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DYNAMIC SOIL-STRUCTURE INTERACTION MODELING STRATEGIES APPLIED TO KASHIWAZAKI-KARIWA NUCLEAR POWER PLANT CASE-STUDY

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Abstract. *On the framework of the French research project SINAPS@, the main goal of this work is to assess the impact of different soil-structure interaction modeling strategies on the Unit 7 Kashiwasaki-Kariwa Nuclear Power Plant reactor building response during the Niigata Chuetsu-Oki earthquake mainshock. his actual nuclear power plant case-study was already investigated during the KARISMA (KAshiwazaki-Kariwa Research Initiative for Seismic Margin Assessment) international benchmark exercise on 2009 organized by the IAEA (International Atomic Energy Agency) and OECD/NEA, which concluded on the difficulty to correctly predict the Unit 7 Reactor Building response during the mainshock by considering available standard soil-structure interaction modeling. The modeling strategies investigated in this work include soil non-linearity, by considering a cyclic critical state elastic-plastic model, and structure-soil-structure interaction influence by directly considering a simplified model of the adjacent Turbine Building.*

All numerical simulations are performed using code_aster Open source software. The comparison of results with recorded signals within the Unit 7 Reactor Building allow to emphasize some conclusions about the role of modeling assumptions. This paper gathers the research work conducted by EDF R&D in the SINAPS@ task 4.3 during the years 2015-2016.

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1 GENERAL CONTEXT

A reliable estimate of seismic safety margins of nuclear power plants remains a priority for the whole nuclear community, especially after the severe nuclear accident at the Fukushima Daiichi Nuclear Power Plant, experienced in March 2011. The research project SINAPS@ [1], currently on-going in France, aims to improve engineering methods in that field, integrating enhanced best-estimate scenarios, seismic analyses and uncertainties appropriate treatment in the whole chain of risk analysis. These innovative methodologies need to be implemented on a demonstrative case study and validated against real data to show that they can improve the margin prediction and the engineering practices.

The Kashiwasaki-Kariwa Nuclear Power Plant (KKNPP) was submitted to Niigata Chuetsu-Oki strong earthquake (NCOE) of magnitude Mw=6.6 in 2007, with recorded ground motions being beyond assumed design criteria. These recordings were subsequently used as basis for the KARISMA (KAshiwazaki-Kariwa Research Initiative for Seismic Margin Assessment) international benchmark exercise on 2009, organized by the IAEA (International Atomic Energy Agency) and OECD/NEA [2]. One important result from the KARISMA benchmark was the difficulty to correctly predict the unit 7 reactor building response during the mainshock by considering available standard soil-structure interaction (SSI) modeling, based on soil equivalent linear analysis, single building modeling and FEM-BEM coupling [3].

The SINAPS@ work package 4 proposes to revisit the KARISMA benchmark by integrating innovative modeling strategies and methodologies. Under this context, the main goal of this work is to assess the impact of different SSI modeling strategies on the unit 7 KKNPP reactor building response during the mainshock. These aspects include soil non-linearity, by considering a cyclic critical state elastic-plastic model, and structure-soil-structure interaction (SSSI) influence by directly considering a simplified model of the adjacent turbine building. Concerning soil non linearity, two different approaches are assessed: either Full-FEM with absorbing boundaries modeling or a hybrid Laplace-time domain approach with FEM-BEM solution [4]. SSSI is considered using equivalent linear properties for the soil domain, determined from a transient automatic procedure on a soil-column, and a frequency domain solution procedure. All numerical simulations are performed using code_aster Open source software [5]. The comparison of results with recorded signals within the KKNPP reactor building allow to emphasize some conclusions about the role of modeling assumptions and to summarize then by appropriate recommendations for future engineering practice.

This paper gathers the research work conducted by EDF R&D in the SINAPS@ task 4.3 during the years 2015-2016. The main contributions to the modeling strategies were the following:

- Definition of input signal to be used on SSI simulation,
- Comparisons of equivalent linear and non linear modeling of the soil,
- Possible SSSI influence of the Turbine Building on the seismic response of the Reactor Building.

This paper is organized as follows: section 2 briefly describes the Kashiwazaki-Kariwa site and the main characteristics of the Unit 7 Reactor Build (RB7); section 3 describes the implemented method to obtain the input RB7 free-field signal to be used in the numerical simulation. Section 4 describes the implemented non linear SSI numerical model and the comparative results under equivalent linear and non linear analysis. Section 5 briefly discuss the influence of the Turbine Building on the Reactor Building response and how SSSI can influence the dynamic performance of main structure. Some general conclusions are drawn in the end of the paper.

2 SITE AND BUILDING DESCRIPTION

Different authors have studied the geological characteristics of Kashiwazaki-Kariwa region. A description of the spatial distribution of landslides following the NCO earthquake is discussed by Collins et al. [6]. A geological cross-section of the site is given by [7], who also worked in the vicinity of the KKNPP site.

The KKNPP site is represented on Figure 1. Unit 7 is located on the NE part of the site, near Units 5 and 6. Several acceleration sensors were initially installed on site in order to monitor the NPP. Figure 1 shows the considered sensors location used in this work. Unit 7 Reactor Building (RB7) was instrumented both at the foundation level (7-R2) and at the third floor (7-R1). Sensor 5-G1 was set at free-field condition. Additionally, a vertical borehole array (BH5) was set close to the 5-G1 sensor with acceleration sensors at different depths (-2.3 m, -36.0 m, -112.0 m, -192.0 m, -312.0 m T.M.S.L. [1]).

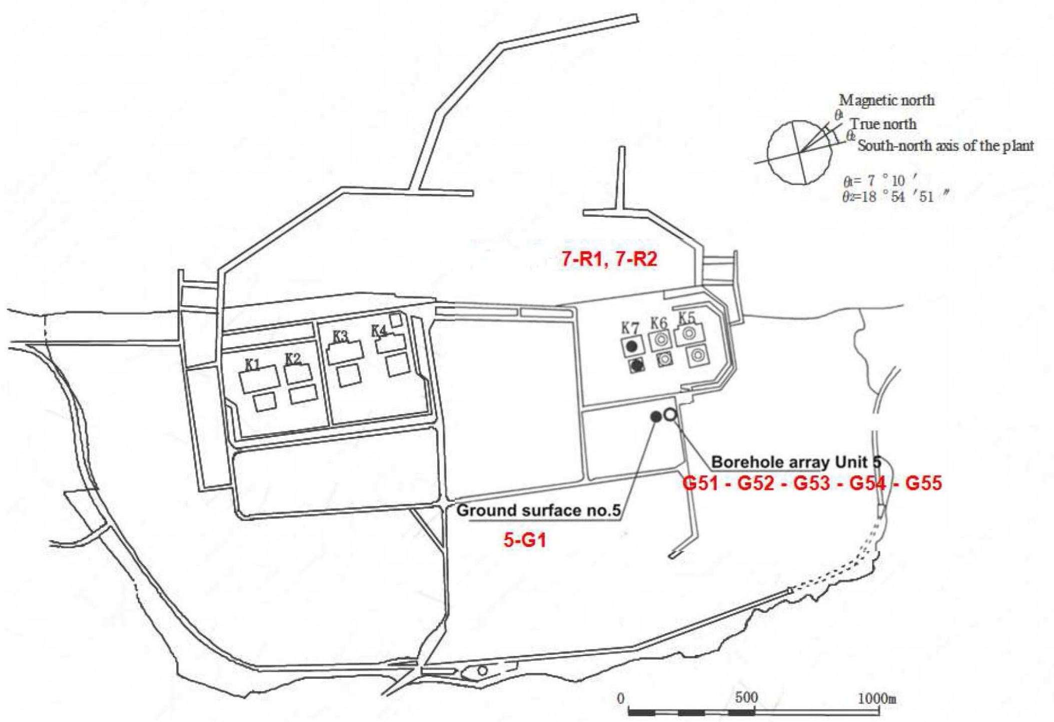


Figure 1: KKNPP site layout and location of considered sensors [8].

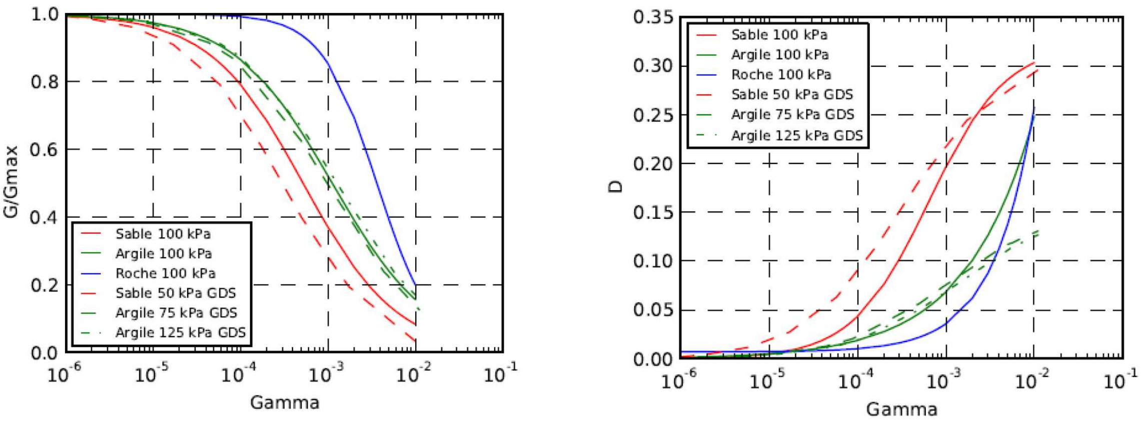
The available geotechnical surveys of the KKNPP site conducted previously to construction were made available by TEPCO for the KARISMA benchmark [2]. The superficial layers next to RB7 are composed by backfill soil followed by Yasuda clay formation (Vs around 300 m/s). Both are expected to have experienced high non linearity during the NCOE mainshock. A soft rock formation (Nishiyama rock, Vs around 500 m/s), follows the Yasuda clay for around 150 m before the engineering bedrock. The water table is considered at +4 T.M.S.L., as so the backfill soil is considered on dry state.

Additional information on the geotechnical characteristics of the soil in place is given in Yee et al. [8], who conducted complementary *in situ* tests (SPT, suspension logging) on Service Hall

[1]Tokyo Mean Sea Level

and laboratory tests (triaxial, resonant column and torsional shear tests). Service Hall is located at the entrance of site, at +67 T.M.S.L. (Figure 1). According to the authors [8], soil settlement was mostly observed at the Service Hall, were backfill soil was probably poorly compacted.

The different shear secant modulus and damping curves for the backfill material, Yasuda clay and Nishiyama rock formation are shown on Figure 2. Under the hypothesis of a mean stress of 100 kPa, these curves were adapted by GDS during the KARISMA benchmark exercise [9] in order to take into account the mean stress on site. The backfill material is considered at 50kPa and the Yasuda clay at 75kPa or 125kPa, depending on the considered soil column (BH5 or RB7).



(a) G/G$_{max}$-γ

(b) D-γ

Figure 2: Cyclic response of backfill (sand), Yasuda clay (argile) and Nishyiama rock (roche) at different confining pressures [9].

The Unit 7 Reactor Building (RB7) is 63 m high, although 26 m are buried, therefore directly reposing over the Nishiyama rock formation. Unit 7 Turbine Building (TB7) is only 2 m away and its base mat is also 23 m buried. Both structures are represented on Figure 3, where the location of the installed accelerometers on both buildings are also shown.

During the NCO earthquake, the RB7 did not present any particular sign of damage, which led to consider linear elastic response for the benchmark [2]. This hypothesis is also considered in this work.

3 DEFINITION OF INPUT RB7 FREE-FIELD MAINSHOCK SIGNAL

During the NCO earthquake mainshock, BH5 sensors registered only the PGA values. Therefore, the only available time acceleration history at the soil during the mainshock is the 5-G1 measurement.

In order to obtain the free-field acceleration time-history next to RB7 during the mainshock, the following methodology was followed:

1. Deconvolution by linear equivalent approach of the 5-G1 free-field signal to the bedrock by considering the same soil column properties of BH5. As only the PGA was available from BH5 sensors, the deconvolution process enforces the obtained signal to match the PGA at the bedrock.

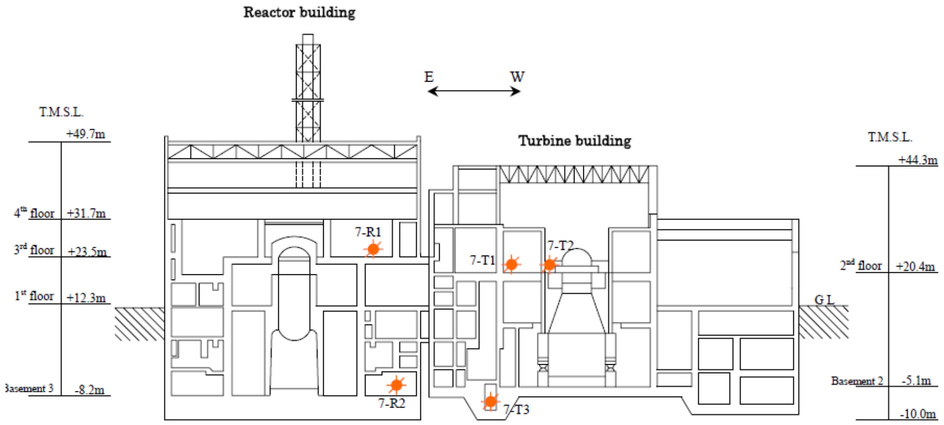
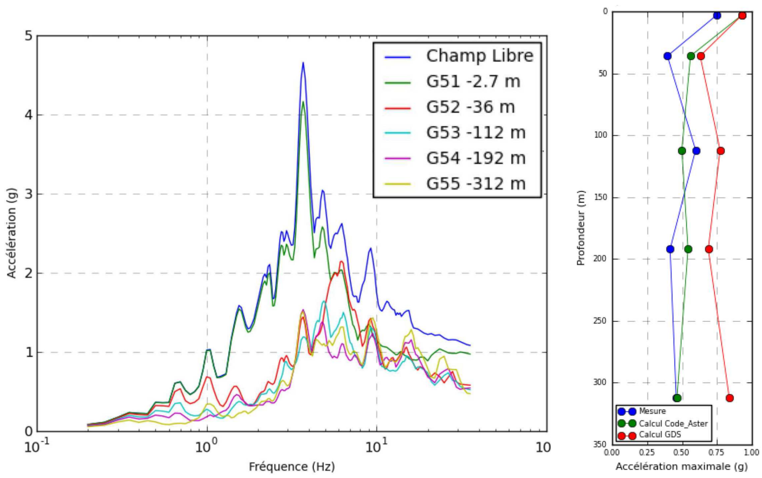


Figure 3: Schematic representation of RB7 and TB7 [3].

2. Reconvolution from the bedrock to RB7 free-field. This stage allowed also to obtain the soil column properties (shear stiffness and damping) to be considered for the Linear Equivalent SSI numerical simulation.

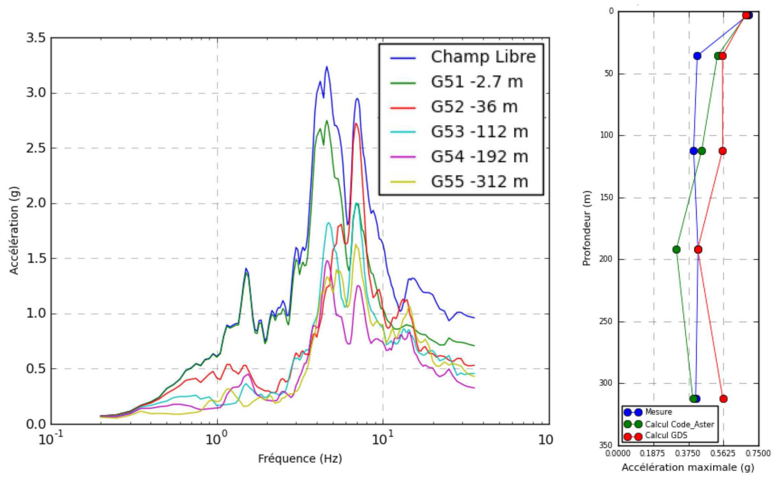
The BH5 spectral accelerations and PGA values obtained from the deconvolution process are presented on Figures 4 and 5. Spectral accelerations present a high content in the frequency range 4-10 Hz, specially on the NS direction. PGA values obtained by this method on all BH5 sensors (green line on left-hand side figure) are compared to those available from measurements (blue line) and those obtained by GDS for the benchmark exercise. PGA values at the bedrock match closely as enforced by the methodology, although values do not match elsewhere in the soil column. The obtained PGA levels are higher on both directions for the -36 m T.M.S.L. sensor compared to measurements, which was also the case for those from the KARISMA benchmark.



(a) Deconvulated spectra.

(b) PGA.

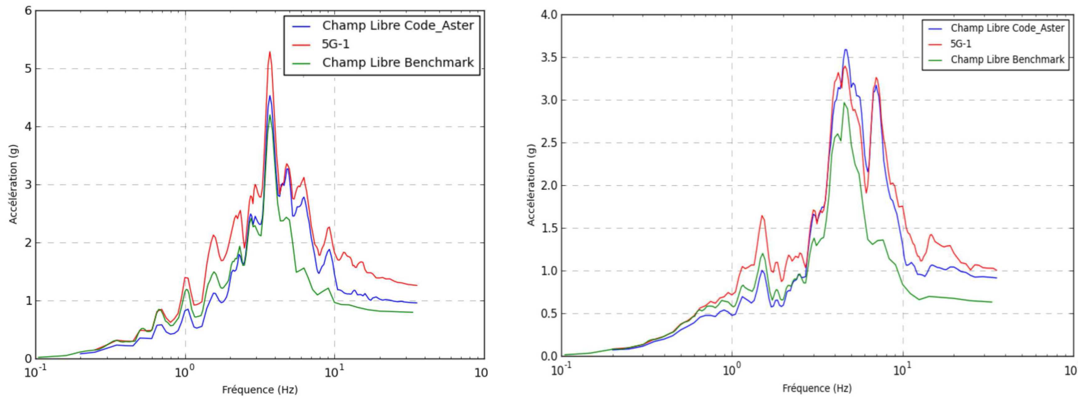
Figure 4: Comparison of obtained deconvoluted spectral accelerations at BH5 (EW direction).



(a) Deconvulated spectra. (b) PGA.

Figure 5: Comparison of obtained deconvoluted spectral accelerations at BH5 (NS direction).

The obtained RB7 free-field spectral acceleration (blue line) is compared to the one provided to the benchmark participants (green line) on Figure 6 and to the 5G-1 measurement. Regarding the EW direction, the obtained RB7 free-field spectral acceleration is attenuated when compared to 5G-1 on both cases and for all the frequency spectrum. Regarding NS direction, the main difference is the 8Hz resonance which is not present on the spectral acceleration given to participants of the KARISMA benchmark. PGA values are on both cases higher for the obtained signal when compared to the benchmark.



(a) EW direction. (b) NS direction.

Figure 6: Comparison of obtained RB7 free-field spectral accelerations. Red line : 5G-1 sensor; green line : KARISMA benchmark signal; blue line : here proposed signal.

4 NONLINEAR SSI ANALYSIS

In this section, the KKNPP model used on the benchmark [2] is revisited by considering non linear mechanical behavior of the soil at the vicinity of the Reactor Building. Soil non linearity is considered as a potential reason to explain the differences in the mid-range frequency obtained between the linear equivalent approach and measurements observed from the benchmark exercise [2].

Under soil visco-elastic assumption, the performed SSI numerical simulation considers substructuring of the mechanical problem. Classically, the substructure procedure allows to split the soil domain and the structure by integrating the soil influence on the structure directly at the soil-structure interface, by means of frequency-dependent impedance operator $Z(f)$. Such procedure is well suited when the soil domain is considered visco-elastic, as in this case classical BEM can be used to perform the impedance calculation. In this case, the FEM/BEM interface is considered as the structure/soil interface. Therefore, soil is not directly modeled, the FEM domain being restrained to RB7 only.

When soil non linearity is considered, the substructure method can still be applied by considering the impedance operator not only frequency but also time-dependent, by an approach known as Time-Laplace domain approach [4]. In this case, the non linear soil domain has to be considered in the FEM model together with the structure (Figure 7). Therefore, FEM/BEM interface is fixed sufficiently away from the structure, in the soil domain zone where linear assumption can be considered as relevant. In this case, once the frequency and time-dependent impedance at the interface is calculated, the FEM model response is computed in time domain by a HHT implicit algorithm.

Another popular approach when taking into account soil non linearity is to consider a Full FEM SSI model. In this case, absorbing elements (e.g. paraxial elements) have to be implemented on soil domain boundaries. Although such approach can be more CPU time consuming, it presents the advantage of allowing a straightforward implementation. Using this approach in the present work also allows to cross-validate the implemented Time-Laplace domain approach. In the present case, an explicit time scheme had to be used with sufficiently small time steps, in order to assure the stability of the time scheme. The calculation time was 4 times higher for the Full FEM model compared to the Time-Laplace domain approach.

The considered soil/structure mesh is presented on Figure 7, where the soil domain covers 100 m around the RB7 (approximately 2 times the RB7 width). RB7 mesh is composed of beam and plate elements, and main internal equipments are represented by spring-mass models.

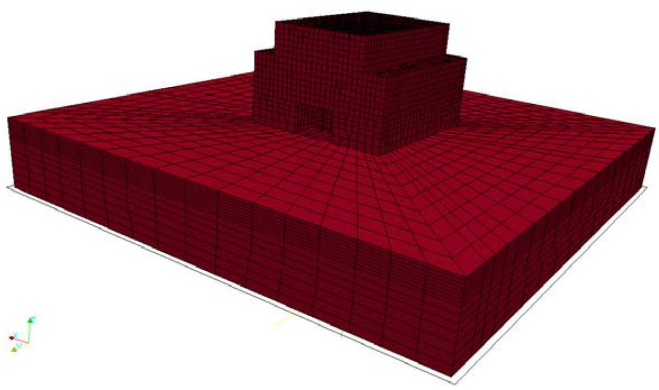


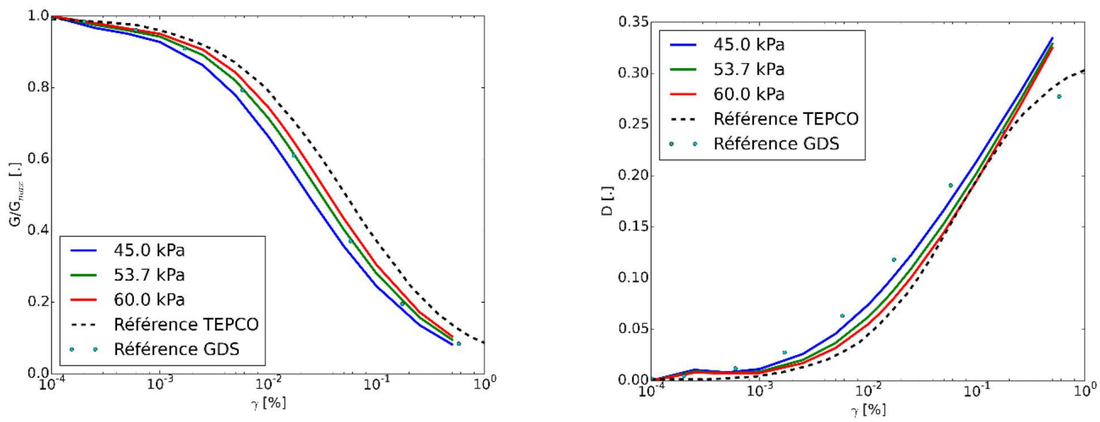
Figure 7: RB7 and soil SSI FEM model.

4.1 Calibration of ECP soil behavior model

The ECP model or Hujeux model [10, 11] is used to consider soil non linearity, as it is capable of modeling the soil behavior under different monotonic and cyclic stress paths. It is based on the critical state approach and it considers a Coulomb type failure criterion. The model is based on multi-surface plasticity and hardening is controlled by plastic strains. Cyclic behavior considers kinematical hardening and a double memory approach for the last load reversal.

The calibration procedure was based on the a available *in situ* and laboratory tests both from BH5 and Service Hall. Concerning the *in situ* tests, correlations from [12] between SPT and overconsolidation ratio (OCR) as well as between plasticity index (PI) and friction angle are considered for the Yasuda clay; for the backfill material, its relative density (D_r) is also estimated from SPT tests performed by Yee et al. [8]. Cyclic behavior is calibrated by considering the mean stress dependent curves 2.

Figure 8 shows the comparison of the cyclic behavior obtained from the model to the laboratory test results for the backfill material as an example of the obtained calibrated behavior. As the model implicitly considers the mean stress influence on the cyclic behavior, parameters were obtained in order to best fit the laboratory tests on the mean stress at the middle of the considered layer. Therefore, the backfill material is divided on four layers of 2 m and the Yasuda clay 2 layers of 5 m.



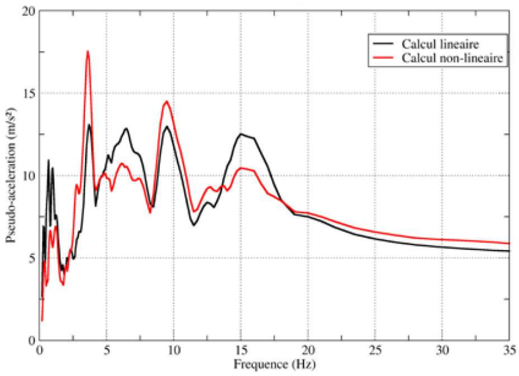
(a) G/Gmax-ε (b) D-ε

Figure 8: Degradation curves obtained for backfill material between +8 and +6 T.M.S.L.

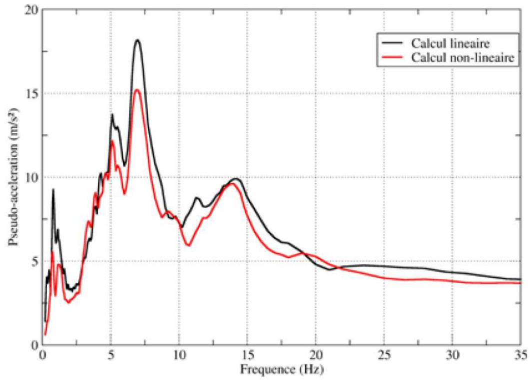
4.2 Comparative results

The obtained spectral accelerations for both equivalent linear and non linear analysis (Time-Laplace method) are presented on Figure 9. The non linear model predicts an important reduction on the low frequency range (< 3Hz) for both directions. In the mid-frequency range, however, the EW direction presents contrasted results, with amplification/deamplification according to the considered frequency. The NS direction presents a small spectral acceleration reduction when considering the non linear model. On both directions, ZPA values are similar.

From these results, it appears that soil non linearity can not explain patently the differences observed between measurements and numerical simulations on the 4-10 Hz frequency range, on the basis of the chosen assumptions.



(a) EW direction.



(b) NS direction.

Figure 9: Comparison of equivalent linear and non linear soil modeling on 7-R2 sensor. Black line: equivalent linear; red line: non linear model.

Figure 10 shows the comparison of the non linear Full-FEM model results to the Time-Laplace domain approach. The BP1 point corresponds to sensor 7-R2 and FP2 corresponds to the top of the RB7. The obtained horizontal spectral accelerations are similar in the frequency range of interest, although at low frequencies the Full-FEM model presents higher attenuation then the Time-Laplace domain approach.

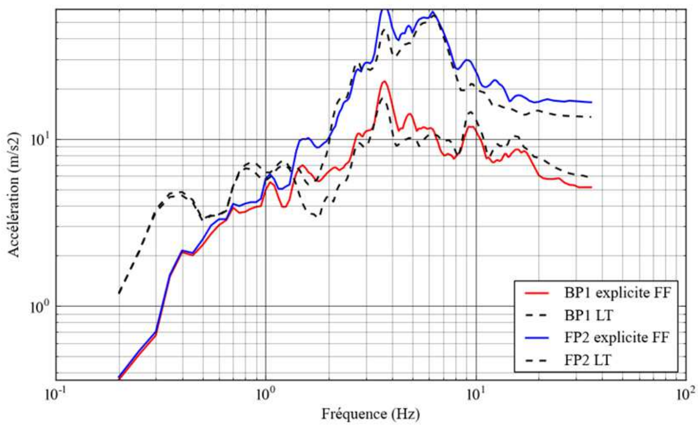


Figure 10: Comparison of Time-Laplace (LT) and Full-FEM (FF) approaches on 7R-2 sensor (BP1) and FP2 (top of RB7, no sensor available).

5 SSSI ANALYSIS

In this section, the influence of TB7 on RB7 is investigated by directly considering the TB on the equivalent linear soil-structure interaction numerical model. A simple 1 dof model is considered as a first approach, following the mechanical and geometrical characteristics given by [13]. The TB total mass is considered as 80% of the RB total mass, concentrated at the barycenter, located at +9 T.M.S.L.. The building base mat is 80x90 m large, 23 m buried (as the RB). The geometrical characteristics of the model are shown on Figure 11. Rigid TB base mat is considered as a first approach. TB first resonant frequency is estimated around 1 Hz, although the following results were not sensible to frequencies up to 2 Hz.

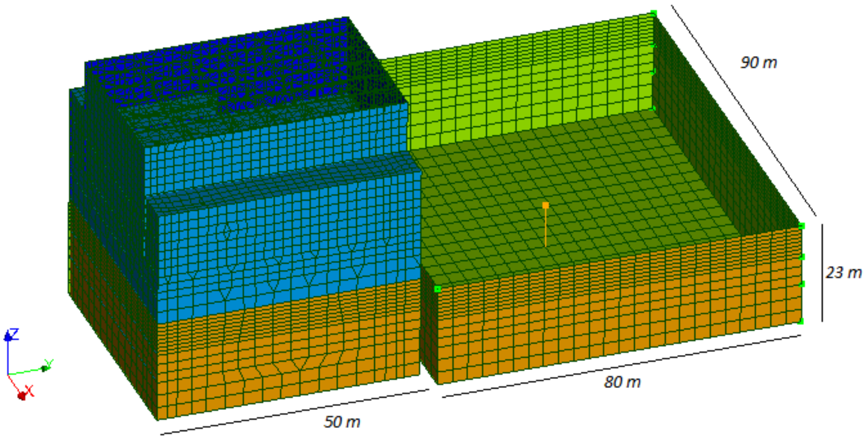
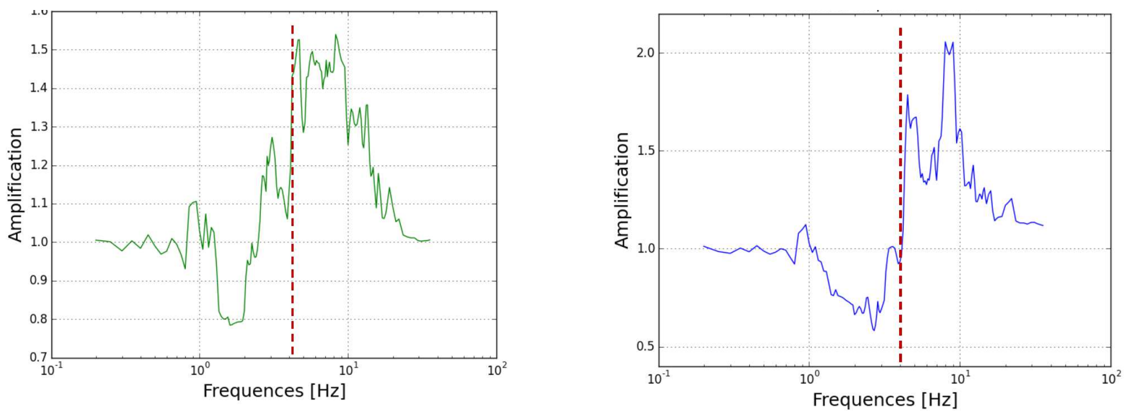


Figure 11: SSSI mesh used on numerical simulations.

Results on Figure 12 are presented in terms of amplification function (i.e. ratio between the SSSI and SSI frequency response function) at sensors 7R-1 and 7R-2. The red dashed line represents the first resonant frequency of the RB (around 4Hz). The SSSI influence is perceptible in this case: deamplification from a SSI simulation is obtained for frequencies lower than the first resonant frequency of the RB, and amplification for higher frequencies.



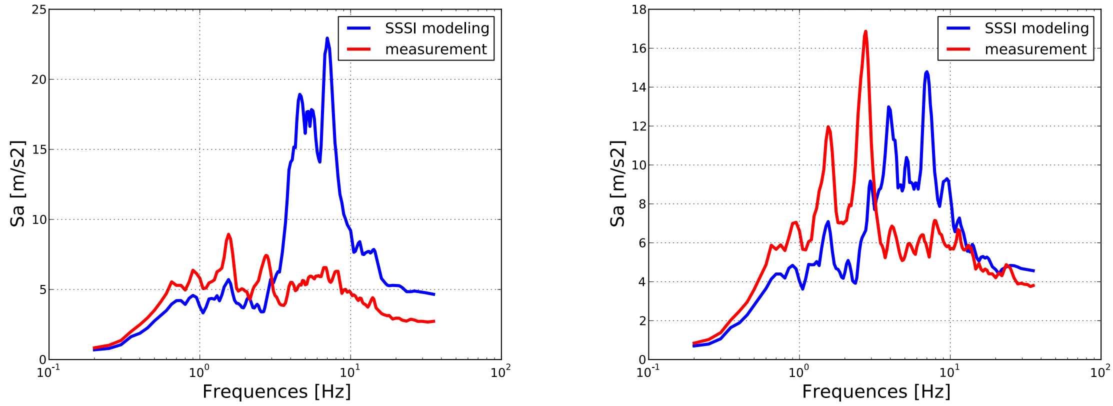
(a) 7R-2

(b) 7R-1

Figure 12: SSSI/SSI amplification function for 7R-2 and 7R-1 numerical results (EW direction). Red dashed line represents the first resonant frequency of the RB (around 4Hz).

The importance of the first resonant frequency of the building of interest (i.e. RB7) was also observed on conducted numerical simulations of the SSSI NUPEC benchmark [14]. Therefore, from these results, considering SSSI can be relevant on frequency range lower than the first resonant frequency of the building, e.g. when relative displacements between buildings are of interest.

However, in the case of the KARISMA benchmark, SSSI does not seem to explain the obtained differences between numerical simulations and measurements during the mainshock. Indeed, the recorded spectral acceleration is compared to the numerical SSSI simulation on Figure 13, and important differences are observed on the 7R-2 sensor NS response, specially in the mid and high-frequency range. Nevertheless, this high spectral acceleration at this frequency range is also observed on both measured 5G-1 and numerically obtained RB7 free-field spectral accelerations (Figures 5 and 6, respectively).



(a) 7R-2 (b) 7R-1

Figure 13: Comparison of spectral accelerations for 7R-2 and 7R-1 sensors (NS direction).

6 CONCLUSIONS AND PERSPECTIVES

According to the performed numerical simulations, it is confirmed that backfill and Yasuda clay presented high non linear behavior, which were triggered during NCOE mainshock. However, as the RB7 base mat slab is constructed directly over the Nishyiama rock formation, considering a non linear model for the two above layers have a minor impact over the RB7 response compared to an equivalent linear approach.

Cross validation between Full FEM and Time-Laplace domain approach have also been performed in the case of non linear SSI, showing that both methodologies give similar results on the range of frequencies of interest. This result consolidates the existing available modeling strategies on code_aster for non linear SSI numerical simulation.

The second aspect verified in this work is the possible effect of Turbine Building on the RB7 response. As already observed in the literature [14], deamplification of the transfer function is observed for frequencies lower than the first RB7 frequency and amplification for higher frequencies. However, SSSI effect do not seem to be the main reason of differences observed between numerical simulations and measurements of RB7 response during NCOE.

Although other physical phenomena could still be considered in order to verify their influence on the RB7 response (basement uplift, spatial variability of seismic signal [15]), further work should also consider revisiting the RB7 free-field signal in order to investigate the high spectral acceleration content on the mid-frequency range, specially on NS direction (Figure 13).

Nevertheless, referring to an actual nuclear plant case-study, these numerical studies have highlighted the improvements made in the chain of analysis, in particular soil behavior modeling, soil-structure interaction, and seismic ground motion definition. We were able to evaluate the respective role of several modeling assumptions, their relevance, the efficiency of Open source simulation solution software in order to produce recommendations and facilitate its dissemination into the engineering practice, according to the industrial stakes in terms of safety margins assessment.

7 ACKNOLEDGMENTS

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