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Division V

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 community is highly active in the field of earthquake engineering and more precisely, regarding seismic risk assessment. Among the existing safety-oriented frameworks, there is one which involves not only nuclear operators such as Electricité de France (EDF), the French Sustainable Energies and Atomic Energy Commission (CEA) and FRAMATOME, but also the French technical support organization which is the Institute for Radiological Protection and Nuclear Safety (IRSN). Within this framework, research activities are conducted, aiming to enhance knowledge in order to improve nuclear safety of either existing or new facilities. These activities deal with topics and challenging issues that appear to be significant in the seismic risk assessment process. More precisely, they aim to better assess the seismic margins when available, to better understand the beyond-design behavior of nuclear buildings or related equipment and to improve the necessary knowledge to produce robust seismic hazard assessment studies. 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 and will especially highlight main findings and future challenges and opportunities in the field of seismic safety of nuclear facilities. To reach the objective, technical focus will be made during the presentation.

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), namely 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 of the conventional assessment approaches to take into account the experience feedback from either in situ measurements or experimental evidence.

Regarding the tasks related to seismic hazard assessment, we can mention, among others, (i) the maintenance of a French seismic database used to assess the local seismicity, (ii) research works on "kappa" attenuation parameter and the definition of reference rock for site amplification studies or (iii) exchanges to homogenize the tools for probabilistic seismic hazard assessment. The aim is to share basic knowledge between organizations. Regarding the tasks related to structural assessment, several issues are investigated. Ongoing activities related to the soil-structure interaction (SSI) or to the soil behavior itself can be mentioned. They aim to improve the understanding of this complex phenomenon, especially when soil nonlinearities appear in the vicinity of building foundations. In addition, civil engineering or equipment behavior is also investigated through dedicated tasks. They aim to better assess the structural behavior of complex buildings or equipment when subjected to a beyond-design seismic loading in order to quantify the margins provided by design basis approaches. Some of these tasks are performed within an international context (OECD/NEA), especially when best practices are to be identified by means of benchmarks. Finally, transverse tasks, such as verification/validation methodologies for best estimate approaches or robust updating methodologies to consider the seismic experience feedback and the experimental evidence when dealing with conventional assessment approaches are also ongoing.

The activities include experimental tasks thanks to access to 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.

THE MECHANICS, STRUCTURE, EARTHQUAKE (MSE) PROJECT

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 acceptability thresholds controlled by dynamic responses of SSCs which is represented by a fragility curve. More precisely, the seismic failure probability is defined as follows:

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

where R is the seismic failure probability (the seismic risk being the convolution of failure probabilities and their consequences), 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). These ingredients are expressed according to appropriate confidence level values. 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, within the combination through a logic tree of the hazard equations. 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 from the needed seismic motion description (time histories, etc.), 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 reliable 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.

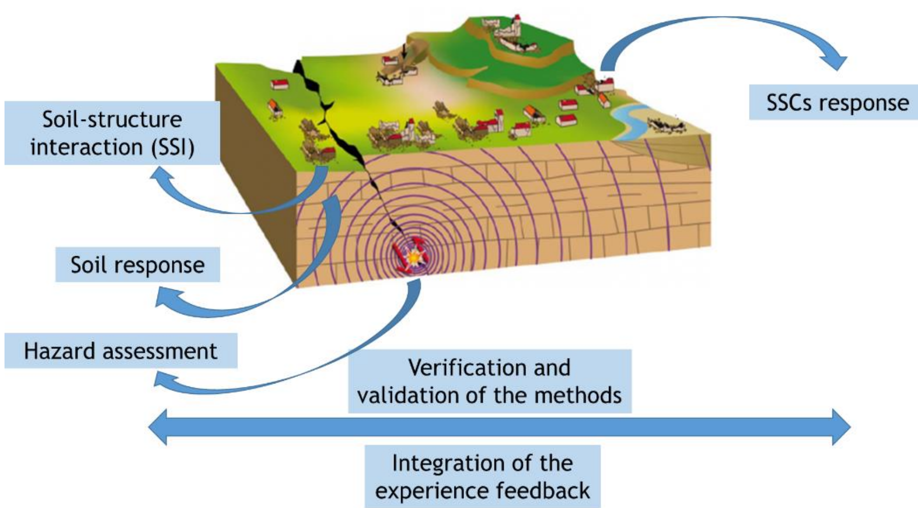

Fig. 1 - Summary of the research activities setup within the MSE project.

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 years. 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; ➢ Develop new methodologies to acquire in-situ data as SSI input for FE analysis ➢ Acquire in-situ data to validate SSI models; ➢ Identify best-modeling practices to take into account nonlinear SSI ➢ Analysis of rocking considering uplifting in nonlinear SSI
NLTA	Damping modeling 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 simulation methods.
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 characterization; ➢ Seismic wave propagation characterization and description; ➢ Site response assessment; ➢ Probabilistic Hazard Seismic Assessment (PSHA).

INSIGHTS ON CURRENT ACTIVITES

ISSNL: Nonlinear soil-structure interaction

Under seismic loading, shallow foundations apply significant stress on the footing-soil contact surface inducing strong nonlinearity in the soil. Hence, it leads to the occurrence of nonlinear phenomena as rocking, uplift, slide, and settlement of the foundation while reducing the bearing capacity of the soil. Continuous efforts are ongoing to improve modeling techniques approximating rocking and uplifting in inelastic soil behavior ([6], [7]). However, tedious calibration of numerical models is required in order to capture these complex phenomena. The ISSNL activity aims to improve the nonlinear SSI tools (Figure 2) of "best-estimate" type thanks to a multi-annual research and development program.

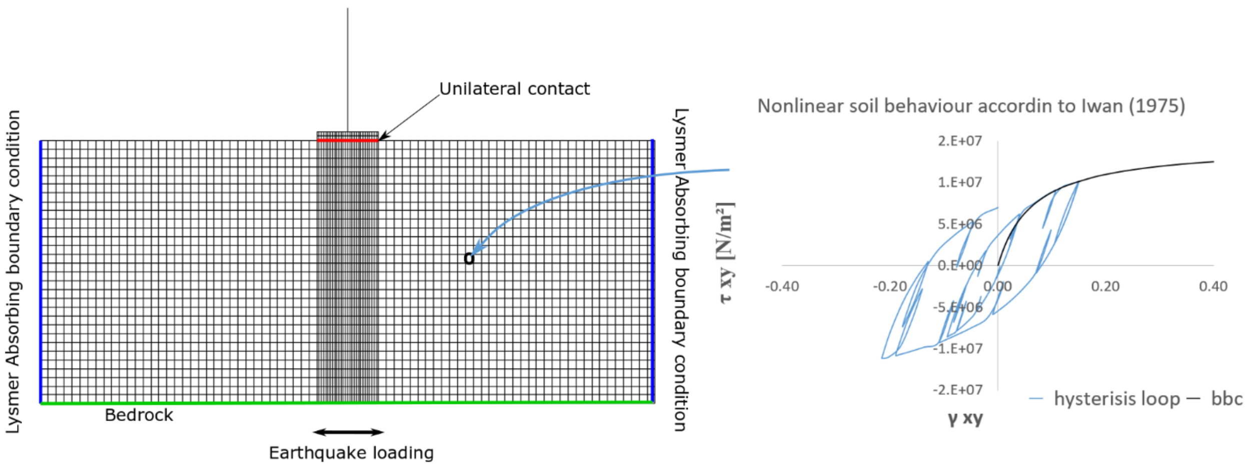

Fig. 2 - Problem definition of nonlinear SSI taking into account rocking and uplifting of the footing.

The state-of-the-art has shown the existence of numerous numerical and analytical studies and a lack in the experimental analyses. In order to propose improvement to foundation-soil interface numerical modeling, controlled experimental tests in-situ and in laboratory are essential. However, difficulties arise on the limitations in the dimensions of the specimen and therefore its representativeness. Compliance with Laws of similarity requirements is indeed not easy to ensure. Therefore, in the frame of this work, the project aims to develop a methodology to measure "more directly" parameters as Impedance Function (IF) for rigid slab type foundation that would be an input in Finite Element analysis (Figure 3).

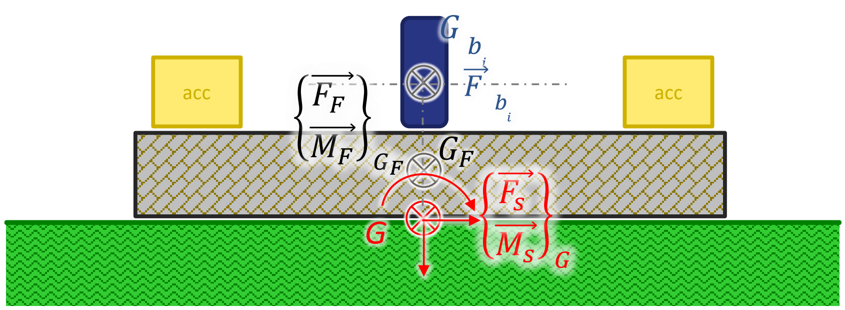

Fig. 3 - Principle of the mechanical system of the experimental system for measuring IF.

The principle of this experimental study lays on the application of uniaxial mono-frequential sinusoidal forces. Hence, setting the equilibrium of forces and momentum applied to the foundation for one particular direction of solicitation and one frequency permits to assess the value of the impedance.

NLTA: Damping modeling 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 questionable. 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 calibration of the proportional Rayleigh damping associated with the implementation of dissipative processes constitutive modelling within FE analyses is not the result of scientific consensus, 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, heavily relying on the feedback from experimental campaigns on regular scale reinforced concrete structures, 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, constitutive modeling, etc.;
- calculating energy balance in order to better understand how the energy is transmitted to the system during the transient response: how much dissipation is provided by the viscous damping, compared to the one associated with the hysteretic cyclic constitutive law used in the analysis;
- developing new approaches for damping modeling in nonlinear analysis. This is obviously a more difficult task than the previous one, since it involves developing consistent nonlinear cyclic constitutive laws accounting for damping, which aims to improve the predictive capabilities of nonlinear concrete models.

On the other hand, another action is added to this activity and consists in identifying the contribution of energy dissipated at the steel-concrete interface of a structure subjected to dynamic loading among the other sources of energy dissipation: viscous dissipation, numerical dissipation due to the time integration scheme, and mainly material dissipation. More precisely, the main objective is to propose a new simple modeling strategy to take into account the behaviour of the steel-concrete bond. To this end, we define the relationship between steel and concrete displacements at the interface in terms of kinematic relationships that depend on the loading level increment. This work fits into the framework of Maryam Trad's PhD thesis, which started in 2020.

CP2R: Seismic behavior of cranes bridges

Within the context of Level 1 Probabilistic Safety Assessment (PSA) studies (which deals with occurrence 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 named SOCRAT endorsed by the Working Group on Integrity and Ageing of Components and Structures (WIAGE) of OECD/NEA/CSNI started in 2020. The main objectives of this action are (i) to identify best practices to model seismic behaviour of crane bridges; (ii) to identify relevant failure criteria.

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 mockup 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 is concluded by a restitution workshop in which the different participants have met to exchange and discuss about their models and results they have obtained. As a result, best practices for modeling overhead cranes under seismic loading were identified and will be published in a forthcoming paper with a synthesis of lessons learnt and recommendations based on findings of the benchmark analysis. Figure 3 gives an overview of the benchmark schedule. For more details, see [15]. For those interested in SOCRAT benchmark, there is a special session during the SMiRT26 conference on this topic entitled "*Overview of the work done in the OECD SOCRAT benchmark dedicated to the beyond design seismic behavior assessment of crane bridges*".

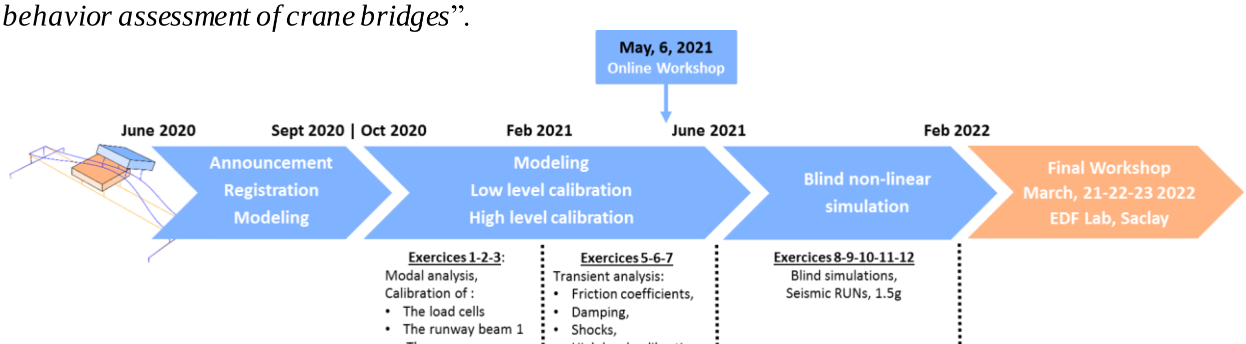

Fig. 3 - SOCRAT Benchmark agenda.

V&V: Verification and validation of nonlinear techniques

Due to the increasing complexity of numerical models and methodologies in computational structural mechanics, it is more and more difficult to ensure the validity of simulation results in the expected use range. 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 [23]. Validation and verification are both strongly related not only to uncertainty quantification but also the quality assurance process of the whole simulation solution. 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 for representative physical cases (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 associated with a methodological flowchart for practitioners 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.

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. In order to achieve this goal, IRSN and EDF have proposed to use feedbacks from the Le Teil earthquake which occurred on the 11th of November 2019 close to the CRUAS nuclear power plant (NPP). More precisely, organizing an international benchmark under the umbrella of OECD/NEA is planned. The above-mentioned Benchmark will start in early 2023 and continue until 2024 in order to assess the adequacy of engineering practices for calculating the seismic response of the structure, especially for the CRUAS NPP isolated seismic base, and to share the experience with the wider community. For more information about the benchmark, please refer to the SMiRT 26 special session entitled "*2019-11-11 Le Teil Earthquake: A special earthquake occurred close to a special NPP*" in which a presentation will be made.

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 safety. 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 and modeling improvement related to the seismic behavior of soil and SSCs.

Especially, one of the activities aims to better understand and assess the seismic behaviour 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 safety margins when exist. In 2020 four new joint actions have been 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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