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Broad-band 3-D earthquake simulation at nuclear site by an all-embracing source-to-structure approach

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ABSTRACT

The scope of this paper is to give an insight into the advantages of a new, all-embracing, modeling approach of a strong ground motion scenario, by carrying out a source-to-structure analysis at regional scale, accounting explicitly for the uncertainties related to the databases and the models. To this end, a suitable case-study is represented by the 2007 Mw6.6 *Niigata-Ken Chūetsu-Oki* seismic sequence (west Japan), that damaged the Kashiwazaki Kariwa Nuclear Power Plant. This study describes the effect of the wave propagation path within the Earth's crust on the seismic response of nuclear reactor buildings located nearby a seismogenic source. The multiscale problem is de-coupled into three steps: (1) a parallel simulation of seismic-wave propagation throughout the Earth's crust at regional scale (≈ 60 km wide, major 3-D geological interfaces found below the nuclear site), reliable up to 5.0 Hz; (2) a mid hybridization step consisting in enriching the synthetic wave-field at high frequency (up to 30 Hz), employing an Artificial Neural Network to predict the short-period (SP) spectral ordinates; (3) a high-resolution structural dynamic analysis, introducing the hybrid broad-band synthetics as input wave-motion. A simplified *stress-test* is performed, by simulating two small point-wise aftershocks at different source-site position. The impact of the underground 3-D geology on the structural components is finally quantified, by injecting the obtained broad-band time-histories in a Soil-Structure Interaction (SSI) model of the nuclear reactor building. The good fit obtained in terms of amplification factor at different recording stations assures the high-fidelity of the holistic philosophy endorsed.

1. Introduction

1.1. Synthetic simulation of 3-D earthquake ground motion from the fault to the structure

The earthquake-related economic losses quickly raised to billion dollars in the last 25 years, due to population dynamics and growth which, in turn, led to the gradual decrease in the availability of safer lands, along with an increased susceptibility to excessive damage and low resilience, i.e. an inevitable increase of potentially dangerous places [1]. Therefore, scientists and regulators are progressively taking advantage of the ever-increasing computational power available, to embrace a *holistic* modeling strategy that couples the large scale seismological models for the region of interest (including the fault mechanism and the geological properties of the Earth's crust), with local engineering models for geotechnical, site-effect and structural analyses (see, for instance, the well established engineering method called Domain Reduction Method (DRM) [2,3], the Micro-Macro Analysis Method (MMAM) [4–6]). To this purpose, one major challenge to be faced resides into the need to enlarge the accuracy of the numerical prediction at higher frequency, so to render a synthetic broad-band strong ground motion field across a wide region, as well as to reproduce the site response to the ground shaking. The reason stems essentially from the interest into a continuous coupling (in time and space) between the wave-propagation problem (typically referring to 0.0–10.0 Hz) and structural vibrational problem (typically referring to 0.0–30.0 Hz). As a matter of fact, the seismic design of buildings and infrastructures requires *reliable* (in terms of frequency content and duration) input ground motion to excite the most important vibrational modes and to study the degradation mechanisms. Moreover, most of the vulnerability studies are based on several earthquake *Intensity Measures* (IM), for instance Peak Ground Acceleration (PGA) and other indicators

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extremely sensitive to the high-frequency (HF) content of the incident ground motion. However, the definition of suitable boundary conditions to inject the input ground motion (eventually including Soil-Structure Interaction, SSI) is still a matter of debate. On the other hand, seismological studies are struggling with the poor characterization of continental discontinuities and geological interfaces in the Earth's crust, which adds to the huge computational burden required to perform wave propagation/inversion studies in complex and large 3-D domains. In this sense, the largest frequency limit, at present, reached by a wave-propagation code is 18 Hz, over a 320 km by 312 km by 40 km region [7], for the simulation of the 1976 Tangshan earthquake (China). The model has a spatial discretization varying between 500 m and 8 m, interpolating a 3-D velocity model of north China with resolutions of 25 km in horizontal and of 1–2 km in the vertical directions including the sediment structures. However, the current trend among analysts ranges around 2.0–5.0 Hz [8,9], shifting progressively towards 10 Hz [10], for regions spanning tens/hundreds of kilometers (see for instance the broad-band platform developed within the framework of the Southern California Earthquake Center, SCEC [11]). This trend is expected to increase in the very near future, owing the seemingly unstoppable growth of the High-Performance Computing (HPC) resources (towards exascale engineering simulations [12]). In the meanwhile, and alternatively, broad-band synthetic ground motion prediction can be obtained by hybrid modeling: starting from an idea of Graves and Pitarka [13], the high-fidelity low-frequency (LF) part of the simulated ground motion is *sealed* at each station with stochastic or empirical prediction at high frequencies, to cope with the intrinsic poor accuracy of numerical physics-based analysis methods employed to simulate the HF part of the synthetic wave-forms.

1.2. The SINAPS@ project

In this context, after the 2011 Fukushima accident, the SINAPS@ project[1] was launched in France, to address the need for exploring the uncertainties associated to databases, physical processes and methods used at each stage of seismic hazard, site effects, soil and structure interaction, structural and nuclear components vulnerability assessments, in a safety approach: the main objective is ultimately to identify the sources of potential seismic margins resulting from assumptions or when selecting the seismic design level or the design strategy.

SINAPS@ represents the first ever French national research program aiming at reviewing and updating the current seismic design standards of nuclear facilities on French territory, by embracing a continuous source-to-structure approach [14]. SINAPS@ unravels into multiple work-packages, animated by a unique yet manifold goal [14]: to review (1) the traditional and current experimental and numerical approaches to investigate an earthquake phenomenon and (2) to design the structural response to a ground shaking, by employing a rigorous uncertainty quantification routine at each modeling stage and to all the input parameters and related databases [15]. One major goal of the SINAPS@ research team is to develop a High-Performance (HP) and portable multi-tool computational platform, capable of dealing with the manifold nature of an earthquake phenomenon itself, i.e. spanning from the simulation of the source mechanisms, to the reproduction of the heterogeneous and non-linear rheology of the geomaterials within the Earth's crust domain and the soil deposits, to the presence of surface/buried topography as well as of the ocean's bathymetry and finally to the interaction with the buildings and the structural components. This endeavor is accompanied by a rigorous yet necessary verification and validation phases, in order to grant a high-fidelity prediction [16, see the guidance provided by]. In spite of the inherent complexity and of the multi-scale nature of those large yet refined 3-D computational models, their power is essentially embodied by the higher broad-band accuracy they provide. However, one major open challenge consists into including the structural components within the overall computational framework, gradually bridging the gap between LF source models obtained via wave-form inversion techniques and the structural modal frequencies (i.e. up to 30.0 Hz).

1.3. Outline of the paper

In this paper, the construction of a 3-D broad-band Source-to-Structure (BBS2S) earthquake scenario is presented. Specifically, the paper refers to the study of the seismic site response of the Kashiwazaki-Kariwa Nuclear Power Plant (KKNPP, owned by the Tokyo Electric Power Company, TEPCO), during the Mw6.6 2007 Niigata-Ken Chūetsu-Oki earthquake (NCOEQ-2007). Fig. 1 shows a map of the epicentral area (approximately 60 km wide) along with the three asperities outlined by Shiba et al. [17]. The synthetic structural response is obtained by a multi-step analysis work-flow. In this regard, this paper is an extension of the previous work presented by Quinay et al. [6]. The authors performed a fault-to-structure two-step numerical simulation for the same applicative case, supplied by verification and validation tests with application to maximum target frequency of 1.0 Hz. The regional model has provided near surface free-field wave motion, employed in a following stage to compute the dynamic responses of the building structure within the nuclear power plant, using a fine-resolution model based on realistic conditions. In this study, the regional scale 3-D earthquake scenario is at first calibrated up to 5.0 Hz [8], exploiting a 3-D spectral-element based software and including the complex folding geology described by several authors, as for instance [19,20] (see Section 3). Two aftershocks are simulated, by prepartitioning the computational domain over a distributed-memory supercomputer. Compared to Quinay et al. [6], a extra mid-step is added herein: the seismic wave-field rendered by the regional scale analysis is enriched at HF (up to 30.0 Hz) by applying the so called ANN2BB hybrid procedure, introduced by [21] and based on the use of Artificial Neural Networks to predict the short-period (SP) part of the pseudo-acceleration response spectra *Sa*. This hybridization step is described in Section 2.3.3. Finally, the hybrid broad-band synthetics are injected as input motion into a SSI structural model of the reactor building at Unit 7 at the KKNPP (RB7) [22]. The simulated structural response is compared to the recorded one, see [23].

2. Data and methods

2.1. Unwrapping a complex earthquake scenario: the case of NCOEQ-2007

This paper focuses on the seismic response of the Japanese nuclear site of Kashiwazaki-Kariwa. A map of the KKNPP site is shown in Fig. 2. KKNPP was damaged by the NCOEQ-2007, although no catastrophic failures occurred. The ground shaking interested an area of approximately 100 km of radius along the coastal line of South-West Niigata prefecture, till a maximum depth of 17 km [24]. The plant consists of 7 reactor buildings (see map in Fig. 2) and it is located on the hanging wall of the seismogenetic fault that triggered the NCOEQ-2007 event. The strong motion sensors indicated that during the main shock the site experienced nearly twice the Peak Ground Acceleration (PGA) considered at the plant design. Moreover, the rather high variability of PGA values within the site area is representative of directivity features of the source radiation (see [24] and [25] for an extensive review of the observed recordings and site-effect reconnaissance). The KSH downhole array (see map in Fig. 2), along with recording devices at surface 1G1 and 5G1 entirely recorded the NCOEQ-2007 main shock. Unit 7 is located on the NE part of the site, near Units 5 and 6. Unit 7 Reactor Building (RB7) was instrumented both at the foundation level (7-R2) and at the third floor (7-R1) [23,26]. The Unit 7 Reactor Building (RB7) is 63 m high, although 26 m are buried [22], therefore directly reposing over the Nishiyama rock formation (see Fig. 5a). During the NCOEQ-

[1] https://www.institut-seism.fr/projets/sinaps/.

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