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Effects of soil-structure interaction on fragility and seismic risk; a case study of power plant containment

Seyed Mojtaba Hoseyni [a], [*], Faramarz Yousefpour [b], Ata Aghaei Araei [a], Keveh Karimi [c], Seyed Mohsen Hoseyni [c]

[a] *Building and Housing Research Center, Tehran, Iran*
[b] *Nuclear Science and Technology Research Institute, Tehran, Iran*
[c] *Faculty of Basic Sciences, East Tehran Branch, Islamic Azad University, Tehran, Iran*

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ABSTRACT

Safety-related structures are designed to provide a safe environment for the occupants and equipment during and after earthquakes. This is due to the fact that any damage imposed to the systems might lead to catastrophic consequences. Seismic probabilistic risk assessment (SPRA) is a systematic approach for the quantification of the seismic risk. One of the crucial steps in this assessment is to determine the seismic capacity of the structures by fragility method. After a review of available methodologies, this article analyzes the seismic fragility for a typical power plant containment considering the effects of soil-structure interaction (SSI). The structure and underneath soil profile are analyzed as a unified model by the subtraction method. Two steps are considered for the assessment of seismic response: In the first step, a fixed-base hypothesis framework is implemented to the computational problem. The second step covers computations taking into account the SSI effects. Using the results of seismic response analysis and safety factor method, seismic fragility of the structure is computed and related fragility curves are developed. Finally, by comparing the fragility curves, the effects of SSI are quantified on the overall seismic risk.

1. Introduction

Safety and integrity of safety-related structures are of crucial importance for the regulators specially those containing hazardous materials (e.g. nuclear and chemical containments). Their sophisticated design is intended to maintain the structural integrity and functionality during and after earthquakes. Any structural damage has the potential to cause catastrophic consequences by jeopardizing health, economy and environment. Therefore, the design is planned in such a way that the seismic induced risk is as low as possible (ASME, 2009).

"The March 2011 earthquake and its subsequent severe accident in Fukushima Daiichi NPP demonstrated that relying on uncertain design could be catastrophic (Hoseyni et al., 2014)". This accident highlighted once again the importance of seismic risk assessment and vulnerability analysis for the NPPs. Lessons learned from this accident motivated the European commission and IAEA to develop the so-called stress test model to reassess the safety of individual NPPs. All nuclear power plants in the EU underwent peer reviews and stress tests in 2011 and 2012 (ESNRG, 2011; Langlois, 2013).

Before the occurrence of 2011 Tōhoku earthquake and its subsequent impacts on Fukushima Daiichi NPP, there has never been any sufficiently strong earthquake in the vicinity of operating nuclear power stations that could cause significant damages and subsequent safety concerns. Now it is clear that in the safety design of the NPPs, the inherent uncertainties must be minimized and a comprehensive reevaluation should be conducted. One of the major uncertainties in the seismic design of NPPs is associated with the effects of soil-structure interaction (Roesset, 1998). Nuclear power plants are structures for which soil-structure interaction effects are important and their evaluation is beneficial. Therefore, the major motivation of this research is to evaluate the significant effects of SSI on the overall seismic induced risk to the NPPs.

This article studies seismic fragility assessment as the main task of seismic PRA. A practical methodology is introduced for seismic fragility analysis; to demonstrate the applicability of the

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[*] Corresponding author.
E-mail addresses: m.hoseyni@bhrc.ac.ir, mojtaba.hoseyni85@gmail.com (S.M. Hoseyni).

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methodology, the framework is applied on a typical PWR containment. "Safety factor method" is selected to perform the fragility analysis. Major efforts are devoted to the quantification of the soil-structure interaction. Moreover, its influence is characterized on the dynamic response of inelastic soil-structure systems and on the resulting fragility curves.

The article is organized as follows: Section 2 provides an overlook of the SPRA methodology. Section 3 discusses the main stages in performing fragility analysis. Section 4 proposes a framework for the study. In Section 5 the proposed framework is applied on PWR containment. Section 6 is devoted to the discussion on the results of the analysis. Finally, Concluding remarks are provided in Section 7.

2. Overview of the methodologies for seismic probabilistic risk assessment

According to the regulations, seismic design of the safety-related structures is conducted in compliance with stringent codes and specifications. Theses strict rules and specifications are established to assure the regulators of the safety of these structures. As a result, margins of safety and conservatism are applied to the deterministic design. The conservative assumptions are intended to address the uncertainties imposed to the problem from lack of knowledge in design and analysis procedures (Hwang, 1988).

"Uncertainty is an unavoidable part of every modeling process. If the objective of modeling is to represent and/or predict reality, uncertainty analysis attempts to quantify the magnitude of the difference between the model's prediction and the reality being represented (Pourgol-Mohamad et al., 2009)". Some of these uncertainties are inherent in nature of the phenomenon (so called aleatory uncertainty), while others emerge from modeling assumptions and limitations in the supporting technical data and knowledge (known as epistemic uncertainty) (Pourgol-Mohammad, 2009). Since earthquake is a random natural phenomenon, it is impossible to precisely predict the spatial and temporal rates of future earthquake occurrences (ANS, 2008b). Similarly, due to idealizations used to simplify the structural model, the structural response may differ from reality. This is also the case for structural capacity which may statistically vary from actual data (Seya et al., 1993). Prediction of the effects of future earthquakes is conducted by probabilistic approach using available knowledge and experiences gained from the past (Konno, 2007). Probability theory has established itself as the science of uncertainty and is utilized to employ the uncertainty into the analysis. To quantify the induced risk to a nuclear power plant, seismic probabilistic risk assessment (Seismic PRA) approach is developed; Seismic PRA is comprised of following tasks (IAEA, 2009):

- Seismic hazard analysis
- Fragility analysis
- System analysis and Consequence (risk) evaluation.

The outcome of a seismic PRA includes the seismic hazard of the site, the structural capacity of structures and equipment, incorporation of uncertainties in seismic hazard, structural fragility and response of the components. It also reveals the failure scenarios of the plant components and their impact on the whole plant system by measures like probability of core melt, probability of release of radioactive materials and potential adverse health impacts (ASME, 2009).

Seismic PRA began in mid 1970s by the USNRC study on reactor safety known as WASH-1400 (USNRC, 1975). There are two available methods for performing SPRA (USNRC, 1983):

i. Safety factor method which the improved format of it was applied on Zion NPP (Pickard et al., 1981).
ii. The Seismic Safety Margin Research Program method (SSMRP). This method was developed by the Lawrence Livermore National Laboratory (Smith et al., 1981).

These two methods were developed according to the basic probability theorem. In 1991, USNRC published a generic letter (USNRC, 1991a) and a guidance (USNRC, 1991b) which requested NPPs to conduct Individual Plant Examination of External Events (IPEEE). The Electric Power Research Institute (EPRI) published a report on methodologies of seismic fragility analysis (Reed and Kennedy, 1994) and guidance on seismic PRA Implementation (Campbell et al., 2002; Wakefield et al., 2003). In the following years, the uses of risk-Informed decisions are implemented on plant licensing, operation and modifications (EPRI, 2000; USNRC, 2000a, 2000b). The American Society of Mechanical Engineers has published standards for performing SPRAs (ASME, 2009).

In recent years, the major efforts are devoted to improvement of the applications on SPRA. There have been significant developments in seismic hazard assessment and ground motion prediction in various researches such as (Panza et al., 2014; Stafford, 2013; Stirling, 2014). More beneficial fragility analysis approaches are proposed in recent references (See (Nakamuraa et al., 2010; Perotti et al., 2013; Pisharady and Basu, 2010; Zentner, 2010)). More standardized procedures have also become available to quantify the uncertainties associated with seismic fragility and risk assessment (See (Baker and Cornell, 2008; Borgonovo et al., 2013; Ellingwood and Kinali, 2009; Kim et al., 2011)). SPRA methods for multi-unit sites were developed in (Hakata, 2007); after the accident at the Fukushima NPP, the importance of multi-unit severe accidents has been emphasized (Schroer and Modarres, 2013).

Nowadays, insights from these methodologies serve in other fields as well and the applications are not limited to nuclear industry. The probabilistic based procedures developed by the nuclear industry are now widely utilized on performance-based design of non-nuclear structures like buildings and bridges (e.g. (Hariri-Ardebili et al., 2014; Kiureghian, 2005; Moehle and Deierlein, 2004; Pirizadeh and Shakib, 2013; Sharma et al., 2014; Yang et al., 2009)).

In this study the safety factor method is selected to quantify the fragility of the case study structure. The safety factor method has been widely used in the SPRA of numerous nuclear power plants around the world. This is mainly due to simplicity and accuracy of the method. The SSMRP method requires more computational efforts and in most cases is not time and cost efficient to be used on a risk assessment of a commercial power plant (ASCE, 1998).

3. Fragility model

Safety-related NPP structures and equipment are designed to withstand against a marginal level of earthquake (i.e. the so called safe shutdown earthquake (SSE)). The intentional conservatisms are considered to assure with high confidence that the probability of failure is low if earthquakes larger than the seismic margin (i.e. SSE) occur. Therefore, the actual capacity of component is found to be much higher than the margin earthquake. Due to the inherent uncertainties, the realistic seismic capacity is incomputable with deterministic methods and is determined by fragility curves using probabilistic approaches. This curve illustrates the conditional probability of failure of the structure or equipment for any given ground motion acceleration (e.g. PGA) (Wakefield et al., 2003).

There is variety of approaches for the fragility analysis. The method of choice here is safety factor method, which is widely used in the nuclear industry. In this approach the ground acceleration