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PHYSICS-BASED SIMULATED ACCELEROGRAMS FOR ENGINEERING APPLICATIONS: THE BB-SPEEDSET

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Abstract: *The sparsity of ground motion recordings in the variety of source and site conditions controlling the seismic hazard at a site is still a challenge for several earthquake engineering applications, such as non-linear time history analyses of structural and geotechnical systems. Such issues may prevent a proper definition of the seismic input, especially in near-source conditions and complex geological configurations. With the progress of high-performance computing, physics-based numerical simulations (PBS) have emerged as one of the most promising tools in providing realistic region- and site-specific ground motions where records are lacking. Building confidence in the utilization of regional-scale PBS requires the availability of datasets of simulated accelerograms, subject to a comprehensive validation process, in a broad frequency range, from both seismological and engineering perspectives. This paper aims at presenting an updated version of BB-SPEEDset, a dataset of near-source broadband accelerograms obtained by the spectral element code SPEED (http://speed.mox.polimi.it/) from multiple earthquakes in different geological contexts. To strengthen the potential engineering uses of BB-SPEEDset, firstly, it is shown that the statistical distributions of different ground motion intensity measures, including directivity features, from BB-SPEEDset are in good agreement with those obtained from a near-source records dataset, within the same magnitude and distance range and in a broad range of frequencies. Secondly, illustrative applications of the BB-SPEEDset accelerograms as spectrum-compatible seismic input for non-linear time-history analyses of Single-Degree-Of-Freedom structures and slope stability studies indicate that simulations do not yield biases with respect to record-based analyses.*

1 Introduction

The last decades have been characterized by a continuous proliferation of worldwide accelerograph arrays that have made, and will continue to make, more and more high-quality data of strong motion records available. In spite of this, issues related to the paucity of records still persist in the near-source region, in particular geological conditions (such as very soft soils or hard rock), or from particularly dense spatial arrays needed for spatial variability studies.

The advancement of high-performance computing allowed physics-based numerical simulations (PBS) to progress notably, providing realistic region- and site-specific predictions of earthquake ground shaking. Based on a rigorous solution of the elastodynamic equation of motion on large-scale domains, simulations provide ground motion time histories that reflect the physics of the whole seismic wave propagation problem: from the fault rupture to the propagation path up to the local site response at shallow geology and to the soil-structure interaction of buildings (Graves and Pitarka 2010; Irikura and Miyake 2011; Mazzieri et al. 2013; Komatitsch et al. 2013; McCallen et al. 2021; Touhami et al. 2022). Therefore, PBS are nowadays well recognized by the scientific community as one of the most promising tools to face the knowledge gaps related to the sparsity of observations, that often prevents a proper definition of seismic input.

International seismic norms (e.g. the US standards ASCE/SEI 7-16, ASCE 2016, the Italian Technical Norms, NTC 2018, or the new draft of Eurocode 8 – EC8, CEN/TC 2021), include a specific reference to simulated ground motion, allowing practitioners to use simulated accelerograms when availability of recordings does not

cover the information needed to characterize the hazard at the site of interest (e.g. source mechanisms, near source data, source-to-site directivity conditions). In the norms it is highlighted that "*simulated accelerograms shall be consistent with the seismogenic features of the source, the propagation medium and the site conditions controlling the target spectrum, in a sufficiently wide range of vibration periods of interest for the specific application*".

In this contest, vetted datasets of simulated ground motions are being addressed to by different international research groups (Baker et al. 2021; Rezaeian et al. 2023; McCallen et al. 2023). In line with these efforts, the group at Politecnico di Miano has developed BB-SPEEDset, a dataset of near-source broadband accelerograms obtained from the 3D PBS (by the code SPEED, http://speed.mox.polimi.it/) of multiple earthquakes with different fault styles and in different geological contexts (Paolucci et al. 2021).

This paper aims at presenting an updated version of BB-SPEEDset (v2.2), which, in its present version includes about 19'000 three-component broadband accelerograms, from earthquakes with moment magnitude Mw between 4.9 and 7.4 at Joyner-Boore distances up to around 100 km. Data are provided as time histories of ground motion, with related information given in the form of extended flat files. Selected results of the seismological and engineering validation workflow conducted on BB-SPEEDset will be shown herein, as an essential proof of its applicability for engineering applications. In particular, an application example involving a dynamic slope stability analysis (Newmark approach) by means of both sets of recorded and simulated accelerograms, compatible with the same target spectrum, is discussed, in order to check the validity of BB-SPEEDset for geotechnical engineering analyses.

2 BB-SPEEDset: a validated dataset of simulated broadband accelerograms

The first version of the BB-SPEEDset was introduced in Paolucci et al. (2021), where an extensive discussion on the approach used to set up the dataset and on its consistency with observations was given.

The dataset consists of three-component time histories, numerically simulated by the code SPEED (Mazzieri et al. 2013) and, then, enriched in the high frequency range using a technique based on Artificial Neural Networks (ANN), referred to as ANN2BB (Paolucci et al. 2018; Paolucci et al., 2021), trained on strong ground motion recordings, in order to predict short period spectral amplitudes consistent with the ones at longer periods. Figure 2 shows the flowchart of the simulation approach to generate the BB-SPEEDset accelerograms.

Before storage, broadband waveforms from a simulated scenario are carefully processed and detailed comparisons with records (in case of the simulation of historical earthquakes) and/or with the observations from the NEar-Source recorded Strong-motion dataset (NESS, v2.0, Sgobba et al. 2021), in consistent ranges of magnitude and distances, are performed, to evaluate the degree of realism of the simulated data.

The dataset is currently in an advanced, updated version, being under continuous development as more processed numerical simulations become available. The current version includes a total of 10 validations of historical earthquakes, and 25 simulation scenarios (both covering a worldwide context). About 60% of the data comes from normal fault mechanisms, slightly less than 40% from strike-slip and only 2 simulations from reverse faulting. Concerning soil classes, the majority of the waveforms (about 76%) is on stiff soil with V_{S30} > 600 m/s, but there are some waveforms (nearly 1%) on very soft sites with V_{S30} < 200 m/s. A number of ground motion intensity measures, IMs, for different horizontal and vertical directions (including rotD50 and rotD100 measures), are stored in the flat-file of the dataset, for each receiver and for each scenario, together with source-to-site distances, receiver and source metadata, site response proxies and information about the postprocessing ANN2BB procedure. IMs were consistently selected with the ones in the NESS flat files (Lanzano et al. 2018, Sgobba et al. 2021).

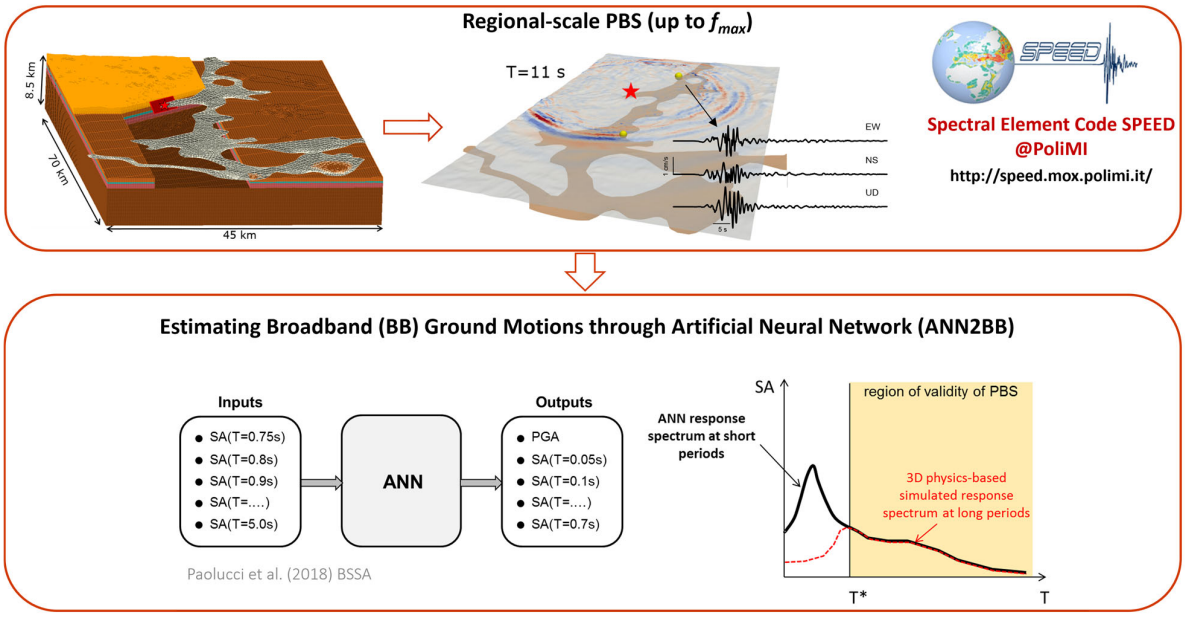

Figure 1. Flowchart of the simulation approach to generate the BB-SPEEDset accelerograms: from the 3D Physics-Based numerical calculations with SPEED code (top panel), to the high frequency enrichment of the ANN2BB technique (bottom panel).

Error! Reference source not found. shows the distribution of the current version of the BB-SPEEDset data against the NESS one, in terms of magnitude Mw and Joyner and Boore distance R_{JB}. Note that comparisons among the two datasets are always performed considering the same Mw- R_{JB} ranges, i.e. the ones highlighted by the shaded region in the figure.

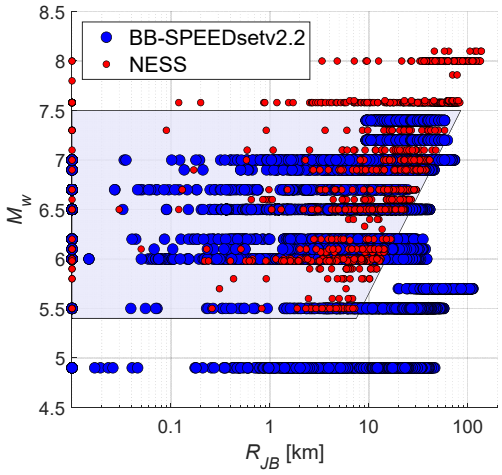

Figure 2. Distribution of data from BB-SPEEDset (blue circles) and NESS dataset (red dots, after Sgobba et al., 2021). The shaded region highlights the data in comparable ranges of magnitude Mw and distance R_{JB}.

Figure 3 shows an example of consistency check, comparing, for the fault normal (FN) component, in consistent ranges of magnitude and distance, the cumulative distribution functions of peak ground acceleration, velocity, duration Ds595, cumulative absolute velocity CAV, Arias and Housner Intensity, from simulated and recorded data. These comparisons show a rather good agreement between the two

independent datasets, both in terms of median and standard deviations (σ_{log10}). PGA, as remarked in Paolucci et al. 2021, tend to underestimate the recorded values, probably because of the inaccuracy of the ANN2BB approach in the estimation of longer periods (in relation to shorter ones). The excellent agreement between the two datasets in the spectral acceleration values at longer periods is clearly shown in this figure as well as in Figure 4.

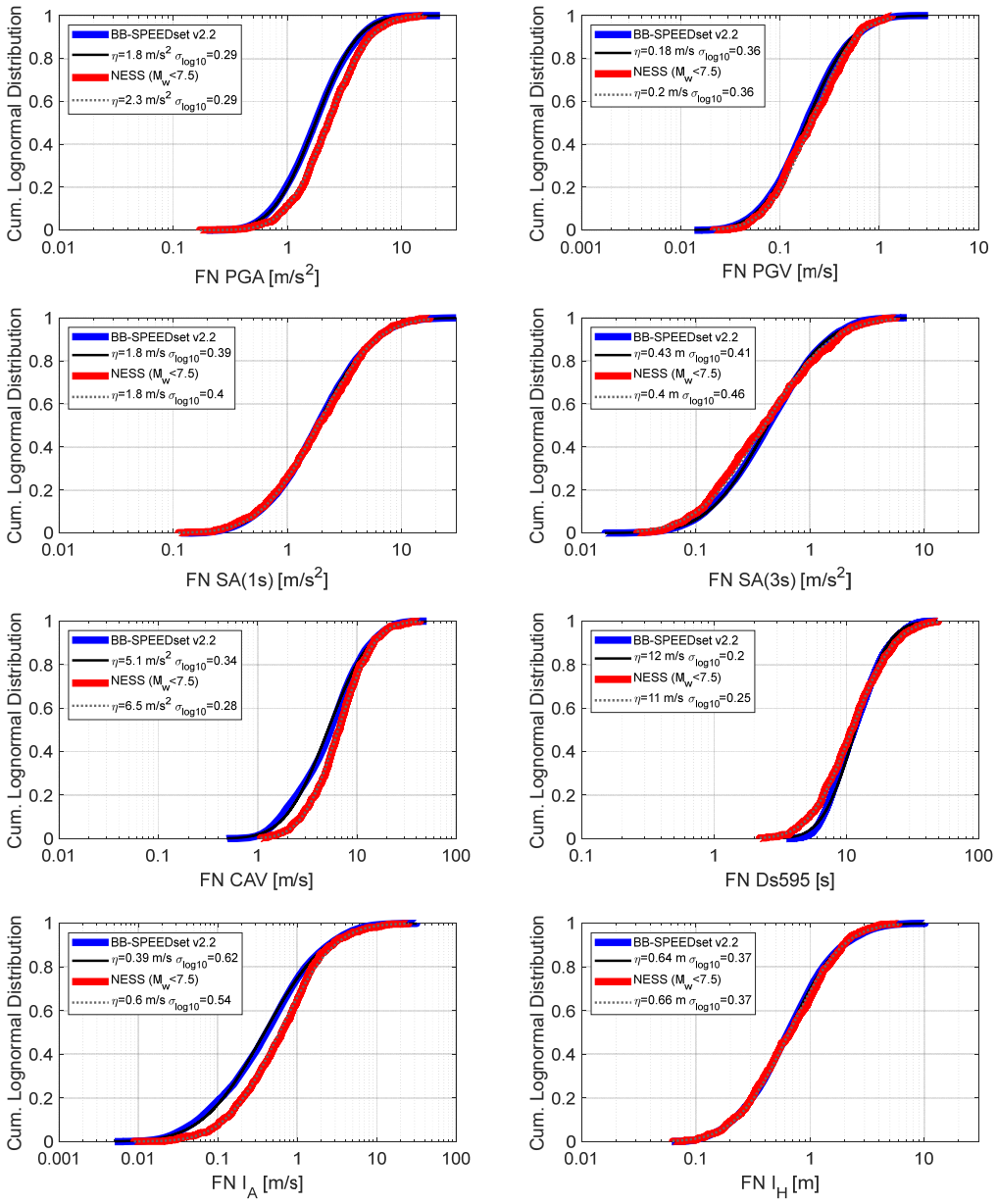

Figure 3. Cumulative distribution functions of peak ground acceleration (PGA), peak ground velocity (PGV), spectral acceleration (SA)(1.0 s), SA(3.0 s), cumulative absolute velocity (CAV), Ds595, Arias intensity (IA), and Housner intensity (IH), as obtained from BB-SPEEDset and from NESS. The empirical distributions are shown in color, while the best-fitting lognormal ones in black (continuous or dashed lines).For all intensity measures (IMs), the fault normal (FN) component is considered.

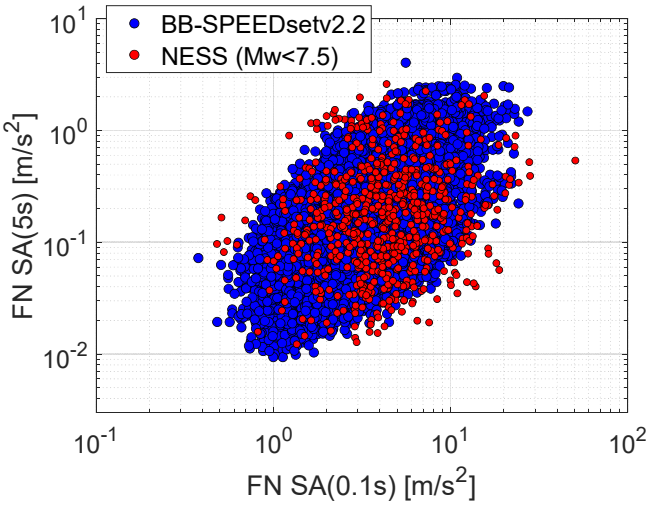

Figure 4. SA(0.1 s) and SA(5 s) distribution from BB-SPEEDset (blue) in comparison with that from NESS (red) in the same range of magnitudes and distances (see shaded region in Figure 2). The FN component is considered for both spectral accelerations.

Owing to the importance of the impulsive characteristics of near fault motion, in engineering applications, a careful investigation on pulse-like features of simulated ground motion has been performed, identifying and comparing pulse period Tp values (i.e., the pseudo-period of the wavelet extracted from the velocity signal, Shahi and Baker, 2014) with the ones estimated in NESS from observations (using consistent techniques). Figure 5 and Figure 6 show respectively comparisons of Tp from BB-SPEEDset and NESS, as a function of Mw, or as a function of the amplitude characteristics of the related motion (in this case given by PGD/PGV, ratio of displacement versus velocity peak values). As explained in Paolucci et al. 2021 in detail, these figures show that the impulsive features of the simulated motion are completely consistent with empirical observations; in particular, Figure 6 shows a reasonably good agreement between the two sets within comparable magnitude ranges (see e.g Mw from 6.0 to 7.4).

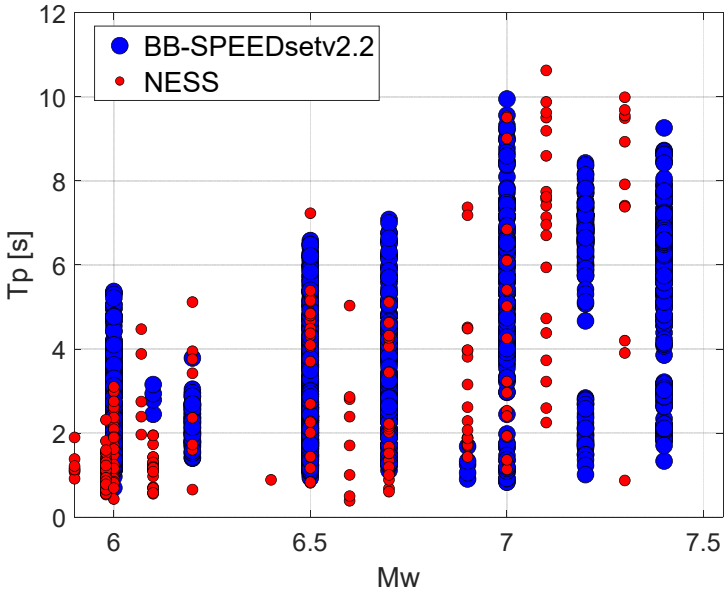

Figure 5. Pulse period Tp versus earthquake magnitude Mw for observed pulse-like ground motions of BB-SPEEDset (15% of set data, in blue) and NESS dataset (almost 30% of whole set data, in red).

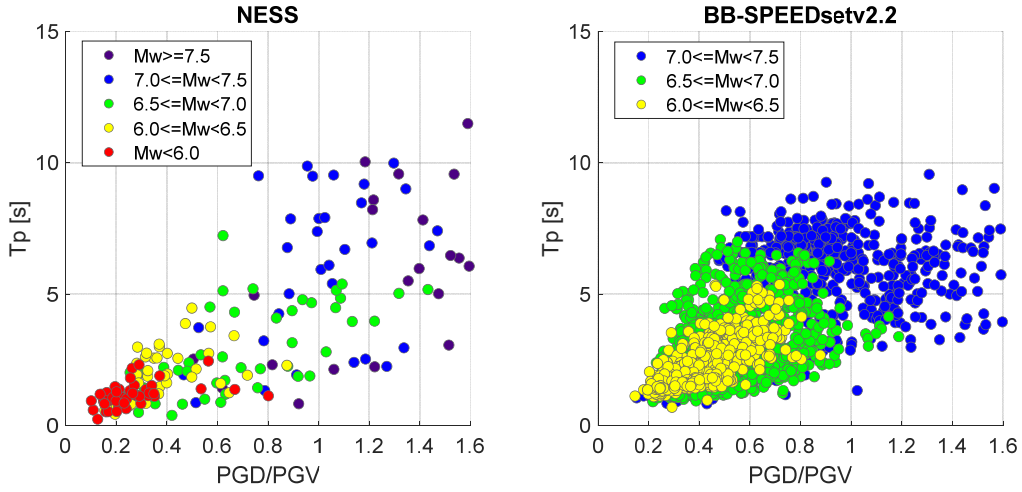

Figure 6. Pulse period Tp as a function of PGD/PGV for NESS (left) and for BB-SPEEDset (right), for different magnitude ranges. To improve the accuracy of the PGD estimations from the NESS dataset, Tp and peak values from the e-BASCO baseline corrected waveforms were herein considered (see Sgobba et al., 2021 for details).

3 Engineering validation of BB-SPEEDset

In line with the efforts in conducting validation studies on simulated motions as available in the literature (see e.g. Galasso et al. 2012; Burks et al. 2015; Zhong et al. 2021; Petrone et al. 2021), this Section aims at presenting a brief overview of the engineering validation made on BB-SPEEDset, with reference to both structural and geotechnical applications. For the structural analyses, elastoplastic Single-Degree-of-Freedom (EPP SDoF) systems, with variable period T and different strength reduction factors R, are considered. For the geotechnical application, a dynamic slope stability analysis has been employed using the simplified approach proposed by Newmark in 1965 (Kramer, 1996). In both cases, the ground motion time series required as input for the dynamic analyses are selected using the software tool Select&Match - S&M (Manfredi et al., 2022). Specifically, for the validation purpose, two sets of spectrum-compatible ground motions, one from a recorded database (NGA-West2, Ancheta et al., 2013) and one from BB-SPEEDset are selected, according to the same spectrum compatibility criteria. Referring to Manfredi et al. (2022) for a detailed presentation of S&M, we limit herein to underline that the key feature of S&M is the integration of datasets of both recorded and simulated motions, allowing the user to perform queries, searches and selection of hybrid suites of ground motions in a flexible way. The tool includes also new options for the selection of pulse-like motions with pulse period within prescribed ranges.

Figure 7 show some illustrative examples of the engineering validation of BB-SPEEDset, using spectrum-compatible sets of recorded (NGA-West2, red) and simulated (BB-SPEEDset, blue) accelerograms, from dynamic analyses on elastoplastic SDoF systems with varying period T and R=4 (a); and from Newmark's slope stability analyses for a canonical slope inclined at angle β=20° and with variable friction angle ϕ (b). The structural analysis in (a) shows the behaviour of the normalized ductility demand (i.e. the inelastic-to-elastic displacement ratio) as a function of T, while the geotechnical analysis in (b) shows the permanent displacement of the slope as a function of ϕ. In general, for both cases, a very good agreement is found both in terms of median values and in terms of standard deviation. For the slope stability analyses, further studies shall be performed to increase the number of input motions to understand the discrepancies at low values of friction angles.

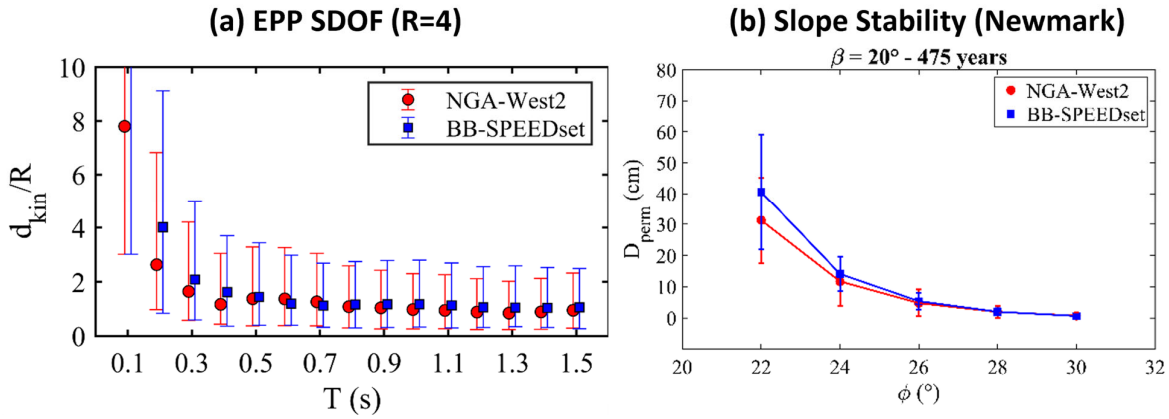

Figure 7. Illustrative examples of the engineering validation of BB-SPEEDset from spectrum-compatible sets of recorded (NGA-West2, red) and simulated (BB-SPEEDset, blue) accelerograms. (a) normalized ductility demand (Dkin/R) of elastoplastic SDoF systems as a function of period T and for R=4; (b) Permanent slope displacement, D_{perm}, as a function of the friction angle, on a plane inclined at β=20°.

4 Conclusions

In this paper, an updated version of the broadband dataset of simulated 3D ground motion (BB-SPEEDset v. 2.2) is presented, together with illustrative examples of the engineering utilization of its ground motion time series. BB-SPEEDset is a dataset of near-source accelerograms simulated with the numerical spectral code SPEED, in a worldwide context of scenarios and earthquakes (Mw=5.5-7.4), suitably enriched in the high frequency range with ad-hoc trained ANN.

Being the validation of simulated accelerograms a seminal step to build confidence in the engineering use of numerical simulations of earthquake ground motion, in this work emphasis is placed on the validation of the BB-SPEEDset, both from a seismological point view and from the point of view of a practical end-user engineer.

Concerning the former requirement, a few results of an extensive verification procedure on the main features of ground motion inferred from BB-SPEEDset are shown, providing a very satisfactory consistency with the ones from the near-source records dataset NESS. From the engineering point view, tests performed to ensure a confident use of simulated ground motion in structural and geotechnical engineering analyses are shown. The behaviour of inelastic SDoF systems under spectrum-compatible sets of recorded and simulated input motions is found to be consistent, as well as results of dynamic slope stability analyses, performed with the Newmark approach, using sets of recorded and simulated accelerograms, compatible with the same target spectrum. Although further analyses shall be performed, such preliminary findings are quite encouraging in showing the potentiality of simulated accelerograms in dynamic analyses of engineering systems.

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