NENE
International Conference
Nuclear Energy for New Europe

Seismic Risk Assessment Of Safety-related SSCs

Matjaž Dolšek
Faculty of Civil and Geodetic Engineering, University of Ljubljana
Jamova 2
SI1000, Ljubljana, Slovenia
matjaz.dolsek@fgg.uni-lj.si

ABSTRACT

Seismic risk assessment for nuclear installations is a multifaceted challenge involving seismic hazard analysis and seismic fragility analysis. Despite advances in probabilistic seismic hazard analysis, uncertainties persist, and seismic fragility analysis remains somewhat simplistic due to computational demands and a scarcity of high-intensity ground motions. This paper summarizes seismic risk assessment for nuclear installations, highlighting challenges and potential innovations in hazard assessment, fragility analysis, and risk estimation. At the end, it briefly presents an alternative approach that combines earthquake-resistant design and seismic risk assessment by utilizing risk-targeted fragility functions at the system level. It encourages interdisciplinary collaboration to enhance assessments of earthquake-induced risks. This approach simplifies the process, requiring engineers to demonstrate that the actual risk is less than the target risk rather than estimating the value of seismic risk with an unknown level of uncertainty.

1 INTRODUCTION

Seismic risk assessment of nuclear installations is a highly complex problem that combines seismic hazard analysis and seismic fragility analysis. It is well known that seismic hazard analysis and seismic fragility analysis involve uncertainties that cannot yet be eliminated. In recent decades, probabilistic seismic hazard analysis has seen significant improvement, driven by the rapid growth of strong ground motion recordings. However, this improvement has not led to a significant reduction in the level of uncertainty in the evaluation of seismic hazard at the site of interest. On the other hand, the seismic fragility assessment is still generally considered to be overly simplistic. This is primarily due to the computationally demanding simulations of seismic responses of structures, systems, and components (SSCs) within nuclear installations. Additionally, the scarcity of ground motions with extremely high intensities and the complexity of nuclear installation systems have contributed to the limited evolution of simplified procedures for seismic fragility assessment over the past forty years [1,2,3].

The paper summarizes the seismic risk assessment of SSCs, addressing challenges and potential innovations in seismic hazard assessment, seismic fragility assessment, and seismic risk estimation.

Section 2 discusses limited results of probabilistic seismic hazard analysis (PSHA), especially concerning the uniform hazard spectrum. The significance of estimating the maximum value of ground motion intensity at the site of interest is also discussed.

Seismic fragility analysis is briefly explained in Section 3. The concept of a seismic fragility function is presented, and discussed why it is particularly challenging to evaluate it in the case of SSCs within nuclear installations.

Follows the discussion on the seismic risk assessment (Section 4) by focusing on the definition of the lower and upper limits in the risk integral from a physics-based perspective. Finally, some insight into alternative possibilities for verifying seismic risk is given. It is argued that if precise seismic risk calculations are unattainable, it may be prudent to develop a methodology that can be used just to demonstrate that the estimated risk is less than the predefined target risk rather than attempting to estimate the absolute numerical value of seismic risk. In conclusion, avenues for future research in this field are proposed, acknowledging the complexity of seismic risk assessment within nuclear installations.

2 SEISMIC HAZARD ASSESSMENT

The knowledge about earthquakes is not yet developed to such a level that it would be possible to forecast seismic events, encompassing both their temporal occurrence and the magnitude of ground motion at a given site of interest. Consequently, the challenge of predicting ground motion in the future is currently addressed by probabilistic seismic hazard analysis (PSHA), which decomposes the problem into different models involving the identification of earthquake sources, determination of earthquake occurrences with specific magnitudes, development of the source-to-site distribution, formulation of a ground motion model as a function of earthquake magnitude, distance, and other relevant parameters influencing ground motion characteristics. These considered uncertain models are then coupled with the total probability theorem to calculate seismic hazard curves defining the relationship between the ground motion intensity measure and the probability of exceeding a defined ground motion intensity threshold. The seismic hazard curves are then used to estimate the uniform hazard spectrum(UHS) that is often prescribed as the basis to define the design seismic action in relation to the target mean return period. The conventional PSHA allows the disaggregation of the PSHA results in order to understand better to what extent the earthquake sources, earthquake magnitudes and to-site distances contribute to, for example, spectral acceleration at a given period and a given mean return period. Based on the PSHA disaggregation, it is possible to define controlling earthquakes that can be used for ground motion selections for seismic response analysis of structures.

In the earthquake-resistant design and seismic risk assessment of nuclear installations, only very limited results from PSHA are usually considered. Some guidelines for seismic fragility assessment of nuclear structure prescribe that the seismic action should be based on the uniform hazard spectrum, but it is well known that spectral accelerations in the uniform hazard spectrum result from different seismic sources and different source-to-site distances, which means that such ground motions cannot occur at a single earthquake event. This issue was solved by Baker [4], who proposed a conditional mean spectrum and, later on, the conditional spectrum to be used for ground motions applied in the seismic response analysis.

The conditional acceleration spectrum is an acceleration response spectrum, which is determined by selecting a spectral acceleration at a specified conditioning period, for example, from the uniform hazard spectrum, while the remaining spectral accelerations are then determined to be most likely, given that the spectral acceleration at the conditioning period has occurred. Thus, the ground motions from the conditional response spectrum can be interpreted as the most likely ground motions given the spectral acceleration at the conditioning period.

An example of the empirically estimated conditional response spectrum is presented in Figure 1. It was obtained by analyzing the ground motions in the strong ground motion database. The conditioning period was set to 0. Thus, the conditional spectrum is conditioned to the peak ground acceleration (PGA). To construct the conditional spectrum, ground motions were queried from the strong ground motion database. Only those ground motion recordings were considered in the construction of the “empirical” conditional spectrum for which the recorded PGA was almost equal to 0.29g. Such recordings in the database were equal to 68, provided that the query was limited to shear wave velocity in the interval from 180 to 360 m/s (i.e. soil type C). The response spectra of 68 ground motion recordings are presented in grey and correspond to earthquake magnitude from 4.3 to 7.9 and source-to-site distances from 0 to 144 km. The mean of response spectra from the database (in red) is the mean conditional spectrum. The 16th and 84th percentile spectra (dotted red curves) represent the ground-motion randomness. The mean conditional response spectrum and the percentile spectra are termed conditional spectrum. It can be observed that it differs from the Eurocode 8 spectrum. There are only slight differences between the two response spectra for high frequencies, but for frequencies lower than four Hz, about 15% reduction in spectral accelerations can be observed with respect to the Eurocode 8 spectrum. Considering the conditional spectrum for seismic risk assessment of nuclear installations would provide more reliable estimates of seismic risk than currently used in different parts of the world.

However, it is also crucial to estimate the upper bound of ground-motion intensity, which has been a subject of research for about half a century [5]. Insufficient attention is paid to such analyses. The upper bound can significantly impact the assessed seismic risk, e.g., the risk of collapse [6], as it is discussed later in the paper. As discussed in [6], an approximate procedure for estimating the upper bound of ground-motion intensity could be based on the ground motion model considered in the PSHA. For example, the predictor parameters that must be chosen to estimate the upper bound of ground motion are at least the source-to-site distance and the threshold level above the median ground-motion intensity. In PSHA, the truncation level is not limited because the main focus is on the design seismic action, but physical limitations most probably exist, especially in relatively soft soils.

In a more general case, the estimation of the upper bound of ground motion intensity should be evaluated with consideration of the seismic response of a structure because the final goal is to understand the upper bound ground motion intensities in the nuclear installation and not just at the free surface. It is well known that the soil-structure interaction of heavy nuclear installations dissipates energy with the nonlinear behavior of the soil in the vicinity of the structure. Further research that will focus on PSHA and seismic fragility assessment is needed to enable the estimation of the physical limits of ground motion intensity. With such knowledge, the seismic risk assessment of nuclear installations would become more reliable, especially in areas with moderate to high seismic hazards.

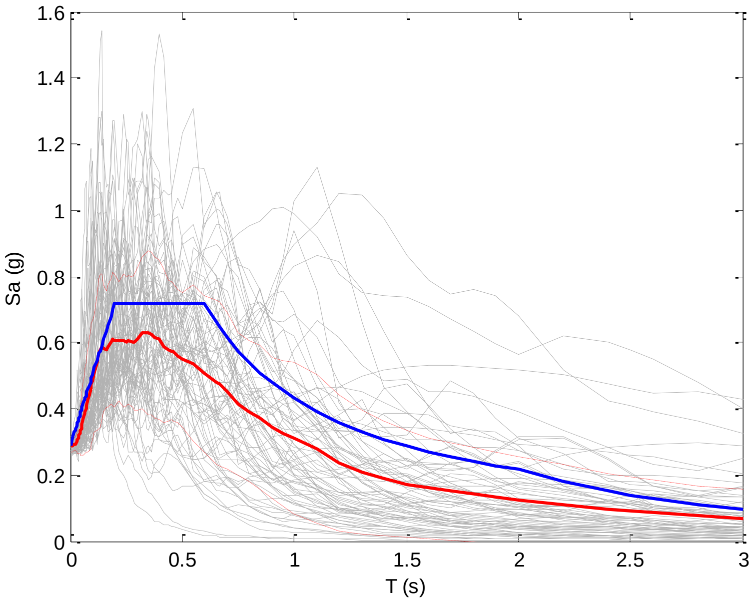

Figure 1. An empirical version of conditional acceleration response spectrum conditioned to PGA, compared with elastic acceleration response spectrum from Eurocode 8 and acceleration spectra of selected ground motion recordings representing ground motion randomness.

3 SEISMIC FRAGILITY ASSESSMENT

The result of the seismic fragility analysis is the fragility function, which represents a probability that the engineering demand parameter (EDP) exceeds a certain limit-state value *edp* given the seismic ground-motion intensity *IM* = *im*. In the simplest case, it is assumed that the seismic fragility function is based on lognormal distribution function:

$$P\left(EDP > edp \,\middle|\, IM = im\right) = 1 - \Phi\left(\frac{\ln edp - \ln \mu_{edp}}{\beta_{edp}}\right) \tag{1}$$

where $\Phi(\bullet)$ represents the standard normal distribution function, μ_{edp} is the median value of the EDP given the intensity im and β_{edp} is a standard deviation of the natural logarithms of the EDP given the $IM = im$. Often, the definition of the fragility functions is expressed as follows:

$$P\left(LS \middle| IM = im\right) = \Phi\left(\frac{\ln im - \ln \mu_{imLS}}{\beta_{imLS}}\right) \tag{2}$$

where $P\left(LS \middle| IM = im\right)$ is the probability of exceeding the limit state *LS* if the ground motion intensity measure takes on a value equal to im, μ_{imLS} is the median limit-state intensity and β_{imLS} is the corresponding standard deviation of natural logarithms. The two parameters, therefore, define the fragility function, the median value μ_{imLS} and β_{imLS}.

In general, seismic fragility analysis is as complex as PSHA, but the treatment of ground motion randomness and uncertainty in the case of seismic fragility analysis is usually significantly simpler than that considered in PSHA due to many challenges that must be overcome to provide unbiased estimates for μ_{imLS} and β_{imLS}.

An example of seismic fragility function estimated by simple procedures is presented in Figure 2. In addition to the median seismic hazard unction, the percentile seismic hazard functions are also presented. It can be argued that estimating the probability of exceedance of a limit state for PGA above 2 g is extremely uncertain.

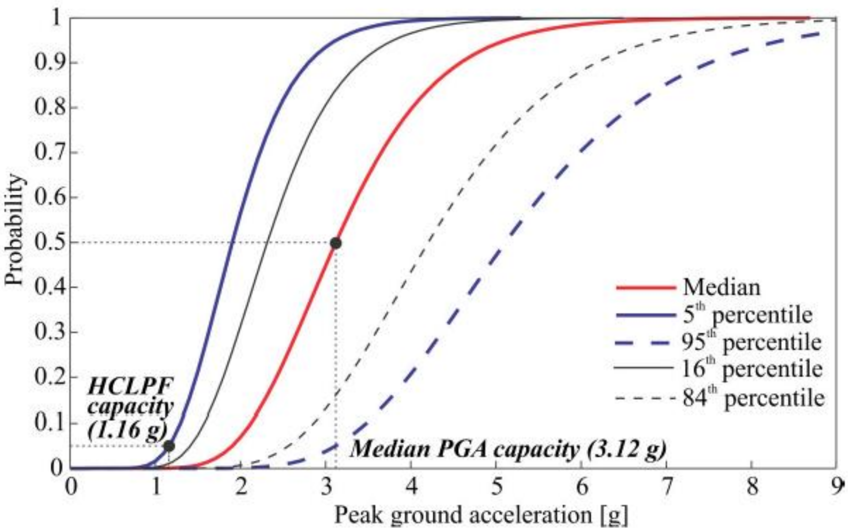

Figure 2. An example of the seismic fragility function, median and percentile curves.

In a general case, the seismic fragility function should be estimated for the loss of function of an SSC, but this is not the case because the functionality of the SSC is not a part of the model considered in seismic response simulations. Consequently, fragility functions are based on the limit-state engineering demand parameters often arbitrarily defined in the structural and other codes.

It is also crucial to recognize that fragility functions are defined for specific ground motion intensity measures, each with varying degrees of efficiency and sufficiency. Nevertheless, it remains a prevalent practice to employ PGA as the primary ground motion intensity measure in fragility analysis for nuclear, despite the awareness that this ground motion intensity measure does not directly affect the seismic demand of SSCs. Because the fragility functions are IM-dependent, it is very important that they are coupled with an adequate seismic hazard function when calculating the risk. This coupling ensures that the fragility functions align effectively with the seismic hazard, enhancing the accuracy and relevance of the risk analysis process. A study on the most appropriate IMs for performing seismic fragility analysis in nuclear installations is ongoing within METIS project.

Nevertheless, the main problem of seismic fragility analysis in nuclear installations is that generally, treatment of ground motion randomness and uncertainties requires many simulations of seismic response of SSc. These simulations should involve:

- nonlinear dynamic soil-structure interaction analyses,
- hazard consistent suits of ground motions to account for ground motion randomness and
- logic trees to account for the input data uncertainty and modelling uncertainty.

Because mathematical models of nuclear structures that include soil structure interaction are very large in terms of degrees of freedom, it is already very computationally demanding to run only one nonlinear dynamic analysis. With the development of software and hardware, this problem may be overcome, but it may still be problematic to obtain ground motion recordings for very high ground motion intensities. Consequently, simplified methods for seismic fragility assessment in nuclear installation have been developed and are often used for practical applications, but their accuracy is actually unknown because of many assumptions incorporated in such methods.

4 SEISMIC RISK ASSESSMENT

Seismic risk assessment couples seismic fragility function and seismic hazard curve in order to calculate the risk of exceedance of a designated limit state, which is often expressed by the mean annual frequency (MAF) of limit-state exceedance that is defined by seismic risk equation:

$$\lambda_{LS} = \int_0^{\infty} P\left(LS \middle| IM = im\right) \cdot \left| \frac{dH\left(im\right)}{d\left(im\right)} \right| \cdot d\left(im\right) \tag{3}$$

where the hazard curve $H(im)$ represents the annual rate of exceedance of im. The Eq.(3) is often used in seismic risk assessment of structures, but the lower and the upper limit are not physics-based. In general, the integral should be integrated from im_1 to im_2, where im_1 represents the minimum intensity causing a violation of a designated limit state, and im_2 represents an upper bound of ground-motion intensity [6]:

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$$\lambda_{LS} = \int_{im_1}^{im_2} P\left(LS \middle| IM = im\right) \cdot \left| \frac{dH\left(im\right)}{d\left(im\right)} \right| \cdot d\left(im\right) \tag{4}$$

The upper bound of ground-motion intensity is related to the physics of earthquakes, the tectonic regime, and the geology of the terrain in the region from the hypocenter to the site of the building. It should be noted that the estimation of the upper bound of ground-motion intensity close to the physical limit is highly uncertain since all the parameters of the problem are not yet well understood. However, the upper bound of ground-motion intensity is not necessarily the physical limit of the intensity at the free surface. The primary objective is to understand the upper limits of ground motion intensity at the foundation of the nuclear installation. If the soil at the site is relatively soft, it is expected that such a limit exists, but it is not considered in the seismic risk assessment.

In general, consideration of the upper bound of ground-motion intensity does not affect just the upper integration limit of the risk equation. The physics-based upper bound of ground motion intensity should be incorporated in the probabilistic seismic hazard analysis because it also has an impact on the hazard curve, especially if the fragility function refers to high ground motion intensities (Figure 3), which cannot be predicted with reasonable accuracy.

Even though the seismic risk would be estimated by Eq.(4), it reflects the seismic risk of only a single SSC, while nuclear installations include many interdependent SSCs, also in terms of their seismic response. The seismic risk of a system of SSCs in nuclear installations is usually treated by the event trees realized by Monte Carlo simulations to simulate the system failure. However, such an approach does not reflect the SSCs interdependency in terms of their seismic response because each SSCs in the event tree is represented by a fragility function that is independent of the fragility functions of other SSCs in the event tree.

The propagation of uncertainties in seismic risk assessment is necessary. Consequently, the estimated risk is also uncertain because of uncertainties in the seismic hazard analysis, seismic fragility analysis and uncertainties in evaluations of seismic risk of a single SSC or a system of SSCs. The question arises of how accurate the results of such an approach are and if it makes sense to verify the seismic performance of the nuclear installations with a target seismic risk associated with the prevention, for example, of the core damage frequency. There are many arguments that such a safety verification is not optimal.

Namely, parts of seismic risk analysis of nuclear installations are prepared by varying levels of detail, as discussed in this paper. The target risk is often defined arbitrarily, with a single value of exceedance probability without accounting for the consequences, as it is considered in contemporary earthquake engineering. There are many other risk measures (e.g. expected annual losses, expected number of fatalities, etc.) that should be included in the definition of target seismic risk and not only the acceptable probability of exceedance of a designated limit state. In the future, the decision-making about the target risk will probably be developed significantly. Finally, for the new SSCs, the earthquake-resistant design and seismic risk assessment of SSCs is usually performed as a two-step approach. In the first step, the standards are used to design the SSCs based on simple seismic response analyses, while in the second step, the seismic risk is estimated by a very simplistic definition of seismic fragility functions and compared with the target seismic risk. Thus, the process of earthquake-resistant design of new SSCs and the seismic risk assessment are considered uncoupled, which is not an optimal approach.

An alternative approach for the current state of practice of earthquake-resistant design and seismic risk assessment was proposed recently by introducing the risk-targeted fragility functions accounting for a target risk at the system level, considering system performance and domino effects [7]. The probabilistic framework based on Monte Carlo simulations makes it possible to calculate the risk-targeted fragility functions of the critical SSCs by considering the system performance and target risk for the entire earthquake-affected area, including domino effects. This approach makes it possible for engineers from different disciplines to continuously improve models and methods for performing various analyses of the probabilistic framework. In general, structural and earthquake engineers, seismologists, chemical, mechanical and electrical engineers and other experts for the estimation of industrial risk should work together to improve assessments of potential loss of life due to earthquake ground motions and related domino effects. Such an approach is not computationally demanding in terms of seismic response analysis because the main aim is to calculate the risk-targeted fragility functions. The resulting functions, should be understood as the target capacity of the SSCs. In the design, the engineer needs to prove that the actual fragility function is on the right-hand side of the target fragility function, which can be done by different methods, including the nonlinear-+ dynamic analysis of the entire system at an appropriate seismic intensity, as also considered by Dolšek and Brozivič [8]. As a consequence, earthquake-resistant design and seismic risk analysis are coupled and performed in a single step. Such an approach may be further investigated within the METIS project.

5 CONCLUSIONS

This paper discusses various aspects of seismic risk assessment for safety-related SSCs in nuclear installations. The complexity levels of different parts of seismic risk assessment can vary. PSHA is commonly regarded as inherently complex, involving comprehensive considerations of epistemic uncertainty. In contrast, both fragility analysis and risk analysis are equally complex but are typically simplified. However, seismic fragility analysis, due to computational demands and inherent limitations, often remains overly simplistic. These assumptions have the potential to impact the accuracy and reliability of the entire analysis. End users of such analyses should be aware that the accuracy of the final results depends on the least accurate sub-analysis.

As seismic risk assessment continues to evolve, it becomes essential to prioritize the verification of risk being below the target rather than estimating the risk by a value that is not known how biased it is. This proposed approach can help reduce the reliance on numerous assumptions prevalent in seismic fragility analysis of SSCs and can streamline the process by coupling earthquake-resistant design and seismic risk assessment into a single step that can be particularly important for the earthquake-resistant design of new nuclear power plants. Furthermore, the paper underscores the growing importance of decision models, which are expected to play a pivotal role in shaping the future of seismic risk management in nuclear installations. These models will facilitate better-informed decisions in this critical domain rather than focusing predominantly on the design PGA.

ACKNOWLEDGMENTS

The work presented herein was carried out with a financial grant from the Slovenian Research and Innovation Agency as part of the Earthquake Engineering Research Program (P2-0185) and the H2020 as part of the research project METIS (MEthods and Tools Innovations for Seismic risk assessment, G.A. no. 945121). This support is gratefully acknowledged.

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