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CSNI Technical Opinion Paper No. 18

Seismic Probabilistic Safety Assessment for Nuclear Facilities

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Cover photos: The four Candu 6 units at Wolsong, Korea (KHNP); Fukushima Daiichi Nuclear Power Plant, Japan (Nuclear Information Center, CRIEPI).

Foreword

The main objective of the Working Group on Risk Assessment (WGRISK) of the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) is to advance probabilistic safety assessment (PSA) understanding and to enhance its utilisation for improving the safety of nuclear installations.

In pursuing this goal, the working group performs a number of activities to exchange PSA-related information among member countries. One of these activities is to develop technical opinion papers (TOPs) on specific subjects of PSA.

The first TOP on seismic probabilistic safety assessment (SPSA) dates back to 2002. Since then, significant progress has been made in the development of SPSA, in particular in the areas of probabilistic seismic hazard analysis and fragility analysis. Therefore, this TOP has been revised, with special attention given to the experience in the member countries applying SPSA.

The NEA Secretariat wishes to thank the following experts who provided valuable time and considerable knowledge towards the revision of this TOP: Kwang-Il Ahn, Korea; Jon Ake, United States; Attila Bareith, Hungary; Stefan Brosi, Switzerland; Kevin Coyne, United States; Felix Gonzalez, United States; Vinod Gopika, India; Dries Gryffroy, Belgium; Yoshikane Hamaguchi, Japan; Jose Pires, United States; Jorma Sandberg, Finland; Gerhard Schoen, Switzerland; Robert Sewell, United States; Nathan Siu, United States; Yann Stempfel, Switzerland; Jim Xu, United States; Smain Yalaoui, Canada.

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List of abbreviations and acronyms

CDF	Core damage frequency
CSNI	Committee on the Safety of Nuclear Installations (NEA)
FA	Fragility analysis
GMPE	Ground motion prediction equations
HCLPF	High confidence of low probability of failure
HEPs	Human error probabilities
HRA	Human reliability analysis
LHS	Latin hypercube simulation
LOCA	Loss-of-coolant accident
M&S	Modelling and simulation
NEA	Nuclear Energy Agency
OECD	Organisation for Economic Co-operation and Development
PSHA	Probabilistic seismic hazard analysis
SEL	Seismic equipment list
SPSA	Seismic probabilistic safety assessment
SRA	Seismic response analysis
SSC	Structures, systems, components
SSHAC	Senior Seismic Hazard Analysis Committee
SSI	Soil-structure interaction
TOP	Technical opinion paper
WGIAGE	Working Group on Integrity and Ageing of Components and Structures (NEA)
WGRISK	Working Group on Risk Assessment (NEA)

Executive summary

Seismic probabilistic safety assessment (SPSA) is a systematic method for examining and evaluating the risk from earthquake-initiated accidents. The significant advances in the area of SPSA since the initial publication in 2002 of the NEA/CSNI Technical Opinion Paper (TOP) No. 2: *Seismic Probabilistic Safety Assessment for Nuclear Facilities* have prompted a revision of the document. The purpose of this revision is to provide the up-to-date international view on the state of the SPSA as it is currently being applied, including a description of the main elements of SPSA. The revision was written by seismic PSA experts of the NEA Working Group on Risk Assessment (WGRISK) member countries. The initial draft and subsequent updates were presented to WGRISK for review and comments. In addition, comments were obtained from seismic experts of the Working Group on External Events (WGEV) and Working Group on Integrity and Ageing of Components and Structures (WGIAGE).

SPSA consists of three main elements, probabilistic seismic hazard analysis (PSHA), fragility analysis (FA) and development of an SPSA model. They can be summarised as follows:

- PSHA provides a comprehensive quantification of the annual exceedance probabilities for the ground-motion parameters of interest for the SPSA. There are large uncertainties associated with the location, size and level of ground shaking of earthquakes. PSHA quantifies these uncertainties in order to produce a realistic description of the ground motion at the site.

- The objective of the FA is to estimate the seismic failure probabilities of the structures, systems and components (SSCs) whose failure may contribute to the risk quantified by the SPSA. There are various established methods for obtaining the parameters of the fragility function, each potentially requiring significantly different levels of effort. In practice, for a given SSC, the method is selected according to the importance of the SSC and to the expected benefit provided by a more realistic estimation compared to a conservative approach. Since the mid-1990s, significant developments in the application and use of probabilistic seismic response analysis (SRA) have increased the realism of the computed structural responses. The increase in computing power has largely facilitated these developments.

- By means of an SPSA model, sequences of events caused by the effects of ground motion can be comprehensively modelled and the associated risk, including uncertainty, can be quantified. In general, an SPSA model is developed using an existing internal-events PSA model. An SPSA model incorporates the results of the PSHA and of the FA.

The main technical opinions of this paper on these elements of SPSA and the application of SPSA are the following:

- Based on the fact that SPSA has served in several countries as a valuable tool for risk-informed decision-making, it can be concluded that SPSA methods are mature enough to analyse the risk of core damage accidents and radiological releases that might result from earthquake-initiated events at nuclear power plants, and to understand the risk significance of SSCs and human actions.
- Due to randomness in nature and the limited available data, especially hazard data, large uncertainties are inherent in (i.e. a factual aspect of) any seismic evaluation. SPSA provides a systematic framework for explicitly tracking and quantifying uncertainties and their impacts (rather than, for example, ignoring them or leaving their treatment obscure or implicit). This feature of SPSA is one of its key strengths.
- By means of the FA, the seismic capacity of SSCs is systematically analysed. Making also use of the SPSA walk-down findings, the FA has a high potential to identify cost-effective seismic capacity improvements, some of which can be easily corrected prior to finalising the SPSA. This has been proven in many applications and is one of the FA's strongest attributes.
- SPSA results themselves, such as on the importance of components, are crucial to point out effective measures to reduce the plant's risk. For example, in case of a plant safety re-evaluation resulting in a significantly different seismic hazard, SPSA has been used to evaluate the impact on the plant safety and to identify the most effective safety enhancements.
- In dealing with the large uncertainties associated with the location, size and level of ground shaking of earthquakes, the so-called Senior Seismic Hazard Analysis Committee (SSHAC) approach is widely accepted in the seismic hazard community as the state-of-the-art PSHA approach. Over the last decade, the original SSHAC methodology has been supplemented by experience-based implementation guidelines.
- Continuing research aims to better understand and, where possible, reduce the uncertainty in seismic evaluation approaches. However, considering the randomness in nature and the limitations in collecting data (especially hazard data), it is to be expected that significant uncertainties will remain a real aspect.
- Challenges faced by SPSA include the following:
  - Estimating the maximum magnitude for a PSHA is particularly challenging in intra-plate regions such as Europe, where large earthquakes are infrequent compared to the length of earthquake catalogues, and earthquakes often occur on previously unrecognised active faults.
  - Although it is possible to conduct scenario-specific seismic Human Reliability Analysis (HRA) quantifications, the number of unknown elements such as the plant status, the distraction caused by the multiple failures of non-safety relevant components, the indications still available

in the main control room, etc. makes this quantification process onerous and challenging. A common practice to resolve this issue consists in modifying the human error probabilities (HEPs) derived for the internal-events PSA.

  - There are few companies and experts on the market that have been trained and have experience with PSHA or with fragility analysis.

- Limitations associated with the state of the art of SPSA include, for example:
  - Ground motion prediction equations (GMPEs) are a very sensitive issue in seismic hazard assessment. The limited number of instrumental strong motion records in large parts of Europe makes it difficult to derive empirical attenuation relations.
  - Traditional PSHA heavily relies on the extrapolation of short records of earthquake data to the very low occurrence probabilities required as input parameters for PSA.

In relation to the challenges and limitations listed above, it is important to note that the majority of them are not SPSA specific. Rather, they are inherent aspects of any seismic safety evaluation.

Recognising that uncertainties and limitations are an important factual aspect that needs to be adequately dealt with, many countries have complemented the regulatory framework with risk-informed approaches where PSA is one element of the decision-making process.

Overall it should be noted that the use of PSA in risk-informed decision-making is particularly meaningful and comprehensive if SPSA is considered. Ongoing discussions in some countries regarding the maturity and realism of SPSA should not overshadow the powerful abilities of SPSA to identify appropriate plant quick fixes and back-fits and to support the strengthening of the safety of nuclear power plants worldwide.

1. Introduction

This technical opinion paper conveys the insights and understanding of risk analysts and experts in the NEA member countries concerning the state of the art in seismic probabilistic safety assessment (SPSA) for nuclear facilities.

SPSA is a systematic method for examining and evaluating the risk from earthquake-initiated accidents. It is composed of the hazard assessment and the consequence analysis. In both parts, uncertainties are systematically considered and explicitly quantified.

SPSA has served in many member countries as a valuable tool for risk-informed decision-making. SPSA methods are mature enough to support the analysis of the risk of core damage accidents and radiological releases that might result from earthquake-initiated events at nuclear power plants, and to understand the risk significance of structures, systems, components (SSCs) and human actions. In case of a plant safety re-evaluation resulting in a significantly different seismic hazard, SPSA has been used to identify the potential impact on plant safety and most effective safety enhancements.

SPSA can also be adapted for use at other nuclear facilities, such as high-level waste processing and storage centres including final repositories.

This paper describes the main elements of SPSA: Probabilistic Seismic Hazard Analysis (PSHA), fragility analysis (FA), and development and quantification of the SPSA model. It also discusses the applicability of SPSA, SPSA applications and ongoing research topics.

2. Probabilistic seismic hazard analysis

The objective of the probabilistic seismic hazard analysis (PSHA) is to quantify estimates of annual exceedance probabilities for the ground-motion parameters of interest in PSA modelling and quantification. There are large uncertainties associated with the location, size and level of ground shaking of earthquakes. The PSHA quantifies these uncertainties in order to produce a realistic description of the ground motion at the site.

The PSHA framework published by the US Nuclear Regulatory Commission (NRC) in 1997 (Budnitz et al., 1997) focuses on systematic treatment of uncertainties, and is now widely accepted within the seismic hazard community as state of the art. The framework provides a systematic way to produce estimates of the hazard (i.e. annual exceedance probabilities), while simultaneously accounting for all significant sources of uncertainty and variations in expert judgement, in order to evaluate confidence levels for the annual exceedance probabilities. The original recommendations (Budnitz et al., 1997) have been supplemented by experience-based implementation guidelines, e.g. in the United States (Kammerer and Ake, 2012) and in Switzerland (Swiss Federal Nuclear Safety Inspectorate, 2019).

A PSHA typically includes the following steps:

- *Seismic source characterisation*: The possible seismic sources are identified and characterised as fault sources representing the three-dimensional character of possible rupture locations on known faults or area sources representing the two-dimensional zone boundaries for earthquakes within a volume of the earth's crust where fault geometries are unknown. For each source, a magnitude-frequency relationship is determined, which is derived from catalogues of seismic events (instrumental, historical) and from available paleo-seismic studies. All credible seismic sources that may contribute significantly to the seismic hazard at the site are addressed in a comprehensive PSHA.
- *Ground-motion modelling*: Relationships quantifying ground-motion parameters of interest (e.g. spectral accelerations and peak ground acceleration [PGA]) in terms of earthquake magnitude, source-to-site distance, the site condition at a selected reference rock level, and various geophysical characteristics are developed. This development is usually based on the review, selection, adaption, and/or possible generation of available ground motion prediction equations (GMPE).

- *Site response analysis*: Dynamic response models are developed of the local soil (and/or rock) deposit; these models convey layer geometries and various soil/rock properties (e.g. density, low-strain shear-wave velocity, strain-dependent damping and shear modulus) of each layer between reference rock and the ground surface. The dynamic models are exercised using representative ground motions in order to assess modifications to the incoming seismic waves.

- *Calculation of the hazard*: Seismic hazard curves that describe relationships between the ground-motion parameters of interest and annual probability of exceedance are assessed together with uncertainties using suitable PSHA software. The hazard curve is used as a basis to develop a set of seismic initiating events and their likelihoods for use in quantifying the PSA model.

- *Additional hazard results*: Another common seismic hazard result are the uniform hazard spectra – i.e. response spectra having specified values of uniform exceedance frequency – which are used to describe the spectral shape of the ground-motion demand in seismic fragility analyses. The fractional contribution – of each seismic source, earthquake magnitude level and source-to-site distance – to the total seismic hazard can be evaluated by means of hazard de-aggregation analyses. As input for the fragility analysis, time histories may be required that are consistent with the results of the PSHA.

To perform a high-level SSHAC-conformant PSHA can take many years and require significant investments. In addition, there are few companies and experts on the market that have been trained and have experience with PSHA or with fragility analysis. Another challenge is to estimate the maximum magnitude of a seismic source. This is particularly challenging in intra-plate regions such as Europe, where large earthquakes are infrequent compared to the length of earthquake catalogues, and earthquakes often occur on previously unrecognised active faults.

Traditional PSHA relies heavily on the extrapolation of short records of earthquake data to the very low occurrence probabilities required as input parameters for PSA. A further limitation associated with PSHA are the GMPEs. The limited number of instrumental strong motion records in large parts of Europe makes it difficult to derive empirical attenuation relations.

In relation to the challenges and limitations mentioned above, it is important to note that these are not PSHA specific. Rather, they are inherent aspects of any seismic safety evaluation.

3. Fragility analysis

A seismic fragility analysis for structures, systems, components (SSC) conveys its failure probability as a function of the seismic ground-motion parameter of interest. The determination of a fragility involves estimates of the characteristics of the seismic demand on the SSC as well as its capacity. The goal of the fragility analysis (FA) is to estimate the seismic fragilities of the SSC, whose failure may contribute to the risk quantified by the seismic probabilistic safety assessment (SPSA). The analysis consists of the following major elements:

- *Scope of SSCs and data collection:* to initially define the scope of SSCs, a seismic equipment list (SEL) is developed based on the internal-events PSA model, supplemented by structures and components that may not be included in the internal-events model but require consideration in the SPSA. To refine and finalise the SEL, a seismic capability walk-down is performed. It serves to: (a) identify additional SSCs and seismic failure modes not adequately captured in the initial SEL; (b) screen out SSCs from further evaluation based on high-capacity configuration; and (c) ensure that, for the unscreened SSCs and their seismic failure modes, all field data and reference information needed to perform a proper fragility analysis are collected. Walk-downs are used to additionally identify any important seismic interactions – i.e. cases where an SSC may induce failure of an SPSA-relevant component. The actual field installation and condition, which may change with age and differ from drawings and specifications, are adequately documented for the purpose of performing realistic capacity analyses. Examples of typical reference information gathered before, during, or after the walk-down include: equipment locations, layout drawings, drawings of pipe runs, seismic design documents and calculations that clarify component layout, dimensions, material properties, anchorage details, failure modes, design methods, and seismic qualification test and/or analysis reports and results.
- *Seismic Response Analysis (SRA)*: the goal of the SRA is to determine structural demands and in-structure response spectra (ISRS) (i.e. acceleration, velocity and/or displacement response at support locations of equipment) for specified seismic input. Since the mid-1990s, the application and use of probabilistic SRA have been developed significantly to increase the realism of structural responses. A significant increase in computing power has largely facilitated these developments. Modern SRAs include the soil-structure interaction (SSI) as well as additional site response characteristics. For the SSI, the creation of a soil model (based on the soil properties, such as density, damping, etc.) and a building model (based on the geometry and the construction material) are necessary. For probabilistic SRA based on a

sampling approach (e.g. Latin Hypercube Simulation [LHS]), the variabilities of structural stiffness and damping, as well as the variabilities of soil properties, are considered together. Input motions for the response analysis can be defined as acceleration response spectra or more commonly sets of acceleration time histories compatible with the probabilistic seismic hazard analysis results. One of the most important advantages of the sampling approach is that in this way all crucial variables for the structural response, particularly the seismic hazard, soil and structure properties and SRA issues, are considered all in a single analysis, and different sources of variability are propagated through the model. On the other hand, the approach is very time consuming.

- *Evaluation of seismic capacity of SSCs*: for the quantification of the seismic capacities of SSCs, different approaches are applied depending on the type of component and the failure mode. For structures as well as structural and mechanical failures of equipment, capacities are determined according to modifications of design calculations and/or use of more realistic strength equations considering geometry and statistical data on material properties. For functional failures of electrical and mechanical equipment, fragility test data and other test and/or earthquake experience data are applied in combination with engineering judgement.
- *Assessment of seismic failure probability*: there are various methods for obtaining the parameters of the fragility function, each potentially requiring significantly different levels of effort. In practice, for a given SSC, the method is selected according to the importance of the SSC and to the expected benefit provided by a more realistic estimation compared to a conservative approach. A more refined approach is to perform a multiple-stage evaluation whereby a lower effort method is used first and then, based on the results of an initial risk quantification, more detailed methods may be used for safety-relevant components. Common approaches for quantifying seismic fragilities are listed below (ranked by increasing effort):
    - Using generic fragilities data given by references such as EPRI (2013). Analysts should however provide justification that the generic fragilities data are applicable to the plant-specific SSCs, including an understanding of the purpose and scope of the source of the generic fragilities data (e.g. fragility test data, generic seismic qualification test data, and earthquake experience data) (ASME, 2017).
    - Estimating the High Confidence of Low Probability of Failure (HCLPF) capacity using the Conservative Deterministic Failure Margin (CDFM) approach (EPRI, 1991).
    - Employing the well-established “separation of variables” (SoV) methodology documented in EPRI (1994) and EPRI (2009). In this methodology, median factors of conservatism relative to a reference analysis (e.g. design analysis or other evaluation), as well as variation and uncertainty in these safety factors are identified and quantified in a comprehensive manner.

– In connection with modern methods for the fragility analysis, it is sometimes warranted to perform nonlinear dynamic time-history analyses, possibly considering SSI. It may also be warranted or preferred to more explicitly address correlation in responses and/or modes in realistically modelling failure. In such cases, a simulation approach such as LHS is preferred.

By means of the FA the seismic capacity of SSCs is systematically analysed. Making also use of the SPSA walk-down findings, the FA has a high potential to identify cost-effective seismic capacity improvements, some of which can be easily corrected prior to finalising the SPSA. For example, SPSA often identify anchorage problems with electrical equipment, pumps, large tanks and relay chatter problems, which can usually be fixed without large expense. The ability to identify cost-effective seismic capacity improvements has been proven in many applications and is one of the FA's strongest attributes.

4. Seismic probabilistic safety assessment model

In general, a seismic probabilistic safety assessment (SPSA) model is developed using an existing internal-events PSA model. New basic events are added in order to consider seismic failures of the structures, systems, components (SSCs) already modelled in the internal-events PSA as well as seismic failures due to damage of both passive SSCs and interacting SSCs. In addition, standards such as the Swiss Federal Nuclear Safety Inspectorate (2019) and ASME (2017) require the consideration of secondary hazards induced by seismic events (for example, seismically induced fires and floods) and methods were developed (EPRI, 2013).

The two most common fundamental approaches to SPSA modelling are the discrete approach and the convolution approach (EPRI, 2013).

- *Discrete approach*: typically, the seismic hazard is represented by about 7 to 20 initiating events each representing a range of horizontal ground accelerations. The frequency of these initiating events is derived by discretising the site-specific seismic hazard curve according to the suitable horizontal acceleration ranges or bins. In general, the seismic event trees are developed based on a general transient event tree and the event trees for loss-of-coolant accidents (LOCAs). The impact of the seismic initiating event is considered by incorporating seismic failures of the SSCs, with failure probabilities determined according to the fragility results. The main advantage of this method is that the PSA model, and not the analyst, identifies the seismic sequences/cut-sets. It also allows the use of common existing PSA software to implement SPSA and thus the implementation of SPSA as part of the overall PSA model.
- *Convolution approach*: the term “convolution approach” does not refer to a single procedure but rather to an ensemble of methods using convolution between hazard curves and fragility curves. Convolution is used to compute the seismic core damage frequency (CDF) or to quantify the seismic initiating events considering also seismic phenomena like seismically induced LOCAs. This approach allows the hazard and the fragility curves to be considered in a high level of detail.

Regardless of the overall modelling and quantification approach chosen, the SPSA involves the following modelling aspects:

- *Seismically induced LOCA*: a seismic event may cause minor cracks or leaks in small piping (such as instrument lines) connected to the reactor coolant system pressure boundary. The effect of individual or cumulative leakage of small piping may result in a non-negligible equivalent small seismic LOCA, which may be referred to as a small seismic LOCA (EPRI, 2013). This small seismic LOCA can be conservatively postulated or a more detailed approach, such as the evaluation of pipe specific fragilities, could be used. In order to model any additional seismically induced (small or large) LOCA, a representative piping section is identified by means of the walk-down and associated analyses, and based on suitable characterisation, a fragility function is determined for this representative section.

Then, the effects of seismically induced LOCAs are investigated. Changes in pressure, loss of inventory and associated reduced time windows, the need for a long-term injection system, as well as loss of accessibility due to flooding and radioactivity exposure, are typically considered.

- *Seismically induced fire*: a review of the operational experience shows that fires can be induced as a consequence of seismic events (EPRI, 1990). In addition to seismically induced fires, seismic degradation of the fire protection system and adverse effects of the inadvertent action of fire suppression systems is considered in the SPSA.

Based on the existing fire PSA, significant sources of ignition (fuel tanks, hydrogen bottles, etc.) are identified and the potential for seismically induced failure of the component themselves or of components (not necessarily safety relevant) near the ignition sources are investigated and their potential for seismically induced fires assessed (EPRI, 2013).

- *Seismically induced flood:* the methodology for identifying and assessing the impact of a seismically induced internal flood is fundamentally similar to that for seismically induced fires (EPRI, 2013). If the integrity of a water source is compromised by the seismic event, then not only is the failure of that source considered but also the failure of all components in the flooding zone.

- *Seismically induced external floods* should also be addressed, taking into account the potential clogging of the plant's heat sink due to debris. The reactor catastrophe of Fukushima Daiichi is the most potent example of seismically induced external flood (tsunami). In order to consider properly a seismically induced flood, the risk of tsunami for coastal nuclear power plants should be investigated. For nuclear power plants located close to a river, the potential failure of dams upstream due to the seismic event should also be considered.

- *Other seismic hazards:* a screening analysis may be performed, based on site characteristics, to assess whether, in addition to the vibratory ground motion, other seismic hazards, such as fault displacement, landslide, soil liquefaction or soil settlement are to be included in the SPSA.

- *Seismic Human Reliability Analysis (HRA):* although it is possible to conduct scenario-specific seismic HRA quantifications, the number of unknown elements, such as the high uncertainty regarding the plant status, the distraction caused by the multiple failures of non-safety relevant components, the indications still available in the main control room, the psychological shock and physical fitness of the operator crew after the seismic event, and the accessibility and operability of the controls makes this quantification process onerous and challenging. A common practice to resolve this issue is to base the human error probabilities (HEPs) for the SPSA on the HEPs derived for the internal-events PSA. This modification (increase) of the HEPs for the seismic case reflects the greater difficulty of the task under the uncertain conditions listed above. In any case, it is acknowledged that the residual uncertainty of the HEPs is high.

For human actions that require an operator to access a specific location within a specific period, the quantification of failure probabilities should consider seismic failures that may adversely affect accessibility and/or preclude, hinder or prolong execution of the needed action.

- *Grouping of SSC failures/failure correlation:* although it seems intuitive to assume that seismic component failures are somehow correlated, there are no comprehensive empirical data on the performance of multiple proximate components subjected to similar ground motion (EPRI, 2013; Budnitz et al., 2017). Therefore, analytical models (e.g. scenario simulation approaches) and expert judgement are usually relied upon to address this issue.

The assumption of full failure correlation (i.e. a failure of one component implies the failure of all components in the group) is recommended, for instance, if identical components in proximity are mounted with similar anchorage. The assumption of full independence may be appropriate if the components are more than nominally different, or are located on different floors in different buildings.

Various guidance exists concerning how to model correlations (including partial correlations) between seismic failures of components under various circumstances (elevation, orientation, Eigen frequency, etc.). A review of such guidance is presented in (EPRI, 2013).

It is worth noting that assuming full correlation between all components in a fragility group (i.e. having a single basic event in the PSA model representing the seismic failure of the component type) is only conservative in cases where the components are in parallel on the success path. When the components are in series on the success path, (a failure of any of the component induces a failure of the whole), full correlation is not conservative. In this regard, where possible, the SPSA analyst should seek to determine the most realistic (as opposed to optimistic or conservative) model.

- *Consideration of success probabilities:* internal-events PSA models typically assume success probability values significantly larger than failure probability values (i.e. under the rare event assumption). In SPSA, especially for large accelerations, the failure probability of a number of SSCs will approach, or exceed, the probability of success. Therefore, outside of rare events, approximation will lead to an overestimation of the risk if this is not addressed in quantification. Most codes offer options to treat adequately successes in fault trees and event trees (although increased computational cost may need to be managed).

A detailed SPSA considering a large number of different earthquake initiators together with a detailed modelling of the various seismic failures of SSCs may result in a very large PSA model that cannot be quantified in a reasonable period or at a sufficiently low truncation limit. Although manageable, it may be challenging to reduce the model to an adequate level of detail.

By now, a rich toolset has been developed for a broad scope of SPSA modelling and quantification issues. SPSA methods for modelling and quantifying these aspects of real scenarios are available and described in PSA/PRA standards.

5. On the applicability of seismic probabilistic safety assessment

This chapter discusses the applicability of the seismic probabilistic safety assessment (SPSA) based on the experience of countries where the methodology has been applied. Specific aspects that highlight the bases and justifications for applying SPSA include the following:

- The members of the NEA Working Group on Risk Assessment (WGRISK) earlier stated (in the former version of this TOP): "Based on the large number of successful applications of SPSA around the world in recent years, it is clear that the methodology is now mature enough for routine use, to analyse the risk of core damage accidents and radiological releases that might arise from earthquake-initiated events at nuclear power plants (NPPs)".

Subsequent to this statement, the various forms of seismic evaluation, including SPSA, have been further refined towards enhancing their realism and increasingly applied in the member countries. As such, the original WGRISK statement has been further validated.

- Significant uncertainty is inherent in (i.e. is a factual aspect of) any seismic evaluation, and SPSA provides the systematic framework for explicitly tracking and quantifying uncertainties and their impacts (rather than, for example, ignoring them or leaving their treatment obscure or implicit). This feature of SPSA is one of its key strengths, lending it broad utility.
- Probabilistic seismic hazard analysis (PSHA) addresses variabilities associated with the size and location of earthquakes, as well as (for each given earthquake) the variability in ground motion experienced at a site, in order to assess the site ground-shaking hazard. The approach is systematic as well as comprehensive concerning the scope of scenarios. As different credible experts generally make multiple alternative assessments for the PSHA input variabilities, collectively their suite of assessments leads to a distribution in PSHA results, from which best-estimate hazard and other hazard statistics are developed. Approaches for synthesising the knowledge base of multiple credible experts in PSHA have been developed and extensively tested – e.g. the original Senior Seismic Hazard Analysis Committee (SSHAC) approach, as mentioned in the previous section, as well as variants on the SSHAC approach. On this basis, a large number of quality PSHAs have been successful performed in various countries, for diverse application areas.
- Fragility analysis (FA) employs best practices from both analysis and use of experience data (empirical performance data and test data). A comprehensive

FA synthesises this information. Thereby, it delivers results in the form of multiple seismic capacity distributions (for each component of interest), from which the most realistic result (best estimate) and other statistics are derived. Making also use of the SPSA walk-down findings, FA facilitates the identification of cost-effective seismic capacity improvement, aside from its role in enabling the determination of CDF and large early release frequency (LERF) (and their respective uncertainties). This is one of its strongest attributes and has been proven in many applications.

- By now, a rich toolset has been developed for a broad scope of SPSA modelling and quantification issues. Some potentially critical aspects of real seismic accident sequences include: human errors and collateral effects caused by earthquakes, such as seismically induced fires and floods. SPSA methods for modelling and quantifying these aspects of real scenarios are available and described in PSA/PRA standards. Real seismic events demonstrate the importance of considering these elements in SPSA.
- SPSA is sufficiently versatile to make use of various types and levels of information (e.g. from generic data to high-precision site-specific data). As such, SPSA is capable of graduated use that can progress in accuracy and realism based on initial findings and study requirements. For achieving maximum insights, SPSA can be highly plant specific and make use of the most advanced analyses. SPSA is often conducted at Level 1 considering full power; however, in an increasing number of countries it is being applied also for other plant states and PSA levels.

As is the case with other PSA applications, the results and insights from SPSA are used as part of risk-informed decision-making. The consideration of the PSA results complements the basis of the decision-making. The use of PSA in the risk-informed decision-making will be particularly meaningful and comprehensive if SPSA is considered. Ongoing claims regarding a supposed lack in the maturity and realism of SPSA should not overshadow the fact that earthquakes can be an important contributor to plant risk, and that SPSA is a useful tool for risk-informed decision-making. In some countries, SPSA is used or encouraged to complement the existing deterministic regulatory approaches. Both for determining site-specific seismic design bases, and for establishing the seismic design factors and rules for structures and equipment, SPSA methods and insights have become embedded in regulations. Additionally, various applications of SPSA have been successfully undertaken (see next section for additional information on application).

Continuing research aims to better understand and, where possible, to reduce the uncertainty in seismic evaluation approaches. Considering the randomness associated with earthquakes and the frequent lack of strong motion data, it can be expected that uncertainties will remain a significant aspect. Performing SPSA allows the systematic identification of seismic-related weaknesses. The current state of the art in SPSA has already permitted the identification of many significant cost-effective back-fits in countries applying SPSA.

In summary, SPSA continues to be a most valuable tool providing useful results and insight and is applicable to support risk-informed decision-making as shown in many member countries. Specific SPSA applications are described in the following chapter.

6. Seismic probabilistic safety assessment applications

Possible seismic probabilistic safety assessment (SPSA) applications that have already been implemented in some member countries include the following:

- *Design specifications:* for future plants, an appropriate estimate of seismic hazard enables the determination of a suitable seismic design-basis earthquake for structures, systems, components (SSCs). Using the site-specific seismic hazard curves (from a probabilistic seismic hazard analysis, PSHA) spectral design requirements (such as the safe shutdown earthquake) can be determined.

For existing plants, modifications may be subject to new design and safety requirements. For instance, the installation of a new safety system or a new emergency diesel generator may need to consider the latest seismic hazard as derived from the most-recent accepted PSHA.

- *Seismic safety re-evaluation:* the state of the art in PSHA is under constant development. In various countries, their national seismic hazard institute may regularly update seismic hazard assessments based on refined and new methodologies and insights. When new hazard estimates meaningfully differ from previous results, a re-evaluation of the seismic safety may be generally necessary.

A probabilistic reassessment of safety involves an update of the SPSA. The results can be used to identify adequate risk-efficient back-fits.

Likewise, a deterministic reassessment of a seismic safety proof for an existing nuclear power plant may be supported by probabilistic considerations. For example, the ground motion input for a deterministic seismic safety proof can be defined by a given annual exceedance probability (WENRA, 2014). In addition, it is admissible in some countries to use fragility parameters as a basis for deterministic demonstration of the stability, integrity and function of the corresponding systems. For example, if the HCLPF capacity is higher than the acceleration of the earthquake considered in the seismic safety proof, then the seismic safety of the component is correspondingly demonstrated for the deterministic assessment.

- *Improving the seismic safety of the plant:* the seismic safety is usually improved in two ways.

First, during the process of performing the SPSA: the detailed analysis of components (including their anchorages) may reveal deficiencies which can be easily corrected prior to finalising the SPSA. During the seismic walk-down, it is an additional objective to identify issues that are easily fixable but nonetheless have a significant impact on the component capacity. Such findings are typically related to equipment anchorage issues and seismic interactions. Interactions may be caused by a non-safety-relevant item physically impacting, or interfering with, a safety-relevant component (for instance, a heavy overhead chain colliding with the shaft or motor of a pump). It is also possible that two safety-relevant components may themselves adversely interact (e.g. two adjacent electrical cabinets colliding) during an earthquake if they are not fixed together.

Second, once the results of the SPSA are available: potential plant weaknesses are identified, thus pointing to effective means for risk reduction. Considering the dominant cut-sets, the risk-importance measures and dedicated sensitivity analyses, the most effective plant improvements can be identified. In addition, SPSA allows the quantification of the risk benefit of potential plant improvements.

- *Seismic housekeeping:* seismic housekeeping involves the development of procedures and the training of plant personnel to avoid exacerbating, or creating new, seismic safety issues when performing maintenance, replacing components or adjusting plant configuration. For instance, the seismic housekeeping may include guidelines for blocking the wheels of the mobile equipment, for undertaking regular controls to verify that the crane is parked in a safe position, or for removing all standing ladders from safety-relevant rooms.
- *Emergency preparedness:* SPSA can play a role in the development of emergency operating procedures (EOPs) and severe accident management guidance covering the failure of multiple components (e.g. emergency diesel generators) simultaneously. SPSA can highlight accident sequences which may not be covered by the existing procedures (e.g. multiple instrumentation failures, inaccessibility etc.). New procedures and guidance can be developed to address these scenarios. SPSA can also provide a basis for the development of accident scenarios for training purposes. Given a predefined value of seismic acceleration, the SPSA can help to identify the components that are likely to fail if exposed to this acceleration. These components can then be assumed unavailable in the accident scenario.
- *Further applications of PSA:* other applications of PSA (e.g. changes to technical specifications and limiting conditions of operation changes, risk-informed classification of SSCs, ageing surveillance and risk-informed in-service inspection) are strengthened by considering the SPSA, in particular if the seismic risk is a significant contributor to the overall plant risk.

Including SPSA in the scope of the PSA accounts for a potentially important risk contributor, and, thus, stands to further strengthen the overall usefulness of a PSA.

7. Areas for seismic probabilistic safety assessment research and development

Some important areas of research and development (R&D) for enhancing seismic probabilistic safety assessment (SPSA) include the following:

- Research on seismic source modelling and empirical ground-motion modelling in the context of probabilistic seismic hazard analysis (PSHA).
- Investigation and development of advanced modelling and simulation (M&S) for fully nonlinear soil-structure interaction (NLSSI) analysis, as well as experimental investigations, in concert with empirical studies, aimed at verification and validation of NLSSI models and simulation results.
- Modelling and quantification approaches for improved treatment of correlations in seismic input and response motions, as well as in seismic failures of structures, systems, components (SSCs).
- Investigation of M&S development for coupled in-structure response spectra, for improved seismic response and fragility treatment for components having multiple support locations.
- Continued experimental seismic test investigations (including seismic fragility testing), in concert with continued collection of earthquake experience data (i.e. seismic performance of SSCs in real earthquakes), for developing improved seismic fragilities.
- Numerical M&S, in concert with experimental and empirical studies, to assess the impacts of ageing on seismic performance and seismic fragility of SSCs.
- Development of improved methods to include secondary hazards induced by seismic events (like seismically induced fires and floods) in SPSA.
- Improvement of the technical basis to support seismic human reliability analysis (HRA) quantifications as well as development of refined HRA methods which can be applied with reasonable effort and which are sufficiently scenario-specific for seismically induced events.

Additionally, work continues on improvement in databases, database and technology management, project management and fragility training in SPSA, as well as updating of the documentation of associated guidance and standards.

8. Conclusions

Seismic probabilistic safety assessment (SPSA) allows the consideration of seismic risk in a PSA and in its applications. As part of the SPSA, the probabilistic seismic hazard analysis (PSHA) includes a comprehensive quantification of the seismic hazard by systematically considering the various sources of the typically very large uncertainty. Several methods with different levels of effort and accuracy are available to perform the seismic fragility analysis (i.e. to quantify the seismic failure probabilities of structures, systems, components). Existing modelling techniques consider earthquake specific phenomena such as the dependence between seismic failures of similar components, seismically induced loss-of-coolant accidents (LOCAs), other seismically induced transients, or secondary hazards (e.g. seismically induced fires or floods). SPSA thus provides a broad scope of insights relating to plant safety. The inclusion of SPSA in a risk assessment results in a more complete risk picture, and thus enables more meaningful PSA applications.

Research is ongoing to refine existing methods in various fields of SPSA. These efforts can help to further improve the quality of SPSA and strengthen its applications. In many member countries, however, SPSA (or key elements thereof) are already systematically applied and accepted as a valuable tool for risk-informed decision-making.

References

American Society of Mechanical Engineers (2017), "Case for ASME/ANS RA-Sb-2013, Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications", ASME/ANS RA-S CASE 1.

Budnitz R.J., G.S. Hardy, D.L. Moore and M.K. Ravindra (2017), "Correlation of Seismic Performance in Similar SSCs (Structures, Systems, and Components)", NUREG/CR-7237.

Budnitz, R.J., et al. (1997), "Recommendations for Probabilistic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts", Senior Seismic Hazard Analysis Committee (SSHAC), NUREG/CR-6372, Vol. 1-2.

Kammerer, A.M. and J.P. Ake (2012), "Practical Implementation Guidelines for SSHAC Level 3 and 4 Hazard Studies", NUREG-2117 Revision 1.

Electric Power Research Institute (2013), "Seismic Probabilistic Risk Assessment Implementation Guide", EPRI 3002000709.

Electric Power Research Institute (2009), "Seismic Fragility Applications Guide Update", EPRI 1019200.[1]

Electric Power Research Institute (1994), "Methodology for Developing Seismic Fragilities", EPRI TR-103959.[1]

Electric Power Research Institute (1991), "A Methodology for Assessment of Nuclear Power Plant Seismic Margin", NP-EPRI-6041, Revision 1.

Electric Power Research Institute (1990), "Survey of Earthquake-Induced Fires in Electric Power and Industrial Facilities", EPRI NP-6989.[2]

NEA (2002), *Seismic Probabilistic Safety Assessment for Nuclear Facilities*, CSNI Opinion Papers No. 2, OECD Publishing, Paris.

1. This reference has been superseded recently by the following report which is so far not publicly available: Electric Power Research Institute (forthcoming), "Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessments", EPRI 3002012994, 27 Sep. 2018.
2. There is a more recent report, which is so far not publicly available: Electric Power Research Institute (forthcoming), "Methodology for Seismically Induced Internal Fire and Flood Probabilistic Risk Assessment", 3002012980, 27 June 2018.

Swiss Federal Nuclear Safety Inspectorate (2019), “Probabilistic Safety Analysis (PSA): Quality and Scope”, ENSI-A05/e.

Western European Nuclear Regulators Association (2014), “WENRA Safety Reference Levels for Existing Reactors”, Issue T4.2.

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Seismic probabilistic safety assessment (SPSA) is a systematic method for examining and evaluating the risk from earthquake-initiated accidents. The significant advances in the area of SPSA since the initial publication in 2002 of *Technical Opinion Paper No. 2: Seismic Probabilistic Safety Assessment for Nuclear Facilities* by the OECD Nuclear Energy Agency have prompted its revision. The objective of this report is to provide the up-to-date international view on the state of the SPSA as it is currently being applied, including a description of the main elements of SPSA. While the uncertainties associated with seismic hazard and the determination of seismic failure probabilities are typically large, the inclusion of SPSA in a risk assessment results in a more complete risk picture, and thus enables more meaningful PSA applications.

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