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OVERVIEW OF THE RESEARCH ACTIVITIES IN EARTHQUAKE ENGINEERING AND SEISMIC RISK ASSESSMENT WITHIN THE JOINT FRAMEWORK CEA-EDF-FRAMATOME-IRSN

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Abstract

The French nuclear industry is highly active in the field of earthquake engineering and more precisely on seismic risk assessment. Among the existing frameworks, there is one which involves nuclear French operators such as Electricité de France (EDF), the French Sustainable Energies and Atomic Energy Commission (CEA) and FRAMATOME, and the French technical support organization the Institute for Radiological Protection and Nuclear Safety (IRSN). Within this quadrilateral framework, research activities are conducted, aiming to enhance the knowledge needed to improve nuclear safety of both existing and new facilities. These activities deal with the topics and challenging issues which appear to be significant in the seismic risk assessment process and can be sorted in four categories. The first category gathers all the activities related to the soil-structure interaction (SSI) or to the soil behavior itself, the goal is to improve the understanding of this complex phenomenon, especially when nonlinearities appear in the soil close the foundations of a building. The second category includes the activities related to civil engineering aimed to a better assessment of the structural behavior of complex buildings when subjected to a beyond-design seismic loading; one of the goal is to quantify the margins (when existing) provided by design basis approaches. The third one is related to the equipment behavior, such as crane bridges. The main objective is to describe their behavior when subjected to seismic loading transferred through the structure and to describe them by a fragility curve. Finally, the last group of activities gathers transverse tasks, such as verification/validation methodologies for nonlinear approaches or robust updating methodologies to take into account the seismic experience feedback and the experimental evidence when dealing with conventional assessment approaches. The main objective of this paper is to give an overview of the past, ongoing and future joint activities carried out by CEA-EDF-FRAMATOME-IRSN by highlighting the main findings, the future challenges and the opportunities in the field of seismic safety of nuclear facilities.

Keywords: Research activities, earthquake engineering, seismic risk assessment, French nuclear industry

1. Introduction

The French nuclear industry is highly active in the field of earthquake engineering and more precisely, regarding seismic risk assessment [1]. The major nuclear energy operators such as EDF, CEA and FRAMATOME have gathered their research efforts and scientific skills with the French technical support organization (TSO) the IRSN in order to make the knowledge move forward on several topics related to seismic risk assessment and earthquake engineering. The framework which has been setup to drive and guide the research activities on the aforementioned topics is linked with a project titled *Mechanics, Structure, Earthquake project (MSE project)* which was setup in 2015. The main objectives of the MSE project are (i) to tackle technical and scientific issues related to methodological practices which may appear in technical safety demonstrations, (ii) to provide to the engineering community recommendations and guidelines approved jointly by the four partners. The MSE project deals with several subjects in the field of seismic risk assessment and earthquake engineering, namely hazard assessment, soil dynamic behavior and soil-structure interaction (SSI), response of structures, systems, and components (SSCs) under seismic loading. In addition, transverse topics are addressed such as the verification and the validation of advanced modeling technics (mostly nonlinear) of SSCs or the updating the conventional assessment approaches to take into account the experience feedback from either in situ measurements or experimental evidence. The activities include experimental tasks thanks to access the well-known TAMARIS experimental facility which is operated by CEA in Saclay, France [2]. The objective of this paper is to give an overview of the activities carried out within the framework of the MSE project. To reach this objective, the MSE project is first presented. Then, the recent and planned activities are introduced.

2. The Mechanics, Structure, Earthquake (MSE) project

2.1 Topical overview

The seismic probabilistic risk assessment (PRA) is based upon the knowledge of two contributions: the seismic hazard which is described by a hazard curve and dynamic response of SSCs which is represented by a fragility curve. More precisely, the seismic risk is defined as follows:

$$R = -\int_0^{\infty} \frac{dH(a)}{da} . f(a) da$$

where R is the seismic risk, a an intensity measure of the seismic input, $H(a)$ the hazard curve (i.e. the annual frequency of shaking exceeding intensity a and $f(a)$ the fragility curve (i.e. the probability that failure occurs given an intensity measure a).

The hazard curve, is computed using the classic Cornell – McGuire approach [3], [4], [5]; based on the following four steps: identification and parameterization of the seismic sources; model of earthquake magnitude recurrence for each source; application of ground motion prediction equations and their uncertainty; integration of uncertainties in earthquake location, earthquake magnitude and ground motion prediction. The input used in hazard assessment (fault structure, seismicity catalogues, maximum magnitude assessment, soil properties at the site of interest, etc.) need continuous efforts to be improved and updated, especially in low-moderate seismicity seismotectonic context like Metropolitan France.

Regarding the fragility curve, four ingredients are needed in order to estimate this quantity in a satisfactory manner: 1) a random model which takes into account both aleatory and epistemic uncertainties; 2) a methodology to propagate uncertainties that permits to optimize the computational demand and does not introduce any statistical bias in the fragility curve; 3) mechanical models to assess the SSCs response, especially in their “beyond design” range; and 4) a failure criteria and related thresholds necessary to define acceptability criterion and safety domain. In addition to the aforementioned needs and topics, the partners

have also decided to gather their efforts to deal with two transverse actions. The first one aims to establish a verification and validation procedure to ensure the safe character of the advanced methodologies to describe the beyond-design behavior of SSCs. The second one aims to setup a framework permitting to take into account the experience feedback from both the experimental evidence and the post-earthquake survey. The recent and ongoing actions are summarized in Figure 1.

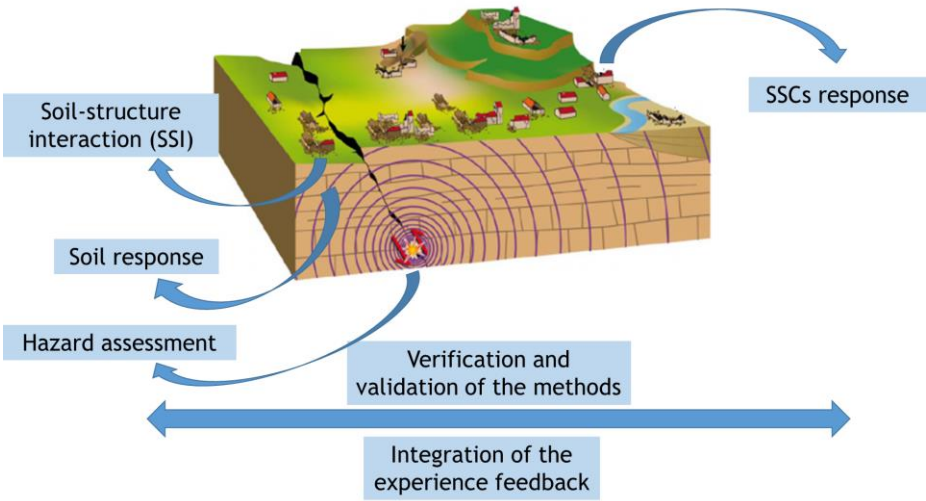

Fig. 1 - Summary of the research activities setup within the MSE project.

2.2 Programmatic overview

Two project reviews are organized each year to follow-up the research activities conducted within the framework of the MSE project, to identify difficulties and, if necessary, to re-schedule some of them. The first one usually takes place in April and is centered on exchanges on each activity. The second one occurs in November and is aimed to draw the main conclusions of each activity, and to confirm the work-plan and the tasks to be accomplished in the following year. Besides these two formal meetings, three to four technical meetings are organized per year; they gather the partner together and promote exchanges on the ongoing work, the obtained results, and on the new directions to be taken, if necessary. Despite the fact that the activities are planned each year, partners define work programs for four to five years before starting any new activity.

Table 1 – Overview of the ongoing activities

Activity label	Title	Starting date	Ending date	Objectives
ISSNL	Nonlinear soil-structure interaction	2018	2023	➢ Quantify the effects of the nonlinearities in the soil on the SSI; ➢ Identify the most preponderant factors acting on SSI; ➢ Acquire in-situ data to validate SSI models; ➢ Identify best-modeling practices to take into account

				nonlinear SSI
NLTA	Damping modelling in time history nonlinear analysis of nuclear buildings: effects on the behaviour of structure and equipment.	2018	2023	➢ Quantify the effects of the material nonlinearities on the motion transfer in a RC structure; ➢ Improve the way to take into account energy dissipation, especially to better describe damping; ➢ Identify best-modeling practices to model damping and energy dissipation
REX	Integration of the experience feedback	2019	2024	➢ Improve existing framework to take into account the experience feedback; ➢ Re-assess conventional engineering assessment techniques.
V&V	Verification and validation of nonlinear techniques	2019	2024	➢ Produce a process allowing to verify and validation nonlinear techniques.
CP2R	Seismic behavior of cranes bridges	2018	2023	➢ Better understand the seismic behavior of crane bridges; ➢ Establish simplified modeling strategies to assess cranes bridges; ➢ Derive specific failure criteria and generic fragilities to describe the seismic behavior of crane bridges.
ALEA	Hazard assessment and in situ data acquisition	2020	To be defined	➢ Source ; ➢ Propagation ; ➢ Site réponse ; ➢ PSHA.

3. Recent and ongoing activities

3.1 ISSNL: Nonlinear soil-structure interaction

Continuous efforts are ongoing to improve the modeling techniques of nonlinear dynamic SSI. However, strong hypothesis such as, the frictionless contact between the soil and the foundation, the vertical propagation of plane waves in horizontally stratified soil or, the elastic boundary conditions, are still considered. The ISSNL activity aims to improve the nonlinear SSI tools of “best-estimate” type thanks to a multi-annual research and development program. The state-of-the-art has shown the existence of numerous numerical and analytical studies and a lack in the experimental analyses, especially in-situ studies ([6], [7]). On this basis, the proposed five-year program focuses on three main actions:

1. *Numerical investigation on nonlinear SSI analyses*

The objective of this action is to assess the influence of the parameters involved in the SSI phenomenon, considered as isolated or dependent on each other, on the seismic response of soils and structures to improve the numerical methods. The case of the NUPEC structure ([8], [9], [10]) is adopted. It consists of a rigid building based on a foundation with a "simple" geometry. In addition, the NUPEC case is well documented and a verification with records may be possible. Then, the objective will be to validate the boundary conditions and to make a sensitivity analysis to assess the influence of several parameters such as: lateral soil-foundation contacts, foundation embedment, thickness and flexibility, rocking, soil stratigraphy, etc. Two soil models will be considered: linear equivalent model and full nonlinear constitutive law.

2. *Experimental in-situ analysis on SSI*

The objective of this action is to have experimental data, acquired at a given site, in order to compare with SSI methods. A benchmark on SSI is scheduled in order to evaluate the confidence of the employed numerical methods. This action will be carried out during the thesis proposed by IRSN, which will start in 2020.

3. *Scale reduction methods for SSI experiments on shaking table*

The objective of this action is to understand the downscaling method that will be applied in an experimental study that may take place around 2023. A synthesis document will gather obtained results and provide suggestions for numerical and experimental nonlinear SSI methods of "best estimate" type.

3.2 NLTA: Damping modelling in time history nonlinear analysis of nuclear buildings: effects on the behaviour of structure and equipment.

Energy dissipation in structures subjected to seismic loading is typically modeled using Rayleigh, Caughey or modal (Wilson-Penzien) damping. It is well known that these techniques are not based on the appropriate energy dissipation mechanisms in structures. The use of these approaches and, in particular the classical Rayleigh damping in nonlinear analyses, is problematic. Indeed, as many studies have shown [11], [12], [13], [14], making use of this type of damping for a relatively high level of seismic loading often leads to inaccurate estimates of displacements and internal forces. These inaccurate estimations are related to the fact that unrealistic viscous forces are generated by the proportional Rayleigh damping, in particular by the stiffness proportional term, when cracks open. The proportion of energy dissipated by the viscous damping model should therefore be better controlled. Despite the fact that the use of Rayleigh damping is inconsistent from a theoretical point of view, it is considered that this way of modelling damping will continue to be used in the near term, in parallel with the development of new model formulations of constitutive laws. The research activities aim at:

- providing guidance on the best way to use Rayleigh and modal damping. This part of the research should make it possible to identify the limits of commonly used models and to develop a set of recommendations for the best use of current methods, depending on the type of structure, seismic level, etc.

- developing new approaches for damping modeling in nonlinear analysis. This is obviously a more difficult task than the previous one, since it involves establishing improved models that reflect the true nature of structural response and energy dissipation.

3.3 CP2R: Seismic behavior of cranes bridges

Within the context of Level 1 Probabilistic Safety Assessment (PSA) studies (which deals with risk of core damage) performed on nuclear power plants, crane bridges failure have been identified as a significant contributor in the probability of core meltdown. Depending on the reactor type and on the age of the reactor design, one of the significant failure mode can be related to anchorage failure during earthquake. Therefore, the issue of dynamic behavior of crane bridges needs to be considered within the global framework of the safety demonstration of a plant.

In this context, it is necessary to improve knowledge about the dynamic behaviour of this equipment in order to fully understand how failure would occur in the case of beyond design loadings induced by most severe earthquakes (that are considered in risk assessment). Therefore, it is important to estimate accurately the forces transmitted to the anchorages. In addition, the incorporation of different sources of uncertainties through a fragility curve still raises several questions such as: what are the main variables to be considered as random? What are the failure criteria to be used? Does the hypothesis of a lognormal distribution remain justified for seismic inputs for which the intensity is in the beyond-design range?

In order to provide answers to these aforementioned questions, a benchmark endorsed by the Working Group on Integrity and Ageing of Components and Structures (WIAGE) of OECD/NEA/CSNI will start in 2020. The main objectives of this action are (i) to identify best practices to model seismic behavior of crane bridges; (ii) to identify relevant failure criteria; and (iii) to establish international consensus on the definition of seismic fragility of cranes.

An experimental campaign on a scaled model of an overhead crane bridge was carried out in 2015 on the AZALEE shaking table of CEA in Saclay, France and the results have been gathered in a large database. The crane bridge mock is shown in Figure 2. On one hand, some of these data will be used by participants to characterize and calibrate their models and, on the other hand, some other data will be used to assess the predictive capacity of the mechanical models.

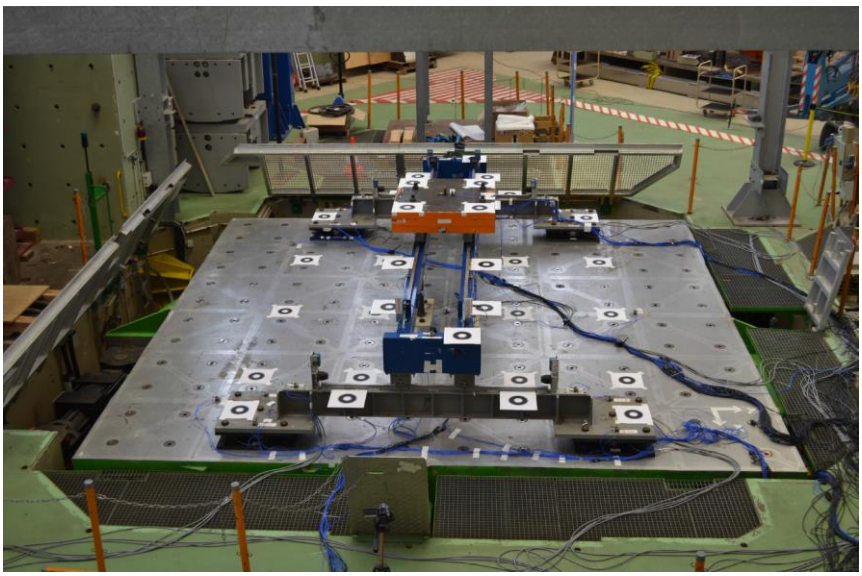

Fig. 2 – Overhead crane bridge mock up put on the AZALEE shaking table.

The benchmark will be concluded by a restitution workshop in which the different participants will be gathered to exchange and discuss about their models and results they have obtained. In this way, best practices for modelling overhead cranes under seismic loading will be identified. The workshop will provide a synthesis of lessons learnt and recommendations based on findings of the benchmark analysis. A proceeding report including documents submitted by the participants is envisaged and the findings of the

benchmark analysis will be summarized during the restitution workshop that will be held in 2021 and a NEA report in 2022. Figure 3 gives an overview of the benchmark schedule. For more details, see [15].

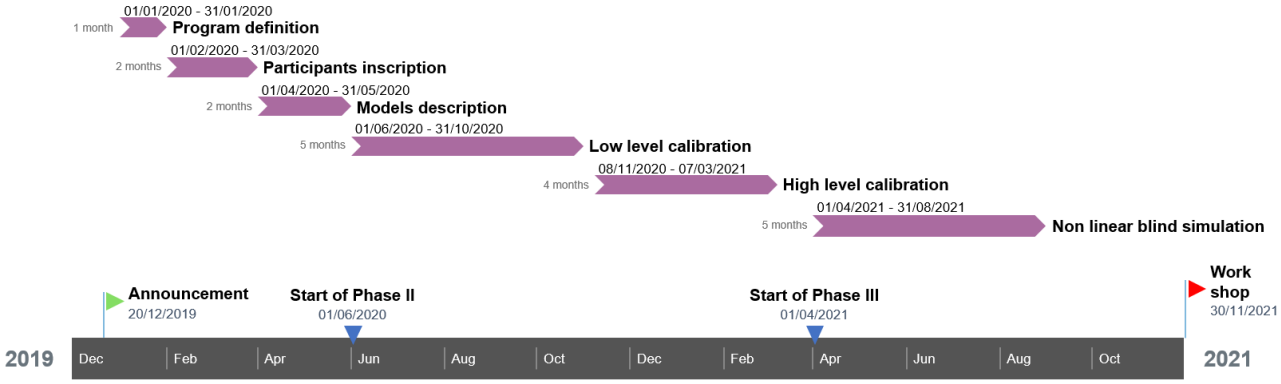

Fig. 3 – Benchmark provisional schedule.

4. Planned activities

4.1 V&V: Verification and validation of nonlinear techniques

Due to the increasing complexity of numerical models in computational structural mechanics, it is more and more difficult to ensure the validity of simulation results. For instance, a model developed by academic research might be discarded because it does not offer sufficient experience feedback for large-scale industrial applications. In the same time, the safety requirements for nuclear structures and equipment become stricter making it essential to have tools to verify and validate theoretical models and their numerical implementation. In order to allow for the use of cutting edge mechanical models in nuclear energy structure assessment, the MSE project wishes to develop a methodological framework for the verification and validation of nonlinear models. Such frameworks have already been proposed in a more general way following different strategies ([16], [17], [18], [19], [20]) or more specifically in other domains, such as soil mechanics [21]. However, while general recommendations are found in the IAEA specific safety guide [22], no guidelines are provided to meet these requirements. The goal of V&V activity is to transpose the frameworks developed in the literature to the specific challenges of the nuclear industry.

Validation and verification are both strongly related to uncertainty quantification. One could define the validation process as the demonstration of the acceptability of uncertainties related to the theoretical model (model form uncertainty), while the verification is the demonstration of the acceptability related to the numerical implementation of this model (discretization, convergence and round-off uncertainties). Both processes require reference data which can be either theoretical, experimental or numerical (provided that it comes from a validated and verified model). Hence, the building of an exhaustive V&V data library is of primary importance for this activity. The collaboration between nuclear operators and IRSN is an opportunity to mutualize the knowledge and expertise of the different partners. The V&V action will be valorized by the drafting of a technical report in 2023.

4.2 REX: Integration of the experience feedback

Conventional approaches can lead to results sometimes very different from post-seismic observations and/or require disproportionate engineering efforts to assess SSCs outputs in a consistent way. In that context, the exploitation of post-seismic or experimental feedback data is a key point in the process of improving their

robustness and their accuracy. Then, the objectives are to have a better understanding of the differences between the results of the current engineering methods and the observations, to quantify and compare those gaps regarding the uncertainties. For example, the development of seismic reliability indicators, such as fragility curves, requires the coupled use of many complex models whose robustness and accuracy mainly depend on available feedback data. When new data are acquired, these models may be challenged and require updating in order to integrate those new information and then reduce uncertainties. In this context, it may be pertinent to identify one or more methodologies which:

- allows updating without a global re-development of the structural models,
- quantify the margin available or the lack of margin.

5. Conclusions and outlook

In this paper, an overview of the research and development activities carried out by CEA, IRSN, EDF and FRAMATOME within the framework of the MSE project has been presented. Their main objective is to reduce the uncertainties when assessing the seismic risk. To reach this objective, the topics of ongoing and planned activities have been briefly presented. Among the ongoing tasks, we mentioned specific effort dedicated to knowledge improvement related to the seismic behavior of soil and SSCs. Especially, one of the activity aims to better understand and assess the seismic behavior of crane bridges. This action is carried out under the umbrella of OECD/NEA in order to share with the international community on this topic. This research and development initiative has been supported by seven member states and will lead to organize an international benchmark over the period 2020 to 2021. Two transversal activities have been initiated in 2019. The aim of the first one is to define and to apply a probabilistic framework to update the input parameters of nonlinear models in order to take into account the experience feedback. In addition, the second transversal activity lies in setting up a framework based upon the available regulatory corpus to verify and validate the best-estimate techniques commonly used to assess the margin when exist. In 2020 four new joint actions will be initiated within the framework of the MSE project, each of them related to different steps of seismic hazard assessment: source, propagation, site response, PSHA.

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7. Copyrights

8. References

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