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PSHAe (Probabilistic Seismic Hazard Analysis enhanced): the case of Istanbul

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ABSTRACT: The Probabilistic Seismic Hazard Analysis (PSHA) only relying on Ground Motion Prediction Equations (GMPEs) tends to be insufficiently constrained at short distances and data only partially account for the rupture process, seismic wave propagation and three-dimensional (3D) complex configurations. Given a large set of 3D scenarios, analysing the resulting database from a statistical point of view and implementing the results as a generalized attenuation function (GAF) into the classical PSHA might be an appealing way to deal with this problem (Villani et al., 2014). Nonetheless, the limited amount of computational resources or time available tend to pose substantial constrains in a broad application of the previous method and furthermore the method is not suitable for taking into account the spatial correlation of ground motion as modelled by each forward physics-based simulation (PBS). Given that, we envision a streamlined and alternative implementation of the previous approach, aiming at selecting a limited number of scenarios wisely chosen and associating them a probability of occurrence. 3D numerical modelling of scenarios occurring along the North Anatolian Fault in the proximity of Istanbul are carried out through the code SPEED in order to implement the results into a PSHA according to the previously mentioned procedure.

1 INTRODUCTION

Forward physics-based modelling has achieved in the recent time an impressive level of reliability (see e.g. Bielak et al. 2010, Guidotti et al, 2011; Smerzini and Villani, 2012) allowing, in certain range of frequencies, the use of synthetic ground motions or scenarios (e.g.: peak ground map obtained from the numerical simulation of an earthquake) as alternative or complementary tool to more traditional techniques mainly based on observed data (e.g., NGA database: http://peer.berkeley.edu/ngawest2/).

In spite of the advantages of using this methodology, some severe drawbacks, like the (i) covered range of frequencies, (ii) geological and geotechnical data required and (iii) computational costs, have been always pointed out as a reasonable justification to limit the use of this kind of methodology only to few selected case study. In order to prove that the limitations previously listed are losing their status of "cogent argument" and to promote a wider use of forward physics-based modelling, the following actions have been undertaken:

(i)creating (and maintaining) a "state-of-the-art" code for the study of elastodynamic wave propagation problems. The open-source code SPEED (SPectral Elements in Elastodynamics with Discontinuous Galerkin; http://speed.mox.polimi.it) described in Mazzieri et al. (2013) and Paolucci et al. (2014), succeeded in quantifying the spatial variability of the ground motion induced by key parameters like (a) complex deep soft soil structure, (b) directivity effect and (c) soil non-linearities;

(ii) creating (and maintaining) a freely available repository of physics-based scenarios (PBS); the large set of footprint scenarios has been identified worldwide in order to cover locations with a severe impact for the society, mainly focusing on areas that have not been already investigated;

(iii) allowing researchers to freely use SPEED (and all its products) and to contribute to its further

development and use.

The use of PBS in a probabilistic seismic hazard analysis (PSHA) environment is clearly one of the most promising areas of advancement in the frame of natural hazard assessment (Boore, 2014). Villani et al. (2014) presented an appealing way to deal with this problem: starting from a large and representative set of 3D scenarios, analysing the resulting database from a statistical point of view and finally implementing the results as a generalized attenuation function (GAF) into the classical PSHA. Nonetheless, the limited amount of computational resources or time available tend to pose substantial constraints in a broad application of the previous method and furthermore the method is unsuitable for properly taking into account the spatial correlation of ground motion as modelled by each forward physics-based simulation.

Given that, this work presents a streamlined and alternative implementation of the previous approach, aiming at (i) selecting wisely a limited number of representative scenarios and (ii) associating each of them with a probability of occurrence. The experience gathered over the past years regarding 3D ground shaking scenarios allowed us to enhance the choice of those latter in order to explore the variability of ground motion, preserving the full spatial correlation necessary for risk modelling, as well as the simulated losses for a given location and a given building stock.

Due to the innovative and challenging character of these tasks, some areas of further development arise as critical in order to accomplish the sketched strategy: tools improvement, process development and methodological advancement.

2 TOOLS IMPROVEMENT

2.1 Design of a software package for automatic earthquake scenario simulation and data post-processing

In addition to SPEED, different pre- and post-processing tools (see following paragraphs) have been created and merged into a single software package, capable to generate automatically a set of PBSs, given a specific fault, a prescribed magnitude range and a number of different realizations required.

2.2 Automatic generation of seismic slip distributions

A pre-processing tool has been devised, in order to automatically construct N physically constrained slip distributions for a given fault and a given earthquake magnitude, taking into account joint probability distributions of the main kinematic parameters. This is necessary to control that the resulting scenario variability will be not affected by systematic bias in the input parameters. Given a fault type (e.g., reverse (R), normal (N) or strike slip (SS)) and a target magnitude M (e.g., 6.5, 7 or 7.5) a Matlab routine computes suitable input parameters for the generation of a slip distribution according to a k^2 model (Herrero & Bernard 1994). In particular the fault length (L), the fault width (W), the maximum displacement (MD) and the average displacement (AD) of the slip distribution are computed using the well-known relations by Wells & Coppersmith (1994). In addition the hypocenter position (Hypo) and the asperity locations (AL) are calculated run-time randomly, using a Gaussian distribution for the former (with mean μ = 10 km depth and variance s^2 = 2 km) and uniform distribution for the latter. After this process, the slip distribution is randomized in a suitable way to radiate seismic energy in a broadband frequency range, limited by the resolution of the numerical mesh.

For each of these N physically constrained slip distributions a PBS is computed through SPEED for a specific area; the synthetic seismograms are, then, post-processed as follows.

2.3 Broadband scenarios through an Artificial Neural Network-based procedure

To overcome the frequency limitation of the numerical simulations, a novel approach is proposed to generate broadband ground motions (referred to as BB hereinafter), with realistic features in the entire frequency range of interest for engineering applications (say between 0 and 25 Hz), using Artificial Neural Networks (ANN) combined with spectral matching techniques.

The main steps of this approach can be summarized as follows (see Figure 1):

1) Training of an ANN based on recorded earthquake ground motions (namely, SIMBAD database, presented in Smerzini et al., 2014) to predict M response spectral ordinates at short period (SP, T≤T*, being T the vibration period and T* a suitably chosen corner period) from N spectral ordinates at long period (LP, T>T*);
2) For each site of interest and for a given scenario, the trained ANN is applied to estimate the SP response spectral ordinates, taking as input the LP spectral ordinates computed from SPEED ground motions. Hence, a target broadband response spectrum is constructed, combining the LP ordinates produced by SPEED with the SP ordinates predicted by the ANN;
3) Application of spectral matching techniques to the LP time histories produced by SPEED to obtain BB ground motions fitting the target spectrum obtained at previous point.

To design the network, the following assumptions have been made: (i) a two-layer feed-forward (2LFF) neural network with 30 sigmoid hidden neurons and a linear output neuron was trained with the Levenberg-Marquaredt algorithm, using the neural network fitting tools (*nftool*) implemented in Matlab; (ii) inputs are N=23 ground motion parameters, specifically, $Log_{10}[SA(T_j)$, PGV, PGD], where SA is the pseudo-acceleration response spectral ordinates at period T_j, ranging from 0.6 s to 5 s, PGV is the Peak Ground Velocity and PGD is the Peak Ground Displacement; (iii) outputs are M=7 ground motion parameters, specifically, $Log_{10}[SA(T_k)]$, at periods T_k = 0 (PGA = Peak Ground Acceleration), 0.05, 0.1, 0.2, 0.3, 0.4 and 0.5 s. Note that T*=0.5 s in this study and its choice is related to the frequency limit of the numerical simulations.

For the application presented in this work, we have limited our attention to the construction of the broadband target response spectrum (step 1 and 2 of the procedure). In this context, training of the ANN has been performed using the geometric mean of the horizontal components; however, the procedure can be extended by training different ANN separately for the three components of motion.

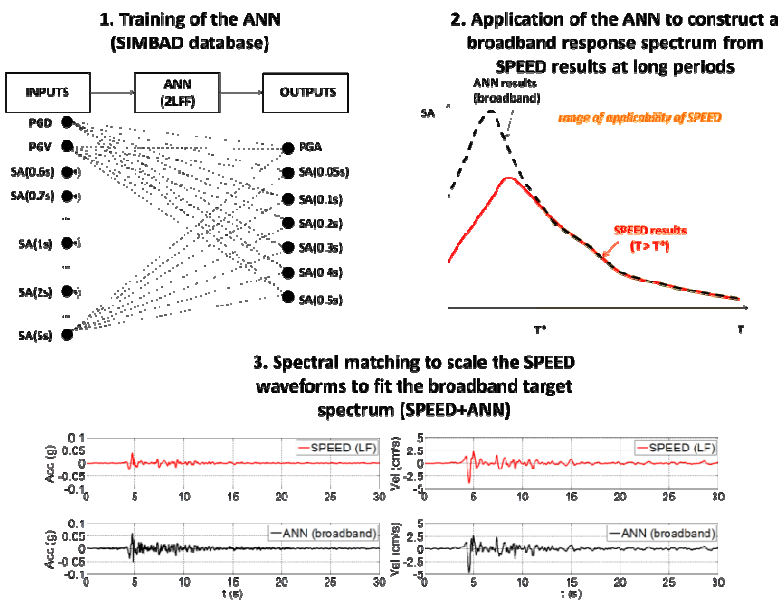

Figure 1 Sketch of the procedure to generate BB ground motions from SPEED scenarios.

3 APPLICATION TO THE ISTANBUL CASE STUDY

The numerical model of the Istanbul case study extends over an area of 165x100x30 km^3, see Figure 2 (left). The top surface of the domain has been built by gluing together the topographic layer, obtained by digital elevation dataset of CGIAR-CSI for the Tracia region (with a precision of roughly 70 x 90 m, for east-west and north-south directions), and the bathymetry model (in agreement with Özsoy et

al. 2000 and Rangin et al. 2001). The geometry of the Central Marmara Basin (CMB) and the North Boundary Fault (NBF) located about 20-30 km south-west and south of Istanbul, respectively, has been also taken into account, see Figure 2. The underlying layers describing the bedrock morphology is derived by the interpretation of seismic profiles presented in Cotton et al. (2006) and Gurbuz et al. (2000), see Table 1.

According to the geotechnical site characterization provided by Özgül (2011), a three-step procedure has been adopted to define the 3D soil model. First the digitalization of the maps presented by Özgül (2011) has been performed and $V_{S,30}$ and rock/soil information for the whole Istanbul region have been obtained. Second, by making use of three sets of data, namely $V_{S,30}$, rock/soil map and slope information (extrapolated by QGIS, www.qgis.org), different site classes have been assigned ranging from $V_{S,30}$ = 250 m/s to $V_{S,30}$ = 1350 m/s, see Figure 2 (right). Third, the model has been improved for the Avcılar zone, in which significant soil effect has been noted in 1999 Kocaeli Earthquake (see Tezcan et al., 2002), by re-assigning the soil class as the softest. Following the third step, six V_S profiles have been considered as shown in Figure 3.

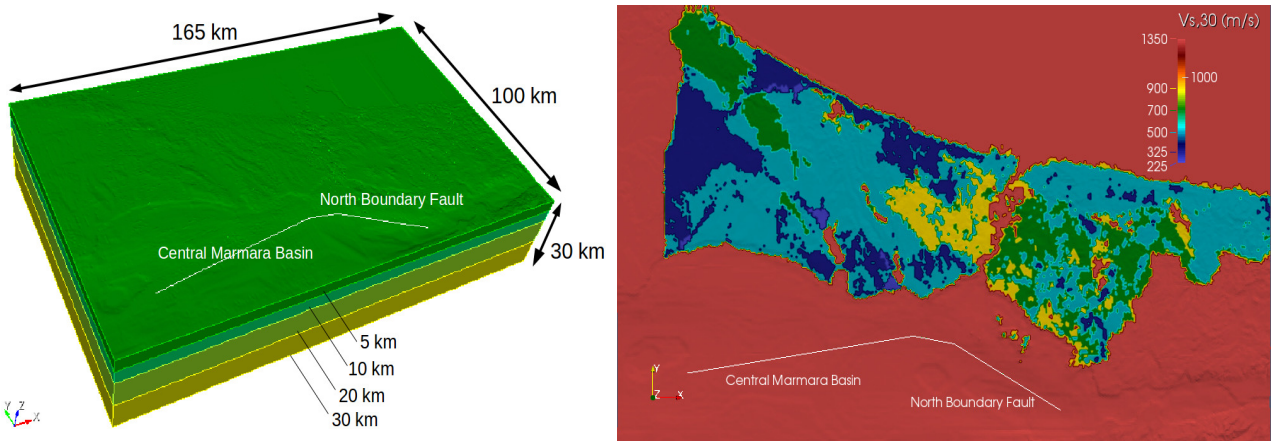

Figure 2 – Computational domain of the Istanbul region adopted in the present work. Fault system (CMB and NBF) included in the domain as well as topography and bathymetry model (left). $V_{S,30}$ classes defined according to Özgül, 2011 (right).

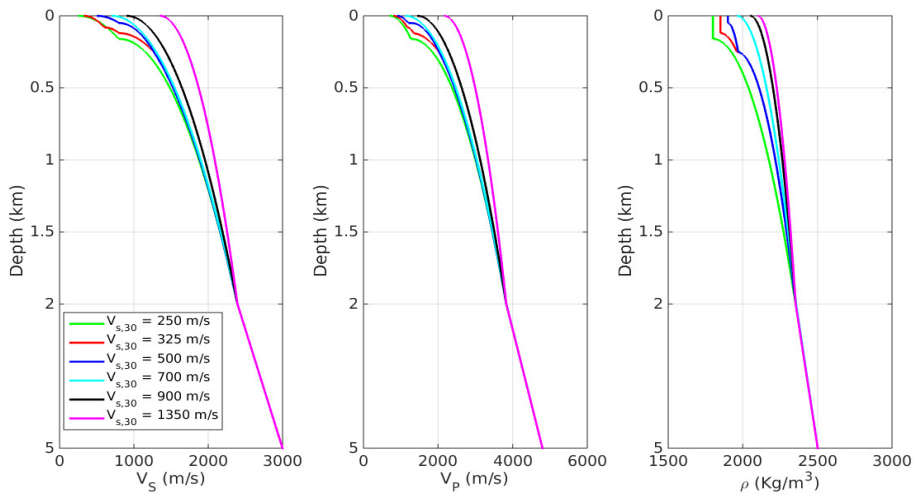

Figure 3 – V_S, V_P and mass density ρ profiles adopted in the present work for the six soil classes considered in the first layer (0 to 5 km depth) of the computational domain.

Finally, according to the geotechnical characterization, the alluvial soft deposits for the classes $V_{S,30}$ = 250 m/s $V_{S,30}$ = 325 m/s are assumed to behave as a non-linear visco-elastic medium, characterized by a unique value of density (ρ), Poisson ratio (ν) and shear wave velocity V_S profile. The non-linear

behavior the above mentioned deposits are idealized by making use of the normalized shear modulus degradation-cyclic shear strain and the damping ratio-cyclic shear strain curves of Darendeli (2001) model with plasticity index (PI) of 10-30, and mean effective stress (p'_0) of 3 atm (see Figure 4).

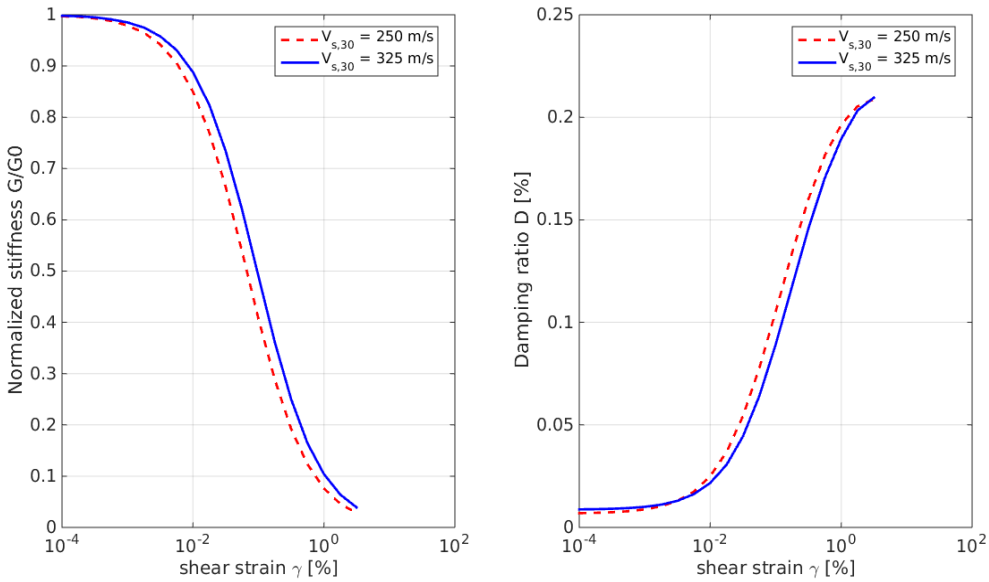

Figure 4 – Normalised shear modulus (left) and damping ratio (right) versus shear strain for the soil class $V_{s,30}$=250,325 m/s.

The quality factor Q is derived directly by the V_S values and is assumed to be proportional to frequency as $Q = Q_0 \cdot f$, with Q_0 set for the target value $Q = V_S/10$ to be obtained at f = 1 Hz. Then, the soil model parameters are summarized in Table 1.

Table 1 – Horizontally stratified crustal model assumed for the Istanbul region.

Depth (km)	V_S (m/s)	V_P (m/s)	ρ (kg/m^3)	Q
0-5	Fig.3	Fig.3	Fig.3	V_S/10
5-10	3490	5770	2600	350
10-20	3500	6390	2700	350
20-30	3920	6790	2800	400

The computational domain has been built based on the model previously described and numerical simulations were performed using the code SPEED (Mazzieri et al. 2013). Considering a rule of thumb of 5 grid points per minimum wavelength for non-dispersive wave propagation in heterogeneous media by the SE approach (cf. Antonietti et al. 2012), and considering a maximum frequency f_{max} = 2 Hz, the model consists of 2,257,482 hexahedral elements, resulting in approximately 475 million of degrees of freedom, using a fourth order polynomial approximation degree. The conforming mesh that has been set up has a size varying from a minimum of 180 m, on the top surface, up to 600 m at 2 km depth and reaching 1800 m in the underlying layers.

The distinctive features of the numerical model are (i) a kinematic representation for the seismic faults CMB and NBF, see Figure 2, and (ii) inclusion of a 3D velocity model of the Istanbul region, taking into account the spatial variation of the most relevant geologic discontinuities beneath the surface sediments, which have significant effects on the seismic wave propagation, see Table 1 and Figure 3. A time step equal to 0.001s has been chosen for the time marching scheme and a total observation time T = 60 s has been considered. The simulations have been carried at FERMI cluster located at CINECA, Bologna, Italy (http://www.hpc.cineca.it/content/fermi-reference-guide), in the context of the Iscra B project PBE4HAS (Physics-based earthquake scenarios for hazard assessment in densely urbanized areas). Each simulation employs 4096 parallel CPUs resulting in a total computation time of

about 23 hours.

Starting from the 3D model developed, a first set of 15 different hypothetical seismic rupture scenarios were assumed, all of them breaking either the CMB or the NBF faults, with magnitude ranging from 7 to 7.5. Realistic slip models along the faults were obtained according to the procedure described in Section 2.1. An overview of the ground shaking map in terms of spatial distribution of PGV (geometric mean of horizontal components), for two M 7 selected scenarios is shown in Figure 5. For each scenario, the surface projection of the seismic fault is superimposed on the *PGV* map and the corresponding kinematic source model is displayed on the bottom panels.

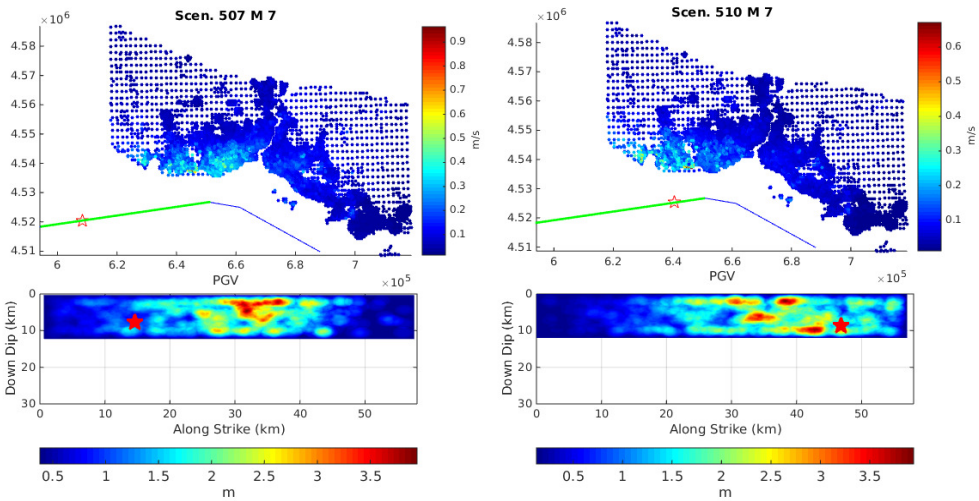

Figure 5 – (Top) PGV maps obtained by SPEED + ANN for two M 7 scenarios. The active fault is highlighted in green and epicenter position is represented by a red star. (Bottom) Slip distribution considered for the scenarios.

4 PROCESS DEVELOPMENT AND METHODOLOGICAL ADVANCEMENT IN VIEW OF A PSHAe

The PSHA introduced by Cornell (1968) involves three steps: (i) definition of the seismic-hazard source model(s), (ii) specification of the ground motion predictive equation(s), GMPEs, and (iii) the probabilistic calculation. As already proposed by different authors (Convertito et al., 2006; Villani et al., 2014), combining the probabilistic and deterministic approaches in the hazard analysis is feasible and allows to overcome some of the limitations inherent in the deterministic and Cornell (1968) classical approaches.

Referring to the PSHA, for a particular site, the seismic-hazard source model provides N earthquakes, each of which has an associated magnitude, location and annual occurrence rate. For a given magnitude and distance, the GMPE provides the distribution of possible ground-motions usually considering also the soil conditions at each site. In the envisioned methodology, we propose to make direct use of PBSs, by choosing wisely certain scenarios out of a set of many that pose a significant threat for a given site. This allows to incorporate important physical effects in the PSHA, such as the radiation pattern, the fault geometry, the directivity effect, the 3D seismic response of soft soil and soil non linearity.

Each PBS will be ranked according to a scalar (or vector) quantity, summarizing the overall scenario effect into an easy manageable parameter (e.g.: the cumulative modelled losses in a certain area). The set of PBSs will be grouped into classes and per class only one representative member will be chosen. The frequency of the class will be computed out of the proportion between the population of each class and the overall population of PBSs. The main methodological advancement aims at combining probabilistic and deterministic approaches for SHA, integrating selected PBSs into a classical logic tree, through the PSHAe methodology as shown in Fig. 6.

A further improvement to reduce CPU time will take advantage of the PBS without the use of a massive set of simulations each time by generalizing the previous findings in a heuristic procedure, allowing the simulation of only a limited amount of PBSs. The experience gathered over the past years regarding 3D scenarios will allow us to enhance this choice, with the aim of, on one hand, (i) exploring the variability of ground motion, preserving the full spatial correlation necessary for risk modelling and properly simulating losses for a given location and a given building stock, and, on the other, (ii) minimizing the amount of simulations required.

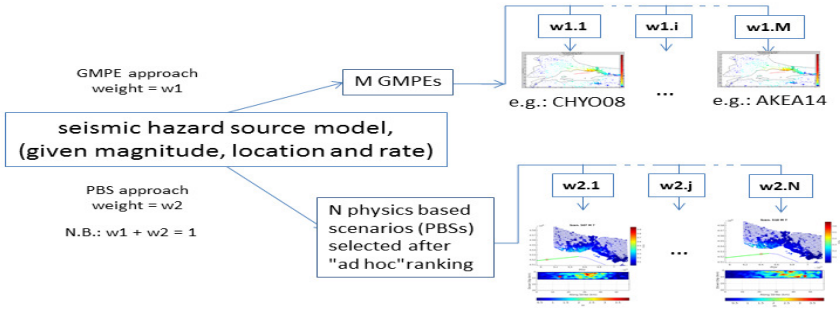

Figure 6 – Integration of selected PBSs into a classical logic tree based approach.

5 CONCLUSIONS

The PSHAe, where "e" stands for enhanced, has been sketched as a streamlined implementation of PBSs into the classical PSHA. Given a limited amount of computational resources or time available and the need of properly taking into account the spatial correlation of ground motion as modelled by physics-based simulation, the PSHAe represents a promising way to implement complex 3D scenarios into a PSHA framework. To illustrate the practical implementation of the methodology, the specific case study of Istanbul was chosen. However, due to the methodological improvements necessary to accomplish this challenging task, the above mentioned methodology still has to be investigated in more detail.

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