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Seismic probabilistic risk analysis based on stochastic simulation of accelerograms for nuclear power plants in the UK

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ABSTRACT

This article presents an approach to probabilistically assess the seismic risk of nuclear power plants (NPPs) in the UK. The approach proposed is based on direct stochastic simulation of the seismic input to conduct nonlinear dynamic analysis of a structural model of the NPP analysed. Therefore, it does not require the use of ground motion prediction equations and scaling/matching procedures to define suitable accelerograms as is done in conventional approaches. Additionally, as the structural response is directly calculated, it does not require the use of Monte Carlo-type algorithms to simulate the damage state of the NPP analysed. However, it demands longer use of computer resources as a relatively large number of nonlinear dynamic analyses are needed to perform. The approach is illustrated using an example of a 1000 MW Pressurised Water Reactor building located in a representative UK nuclear site. A comparison of risk assessment is made between the conventional and proposed approaches. Results obtained are reasonable and well constrained by conventional procedures; hence, it can confidently be used by the UK New Build Programme in the next two decades to generate 16 GWe of new nuclear capacity.

1. Introduction

The UK nuclear industry has gained an established reputation due to nearly 60 years of successful and safe exploitation of low-carbon nuclear power plants. At present, around 20% of the total electricity supply in the UK is provided by nuclear power (HM Government, 2013). Although no NPP has been built in the UK since 1995 and the majority of UK plants are on their way to be decommissioned, the industry is in the early stages of a long-lasting renaissance. The New Build Programme, intended to build 16 GWe of new nuclear capacity by 2030 involving the construction of at least 12 new reactors plus its likely expansion until 2050 with the development of Generation III+, IV and Small Modular Reactors, is currently under way (NIA, 2012). The necessity of correctly assessing all safety aspects of the new generation NPPs buildings in the UK has become a vital issue for the industry, including their seismic performance. Although the UK is a tectonically stable continental region that possesses medium-to-low seismic activity (Musson, 1996), its seismic hazard is non-negligible as strong ground motions capable of jeopardising the structural integrity of NPPs, although infrequent, can still occur (Musson, 2014). In addition, the occurrence of the Fukushima Dai-ichi nuclear accident (Hirano et al., 2012) in 2011 rose major questions on the seismic safety of nuclear installations worldwide, certainly including the UK. As a response of this accident, Her Majesty's Chief Inspector of Nuclear Installations (Weightman, 2011) recommended that the British nuclear industry should conduct further studies to continue the validation of methodologies for analysing the seismic performance of structures, systems and safety-related components of NPPs. This article is intended to make a contribution towards that aim.

In order to conduct seismic probabilistic risk analysis (SPRA), it is necessary to perform non-linear time history (NLTH) analysis of a structural model. The main obstacle for conducting NLTH analysis of structures is the scarcity of accelerograms compatible with the seismic scenarios that contribute most strongly to the hazard of the site selected. This is an even more remarkable problem for areas of medium-to-low seismicity because: (i) strong earthquakes rarely occur, and (ii) those areas have limited monitoring networks (Lubkowski et al., 2004). These recordings need to be able to realistically represent the frequency content, intensity distribution, and time duration of the strong shaking phase of accelerograms

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associated with the seismic scenarios that contribute most strongly to the hazard of the site selected (Rezaeian and Der Kiureghian, 2010; Rezaeian and Der Kiureghian, 2008). The paucity of accelerograms has led structural engineers to using techniques on selecting, scaling and matching procedures applied to available records (Huang et al., 2011a; Katsanos et al., 2010; NIST, 2012). In general, these procedures are intended to match a spectral shape predicted by *ad-hoc* ground motion prediction equations (GMPEs). Currently, GMPEs play a critical role in seismic hazard and risk analysis and much research effort has been placed on the development of such models (Bozorgnia et al., 2014; Douglas et al., 2014). However, as SPRA requires the direct specification of sets of accelerograms, promising trends in earthquake engineering have been developed aiming at considering alternatives to GMPEs (Musson, 2000; Atkinson, 2012). This article presents an alternative and straightforward approach that does not make use of GMPEs to conduct SPRA for NPPs in the UK, through an example of application. In this procedure, a large set of accelerograms are generated by direct stochastic simulation by means of a predictive model developed previously by the authors (Medel-Vera and Ji, 2016) that are compatible with seismic scenarios of magnitude $4 < M_w < 6.5$, distance-to-site $10 < R_{epi} < 100$ km in rock, stiff and soft soil conditions. Such a model was calibrated using a dataset of accelerograms recorded in the same stable continental region that the UK belongs to, namely NW Europe. A hypothetical UK nuclear site was selected as a representative of a high seismic demand area (for British standards) and the risk is assessed using a simplified model of a 1000 MW Pressurised Water Reactor building. For completion, the alternative procedure is compared to the usual GMPE-based procedure to perform SPRA for nuclear facilities, in order to highlight that the risk assessment procedure becomes remarkably more straightforward when using the approach proposed.

This article is organised as follows: Section 2 provides a general comparison to define seismic inputs and calculate structural outputs in SPRA between the conventional GMPE-based approach and the alternative approach proposed based on direct stochastic simulation. Section 3 describes the structural model used to perform risk assessments that is based on a 1000 MW Pressurised Water Reactor building and the selection of its critical components. It also presents the choice of the nuclear site and a description of its seismic hazard for nuclear design. Then, it shows a detailed comparison to define accelerograms suitable for use in SPRA between the conventional and the alternative approach proposed. Section 4 explains in detail the determination of the fragility curves used to characterise the critical components of the sample NPP. Later, it explains how the structural response is handled when using both approaches and summarises the calculations of risk performed. Section 5 discusses further aspects regarding the appropriateness of the approach proposed and Section 6 presents the conclusions from this study.

2. Description of methodologies

This work is based on the approach to perform SPRA for nuclear power plants reported by Huang et al. (2011b, 2011c, 2010). which in turn was based on the methodology for seismic performance assessment of *buildings* reported in FEMA-P-58 (FEMA, 2012). This methodology involves performing five steps: (i) perform plant-system and accident-sequence analyses, (ii) characterise seismic hazard, (iii) calculate and simulate structural response, (iv) assess damage of NPP components, and (v) compute the risk. These steps are graphically summarised in Fig. 1.

As seen in Fig. 1, such a methodology considers three types of assessments: (i) intensity-based, (ii) scenario-based and (iii) time-based assessments. Intensity-based assessments are intended to estimate the probability of unacceptable performance when a NPP is subjected to a specific intensity of shaking (e.g. PGA = 0.25 g). Scenario-based assessments estimate the probability of unacceptable performance of a NPP under a specific earthquake, defined by a pair of magnitude and distance (e.g. M_w 6 and epicentral distance $R_{epi} = 25$ km). Finally, time-based assessments estimate the annual frequency of unacceptable performance of a NPP taking into account all potential damaging earthquakes that may occur in the selected nuclear site. This work is focused on scenario-based assessments, although the methodology proposed could also be used for applications in the two other assessments.

When performing scenario-based assessments, it is required to define the seismic input for the single scenario (or all scenarios of interest) that contributes most strongly to the hazard of the nuclear site. Such a scenario can be obtained by means of the deaggregation of the hazard curve of the site (Goda et al., 2013). Then, a spectral shape predicted by *ad-hoc* GMPE(s) compatible with such scenario is estimated and few available accelerograms are scaled to match such a spectral shape. The scaled accelerograms are then used to perform nonlinear time-history analysis of a suitable structural model in order to estimate the damage state of the NPP. However, in order to estimate the probability of unacceptable performance with high statistical confidence, a great number of observations of the damage state are required. This leads to the necessity of sampling the structural response (i.e. the *output* of nonlinear time-history analysis) by means of Monte Carlo-type procedures. Such an approach for the simulation of structural response in probabilistic analysis is a known and used technique in earthquake engineering research (see for example Basim and Estekanchi (2015), Gencturk et al. (2016), Spence et al., Fragiadakis et al. (2015), among others). For illustration purposes, Fig. 2 summarises the steps involved to define the seismic input and calculate the structural output in scenario-based SPRA when using the traditional GMPE-based procedure.

The procedure summarised in Fig. 2 is somewhat cumbersome as a number of intermediate steps are required in order to obtain both suitable accelerograms and a great number of observations of the damage state of the NPP studied. The approach presented in this work that makes use of a stochastic accelerogram model previously calibrated by the authors (Medel-Vera and Ji, 2016) is more direct than the traditional procedure. Indeed, once the seismic scenario (or all scenarios of interest) that contributes most strongly to the hazard of the nuclear site is determined, an unlimited number of accelerograms compatible with such a scenario can be simulated. In this light, neither GMPEs nor scaling/matching procedures are necessary. In this approach, the ground motion *input* is sampled and the damage state is directly calculated rather than sampled. Clearly, no Monte Carlo-type procedures would be required to simulate the structural output. For illustration purposes, Fig. 3 summarises the steps involved to define the seismic input and calculate the structural output in SPRA when using the proposed procedure.

The following sections are devoted to present a step-by-step comparison of SPRA between the traditional GMPE-based methodology and the proposed alternative approach through a particular application for NPPs in the UK. For both analyses performed, the seismic hazard curve of the nuclear site was considered to be known.

3. Reactor building, seismic hazard and input definition

3.1. Sample nuclear reactor building

Risk assessments conducted in this article were performed considering a sample NPP based on a 1000 MW Pressurised Water