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Application of Bayesian statistics to seismic probabilistic safety assessment for research reactor

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A B S T R A C T

Nuclear facilities are susceptible to the damage due to earthquake hazards. The recent strong earthquake events show the need to explore scenarios in which the expected seismic hazard exceeds a design basis earthquake. In this regard, the seismic probabilistic safety assessment (SPSA) methodology has been developed and utilized to access the overall risk to a nuclear power plant. However, it remains challenging to deal with various uncertainties, accurately to describe correlated events, to accommodate newly observed data and to consider severe accident scenarios within the current framework. In order to overcome such challenges and take advantage of the merits of recent systems analysis concepts, this paper explores a SPSA approach by integrating the current SPSA framework with a Bayesian network and Bayesian inference instead of utilizing the standard fault tree-based technique. The proposed approach enables one to account for what are known as Aleatory and Epistemic uncertainties, to consider the correlated events, to incorporate the additional data and to conduct vulnerability assessments in an accident condition. The proposed Bayesian-based method is demonstrated by its application to a research reactor as an example. Several case studies are conducted to demonstrate how additional information such as correlated events and newly observed data changes the system-level fragility and risk. In addition, a critical scenario is investigated in a situation in which an accident has occurred for a vulnerability assessment beyond a design-basis event. Consequently, it is shown that the proposed approach provides an enhanced framework for risk assessments at nuclear facilities under earthquake hazards. This framework is ultimately expected to be extended to effective plans to mitigate system-level risk and to enhance decision support for risk-informed designs.

1. Introduction

Nuclear facilities such as nuclear power plants, research reactor plants and nuclear fuel cycle facilities operate as critical backbones of urban communities to support sustainable societies in many countries. However, due to the risks inherently associated with nuclear development, the safety of these facilities is a growing, major concern to residents in area affected by natural hazards. Historically, strong earthquakes have occurred near the current sites of nuclear facilities. Examples include, but are not limited to, the 1811–1812 New Madrid earthquake, the 1886 Charleston earthquake, and the 1994 Northridge earthquake in the US. The 2011 Tohoku earthquake which occurred near the Fukushima Daiichi nuclear power plants of Japan exceeded the design-basis earthquake levels and demonstrated the need to explore various vulnerable scenarios beyond design-basis events. In this regard, the nuclear regulatory organizations of the EU, IAEA, US and Korea has been motivated to perform stress tests which reassess the safety of nuclear facilities and evaluate the seismic margins and risk levels of such facilities (ESNRG, 2011; USNRC, 2012; KINS, 2013). However, evaluating the seismic risk and margin is inherently complex due to the large number of structures, components, systems, and structure/component/system interdependencies as well as the absence of important information and the significant number of uncertainties related to seismic hazards and systems.

Seismic margin and risk assessments of nuclear facilities are currently performed by means of the seismic margin assessment (SMA) approach (Budnitz et al., 1985; EPRI, 1991) and by seismic probabilistic safety assessments (SPSA) (USNRC, 1975; USNRC, 1983; IAEA, 1992; EPRI, 1994; ASME/ANS, 2009; ASCE, 2016). The SMA seeks to estimate how much margin exists at a facility above a design-basis earthquake event based on the seismic fragility information of major systems, structures and components, and a systems analysis conducted based on this information. The SPSA is a more complete framework than the SMA because it integrates system-level seismic fragility data and seismic hazard information. One factor in common regarding the two methodologies is that they rely fundamentally on the accurate treatment of

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seismic fragility data and on a proper systems analysis.

The currently used methodology for a systems analysis at a nuclear facility is an event tree approach combined with a fault tree analysis. From an analysis perspective, this approach depends solely on the fault tree analysis technique because the plant damage state of core damage (CD) in the event tree can be mapped into a single combined fault tree. In other words, the plant CD risk can be acquired by solving such integrated fault tree (Yang, 2012). The fundamental assumption when using the standard fault tree is that the basic events are considered as statistically independent. The relationships among the basic/intermediate/top events are defined using logic gates, and the analysis depends on the design-basis events. Furthermore, a traditional implementation of the standard fault tree analysis is fairly static in nature. Therefore, the intrinsic characteristics of the standard fault tree analysis include the limitations in that (1) such an analysis cannot enable the expressing of the statistical dependencies and correlations among events beyond logic gates, (2) it cannot deal with beyond-design accident conditions within the fault tree structure, (3) it cannot accommodate additional data in the fault tree formalism, and (4) *Aleatory* and *Epistemic* uncertainties in the basic events are not explicitly considered.

The limitations of the standard fault tree analysis mentioned above have been attempted to overcome by employing an alternative approach or by combining this method with other techniques. For example, the uncertainties in basic event probabilities are considered by implementing an FTA along with Monte-Carlo simulation (USNRC, 1975), Latin hypercube sampling (Ellingwood, 1990; Kim et al., 2011; Kwag and Ok, 2013) or Fuzzy set theory (Tanaka et al., 1983; Singer, 1990; etc.). The statistical dependencies between events are handled by introducing the correlation coefficients (Zhang 1989; Fleming and Mikschl, 1999; Ebisawa et al., 2015) or utilizing a binary decision diagram or using a common cause failure analysis within a fault tree. The concept of a Bayesian network can manage not only the logic gate relationships but also various statistical dependencies that cannot otherwise be represented by the standard fault tree. Accordingly, Bobbio et al. (2001) proposed a mapping method which converts a fault tree into a corresponding Bayesian network and demonstrated the possibility of considering general dependencies between events. Kwag (2016) presented a representation of a beyond-design accident condition for the multi-hazard scenarios using a Bayesian network. Finally, Bayesian updating has been found to be quite effective for accommodating any type of new discrete or continuous data/information (Hamada et al., 2004; Wilson and Huzurbazar, 2007; Kelly and Smith, 2009; Kwag and Gupta, 2016, 2017; Kwag et al., 2017, 2018). Specifically, the work of accommodating continuous data into the present distributions of the events is accurately capable of describing the current actual status of the events. Such work also further enable exploring the critical scenarios which would never be identified without additional data. Thus, utilizing the Bayesian updating has a strong merit to make feasible the works which cannot be easily previously reflected and to evaluate the actual status of events and overall scenarios in the real-time.

Consequently, in this paper, we explore an assessment approach in which a Bayesian network and Bayesian updating are embedded in the current SPSA method. The proposed Bayesian network-based SPSA approach enables accounting for general statistical dependencies among events and exploring the scenarios subjected to beyond-design-basis events in a single integrated framework. The approach also allows the analyst to incorporate newly observed data from experiments and plant operation experience and to deal with the *Aleatory* and *Epistemic* uncertainties in the seismic fragility data of basic events. The proposed approach is applied to a pool-type research reactor in Jordan. The effectiveness of the approach is demonstrated by a comparison study with the fault tree-based SPSA. Finally, the proposed approach is expected to be utilized for identifying the real-time risk status of a nuclear facility and to aid in making risk-informed decisions.

This paper is organized as follows. It initially presents a current brief overview of the SPSA which includes seismic hazard and fragility analyses. In Section 3, the basic concept of the standard fault tree analysis adopted in the current SPSA is explained, and concepts of a Bayesian network including a mapping algorithm and Bayesian inference are introduced. The introduction of the concepts is limited to the aspects that are necessary in this study. In Section 4, we describe the explored proposed approach. Essentially, the current SPSA procedure is integrated with a Bayesian network and Bayesian inference. Section 5 illustrates the performance of the proposed approach when applied to an example of a pool-type research reactor; this section also discusses important findings. To do this, we compare the results of the standard fault tree-based approach with those of the proposed method by utilizing several cases. Section 6 concludes with a summary and discussion.

2. Overview of the SPSA

The quantitative seismic risk of nuclear facilities in the event of a beyond-design-basis earthquake can be obtained by a seismic probabilistic safety assessment (SPSA) (USNRC, 1975; USNRC, 1983; IAEA, 1992; EPRI, 1994; ASME/ANS, 2009; ASCE, 2016). Unlike an internal probabilistic safety assessment, the SPSA covers different accident scenarios caused by the external event of an earthquake. The end result of the SPSA shows how vulnerable the entire nuclear system of interest is under all possible magnitude ranges of earthquake events by representing the annual core damage frequency (CDF) or large early release frequency (LERF) of radio-active materials. This is utilized to identify the weakest scenario in the system, to modify the current design and ultimately to undertake risk-informed decision making to enhance the safety of the system. The comprehensive SPSA process is represented in Fig. 1 (EPRI, 1994). The basic elements of a SPSA include the following tasks:

- Probabilistic seismic hazard analysis
- Seismic fragility analysis
- Systems analysis
- Consequence analysis, i.e., risk quantification

The seismic hazard curve expresses the annual probability of exceedance as a function of the intensity measure employed to characterize the hazard. The fragility curve of components is described in terms of the conditional probability of failure as a function of the intensity measure for a given hazard. The systems analysis is performed to determine the system fragility curve using an event tree and/or a fault tree. The final risk of the CDF is quantified by convolving the system fragility curve with the seismic hazard curve, as follows:

$$Risk = \int P_f(a)\cdot\left|\frac{dH(a)}{da}\right| da \tag{1}$$

Here, a is a seismic hazard intensity parameter, which is the peak ground acceleration (PGA) in this study; $P_f\ (a)$ is the system fragility curve; and $H\ (a)$ represents the hazard curve. In the following subsections, each step except for the systems analysis is detailed. In Section 3, the typical systems analysis of a fault tree as currently utilized in the SPSA is explained, and new systems analysis concepts are introduced.

2.1. Probabilistic seismic hazard analysis

At a given site, questions arise regarding what the intensity of an earthquake will be and what level of ground motion can be expected during a specified time under significant uncertainties. These types of questions give rise to a probabilistic seismic hazard analysis (PSHA). The PSHA sets the goal of quantifying uncertainties about the sources, size, distance, and ground motion of future earthquakes, as well as integrating them to produce an explicit description of the distribution