Thrust Fault), $V_{s,min}$=minimum shear wave velocity, f_{max}=maximum frequency of the numerical model. The scenarios included in BB-SPEEDset are specified in the last column.

Case Study	Fault (SoF)	M_w	Model size (km^3)	$V_{s,min}$ (m/s)	f_{max} (Hz)	Event for validation	References	Included in BB-SPEEDset
Grenoble, France	Belledonne (SS)	6.0	41x50x8	300	3	Benchmark	Stupazzini et al. (2009)	not included yet
Gubbio plain, Central Italy	Colfiorito (NF)	6.0	85x62x10	250	3	26 Sept 1997	Smerzini et al. (2011)	not included yet
Tagliamento plain, Northern Italy	Gemona Faults (TF)	6.1	57x53x12	300	2.5	15 Sept 1976	Smerzini (2010)	not included yet
L'Aquila, Central Italy	Paganica (NF)	6.2	58x58x20	300	2.0	6 Apr 2009	Evangelista et al. (2017)	6.2 Aquila 2009
Sulmona, Central Italy	Mt. Morrone (NF)	6.0	49x42x13	500	2.5	Ideal scenarios	Villani et al. (2014)	6.0 SulmonaS03 6.0 SulmonaS04
		6.5						6.5 SulmonaS03 6.5 SulmonaS05
Christchurch, New Zealand	Lyttelton (TF)	6.3	60x60x20	300	2.0	22 Feb 2011	Guidotti et al. (2011)	not included yet
Po Plain, Northern Italy	Mirandola (TF)	6.0	74x51x20	300	1.5	29 May 2012	Paolucci et al. (2015)	6.0 Emilia 2012
Marsica, Central Italy	Fucino (NF)	6.7	56x46x20	100	2.0	13 Jan 1915	Paolucci et al. (2016)	6.7 Marsica 1915
Thessaloniki, Northern Greece	Gerakarou (NF)	6.5	82x64x31	300	1.5	20 Jun 1978	Smerzini et al. (2017)	6.5 Salonicco 1978
	Anthemountas (NF)	7.0				Ideal scenario	Smerzini et al. (2018)	7.0 SaloniccoS01
Norcia, Central Italy	Mt.Vettore-Mt.Bove (NF)	6.5	50x40x21	280	1.5	30 Oct 2016	Özcebe et al. (2019)	6.5 Norcia 2016
		5.8						5.8 NorciaS01

Case Study	**Fault (SoF)**	**M_w**	**Model size (km^3)**	**$V_{s,min}$ (m/s)**	**f_{max} (Hz)**	**Event for validation**	**References**	**Included in BB-SPEEDset**
		5.5				Ideal scenarios		5.5 NorciaS01
Wellington, New Zealand	Wellington–Hutt (SS)	6.0-7.0	80x50x45	300	2.0	Ideal scenarios	Paolucci et al. (2014)	not included yet
Santiago, Chile	San Ramon (TF)	6.0 6.5 7.0	97x77x19	400	2.0	1 Apr 2010	Pilz et al. (2011)	not included yet
Istanbul, Turkey	North Anatolian Fault - Marmara Sea (SS)	5.7	165x100x30	250	1.5	26 Sept 2019	Infantino et al. (2021a) Stupazzini et al. (2021)	not included yet
		7.0				Ideal scenarios		7.0 IstanbulS16 7.0 IstanbulS20 7.0 IstanbulS23
		7.2				Ideal scenarios		7.2 IstanbulS05 7.2 IstanbulS09 7.2 IstanbulS19
		7.4				Ideal scenarios		7.4 IstanbulS02 7.4 IstanbulS12 7.4 IstanbulS20
Beijing, China	Shunyi-Qianmen-Liangxiang (TF)	6.5 6.9 7.3	70x70x30	200	1.5	Ideal scenarios	Antonietti et al. (2020)	not included yet
Groningen, the Netherlands	NF	3.4	20x20x5	150	10	8 Jan 2018	Paolucci et al. (2021)	not included yet
Kumamoto, Japan	Hinagu-Futagawa-Aso Caldera (SS)	7.0	53*46*22	500	1.5	15 Apr 2016 (16:25 UTC)	Sangaraju et al. (2021)	7.0 Kumamoto2016
	Hinagu-Futagawa (SS)	6.1				14 Apr 2016 (12:26 UTC)		not included yet
	Aso Caldera (SS)	5.5				15 Apr 2016 (18:03 UTC)		not included yet

Table 2 Structure of the BB-SPEEDset flat-file.

Source Metadata	Scenario ID	Hypocenter Lat/Lon/Depth	Strike, Dip, Rake	Fault mechanism
	Event ID	M_w	References	Rupture top
	Scenario ID card	Mo	ANN_database	Fault Vertices (*)
	Event_Time	Average slip	Transition period	Length (*)
	Event Nation Code	No. segments	ANN2BB_procedure	Width (*)
Receiver Metadata	Receiver ID			
	Receiver East/North coordinates			
	Receiver elevation			
Site Response Proxies	V_{S30}	H_{bed} (depth of the alluvial-bedrock interface)	V_{Sbed} (time averaged Vs from the surface to H_{bed})	
	V_{Seq}	H_{800} (depth to Vs>=800 m/s)	V_{S800} (time averaged Vs from the surface to H_{800})	
Source-to-Site Distances (†)	Epicentral dist.	R_line	Joyner and Boore distance, R_{jb}	
	Hypocentral dist.	Rx	R_rup	
Intensity Measures (‡)	PGA	SA(T) for T from 0.01 to 10 s	Pulse-like flag	Housner Intensity
	PGV	Permanent displacement	Pulse period	Arias Intensity
	PGD	Mean period	Ds595, Ds575	Cumulative Absolute Velocity

(*) Fault dimensions are given with respect to 'numerical fault' and 'effective fault'

(†) Distances from the fault are computed with respect to its "effective" dimensions

(‡) Except pulse features, Intensity Measures are defined for the following directions: NS, EW = horizontal; UD = vertical; HGM= horizontal geometrical mean; FN=Fault Normal; FP=Fault Parallel; D50 = median value of the IM distribution obtained from rotated waveforms; D100 = maximum value of the IM distribution obtained from rotated waveforms. (Rotation angles are given as well.)

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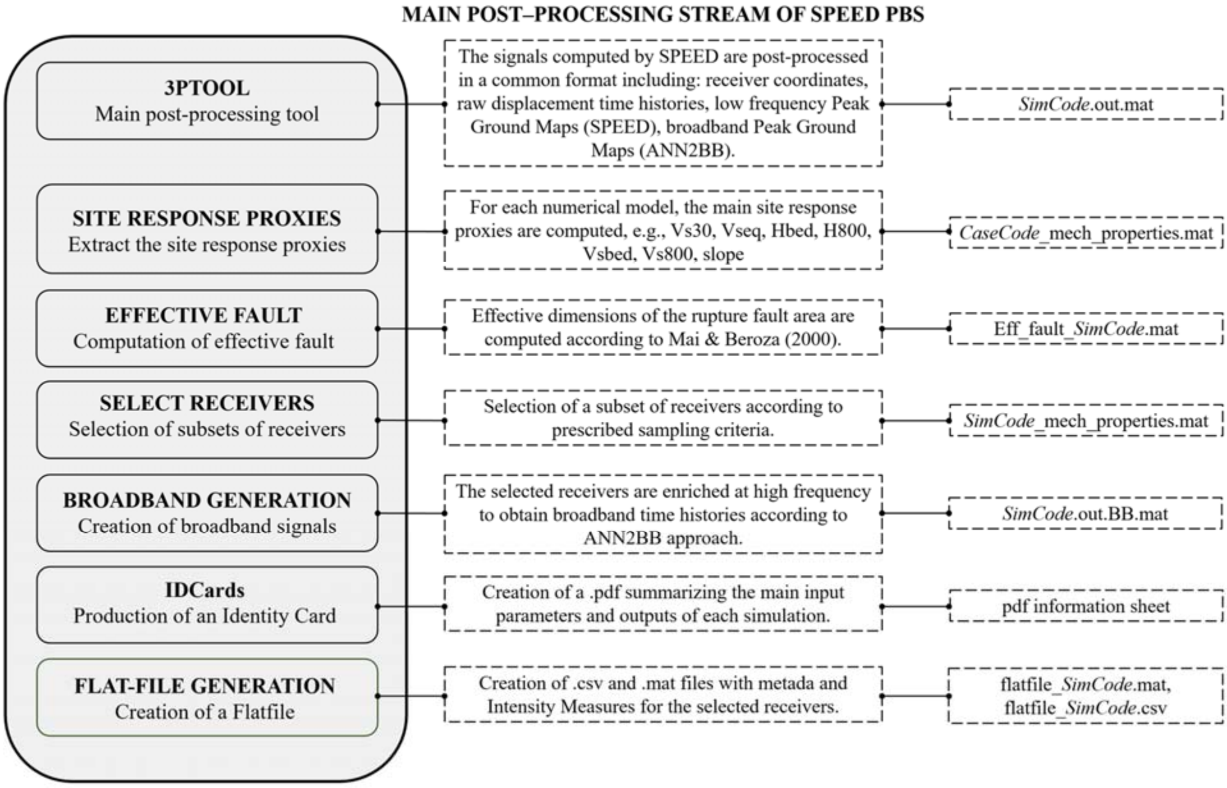

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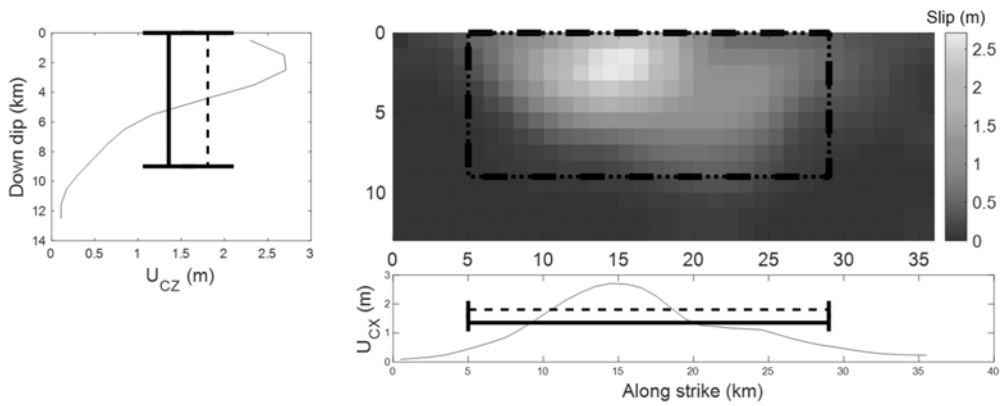

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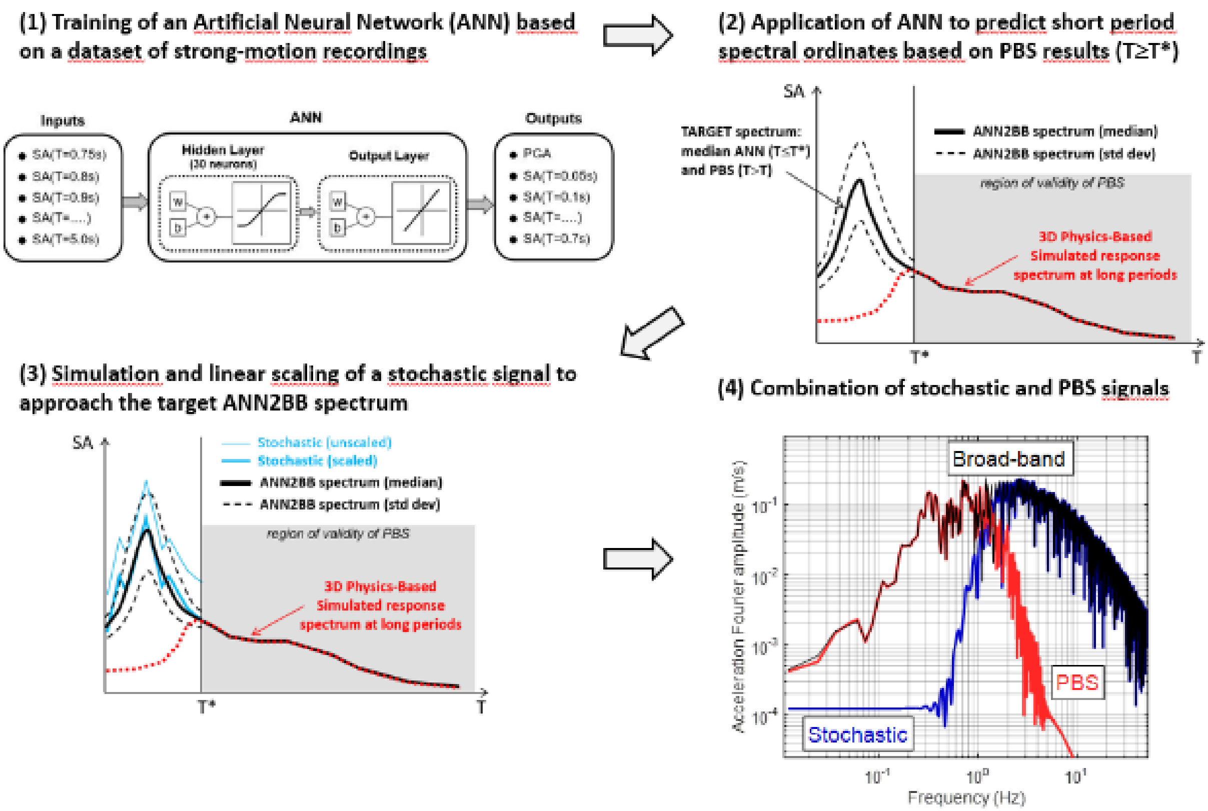

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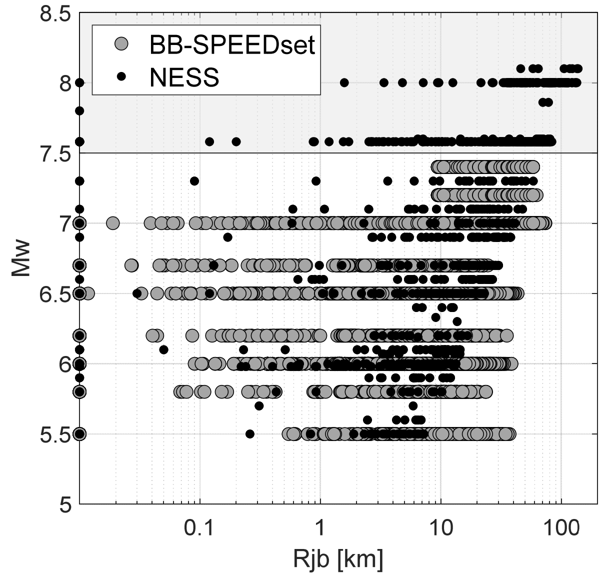

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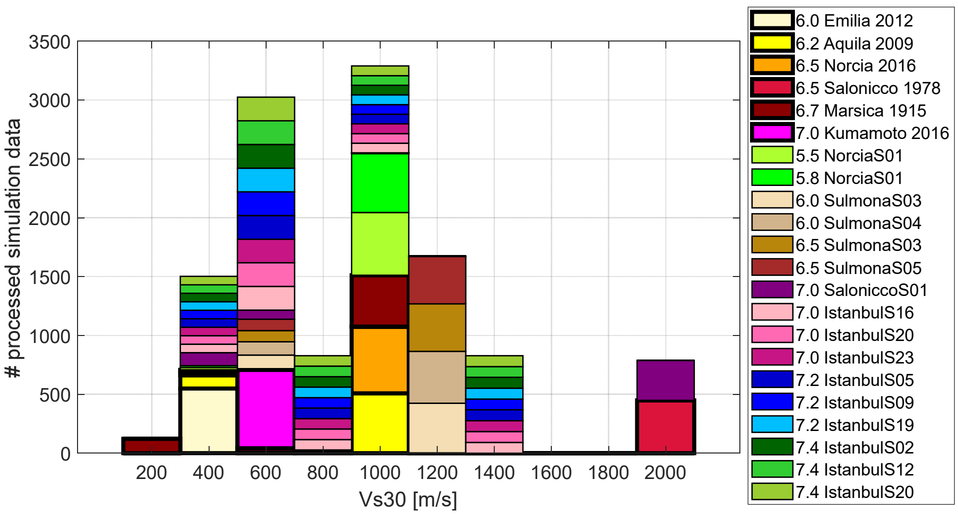

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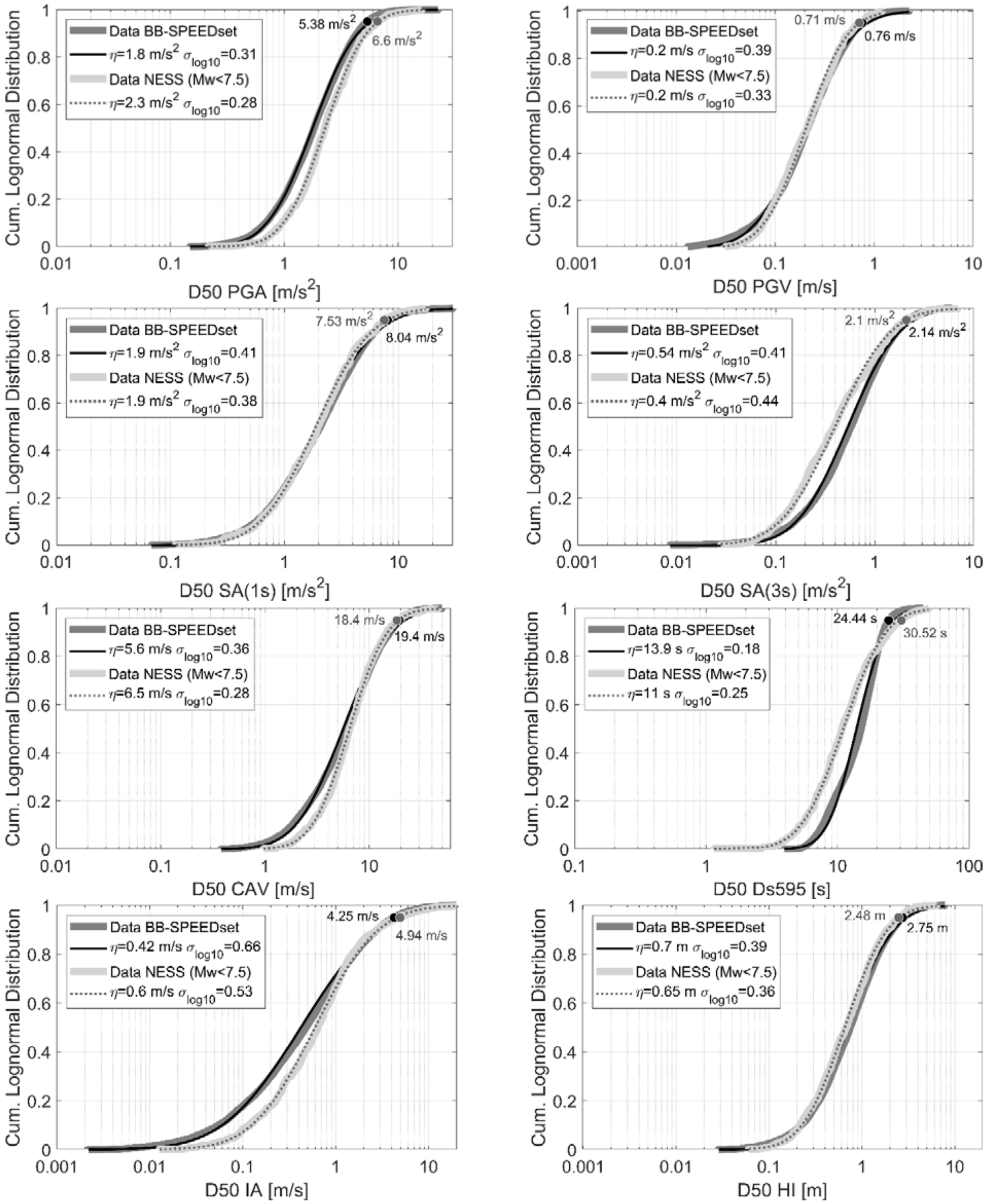

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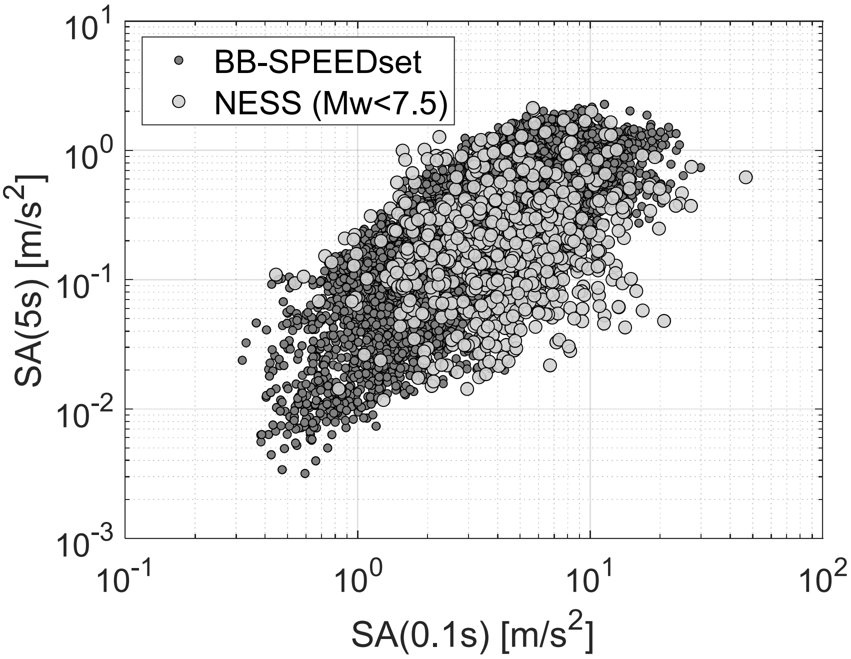

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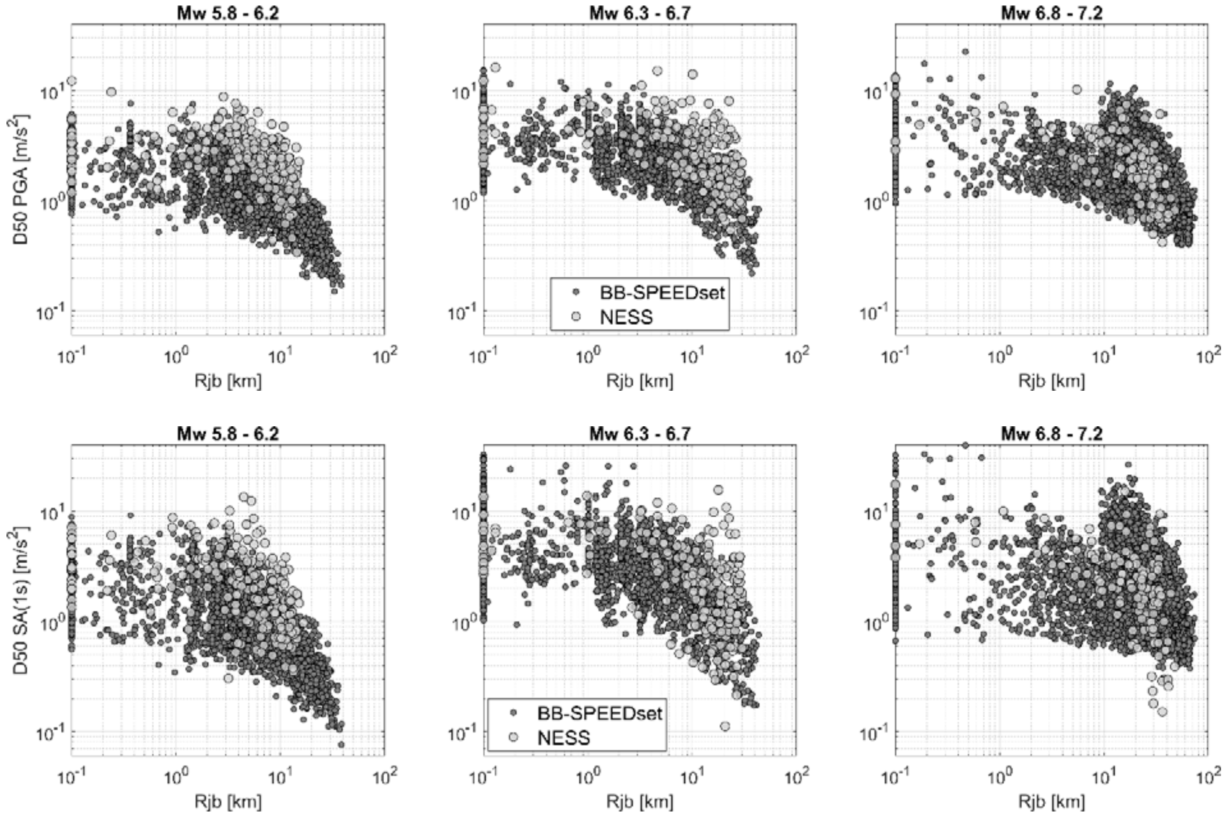

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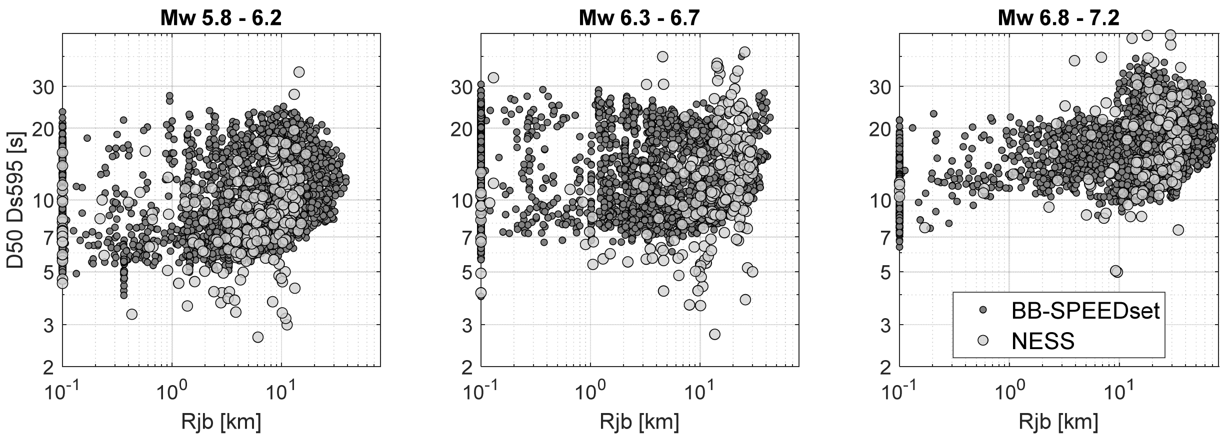

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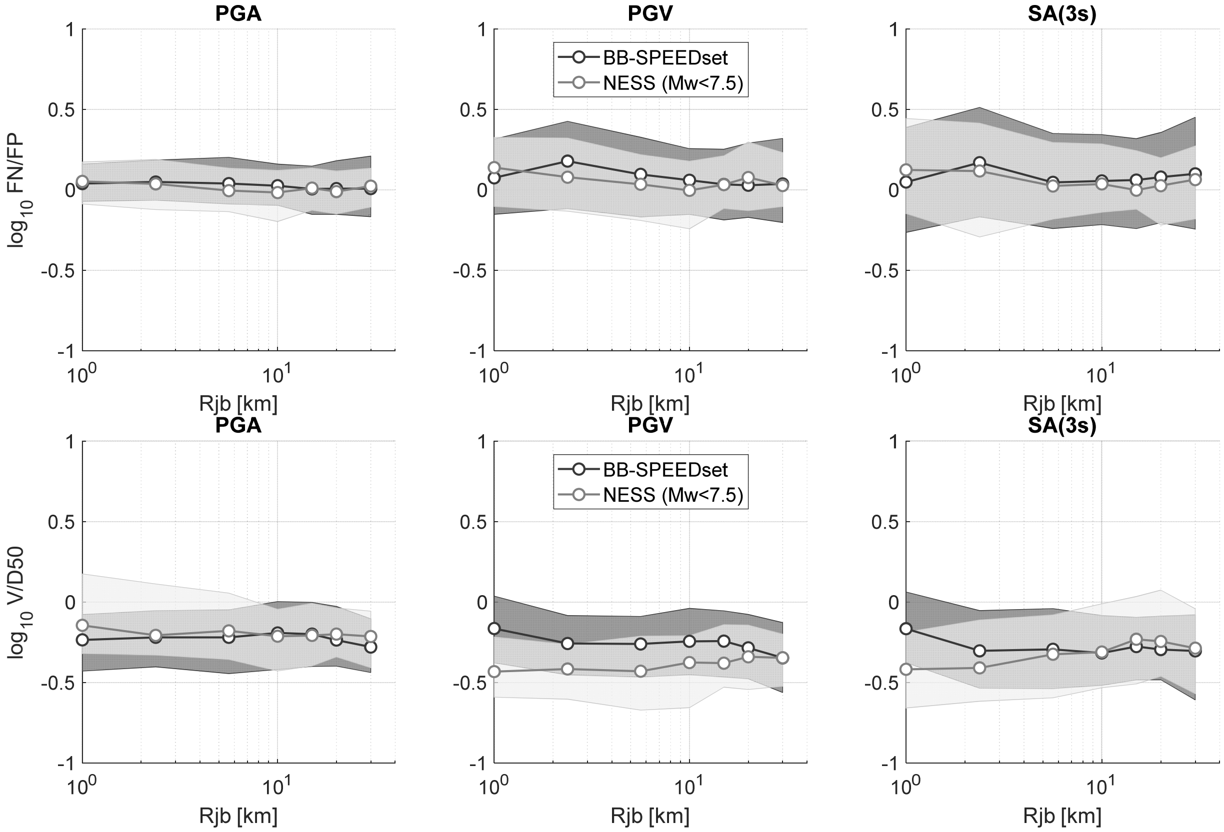

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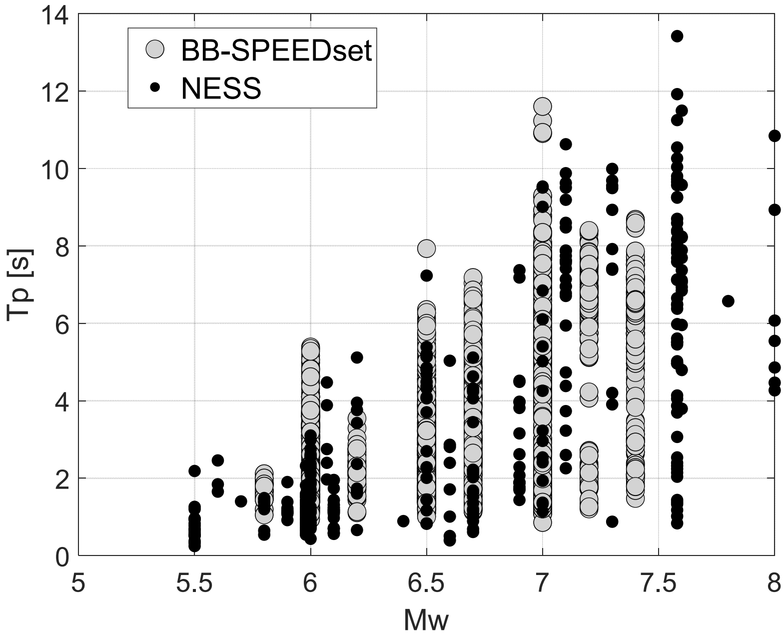

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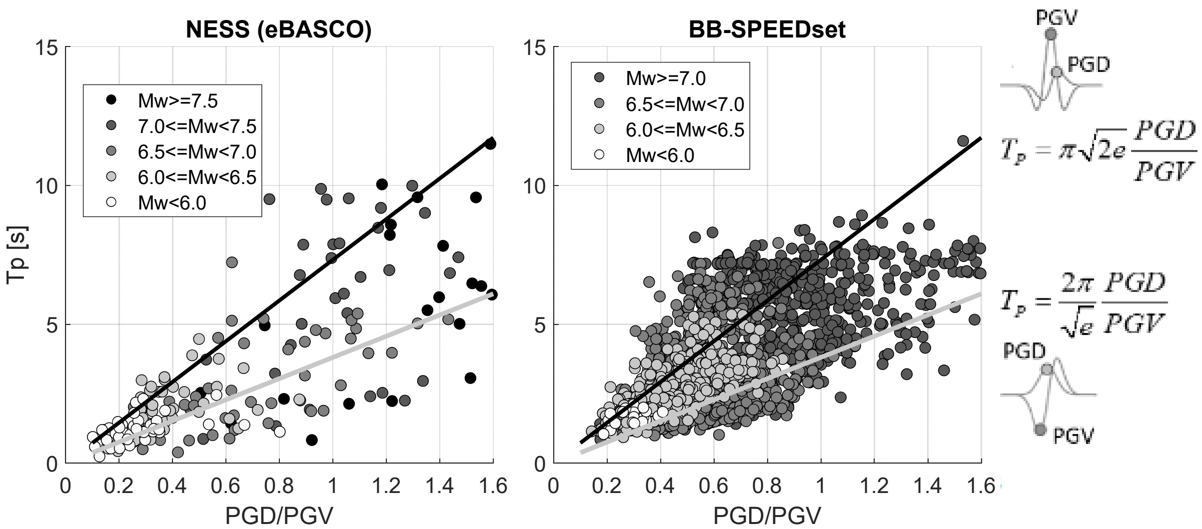

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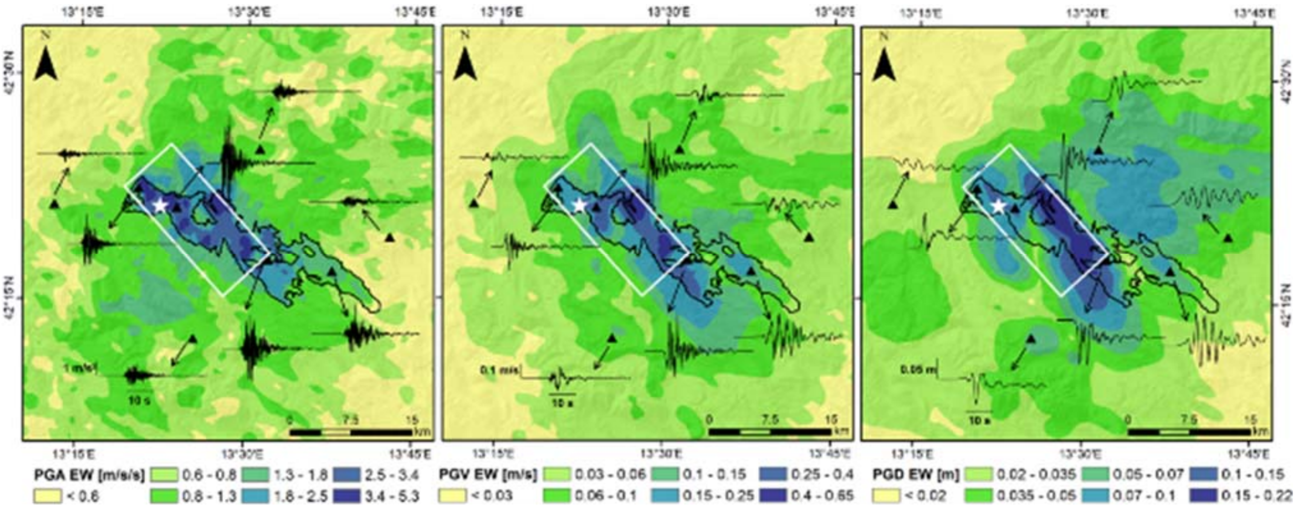

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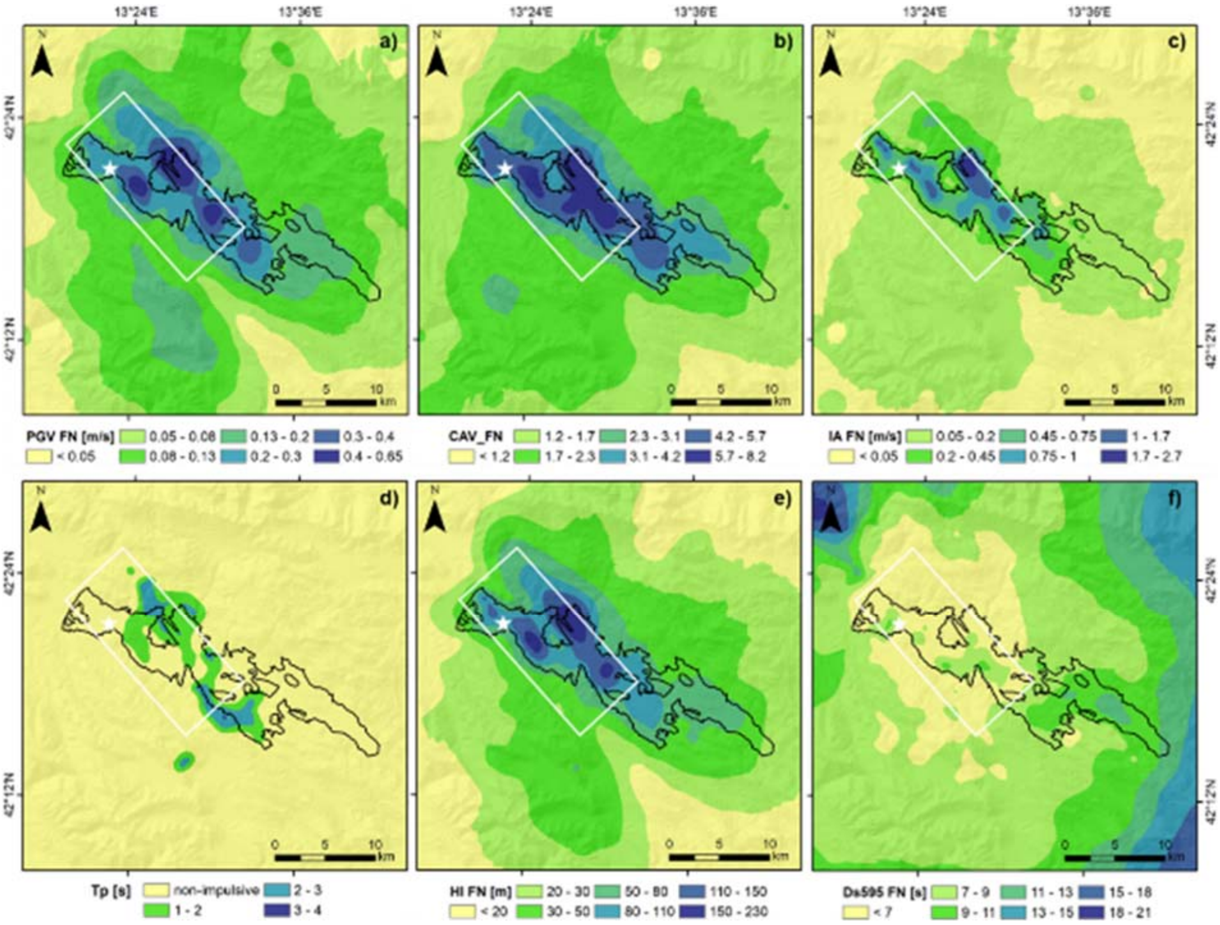

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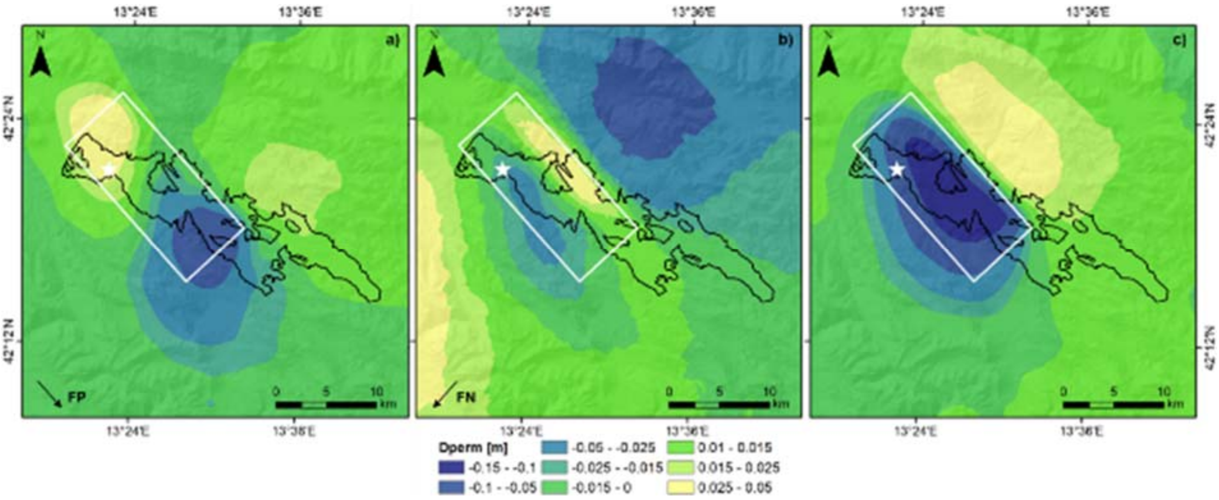

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