## INTRODUCTION

The OECD Nuclear Energy Agency (NEA) was established on February 1958. Current NEA membership consists of 33 countries. The mission of the NEA is to assist its member countries in maintaining and further developing, through international co-operation, the peaceful use of nuclear energy.

The NEA Committee on the Safety of Nuclear Installations (CSNI) has broad responsibilities for safety technology and research programs, as well as representatives from regulatory authorities. It was set up in 1973 to develop and co-ordinate the activities of the NEA concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations.

The main mission of the Working Group on Integrity and Ageing of Components and Structures (WGIAGE) is to advance the current understanding of the relevant aspects related with ensuring the integrity of structures, systems and components (SSC), and to propose general principles on the optimal ways of dealing with respective challenges facing operating and new nuclear power plants as well as other nuclear facilities, and to make use of an integrated approach to design safety and plant life management.

The Working Group also meets in three sub-groups dealing with a) integrity and ageing of metal structures and components, b) integrity and ageing of concrete structures and c) seismic engineering. Within the WGIAGE, the seismic engineering sub-group was initiated in 1996. The sub-group deals with any type of activity relating to the seismic safety of nuclear installations and implication of SSC ageing in its seismic capacity. It covers a large spectrum of topics in the field of Earth sciences (geology, seismology ...) and in the field of engineering sciences (geotechnics, earthquake engineering, structures, mechanics …) in their respective interaction with the seismic safety of nuclear installations. It also addresses historical seismicity and humanistic studies related to seismic issues. It pays a special interest to “soft” issues of seismic safety such as those related to synergy between key actors, communication, continuous education and generation renewal. Its activities may be dedicated to future, new built or ageing facilities, either nuclear power plants or other nuclear facilities (fuel cycle facilities, research laboratories, final repositories for spent nuclear fuel ...).

The objective of this paper is to present recent activities of OECD/NEA/CSNI/WGIAGE seismic engineering sub-group, which covers seismic hazard (comparison of PSHA in areas with different level of seismic activity ; assessment of the safe shutdown earthquake robustness against on site observations …), seismic behavior of civil engineering structures (seismic capacity of reinforced concrete shear walls, analysis of floor response spectra …) and seismic behavior of mechanical equipment (metallic component margins under high seismic loads ; impact of single pipe support failure on nuclear class 1 piping during a seismic event …).

## MEDIUM-TERM STRATEGY FOR THE SEISMIC ENGINEERING SUB-GROUP (2015–2020)

A seismic engineering sub-group Medium-Term Strategy document was under finalization in the early 2011, just before the Fukushima-Daiichi accident. It was stated in 2013 that the Medium-Term Strategy document should be updated to account for the experience feedback and consequences of this accident, also considering that the “Fukushima effect” should not drive the entire activity of the sub-group. In 2014, it was more precisely agreed that the lessons learnt from the Big East Japan Earthquake (BEJE), in terms of seismic risk for nuclear facilities, will be added to the mid-term strategy plan. The current version of the document reflects the Medium-Term Strategy of the seismic engineering sub-group in the spirit of the 2013 and 2014 decisions.

### *Before Big East Japan Earthquake background*

At the time when the sub-group was set up, the following technical issues have been regarded as important:

- Probabilistic seismic hazard assessment (such as PSHA testing ; Bayesian techniques …)

- Engineering characterization of seismic input (such as Low–medium magnitude near-field input motions ; Damaging potential indicators ; Seismic Input Definition ; Soil-Structure-Interaction ; Re-evaluation of existing facilities and assessment of beyond design basis ; Ageing …)
- Information Cooperation and Education (such as Synergy among Earth Scientists, Geotechnical and Structural Engineers ; Synergy with other CSNI groups and sub-groups ; Survey of nuclear facilities that have experienced an earthquake ; Generation renewal and education …)

It was also progressively pointed out that, concurrently with technical issues, there are some key issues of earthquake engineering that are related to the management of human resources as well as information and communication. In particular: Synergy between seismologists and structural engineers ; Synergy between the seismic engineering sub-group and the two other WGIAGE sub-groups ; Exchange of information among OECD/NEA countries and experts ; Generation renewal and continuous education ; Cooperation with other institutions.

**After Big East Japan Earthquake background - Lessons learnt and consequences on the seismic engineering sub-group midterm activities**

Root causes of the Fukushima accident

The experience feedback of recorded seismic motions on Japanese NPP sites indicates that the seismic hazard was underestimated at the moment of their original design. The large design margins were compensating for the hazard underestimation as exemplified by the Kashiwasaki-Kariwa NPP in 2007 and of the Onagawa NPP in 2011. Unfortunately, in Fukushima, the earthquake resulted not only in a strong ground motion but also in a tsunami and the nuclear accident occurred

As a conclusion, the strong ground motion on the Fukushima-Daiichi site was not the cause of the nuclear accident.

**Prioritization of the Seismic Sub-Group Activities**

Scientific and technical issues

Considering that the vast majority of NPPs in the NEA member countries are not concerned with the tsunami hazard, the purpose of the WGIAGE seismic engineering sub-group, at least in a first step, is to focus on strong ground motion. As a Post-Fukushima priority the sub-group has agreed to address the first question given below and if necessary the second question will be addressed later on:

***Question 1: On the basis of seismic motion records on NPP sites (or in their vicinity), are there evidences in some countries or regions (other than Japan) that the seismic hazard is at the moment, or was at the moment of the design, likely underestimated?***

***Question 2: If yes, are the current design practices for seismic events appropriate to provide necessary margins as it was the case in Japan on the Kashiwasaki-Kariwa site in 2007 and Onagawa site in 2011?***

As a generic issue, seismic hazard assessment is clearly a major concern in many Member States because of the uncertainties that are generally associated with these assessments. In this regard, the concept of PSHA testing should be encouraged and their use should be promoted.

In year 2019 the seismic engineering sub-group published a report (NEA/CSNI/R(2019)1) which provides comparisons of PSHA outputs between high activity areas and low-medium activity.

In future seismic engineering sub-group could concentrate on the following activities in cooperation with WGIAGE concrete and metal sub-groups:

- assessment of site effect of large earthquakes

- assessment of soil-structure interaction issues
- assessment of effects of Beyond Design Basis Events (BDBEs) on the operating NPP including the existing seismic margins of SSC as well as possible methods to manage the effects of BDBEs

In long term, the following activities could be touched:

- better alternate indicators of the seismic input motion damaging capability than the PGA should be proposed and assessed by the earthquake engineering community and used in the future seismic hazard assessments
- revision of the position paper on ageing
- assessment on consequences of higher seismic input motions on the design of new NPPs
- assessment on seismic behaviour of components: fuel assemblies, mechanical components, electrical components, I&C)

Information Cooperation and Education

The maintenance of the database of NPPs that have experienced an earthquake (hosted by IAEA) is regarded by the seismic engineering sub-group as a priority. Actions should be taken so that it is sustainable. The sub-group is willing to pursue its continuous effort for developing synergies among earth scientists, geotechnical and structural engineers through the organization of periodic workshops, including workshops dedicated to PSHA activities as indicated above.

## PAST ACTIVITIES AND WORKSHOPS: MAIN FINDINGS AND RECOMMENDATIONS

This section highlights the main activities, findings and recommendations developed or issued by the seismic engineering sub-group during the past decade. More detailed information can be found in Sollogoub et al. 2005, Murphy et al. 2007 and Murphy et al. 2009.

### *Past Workshops: Objectives and main outcomes*

Specialist Meeting on the Seismic Probabilistic Safety Assessment (SPSA) of Nuclear Facilities (Jeju, Korea, 2006)

In November 2006, the seismic engineering sub-group cosponsored a workshop with the Working Group on Risk (WGRisk) on seismic probabilistic safety assessment (SPSA) at Jeju Island, Korea, see OECD/NEA/CSNI (2007) for more details. The International Atomic Energy Agency (IAEA) also cooperated in sponsoring the workshop. One specific objective was to compare the situation today with the situation at the time of a previous workshop on this topic held in Japan in 1999 and to develop an updated set of findings and recommendations.

The main outcomes of this workshop were the following:

- PSHAs must be performed in a realistic manner to produce realistic results that include the same level of uncertainty and variability observed in nature. The results should be compared to all available field observations, such as those associated with recurrence records.
- Uncertainty in the area of quantifying human reliability responses in operating personnel and emergency organizations continues to be an issue. The issue is generic to all human reliability analysis and involves the uncertainty in data and the lack of data.
- The analysis of correlations among various components of similar function and construction, specifically the quantification of the correlation of failure of similar equipment or structures because of an earthquake, is another continuing issue.

Recent Findings and Developments in Probabilistic Seismic Hazard Analysis (PSHA) Methodologies and Applications (Lyon, France, 2008)

The seismic engineering sub-group sponsored a workshop entitled "Recent Findings and Developments in Probabilistic Seismic Hazard Analysis Methodologies and Applications," in Lyon, France on April 7 – 9 April 2008, see OECD/NEA/CSNI (2009) for more details.

The main objectives of the workshop were to discuss recent research and the regulatory, utility and industry issues associated with PSHA (Probabilistic Seismic Hazard Assessment).

Among the 14 recommendations that were issued, the main ones are given below:

- A "procedures guide" that would provide more detailed guidance than the guidance now available in the SSHAC report itself is needed. Funding agencies should consider supporting the development of such a guide as high priority.
- Guidance on how to develop robust quantitative and realistic descriptions of uncertainties should be a major part of any broader PSHA "procedures guide".
- There needs to be continuing emphasis on reducing uncertainties. This will require both research to provide guidance, and the use of care whenever a PSHA study is undertaken.
- Guidance on consistency checks should also be a major part of any broader PSHA "procedures guide."
- Using Bayesian updating methods can be of important value, but further work (both research work and applications) in this area is to be encouraged.
- Among the subjects within the scope of this workshop was the issue of the comparisons between PSHA studies performed in regions of high seismicity and other studies performed in regions of moderate or low seismicity.

Workshop on Soil Structure Interaction (SSI) Knowledge and Effect on the Seismic Assessment of NPPs Structures and Components (Ottawa, Canada, 2010)

This workshop, coordinated by OECD/NEA/CSNI and with the IAEA, was dedicated to seismic soil-structure interaction. Its objective was to review and disseminate recent findings and issues in SSI knowledge and effect on the seismic assessment of NPP Structures and Components, see OECD/NEA/CSNI (2011) for more details.

The main findings and recommendations can be summarized as follows:

- Enhancing common understanding between seismic hazard practitioners and the end users of the output of seismic hazard studies. The user community includes earth scientists, and engineers. A common understanding of concepts and nomenclature is needed.
- Identifying common goals for researchers and practitioners to ensure the development of practical approaches to SSI analysis that appropriately account for important aspects of SSI as a function of seismic input, site conditions, and structural characteristics. These goals should include the consideration of the capabilities and limitations of using simplified or complex models. It should be recognized that the combination of simplified models and sensitivity studies are important to understanding SSI phenomena.
- A strong emphasis on validation of seismic input and the SSI simulation models using recorded earthquake motions in the free-field and in-structures. In Japan (Kashiwazaki-Kariwa) and Taiwan (Chi-Chi), and China (Wenchuan) the relatively common occurrence of significant earthquakes and the large number of free-field and in-structure instruments in NPPs presents the best situation to acquire data for validation of seismic input, SSI phenomena, and the SSI analysis of these phenomena.
- Enhancing SSI analysis guidance and industry codes as agreed upon by appropriate practitioners of the SSI analysis.

Workshop on Testing Probabilistic Seismic Hazard Analysis Results and the Benefits of Bayesian Techniques (Pavia, Italy, 2015)

This workshop was the fourth in a series of NEA meetings (Tokyo, Japan, August 1999, Jeju, Korea, November 2006, Lyon, France, April 2008), dedicated to probabilistic approach of seismic hazard or seismic risk. The main objectives were to foster exchanges between earth scientists, statisticians and engineers so as to share experiences in progress related to developments in testing the results of probabilistic seismic hazard analyses (PSHA) with special focus on assessing the benefits of using Bayesian techniques for such a purpose. The goal was to address the current status of the regulatory arena, identifying and recommending good practices for member countries and exploring R&D to be developed on this topic.

The scientific content consisted of 3 invited lectures and 25 contributions from the participants, see OECD/NEA/CSNI (2015-15) for more details. It was noted during the workshop that the conclusions and recommendations are not limited to the hazard assessment of nuclear facilities only.

The main findings and recommendations followed the recommendation of earlier workshops and can be summarized as follows:

- As already stated by the previous workshops, it is recommended that comparison between results of PSHA studies performed in regions of high seismicity and those from PSHA performed in regions of moderate or low seismicity be carried out at a future NEA workshop. The comparison is necessary for better understanding of the methodological differences of regional PSHA’s.
- A state-of-the-art PSHA should include a testing phase against any available observation, including any kind of observation and any period of observation, including instrumental seismicity, historical seismicity and paleoseismicity data if available. It should include testing not only against its median hazard estimates but also against their entire distribution (percentiles).
- The PSHA results should be realistic; therefore, use of Bayesian techniques in PSHA is strongly encouraged in order to take into consideration any available observation. It is recommended to develop common guidelines for systematic implementation of Bayesian updating approaches in PSHA, including a clear description of possible techniques, ways to implement them and including special care on sensitive issues (e.g. correlation between ground motion intensity at different stations, stability tests, high quality “open” data, risk on double counting data, and treatment of uncertainties).

***Past Activities: Objectives and main outcomes***

Survey on Nuclear Facilities That Have Experienced an Earthquake

The CSNI approved in 2001 a proposal from the WGIAGE to collect information on the seismic feedback experience of Nuclear Power Plants (NPP) worldwide in full co-operation and coordination with the IAEA. An important conclusion is that although several nuclear power plants have experienced an earthquake, none have been damaged. More conclusions and feedback were expected at the time this activity was launched.

Since this time, OECD/NEA and IAEA/ISSC (now IAEA/EESS) have been gathering information and both organizations are still willing to collect experience feedback from Members States and make it available to nuclear seismic engineering community. This activity is still under progress.

SMART program and benchmark

The seismic engineering sub-group has also endorsed and recommended that its member countries participate in a blind benchmark competition of a model three-story reinforced concrete (RC) structure organized by Commissariat à l’Energie Atomique (CEA) and Électricité de France (EDF). Because three dimensional (torsion) effects and nonlinear response are a concern in the field of earthquake engineering research and building regulation, CEA and EDF have organized and supported this benchmark competition. A three-story RC structure at ¼ scale was built and placed on the AZALEE shake table at the CEA laboratory in Saclay, France. The aim of the benchmark was to compare and validate various approaches used by the international participants to model the dynamic response analysis techniques for RC structures subjected to simulated earthquakes and exhibiting both three-dimensional (torsion) and nonlinear behaviour. This analysis includes evaluation of loads induced by internal equipment, quantification of margins in design methodologies, and conducting realistic methods to quantify variability to produce fragility data.

The blind benchmark competition has the following two objectives: i) assess design methods for structural dynamic response analysis and floor response evaluation and ii) compare best-estimate methods for structural dynamic response analysis and floor response evaluation including various practices, depending on participants' experiences.

A two-phase program was built, with the first phase being associated with pre-test activities and a second phase associated with model testing, blind prediction and lessons learnt.

Finally, two main test campaigns and benchmarks were conducted, called SMART 2008 and SMART 2013. Detailed description of the objectives and main findings can be found in Lermitte et al (2007) and Richard et al. (2015).

Current Practices in Defining Seismic Input for Nuclear Facilities

This activity was developed in order to provide a brief review of current practices regarding the definition of the seismic input for design and reevaluation of nuclear power plants. It was taken for granted that, prior to conducting the seismic design of a nuclear facility, a seismic hazard analysis (SHA) has been conducted for the site where the facility is located. This provides some reference motions for defining those that will later be used as input for the dynamic analyses of the facility.

The objective of this activity was to clarify the current practices in various OECD Member States for defining the seismic input to be used in the dynamic calculations of NPPs, once the SHA results are already at hand. Current practices have been summarized for Canada, Czech Republic, Finland, France, Germany, Japan, Slovenia, South Korea, Spain, Sweden, The Netherlands, United Kingdom and United States, see OECD/NEA/CSNI (2015-9) for more details.

The main findings are:

- The approaches followed by the regulatory bodies of OECD Member States differ substantially, certainly in relation with the consideration of site effects, but also in the probability level of the event that a nuclear facility should be required to withstand.
- In many countries a probabilistic approach is adopted for the design, in some cases combined with a deterministic one; in other cases, like France, Japan or South Korea, a deterministic approach is followed.
- The US and Japan have the more complete guidelines in relation with site effects. The former provide specific approaches for definition of the seismic input. The latter clearly recognizes the need to propagate the bedrock motion to foundation level, thereby introducing the site effect in some way.
- The definition of bedrock is very heterogeneous in the various countries, although this should not constitute a serious problem if the starting information is reliable and is adequately incorporated to the analysis of the soil response.

## RECENT AND CURRENT ACTIVITY: MAIN OBJECTIVES AND FINDINGS

This section highlights the main activities that have been developed recently or under development, and gives the main outcome or the objective, depending on the status of the activity.

***Hazard: Comparison of PSHA in areas with different level of seismic activity (CompPSHA)***

The focus of CompPSHA has been to enhance the common understanding of probabilistic seismic hazard analysis (PSHA) method as means of predicting earthquake hazard at NPP sites. The goal was to understand what divergences exist in the PSHA applied methodologies, for instance in adapting data from measured seismicity, geology etc., and if such divergences may explain differences of PSHA outputs. The general target of CompPSHA was to contribute to the increasing of quality of PSHA studies in the nuclear field by highlighting the shared and diverging practices. Scrutinising methodological choices of PSHA studies in member countries allows practitioners to benchmark their work, leading to an improvement in processes in the respective PSHA groups.

The topic was included in the recommendations of the Pavia Workshop in Italy in 2015, OECD/NEA/CSNI/R(2015)15. Specifically, it was recommended to carry out comparison between results of PSHA studies performed in regions of high seismicity and those from PSHA performed in regions of moderate or low seismicity. The recommendation was originally made in the CSNI Workshop in the Republic of Korea in 2006, OECD/NEA/CSNI/R(2007)14, and reiterated in the Lyon Workshop in 2008, OECD/NEA/CSNI/R(2009)1.

CompPSHA activity of WGIAGE seismic engineering sub-group performed in 2016-2018 developed and distributed a detailed questionnaire to screen PSHA practices in NEA countries. The questionnaire was answered by thirteen countries with a broad spectrum of seismic activity levels ranging from very low (Finland, Sweden) to medium (France, Germany) and high (Japan).

The result report of CompPSHA activity (NEA/CSNI/R(2019)1) recognise that there is an international agreement on the usefulness of the PSHA methodology for defining seismic hazard. The general steps of the PSHA methodology are part of this consensus. However, in the details of applying the methodology there are differences, often driven by expert opinions. Several parameter needs to be clarified case-by-case, and within the general PSHA methodology there is much freedom. Hence, it is very possible, that different expert groups within one study obtain different results.

The global picture of maximum catalogue magnitude $M_{max}$ compared to the resulting free-field design PGA is presented in Figure 1. Not surprisingly, the plot shows very large scatter, with methodological differences, GMPEs, the quality of seismic catalogues, catalogue completeness intervals and several other factors contributing to the scatter. These factors all influence the site specific PSHAs. However, a general relationship between catalogue $M_{max}$ and PGA values in PSHAs can be identified.

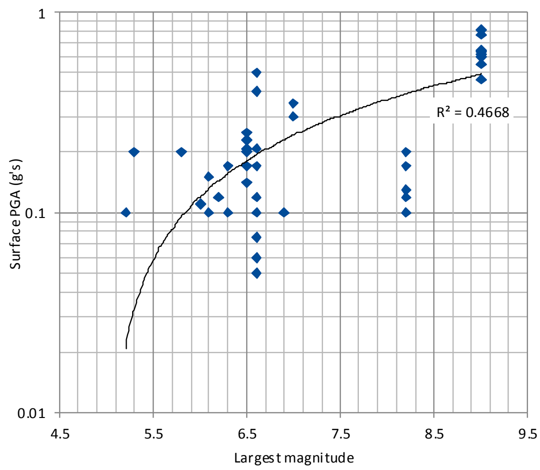


*Figure 1: Aggregate plot of all surface PGA values and largest magnitudes in the earthquake catalogue*

PSHA in regions with different levels of seismicity have been compared on the basis of answers from Japan and European countries. The methodologies used for both regions are similar, but earthquakes with identified sources contribute more to the hazard in Japan, whereas crustal earthquakes and diffuse seismicity are the key contributors in Europe. The uncertainty treatment is also different. More tightly data-driven in Japan, while conservative assumptions are preferred in Europe to compensate for unavailability of data.

A comparisons of the PSHA output for the geographical region around Switzerland was also reported, based on results of the PEGASOS project. The SSHAC Level 4 procedure, followed by a project to refine some of the conservative assumptions (Swissnuclear, 2014) resulted in significantly higher hazard than earlier estimates for Switzerland. The outcomes for the Swiss NPPs have consequences on the surrounding areas. The CompPSHA report (NEA/CSNI/R(2019)1) discusses how cross-border comparisons can aid better understanding of the validity of assumptions in the PSHA studies and formulated the following recommendations concerning PSHA practice:

- A systematic survey of the technical literature concerning PSHA is needed, between review intervals in NPPs. If new data emerges, a procedure is required to asses it and decide any further actions. This suggestion does not imply updating the hazard levels frequently; on the contrary the need for stable operating environment for the NPP is fully acknowledged.
- The publication of relevant parts or entire outcomes of PSHA studies should be encouraged, as potent instrument of ensuring quality control to the findings. The independent peer-review procedure should be employed for quality assurance and greater transparency.
- Neighbouring countries should better coordinate the implementation and review of PSHA studies. Such practice could lead to better use of national resources and increase of quality and transparency of the studies. Each national PSHA study and its update should be reviewed according to clear requirements including reviews with independent opinions.
- As instrument to implement the above recommendations, the continuous cooperation between CSNI WGIAGE seismic engineering sub-group and IAEA External Events Safety Section (EESS) is encouraged.

***Hazard: Assessment of the Safe Shutdown Earthquake Robustness Against on Site Observations***

The question on underestimation or overestimation of seismic hazard now or during the original design of NPPs was raised in the WGIAGE working group and an activity was launched in order to look for the evidences on this issue. The objective was to collect and analyse any relevant observation that could help to assess seismic hazards results and identify possible evidence of underestimation of them or the opposite, and to provide international community with a new, generic, and efficient procedure that could be widely applied on NPP sites (especially in countries with low to moderate seismicity).

The main tasks were the following:

- Collect relevant information on seismic monitoring and all seismic motion records on the NPP sites (or in their vicinity), or any other relevant observation,
- Collect also Safe Shutdown Earthquake (SSE) for the sites under consideration (could include original SSE and any re-evaluated SSE),
- Perform consistency checking between SSE and available observation (during February 2015 OECD workshop in Pavia, several experts presented methods to perform such checking that would be applied in this activity),
- Draw conclusions based on previous task results.

The activity was finalised in 2019 and the result report will go for CSNI approval in June 2019. The main results of the report approved in WGIAGE working group in March 2019 are given below:

- 12 OECD member states have replied to the OECD/NEA/CSNI questionnaire, which represent 73 NPP sites, which correspond to 2464 cumulated years of observations in the time period 1967 - 2017,
- The current status of the survey indicates that more than 90% of the NPP worldwide have instrumentation installed on site that allows to record any PGA (Peak Ground Acceleration) higher than 0.01g to 0.02g,

- The survey includes 97 reported earthquake events, including 45 events with a PGA higher than 0.01g (maximum observed earthquake PGA is 0.69g),
- Compared with original design PGA, the maximum observed PGA is approximately 1.5 x Original Design PGA and compared with current SSE PGA, the maximum observed PGA is approximately the same as the current SSE (Safe Shutdown Earthquake) PGA,
- In term of consistency checking, the comparison between observed earthquakes and expected ones, assuming that the SSE is equivalent to a 10 000 years return period was performed. The results are presented in Figure 2. These results should encourage member states to further consider their design and re-evaluation practices including the equivalent return period and its margins related to Seismic Hazard Assessment in order to improve the confidence of such assessments (the results of the comparisons performed through this activity give evidence of over-estimation or under-estimation, depending on national approaches).

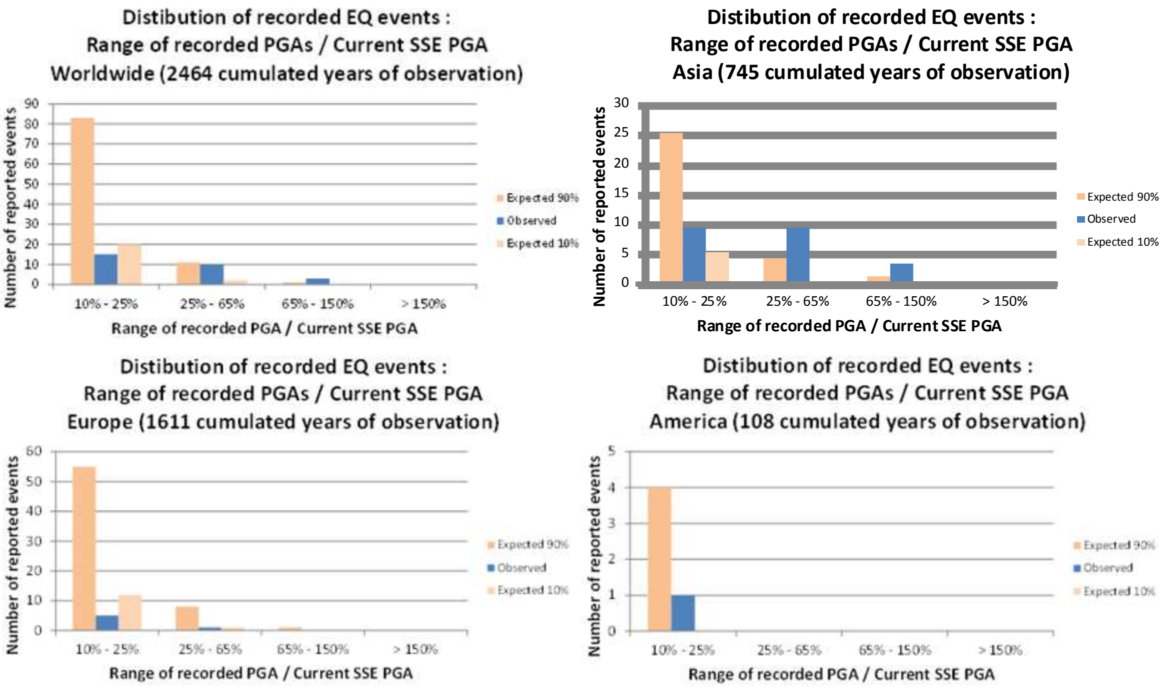


*Figure 2 : Distribution of recorded earthquake events compared with expected distribution (dimensionless: recorded PGA / current SSE PGA) – **Asia**,*

Further actions could be performed in order to incorporate other member states experience feedback. Further assessments of observed earthquakes compared with expected ones, relying on NPP hazard assessments, could also be performed. For instance, the assessing process would be improved if member states could provide actual hazard curves coming from site specific PSHA, which would allow to reduce epistemic uncertainties that were propagated in the present study.

Finally, performing consistency checking of the results of Seismic Hazard Assessments against on site observations appears to be an objective and necessary task to be performed among all NEA member states. Regularly updating this survey and corresponding consistency checking would encourage the international community to further improve nuclear safety and would also help to disseminate knowledge and good practices among member states.

Of course, the method developed and applied in the above mentioned perspective can be used in any context or by any member state, which fulfils the initial objective of this activity, being aware that the larger the number of sites under consideration is, the more valuable the assessment is.

***Structures: CASH Benchmark on the beyond design seismic Capacity of Reinforced Concrete Shear Wall***

CASH is an international benchmark program organised by the OEDC-NEA (Nuclear Energy Agency) and carried out between 2014 and 2018. The result report of work is under preparation and it is planned to be published by NEA in 2020. The main objective of this initiative was to evaluate the reliability of analysis tools and methods as well as engineering practice know-how in assessing the capacity of reinforced concrete (RC) shear walls against earthquake actions exceeding the design level.

The benchmark program consisted of two phases. The first one (CASH 1) was related to the experimental testing of RC shear wall panels within the framework of the SAFE experimental program at the European Laboratory for Structural Assessment (ELSA, Joint Research Centre) between 1997 and 1998. During this phase, 11 participating teams were tasked with qualifying and calibrating their Finite Element (FE) numerical models of the reference structures under different loading conditions (static pushover, cyclic and pseudo-dynamic) in line with the experimental program. An additional refinement phase as well as a workshop were provided to reduce the scattering of the results achieved and to allow the participants to discuss and share their experience with each other.

Using the calibrated material models and lessons learned regarding numerical modelling, a full-scale FE numerical model of a typical RC wall in an auxiliary Nuclear Power Plant (NPP) building had to be investigated in the second phase (CASH 2). The main objective for the 8 remaining teams was to investigate the linear and the non-linear seismic response of a full-scale multi-story wall to various seismic loading intensities (modal spectral analysis and both pushover and dynamic time history analyses). In particular, the effect of wall irregularity caused by large openings was to be examined. Again, an additional refinement step was performed. The results of CASH 2 were finally used to verify the simplified formula for calculating the ductility factor of an irregular RC structure proposed by ASCE 43-05.

The CASH benchmark results highlight the big potential of non-linear FE analysis of RC shear walls under seismic action, but also a lot of associated challenges.

It could be stated that applied numerical models give coherent results as long as nonlinear behaviour is not activated, in terms of frequencies, displacements in the modal spectral analysis and initial slope of pushover curve. However, significant scattering of results was observed, as soon as non-linear behaviour was triggered. This scattering increases with increasing intensity of the seismic input. In general, the failure mode is not easy to predict and can even be mesh-size dependent, which underlines that additional research and stable numerical FE models for RC are necessary.

Both organisers and participants agree that workshops are an indispensable part of the benchmark program as a platform for discussing results and exchanging experience.

The nonlinear FE modelling of structures, especially in the case of beyond design seismic action, is very demanding and requires experienced staff with solid understanding of limitations of available numerical tools. Taking into account the fact that the validity of obtained results is often not obvious, robust and transparent simplified models for plausibility checks are needed more than ever.

Finally, results of the CASH benchmark program, and in particular the investigation of the ductility of the RC walls in phase CASH 2, has shown that the ductility of irregular structures can be higher than those calculated using the formula from ASCE 43-05 for a structure with a weak or soft story.

***Equipment: MEtallic COmponent Margins Under High Seismic Loads (MECOS)***

MECOS Programme
In the wake of the Fukushima-Daiichi accident, the Committee for the Safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency (NEA) took initiatives on the evaluation of margins encompassed in the nuclear industry design procedures. Regarding piping systems the conclusion was that the Fukushima accident did not raise any new issue. It triggered a new interest on the subject of design margins already identified at the occasion of previous experimental campaigns and on their possible use to cope with the effects of beyond design earthquakes. It was therefore decided by the CSNI that the available

experimental data should be reviewed and an international benchmark organized on this basis so that the international community of mechanical engineers share these experimental evidences, forge a common understanding on the subject and possibly make some proposal for the evolution of piping system design/verification criteria.

MECOS (MEtallic COmponent margins under high Seismic loads) programme was launched in 2015. The first part of MECOS consisted of gathering information on i) current design practices and ii) piping system experimentation carried out around the world that could be suitable for benchmarking. Part 2 is the benchmark itself and Part 3 proposals for new criteria. The results of MECOS program part 1 and 2 were published in 2018 in a result report NEA/CSNI/R(2018)3. The third part of MECOS program is going on and NEA will publish the result report of MECOS part 3 in 2020.

Benchmark exercise – part 1 and 2

A series of 114 reports on seismic tests and analyses of piping systems has been compiled by EDF. As consequence, it was decided to concentrate on the Indian test campaign. This programme consists of a series of tests funded by Bhabha Atomic Research Centre, Mumbai, and carried out by the Central Power Research Institute (CPRI) of Bangalore, India. It consists of a pressurized piping system tested on a shaking table. Shake table testing has been carried out on two sets of stainless steel (SS304L) and two sets of carbon steel piping systems with same configuration. The observed failure mode was the expected fatigue-ratcheting. The BARC programme also encompasses simple component tests (pressurized straight pipes and elbows in cyclic pure bending) as well as other piping configurations. It is still under progress.

The OECD-NEA MECOS benchmark exercise is composed of two successive phases:

- MECOS#1 deals with fatigue-ratcheting on 6" stainless steel components and piping systems; all the available information is provided to the participants, including responses of the system, so that they can adjust their models and computations to the best possible extent;
- MECOS#2 is about the same piping system made of carbon steel. The same exercise is proposed, but this time the experimental results are not provided to the participants (blind predictions).

14 teams all around the world and coming from a wide range of industries and research institutions, participated to the exercise. A view of the experimental facility is given in Figure 3.

*Figure 3: Piping System on the BARC Shaking Table*

The main findings of the BARC experimental cases are:

- Observed failure: fatigue ratcheting at elbow crowns and not plastic collapse
- Large number of base excitation time history (>2,000 sec) to reach through wall cracked
- Elastic stress evaluation shows a large exceedance compared to design allowable stress

Concerning comparisons between numerical calculations and experiments:

- Challenging task to compute experimental case, including long test procedure (> 2,000 sec), non-linear constitutive laws to account for ratcheting and procedure for design or re-assessment process
- Fair agreement regarding global behavior and large scattering regarding local evolution of strain
- Criteria development on prevention against fatigue ratcheting damage should not rely upon numerical calculations but directly upon experimental cases

Towards New Criteria – part 3

Failure mode taken into account in design codes is plastic instability, which means that, a priori, the current design criteria do not pertain for prevention against the observed fatigue-ratcheting failure mode. According to the experts, this lack of adequacy is the root cause of the large margins observed in the past at the occasion of experimental campaigns carried out in different countries.

For that objective, in the Part 3 of MECOS program, an International Group of Experts (MECOS-GE) has been established by OECD/NEA with the following objectives:

- Revisit the past test results as well as the interpretations that were carried out and conclusions that were drawn at that moment. Reanalyze them in the light of recent developments.
- Consider recent experimental programs that have been carried out in Japan and in India.
- Make proposals for design criteria that address the fatigue-ratcheting failure mode as well as plastic instability.

The Kick-Off meeting of MECOS-GE took place in Paris on 1st December 2016, after the second MECOS Workshop. 15 persons from different countries (Canada, France, Greece, India, Japan, Russia, and USA) are actively participating to the activity. Up to now, 8 meetings, physical and/or by internet, were the occasion of reach exchanges. The following points were reviewed and discussed; they contribute to the elaboration of new criteria:

- Review and drawbacks of conventional approach for seismic design of piping systems
- Revisit of R/D programmes around the world
- History of code modifications in different countries
- Physical phenomena to be considered for seismic piping design
- Stress classification (Primary, Secondary): The usual classification of seismic loads as primary is not justified from a mechanical point of view
- Review of available design analysis approaches: linear, linear equivalent approaches, non-linear analyses…
- Consideration of seismic anchor movements and seismic fatigue evaluation
- Proposals for new criteria

All the findings are grouped in a report under final drafting. A benchmark exercise is under development in order to help for the validation of new criteria. As a final step, arranging an international workshop to transfer of results and knowledge to structural engineers and designers is under preparation in the MECOS group.

***Equipment: Impact of Single Pipe Support Failure on Nuclear Class 1 Piping During a Seismic Event***

This activity was launched by the WGIAGE seismic engineering sub-group in 2018. Its objective is to assess the structural integrity of the piping system and also to quantify the remaining seismic design margin if a pipe support completely fails during a seismic event. Piping support failure mechanisms can include the following:

- Cracking in the concrete with a cone type failure in the influence zone can cause some bolts in support plate to pullout leading to support failure.
- The piping support welded frame members can experience high cycle, low amplitude flow induced vibrations during the plant life. For the 'end of reactor life' scenario, the vibrations coupled with corrosion, may develop cracks leading to the member failure.

The failure of a single pipe support can produce a larger free span. In addition, a service induced degraded piping, experiencing a large earthquake, will see excessive seismic loading which can challenge or even overwhelm the piping. This proposed investigation will assess the increase in piping loads due to formation of a free span resulting from an assumed failure of a single pipe support. For end of life reactor operation, the structural integrity of degraded nuclear Class 1 piping will then be assessed under this increased load.

The results of this activity is planned to be a series of simulations using structural integrity software. Both linear and non-linear transient dynamic stress analyses shall be carried out on the 10 to 12" NPS piping. The seismic design margins will be established for strong motion earthquakes. The failure assessment diagrams (FAD) will be used to assess margins for the piping to withstand rupture because of cracking. Discussions on possibilities to continue the activity with decreased number of participants are going on. The WGIAGE group will done the decision to continue the activity in 2019.

***Equipment: International benchmark to establish consensus on the crane bridges seismic behaviour and on the way to represent them by a fragility curve***

Crane bridges are handling devices used to lift and transfer heavy loads. They are essential equipment in the nuclear industry. Assessing the dynamic behaviour of crane bridges is a very important issue for nuclear safety and a motivating scientific challenge.

Within the context of Level 1 Probabilistic Safety Assessment (PSA) studies, these devices have been identified as a contributor to the probability of core meltdown. Depending on the reactor type and on the age of the reactor design, the risk of anchorage failure could be an important contributor to the probability of core meltdown during earthquake and internal hazards part of PSA level 1. Therefore, the risk to fuel damages and following releases could be important for safety especially during shutdown states, when reactor and containment are open. Furthermore, depending on design, the aforementioned issue is also related to spent fuel storage pools inside containment and loss of heat removal.

It is necessary to improve knowledge of the behaviour of this equipment in order to fully understand their failure mode when subjected to an earthquake and, in particular, to estimate the forces transmitted to the anchorages. In addition, the way in which this type of equipment is represented by a fragility curve raises several questions that are still open: 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?

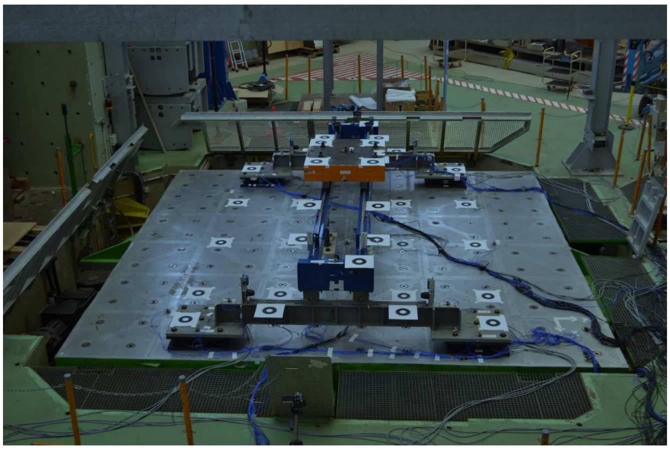

*Figure 4: The crane bridge on the AZALÉE shaking table - CEA/Saclay*

To provide answers to these questions, a benchmark as an activity of the WGIAGE seismic engineering sub-group is planned for 2020. The main objectives of this action are (i) to identify best practices to model 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 France and has produced a large database, see Figure 4: The crane bridge on the AZALÉE shaking table - CEA/Saclay (Feau et al., 2015). On one hand, some of these data will be used by participants to characterize and calibrate their models and, on the other hand, the other data will be used to assess the predictive capacity of the models.

The Benchmark will be concluded by a restitution Workshop in which the different participants will be gathered to exchange and discuss their models and results they have obtained. In this way, best practices for modelling overhead cranes under seismic load 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 participants is envisaged and the findings of the benchmark analysis will be summarized in a workshop in 2021 and a NEA report in 2022.

## CONCLUSION

Within the OECD/NEA/CSNI/WGIAGE, the seismic engineering sub-group was initiated in 1996. The sub-group deals with any type of activity relating to the seismic safety of nuclear installations. It covers a large spectrum of topics in the field of Earth sciences (geology, seismology ...) and in the field of engineering sciences (geotechnics, earthquake engineering, structural dynamics, mechanics …) in their respective interaction with the seismic safety of nuclear installations.

Since this time, the seismic engineering sub-group has developed many activities and organized numerous seismic safety-related workshops, in order to consolidate and disseminate knowledge.

After Big East Japan Earthquake, the seismic engineering sub-group has updated its strategic plan. As a Post-Fukushima priority the sub-group has agreed to address the first question given below and if necessary the second question will be addressed later on:

*Question 1: On the basis of seismic motion records on NPP sites (or in their vicinity), are there evidences in some countries or regions (other than Japan) that the seismic hazard is at the moment, or was at the moment of the design, likely underestimated?*

*Question 2: If yes, are the current design practices for seismic events appropriate to provide necessary margins as it was the case in Japan on the Kashiwasaki-Kariwa site in 2007 and Onagawa site in 2011?*

The WGIAGE seismic engineering sub-group has already and will arrange a number of international workshops in order to discuss these questions. Sub-group has also finalized a handful of remarkable result reports on explaining and assessing the design practices in member countries related to these questions. The reports of Comparison of PSHA in areas with different level of seismic activity, NEA/CSNI/R(2019)1, and the report on Assessment of the Safe Shutdown Earthquake Robustness Against on Site Observations to be published by NEA in 2019 are providing some answers to these questions. The results of MECOS group to be published in 2020 in order to make proposals for design criteria that address the fatigue-ratcheting failure mode as well as plastic instability are also important for seismic design and engineering in future.

The recent results in WGIAGE seismic engineering sub-group reports should encourage member states to assess their designs and re-evaluation practices and their margins related to the Seismic Hazard Assessment. The results and lessons learned of previous seismic events should be used for improving design of new units as well as original design of old units to ensure that no new nuclear disaster based on the design deficiencies of any nuclear plant or facility could happen.

The sub-group also regards the education of the new generation as an acute issue at the moment when numerous experienced engineers retire. Member States are encouraged to propose training and education activities dedicated to the new generation of engineers.

Finally, the sub-group is willing to promote initiatives that might foster synergies with the other CSNI sub-groups, in particular with the working group on risks and the newly established working group on external hazards. Similarly, the seismic engineering sub-group is interested in any form of cooperation with other parties such as the IAEA-EESS or the European Joint Research Centre.

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