AN INNOVATIVE APPROACH TO PERFORM SEISMIC RISK ANALYSIS OF NUCLEAR FACILITIES THROUGH THE MULTIDISCIPLINARY SINAPS@ RESEARCH PROJECT

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Abstract

This contribution gives an overview of the SINAPS@ French research project and its main achievements. SINAPS@ means "Earthquake and Nuclear Facility: Improving and Sustaining Safety" and has gathered broad research community in order to propose an innovative seismic risk assessment for nuclear facilities. This five-year project has been funded by the French government after the 2011 Japanese Tohoku large earthquake and associated tsunami that caused the major accident at the Fukushima Daïchi Nuclear Power Plant. Soon after this disaster, the international community involved in nuclear safety questioned the current methodologies used to define and to account for seismic loadings for nuclear facilities during the design and assessment phases. In this framework worldwide nuclear authorities asked nuclear licensees to perform "stress tests" to estimate the capacity of their existing facilities sustaining extreme seismic motions. SINAPS@ aims at conducting a continuous analysis of completeness and gaps in data bases (all data types, from geology, seismology, site characterization and materials), of the reliability or deficiency of models available to describe physical phenomena (prediction of seismic motion, site effects, soil and structure interaction, linear and nonlinear wave propagation, materials constitutive laws in nonlinear domain), and of the relevance or weakness of methodologies used to perform seismic risk assessment. This critical analysis confronting methods, either deterministic or probabilistic, and available data to the international state of the art systematically addresses the uncertainties issue. We present the key issues addressed in SINAPS@ at each step of the whole seismic analysis, focusing on the uncertainties identification, quantification and propagation. The main lessons learned from SINAPS@ will be introduced (and detailed during the workshop through several contributions). SINAPS@ promotes an innovative approach fully in line with the Guide 22 recently published (2017, [1]) by the French Nuclear Authority and then opens perspectives to improve the current French practice.

Key Words: Seismic risk analysis, Uncertainties, Seismic Margin, Nuclear Facilities

1. Introduction

1.1 Post-Fukushima context, Complementary Safety Studies and PSHA studies in France

Following the Tohoku earthquake (Magnitude Mw 9) on the Pacific coast of Japan in March 2011, a tsunami caused many deaths and damage, but also led to the major nuclear accident on the Fukushima Daïchi plant. The international community involved in nuclear safety was immediately questioned about the reliability of its estimates, especially regarding external events (earthquake, flood), the appropriateness of the approaches deployed and the adequacy of the margins retained at the design stage (or during assessment) of nuclear facilities. The nuclear accident triggered an immediate reaction by nuclear authorities worldwide to urge all licensees of nuclear plants to carry out seismic risk and safety analysis (stress tests) on their existing structures. The objective of these stress tests was to verify the adequacy of the safety standards used when Nuclear Power Plants (NPPs) received their authorizations, in view of potential extreme hazards (seismic, tsunamic, flood, or human induced). In France, this on-site analysis and verification, carried out in 2011, was the initial phase of the Complementary Safety Studies (CSS): it allowed an appreciation of the seismic margins of the various structures. In a second step, the Nuclear Safety Authority (ASN) and the licensees have defined a new concept, the "Hard Core" (HC) "as being a set of engineering buildings, equipment and organizations processes that will significantly increase the seismic safety of the plant, allowing it sustaining extreme natural events". This core aims to make the installation even more robust and able to withstand rare and extreme natural aggressions (or conjunction of aggressions). Structures and equipment associated with the Hard Core shall be dimensioned for seismic levels known as "*Hard Core Seismic Levels*" (HCSL). The proposal by the licensees of these HC levels was the subject of discussions with ASN and its technical support the IRSN between 2012 and 2016. During this period, the review of French CSS studies by a committee of experts, (ENSREG) (end of 2012) led the French safety authority to request (in 2013) the licensees to supplement their HCSL proposals based on purely deterministic French historical practice, by probabilistic seismic hazard assessments to characterize these HCSL via a probability of occurrence (see ref[2]).
The use of ("state of the art") probabilistic approaches for the estimation of seismic hazards is a first in France for nuclear plants and has given rise to numerous expert discussions between licensees and the technical support of ASN (between 2014 and 2016).

1.2 Implementation of the SINAPS@ project

In the "post-Fuskushima" context described above, in 2012, the French government, through the National Agency for Research (ANR), published a call for tender (http://www.agence-nationale-recherche.fr/investissements-d-avenir/appels-a-projets/2012/recherche-en-matiere-de-surete-nucleaire-et-de-radioprotection/), to stimulate research on nuclear safety and radiation protection. The CEA, EDF, École Normale Supérieure de Cachan, CentraleSupelec, Institute of Radiation Protection and Nuclear Safety, Polytechnic Institute of Grenoble, École Centrale de Nantes, EGIS, AREVA, ISTerre, IFSTTAR and the CEREMA have built the SINAPS@ (Earthquake and Nuclear Installations, Improving and Sustaining Safety) research project. SINAPS@ is the first research project in France where seismic risk is continuously evaluated from the fault to civil engineering works and equipment, with emphasis on the quantification and propagation of uncertainties related to databases, knowledge and modeling of physical processes, and the methods used at each stage of the assessment. Selected by the French government in 2013, this 5-year project SINAPS@ has provided funding for twelve PhD theses and 20 post-doctoral one year positions.

SINAPS@ is structured around 5 panels scanning the entire seismic analysis chain (1) the seismic hazard assessment (2) the non-linear interactions between near and far field wave field, the geological medium, and the structures (3) the seismic behavior of structures and components (4) the seismic risk and safety assessment (5) the experimental contributions to study interaction between buildings and reinforced concrete (RC) damping modelling. A sixth and last panel is dedicated to the knowledge dissemination through training sessions. The main objectives of SINAPS@ are to:

- rank the parameters and the impact of uncertainties on all key steps of a seismic risk analysis,
- propose an innovative method (verified and validated calculation codes) for the modeling of seismic wave propagation, in the most integrated and continuous way from the fault to the seismic response of the structures and equipment,
- identify/quantify the seismic margins,
- formulate recommendations on R&D (Research and Development) actions and data acquisition, recommendations on engineering practices, in particular for the assessment of the vulnerability of structures and components, the reinforcement of analytical methodologies including preparation of their dissemination and the evolution of regulations (deterministic / probabilistic approaches),
- organize 2 training sessions.

1.3 Seismic risk regulatory framework in France for the nuclear facilities

Nuclear safety, placed under the Nuclear Safety Authority http://www.asn.gouv.fr/ is framed in France by a set of texts that have different legal scope, as illustrated in Figure 1:

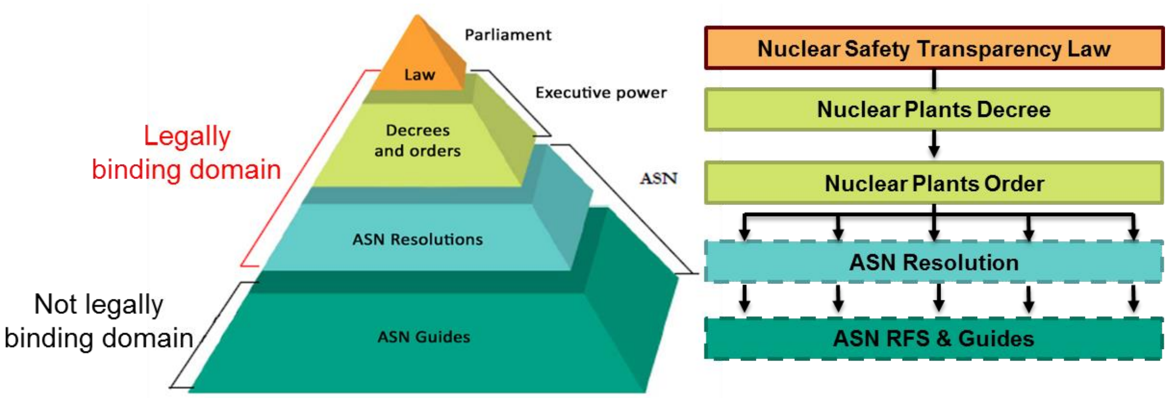

Figure 1: Description of the texts related to nuclear safety in France.

At the top of the "regulatory corpus", the Nuclear Safety and Transparency Law ("TSN Law") promulgated in 2006 (ref. [3]) is declared by the ASN through decrees and decisions: these texts constitute a legally binding area for licensees. In addition the ASN publishes a set of technical documents, of approaches considered acceptable to be used in the safety demonstration: Guides and Fundamental Rules of Safety. These documents are not legally binding, meaning that licensees can propose alternative methods supported by the necessary justifications.

Taking into account the seismic risk for the safety of nuclear installations can thus refer to several documents published by the ASN as illustrated in Figure 2:

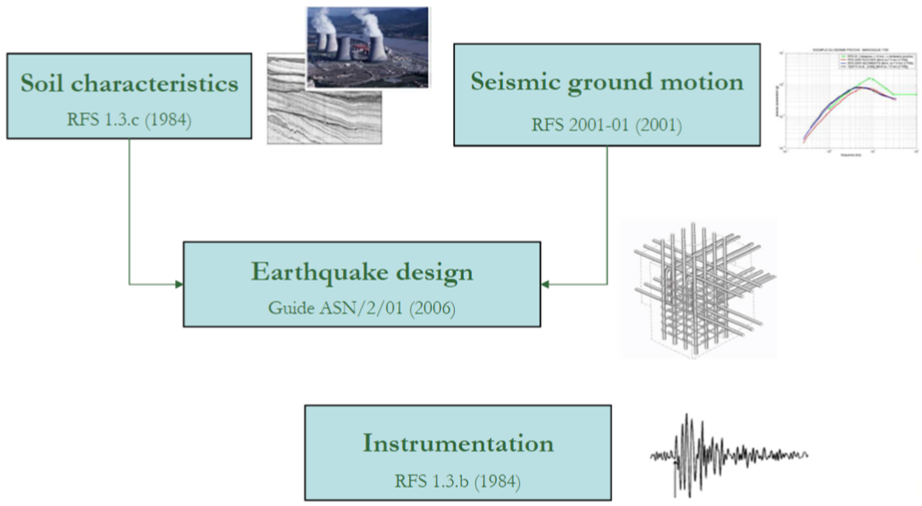

Figure 2: Presentation of the reference texts in force in France, with the date of publication of their update, concerning the seismic risk for nuclear plants safety.

RFS 1.3.c (ref. [4]) deals with "geological and geotechnical studies of the site; determination of soil characteristics and studies of soil behavior". RFS 2001-01 (ref. [5]) proposes an acceptable method for the determination of seismic motions. The ASN/2/01 Guide (ref. [6]) proposes acceptable methods for the ASN to determine the seismic response of civil engineering structures by considering their interaction with the materials and evaluating the stresses to be considered for their design. Finally, RFS 1.3.b (ref. [7]) is to define the nature, location and operating conditions of the seismic instrumentation required for the rapid acquisition of on-site seismic motions. RFS 1.3.b and c were published more than thirty years ago, the Guide ASN/2/01 more than ten years ago, and more than fifteen years for the RFS 2001-01.

On the other hand, the French nuclear safety approach is based on a deterministic principle. This means in particular, that the estimation of the seismic hazard is of "seismic scenario" type in relation to "reference" earthquakes resulting from the seismic catalogs analysis. The methodology introduces some conservatisms (implicit or explicit) such as safety coefficients, in order to account for uncertainties.

Two obvious consequences of this approach are that the seismic hazard results (i) are not characterized by confidence levels (uncertainties not explicitly explored), and (ii) they are not associated to any probabilistic information (such as the annual frequency of occurrence or exceedance): **because of this latter reason, these deterministic SHA are not usable as inputs of the probabilistic safety studies currently carried out for example during the quantification of seismic margins.**

This deterministic approach prevails in RFS 2001-01 and Guide ASN/2/01 which distinguishes the French practice in other nuclear countries and international recommendations, which have turned to probabilistic approaches for several decades. In the most recent references, nevertheless, the IAEA (e.g. SSG9, 2010), WENRA (Safety Reference Levels for Existing Reactors) and the ASN guide 22 published in 2017 (ref. [1])recommend the use of both deterministic and probabilistic methods to assess the hazard (for the design et review phases) and to perform probabilistic safety analysis (PSA). In this latter Guide ASN 22, the target value is an annual frequency of 10^{-4} for the design, and the need to reach at least the minimal spectral acceleration of 0,1g.

RFS 1.3.b and 1.3.c apply to nuclear power plants with pressurized reactors, while the Guide ASN/2/01 and RFS 2001-01 are applicable to all basic nuclear facilities (both generating stations electricity, including power reactors, laboratories and plants, and research reactors), with the exception of long-term radioactive waste storage covered by another set of rules. The Guide ASN 22 is applicable to nuclear power reactors.

There is therefore no grading of the seismic hazard estimate depending on the nature of the nuclear facility and its potential to cause damage to humans and / or the environment, (i.e. risk). That is, earthquake-related stresses are estimated using the same approach for a laboratory or plant as for a Pressurized Water Reactor (PWR): these are the safety requirements and therefore the performance requirements of the structures which may differ. It should be noted that, at the international level of the nuclear countries, the IAEA Safety Standards (cf. Chapter 10 Guide SSG-9, 2010, ref. [8]) recommend that the importance of seismic levels be classified according to the category of the facility according to the importance of the risks and stakes (radiological contamination in particular). This difference stems directly from the application of a deterministic approach to define the seismic hazard in France (RFS 2001-01): on the contrary, the definition of the seismic hazard through a probabilistic approach implies a target in terms of the level of protection (probability of exceeding a parameter over a given period of time).

In addition, RFS 2001-01 (ref. [5]) (and Guide ASN / 2/01, ref. [6]) provide acceptable methods for defining seismic movements for design of structures. There are no specific reference documents for the safety assessment phases of installations, which take place every ten years in France. The Guide ASN 22 published in 2017 and applicable to design power reactors is also considered as the main reference for the plant safety assessments. During these review periods, the safety is completely revised by the licensee. From the point of view of seismic risk, this includes conducting seismic margin studies of the existing installation in the light of a seismic hazard re-evaluated in the state of the art. **These studies require the implementation of the most up-to-date databases, also the most representative methods to account for the actual behavior of the structure under earthquake. Taking uncertainties into account in all seismic analysis is a necessity in order to assess the good behavior of the installation with respect to an updated hazard or, on the contrary, to identify weaknesses, of the possibilities (or not) to improve its behavior to the earthquake, or to confirm the safety coefficients.** The SINAPS@ project is fully in line with this framework for the estimation and quantification of the seismic margins of nuclear facilities (to be designed or existing).

1.4 Synthesis of the French framework managing seismic risk for nuclear plant safety: from 1960 to the present, and perspectives

Figure 3 summarizes the history of the reference texts applicable in France to account for seismic risk for all basic nuclear facilities (excluding deep storage), between 1960 and 2006, the date of the last revision of design principles.

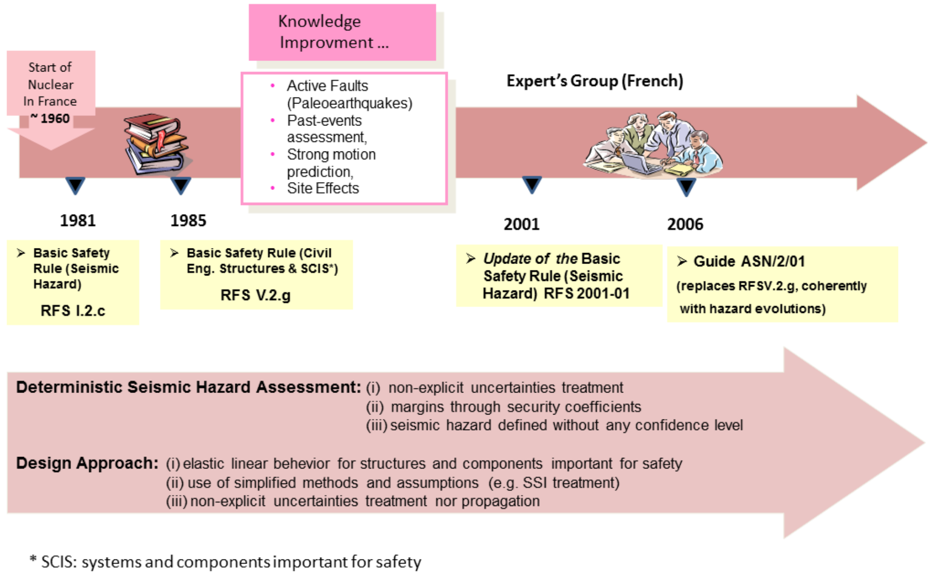

Figure 3: Historical milestones for the publication and updating of French reference texts relating to seismic risk.

To theses texts are added references shared between licensees for the design, such as the RCC-s (mechanical components, Civil Engineering ...), in line with other international standards (ASME, ASCE ...).
Figure 4 complements the previous important elements related to the seismic risk with respect to the safety of nuclear installations, since 2001 and 2005, the date of the last updating of the RFS "seismic hazard" and the Design guide.

From the point of view of the reference texts, the TSN Law was published in 2006 (ref. [3]). In 2012, the "Basic Nuclear Plant decree" is published laying down the general rules for nuclear plants (ref. [9]). This decree stipulates that "their application shall be based on an approach commensurate with the importance of potential risks that could be caused by the facility. Finally, in 2015 ASN published a decision (Décision ASN 2015, ref. [10]) establishing a classification of the basic nuclear installations with regard to the risks and disadvantages they pose for the interests mentioned in Article L. 593-1 of the Environment Code: 3 categories are defined on the basis of criteria set out in the Decision. ASN confirms this classification by decision in 2017 by publishing a list (Décision ASN 2017, ref. [11]) of all basic nuclear installations in France and associating them with a category. These texts are thus an evolution in relation to the initial doctrine, recalled above.

From the point of view of the international seismic context in relation to nuclear issues, in particular, the Niigata-Chuetsu Oki earthquakes in 2007 and especially Tohoku in 2011 in Japan have in fact reinforced the need to characterize and quantify the seismic margins of nuclear facilities. Complementary Safety Studies have led the Nuclear Safety Authority to prescribe seismic levels "beyond design" for the structures and components of the hard core. In particular, the ASN has enjoined licensees to propose hard core spectra of deterministic (RFS 2001-01) and probabilistic spectra to 20,000 years of return period (without confidence level precision) and including site effects. This decision is the first one regarding the use of PSHA (as recommended by the IAEA). At the same time, international and French experience feedback from post-Fukushima and research programs on seismic margins and all seismic risk themes (including SINAPS@), provide an opportunity for stakeholders to update the French corpus of regulations.

The possible evolution towards integrated "risk" approaches is that carried out by the Nuclear Regulatory Commission of the USA as illustrated in Figure 5.

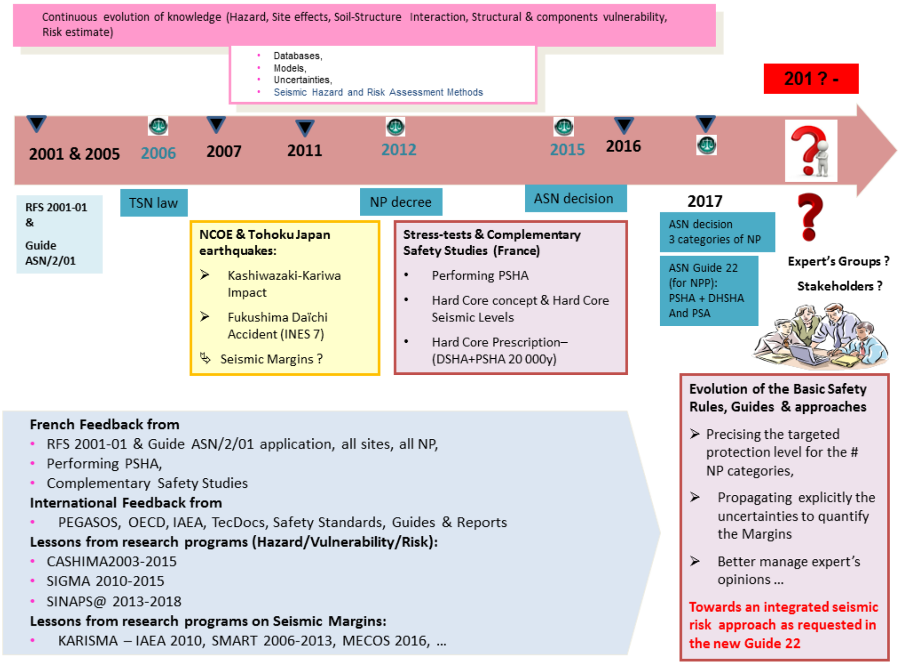

Figure 4: Highlights (major earthquakes, REX, CSS ...) since the last revision of the reference texts in France. Emergence in France and prescription of the PSHA for the hard core levels defined after the Fukushima accident in the framework of the French ECS. PSHA & DSHA promoted in the new Guide 22 (2017 applicable to NPP) and request for performing PSA.

The explicit propagation of uncertainties to define seismic hazard (via PSHA) has been required by the NRC since 1996, and the evolution towards integrated risk approaches has been effective (through Regulatory Guides and supporting texts) since 2005, under the term "Risk-informed" Performance Based Seismic Design.

1.5 SINAPS@ objectives, scientific issues regarding current practice

The SINAPS@ project, its content and scientific challenges are extensively presented in Berge-Thierry et al., 2017a (ref. [12]). In particular, the authors propose for each step of the seismic risk analysis a review of the state of practice in France in the nuclear field and then precise the objectives and research strategy of SINAPS@ to overcome identified limitations or weaknesses. We therefore suggest first reading it in order to catch the scientific locks of current practice, and to clearly have in mind the main orientations of SINAPS@ through for example the definition of two test-sites (one in Greece – Argostoli, the other being the Kashiwazaki-Kariwa nuclear site in Japan, see Altinyollar A. et al., 2013, ref [13]), where numerous and various empirical data have been acquired or collected and have been used in order the elaborate models, verify and validate numerical developments especially in the seismic wave field propagation modeling (from fault to structures and equipment). In the rest of present paper, we only mention main achievements of SINAPS@ and we introduce the various contributions that will be presented during the workshop.

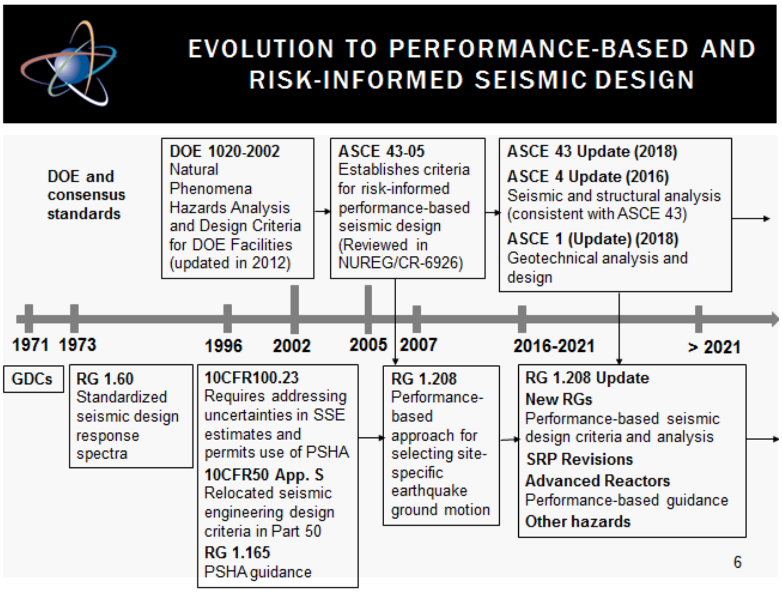

Figure 5: Evolution and revisions of seismic risk for nuclear power references, as carried by the US NRC in 2017 (source: N. Chockshi, SMIRT-24, Busan, 2017). RG (Regulatory Guide); DOE (Department of Energy Technical Standards); ASCE (American Society of Civil Engineering); ASME (American Society of Mechanical Engineers).

2. Lessons learned from the « Seismic Hazard Assessment (S.H.A.) » research

Several scientific challenges were identified at the beginning of SINASP@ regarding the S.H.A. that are:

- the characterization of input data specific to the French metropolitan territory (seismogenic potential of the faults, seismic catalogues, seismic motion at the reference bedrock condition, site effects ...), with a systematic quantification of uncertainties,
- the need to perform sensitivity analysis of deterministic and probabilistic approaches to input data, models and associated uncertainties,
- the identification and ranking of key parameters in the assessment of the seismic hazard,
- and the seismic hazard definition through ground motion parameters and intensity measures adapted to the needs of structural and geotechnical engineers.

In particular, a key issue of SINAPS@ is to track and quantify all sources of uncertainty, and to properly and explicitly propagate these uncertainties in order to produce results that could be appreciated through confidence levels.

The main expected outputs of the S.H.A. SINAPS@ research were to:

- contribute to the continuous improvement the seismic catalog completing and improving the previous ones (especially in the frame of Sihex and SIGMA projects),
- perform sensitivity studies on the influence of parameters, metadata, methods and uncertainties on the estimation of the seismic hazard,
- formulate recommendations for possible practical and/or regulatory evolutions.

2.1 Regulatory "constraints" and evolutions identified in the topics of the seismic hazard assessment related to nuclear risk management from the beginning of SINAPS@ until now

The introduction of this paper presents in details the recent evolution of the regulation and the practice related to the assessment of seismic hazard in the field of nuclear safety: from a purely deterministic philosophy since the 80's (with the RFS 1.2.c and its updated version the RFS 2001-01), the use of the probabilistic approach has been required during the CSS phase (2012-2016) and became mandatory for the definition of the hard core seismic levels ("beyond design") through constraining decisions of the ASN (with a 20 000 years return period target). It is essential to remind that the research performed in SINAPS@ took place during this unusual "post-Fukushima" period that deeply questioned all the nuclear actors (operators but also the IRSN and the ASN) on their practices in the field of seismic risk management. The recent publication of the Guide ASN 22 (July 2017, ref [1]), applicable to the NPP design (then not necessary adapted for other nuclear facilities related to less severe categories with respect to the ASN 2015 and 2017 decisions, ref [10] and [11]), highlights a preference of the ASN and IRSN for the deterministic approach in the assessment of the reference external hazards, as seismic hazard. On the other hand however, the Guide ASN 22 requires performing, when possible, probabilistic seismic hazard assessment, with a target annual frequency of exceedance of 10^{-4} (see 3.3.3.2.6 of the Guide ASN 22). Finally, the Guide ASN 22 also requires the operator of the NPP to perform probabilistic safety assessment related to the risk of damage nuclear fuel and the risk of abnormal releases of radioactive substances.

2.2 Main achievements or lessons in S.H.A.

Currently and since several decades now, two seismic hazard assessment approaches or philosophies have co-existed: the deterministic and the probabilistic way (respectively DSHA and PSHA). In France, the current "reference" approach to assess the hazard is guided by the RFS 2001-01 text, which prescribes a DSHA-type method where the seismic hazard is defined through various seismic levels. **The RFS 2001-01 methodology must be considered in its entirety. Indeed, the treatment of uncertainties cannot be separated from the whole approach which is precisely intended to cover the uncertainties inherent to the definition of the reference earthquakes. The uncertainties taken into account within the RFS 2001-01 approach imply that some safety margins are taken in the seismic design. As a consequence, reconsidering the treatment of the uncertainties in the framework of the RFS 2001-01 would necessary lead to reconsider the current margins.**

It is also crucial to remind that DSHA and PSHA, performed in a target site, share:

- the overall knowledge in the seismic hazard field, the references (guides, practices, scientific publications …),
- the basic data (geological, geophysical, seismological …),
- the available codes, empirical and numerical predictions models.

In the same time, DSHA and PSHA usually differ:

- first of all, in their intrinsic objective: DSHA aims to assess the hazard related to one (or several) reference seismic event(s) whose seismic characteristics (magnitude, intensity, depth, distance) are directly translated into a seismic motion (usually through a spectral response spectrum) using a (or several) prediction model(s). Whereas the PSHA produces a seismic hazard through a probability of exceeding of a certain seismic motion measure (acceleration, pseudo acceleration …) during a defined duration (or an annual frequency of exceedance), and the output is usually a Uniform Hazard Spectrum: in this case, there is no reference event(s) associated the UHS as it is the result of the seismicity distribution relationship (called "Gutenberg-Richter relationship", that represents the frequency occurrence of the earthquakes given their magnitude). **This conceptual difference explains why only a PSHA is by definition providing an annual frequency of exceedance whereas a DSHA will never give this probabilistic information. As an extension, it means that whatever it is performed, a DSHA will never produce an output which can be considered to perform a full seismic risk analysis as it requires a probabilistic description of the hazard.**

- in the treatment of uncertainties (both on data and models), be it epistemic or aleatory. On this point, SINAPS@ WP1 research proposes some alternatives to the current French practice (essentially through the RFS 2001-01 approach, ref. [5]).

As a consequence, several SINAPS@ S.H.A. works finally benefit both the DSHA and the PSHA approaches: this is the case of the improvement of all basic data, predictions models and the characterization of the uncertainties. In addition, the knowledge evolution globally in the field of seismic hazard (without forgetting the context in which the SHA is performed, especially in the frame of a full probabilistic seismic risk analysis for nuclear safety in SINAPS@, aiming at characterizing the potential seismic margins), or in specific topics (such as the ground motion prediction, or the site geology/geotechnical characterization) should be accounted in both DSHA and PSHA approaches, and/or should motivate the updating of obsolete practice, simplified assumptions, or references. These recent improvements in seismological databases, in hazard modeling and ground motion prediction models are extensively discussed in Berge-Thierry et al., 2017b (ref. [14]) where the recommendations from SINAPS@ to perform S.H.A. are developed. In particular SINAPS@ points out the improvement (i) in the strong motion databases since the 2000's (date of the last French regulatory document) in terms of number of records and quality of their associated metadata and uncertainties characterization (Baumont et al., 2017, ref. [15], Manchuel et al., 2017, ref. [16] (ii) of ground motion prediction models either empirical (GMPEs) or numerical (Del Gaudio et al., 2017, ref. [17], Dujardin et al., 2018, ref. [18]), including the physical based models (illustrating nevertheless some limitations regarding the use in low seismic area of EGF summation methods) (iii) of the site-specific SHA through host-to-target approach (Laurendeau et al., 2017, ref. [19], Bora et al., 2017, ref. [20]) or more simply (and more adapted to French seismic site response knowledge) using Vs30m (and other site parameters) as proxy in the GMPE's functional form. We finally highlight the potential already operational of the Bayesian method to complete the expert's opinions when selecting and weighting ground motions models, but we also underline the need of defining a reference dataset to challenge these various models (Bertin et al., 2018, ref. [21]). The BMA is also used in order to check the PSHA results using accelerometric and macroseismic data. The conclusions and recommendations regarding the unavoidable evolution of the SHA practices in the nuclear French field are valid for deterministic or probabilistic approach. Finally, SINAPS@ underlines that any databases or models used in SHA studies must be published, accessible to all: the procedures for data processing and modeling must be explained, justified (need of traceability and transparency). The most recent releases are preferred: in case of expert debate, the data (or database, model ...) as published is acceptable until superseded, with justification in a new publication (peer review, international as much as possible).

To end this section, we underline a major lesson of SINAPS@. As mentioned, SINAPS@ aims to propose innovative method to assess the seismic risk, in a continuous way from the fault to the structures and equipment, properly propagating the epistemic and aleatory uncertainties. To reach this objective, the use of full probabilistic approach is unavoidable, and it is also necessary to pay attention on following key steps (i) first one being the definition of the "control point" which is the spatial location where the S.H.A. is assessed and its associated properties regarding seismic waves response, (ii) as a consequence the need to define the “reference bedrock” complementary to the classical “standard bedrock” usually taken at the outcropping level: the number and type of proxys considered to characterize the bedrock (but also other type of soils) might be sufficient and appropriate to restore its seismic behavior (iii) and finally the site response has to be assessed independently accounting for the possible nonlinear between the geological environment and the structural foundations (Régnier et al., 2018 [21bis]). Performing such a seismic analysis is clearly far from the current practice at least and absolutely incompatible with the RFS2001-01 and ASN Guide /2/01 guidelines, strongly anchored in pure deterministic ways and including some fixed safety coefficients to manage some uncertainties. On the contrary, the innovative and continuous approach proposed in SINAPS@ enables an accurate estimate of seismic margins, with an explicit propagation of uncertainties and results that are assessed with confidence levels. These key issues are discussed and illustrated on the KK test-case in Berge-Thierry et al., 2017 c (ref. [22], Wang and Feau 2017 (ref. [23]), Wang and Feau 2018 (ref. [24]), Gatti et al. 2018 (ref. [26]). Last but not least, the price to pay to perform advanced site-specific seismic analysis is to acquire the site-data (surface and in-depth) necessary to accurately predict its linear and nonlinear seismic response using state of art 3D numerical simulation (Gatti et al. 2018, ref [26]).

2.3 S.H.A. SINAPS@ research presented during the BESTPSHANI 2018 workshop

Bollinger et al., 2018 (ref. [27]) investigate the influence of climatic and especially periglacial effects on the seismic cycle. The occurrence of huge earthquakes suggested by paleoseismological studies are then discussed in the framework of seismic activity models classically used either in DSHA or PSHA.

The work presented by Turquet et al., 2018 (ref. [28]) gives an illustration of the characterization and quantification of uncertainties on seismic metadata, focusing on the 3D location of French metropolitan seismic events, and on their focal mechanism: these parameters are interdependent it is then essential to highlight their links especially when propagating the associated uncertainties to avoid any over counting.

Bard et al., 2018 (ref. [29]) gives an overview of the state of the art to perform site-specific S.H.A., highlighting the potential and limits of currently promoted methods (such as the Host-to-target GMPE adjustments). Authors present original works developed during SINAPS@ taking advantage from boreholes data or using the IRVT approach. This latter work (Bora et al., 2015, ref. [30] and 2017, ref. [20]) is particularly attractive with the publication of new GMPE’s established directly on the Fourier spectrum instead of the classical response spectrum which is certainly a comfortable tool for the engineering practice but already far from the original complete seismological information: the response spectrum providing only an amplitude information (loss of duration) is also intrinsically conservative (as being the maximum responses of 1DOF oscillators). Such IRVT techniques should be used more extensively in the future, and we could also expect to perform SHA with Fourier spectra as being the output: this would have the huge advantage to improve the step of selecting time-series adjusting response spectra (which has no physical meaning and introduces more uncertainties in the seismic analysis, see Wang and Feau 2018, ref. [24]).

Bertin et al. 2018 (ref. [21]) evaluate the feasibility of using Bayesian Model Averaging (BMA) techniques when applied with Ground Motion Prediction Equations to describe the mainland France's seismicity. The model averaging calibration is computed with records from the Resorce strong motions database. Such Bayesian techniques appear promising in order to select and weight among a large set of available GMPE's in a more objective way than the common expert's opinion process. This work serves as much as DSHA as PSHA approaches.

Finally, Dujardin et al. 2018 (ref. [18]) illustrate SINAPS@ research performed on the strong motion prediction using physic-based source modeling. Such models are an alternative to using GMPE's, but require obviously quantity of parameters (from de geological medium properties, to the seismic source geometry and rupture process). In the frame of SINAPS@ the near extended source effects are deeply studied in order to identify the physical processes that produce the saturation of the ground motion when the source-to-station decreases. This study is conducted through a numerical simulation approach, using stochastic source model and the Empirical Green Function (EGF) summation technique. Finally, the potentiality and cautions when using one or few EFG in order to describe the wave path from an extended source to the source are explored. The use of such physic-based models is then discussed with respect to the quantity, quality and large uncertainties attached to French metropolitan seismic data.

3. Lessons learned from the non-linear site effects (NLSE) and soil-structure interactions (SSI) research

3.1 Scientific context and Objectives

In the framework of the wave propagation from the source to the equipment at the structure, SINAPS@ could be placed at the interface between the soil and the structure, the seismology and the structural dynamics, the hazard and the structural vulnerability. Even if the soil-structure interaction effects are well known from the 70's, they have often been tackled under simplified assumptions: Winkler springs, uniform incident wave field, shallow rigid footings or linear equivalent soil behavior, among others. Some of these assumptions have been improved in recent years highlighting the intrinsic safety margins (see discussion above concerning the definition of the seismic hazard and ground motion prediction, reference bedrock definition, site-effects to be accounted through the SSI modeling among others). Moreover, those works showed their high sensitivity to the uncertainty on both the seismic loading and the soil surrounding the structure. Furthermore, so as to take into account extreme events in the post-elastic behavior of structures, it is necessary to have a more detailed description of the seismic loading, in both time and space, exceeding the given maximum acceleration or code spectrum. Finally, the instrumental and theoretical seismology has highlighted the complexity and variability of the incoming seismic waves: near field effect, site effects, non-linear filtering strong movements, spatial variability. These advances build now a big picture, which combines divers methods with difficulties to be associated and sometimes inconsistent with the regulations and common methods used in the world. In this context, SINAPS@ research is focused on the development and implementation of methods that consider the seismic wave field in a continuous way from its origin at the seismic fault, through its propagation in the complex 3D geological medium, up to the foundations of the structure. One of the objectives is to model the physical processes in the most realistic way possible (meaning in the post-Fukushima context that non-linearities in media and interactions are unavoidable and have to be properly modeled), but also to account and propagate also realistically the uncertainties attached to all components (propagation medium, seismic source and structure seismic properties …).

SINAPS@ research has been oriented in order to:

(i) improve the traditional methods defining the input motion at structure base in close relationship with the S.H.A. progress discussed in section 2. Among several challenges, the spatial variability of seismic motions and the quantification of uncertainties of various soil materials are explored.

(ii) develop new methods, modeling the seismic wave field from the fault to the equipment and including non-linearity and variability of soil properties. To reach this objective coupling structural and wave propagation codes is needed.

(iii) acquire new geological, geophysical, geotechnical and seismic data to constrain models, verify and validate numerical developments. One highly seismic active site (in Japan) and a second one in a moderate active context Validation site (Argostoli site, Kephalonia Island, Greece) were chosen.

3.2 Main achievements or lessons in N.L.S.E. and S.S.I.

3.2.1 Validation of non-linear soil models for the strong ground motions

The evaluation of site effects can be performed through the analysis of earthquake recordings but is limited to a specific location, and, most often for moderate seismic hazard region, to weak motion recordings only. Evaluation using site classification (Vs30 or fundamental resonance frequency) is low cost and can be executed on a large scale but will be associated with strong uncertainties. Thus, numerical simulations are the only method to be site-specific and to be able to predict the non-linear site response during a strong motion. This requires i) a detailed definition of the soil parameters, ii) a constitutive model of soil that mimics the real soil behavior during earthquakes and iii) an input motion. The natural soil variability, the measurements errors, the model approximations and the earthquake variability are the four sources of uncertainty when evaluating site amplification. One of the main objectives of the PRENOLIN benchmark was to evaluate the uncertainties in 1-D non-linear site response analysis. Several codes were tested on canonical cases (Régnier et al., 2016, ref. [31]) and the results were compared to observations on sites of the Japanese accelerometric network (Régnier et al., 2018, ref. [32]). The benchmark presently involves 21 teams and 21 different non-linear computations. To constrain the linear and non-linear soil parameters, in-situ measurements and multiple laboratory measurements were conducted on disturbed and undisturbed soil samples. In general, these numerical models allow simulating the dynamic soil behavior in a simple way with an acceptable level of accuracy. The code-to-code variability was calculated on two sites and compared to the part of the uncertainty in GMPE's (Ground Motion Prediction Equation) that is associated to the site amplification.

3.2.2 Soil-structure weak coupling: modeling of Nonlinear soil structure interaction: "Domain Reduction Method" approach.

Stating from common approaches widely used by the engineers to take into account the SSI (Soil-Structure Interaction), the main purpose of the SINAPS@ project was to improve several aspects in order to define more realistic models. An approach based on the Domain Reduction Method (DMR) was tested in order to reduce the computational time. Usually a Non Linear Soil Structure (NL-SSI) problem is solved using Direct Methods, which could be very expensive in terms of computation time due to treatment of infinite domain (i.e. fictive boundaries for a large scale domain). In order to reduce the computation time, a possible strategy is to reduce the computational domain (i.e. soil domain) and getting close the soil boundaries to the structure. In this case two aspects are very important: i) in the full FEM approach the incident waves must be imposed in according to the hypothesis of soil behavior at the fictive boundaries; and ii) moving close the fictive boundaries to the structure means that the influence of the outgoing waves induced from them are important. Then, absorbing boundaries are needed so as to satisfy a radiation condition for the incompatible outgoing waves. Thus, the efficiency of the absorbing layer is key point in order to reduce the size of the problem. The points mentioned above are the main highlights concerning the DRM methods (Domain Reduction Method) as proposed by (Bielak et al. 2003, ref. [33]).

3.2.3 Numerical analysis of the effects of regional and local geology on ground motion

A proper estimation of the earthquake ground motion is required at the site of interest to assess the seismic structural response and draw hazard maps. Nowadays, due to the increased computational power, complex structural time-domain analysis is possible. This requires several realistic time-histories as input motions. The 3D numerical simulation of strong ground motions at a regional scale has therefore become the leading and most reliable tool to reproduce artificial wave-forms. Those earthquake scenarios are very appealing to better understand the physics of strong ground motions (especially in near-field conditions). Moreover, recent numerical methods such as the Spectral Element Method or the Discontinuous Galerkin Method combined with massively parallel computers have proved to be very effective at modeling the propagation of seismic waves from the source to the site even in complex tri-dimensional geological environments. However, the accuracy of such predictions remains limited due to either the lack or the large uncertainties on the data that will be introduced in the model, namely, i) the geometric and kinematic characterization of the seismic source, ii) the detailed numerical model of the source-to-site propagation path and iii) inclusions of possible non-linear response. Thus, even very extensive geophysical surveys fail at reducing the resulting uncertainties on the predicted ground motion. In addition, such large-scale surveys cannot be conducted for all practical cases. For those raisons, the construction of a regional model that simulates the seismic phenomenon from the source to the structure could help to better analyze the recorded signals.

In the SINAPS@ project, some 3D regional scale non-linear and probabilistic models using the SEM3D (ref. [25]) code were performed. Numerical applications using the implemented libraries (i.e. generation of the gaussian random-field and a non-linear constitutive relationship to represent the soil behavior) were done. A special attention is given to the overall set-up of an efficient numerical workchain to solve large wave propagation problems over tens of hundreds of processors on massively parallel supercomputers. Finally, the effect of both geology and spatial variability on the ground motion prediction equations at a regional scale were studied numerically. The studied sites were located at Kefalonia Island (Greece) and at KKNPP (Japan) (Gatti et al. 2018, ref. [26]).

3.2.4 Validation site and Data acquisition at Argostoli test site:

In September 2013, a first geological and geophysical survey was conducted at Argostoli site in the framework of SINAPS@ project. It leaded to a new geological map and 2D cross-section, estimation of Vs profiles (obtained with surface wave based non-invasive methods), and a 3D overview of the basin through H/V measurements. In addition, due to the 26th January 2014, a Mw=6.2 earthquake. It was decided to launch a post-seismic survey with two main objectives: i) to install temporary accelerometers in anticipation to the installation of the permanent array in order to record possible strong after-shocks and ii) to install a dense array of sensors in order to get a database to study spatial short-scale variably. Different sensor types were used: accelerometers, broadband velocimeters, rotational sensor and were deployed on different soil conditions. This kind of database, even if it does not address the NL issue, is also essential for soil-structure interaction researches. The temporary accelerometric network is in operation since 3rd February 2014 (few hours after the second strong earthquake with Mw=6.0) and recorded several thousands of events. A first analysis of this database allowed to computed standard spectral ration between a rock site and several sites within the basin. The dense array was composed by 21 broadband seismometers, arranged on a five branches star with a maximum radius 180 m. It was in operation over a 5 weeks period. A database composed by more than 1800 well-recorded earthquakes is now available. These two outstanding databases will be extensively used within the whole Sinaps@ program. It is well known that the non-linear (NL) behaviour of soil can drastically change the site response in case of strong ground motions. It is necessary to validate the NL evaluation practices by comparing simulation results to real data. In parallel to the work done in PRENOLIN task, it was decided to install accelerometers along a vertical array (and in a rock reference site) within a small sedimentary basin, near the town of Argostoli, on the Kefalonia Island (Greece), one of the most seismic areas of Europe. This array is long term investment toward the constitution of a new database for a possible NL practice validation in a 3D case. This site was chosen thanks the feedback of previous works, especially the NERA European research program.

Finally, this experiment was the opportunity to complement standard translational measurements by rotational measurements allowing “six degrees of freedom” recordings. The rotational measurements were performed on different sites, allowing the study of soil condition on rotation motions. The rotation measurements led to the recordings of a total of 1373 events on three successive sites.

3.3 N.L.S.E. & S.S.I. SINAPS@ research presented during the BESTPSHANI 2018 workshop

Régnier et al., 2018 (ref. [32]) present the analysis of the correlation between the effect of non-linear soil behavior on site response and parameters that characterize the site or the input motion. The first step involves the definition of (1) pertinent parameters that illustrate the influence of the non-linear soil behavior on site response called observed parameters and (2) pertinent geotechnical parameters or input motion parameters that could explain those observations called explanatory parameters. Then, two methods to correlate the observed and explanatory parameters dataset were used: the so-called canonical correlation that is a multivariable linear correlation method and a neural network. The analysis was performed on an empirical dataset (KiK-net) and then on a synthetic one.

Second contribution is the work done by Touhami et al., 2018 (ref. [34]). This work illustrates the effort done in SINAPS@ to develop, verify and validate new numerical solution software enabling to realistically predict the site response using advanced physic-based models. The seismic wave field is simulated in its entirety: from the seismic source to the site using a representative model of the complexity of the wave path using the numerical code SEM3D. This software is based on the spectral element method allowing solving of waves-propagation problems in three-dimensional media. Concerning the studied site, the Argostoli located at Kefalonia Island was selected. This site was chosen because of geological reconnaissance and geophysical acquisition field trips were carried out in the framework of SINAPS@ project and the NERA European research program among others. Authors also took advantage of the numerous weak and moderate motions recorded by the recorders installed thanks to the SINAPS@ initiative. This work aims to study numerically the effect of both geology and spatial variabilities on ground motion prediction at a regional scale. For this purpose, a 3D model based on the new geological map was developed. In order to validate the proposed numerical simulation software, several recorded earthquakes issued from the accelerometers array database are compared with the numerical simulated ones. The first obtained results show the importance of the in-situ measures (i.e. geology, geotechnical data and ground motion time history) on the regional scale simulations.

Finally, in Hollender et al. 2018 (ref. [35]), the Argostoli experimental test site will be presented. As recalled before, since September 2013, many actions were conducted on this site within the SINAPS@ framework: geological and geophysical surveys in order to build a 3D model, temporary post-seismic campaign, installation of a permanent vertical accelerometric array (in operation since July 2015), etc. Data from post-seismic survey are open and available from web-repositories; data from the vertical array will be open soon. Within the Sinaps@ project framework, many studies concerning both data analysis and numerical simulations have already done using the collected data, such as: non-linearity analysis, wave-field characteristics, 6-degrees of freedom (translation + rotation) studies, wave-field coherency analysis, seasonal variation of site response, variability of site amplification according to source features among others. This site produced a lot of learnings valuable for seismic hazard assessment. The main goal of this work is to present the available datasets and to propose a review of all works performed on this site within the framework of the Sinaps@ project. In addition, as shown in Touhami et al., 2018 (ref. [34]), the seismological and geological data obtained from Argostoli site are used to build and to validate the large-scale non-linear model developed in the same project. Beyond the actual results of each of these studies, the most important outcome of the Argostoli test-site is the emphasis of the need for multidisciplinary approach.

4. Lessons learned from the “Seismic behaviour of Structures & Equipment” research

4.1. Scientific challenges

In order to transmit seismic signals (in terms of frequency content and amplification) from the soil and foundation till structural elements and equipment, models for structural analysis may allow taking into account the different mechanisms prevailing in material and structural responses. However, such models should permit to evaluate the robustness of the overall structure and fragility of safety related equipment thanks to margins assessment regarding the design. One should note that model means the geometrical and the kinematics description of the structural members as well as the refine modeling of involved materials response.

The seismic ground motion is clearly non-deterministic, regarding the acceleration level as well as the frequency and time features of the signal waves reaching the building. The vulnerability assessment of the structure and its equipment is part of a general approach for criticality studies. Accounting for uncertainties has to be achieved at the structural level. Such studies imply refinement levels which should be in accordance with the engineering computing usual practice.

The concern of SINAPS@ vulnerability research consists in developing or increasing the robustness and capacity of several types of modelling (from simplest ones to more complex ones), to address their identification regarding available data and at last to appreciate their usefulness in the framework of vulnerability analysis. Models able to handle this former feature are the elementary bricks allowing seismic hazard assessment analysis. Such qualities are emphasized thanks to three specific applications: evaluate the model’s ability to propagate uncertainties in function of their refinement or simplicity level, the ranking of critical equipment of NPP facilities regarding seismic loadings scenario and the study of structural seismic mitigation allowed by building isolation.

4.2 Main achievements or lessons in structural & equipment vulnerability research

4.2.1 Structures modelling

The study of the vulnerability of reinforced concrete structures requires powerful and validated numerical tools. Two different options have been developed in SINAPS@ linked to the enhancement of the mechanical response of structural elements subject to seismic loads:

(1) kinematics enhancement of structural elements, decreasing the number of degrees of freedom. Different kinds of models have been developed or enhanced allowing to sum up their

complex behavior to their 1D (beam) or 2D (plates) responses thanks to adequate enriched kinematics.

For nonlinear dynamic calculations, 1D finite element analyses of beam type present a good compromise between calculation time and precision of the results. Numerous finite element beam models based on the Timoshenko kinematics have been developed in recent years, including elements adopting a force or a displacement formulation. In the frame of SINAPS@, three enriched finite element beam models have been developed (I. Bitar 2017, ref. [36], S. Capdevielle 2016 ref. [37] and N. Khoder et al., 2017, ref. [38]) for the calculation of reinforced concrete beams.

In the 2D-plate modelling field, SINAPS@'s partners EGIS, ECN and EDF a stress resultant non-linear constitutive model (GLRC-HEGIS, see Huguet et al., 2017, ref. [39]) for cracked reinforced concrete panels has been developed and implemented in the finite element Code Aster (ref. [40]). The model takes into account concrete damage, cracking, steel-concrete bonding and yielding of the reinforcement bars. While the work has started prior to the SINAPS@ project, the SINAPS@ project made possible to finalize and consolidate different aspects: identification of the model parameters: validation and robustness.

EDF, for its part, confirmed its practice of 2D-plate RC nonlinear constitutive models and assessed the capabilities of the two constitutive models previously developed in Code_Aster: GLRC_DM and DHRC (Voldoire, 2015, ref. [41]). Although these models were developed prior to the start of the SINAPS@ project, this project consolidated many aspects: implementation of identification tools to help the engineer, validation, robustness enhancement. They aim at the floor response amplification prediction in RC buildings and fragility curves calculations.

Finally, CEA and ENS Paris-Saclay have developed modelling strategy dedicated to the physical description of cracking in reinforced concrete structural elements (Kishta et al., 2017, ref. [42]).

(2) keeping the 3D description of the structural behavior but reducing the CPU time consuming by several techniques (model reduction or structural zooms on regions of interest), accounting for all dimensions and complexity of the seismic input.

During SINAPS@ the PhD thesis of Matthieu Vitse (ref. [43]) focused on the mechanical response of reinforced concrete structures subjected to cyclic loading conditions, which is critical when dimensioning structural elements. In order to reduce the computation cost of such problems, a PGD-based reduced-order modeling approach was implemented, for which the uncertain parameters were considered as additional variables of the problem. These solutions lead to what is called a "virtual chart" which once post-processed at an extremely low cost, makes it possible to draw conclusions about the influence of uncertainties on the response of the structure.

4.2.2 Structural applications

4.2.2.1 Simplified models and uncertainties propagation

It is fundamental to provide engineers with quantitative elements able to assess the influence of material parameters uncertainties on certain characteristic structural responses, for multiple modelling strategies and for different structural typologies. The undertaken work provides also a critical view on all of the development studies carried out within SINAPS@ by analyzing the capacity of a modelling strategy to propagate more or less the materials uncertainties. More specifically, two reinforced concrete structures have been considered from former experimental campaigns: SMART 2013 (walls and slabs, see Richard et al., 2016, ref. [44]), which is representative of a real nuclear building designed according French standard and BANDIT (beams and columns frame). Such structures were modelled via different strategies (1D, 2D and3D). For each model, a certain number of material parameters were considered as random variables (concrete tensile strength, crack energy, steel yielding stress, damping ratio, concrete Young modulus). A probabilistic study has been carried out in order to assess the variability of some output quantities (ZPA, maximum spectral acceleration, dissipated energy, etc.). The obtained results allow classifying the uncertainties on the base of their effect on quantities usually used by engineers. Such classification is considered to be fundamental for engineers who have to face choices in terms of modelling techniques in their daily practice, whether it is a design or assessment activity (see Stocchi et al., 2017, ref. [45]).

4.2.2.2 Seismic Isolation

Seismic base isolation is one of the most efficacious seismic mitigation methods. Regarding nuclear facilities, an important expected benefit is the reduction of equipment demand through filtering of the higher excitation frequencies. Nevertheless, in some cases, an amplification of the response of higher modes arises which may considerably reduce the efficiency of seismic isolation. The objectives of this activity of the project are: a) study the sources of the amplification of the response of the non-isolated modes (modes other than the first modes at low frequency) and b) investigate possible remedies to the above undesirable amplification.

Regarding objective a) it has been shown that in the case of rather rigid superstructures, such as met in nuclear facilities, the possible sources of the amplification of the non-isolated modes are:

- ✓ High base energy dissipation (linear or nonlinear viscous dampers, elastoplastic of friction dissipative devices, etc.).
- ✓ Base rocking-induced excitation due to horizontally propagating waves or to the scattered motion in the case of embedded foundation.
- ✓ Coupling between vertical excitation and horizontal response in the case of asymmetric superstructures.

The above amplification mechanisms were investigated theoretically and numerically based on simple yet representative models. These studies gave qualitative and quantitative results which allowed us to draw clear and meaningful conclusions which are helpful to guide the design phase and, also, to gain a further insight into numerical simulations' results of more complex models.

As for objective b) two alternatives to the commonly used isolation devices were examined:

- ✓ Full 3D isolation devices (i.e. flexible in the vertical direction also) without anti-rocking devices. Such devices are quite effective against rocking excitation but they may have adverse effects even in the case of "classical" translational excitation due to unavoidable eccentricities inducing coupling between vertical and horizontal directions. Hence they are not recommended (unless further studies give more evidence of their beneficial effects).
- ✓ A relaxation isolator combining a device such as a classical low damping rubber bearing in parallel with a Maxwell element. This kind of isolator is proposed for seismic isolation for the first time in this work. It has been shown that it is very efficient to reduce base displacement without amplifying the response of the non-isolated modes. To make the use of this kind of isolators more appealing, technological issues related to their practical realization, should be studied further.

4.2.2.3 Critical equipment ranking

In order to reduce the seismic risk of a Nuclear Power Plant, a solution is to progress in the understanding and modelling of the components that drive the overall fragility. In the frame of the SINAPS@ project, first action of AREVA has been to identify those components. To do so, AREVA has developed a generic method to classify the components of the Seismic Equipment List (SEL), based on the results of a Seismic Probabilistic Risk Assessment (PRA). The application of this method to the results of EPR@, completed by the experience feedback on seismic reassessment projects, has led to the establishment of a Generic Seismic Equipment List (GSEL) that contains major contributors to the seismic risk. Clearly, the seismic vulnerability of some components of the GSEL is overestimated because of the use of too many conservative methods of analysis.

4.3. SINAPS@ structural & equipment vulnerability research presented during the BESTPSHANI 2018 workshop

Ragueneau et al. 2018 (ref. [46]) gives an overview of the contributions from the SINAPS@ project on the multi-level modelling approach of RC Structures under earthquake loading. This presentation goes through the various strategies, from 1D to 3D modellings, providing a critical analysis of their respective potentials and limits, regarding their time computing cost but also with respect to their ability to propagate diverse sources of uncertainties.

Robin-Boudaoud et al. 2018 (ref. [47]) presents the work performed by AREVA in the frame of SINAPS@ to develop efficient methods to point out components that could need to be redesigned, in order to increase the robustness of the nuclear power plant in regards of seismic risk. Firstly, a generic list of potential high contributors to seismic risk is built, from the already performed seismic probabilistic assessment. It allows defining families of structures that could drive the overall fragility of the nuclear plant. Then, a critical analysis of the engineering methods used to evaluate the capacity of those components is performed.

Banci et al., 2018 [48] gives an overview of the enhancements of analysis methods devoted to the calculation of structural and equipment responses and seismic margin assessment which have been elaborated during the SINAPS@ project. These authors first underline several improvements of the current engineering practice, based upon the same linear assumptions. Then, they highlight the advanced methodologies based upon nonlinear constitutive models for reinforced concrete structures and equipment, which are needed for best-estimate analyses and uncertainties propagation. Both approaches take profit of enhanced definition of the seismic motion and associated intensity measure parameters. Results provided by different methods are appreciated through the floor response spectra. This work has been achieved thanks to experimental campaigns and numerical contests to strengthen the verification and validation process of used methodologies and simulation tools for practitioners, in particular in Code_Aster (ref [40]).

5. Lessons learned from the “Seismic risk assessment” research

5.1 Scientific challenges

The seismic risk assessment consists in aggregating the various elements of the analysis chain within the convolution of the seismic hazard, parameterized in terms of intensity measures, and the various conditional probabilistic estimates of the damage (or required performance critical values) of structures and components (via fragility curves or distribution functions). Risk assessment can be based on a multiphysical expertise analysis for a given component, during the design stage as in a periodic safety review.

The scientific challenges in the Seismic risk analysis SINAPS@ research consist in

1. Establishing the overall methodological approach for quantifying the seismic margins of the facility by a coordinated implementation to a global validation by confronting the measures and data available on the case of Unit 7 of the Kashiwazaki-Kariwa NPP site, see Altinyollar A. et al., 2013 (ref. [13]), submitted to the earthquake of 16th July 2007, beyond its design level.
2. Consolidating the performance of probabilistic risk assessment methods: uncertainty propagation technique and probabilistic meta-models, fragility curves calculations and extreme statistics and Bayesian methods.

5.2 Limitations at the beginning of the SINAPS@ project and regulatory "constraints" identified in the topics of the risk assessment

The general approach of French safety regulation with regard to the seismic risk has a deterministic nature; margins are introduced both at level of analysis methodologies and input data collection. The economic stakes on the equipment seismic safety assessment are very strong for the French NPPs.

The uncertainties inherent in the input data, knowledge of the physical processes and analytical methods used at each stage of the assessment of the seismic hazard and the vulnerability of the nuclear structures and components are not dealt in the practice with a coordinated manner. Current regulatory requirements define conservatism at each stage, independently. Uncertainties on the same parameter could be taken into account several times, for example on the quantification of the site effect: in seismic hazard studies and also in dynamic soil-structure interaction analysis.

The main items of the current analytical methodologies used in engineering are discussed below. These are the topics under discussion for the R & D contributions of the SINAPS@ project.

The HCSL ("hard core") soil target response spectrum is defined as a "load case" by two components (i) the median UHS probability spectra of return period 20000 years and (ii) the deterministic SMS[1] spectrum amplified by an overall coefficient of 1.5. The HCSL does not therefore represent a physically possible event because composed of two spectra, especially since the UHS spectrum itself cannot be considered physical

Therefore, there are many epistemological uncertainties in selecting or generating accelerograms and their representative variability that are compatible with the SHA output (UHS and/or seismic scenario response spectrum); for example, we know that the strong motion phase duration is an indicator having an important consequence (effect on the behavior of civil engineering, effect on the behavior of electrical equipment, effect on the amplitude of the differential displacements, etc.).

The representation of vertical seismic motion (according to the RFS 2001-01) is another topic under discussion: it is determined by the assignment of a coefficient 2/3 for all frequencies of the horizontal response spectrum. The vertical component of the signal is not processed in a manner consistent with the de-convolution of the horizontal motion. In addition, different soil characteristics (stiffness, damping) are adopted to cover uncertainties (by means of the rule 2/3 and 3/2).

Structure-soil-structure interaction was almost never taken into account in traditional design practices; nevertheless its use is more and more widespread, e.g. (Ostadan and Kennedy, 2014,

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[1] *Séisme majoré de sécurité*, corresponding to the so-called Safe Shutdown Earthquake.

ref. [49] The ASN 02/01 guide (ref. [6]) stipulates enlargements of floor spectrum +/- 15%; however, the extrapolation of this requirement to transient studies is not easy to justify: the elasticity modulus variability is then chosen in an arbitrary manner.

For equipment analysis, the simplest approaches take into account a margin factor of 1.5 between the floor response spectrum established from building calculations and the demand used in the re-assessment of the equipment. This coefficient can be particularly penalizing, especially for pipe systems, although the post-seismic observations are very favorable. A simplified rule is also used to evaluate the spectrum at another reduced damping value. It is known, that the decoupled dynamic analysis of building and equipment via the floor response spectrum with enlargement and smoothing/envelope procedure introduces a non-uniform and sometimes excessive margin.

Spectral modal analysis is the most commonly used linear dynamic analysis method, especially in design - although some studies use transient (often linear, rarely nonlinear) analyzes. However, its result is limited to providing conservative estimates of maxima (e.g. floor ZPA, stresses in structural elements or equipment anchorages, etc.). The combination rules allow to efficiently accounting for the correlations of modal and directional responses, with other contributions (differential displacements…). The method of ellipses (taking into account of statistical correlations between components of an effort in a more realistic manner) is not systematically implemented.

Less frequently, the linear random vibration analysis method can be used, using the passage between the Power Spectral Density and the response spectra (according to works of E. Vanmarcke and O. Rice); in these cases, the soil-structure interaction can be modelled by the traditional FEM-BEM approach, including equivalent linear modeling of the soil column. It allows overcoming some of the simplifying assumptions of spectral modal analysis, while proposing a chained dynamical analysis tool, from seismic motion to safety-related equipment response.

The overall seismic risk assessment is carried out within the framework of the probabilistic safety analysis (PSA), One of the objectives is to identify the major contributor (s) to the risk. Fragility curves are in practice determined in a simplified way. Up to now this approach was produced in a complementary way during the periodic reassessment surveys of French NPPs, using the state of international available practice. Nevertheless, since July 2017, the French regulation imposed to the licensee of power reactor to perform PSA not only in the framework of plant re-assessment but also during its design stage (Guide ASN/22, ref. [1]).

5.3 Main Scientific Advances in the Seismic Risk Assessment through SINAPS@ research

The first action in this area deals with the development and the consolidation of the computational chain in probabilistic and sensitivity analysis, through the establishment of meta-models (to increase numerical performance, because we have to cope with the exploration of wide ranges of variability) and the calculation of fragility curves by best-estimate simulations. The use of neural networks regression meta-models has been evaluated (Ferrario et al., 2017, ref. [50]): it has been observed that the efficiency of this approach for applications is sensitive to the modeling choices; in particular the training algorithm may need a large computational time to produce an adequate precision. Another way to produce meta-models has been evaluated, using Gaussian process model: on a specific nonlinear structural case, it was concluded that satisfactory accuracy and CPU times can be achieved. The implementation of Bayesian analysis methods and extreme statistics for the calculation of fragility curves is still under progress in 2018.

The main conclusions of the demonstrative case study based on data from the former benchmark Karisma (2010, organized by IAEA and OECD/NEA, see Altinyollar A. et al., 2013, ref. [13]), about unit 7 of the Kashiwazaki-Kariwa NPP site of the SINAPS@ project are:

- The capability of producing synthetic ground motion signals (Zentner, 2014 and 2015 ref. [51] and [52]) has been shown on the basis of a scenario adapted to the case of the seismic event considered (here NCOE July 2007 event) using a Campbell-Bozorgnia-type GMPE (Bozorgnia et al., 2010, ref. [53]); the parameterization of this signal generation (e.g. with Code_Aster, ref. [40]) makes it possible to take into account many characteristics representative of the real ground motions: nonstationarity, correlation of the H/V components, spatial variability of the characteristics, e.g. (Svay et al., 2017, ref. [54]), while ensuring the compatibility associated with a target spectrum, and the selected seismic intensity measure indicators (IMs);
- To reduce the limitations arising from the definition of uniform hazard spectra (UHS), the possibility of disaggregating the UHS in scenario spectra (CMS - conditional Mean Spectra) was evaluated, based on a different seismic scenario and associated IMs (such as the strong phase duration). A more detailed analysis of the safety margins of the equipment can be derived;
- Progress has been made in the methodology of site-structure interaction modeling, according to the following steps:
    - First, EDF and AREVA have challenged their methods of modeling the soil-structure interaction, which led to AREVA's choice of the Opensource Code_Aster + Miss3D solution.
    - Then CEA and EDF reinforced their "FULL-FEM" simulation methodologies with an equivalent linear elastic 3D model of the stratified soil domain, (Alves-Fernandes et al., 2017, ref. [55]), which is calibrated using a one-dimensional soil column model, based on the geotechnical profile data as well as on the maximum amplitude of the seismic motion prescribed on the substratum;
    - This one-dimensional soil column model based on the equivalent linear assumption, within its limit of validity, is implemented at CEA and also at EDF to perform the de-convolution/re-convolution processing of the seismic motion towards the level of the foundation from the substratum and previously from the free field (Berge-Thierry et al., 2017a, ref. [12]); the corresponding operator DEFI_SOL_EQUI of Code_Aster is used for engineering purpose at EDF and subcontractors.
    - The work carried out by CEA and EDF on the influence of the "control point", e.g. (Berge-Thierry et al., 2017a, ref. [13]) (location of the transfer of the seismic motion resulting from the estimation of the seismic hazard to the soil-structure interaction – SSI – computation tool) lead to significant questions regarding the current practice: it has been confirmed that the level of epistemic uncertainty is reduced by defining the seismic motion in depth rather than at the surface, even if it underlines the difficulty about currently available data. Indeed, the motion defined at the "outcropping rock" is not as affected by the non-linearity of the superficial soil layers;
    - The limit of validity of the equivalent linear elastic model can be overcome by using a nonlinear soil behavior model, which offers the advantage of being able to represent in 3D the evolutions of all the components of the fields during the transient, and to identify the amplification and the de-amplification at the free-field of the seismic ground motion, according to the frequency level. However, such models often require more data for the calibration procedure.
- As explained above, the relevancy of accounting for the degradations of the soil behavior which produces a saturation of the amplitude of transfer capacity of the seismic motion

within the soil column from the substratum is assessed: the uncertainties in resulting signal magnitude at the foundation due to the increase in the levels of seismic IMs via empirical attenuation relationships are thus reduced and their realism is increased;

- The structure-soil-structure interaction (influence of neighboring buildings) has been identified on the case of demonstrative study as having a significant role, depending on site configuration, building characteristics, signal frequency content; as well as taking into account the spatial variability of the incident field, in particular on the "high frequency" content range;
- The various items mentioned above are already the subject of operational applications in the engineering practice at EDF (Post-Fukushima studies);
- The demonstrative case-study made it possible to progress on the implementation of the SEM3D explicit dynamics spectral element software applied to seismic wave propagation in the vicinity of the NPP site, by evaluating an extended source model, by studying the necessary data: soil profile, ground motions recorded at different depths. This prepares future in-depth analyzes of the wave propagation properties of nuclear sites on a scale of about 50 km x 50 km x 15 km (Gatti et al. 2018, ref. [26]);
- However, the demonstrative case study did not make possible to implement and evaluate the progress made in the modelling of the nonlinear mechanical behavior of civil engineering structures: indeed, the very robust building studied here remains in linear elastic range even under this severe seismic event;
- An integrated approach, based on the decomposition of UHS in CMS and the transfer from the bedrock to the soil surface and finally the equipment has been proposed, see Zentner, 2017 (ref. [56]).

All these developments have been the matter of numerous publications and the associated methods and tools have been documented and disseminated via Opensource platforms (*Salomé_Méca* and *Code_Aster* (ref. [40]) for mechanical analyses , *SEM3D* (ref. [25]) for site effects analyses, increasing the ergonomics and numerical performances needed for use in engineering.

5.4 SINAPS@ seismic risk assessment research presented during the BESTPSHANI 2018 workshop

Gatti et al. 2018 (ref. [26]) present a broad-band 3-D physics-based simulation of earthquake-induced wave-field at the Kashiwazaki-Kariwa nuclear power plant (KKNPP) in Japan. The influence of the regional 3-D geology (≈ 60 km wide) on the synthetic earthquake ground motion prediction is herein assessed, studying the seismic response of KKNPP, during the 2007 Niigata seismic sequence (west Japan), so to explore the potentiality and practicability of the innovative computational tools available. The synthetic wave-field (0-7 Hz) is obtained by employing SEM3D (ref. [25]), a high-scalable software based on the Spectral Element Method. The synthetic wave-motion simulated using SEM3D was exploited as input motion for a Soil-Structure Interaction numerical model (Finite Element Method - Boundary Element Method, Code_Aster-MISS3D) of the standard reactor building at KKNPP. This work stresses the importance of the 3-D geology and explicates the observed high ground motion spatial variability, as well as the strong dependence of the site response on the incident wave obliquity.

Wang and Feau, 2018 (ref. [24]) illustrate still on the KKNPP test-site the importance of properly defining the seismic input when performing full soil-structure interaction analysis especially in case of large seismic events. This paper focused on the uncertainty propagation through the soil-structure system. For this purpose, a simplified model representing the largely embedded reactor building has been used for computation efficiency as a large number of numerical simulations were necessary. Seismic signals have been generated with respect to the

NGA GMPE response spectrum prediction according to the July 2007 NCO earthquake scenario; these inputs have been used to estimate the fragility curves. In the process, soil non-linearity caused by each seismic signal has been taken into account using the equivalent linear method. The results suggest that defining the control point of the input motion at the soil surface as prescribed in the French nuclear practice is not appropriate and may lead to biased results when performing non-linear soil-structure fragility analysis. The control point should be defined at the "outcropping bedrock" level.

6. Lessons learned from the « Experimental studies of Damping and Building-Building Interaction » research

6.1 Scientific challenges

Following the Fukushima Daiichi nuclear disaster, an analysis of the cliff effects in extreme events was carried out for nuclear installations in France, particularly with regard to seismic risk. In addition to the experience feedback analysis, the experimental approach is also able to characterize and model some phenomena appearing in these extreme situations.

Thus, SINAPS@ project provides experimental data coming from shaking table test in order to:

- Refine the evaluation of seismic margins in nuclear reinforced concrete buildings by quantifying the various damping mechanisms (IDEFIX test campaign). Indeed, the models of damping used today suffer from a lack of physics. Interacting with the work performed in SINAPS@ on vulnerability (see §4), the IDEFIX test campaign was therefore carried out.
- Evaluate the number, magnitude and effects of impacts between buildings during an earthquake. This problem of the Interaction Between Buildings (IBB test campaign) under high seismic loads was clearly identified at the CSS in 2011 (see ref. [2]). Indeed, with the increase of probable seismic levels in France, this interaction between nuclear buildings is sometimes possible due to the small distance between structures. However, regulation suggests interaction avoidance. In addition to local damage, the impact between structures can amplify floor spectra in frequency ranges that penalize equipment fixed to these floors. There is very little experimental data available on this subject, which is too complex to be dealt with only numerical studies. This test campaign has therefore created experimental data in order to construct a numerical model to estimate the effect of interactions between buildings.

In conjunction with the other research within SINAPS@, industrial and academic experts from these fields have been integrated into the organization of these two original testing campaigns, which makes it possible to obtain numerical analyses based on experimental results.

In the first phase of these two experimental campaigns, bibliographic studies and numerical analyses are used to design the models, measurements and test conditions. A second phase is dedicated to manufacturing and development of models and their setup. A third phase allows for the analysis of test data to identify some parameters and refine numerical models. Finally, the results obtained are disseminated through presentations and papers, as well as through a web-based database.

6.2 Interaction between buildings

Despite rather extensive research in this field, the potential damaging effect of pounding is a subject of controversy. Previous work mainly focus on theoretical, numerical and small scale experimental studies. Consequently, the effect of pounding on inter-story drift, forces and floor response spectra of actual buildings is difficult to estimate. Thus, it is important to experimentally investigate the effect of pounding on large scale structures.

The objectives of this research are: a) to gain further insight into the response of pounding buildings, b) experimentally investigate the effect of pounding on large scale structures, c) evaluate the capability of numerical simulation tools to accurately predict the dynamic response of interacting buildings, d) study the effectiveness of alternative solutions to prevent pounding.

6.3 Behavior and numerical modeling of damping in civil engineering structures

The ability of a structure to withstand a seismic event is driven by its capability to store and/or dissipate and/or distribute the input energy without compromising its integrity. Even though available material constitutive laws are now able to provide realistic and accurate results about the nonlinear behavior of RC, the computational cost and the constitutive model parameter identification stage are a strong counterpart that designers and engineers are rarely prone to pay for when dealing with full-scale structures. Overshadowing the uncertainties coming from external sources which are considered in the other work packages, and apart from the dimensional constraints leading to this need of computational resources, important uncertainties arise from the material properties and could sometimes require extensive numerical sensitivity studies. That is why simplified modeling strategies are still popular among the engineering and research communities.

In practice, an additional viscous damping is often used to represent the dissipations not taken into account by the structural model (Ragueneau, 1999, ref. [57]; Crambuer et al., 2013, ref. [58]). The amount of viscous damping depends on the phenomena included. In fact, the structural model can represent only a part of the energy dissipation, given that the additional viscous damping accounts for the remaining dissipated energy.

Another notion is the equivalent viscous damping ratio (EVDR) which is calibrated in order to dissipate the right amount of energy by a viscous force field, acting in opposition and proportionally to the velocity field. Again, the question of the assessment of the EVDR arises. Different tests can be found in the literature, and they do not necessarily involve the same phenomena. The choice of the experimental method to evaluate the EVDR is of primary importance, keeping in mind that the ideal test does not exist.

To address the aforementioned questions, a testing procedure that will provide the key information regarding the dependency of the dissipated energy on structural and signal characteristics (i.e. material properties, structural design, signal content, response amplitude, etc.) is designed. The resulting IDEFIX experimental campaign (French acronym for Identification of damping/dissipations in RC structural elements) will be explained.

6.4 Research on damping characterization & IBB presented during the BESTPSHANI workshop

The IDEFIX and the IBB experimental campaigns, numerical modelling and associated research are presented during the workshop through following contributions.

Crozet et al., 2018 (ref. [59]) present the research performed in SINAPS@ on IBB topic. An important shaking table experimental campaign (using the CEA TAMARIS platform) has investigated the effect of pounding on two adjacent, two stories, 5 meters high, steel frames, with concrete slabs at each floor. Four different accelerograms were applied to different configurations with various initial gap values, a configuration with a rigid link between the structures as well as tests with only one storey structures. Tests exhibiting impacts have been directly compared with those without impact. Finally, the two structures were subject to higher excitation levels so that yielding occurred at the first storey columns of both structures. As an overall observation, the experimental results highlight the important effect of pounding on acceleration time history and corresponding floor response spectra. During the tests with impacts an important excitation of the higher modes of the structures was observed. Moreover, for some excitation signals, a significant alteration of the interstorey drift of both structures was measured with respect to the tests without pounding. Regarding pounding mitigation, a significant improvement of the floor response spectra was obtained using a rigid link between the two structures compared with the tests with pounding. The tests have been interpreted by numerical simulation also. The agreement of the analytical and experimental results is quite satisfactory.

Heitz et al., 2018 (ref. [60]) present the work performed in SINAPS@ focusing on the damping characterization. Nonlinear time-history analyses are probably the most advanced techniques to assess engineering demand parameters (displacement ductility, inter-storey drift, energy dissipation, etc.). However, because of the numerical cost and the difficulties associated to the modelling of dissipations induced by nonlinearities taking place in civil engineering structures under dynamical loads, an additional viscous damping is often used to account for the dissipations not taken into account by the constitutive laws. That is why an equivalent viscous damping coefficient is calibrated in order to dissipate the required amount of energy through a viscous forces field. The way to perform this calibration often relies on fuzzy considerations and lacks of predictability. This work aims to study and compare different assessment methods of the equivalent viscous damping, and the influence of material and structural parameters. An ambitious experimental campaign consisting in quasi-static and dynamic shaking table tests carried out on reinforced concrete beams is set up and provides numerous results. Specifically developed analysis techniques allowed for the outcome of significant results. In particular, the development of a simplified single degree-of-freedom nonlinear model of the beam modal behaviour allowed for the identification of a relationship between displacement demand and the maximum time-history displacement has been identified. This observation suggests the possibility to update the damping ratio during nonlinear time-history analyses in a more physical-wise and predictive way than the traditional Rayleigh-type damping models.

7. Conclusion

In order to conclude this overview of SINAPS@ research actions, some possible evolutions of engineering practices and regulatory approaches are emphasized:

- Identify key contributors to the **uncertainties in the seismic motion** transmitted to buildings and equipment, by refining methods of uncertainties propagation and each numerical model in the analysis chain, and by improving their efficiency. Progress is thus made on the probabilistic establishment of the seismic hazard and the selection of seismic ground motions. This allows better allocation of engineering resources in new site studies and in re-assessments of existing nuclear power plants, thus focusing on improving the knowledge of these main contributors.
- Identify the importance of **seismic ground motion data control** at the bedrock or outcropping rock instead of the free-field motion. This analysis of the **site effect** makes it possible to reduce the difficulty and the uncertainty associated with the de-convolution of the signal in a soil column defined by the geological profile of the site, taking into account the degradation of the properties of the soil according to the intensity of the seismic loading, the signal directivity. This approach may be associated with a "*host to target*" adjustment of ground motion prediction equations. The epistemic uncertainties are also reduced by using a

suitable geophysical, geotechnical site data analysis and an appropriate V&V procedure for tools and methods.

- By means of this new methodology for controlling the seismic loading data, an easier **confrontation with seismological observations** can be considered, making it possible to reduce the uncertainties by treating the site effect separated from the analysis of the seismic hazard.
- The development of the tools required for **probabilistic risk analysis** (convolution of vulnerability with hazard) and the associated study methodologies have reached a stage of maturity making them relevant for their industrial use. These tools should be useful and in line with the recent requirements of French Nuclear authority (Guide ASN 22, 2017).
- A more refined estimate of contributors to failure and risk; recommendations in terms of IMs of seismic ground motions could be formulated (e.g. for filtering). All the needed computing elementary bricks and methodologies are available, for instance in Code_Aster, and validated; an integrated tool, *Fragility*, will be developed to facilitate its dissemination. Finally, some promising ways to produce meta-models have to be pursued, to enhance the performance of fragility curves calculations.

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