



**HAL**  
open science

# Assessing the impact of regional geology on the ground motion model variability at the Kashiwazaki-Kariwa Nuclear Power Plant (Japan) via physics-based numerical simulation

David Castro-Cruz, Filippo Gatti, Fernando Lopez-caballero

## ► To cite this version:

David Castro-Cruz, Filippo Gatti, Fernando Lopez-caballero. Assessing the impact of regional geology on the ground motion model variability at the Kashiwazaki-Kariwa Nuclear Power Plant (Japan) via physics-based numerical simulation. *Soil Dynamics and Earthquake Engineering*, 2021, 150 (1), pp.106947. 10.1016/j.soildyn.2021.106947 . hal-03325660

**HAL Id: hal-03325660**

**<https://hal.science/hal-03325660>**

Submitted on 16 Oct 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

# Assessing the impact of regional geology on the ground motion model variability at the Kashiwazaki-Kariwa Nuclear Power Plant (Japan) via physics-based numerical simulation.

David Castro-Cruz<sup>a</sup>, Filippo Gatti<sup>a</sup> and Fernando Lopez-Caballero<sup>a</sup>

<sup>a</sup>Université Paris-Saclay- CNRS - CentraleSupélec

Laboratoire de Mécanique des Sols, Structures et Matériaux (MSSMat) UMR CNRS 8579

8-10 rue Joliot Curie 91190, Gif-sur-Yvette, France

## ARTICLE INFO

### Keywords:

Physics-Based earthquake Simulation

2007  $M_W$ 6.6 Niigata earthquake

Kashiwazaki-Kariwa Nuclear Power

Plant

Site-effects

Ground Motion Prediction Equations

## ABSTRACT

This study investigates the sensitivity of physics-based earthquake prediction to the choice of the regional geological model. The generally poor information on the mechanical properties of the Earth's crust induces large uncertainty margins on the synthetic seismic response. Therefore, uncertainty quantification must be associated with high-fidelity numerical simulation, especially when verging on broad-band simulations (i.e., numerical theoretical accuracy higher than the conventional 1 Hz limit). In this paper, the synthetic seismic response of the Niigata region (Japan), during the Chūetsu offshore earthquake ( $M_W$ 6.6) serves as representative case study. Three plausible three-dimensional (3-D) geological structures are compared for two point-wise aftershock numerical simulations, duly validated. The framework of comparison targets the Ground Motion Prediction Equation (GMPE) for pseudo-spectral acceleration at the surface. The impact of the geology on the variability of between-event and the within-event residuals is inferred from synthetic simulations and related to common parameters representing site-specific conditions.

## 1. Introduction

With the increasing broader access to high-quality seismic databases, empirical relationships to predict ground motion intensity flourished, cast into Ground Motion Prediction Equations (GMPEs, whose omni-comprehensive compendium can be found at <http://www.gmpe.org.uk/>, see Douglas, 2021), of the general form:

$$\log(Y_{es}) = f(\{X\}_i; \{\theta\}_j) + \Delta_{es} \quad (1)$$

where  $Y_{es}$  is the generic intensity measure (IM) for earthquake  $e$  at station  $s$ . The pseudo-spectral acceleration  $Sa$  (approximating the maximum absolute acceleration of the single degree of freedom system with 5% damping), the Peak Ground Acceleration (PGA) and the Peak Ground Velocity (PGV) are among the most commonly used IMs. The functional form  $f$  embodies the geometric mean IM prediction (log value).  $\{X\}_i$  embraces the source characteristics (usually earthquake magnitude, type of earthquake, focal mechanism), the notion of source-to-site distance (hypocentral, epicentral and Joyner-Boore among others), the site parameters (usually the site class based on the average shear-wave velocity of the first 30 m below the ground surface, noted as  $V_{S,30}$ ).  $\{\theta\}_j$  is the set of coefficients obtained via non-linear regression on large seismic databases.

The residual  $\Delta_{es}$  represents the shift between the geometric mean prediction  $f$  and observations.  $\Delta_{es}$  is usually modeled as a centered normal random variable with distribution  $\mathcal{N}(0, \sigma)$  (Atik et al., 2010; Rodriguez-Marek et al., 2013). Moreover,  $\Delta_{es}$  is modeled as the sum of the *between-event variability*  $\delta B_e$  (the earthquake-wise station-average deviation of the observed ground motion from the geometric mean  $f$ ) and of the *within-event variability*  $\delta W_e$  (the station-wise misfit between the  $e$  observed earthquake ground motion and the sum  $f + \delta B_e$ , Rodriguez-Marek et al., 2013).

$$\Delta_{es} = \delta B_e + \delta W_{es} \quad (2)$$

\*Corresponding author

ORCID(s): 0000-0002-2404-8653 (D. Castro-Cruz); 0000-0001-7174-4048 (F. Gatti); 0000-0002-1010-1230 (F. Lopez-Caballero)

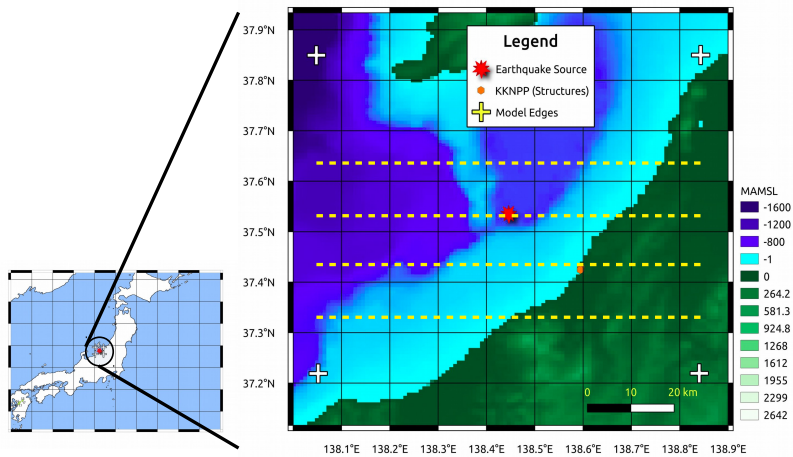
37  $\delta B_e$  and  $\delta W_{es}$  are both modeled as centered normal random variable with distributions  $\mathcal{N}(0, \tau)$  and  $\mathcal{N}(0, \phi)$  respec-  
38 tively.

39  
40 GMPEs usually benefit from the ever-increasing access to seismic data and meta-data. More complex functional  $f$  can  
41 be calibrated by adding new parameters  $\theta_j$  to the recipe in order to take into account site-specific and source-specific  
42 features. However, current seismic hazard analysis struggles in reducing the uncertainty  $\Delta_{es}$  and the associated stan-  
43 dard deviation  $\sigma_t$  (especially for earthquakes with high return periods, Strasser et al., 2009). Some authors achieved  
44 this goal by removing the so-called *ergodicity assumption* (see, for instance, Atik et al., 2010), i.e. including site- and  
45 scenario-dependent parameters. However, this approach suffers from (1) a lack of observed records in some regions  
46 to sufficiently constrain the regression process and (2) poor generalization, i.e., the impossibility of extrapolating re-  
47 liable predictions in general contexts (Abrahamson and Hollenback, 2012; Chen and Tsai, 2002). Those drawbacks  
48 hinder the establishment of high-fidelity site-/scenario-specific GMPEs. A very appealing alternative is provided by  
49 high-fidelity earthquake simulations, duly validated against past recorded earthquakes (Bradley, 2018). This approach  
50 sacrifices the GMPE handy regression framework to explicitly tackle the modeling uncertainties at stake, namely: (1)  
51 the definition of a reasonable and realistic rupture scenario on active faults is required, (2) the 3-D crustal structure, (3)  
52 the surficial site conditions (related to the so-called *site effects*). For those reasons, waveform inversion and array back-  
53 projection are employed to detect and characterize fault asperities that generated the strong ground motion (Aoi et al.,  
54 2008; Honda and Aoi, 2009). GMPEs and numerical simulations are being used together for Probabilistic Seismic  
55 Hazard Assessment (PSHA). For instance, Milner et al. (2021) managed by updating non-ergodic PSHA for Southern  
56 California via direct numerical simulation.

57  
58 The identification of the geology in the region of interest (bedrock and softer sediments) is either achieved by interpre-  
59 tation and analysis of borehole logs in the surroundings (Fantoni and Franciosi, 2010), or by seismic tomography (Lee  
60 et al., 2014; Jian and Fanhua, 2009). Finally, laboratory tests are necessary when including non-linear soil rheology (see  
61 the PRENOLIN international benchmark on 1-D numerical wave-propagation in Régnier et al., 2016). Despite the  
62 computational performance achieved by the numerical tools, the mentioned uncertainties prevent the complete charac-  
63 terization of broad-band ground shaking scenarios, especially at short periods (i.e.  $T < 0.5$  s, Paolucci et al., 2018). In  
64 recent years, physics-based numerical simulation improved by merging its fidelity at long periods (usually for natural  
65 periods  $T > 0.2$  s) with data-driven ground motion models, conditioned by the outcome of the numerical analy-  
66 sis (Gatti and Clouteau, 2020; Castro-Cruz et al., 2021; Jayalakshmi et al., 2021). Several comparisons (Olsen et al.,  
67 2000; Smerzini et al., 2011) showed large differences between 1-D 2-D and 3-D simulations, establishing that 3-D  
68 simulations can better capture the source footprint and the impact of the geological structures. However, the power of  
69 3-D models is sometimes limited by the only available 1-D velocity profiles around specific areas.

70  
71 In this work, high-fidelity 3-D numerical simulations are exploited to clarify their sensitivity to the geological model  
72 considered in a relatively low-frequency range (0-3 Hz). The uncertainty quantification is inferred from the reproduced  
73 variability of the ground motions for three different yet plausible geological models. The analysis follows the context  
74 of GMPE predictions, given the large number of synthetic time-histories extracted from the numerical simulation at  
75 several geographical locations in the region of interest. This work focuses on a real case study, the Niigata prefecture  
76 (central-west Japan), which hosts the largest nuclear power plant in the world, located in Kashiwazaki-Kariwa (KKNPP,  
77 see Figure 1).

78 This region has been struck by several significant earthquakes, with the remarkable  $M_W$  6.6 Niigata Chuetsu-Oki earth-  
79 quake of 2007 (NCOEQ2007), which did cause the KKNPP shut-down. Gatti et al. (2018a) showed the importance  
80 of considering the complex 3-D shallow underground structure to approach the recorded seismic response, compared  
81 to traditional layered geology. They confirmed an improved fit of the recorded time-histories at KKNPP, when the  
82 complex *folded* geology below KKNPP was included in their numerical model. Gatti et al. (2018c) employed the tech-  
83 nique named ANN2BB (Paolucci et al., 2018) to enrich this synthetic wave-motion at high-frequency and successfully  
84 perform a Soil-Structure Interaction (SSI) study of the Unit 7 reactor building at KKNPP. These studies highlighted the  
85 difficulty of constructing and calibrating a regional digital twin, including the uncertainty of the available geological  
86 information (usually 2-D geological maps) and the uncertainty related to the numerical discretization.



**Figure 1:** Digital Elevation Model of the region considered in the analysis, including the Niigata basin and the surroundings of the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP). Yellow dashed horizontal lines represent the traces of the vertical clips shown in Figure 4.

## 2. Data

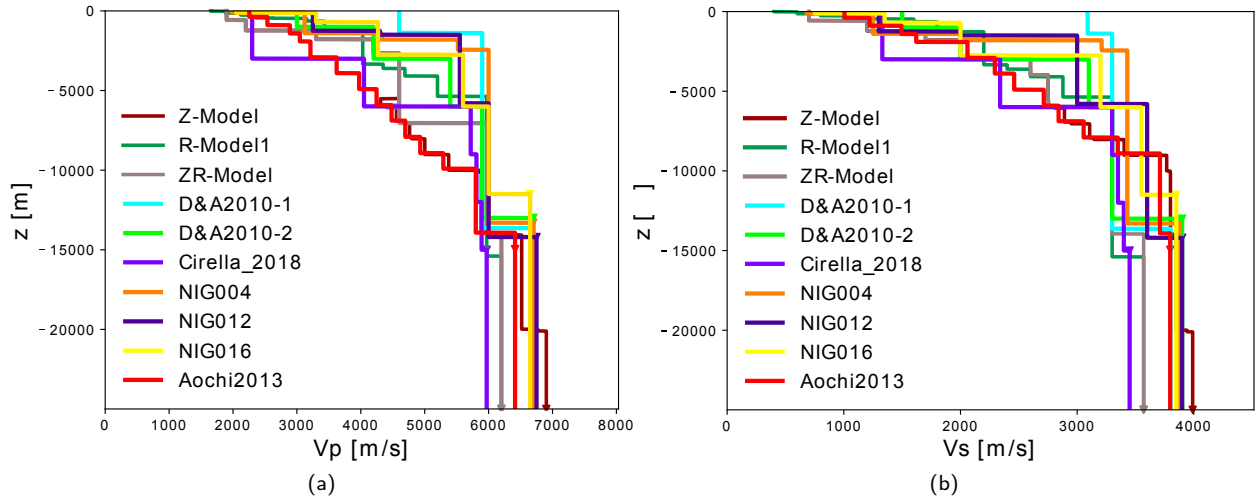
3-D numerical models require detailed information on the site geological configuration and source characteristics, in order to accurately reproduce the complex 3-D wave field. Ideally, high-quality information is required at three different scales: the regional scale (strictly connected to the long-period part of the rendered ground motion), the site-scale (at which most of the non-linear multi-path effects take place), and the borehole scale (necessary when investigating complex SSI effects). Nevertheless, these ideal conditions are rarely met, given the tremendous effort needed to collect seismological observations, to perform geophysical and geological campaigns, to invert and to exploit those data. More realistically, 1-D geological profiles are provided for the seismological region (characteristic dimension  $\approx 1$  km). 2-D or 3-D geological structures are also available for some sites of interest, such as at the KKNPP (Watanabe et al., 2009).

### 2.1. Available 1-D velocity structures

Figure 2 compares the available 1-D vertical profiles proposed in the literature for the region surrounding KKNPP. Specifically, DA&2010-1 and DA&2010-2 were proposed by Ducellier and Aochi (2010), in their numerical simulations of the NCOEQ2007 mainshock. Aochi2013 was proposed by Aochi et al. (2013), for their finite difference analysis of the NCOEQ2007 mainshock and aftershock sequence. Cirella2008 velocity values were employed by Cirella et al. (2008) to perform a waveform inversion of NCOEQ2007 source mechanism. Finally, the profiles at stations NIG004, NIG016, NIG026 belong to K-NET network and NIGH12 to KiK-Net network (NIED, 2019; Aoi et al., 2004). Those crustal models are reliable at a very low-frequency range ( $f < 0.5$  Hz).

### 2.2. Other geological models

Figure 3 displays the cross-section SC of a local *folded* geology striking at N 145° E and located underneath KKNPP. Watanabe et al. (2009) employed it in a 2-D finite element earthquake analysis. The folded structure was constructed from a boring and seismic reflection survey (Kobayashi et al., 1995). The SC cross-section spans approximately a region 7.6 km wide and 4.8 km. Seven strata are reported, including the seismic bedrock (see Table 1). The simulation results rendered by Watanabe et al. (2009) showed good agreement with the observed strong motion records at Unit 1, explaining the strong ground motion spatial variability within the nuclear facility (due precisely to the first and second boundaries). Those findings are confirmed by Tokumitsu et al. (2009). Tsuda et al. (2011) clarified the role of this folded structure by performing a 3-D finite difference earthquake simulation of the NCOEQ2007 mainshock and aftershock sequence. The 3-D velocity structure they proposed is the combination of a *broad model*, proposed by Japan Nuclear Energy Safety Organization (JNES, see Kamae, 2016). Although accurate for the regional wave field, JNES did not include the folding structure. Therefore, Tsuda et al. (2011) included a 3-D version of the folding



**Figure 2:** 1-D velocity models of the different boreholes from the region around KKNPP. The triangles are located at the maximum borehole depths. a) Compressional wave speed  $V_p$  profile; b) Shear wave speed  $V_s$  profile.

**Table 1**

Geological properties of the folding structure underneath KKNPP.  $V_p$  and  $V_s$  are the compressional- and shear-wave velocities, respectively. The \*\* indicates the interface chosen to plug the folding structure into the original 1-D *Aochi2013* profile, granting a smooth transition from one model to another.

Layer	$V_s$ [m/s]	$V_p$ [m/s]	$\rho$ [kg/m <sup>3</sup> ]
Nishiyama	700	1900	1700
Shiia	1200	2200	2100
Upper Teradomari	1700	3300	2300
Lower Teradomari	2000	4200	2400
Nanaya	2000	4600	2500
** Green tuff	2600	5200	2600
Seismic bedrock	2600->2750	5200	2600

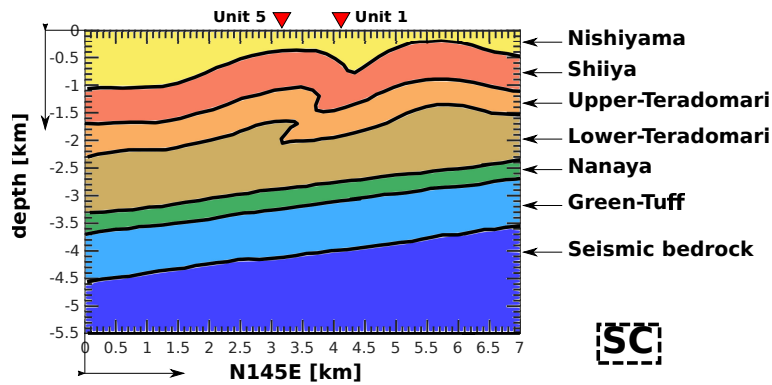
116 structure, based on the previous studies of Tokumitsu et al. (2009), which consists of 7 cross-sections. This *local*  
 117 *folding model* was interpolated to reconnect to the external *broad model*. Using the horizontal-vertical (H/V) ratio  
 118 technique (Nakamura, 1989), Tsuda et al. (2011) matched the synthetic H/V with those of the observed records for  
 119 some sites on the KKNPP, obtaining a good agreement of the predominant frequencies around 0.3 Hz. The numerical  
 120 simulation for the NCOEQ2007 showed good agreement with the recorded time-histories at KKNPP, in the range 0-4  
 121 Hz.

122 Finally, Gatti et al. (2018a) validated a similar 3-D geological model by comparing the synthetic records with the  
 123 recorded shakings from two aftershocks ( $M_{JMA}4.4$  and  $M_{JMA}4.2$ ) of the NCOEQ2007 (NIED DMC; Obara et al.,  
 124 2005; Okada et al., 2004), confirming that a simple layered 1-D model (Aochi2013 proposed by Aochi et al. (2013))  
 125 cannot reproduce the ground motion amplification accurately at Unit 1 and the focalization effect due to the folding  
 126 structure.

### 127 2.3. Proposed 3-D geological models

128 In this work, three geological models are considered, obtained from the interpolation of the available 1-D and 2-  
 129 D geological information described in the previous subsection, integrated with the geological model of reference,  
 130 provided by the Geological Survey of Japan for the Niigata area (Sekiguchi et al., 2009). Available information was  
 131 alternatively combined in each model, aiming at reproducing the regional and site path effects. Namely, the three  
 132 models are referred to as:

133 1. **Z-Model:** this virtual geology corresponds to the model proposed by Gatti et al. (2018a) and Gatti et al. (2018c)



**Figure 3:** Cross-section (SC) of the folded geology below KKNPP (Unit 1 and Unit 5) proposed by Watanabe et al. (2009); Tsuda et al. (2011). Layer names are reported in Table 1. Reprinted from Gatti et al. (2018a).

134 to predict the structural response of the KKNPP Unit 7 reactor building. It blends two geological structures: a  
 135 regional sub-horizontally layered geology inspired by Aochi et al. (2013) (labeled as Aochi2013 in Figure 2) and  
 136 a model obtained from the extrusion of SC cross-section in Figure 3. The two geological structures are joined by  
 137 linear interpolation. The Aochi2013 model was calibrated to reproduce the regional wave field in the 0-0.5 Hz  
 138 frequency range. The hybrid model, including the folding, was instead verified in the 0-5 Hz frequency range, for  
 139 two NCOEQ2007 aftershocks, at several locations within the KKNPP site (the borehole arrays deployed within  
 140 the nuclear site) and at several KiK-Net and K-NET stations.

- 141 2. **R-Model:** this model was proposed by the Geological Survey of Japan (GSJ, Sekiguchi et al., 2009). It is an im-  
 142 provement of the previous NIED model (National Research Institute for Earth Science and Disaster Prevention)  
 143 proposed by Fujiwara et al. (2006) for the Niigata area, based on several seismological observations. The depth of  
 144 layer boundaries is provided on a grid mesh of approximately  $0.5 \times 0.5$  km. The model contains 50 layers above  
 145 the Moho (Mohorovicic discontinuity). Aochi et al. (2013) tested and compared this geological structure with  
 146 two other 3-D models of the Niigata basin and reproduced the NCOEQ2007 mainshock time-histories at several  
 147 KiK-Net (NIGH11) and K-NET stations (NIG019 and NIG017) in the frequency range 0.1-0.5 Hz. The authors  
 148 specified that the synthetics at near-field soil sites were quite realistic, but the model needed improvements and  
 149 a finer shallow structure.
- 150 3. **ZR-Model:** this synthetic 3-D configuration is a combination of the previous two, i.e., the folding structure  
 151 (Z-model) is included in the regional structure of the Niigata basin (corresponding to the R-model). This hybrid  
 152 geological structure shares the deepest layers ( $> 6$  km) with the R-Model and the surficial ones with the Z-Model.  
 153 The main reason why this geology was considered to coincide with the purposes of Tsuda et al. (2011) to include  
 154 the prediction of both the regional wave field (interacting with the Niigata basin-like geology) and the influence  
 155 of the local geology on it.

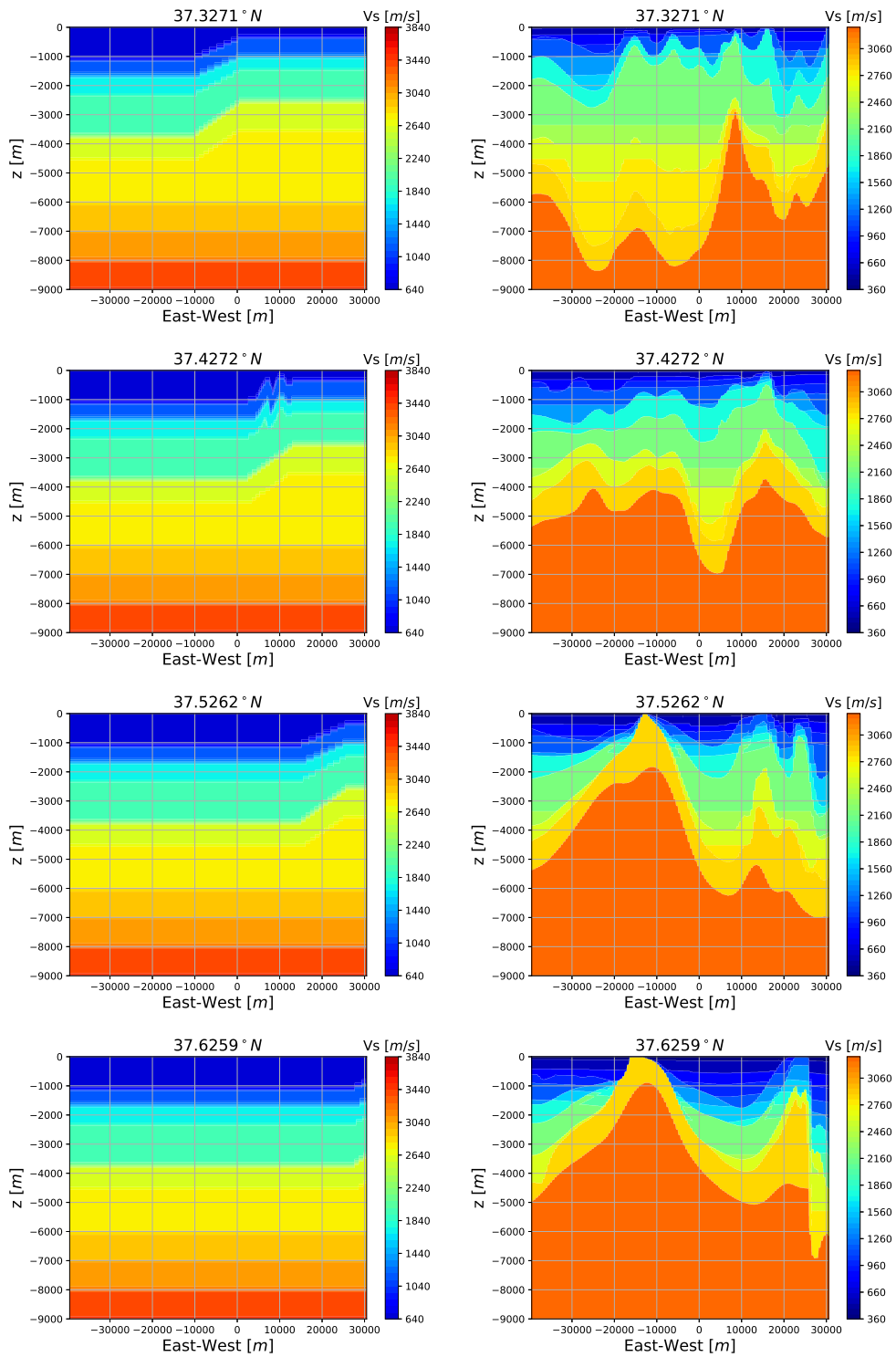
156 The left and right columns in Figure 4 show four West-East cross-sections of the Z-Model and the R-Model, respec-  
 157 tively. In Appendix A, the detailed 3-D cuts of the three geological structures in the Niigata region are reported. It is  
 158 important to note that the Z-model is relatively regular for depths below 5 km (layered velocity structure proposed by  
 159 Aochi et al., 2013), whereas the R-model shows 3-D sharp basin-like structures reaching a depth of 10 km.

## 160 3. Physics-based numerical simulation

### 161 3.1. 3-D Numerical Model

To assess the uncertainty related to the geological and geophysical models proposed in the previous section, the con-  
 structured numerical model covers  $64 \text{ km} \times 64 \text{ km}$  around the earthquake position (see Figure 1). The model charac-  
 teristics are summarized in Table 2. All three models exploit the very same hexahedral mesh, neglecting the regional  
 topography. Since different geologies characterize the three models, their accuracy varies from model to model. How-  
 ever, all the models are accurate enough to study the influence of the geology for periods  $T > 0.5 \text{ s}$ .

Earthquake simulations were performed using SEM3D (CEA and CentraleSupélec and IPGP and CNRS, 2017), a high-



**Figure 4:** West-East cross-sections at different latitudes (reference system: Tokyo CS VIII EPSG:30168 system), showing the  $V_s$  contours. Figure 1 shows the position of the cross-sections in the map. Left column belong to the Z-Model and right column to the R-Model.

**Table 2**

Parameters of the template numerical model employed in this paper.  $n_{el}$  and  $n_{DOF}$  represent the number of hexahedral elements and degrees of freedom (DOF) respectively.  $\Delta L_{min}$  is the minimal element characteristic size,  $N_{GLL}$  is the number of Gauss-Lobatto-Legendre integration points per element size,  $f_{max}$  is the maximum frequency that the model can theoretically propagate.

Model	$n_{el}$ [1]	$n_{DOF}$ [1]	$\Delta L_{min}$ [m]	$N_{GLL}$ [1]	$V_{s,min}$ [m/s]	$f_{max}$ [Hz]
Z	$\approx 4.02 \cdot 10^6$	$\approx 1.50 \cdot 10^9$	139	5 × 5 × 5	700	5
R/ZR	-	-	-	-	400	2.1

performance software, implementing the spectral element method (SEM, Komatitsch and Vilotte, 1998; Faccioli et al., 1997). This software is based on RegSEM code (Cupillard et al., 2012; Festa and Vilotte, 2005). The SEM represents a high-order version of the finite element method (FEM), and it is well known for the relatively easy parallelization algorithm associated (domain decomposition over distributed memory computing cores, using MPI protocol Goddeke et al., 2014). Those aspects make the 3-D simulation an attractive tool for seismic hazard analysis (Olsen et al., 1995; Bradley, 2018). The mesh has higher refinement at shallow layers to preserve the numerical accuracy where slowness values are larger. The maximum theoretical frequency propagated can be estimated as:

$$f_{max} = \frac{V_{S,min} \cdot N_{GLL}}{5 \cdot \Delta L} \quad (3)$$

162 with  $V_{S,min}$  being the minimum shear wave velocity in the domain,  $\Delta L$  the corresponding element characteristic size  
 163 and  $N_{GLL}$  the number of Gauss-Lobatto-Legendre integration points featuring the mesh element (for the SEM,  $N_{GLL}$   
 164 is usually greater than 5).

165 Given the intricate geologies at stake and due to the adopted integration rule over 3-D hexahedra, a *not-honoring*  
 166 approach is adopted to associate the spatially distributed geological properties to the mesh point locations (Casarotti  
 167 et al., 2008). In other words, the geological discontinuities are not directly meshed, but rather *interpolated* over the  
 168 GLL grid. This approach has the advantage of simplifying the inclusion of surfaces of complex geometry, yet induc-  
 169 ing some spurious amplification due to spatial interpolation. The influence on the earthquake numerical predictions  
 170 presented in this study was duly checked and it can be neglected, due to the rather low-frequency range considered.  
 171 Finally, Gatti et al. (2018a) verified the limited influence of surface topography on the seismic response at KKNPP,  
 172 which was not therefore included. Appendix B provides some insights on the computational resources employed for  
 173 each simulation.

174  
 175 As far as the source is concerned, in order to assess the uncertainty related to the geological model, two earth-  
 176 quake point sources were adopted: (1) EQ1, corresponding to the  $M_{JMA}4.4$  (Japan Meteorological Agency) after-  
 177 shock of the NCOEQ2007 sequence (employed by other authors (Gatti et al., 2018a)) and (2) EQ2, corresponding  
 178 to the NCOEQ2007 mainshock hypocenter location. Table 3 summarizes the focal mechanism and location of the  
 179 two sources. These parameters represent the small aftershocks employed to validate the numerical model by Gatti  
 180 et al. (2018a) against the observed recordings. Statistical analysis on the source's uncertainty, such as by Shang and  
 TkalADiAG (2020), are out of the scope of this paper. For the sake of simplicity, the mainshock source (EQ2) was

**Table 3**

Summary of the aftershock parameters employed in this analysis.  $(\phi_S; \lambda; \delta)$  represent the strike, rake and dip angles, respectively, estimated by F-NET Centroid Moment Tensor solution (Kubo et al., 2002).  $\tau_R$  represents the source rise-time.

Event	$M_{JMA}$	$M_0$ [Nm]	$(\phi_S; \lambda; \delta)$ [°]	$d$ [km]	$\tau_R$ [s]
EQ1 (07/16/07-21:08)	4.4	$5.21 \cdot 10^{15}$	187; 70; 54	11	0.113
EQ2 (07/16/07-01:13)	6.8	$7.72 \cdot 10^{18}$	30; 78; 38	17	8.015

181  
 182 considered as a point source to be coherent with the idea of this paper of studying the effect of epistemic uncertainty on  
 183 geological and geophysical information. The full moment tensor components were provided by F-NET. More accurate  
 184 analysis requires an extended source model, whose rupture path highly affected the mainshock pulse-like seismic re-  
 185 sponse at the site (near-source effects shown by Aoi et al., 2008; Gatti et al., 2018a). However, the following sections



186 show the interest in considering a mainshock source due to its Source Time Function (STF) featured by large rise-time  
187  $\tau_R$  compared to EQ1 (see Table 3).

### 188 3.2. Synthetic seismic response of the Niigata region

189 Before performing statistical analyses on the post-processed results (see Section 4), a validation task is presented here-  
190 after. In doing so, synthetic time-histories are compared to recorded signals for EQ1, an aftershock widely recorded  
191 by the down hole arrays and surface seismometers located within KKNPP (see Figure 5). The site is instrumented  
192 with two recording networks, including four borehole arrays (Gatti et al., 2017), with KSH in Figure 5 representing a  
193 free-field control point for this analysis (Gatti et al., 2018a).

Given the accuracy of the numerical models, all the synthetic and recorded time-histories were band-pass filtered in

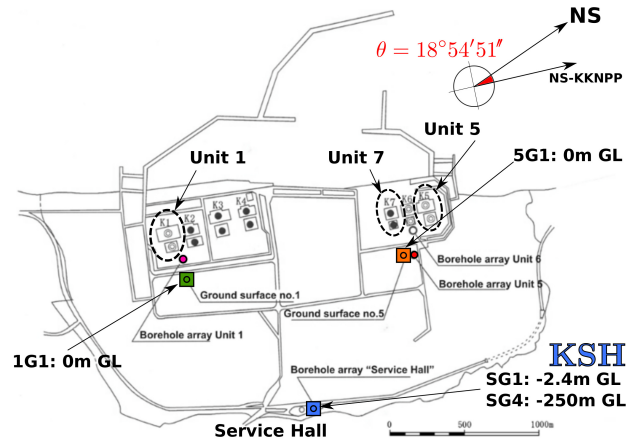
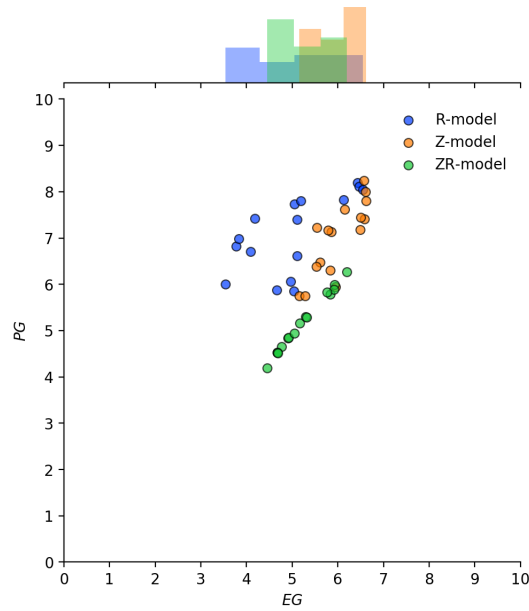


Figure 5: Map of the KKNPP site. The locations of downhole arrays of seismometers are reported: KSH represents the Service Hall array (four devices, SG1-SG4, reaching depth of -250 m G.L.), which entirely recorded the NCOEQ2007.

194 the 0.1-2.8 Hz frequency band (4<sup>th</sup> order Butterworth filter). Moreover, to quantify the predictive capabilities of the  
195 numerical model, the criterion proposed by Kristekova et al. (2009) was adopted, which proposes a time-frequency  
196 metrics in order to quantify the Goodness of Fit (GoF) between synthetic and recorded signals. Kristekova's crite-  
197 rion defines two indices that quantify the misfit in time and frequency domains: Envelope Goodness (EG) and Phase  
198 Goodness (PG). Figure 6 summarizes the EG and PG GoF values obtained for three EQ1 runs at the KKNPP, each one  
199 featuring a different geological model among the investigated ones (R-, Z-, ZR-model respectively). The comparison  
200 at other stations outside the KKNPP is out of the scope of this paper, being those stations located too far away from  
201 the nuclear site. The synthetic and recorded time-histories at KSH, employed for the validation exercise, are reported  
202 in Appendix C, along with the time-frequency GoF values (see Figure 21). Overall, the GoFs are satisfactory in both  
203 Envelope ( $\approx 5$ ) and Phase ( $\approx 6$ ) for the three virtual geologies, with slight differences among them. The Z-model, as  
204 already verified by Gatti et al. (2018b), appears as the most adapted to predict the KKNPP seismic response, being  
205 primarily influenced by the layered folding striking underneath KKNPP. However, Figure 6 proves that the three mod-  
206 els are all equally plausible in this relatively low-frequency range, thus suggesting the need for an accurate uncertainty  
207 quantification study.

## 209 4. Uncertainty quantification on the synthetic ground motion

210 In this section, the uncertainty of the numerical earthquake prediction related to the chosen digital geological model  
211 is assessed, exploiting EQ2 source. The outcomes of each simulation, obtained by plugging in the three different  
212 geological models rendered in Figure 4, are compared in terms of trends and residual values, following the GMPE  
213 framework (Rodriguez-Marek et al., 2013). Compared to GMPE, numerical earthquake simulations yield a more  
214 accurate prediction of site-specific seismic response, which is generally difficult to cast into non-linear regressions,  
215 given their intrinsic uniqueness. Moreover, in this paper, up to 261120 virtual stations were deployed across a square  
216 grid, allowing a significant statistical analysis in the post-processing phase.



**Figure 6:** Average time-frequency Envelope GoF (EG) and Phase GoF (PG) (proposed by Kristekova et al., 2009) for recording stations at KKNPP, during EQ1 (aftershock). Synthetic and recorded time-histories were band-pass filtered in the 0.1-2.8 Hz frequency range. GoFs were computed between each numerical model (R-model (blue), Z-model (orange) and ZR-model (green) and recorded signals. The histograms collecting EG and PG GoFs are reported on each axis.

#### 4.1. Sensitivity of physics-based simulations to geological structure

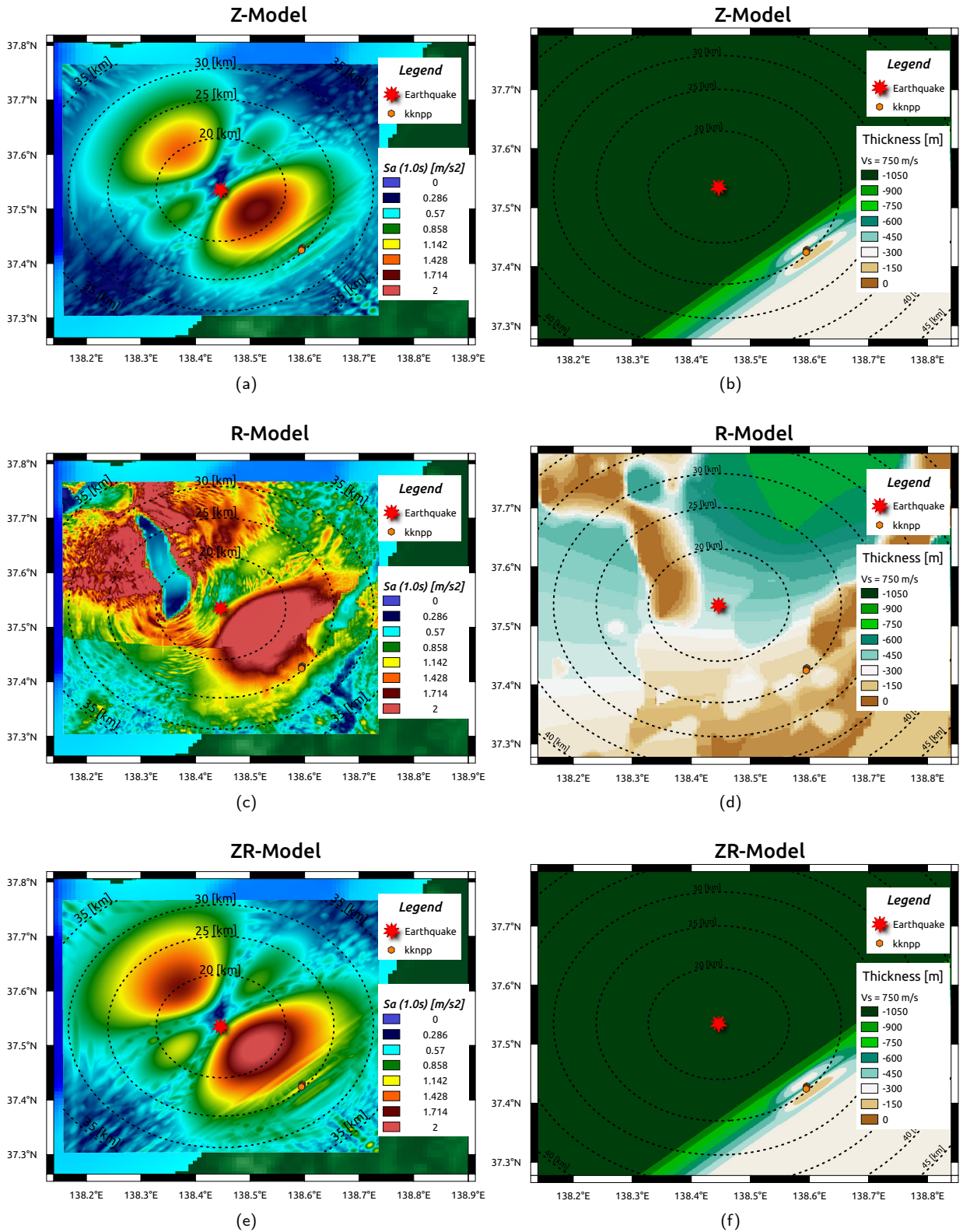
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236

For engineering purposes, the pseudo-spectral acceleration  $Sa$  (5% damping) is usually adopted as an insightful IM characterizing the local seismic response. Figure 7 shows the contour values of  $Sa(T = 1s)$  for each model (Figure 7a, 7c and 7e), along with the respective contour maps of the thickness of the layer with  $V_s < 1500$  m/s (Figure 7b, 7d, 7f). The difference between the synthetic seismic response obtained with R-Model (Niigata basin) and the one obtained with the Z-model (layered regional geology) is evident, which leads to infer that this discrepancy relies on the thickness of surficial soil layers. Compared to the Z-Model and the ZR-Model, which share the same horizontal layering close to the surface, the R-model induce a much more heterogeneous  $Sa$  distribution.

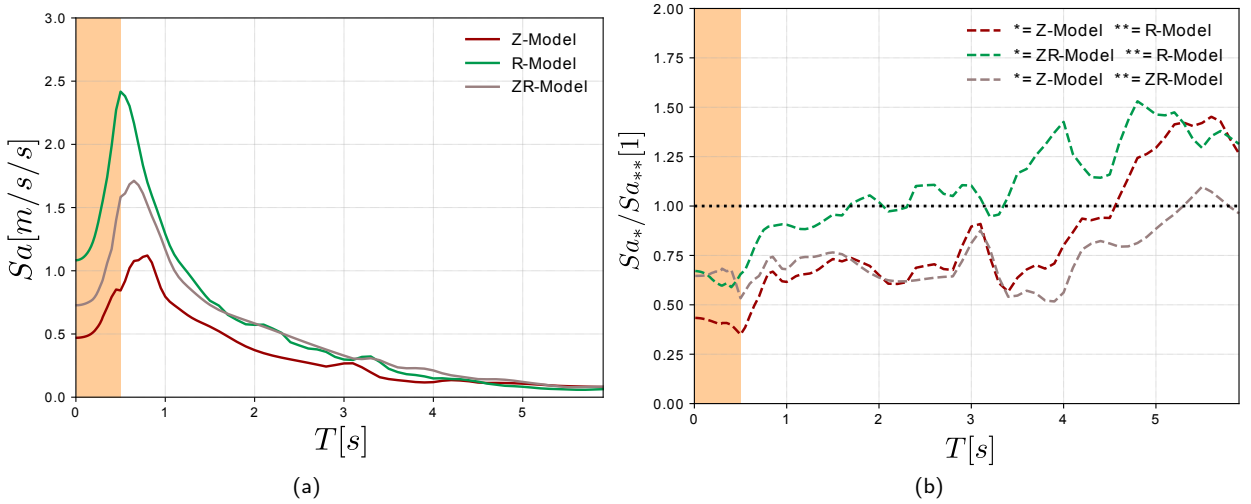
Z-model seemingly better fits the recorded response (see Figure 6), whereas including the Niigata basin geology into the earthquake simulation (R-model) over-amplifies the response at shorter periods. This statement is supported by Figure 8a, which shows the response spectra  $Sa$  for the three geological models considered. It is observed that Z-Model (layered regional geology and local folding structure) provides the lowest  $Sa$  values overall. On the other hand, Figure 8b reports the spectral ratio  $Sa_*/Sa_{**}$  between two alternative synthetic responses, \* and \*\*, respectively. The spectral ratio assesses the relative amplification - at several natural periods - of two seismic responses predicted by considering two different geological models. The influence of the geological structures interacting with the impinging wave field is highlighted according to their characteristic dimensions (e.g., layer thickness) relative to the incident wavelengths. In the period range,  $0.5 s < T < 5 s$ , the ratios range between 0.5 and 1.5, with  $Sa_{ZR}$  and  $Sa_Z$  exhibiting the far-most comparable response in the range 1.5-3.3 s, where the significant impact of the local folding geology is evident on the synthetic ground motion at KKNPP.

The simulated seismic response was compared to the Abrahamson et al. (2016) GMPE, suitable for the seismic context at stake. Figure 9 displays this comparison, for  $Sa$  values at  $T = 1 s$  (all stations in Figure 9a and geometric means in Figure 9c) and  $T = 3 s$  (all stations in Figure 9b and geometric means in Figure 9d) along the source-to-site distance  $R$ .  $\bar{S}a$  represents the geometric mean response spectra (García-Fernández et al., 2019) expressed as:

$$\bar{S}a(T) = \frac{1}{N} \sum_{s=1}^N \log Sa_s(T) \quad (4)$$



**Figure 7:** Contour plot of  $S_a$  values at  $T = 1$  s (5% critical damping) for the three different models: (a) Z-model, (c) R-model, (e) ZR-model. Contour maps of the thickness of the geological layers with  $V_S < 1500$  m/s for the three models: (b) Z-model, (d) R-model, (f) ZR-model.



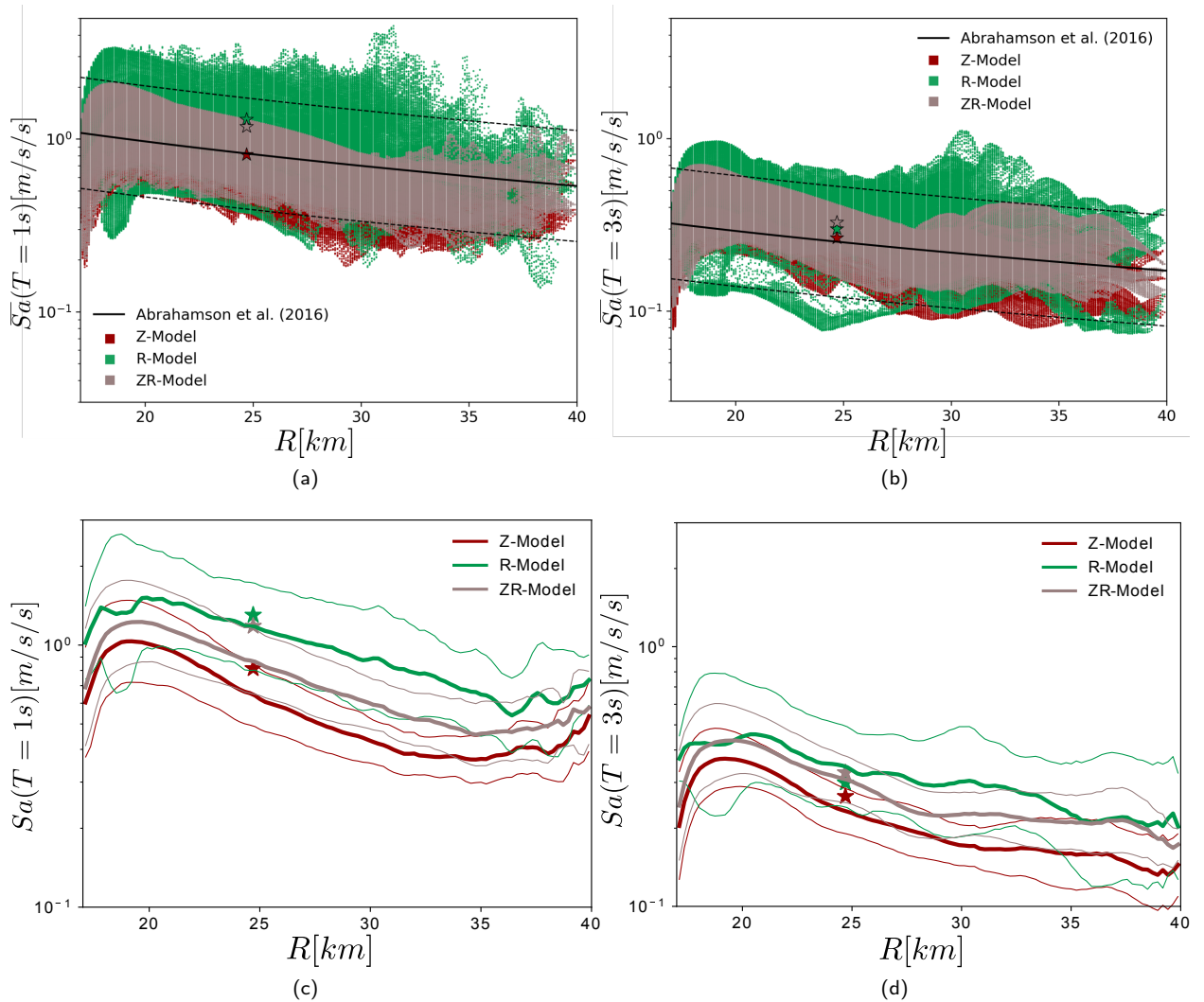
**Figure 8:** Comparison of the response spectra  $Sa$  at the KKNPP location (KSH - 37.4° N, 138.6° E) for the three geological models considered. (a) measures the  $Sa$  geometric average of the horizontal components. (b) measures the ratio  $Sa_*/Sa_{**}$  between two alternative synthetic response \* and \*\*, corresponding to different geological models. Orange area covers the frequency band highly affected by the applied filter ( $T < 1/f_{max}$ ).

237 with  $Sa_s$  being the response spectra at the station  $s$ . For each model, the synthetic  $Sa$  values (both at  $T = 1$  s and  $T = 3$   
 238 s) are quite dispersed, compared to the  $\pm\sigma$  (i.e. plus/minus one standard deviation) margins indicated by the Abrahamson  
 239 et al. (2016) GMPE, for a reference  $V_{S,30} = 400$  m/s (approximately corresponding to the lowest  $V_S$  value in the  
 240 R-model, see Figure 4). However,  $Sa$  values computed at the KKNPP (KSH-SG1 station in Figure 5, referenced by a  
 241 star in Figure 9a and Figure 9b) for R-model are higher than  $\bar{S}a$ , at the same distance from the source. On the contrary,  
 242 despite the fact that the smallest  $V_S$  value in Z-model is 700 m/s (the Nishiyama layer in Table 1) the corresponding  
 243  $Sa$  value computed at the KKNPP is in very good agreement with the  $\bar{S}a$  prediction of the Abrahamson et al. (2016)  
 244 GMPE. This inconsistency can be explained by the fact that the GMPEs generally lack an explicit description of 3-D  
 245 site effects, that cannot be effectively condensed into the  $V_{S,30}$  value.

246 It is interesting to notice that trends in Figure 9c and Figure 9d can be adopted as site-specific and scenario-specific  
 247 GMPE predictions. A stable decaying trend is observed within the 0-35 km distance range, where the number of stations  
 248 is statistically representative. The thinner solid lines in Figure 9c and Figure 9d represent the deviation from the  
 249 station-average  $Sa$  value at a fixed distance to the source. The R-model and the Z-Model present the overall largest  
 250 and smallest deviation. Compared to horizontally layered geology (featuring the Z-model), the R-Model embraces the  
 251 intricate basin-like structures of the Niigata region, arguably inducing an incoherent ground motion across the region  
 252 of interest. The ZR-model and Z-model show comparable trends, seemingly due to the folding structure they share,  
 253 located underneath the KKNPP, which focuses the wave field in that region, compared to the coherent wave field in  
 254 the rest of the region due to the sub-horizontally layered geology (as observed and numerically reproduced by Tsuda  
 255 et al., 2011; Gatti et al., 2018c, , among others, see Figure 7).

256 To summarize, the R-model has an intricate geology, with softer sediments close to the surface, which amplify the  
 257 ground motion in the surroundings. The outcome from the Z-model is systematically lower than the others at all distances  
 258 from the source (see Figure 9), although representing a valid geological model to predict the seismic response  
 259 at the KKNPP. The ZR-model represents a trade-off between the Z-model and R-model.

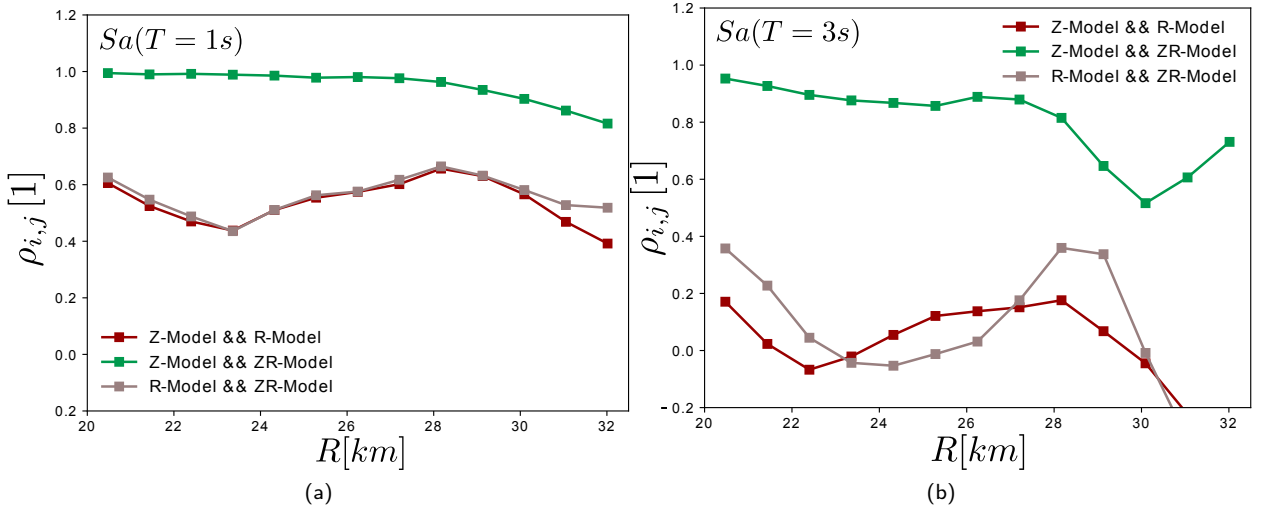
260  
 261 In order to further highlight the correlation between different geological model, Figure 10 displays the correlation  
 262 coefficient  $\rho$  of the  $Sa$  values simulated by each numerical model, all sharing the same earthquake sources. Figure  
 263 10 shows the high correlation between the Z-Model and the ZR-Model ( $\rho_{Z,ZR} \geq 0.6$ ), for both  $Sa(T=1$  s) and  
 264  $Sa(T=3$  s). This is seemingly related to the folding structure underneath KKNPP, shared by both Z- and ZR-model  
 265 models and that impacts the correlation at short distances (i.e., around 22-24 km, where the near-field effects are pre-  
 266 dominant). The correlation coefficients  $\rho_{Z,R}$  and  $\rho_{R,ZR}$  range around a value of  $\approx 0.5$  for  $Sa(T=1$  s), evolving in the



**Figure 9:**  $Sa$  values obtained at surface for the three physics-based simulations at: (a) and (c)  $T = 1$  s; (b) and (d)  $T = 3$  s. (a-b) show the synthetic response at each station, compared with the GMPE proposed by Abrahamson et al. (2016) (computed for a reference  $V_{s,30} = 400$  m/s. The geometric mean  $\bar{S}a$ , for the three physics-based simulations, is depicted with a solid thick line in (c-d), whereas the respective  $\pm\sigma$  margins are marked by thinner dashed lines. Stars indicate the free-field response at KSH station, located within the KKNPP.

267 same way along with the source-to-site distance, but they consistently drop below 0.4 at longer period (see Figure 10b).  
 268 A possible explanation comes from the impact of the deep geological structure of the Niigata basin (R-model) on the  
 269 long-period ground motion prediction ( $Sa(T=3\text{ s})$ ), which is remarkably different from the one estimated with the  
 270 layered configuration in the Z-model. However, the influence of the complex yet deep geological structure seemingly  
 271 vanishes at shorter periods (e.g., at  $T = 1$  s), where  $Sa$  values are mainly affected by the folding structure located  
 272 within the first 5 km below the surface.

273  
 274 Hereafter, the synthetic seismic response estimated for the three geological models is analyzed in order to estimate the  
 275 residual of the synthetic strong ground motion prediction.



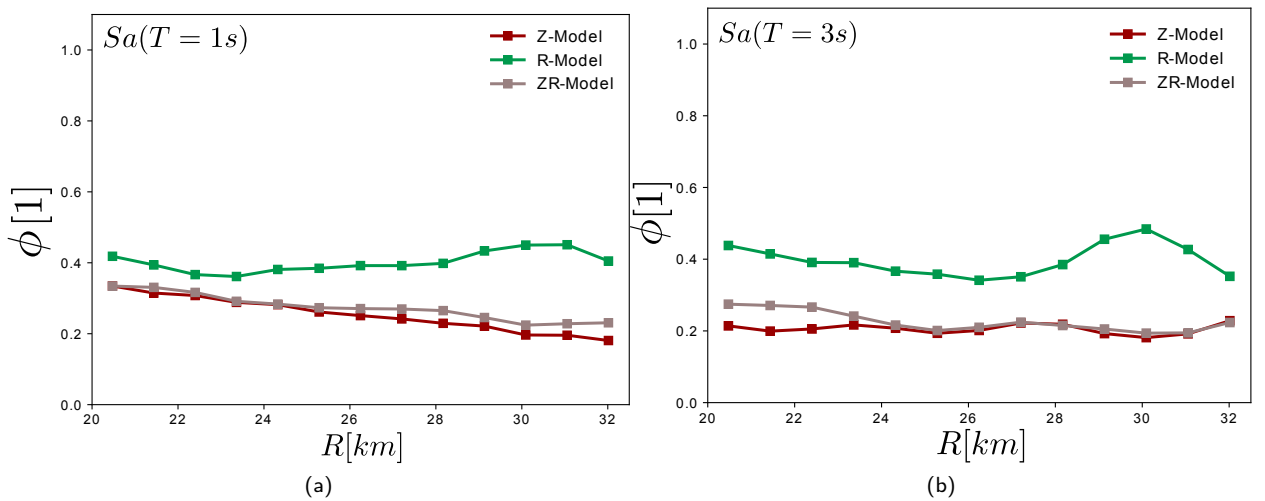
**Figure 10:** Correlation coefficient  $\rho_{i,j}$  of the  $Sa$  values, computed between the  $i^{\text{th}}$  and  $j^{\text{th}}$  numerical models as a function of the source-to-site distance  $R$ . (a) Correlation coefficient of  $Sa(T = 1 \text{ s})$ ; (b) correlation coefficient of  $Sa(T = 3 \text{ s})$ .

#### 276 4.2. Estimation of within-event variability

Several studies (e.g., Atkinson, 2011; García-Fernández et al., 2019) estimated the standard deviation  $\phi$  of the within-event residual  $\delta W_{es}$  at a certain source-to-site distance as:

$$\phi(T) = \sqrt{\frac{1}{N-1} \sum_{s=1}^N \left[ \log \left( \frac{Sa_s(T)}{\bar{Sa}(T)} \right) \right]^2} \quad (5)$$

277 Figure 11 displays the estimation of  $\phi$  for the present study, at different source-to-site distances and for  $T = 1 \text{ s}$  and  $T = 3 \text{ s}$ . For Z-model and ZR-model and for both natural periods, Figure 11 depicts a rather constant trend along



**Figure 11:** Standard deviation  $\phi$  of the within-event residual  $\delta W_{es}$  computed on  $Sa$  with respect to the source to site distance  $R$ , at natural period  $T = 1 \text{ s}$  (a) and  $T = 3 \text{ s}$  (b).

279 with the source-to-site distance. This constant trend is insignificant for  $T = 3$  s. Since those models share the same  
 280 shallow horizontal layering (including the folding),  $\phi$  is mainly related to shallow geology, indicating once again its  
 281 major impact compared to deep geology. Exploiting the rare advantage of having many stations close to the source  
 282 for a single event, Figure 11 proves that  $\phi$  is approximately independent of the distance, even in the case of R-Model  
 283 where there is a complex layering (non-horizontal). In many cases, the value of  $\phi$  is considered to be independent on  
 284 the distance to the source (Atkinson, 2011). However, recent studies proposed a functional dependence of  $\phi$  on the  
 285 distance from the source (see Boore et al., 2014), although this variation occurs at distances larger than 80 km.

### 286 4.3. Influence of the site effects on the within-event variability

287 To explain the variability of the within-event residuals ( $\delta W_{es}$ ), its sensitivity with the respect to the local site conditions  
 288 is hereafter analyzed. In doing so,  $\delta W_{es}$  is related to several parameters such as: (1) the harmonic-mean shear velocity  
 289 in the first  $d$  m below the surface ( $V_{S,d}$ ) and (2) the thickness of the equivalent basin-like structure ( $H_v$ ). Those pa-  
 290 rameters are used in the recipes proposed by Eurocode 8 (EC8, CEN, 2004) and they are currently being discussed in  
 291 the framework of the EC8 site categorization update (Paolucci et al., 2021).  $V_{S,d}$  is often computed for  $d = 30$  m and  
 292  $d = 100$  m. The thickness of the equivalent basin-like structure is instead defined based on the shear-wave velocity  
 293 value of the *engineering bedrock*, such as  $H_{800}$ , corresponding to the depth at which the *engineering bedrock* is found,  
 294 i.e. the geological layer at which the shear velocity ranges around 800 m/s (according to Ansal and Tönük, 2007).  
 295 In this study,  $H_{1500}$  is also considered, in order to assess the role of deeper geological layers (such as the Shiiya and  
 296 Upper-Teradomari layers in the folding structure, see Figure 3). Table 4 shows the correlation between the R-Model  
 297 parameters for each mesh point location at surface. As expected,  $V_{S,30}$  and  $V_{S,100}$  are well-correlated with  $\rho = 0.98$ .  
 298 Similarly, the thicknesses  $H_{800}$  and  $H_{1500}$  are correlated with  $\rho = 0.78$ .  $V_{S,30}$  and  $V_{S,100}$  and  $H_{800}$  and  $H_{1500}$  are poorly  
 correlated and they can be used as complementary parameters to predict  $\delta W_{es}$  better and reduce  $\phi$ . Figure 12 shows

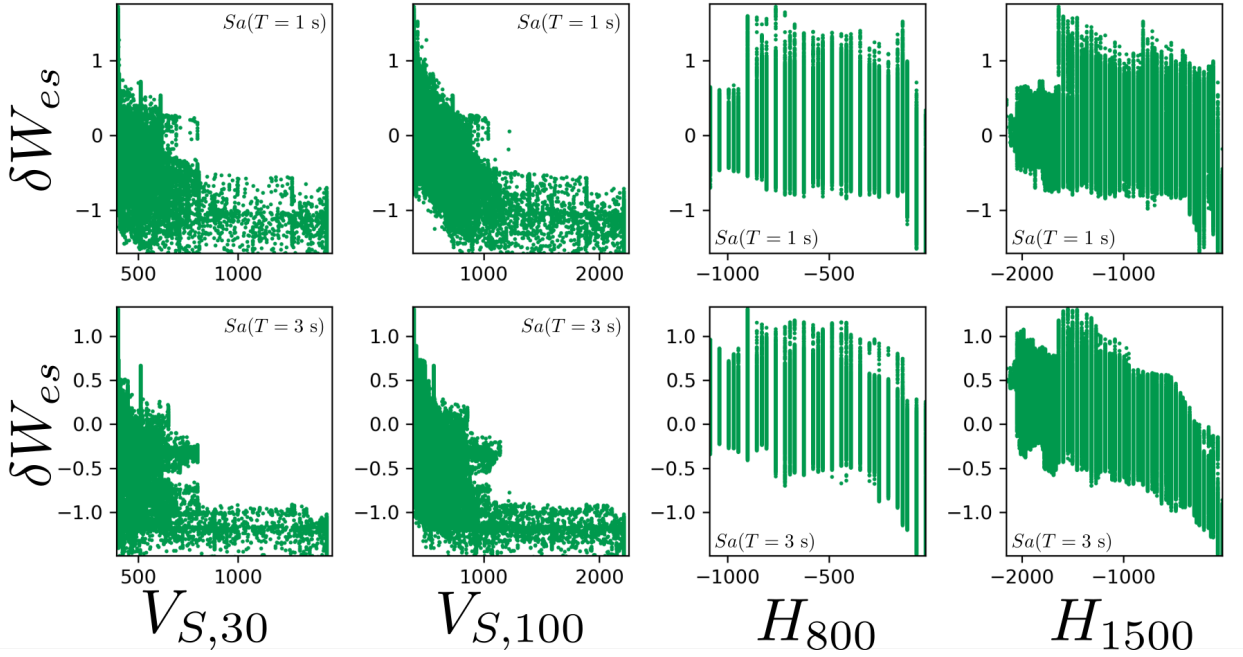
**Table 4**

Correlation matrix of the four analyzed site parameters for the R-model:  $V_{S,30}$ ,  $V_{S,100}$ ,  $H_{800}$  and  $H_{1500}$ .

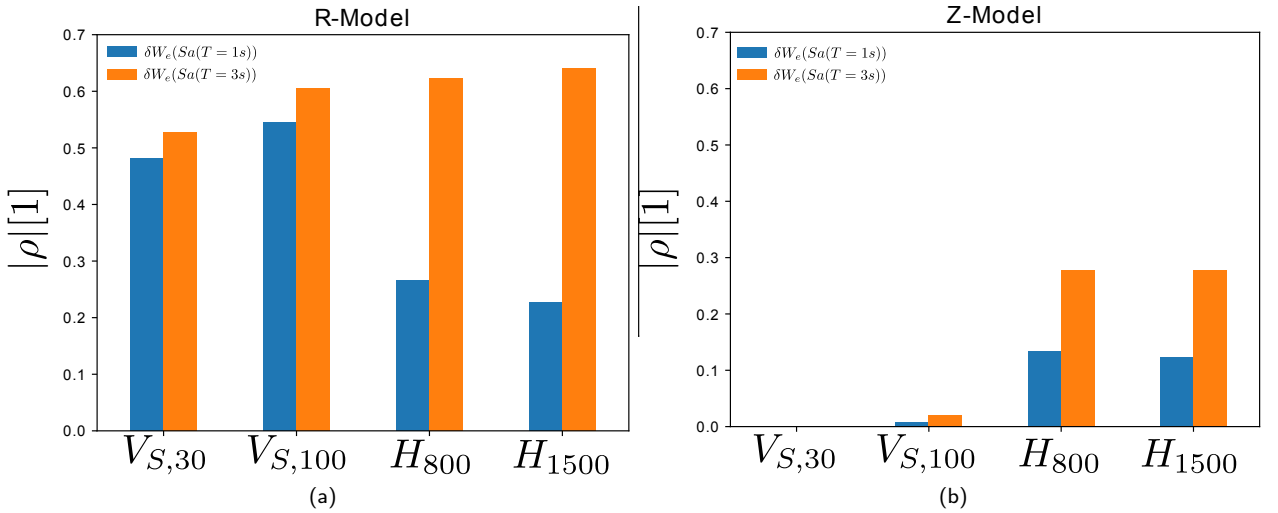
	$V_{S,30}$	$V_{S,100}$	$H_{800}$	$H_{1500}$
$V_{S,30}$	1.0	0.98	0.40	0.40
$V_{S,100}$		1.00	0.50	0.46
$H_{800}$			1.00	0.78
$H_{1500}$	sym			1.00

299  $\delta W_{es}$  values as a function of the four parameters  $V_{S,30}$ ,  $V_{S,100}$ ,  $H_{800}$  and  $H_{1500}$  respectively. Positive  $\delta W_{es}$  indicate  
 300 that the synthetic ground motion at the station of interest is larger than the geometric mean prediction. Negative  $\delta W_{es}$   
 301 values, on the contrary, point out that the synthetic IM at the station underestimate the geometric mean prediction.  
 302 Adopting the R-model, the  $\delta W_{es}$  estimation (for both  $T = 1$  s and  $T = 3$  s) is positive but it rapidly decays with  $V_{S,30}$   
 303 and  $V_{S,100}$  values below 800 m/s, whereas it remains approximately constant and close to -1 for larger shear-wave  
 304 velocity values. Numerical simulations seemingly overestimate the  $\bar{S}a$  values across softer sediments, highlighting  
 305 the presence of 3-D site effects that the GMPEs can barely picture. Moreover, the trend in Figure 12 are in agreement  
 306 with the EC8 classification and with the GMPE guidelines (e.g., Abrahamson and Silva, 1993; Lee et al., 1995) that  
 307 usually classify a site according to its  $V_{S,30}$ , being a *soil deposit* for  $V_{S,30} < 800$  m/s and *engineering bedrock* for  
 308  $V_{S,30} \geq 800$  m/s. In addition, this result supports the choice of  $H_{800}$  to condense the basin-like site effects.  
 309 On the contrary, no clear trend is observed for the estimated  $\delta W_{es}$  at  $T = 1$  s neither with respect to  $H_{800}$  nor with the  
 310 respect to  $H_{1500}$  (see Figure 12). At longer period (i.e.,  $T = 3$  s), as suggested by decaying  $\delta W_{es}$  trend approaching  
 311 small  $H_{800}$  or  $H_{1500}$ , the residual  $\delta W_{es}$  diminishes for lower  $H_{1500}$ , highlighting the influence of harder and deeper  
 312 rock layers on the site effect prediction.  
 313

314  
 315 Figure 13 shows the absolute correlation coefficient  $|\rho|$  between  $\delta W_{es}$  and each parameter  $V_{S,30}$ ,  $V_{S,100}$ ,  $H_{800}$  and  
 316  $H_{1500}$ , at  $T = 1$  s (blue histogram) and  $T = 3$  s (orange histogram). In this figure, the same correlation is computed  
 317 for the Z-model for the sake of comparison.  $|\rho|$  with respect to  $H_{800}$  and  $H_{1500}$  almost doubles at long period ( $T = 3$   
 318 s) highlighting the importance of site effects on the residual estimation. In the case of Z-Model (Figure 13b), there is  
 319 no correlation between  $\delta W_{es}$  and  $V_{S,30}$  and poor correlation with  $V_{S,100}$ , due to the horizontal layering and the coarse  
 320 geological model. Both parameters  $V_{S,30}$  and  $V_{S,100}$  are uninformative at this scale and resolution. However,  $H_{800}$   
 321 and  $H_{1500}$  represent complementary site-characterization parameters to  $V_{S,30}$ .



**Figure 12:** Within-event residual  $\delta W_{es}$  computed for the R-model, as function of  $V_{S,30}$ ,  $V_{S,100}$ ,  $H_{800}$  and  $H_{1500}$ . Top panels:  $\delta W_{es}$  computed for  $Sa(T = 1 \text{ s})$ . Bottom panels:  $\delta W_{es}$  computed for  $Sa(T = 3 \text{ s})$ .



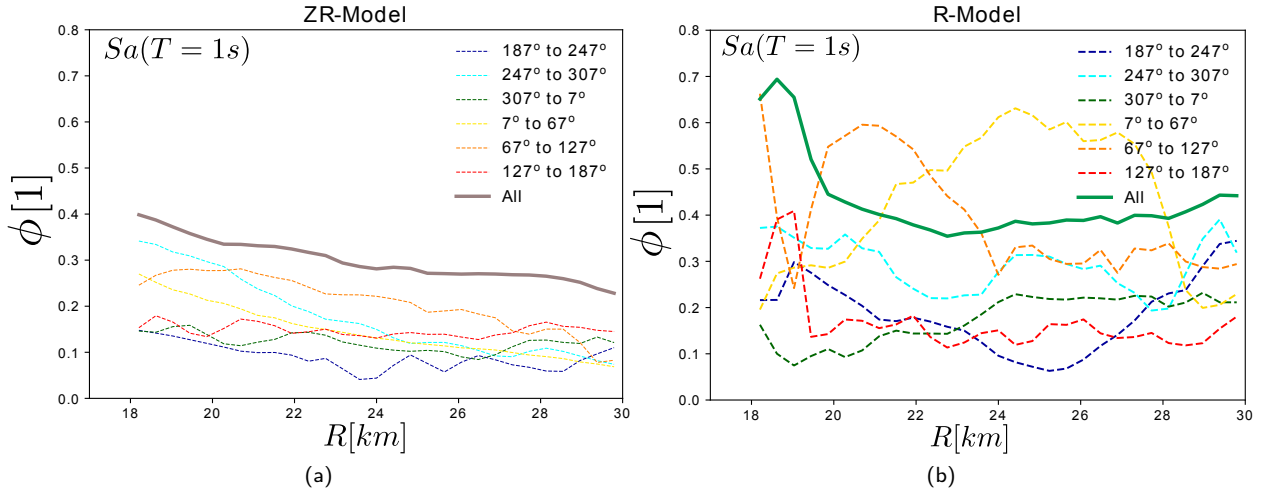
**Figure 13:** Absolute correlation coefficient  $|\rho|$  of  $\delta W_{es}$  with site parameters. R-Model (a) and Z-Model horizontal layered case (b).

322

323 Finally, the intensity of the ground motion is affected by the pattern of the source. Figure 7 showed that  $Sa$  spatial  
 324 variability at surface depends on the station back-azimuth. Figure 14 confirms this assumption, displaying the value  
 325 of  $\phi$  by clustering each station based on its back-azimuth.

326





**Figure 14:** Standard deviation  $\phi$  of the within-event residual  $\delta W_{es}$  as a function of the source-to-site distance  $R$ .  $\phi$  values at each station are clustered based on the station back-azimuth. (a) ZR-Model; (b) R-Model.

327 For the ZR-model, featured by a horizontally layered regional geology (see Figure 14a), the  $\phi$  clustering based on the  
 328 back-azimuth highlights a maximum difference of up to 40% between clusters. When considering the R-Model (see  
 329 Figure 14b), those discrepancies between cluster are less evident. For back-azimuths between  $7^\circ$  and  $127^\circ$ , the high  
 330  $\phi$  values are seemingly related to the complex geology in this zone. This is congruent with several studies (such as  
 331 Ripperger et al., 2008; Vyas et al., 2016) that also proved the variation of  $\phi$  as a function of the source pattern effects.  
 332 In this study, point sources are considered, although the back-azimuth dependency could be higher for extended-fault  
 333 scenarios due to directivity effects.

#### 334 4.4. Estimation of between-event variability

As far as  $\delta B_e$  is concerned, the extensive number of monitoring points allows to draw solid statistics in a large source-to-  
 site distance range. In this study, the quota of epistemic uncertainty linked to the source mechanism is not investigated.  
 Therefore,  $\delta B_e$  can be indirectly estimated by disentangling it from the within-event variability. Figure 15 shows the  
 estimated  $\delta B_e$  for both  $Sa(T=1\text{ s})$  and  $Sa(T=3\text{ s})$ . However, the fact that the three cases considered herein display  
 the same source pattern and location affects its estimation (Atik et al., 2010). Concerning the variability of the between-  
 event residual  $\tau$ , one easily observes that the variance of the total residual  $\sigma^2$  is the sum of the variances of between-  
 event and within-event residuals, which are modeled as independent random variables. Therefore, the between-event  
 variance is estimated as:

$$\tau^2 = \sigma^2 - \phi^2 \quad (6)$$

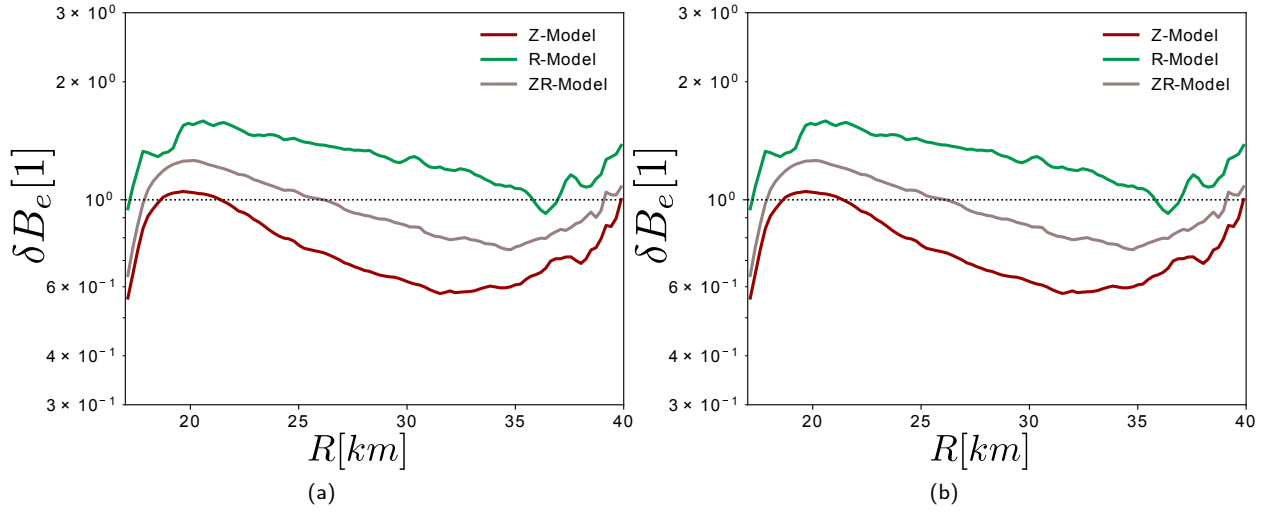
with  $\phi^2$  estimated in Section 4.2 from the synthetic time-histories. Therefore, the first step is to compute the model-  
 to-model deviation, inferred directly from the  $Sa_*/Sa_{**}$  ratio, according to the following expression:

$$\Delta_{Sa_*/Sa_{**}} = \Delta_{Sa_*} - \Delta_{Sa_{**}} \quad (7)$$

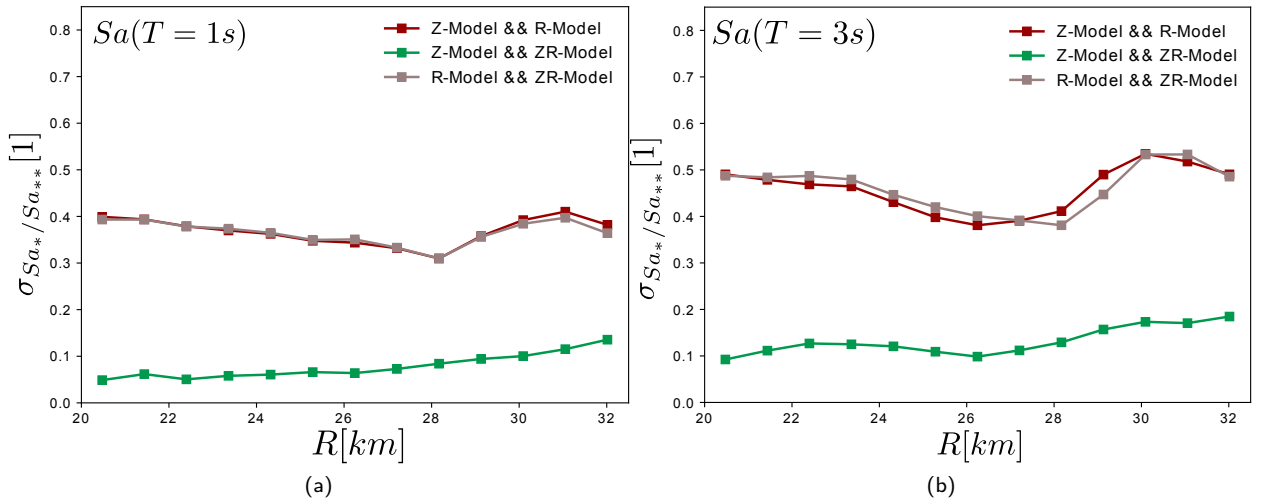
where  $\Delta_{Sa}$ , for any model and period, is considered as distributed as centered log-normal random variable. With this  
 assumption, the variance of  $\Delta_{Sa_*/Sa_{**}}$ , namely  $\sigma_{Sa_*/Sa_{**}}^2$  is computed as:

$$\sigma_{Sa_*/Sa_{**}}^2 = \sigma_{Sa_*}^2 + \sigma_{Sa_{**}}^2 - 2 \cdot \rho_{Sa_*, Sa_{**}} \cdot \sigma_{Sa_*} \cdot \sigma_{Sa_{**}} \quad (8)$$

335 with  $\sigma_{Sa}^2$  corresponding to the variance of the total residual of each model and  $\rho_{Sa_*, Sa_{**}}$  being the correlation coeffi-  
 336 cient between each combination of models, displayed in Figure 10. The evolution of  $\sigma_{Sa_*/Sa_{**}}$  for each model duos,  
 337 as a function of the source-to-site distance, is displayed in Figure 16. The standard deviation of the  $\sigma_{Sa_Z}/Sa_{ZR}$  ratio



**Figure 15:** Between-event residuals for (a)  $Sa(T=1\text{ s})$  and (b)  $Sa(T=3\text{ s})$  as functions of the source-to-site distance  $R$ .

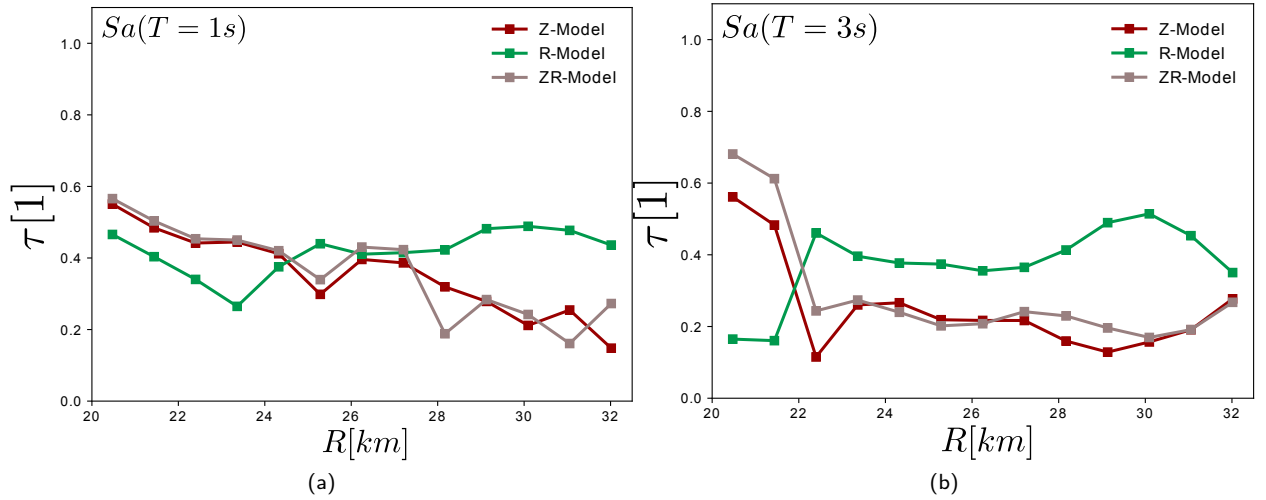


**Figure 16:** Standard deviation  $\sigma_{Sa^*/Sa^{**}}$  computed along source-to-site distance  $R$  for each model duos (\*,\*\*) and for (a)  $T=1\text{ s}$  and (b)  $T=3\text{ s}$ .

338 is very low. This aspect, along with the high correlation between both models (see Figure 10), indicates that, even if  
 339 they do not share similar geologies at depth, the two models are almost interchangeable for this very earthquake.

340

341 The second step to estimate the variability of  $\delta B_e$  consists into assembling a system of the three equations in the form  
 342 of Equation (8), considering  $\sigma_{Sa_R}$ ,  $\sigma_{Sa_Z}$  and  $\sigma_{Sa_{ZR}}$  as unknowns. The system is iteratively solved by exploiting the  
 343 outcome of the three earthquake simulations. Finally,  $\tau$  is computed by exploiting Equation (6). Figure 17 depicts  
 344 the  $\tau$  estimation along the source-to-site distance (not taking into account the variability that could come from the  
 345 model or the parameterization of the source event). Figure 17 shows that the three  $\tau$  curves are slowly varying along  
 346 the source-to-site distance. Despite some minor fluctuation between 20 and 24 km,  $\tau$  is practically constant for all  
 347 the three models at  $T=3\text{ s}$ . Moreover, the curves referring to the ZR-Model and the Z-Model are very similar for  
 348 both  $T=1\text{ s}$  (slowly decaying values with increasing distance from the source) and  $T=3\text{ s}$  (lower deviation, constant



**Figure 17:** Standard deviation  $\tau$  of the between-event residual  $\delta B_e$  computed along source-to-site distance  $R$ , for  $T = 1$  s (a) and  $T = 3$  s (b).

349 along the source-to-site distance). The deviation associated to the R-model is almost insensitive to the natural period  
 350 ( $\tau \approx 0.45$ ) except for its drop to lower values at short distances and long period, arguably due to the rather constant  
 351 geological properties (compared to the layered medium in Z-model) at the surface depth.

## 352 5. Conclusions

353 This study compares the synthetic outcomes of three physics-based numerical models, each featuring a different yet  
 354 plausible geological structure for the region at stake. A realistic test case (the 2007 Niigata earthquake) is studied,  
 355 so to prove the sensitivity of high-fidelity earthquake simulators to input geological information. The comparison  
 356 proved that complex geological features (the Niigata regional basin plugged into the R-Model), compared to horizon-  
 357 tally layered deep geology and folding geology close to the surface (Z-model and ZR-Model) might induce less than  
 358 10% difference on the surface seismic response (in terms of  $Sa$  values), leading to the possibility of simplifying the  
 359 geological medium to reduce the computational costs). Moreover, physics-based simulations were employed to study  
 360 the geology's influence on the spatial variability of the ground shaking.

361  
 362 Considering the 261120 virtual stations covering the region of interest, the paper adopted the GMPEs formulation in  
 363 Equation (1) to infer synthetic site-specific ground motion prediction variability. From the analysis, we evinced that  
 364  $\phi$  (i.e. the within-event residual standard deviation) mostly depends on shallow layers properties, increasing with the  
 365 geological complexity. Furthermore, the two models sharing the surficial site conditions but different ones at deep lay-  
 366 ers (Z-Model and ZR-Model) show a remarkable difference in the estimated between-event residual  $\delta B_e$  by an almost  
 367 constant factor (with source-to-site distance). This suggests that records from different tectonic regions but similar  
 368 site conditions (basin-like structures) can be integrated into a site-specific GMPE, by applying a correction factor that  
 369 considers the diverse deep geology.

370 The impact of complex layering on  $\tau$  (i.e. the between-event residual standard deviation) is reflected in the R-model  
 371 results, where higher  $\tau$  is obtained than in simpler geology models. Shallow geology is proven as a significant factor  
 372 in determining the average trend and variability of the synthetic seismic site response. At long period ( $T = 3$  s), the  
 373 between-event variability  $\tau$  is seemingly highly affected by the choice of the geological model, in a source-to-site dis-  
 374 tance range of 0-25 km.

375 The outcome of the numerical exercise suggests the possibility of disentangling the contribution of shallow and deep  
 376 geological structures on the overall synthetic seismic prediction at the site.  
 377 Finally, we unveiled a relation between the within-event residuals ( $\delta W_{e_s}$ ) and the properties of the sedimentary layers,  
 378 such as basin thickness and harmonic shear-wave velocity. Those two parameters are seemingly equally correlated to

379 the residual  $\delta W_{es}$ . In particular, the depth of the *engineering bedrock* is a rather easily accessible information, inferred  
380 from regional geological maps or obtained by non-invasive geophysical tests. Therefore, either  $H_{800}$  or  $H_{1500}$  are  
381 suitable to reduce the variability  $\phi$  of the *Sa* GMPE prediction, especially at long period. In this study, the influence  
382 of the source pattern and the back-azimuth on both  $\phi$  and  $\tau$  variability is assessed.

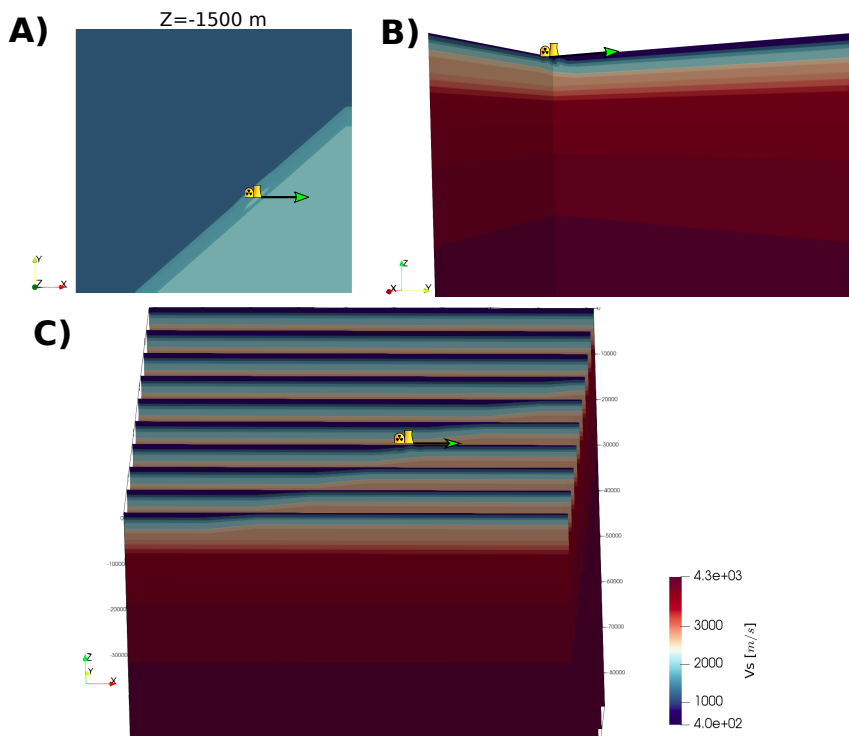
383

384 For the present case study, the results of this numerical analysis are congruent with several previous studies on real  
385 records. This shows that the numerical simulation from a well-calibrated model can be integrated with real records to  
386 create synthetic GMPEs, or complete the database of a region to produce more accurate GMPE. The previous results  
387 were found with a frequency band 0-2.1 Hz and not including the topographical effects. It is possible that at higher  
388 frequencies, the local conditions are more relevant, especially in the value of  $\phi$ . However, the results found in this  
389 simulation are still valid.

## 390 Acknowledgements

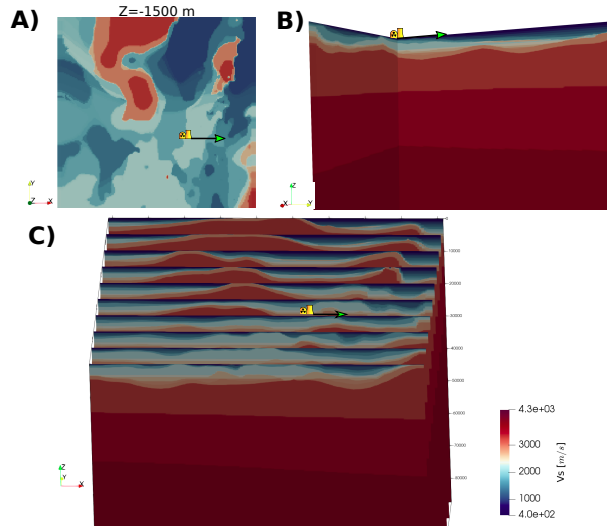
391 The research reported in this paper has been supported in part by the SEISM Paris Saclay Research Institute. This work,  
392 within the SINAPS@ project, benefited from French state funding managed by the National Research Agency under  
393 program RNSR Future Investments bearing Reference No. ANR-11-RSNR-0022-04, from the FY 2018 Postdoctoral  
394 Fellowship issued by the Japanese Society for Promotion of Science (JSPS) International Fellowships for Research  
395 in Japan, hosted by Prof. H. Kawase at Disaster Prevention Research Institute (DPRI) and by the digital geological  
396 data provided by Prof. H. Sekiguchi, as well as from valuable strong motion records during the 2007 Niigataken  
397 Chuetsu-Oki earthquake disseminated by TEPCO (Tokyo Electric Power Company).

## 398 A. Details of the geological models

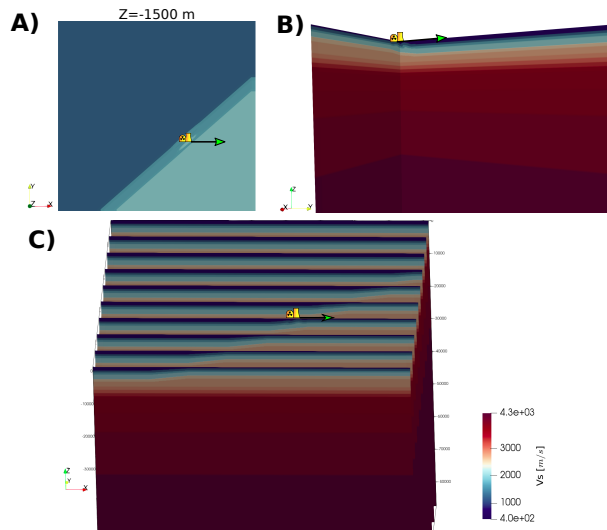


**Figure 18:** View-clips of the Z-Model. A) Superior view at  $z = -1500$  m. B) Longitudinal cut by the South-North direction (y-Axis). C) different slips by the East-West (x-axis) direction.

399



**Figure 19:** View of the R-Model marking the KKNPP complexes with the nuclear plant symbol. A) Superior view at  $z = -1500$  m. B) Longitudinal cut by the South-North direction (y-Axis). C) different slips by the East-West (x-axis) direction.



**Figure 20:** View of the ZR-Model marking the KKNPP buildings with the nuclear plant symbol. A) Superior view at  $z = 1500$  m. B) Longitudinal cut by the South-North direction (y-Axis). C) different slips by the East-West (x-axis) direction.

## 400 B. Performance of the numerical analysis

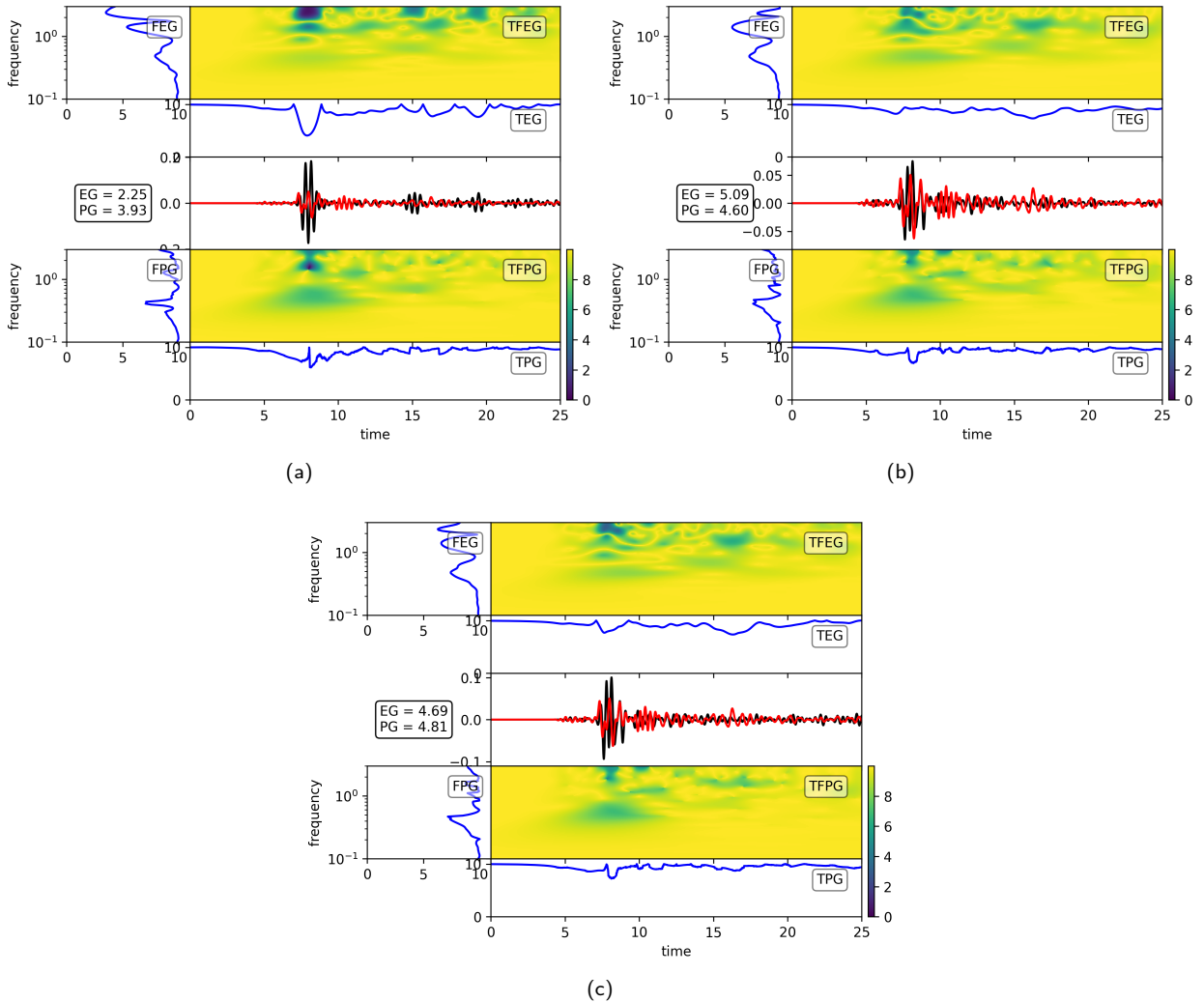
401 This work was granted access to the HPC resources of CINES under the allocation 2018-A0040410444, 2019-A0060410444,  
 402 2020-A0070411083 and 2020-A0080410444, made by GENCI (Grand équipement national de calcul intensif). Com-  
 403 putations were also performed using HPC resources allocated by the Mésocentre Moulon, the super-computer of Cen-  
 404 traleSupélec and École Normale Supérieure de Paris Saclay, Paris Saclay University.

405  
 406 Given the scalability properties of SEM3D ([https://www.researchgate.net/publication/349254101\\_SEM3D-High-res](https://www.researchgate.net/publication/349254101_SEM3D-High-res))  
 407 seismic\_wave\_propagation\_modelling\_from\_the\_fault\_to\_the\_structure\_for\_realistic\_earthquake\_

408 scenarios\_GENCI\_Allocation\_A0080410444/stats), each run (30 s earthquake simulation, on the template  
 409 model) took approximately 80 minutes ( $\approx$  960 hours CPU-time) on 720 MPI cores Intel Xeon Gold 6230 20C @2.1  
 410 GHz Cascade Lake.

### 411 C. Numerical model validation

412 In Figure 21, the synthetic and recorded accelerograms and Kristekova's GoF at KSH (SG4) are compared, considering  
 413 each numerical model (R-model, Z-model and ZR-model respectively). As expected, the synthetic ground motion  
 414 rendered at the KKNPP differs remarkably from model to model. Moreover, Z-Model displays a shorter *coda*-wave  
 415 compared to the R-Model, where the scattering effect caused by the more intricate geological structure increases the  
 effective propagation path and rendering large-duration time-histories.



**Figure 21:** Synthetic acceleration time-histories (EW component, filtered between 0-2.1 Hz) at KSH location (device SG4, G.L. -250 m) for the three models for EQ1. Red time-histories refer to earthquake recording (TEPCO, 2007), whereas black time-histories refer to the outcome of the numerical simulation. (a) R-model; (b) Z-model; (c) ZR-model.

## References

- 417  
418 Abrahamson, N., Gregor, N., Addo, K., 2016. BC Hydro ground motion prediction equations for subduction earthquakes. *Earthquake Spectra* 32,  
419 23–44. doi:10.1193/051712EQS188MR.
- 420 Abrahamson, N., Hollenback, J., 2012. Application of single-station sigma ground motion prediction equations in practice, in: *Proceedings of the*  
421 *15<sup>th</sup> world conference on earthquake engineering*, Lisbon, Portugal, paper.
- 422 Abrahamson, N., Silva, W., 1993. Attenuation of long period strong ground motions. *ASME-PUBLICATIONS-PVP* 256, 187–187.
- 423 Ansal, A., Tönük, G., 2007. Source and site factors in microzonation, in: *Earthquake geotechnical engineering*. Springer, pp. 73–92. doi:10.1007/  
424 978-1-4020-5893-6\_4.
- 425 Aochi, H., Ducellier, A., Dupros, F., Delatre, M., Ulrich, T., de Martin, F., Yoshimi, M., 2013. Finite difference simulations of seismic wave propaga-  
426 tion for the 2007 Mw 6.6 Niigata-ken Chuetsu-Oki earthquake: Validity of models and reliable input ground motion in the near field. *Pure and Ap-  
427 plied Geophysics* 170, 43–64. URL: <https://hal-brgm.archives-ouvertes.fr/hal-00980238>, doi:10.1007/s00024-011-0429-5.  
428 Springer Verlag (Germany).
- 429 Aoi, S., Kunugi, T., Fujiwara, H., 2004. Strong-motion seismograph network operated by NIED: K-NET and KiK-net. *Journal of Japan association*  
430 *for earthquake engineering* 4, 65–74.
- 431 Aoi, S., Sekiguchi, H., Morikawa, N., Kunugi, T., 2008. Source process of the 2007 Niigata-ken Chuetsu-oki earthquake derived from near-  
432 fault strong motion data. *Earth, Planets and Space* 60, 1131–1135. URL: <http://dx.doi.org/10.1186/BF03353149>, doi:10.1186/  
433 BF03353149.
- 434 Atik, L.A., Abrahamson, N., Bommer, J.J., Scherbaum, F., Cotton, F., Kuehn, N., 2010. The Variability of Ground-Motion Prediction Models and  
435 Its Components. *Seismological Research Letters* 81, 794–801. URL: <https://doi.org/10.1785/gssrl.81.5.794>, doi:10.1785/gssrl.  
436 81.5.794, arXiv:<https://pubs.geoscienceworld.org/ssa/srl/article-pdf/81/5/794/2762386/794.pdf>.
- 437 Atkinson, G.M., 2011. An empirical perspective on uncertainty in earthquake ground motion prediction. *Canadian Journal of Civil Engineering*  
438 38, 1002–1015. doi:10.1139/l10-120.
- 439 Boore, D.M., Stewart, J.P., Seyhan, E., Atkinson, G.M., 2014. NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow  
440 crustal earthquakes. *Earthquake Spectra* 30, 1057–1085. doi:10.1193/072114EQS116M.
- 441 Bradley, B.A., 2018. On-going challenges in physics-based ground motion prediction and insights from the 2010–2011 Canterbury and 2016  
442 Kaikoura, New Zealand earthquakes. *Soil Dynamics and Earthquake Engineering*, –URL: [https://www.sciencedirect.com/science/  
443 article/pii/S0267726117308631](https://www.sciencedirect.com/science/article/pii/S0267726117308631), doi:<https://doi.org/10.1016/j.soildyn.2018.04.042>.
- 444 Casarotti, E., Stupazzini, M., Lee, S., Komatitsch, D., Piersanti, a., Tromp, J., 2008. Cubit and seismic wave propagation based upon the spectral-  
445 element method: An Advanced Unstructured Meshier for Complex 3D Geological Media, in: *Proceedings of the 16<sup>th</sup> International Meshing*  
446 *Roundtable*, pp. 579–597.
- 447 Castro-Cruz, D., Gatti, F., Lopez-Caballero, F., 2021. High-fidelity broad-band prediction of regional seismic response: a hybrid coupling of  
448 Physics-Based synthetic simulation and Empirical Green’s functions. *Natural Hazards* URL: [https://link.springer.com/article/10.  
449 1007/s11069-021-04766-x](https://link.springer.com/article/10.1007/s11069-021-04766-x), doi:10.1007/s11069-021-04766-x.
- 450 CEA and CentraleSupélec and IGP and CNRS, 2017. SEM3D Ver 2017.04 Registered at French Agency for Protection of Programs (Dépôt APP).
- 451 CEN, 2004. Eurocode 8: design of structures for earthquake resistance-part 1: general rules, seismic actions and rules for buildings. Technical  
452 Report. URL: <https://eurocodes.jrc.ec.europa.eu/showpage.php?id=138>.
- 453 Chen, Y.H., Tsai, C.C.P., 2002. A new method for estimation of the attenuation relationship with variance components. *Bulletin of the Seismological*  
454 *Society of America* 92, 1984–1991. doi:10.1785/0120010205.
- 455 Cirella, A., Piatanesi, A., Tinti, E., Cocco, M., 2008. Rupture process of the 2007 niigata-ken chuetsu-oki earthquake by non-linear joint inversion  
456 of strong motion and gps data. *Geophysical Research Letters* 35.
- 457 Cupillard, P., Delavaud, E., Burgos, G., Festa, G., Vilotte, J.P., Capdeville, Y., Montagner, J.P., 2012. RegSEM: a versatile code based on the  
458 spectral element method to compute seismic wave propagation at the regional scale. *Geophysical Journal International* 188, 1203–1220.
- 459 Douglas, J., 2021. Ground motion prediction equations 1964–2021. Technical Report. arXiv:<http://www.gmpe.org.uk/gmpereport2014.pdf>.
- 460 Ducellier, A., Aochi, H., 2010. Numerical simulation of the mw 6.6 niigata, japan, earthqhake: Reliable input ground motion for engineering  
461 purpose, in: *14<sup>th</sup> European Conference on Earthquake Engineering*, pp. 8–p.
- 462 Faccioli, E., Maggio, F., Paolucci, R., Quarteroni, A., 1997. 2D and 3D elastic wave propagation by a pseudo-spectral domain decomposition  
463 method. *Journal of Seismology* 1, 237–251. doi:10.1023/A:1009758820546.
- 464 Fantoni, R., Franciosi, R., 2010. Tectono-sedimentary setting of the Po Plain and Adriatic foreland. *Rendiconti Lincei* 21, 197–209. doi:10.1007/  
465 s12210-010-0102-4.
- 466 Festa, G., Vilotte, J.P., 2005. The Newmark scheme as velocity–stress time-staggering: an efficient PML implementation for spectral element  
467 simulations of elastodynamics. *Geophysical Journal International* 161, 789–812.
- 468 Fujiwara, H., Kawai, S., Aoi, S., Senna, S., Ooi, M., Matsuyama, H., Iwamoto, K., Suzuki, H., Hayakawa, Y., 2006. A subsurface structure modeling  
469 of whole of Japan for strong-motion evaluation, in: *12<sup>th</sup> Japan Earthquake Engineering Symposium*, pp. 1466–1469.
- 470 García-Fernández, M., Gehl, P., Jiménez, M.J., DáÁyala, D., 2019. Modelling Pan-European ground motions for seismic hazard applications.  
471 *Bulletin of Earthquake Engineering* 17, 2821–2840. doi:10.1007/s10518-019-00605-4.
- 472 Gatti, F., Clouteau, D., 2020. Towards blending Physics-Based numerical simulations and seismic databases using Generative Adversarial Network.  
473 *Computer Methods in Applied Mechanics and Engineering* 372, 113421. URL: [http://www.sciencedirect.com/science/article/  
474 pii/S004578252030606X](http://www.sciencedirect.com/science/article/pii/S004578252030606X), doi:10.1016/j.cma.2020.113421.
- 475 Gatti, F., Lopez-Caballero, F., Clouteau, D., Paolucci, R., 2018a. On the effect of the 3-D regional geology on the seismic design of critical structures:  
476 the case of the Kashiwazaki-Kariwa Nuclear Power Plant. *Geophysical Journal International* 213, 1073–1092. doi:10.1093/gji/ggy027. doi:  
477 10.1093/gji/ggy027.
- 478 Gatti, F., Lopez-Caballero, F., Paolucci, R., Clouteau, D., 2018b. Near-source effects and non-linear site response at Kashiwazaki-Kariwa Nuclear  
479 Power Plant, in the 2007 Chuetsu-Oki earthquake: evidence from surface and downhole records and 1D numerical simulations. *Bulletin of*

480 Earthquake Engineering 16, 1105–1135. URL: <https://doi.org/10.1007/s10518-017-0255-y>, doi:10.1007/s10518-017-0255-y.

481 Gatti, F., Paludo, L.D.C., Svay, A., Cottureau, R., Clouteau, D., et al., 2017. Investigation of the earthquake ground motion coherence in heteroge-  
482 neous non-linear soil deposits. *Procedia engineering* 199, 2354–2359. doi:10.1016/j.proeng.2017.09.232.

483 Gatti, F., Touhami, S., Lopez-Caballero, F., Paolucci, R., Clouteau, D., Fernandes, V.A., Kham, M., Voltaire, F., 2018c. Broad-band 3-D earthquake  
484 simulation at nuclear site by an all-embracing source-to-structure approach. *Soil Dynamics and Earthquake Engineering* 115, 263–280. URL:  
485 <http://www.sciencedirect.com/science/article/pii/S0267726118303890>, doi:10.1016/j.soildyn.2018.08.028.

486 Göddeke, D., Komatitsch, D., Möller, M., 2014. Finite and Spectral Element Methods on Unstructured Grids for Flow and Wave Propagation  
487 Problems, in: *Numerical Computations with GPUs*. Springer, pp. 183–206.

488 Honda, R., Aoi, S., 2009. Array back-projection imaging of the 2007 Niigataken Chuetsu-Oki earthquake striking the world’s largest nuclear power  
489 plant. *Bulletin of the Seismological Society of America* 99, 141–147. doi:10.1785/0120080062.

490 Jayalakshmi, S., Dhanya, J., Raghukanth, S., Mai, P.M., 2021. Hybrid broadband ground motion simulations in the indo-gangetic basin for great  
491 himalayan earthquake scenarios. *Bulletin of Earthquake Engineering*, 1–30doi:10.1007/s10518-021-01094-0.

492 Jian, W., Fanhua, L., 2009. Prediction of oil-bearing single sandbody by 3d geological modeling combined with seismic inversion. *Petroleum*  
493 *Exploration and Development* 36, 623–627. URL: <https://www.sciencedirect.com/science/article/pii/S1876380409601506>,  
494 doi:[https://doi.org/10.1016/S1876-3804\(09\)60150-6](https://doi.org/10.1016/S1876-3804(09)60150-6).

495 Kamae, K. (Ed.), 2016. *Earthquakes, Tsunamis and Nuclear Risks*. Springer Japan, Tokyo. URL: [http://link.springer.com/10.1007/](http://link.springer.com/10.1007/978-4-431-55822-4)  
496 [978-4-431-55822-4](http://link.springer.com/10.1007/978-4-431-55822-4), doi:10.1007/978-4-431-55822-4.

497 Kobayashi, I., Tateishi, M., Yoshimura, T., Ueda, T., Kato, T., 1995. *Geology of the Kashiwazaki District*. Geological Survey of Japan.

498 Komatitsch, D., Vilotte, J.P., 1998. The Spectral Element Method: An Efficient Tool to Simulate the Seismic Response of 2D and 3D Geological  
499 Structures. *Bulletin of the Seismological Society of America* 88, 368–392.

500 Kristekova, M., Kristek, J., Moczo, P., 2009. Time-frequency misfit and goodness-of-fit criteria for quantitative comparison of time signals. *Geo-*  
501 *physical Journal International* 178, 813–825. doi:10.1111/j.1365-246X.2009.04177.x.

502 Kubo, A., Fukuyama, E., Kawai, H., Nonomura, K., 2002. NIED seismic moment tensor catalogue for regional earthquakes around Japan: quality test  
503 and application. *Tectonophysics* 356, 23 – 48. URL: <http://www.sciencedirect.com/science/article/pii/S004019510200375X>,  
504 doi:10.1016/S0040-1951(02)00375-X. seismic Source Mechanism through Moment Tensors.

505 Lee, E., Chen, P., Jordan, T.H., Maechling, P.B., Denolle, M.A.M., Beroza, G.C., 2014. Full 3D tomography for crustal structure in Southern  
506 California based on the scattering integral and the adjoint wavefield methods. *Journal of Geophysical Research: Solid Earth* 119, 6421–6451.  
507 URL: <https://doi.org/10.1002/2014JB011346>, doi:10.1002/2014JB011346.

508 Lee, V., Trifunac, M., Todorovska, M., Novikova, E., 1995. Empirical equations describing attenuation of peaks of strong ground motion, in terms  
509 of magnitude, distance, path effects and site conditions. *Terms of Magnitude, Distance, Path Effects and Site Conditions*, 95–02.

510 Milner, K.R., Shaw, B.E., Goulet, C.A., Richards, K.B., Callaghan, S., Jordan, T.H., Dieterich, J.H., Field, E.H., 2021. Toward Physics-Based Nonergodic PSHA: A Prototype Fully Deterministic Seismic Hazard Model for  
511 Southern California. *Bulletin of the Seismological Society of America* 111, 898–915. doi:10.1785/0120200216,  
512 arXiv:<https://pubs.geoscienceworld.org/ssa/bssa/article-pdf/111/2/898/5258622/bssa-2020216.1.pdf>.

513 Nakamura, Y., 1989. A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. *Railway Technical*  
514 *Research Institute, Quarterly Reports* 30. URL: <http://worldcat.org/oclc/3127232>.

515 NIED, N., 2019. K-net, kik-net, national research institute for earth science and disaster resilience doi:10.17598/NIED.0004.

516 NIED DMC, D., . Nied hi-net, national research institute for earth science and disaster resilience doi:10.17598/NIED.0003.

517 Obara, K., Kasahara, K., Hori, S., Okada, Y., 2005. A densely distributed high-sensitivity seismograph network in Japan: Hi-net by National  
518 Research Institute for Earth Science and Disaster Prevention. *Review of Scientific Instruments* 76, 021301. URL: [https://doi.org/10.](https://doi.org/10.1063/1.1854197)  
519 [1063/1.1854197](https://doi.org/10.1063/1.1854197), doi:10.1063/1.1854197, arXiv:<https://doi.org/10.1063/1.1854197>.

520 Okada, Y., Kasahara, K., Hori, S., Obara, K., Sekiguchi, S., Fujiwara, H., Yamamoto, A., 2004. Recent progress of seismic observation networks  
521 in Japan Hi-net, F-net, K-NET and KiK-net. *Earth, Planets and Space* 56, xv–xxviii. doi:10.1186/BF03353076.

522 Olsen, K.B., Nigbor, R., Konno, T., 2000. 3D Viscoelastic Wave Propagation in the Upper Borrego Valley, California, Constrained by Borehole  
523 and Surface Data. *Bulletin of the Seismological Society of America* 90, 134–150. URL: <https://doi.org/10.1785/0119990052>, doi:10.  
524 [1785/0119990052](https://doi.org/10.1785/0119990052), arXiv:<https://pubs.geoscienceworld.org/ssa/bssa/article-pdf/90/1/134/2710460/134.pdf>.

525 Olsen, K.B., Pechmann, J.C., Schuster, G.T., 1995. Simulation of 3D elastic wave propagation  
526 in the Salt Lake Basin. *Bulletin of the Seismological Society of America* 85, 1688–1710.  
527 arXiv:<https://pubs.geoscienceworld.org/ssa/bssa/article-pdf/85/6/1688/2708590/BSSA0850061688.pdf>.

528 Paolucci, R., Aimar, M., Ciancimino, A., Dotti, M., Foti, S., Lanzano, G., Mattevi, P., Pacor, F., Vanini, M., 2021. Checking the site categorization  
529 criteria and amplification factors of the 2021 draft of Eurocode 8 Part 1a. *Bulletin of Earthquake Engineering* URL: [https://link.](https://link.springer.com/10.1007/s10518-021-01118-9)  
530 [springer.com/10.1007/s10518-021-01118-9](https://link.springer.com/10.1007/s10518-021-01118-9), doi:10.1007/s10518-021-01118-9.

531 Paolucci, R., Gatti, F., Infantino, M., Ozcebe, A.G., Smerzini, C., Stupazzini, M., 2018. Broad-band ground motions from 3D physics-based  
532 numerical simulations using Artificial Neural Networks. *Bulletin of the Seismological Society of America* 108, 1272–1286. doi:10.1785/  
533 [0120170293](https://doi.org/10.1785/0120170293).

534 Régnier, J., Bonilla, L.F., Bard, P.Y., Bertrand, E., Hollender, F., Kawase, H., Sicilia, D., Arduino, P., Amorosi, A., Asimaki, D., Boldini, D., Chen,  
535 L., Chiaradonna, A., De Martin, F., Ebrille, M., Elgamal, A., Falcone, G., Foerster, E., Foti, S., Garini, E., Gazetas, G., Gélis, C., Ghofrani, A.,  
536 Giannakou, A., Gingery, J., Glinsky, N., Harmon, J., Hashash, Y., Iai, S., Jeremić, B., Kramer, S., Kontoe, S., Kristek, J., Lanzo, G., di Lernia,  
537 A., Lopez-Caballero, F., Marot, M., McAllister, G., Diego M., E., Moczo, P., Montoya-Noguera, S., Musgrove, M., Nieto-Ferro, A., Pagliaroli,  
538 A., Pisanó, F., Richterova, A., Sajana, S., Santisi d’Avila, M., Shi, J., Silvestri, F., Taiebat, M., Tropeano, G., Verrucci, L., Watanabe, K., 2016.  
539 International Benchmark on Numerical Simulations for 1D, Nonlinear Site Response (PRENOLIN): Verification Phase Based on Canonical  
540 Cases. *Bulletin of the Seismological Society of America* 106, 2112–2135. URL: <http://www.bssaonline.org/content/106/5/2112>.  
541 abstract, doi:10.1785/0120150284, arXiv:<http://www.bssaonline.org/content/106/5/2112.full.pdf+html>.



- 543 Ripperger, J., Mai, P.M., Ampuero, J.P., 2008. Variability of Near-Field Ground Motion from Dynamic Earthquake Rupture Simulations. *Bul-*  
544 *letin of the Seismological Society of America* 98, 1207–1228. URL: <https://doi.org/10.1785/0120070076>, doi:10.1785/0120070076,  
545 arXiv:<https://pubs.geoscienceworld.org/ssa/bssa/article-pdf/98/3/1207/3670862/1207.pdf>.
- 546 Rodriguez-Marek, A., Cotton, F., Abrahamson, N.A., Akkar, S., Al Atik, L., Edwards, B., Montalva, G.A., Dawood, H.M., 2013. A Model for  
547 Single-Station Standard Deviation Using Data from Various Tectonic Regions. *Bulletin of the Seismological Society of America* 103, 3149–  
548 3163. URL: <https://doi.org/10.1785/0120130030>, doi:10.1785/0120130030.
- 549 Sekiguchi, H., Yoshimi, M., Horikawa, H., Yoshida, K., Suzuki, H., Matsuyama, H., Morino, M., Takizawa, F., Ying, L., 2009. 3d subsurface  
550 structure model of the niigata sedimentary basin. *Geological Survey of Japan* *AIIST annual report on active fault and paleoearthquake*  
551 *researches* 9, 175–259.
- 552 Shang, X., Tkalčić, H., 2020. Point-source inversion of small and moderate earthquakes from p-wave polarities and p/s amplitude ratios  
553 within a hierarchical bayesian framework: Implications for the geysers earthquakes. *Journal of Geophysical Research: Solid Earth* 125,  
554 e2019JB018492. URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB018492>, doi:[https://doi.org/](https://doi.org/10.1029/2019JB018492)  
555 [10.1029/2019JB018492](https://doi.org/10.1029/2019JB018492), arXiv:<https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019JB018492>.
- 556 Smerzini, C., Paolucci, R., Stupazzini, M., 2011. Comparison of 3D, 2D and 1D numerical approaches to predict long period earthquake ground  
557 motion in the Gubbio plain, Central Italy. *Bulletin of Earthquake Engineering* 9, 2007–2029. doi:10.1007/s10518-011-9289-8.
- 558 Strasser, F.O., Abrahamson, N.A., Bommer, J.J., 2009. *Sigma: Issues, Insights, and Challenges*. *Seismologi-*  
559 *cal Research Letters* 80, 40–56. URL: <https://doi.org/10.1785/gssrl.80.1.40>, doi:10.1785/gssrl.80.1.40,  
560 arXiv:<https://pubs.geoscienceworld.org/ssa/srl/article-pdf/80/1/40/2760588/040.pdf>.
- 561 TEPCO, 2007. The data analysis recorded at the Kashiwazaki Kariwa Nuclear Power Plant during the 2007 Niigata-ken Chuetsu-oki earthquake.  
562 Technical Report. The Tokyo Electric Power Company, Inc. URL: [http://www.tepco.co.jp/cc/press/betu07\\_j/images/070730d.](http://www.tepco.co.jp/cc/press/betu07_j/images/070730d.pdf)  
563 [pdf](http://www.tepco.co.jp/cc/press/betu07_j/images/070730d.pdf). in Japanese.
- 564 Tokumitsu, R., Kikuchi, M., Nishimura, I., Shiba, Y., Tanaka, S., 2009. Analysis of the strong motion records obtained from the 2007 Niigataken  
565 Chuetsu-Oki earthquake and determination of the design basis ground motions at the Kashiwazaki Kariwa Nuclear Power Plant. Part 1. Outline  
566 of the strong motion records and estimation of factors in large amplification. Technical Report.
- 567 Tsuda, K., Hayakawa, T., Uetake, T., Hikima, K., Tokimitsu, R., Nagumo, H., Shiba, Y., 2011. Modeling 3D Velocity Structure in the Fault Region of  
568 the 2007 Niigataken Chuetsu-Oki Earthquake with Folding Structure, in: *4<sup>th</sup> IASPEI/IAEE International Symposium-Effects of Surface Geology*  
569 *on Seismic Motion*, pp. 1–11.
- 570 Vyas, J.C., Mai, P.M., Galis, M., 2016. Distance and Azimuthal Dependence of Ground Motion Variability for Unilateral Strike Slip  
571 Ruptures. *Bulletin of the Seismological Society of America* 106, 1584–1599. URL: <https://doi.org/10.1785/0120150298>, doi:10.  
572 [1785/0120150298](https://doi.org/10.1785/0120150298), arXiv:<https://pubs.geoscienceworld.org/ssa/bssa/article-pdf/106/4/1584/2646281/1584.pdf>.
- 573 Watanabe, T., Moroi, T., Nagano, M., Tokumitsu, R., Kikuchi, M., Nishimura, I., 2009. Analysis of the strong motion records obtained from the  
574 2007 Niigataken Chuetsu-Oki earthquake and determination of the design basis ground motions at the Kashiwazaki Kariwa Nuclear Power Plant.  
575 Part 2. Difference of site amplification based on the 2D FEM analysis of the folded structure. Technical Report.