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# Seismic risk control of nuclear power plants using seismic protection systems in stable continental regions: The UK case

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## HIGHLIGHTS

- Strategies to reduce seismic risk for nuclear power stations in the UK are analysed.
- Efficiency of devices to reduce risk: viscous-based higher than hysteretic-based.
- Scenario-based incremental dynamic analysis is introduced for use in nuclear stations.
- Surfaces of seismic unacceptable performance for nuclear stations are proposed.

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ABSTRACT

This article analyses three different strategies on the use of seismic protection systems (SPS) for nuclear power plants (NPPs) in the UK. Such strategies are based on the experience reported elsewhere of seismically protected nuclear reactor buildings in other stable continental regions. Analyses are conducted using an example of application based on a 1000 MW Pressurised Water Reactor building located in a representative UK nuclear site. The efficiency of the SPS is probabilistically assessed to achieve possible risk reduction for both rock and soil sites in comparison with conventionally constructed NPPs. Further analyses are conducted to study how the reduction of risk changes when all controlling scenarios of the site are included. This is done by introducing a scenario-based incremental dynamic analysis aimed at the generation of surfaces for unacceptable performance of NPPs as a function of earthquake magnitude ($M_w$) and distance-to-site ($R_{epi}$). General guidelines are proposed to potentially use SPS in future NPPs in the UK. Such recommendations can be used by the British nuclear industry in the future development of 12 new reactors to be built in the next two decades to generate 16 GWe of new nuclear capacity.

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## 1. Introduction

Nuclear power plays a crucial role in energy supply in the world: around 15% of the electricity generated worldwide is provided by nuclear power stations avoiding around 2.5 billion tonnes of $CO_2$ emissions (Meiswinkel et al., 2013). The seismic design of new nuclear power plants (NPPs), in order to ensure their safe seismic performance, has received much greater research interest after the Fukushima Dai-ichi accident (Hirano et al., 2012). Currently, it is estimated that around 20% of nuclear reactors worldwide are operating in areas of significant seismic activity (WNA, 2014). In the UK, a tectonically stable continental region that possesses medium-to-low seismic activity (Musson, 1996), strong earthquakes capable of jeopardising the structural integrity of NPPs, although infrequent, can still occur (Musson, 2014). Despite that no NPP has been built in the UK after 1995, a New Build Programme intended to build 16 GW of new nuclear capacity by 2030 is currently under way (NIA, 2012). The necessity of correctly assessing all aspects regarding seismic safety of new generation NPPs in the UK has become a vital issue for the industry (Weightman, 2011). This article is intended to make a contribution towards that aim.

Seismic protection systems (SPS), such as elastomeric-based bearings and energy dissipation devices, have been successfully used in more than 10,000 applications (Martelli et al., 2012). However, only two reactor buildings have been designed with such technology: Koeberg NPP in South Africa and Cruas NPP in France (Forni et al., 2012). Although these two applications were designed more than 40 years ago, extensive research has been conducted since then in order to include SPS in NPPs (Medel-Vera and Ji,

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2014). In the UK, laboratory tests were carried out in early 1990s on small-scale specimens of low-damping rubber bearings and viscous dampers for applications in Liquid-Metal-Cooled Reactors (LMRs) (Austin et al., 1991). Nowadays, several new projects of isolated reactors in medium-to-low seismic areas are currently under way: (i) the Jules Horowitz Reactor (JHR) currently under construction in Cadarache, France (Bignan et al., 2011); (ii) the International Thermonuclear Experimental Reactor (ITER), also under construction in Cadarache, France (Syed et al., 2014); (iii) APR1400, currently under construction in South Korea (Lee et al., 2015). Additionally, some other prominent projects of Generation IV reactors are currently in their early stages: (i) the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID) to be built in France (CEA, 2012); and (ii) the Advanced Lead Fast Reactor European Demonstrator (ALFRED) to be built in Romania (Alemberti et al., 2014). All these applications of reactors consider the use of different types of elastomeric-based bearings: JHR and ITER share the same design of low-damping rubber bearings (Sollogoub, 2014), APR1400 uses lead–rubber bearings (Lee et al., 2015), and ASTRID and ALFRED will use lead–rubber bearings and/or high-damping rubber bearings (Forni, 2015; Moretti and Pasquali, 2013). Additionally, other approaches to seismically protect reactor buildings without isolating the entire nuclear island have been investigated: e.g. the Russian VVER-1000 has been the subject of studies that propose the use of high performance viscous dampers to protect its critical components in future applications (Kostarev et al., 2003). This work investigates the suitability of several SPS that can be used in next generation UK reactors subjected to the seismic conditions of the British Isles.

In this work, a sample NPP reactor building based on a 1000 MW Pressurised Water Reactor building equipped with three different types of SPS was analysed: (i) an isolated nuclear island using low-damping rubber bearings plus viscous dampers; (ii) an isolated nuclear island using lead–rubber bearings, and (iii) a non-isolated nuclear island using only viscous dampers located at the critical components of the NPP. The efficiency of these SPS was assessed to achieve possible risk reduction for both rock and soil sites in comparison with a conventional NPP. The risk was calculated following the methodology for seismic probabilistic risk assessment (SPRA) for NPPs in the UK reported by Medel-Vera and Ji (2016a). A representative location of a UK nuclear site was selected and the risk was initially assessed for the single scenario that contributes most strongly to the hazard of such a site. Then, the variation of risk is studied for different controlling scenarios, following a proposed scenario-based incremental dynamic analysis (IDA). Scenario-based IDA, as introduced in this article, aims at the generation of surfaces for the unacceptable performance of NPPs in the UK as a function of earthquake magnitude ($M_w$) and distance-to-site ($R_{epi}$). Unacceptable performance surfaces can be a substantial contribution to the UK nuclear industry in order to provide insights as how the seismic risk varies when the NPP is subjected to most (or all) dominant scenarios of the selected nuclear site.

This work is organised as follows: Section 2 describes the two specific objectives of this article and the methodology used. Section 3 provides details about the structural models and their mechanical properties, including the definition of the SPS analysed and the modelling of the soil-structure interaction. Additionally, description of the fragility curves used to characterise the critical components of the sample NPP building is provided. Section 4 presents the seismic input definition for the choice of the nuclear site and summarises the risk assessment calculations performed. Section 5 provides a step-by-step definition of scenario-based IDA and the estimation of unacceptable performance surfaces. Section 6 discusses further aspects regarding the appropriateness of SPS for NPPs in the UK and advantages and limitations of scenario-based IDA and presents the conclusions from this study.

## 2. Objectives and methodology

This work has two specific objectives: (a) to determine an efficient approach of SPS to reduce the seismic risk of NPPs buildings subjected to the UK seismic conditions including the influence of the foundation soil; and (b) to investigate how the reduction in seismic risk of NPPs buildings changes when considering several or all dominant scenarios for the particular site selected.

All analyses carried out in this work were made considering a simplified structural model based on a 1000 MW Pressurised Water Reactor building. Such a structural model was used to define two types of models: (1) a conventional NPP and (2) a seismically protected NPP. The former models the reference case, i.e. a traditionally built fixed-to-the-ground NPP (Model 1 hereafter), whereas the latter comprises three models that use different types of seismic protection devices suitable for NPPs. The following devices were analysed: (a) low-damping rubber bearings (LDRB) in combination with linear viscous dampers (LVD) aimed at adding a 10% critical (viscous) damping (Model 2a hereafter); (b) lead–rubber bearings (LRB), aimed at adding a 20% critical (hysteretic) damping (Model 2b hereafter); and finally, (c) linear viscous dampers located at the critical components of the NPP, aimed at adding 30% critical (viscous) damping for each local device (Model 2c hereafter). Then, a site was selected that is typical UK NPP site with relatively moderate seismicity, including two types of foundation soil: (i) generic rock site and (ii) generic soil site. The efficiency in reducing the seismic risk of the NPPs was made using the methodology of SPRA reported by Medel-Vera and Ji (2016a). In order to give answer to the first objective of this article, the risk was assessed considering the single scenario (moment magnitude, epicentral distance) that contributes most strongly to the hazard of the site selected. Fig. 1 summarises the tasks performed to comply with Objective (a) of this work.

Regarding Objective (b), the change in seismic risk of the NPP building are assessed considering all dominant scenarios of the particular site selected. For this purposes, it is introduced in this article a scenario-based incremental dynamic analysis (IDA) intended to generate surfaces for the probability of unacceptable performance of NPPs as a function of earthquake magnitude and distance-to-site. Such surfaces were generated for two models, conventional NPP and seismically protected NPP, in generic rock site. Then, the relative performance between those surfaces was studied in order to gain in-depth knowledge about the behaviour for the reduction of risk for all dominant scenarios of the particular site selected. Fig. 2 summarises the tasks performed to comply with Objective (b) of this work.

## 3. Structural models

### 3.1. Sample nuclear reactor building

All structural models used in this work were based on a 1000 MW Pressurised Water Reactor (PWR) shown schematically in Fig. 3a. This sample nuclear reactor building is composed of two structural units: (i) the containment structure (CS), composed of a post-tensioned concrete cylindrical wall, and (ii) the internal structure (IS), to which the critical key components of the NPP are attached. These structural units are independent from each other; hence, they are only connected at the foundation level. The height of the CS and IS are 60 m and 39 m, respectively, whereas the total weight of the reactor building is approximately 62,000 ton. Fig. 3b shows the simplified structural model of the sample NPP used in this work. Both the CS and IS are modelled as lumped-mass stick models that are the same in both horizontal directions. Fundamental periods of vibration of the CS and IS are

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