17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

BROADBAND SEISMIC SOURCE-TO-STRUCTURE ANALYSIS OF THE KASHIWAZAKI-KARIWA NUCLEAR POWER PLANT.

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Abstract

In this paper, the seismic response analysis of the Kashiwazaki-Kariwa nuclear power plant (KKNPP, Japan) is presented. The basic earthquake scenarios correspond to a Mw4.4 aftershock that followed the Mw6.6 2007 Chuetsu Earthquake, which largely damaged the KKNPP site. A high-fidelity source-to-site earthquake simulator is exploited to generate physics-based (PBS) ground motion in 0-5 Hz frequency range (long period, LP). Based upon those results, hybrid (HYB) broad-band (0-30 Hz) ground motion at surface is rendered by exploiting Neural Networks to generate the 5-30 Hz part of the synthetic spectra (broad-band BB). The novelty of this paper are two: (1) a random fluctuation is added to the PBS LP portion of the spectrum to render 200 different input-motion scenarios; (2) these synthetic ground motion realizations are injected into a numerical model of the Unit 7 reactor building to assess its dynamic response. The wave propagation problem is solved by means of the Spectral Element Method (SEM), over a ~50.8 km × 50.8 km × 68 km domain in the surrounding of the KKNPP, with smallest grid-size of ~200 m ×200 m × 200 m. The overall numerical accuracy is granted in a 0-5 Hz frequency band. The complex regional geology is included (after verification). PBS synthetic time-histories are enriched at high frequency (5-30 Hz), exploiting ANN2BB, a 2-layer Neural Network trained on a set of strong-motion records, to predict the response spectral ordinates at short periods, based on the long period ones. Broad-band (0-30 Hz) synthetics are obtained by iterative scaling the Fourier spectra obtained via simulation, until their response spectrum matches the ANN2BB target spectrum (with no phase change). Following this strategy, 200 strong ground motion realizations are produced via quasi Monte Carlo algorithm, adding small fluctuations to the low-frequency part of the spectrum (produced by the uncertainty on the geology) before undergoing ANN2BB hybridization. The free-field ground motion realization are finally employed as input motion for the local Soil-Structure Interaction model of the KKNPP Unit 7 reactor building. The seismic response at different monitoring point on the nuclear installation is drawn by exploiting this powerful hybrid technique in order to assess the vulnerability of this critical structure and the sensitivity to the uncertainty on the regional geological model.

Keywords: earthquake simulation; uncertainty quantification; SEM3D; ANN2BB

1. Introduction

In recent years, the digital simulation of seismic scenarios on a regional scale for the study of the seismic vulnerability of critical structures and the quantification of associated uncertainties has become a tool increasingly used. The originality lies in the holistic and multi-scale approach to the study of seismic phenomena, including: simulation of active faults, interaction between wave fields and structures geological, nonlinear near-surface effects, soil-structure interaction. Extreme scenarios for seismic hazard studies are now feasible [1] as well as direct exploration of the statistical distribution of seismological, geophysical and geotechnical parameters (deep geology, mechanical properties of sedimentary layers, mechanism failure on the fault) [2,3]. The French research project SINAPS@ [4,5] validated and verified those tools in the framework of risk assessment of nuclear power plants, including the specific objective is the improvement of common seismic design practices.
Fig. 1 shows the context of the analysis of the fault in the structure, with crucial aspects included (source, propagation in the crust, site effects and response of the structure).

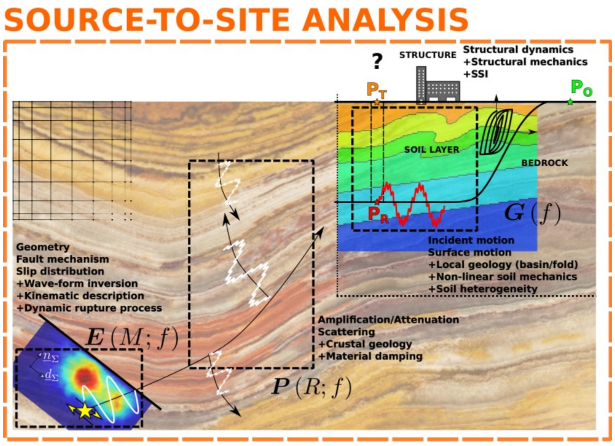

Figure 2: Schema representing the approach from the source to the structure proposed for the simulation of a seismic scenario [6]

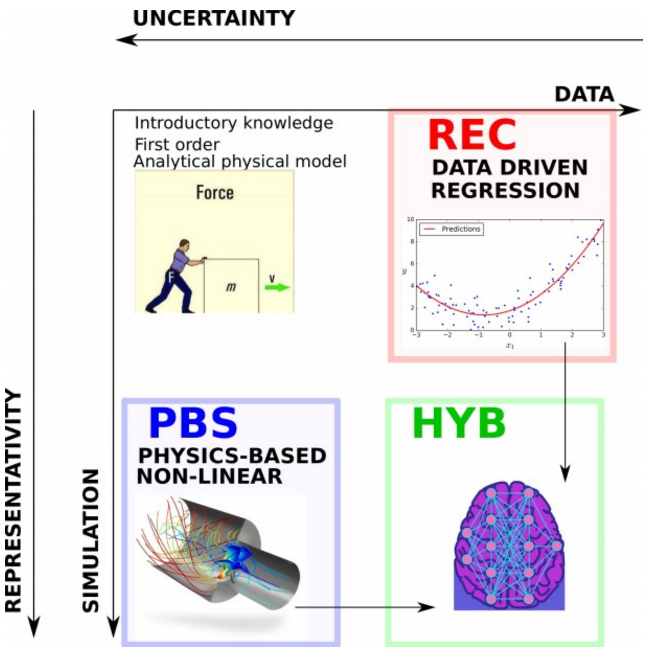

Figure 1: Figure 2: Strategy to improve the prediction of a physical phenomenon using physics-based digital simulation (PBS) to improve representativeness and Machine-Learning (ML) methods, to integrate experimental data and observations (REC) thanks to a hybrid approach (HYB). Adapted from [9].

To faithfully represent seismological observations using these digital models complex and characterized by great epistemic uncertainty, part of the research was then devoted to hybrid meta-modeling of the seismic wave field (Fig. 2).
The strategy followed provides for coupling be deterministic physics-based numerical simulations (PBS) and learning by artificial neural networks (ANNs) from large seismic record databases (REC) now available worldwide (the technique goes under the name of ANN2BB [7]). This hybrid modeling technique (HYB) innovation (from the work of [8]) overcomes the limitations of direct simulation at frequencies above 10 Hz, due, on the one hand, to the lack of data at fine scales (e.g. geology deep, the heterogeneities of the crust, the non-linearity of the soil layers, the fault dynamics of the fault) and on the other hand the cost of simulation

still high at fine scales. This technique thus makes it possible to extend the frequency band of synthetic signals thanks to the integration of high-frequency spectrum prediction obtained by ML and conditioned by digital simulation at lower frequencies. In order to complete the modeling of an earthquake from the fault to the structure with quantification of the uncertainties, the analysis must finally focus on Soil-Structure Interaction (SSI), to characterize the seismic response of the buildings of a nuclear power station, using as incident wave fields the synthetic signals obtained from the modeling of the regional seismic scenario and from the hybrid modeling exploiting the algorithms of ML. For this purpose, it is first necessary to integrate a consolidated procedure of weak coupling between the wave propagation on a regional scale (to generate the incident wave fields at the outcrop) and the SSI calculation methods, including hybrid modeling based on ML algorithms.
In this paper, promising results obtained in terms of structural seismic prediction based on high-performance numerical simulation (HPC) and meta-modeling by ANN are shown. These results are the result of the development of a modular HPC digital platform, developed as part of an ongoing collaboration between the MSSMat Laboratory of CentraleSupélec, Électricité de France (EDF), the French Atomic Energy and Alternative Energy Commission (CEA).

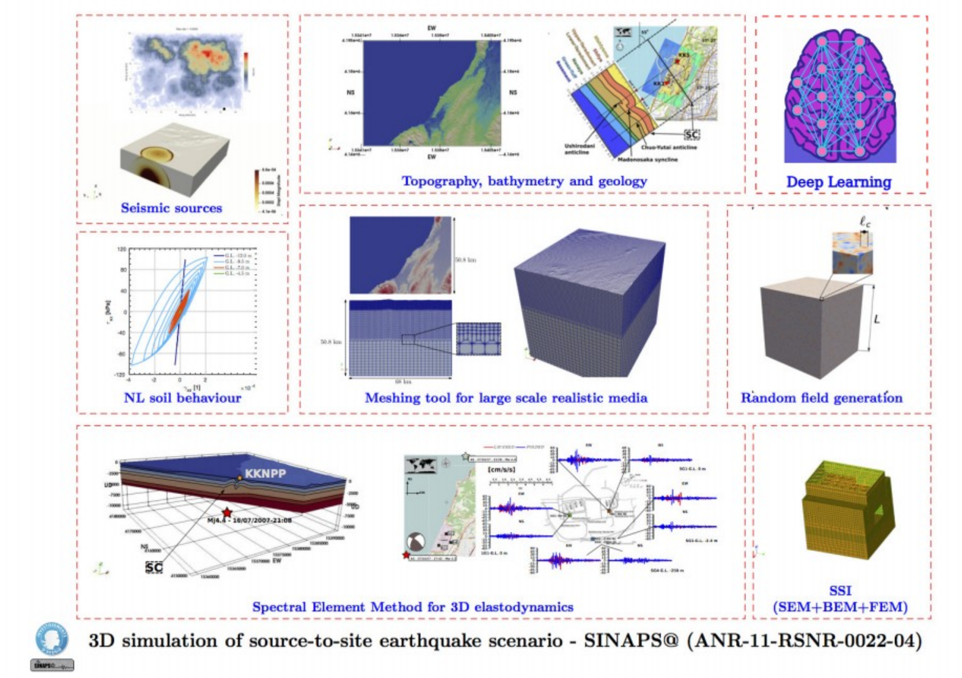

Figure 3: Digital platform developed within the SEISM institute for the prediction of strong seismic movement from the fault to the structure, by HPC numerical modeling and data integration by Machine Learning.

In this paper, the seismic response analysis of the Kashiwazaki-Kariwa nuclear power plant (KKNPP, Japan) is presented. The main novelties of this work are four: (1) a high-fidelity source-to-site earthquake simulator is exploited to generate physics-based (PBS) ground motion in 0-5 Hz frequency range (long period, LP); (2) based upon those results, hybrid (HYB) broad-band (0-30 Hz) ground motion at surface is rendered by exploiting Neural Networks to generate the 5-30 Hz part of the synthetic spectra (broad-band BB); (3) random fluctuation is added to the PBS LP portion of the spectrum to render 200 different input-motion scenarios; (4) these synthetic ground motion realizations are injected into a numerical model of the Unit 7 reactor building to assess its average dynamic response and the uncertainty margins.

2. Data and Methods

2.1 Physics-based earthquake numerical simulation

The 2007 Mw6.8 Niigata earthquake (NCOEQ) represents an exceptional and well documented case study to test the predictive capabilities of the computational platform presented in Fig. 3: complex regional and site geology, a fault located very close to the sensitive installation, recorded strong ground motion at free-field and on the nuclear reactor/turbine buildings. In [1,6], the 3-D numerical model of the region (~68 km × 50 km × 50 km) surrounding the KKNPP was constructed. The folded geological model (consisting of a structure in folded layers, shown in Fig. 4a) was tested for a Mw4.4 aftershock event, with the objective to characterize the seismic response of the reactor building of Unit 7. The regional model duly renders the spatial variability of the ground motion at free surface due to, among other factors, the deep geology of the site responsible for a wave focusing at the 1G1 site, corresponding to Unit 1 of the KKNPP site (Fig. 4b).

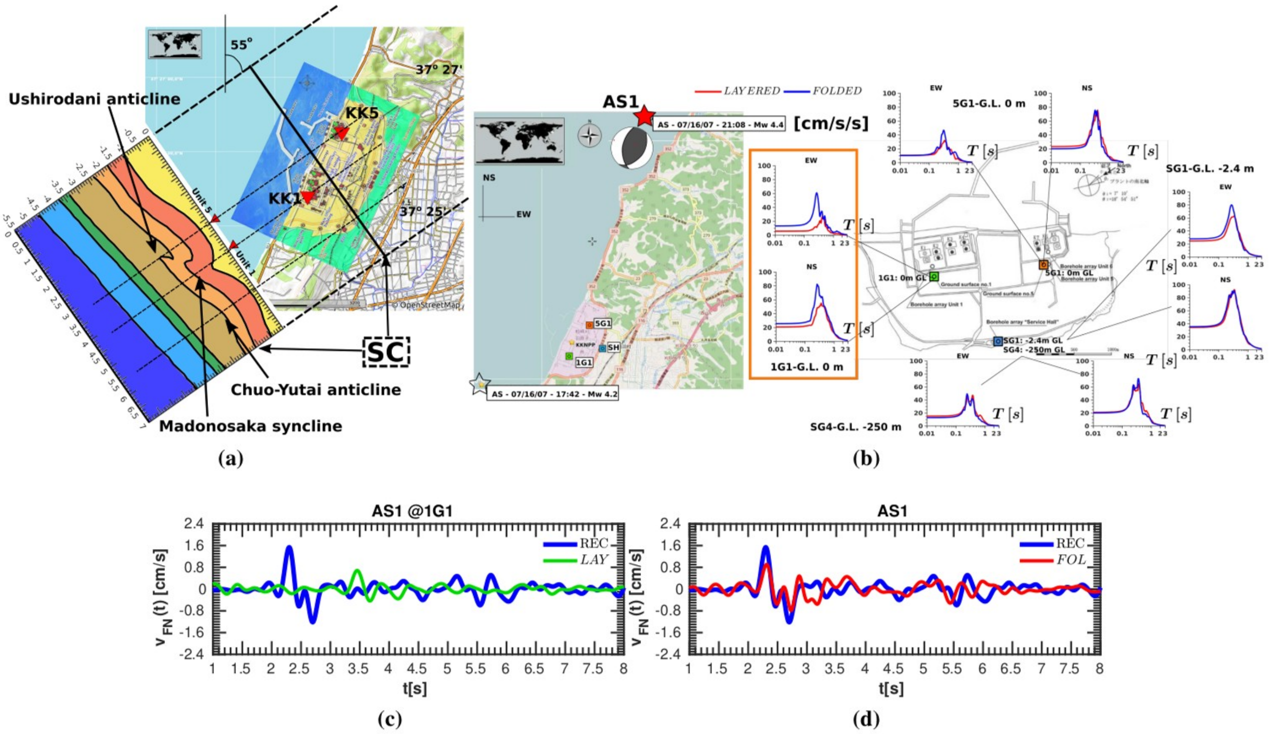

Figure 4: (a) Folding geology proposed by [10,11]; (b) simulated seismic site response (in terms of Sa pseudo-acceleration response spectrum) at KKNPP; (c-d) synthetic records obtained for layered regional geology (LAY, green) and folded regional geology (FOL, red), compared to recorded sianglas (REC, blue).

Fig. 4b also shows the consistent amplification in Unit 1 obtained thanks to the inclusion of a more realistic geology in the numerical model. The introduction of this modeling detail has brought a significant improvement in the prediction of the seismic response recorded during the most intense aftershock, as can be noted by comparing the accelerograms (precise between 0-5 Hz) in Fig. 4c, obtained by including a geology by parallel layers, with those in Fig. 4d obtained by including the folded structure in Fig. 4a. The study of KKNPP's seismic response has shown the importance of considering the phenomenon on a regional scale, especially in the case of a near source. With this deterministic approach, the seismic response can be simulated with high fidelity between 0-10 Hz [12]. However, the uncertainty linked to geological and seismological data is still not negligible.

2.2 ANN2BB: High frequency enrichment of synthetic signals by neural networks

A critical factor in the numerical simulation of 3-D wave propagation is the maximum period T* up to which this simulation is considered *accurate*. T* is a function of the spatial resolution of the model with the consequence increased computing costs. Even with infinite computational resources at hand, the information available on the geological and seismological models is often insufficient to properly condition the twin digital model of the site at high frequencies. This is why alternative strategies have been developed to generate broad-band (0-30 Hz) synthetic signals, to be used as incident motion for SSI studies. Among these techniques, hybrid meta-modeling is becoming increasingly dominant: the data is directly integrated into numerical simulations, either by a data-driven approach or in a multi-fidelity framework. ANN2BB [7] represents a meta-modeling technique complementary to purely deterministic analyzes. It is a question of predicting the short-term spectral ordinates (T<T*). From the portion T ≥ T* response spectrum (which can be reproduced fairly well with digital simulations), using an Artificial Neural Network (ANN). Fig. 5 shows the high-fidelity mapping (T ≥ T*) → high-uncertainty (T <T*) and the different phases of train and prediction.

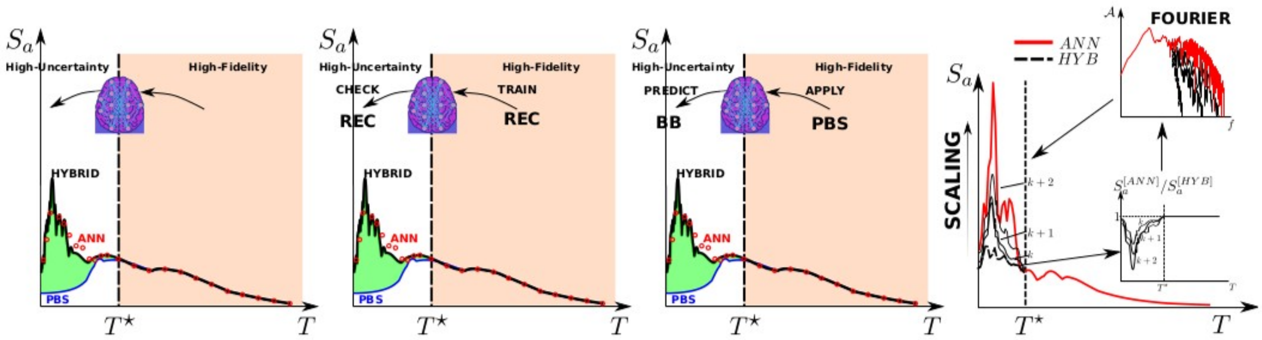

Figure 5: Schema for training and applying the ANN2BB technique on synthetic records.

The ANN learning task is perfomed on recorded signals (REC in Fig. 5), iteratively minimizing (by stochastic gradient descent) the weights from the value of the cost function calculated on the spectral ordinates at T <T* . Once a satisfactory predicting capability is learned (avoiding over-learning), the part T <T* of the spectrum is predicted by the ANN from the portion T ≥ T* obtained by physics-based simulation (PBS, in Fig. 5) Finally, broadband synthetics (BB in Fig. 5) are obtained by iterative scaling of the initial Fourier spectrum T <T* so that the corresponding response spectrum coincides with that predicted by the ANN. ANN2BB was applied to the Niigata and KKNPP scenario by [1]. The incident wave field, generated by SEM3D (see Figs. 4d), was previously enriched at high frequencies, thanks to the ANN2BB method: the outcome signals in free fields result more likely and close to the real signals recorded, with broadband frequency content (0-30 Hz), as shown in Fig. 6a. The signals thus obtained (black spectrum ANN2BB in Fig. 6a) were obtained at the free-field recording station SG1, located at the Service Hall of the nuclear power plant.

2.3 Montecarlo SSI analysis

To complete the analysis, the wave motion obtained via PBS was injected into the SSI model of Unit 7 of KKNPP (Finite Element Method) produced by EDF (see [1,12,13,14]). In doing so, the closest downhole seismometer (located at G.L. -36 m) was considered as injection point, placed approximately at the bottom of the SSI model (see the mesh in Fig. 6b). The incident wave motion (obtained via SEM3D analysis, whose time-histories were enriched via ANN2BB at high-frequency) was introduced as three-component plane wave at the base of the numerical model. The latter includes the stratified 1-D geology provided by the Tokyo Electric Power Company (TEPCO) [16].

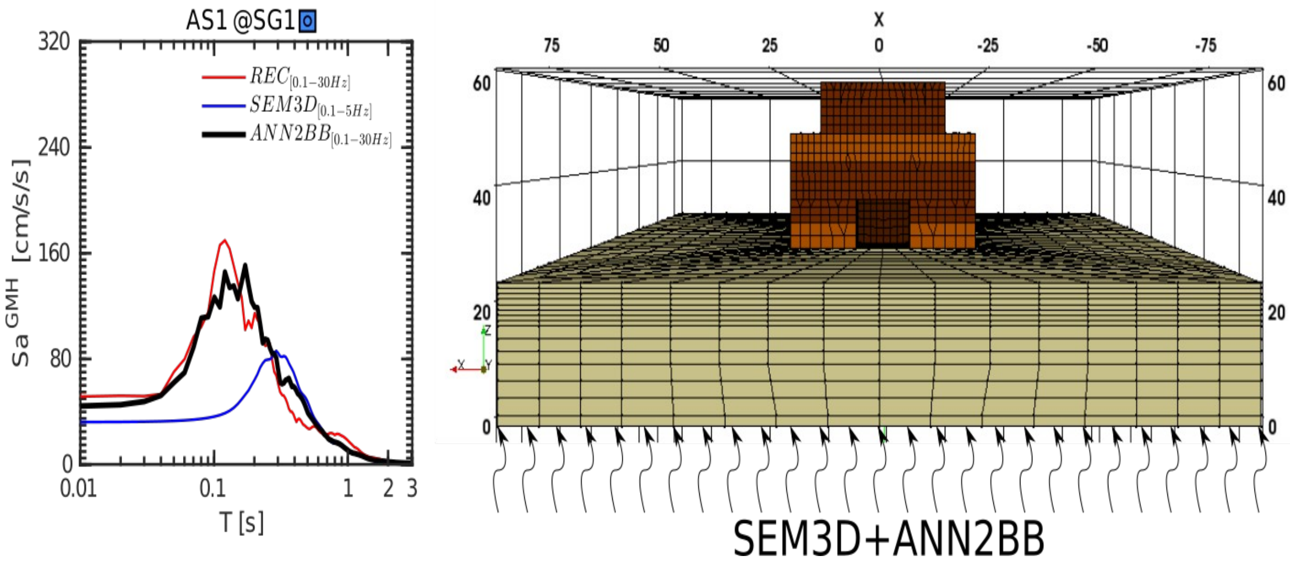

Figure 6: (a) Comparison between recorded (red), simulated via PBS (blue) and enriched at high-frequency via ANN2BB (black) Sa spectra (geometric mean of horizontal components) at SG1 (at G.L. 0, located close to the KKNPP Service Hall). (b) Scheme of the SSI analysis performed by two-step weak coupling.

Following the sensitivity analysis performed by [15] and in continuity with their work, a Monte Carlo (MC) analysis was performed on the ANN2BB procedure. This analysis consisted into adding random decorrelated fluctuations to the long period Sa ordinates obtained via PBS and predicting the corresponding ANN2BB response at short period. 200 MC realizations were performed. Fig. 7 shows the outcome of the SSI transient analysis (in elastic regime): the Sa spectra at two significant recording seismometers 7R1 (3rd floor) and 7R2 (basement).

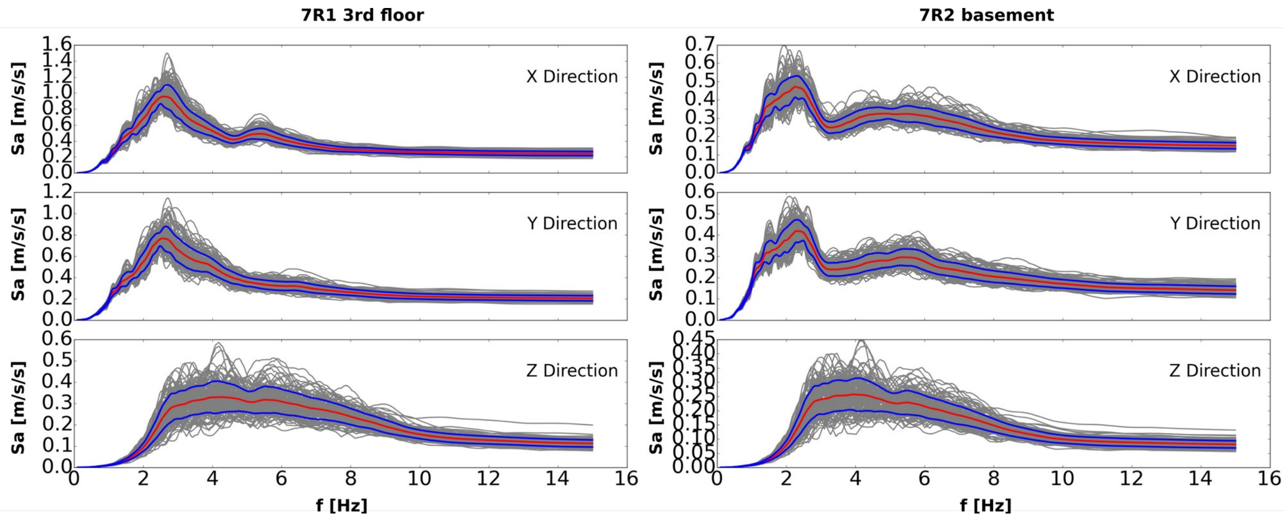

Figure 7: Pseudo-acceleration spectra obtained via Monte Carlo simulation on Unit 7 FEM model. Grey lines represent the response of each simulation, red lines the geometric average and the blue ones the average +/- one standard deviation margins. 7R1 is the recording seismometer located at the third floor on Unit 7, whereas 7R2 is located at its basement.

The outcome of the MC analysis highlights the great variability of the transient structural response, when ones considers the uncertainty of the synthetic response at long periods (low-frequency) obtained via PBS.

Moreover, this uncertainty is incremented by the use of ANN2BB, which maps the low-frequency spectrum into the high-frequency one, based on the training phase performed on recording database.

3. Conclusions and Perspectives

In this paper, the estimation of the uncertainty and the sensitivity of the transient structural response of a reactor building of a nuclear power plant is attempted, by only using synthetic incident ground motion. The latter is generated as combination between high-fidelity/long-period numerical simulation from the source to the site and a broad-band/data-driven artificial neural network prediction, that maps the long period part of the spectrum obtained via simulation into its higher part (generally hard to characterize due to the lack of geological data and subjected to high numerical dispersion). An elastic SSI model is used to represent the structural components and the hybrid synthetic ground motion is applied at its base. 200 Monte Carlo simulations are performed to assess the variability of the final structural response. The outcome of this chained analysis suggests that the use of synthetic high-fidelity and/or data-driven predictive tools must be carefully adopted, since its sensitivity to random fluctuation and numerical dispersion can greatly affect the structural response, with enormous consequences on the design and risk assessment of critical structures such as nuclear power plants. However, this result encourages the development of synthetic broad-band ground motion generators in a omnibus-comprehensive uncertainty quantification framework.

4. Acknowledgements

This work, within the SINAPS@ project, benefited from French state funding managed by the National Research Agency under program RNSR Future Investments bearing reference No. ANR-11-RSNR-0022- 04. The research reported in this paper has been supported in part by the SEISM Paris Saclay Research Institute.

5. Copyrights

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