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Seismically induced uplift effects on nuclear power plants. Part 1: Containment building rocking spectra

A.G. Sextos [a,b], G.D. Manolis [a,*], A. Athanasiou [a], N. Ioannidis [a]

[a] Department of Civil Engineering, Aristotle University of Thessaloniki, Greece
[b] Department of Civil Engineering, University of Bristol, UK

HIGHLIGHTS

- In part I of this work we explore soil-structure interaction effects and the potential development of geometrically nonlinear effects in the response of the containment structure of a nuclear power plant.
- This is achieved by developing a 3D finite element model of a typical nuclear power plant containment structure is developed resting on either competent rock or stiff soil formations.
- This model is first subjected to a suite of ground motions with distinct frequency content and then to three subsets of 30 ground motion records in ensembles according to their frequency content, normalized to a PGA of 0.36 g.
- Ground motions with low mean frequency content are observed to lead to the onset of geometrically nonlinear phenomena, along with a higher displacement demand.
- More specifically, it is shown that stiff containment structures on soft soils are more prone to foundation uplift, a fact that is often neglected in design codes and may cause damage under certain circumstances to the internal power generation equipment.

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ABSTRACT

Current nuclear regulatory codes specify design considerations for extreme seismic scenarios, focusing primarily on the response of the containment structure of a nuclear power plant. However, in current state-of-practice and in most seismic regulations worldwide, the consideration of soil-structure interaction and potential development of geometrically nonlinear effects, such as rocking and sliding with uplift, is not taken into consideration. To explore this issue, a refined 3D finite element model of a typical nuclear power plant containment structure is developed, comprising solid elements for the soil and foundation, plus shell elements for the structure. The aim is identification of foundation-soil separation phenomena under a suite of ground motions with distinct frequency content. At first, harmonic excitations are used, for both cases of stiff sand and rock subsoil profiles, leading to rocking spectra that depict the displacement demand in connection with nonlinear separation. Clear influence zones can be distinguished, especially in the low frequency bands for the stiff sand case. Next, three subsets of 30 ground motion records are carefully selected and grouped in ensembles according to their frequency content, normalized to a PGA of 0.36 g, which corresponds to the highest design acceleration in Europe. Ground motions with low mean frequency content are observed to lead to the onset of geometrically nonlinear phenomena, along with a higher displacement demand. The interplay between ground motion characteristics, dynamic properties of the containment structure and stiffness of the soil is also highlighted. More specifically, it is shown that stiff containment structures on soft soils are more prone to foundation uplift. This possibility is often neglected in design codes and the consequence is that under certain circumstances, damage may be caused to the internal power generation equipment.

* Corresponding author.
E-mail address: gdm@civil.auth.gr (G.D. Manolis).

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1. Introduction

Power generation from nuclear energy is a dependable source, but it is also associated with high environmental, financial and social risks, as the recent Fukushima, Japan nuclear power plant accident of March 11, 2011 from the tsunami triggered by the $M_w = 9.0$ Tohoku earthquake vividly demonstrated. This event resulted in a new round of research on nuclear energy, not only with regards to its production, but also on the design specifications for nuclear reactor structures. Focus is primarily on one of the most important edifices of a nuclear power plant (NPP), namely the nuclear containment building, as this structure protects critical equipment used for nuclear energy generation. Design of NPP has long been performed on the basis of standard guidance (American Society of Civil Engineers (ASCE), 2005, 1998a,b, European Commission, 1996) that prescribe design considerations for seismic intensity measures of appropriately low mean annual frequency of exceedance, focusing primarily on the response of containment structures. Until recently, however, research conducted on the interaction between the containment building and the underlying soil has been scarce, even though the problem was very early identified (Newmark and Hall, 1969). Moreover, issues of geometrical nonlinearities at the building-soil interface, such as uplift and sliding, have also been neglected due to the complexity of numerical modeling and particularly due to the fact that most widely used codes available for soil-structure-interaction (SSI) analysis (Lysmer et al., 1999) were traditionally addressing the problem in the frequency domain.

On the other hand, recent research has identified cases of NPP and high-hazard nuclear waste facilities where nonlinear interface issues need to be carefully accounted during seismic design and assessment. Saxena and Paul (2012) studied the effect of slip and separation due to soil-foundation-structure interaction (SFSI) on the seismic response of the foundation of a nuclear reactor containment building, using 3D finite element method (FEM) analysis. They also showed that any increase of the foundation's embedment depth reduces the horizontal slip and vertical separation phenomena from the underlying soil. Next, Bhaumik and Raychowdhury (2013) studied the seismic response of an internal shear wall of a reactor using a 2D FEM model considering nonlinear soil-structure interaction. They concluded that containment buildings on soft soils have higher plasticity demands as compared to those founded on competent rock, and are prone to manifestation of geometrically nonlinear effects. Jeremić et al. (2013) showed that the frequency content of the ground excitation greatly influences the response of both surface and embedded containment building foundations, especially when nonlinear effects are present. Recent studies (Kumar et al., 2015) concluded that nonlinear effects, in the presence of SFSI, may alter the dynamic characteristics of the structure itself, something which primarily depends on the frequency content of the seismic excitation. Other studies have further demonstrated a thorough non-linear SSI methodology for NPP constructions in the time domain, incorporating the presence of material (Kabanda et al., 2015) and geometrically nonlinearities (Coleman et al., 2015; Huang et al., 2010) at the soil-foundation interface, such as gapping and sliding. All these studies highlight the potentially significant impact of nonlinear phenomena, particularly for ground intensities exceeding the Design Basis Earthquake. Notably, the original design value in Fukushima was 0.26 g (updated to 0.45 g in 2009), while the recorded one was 0.56 g. Similar exceedances have also been reported (Coleman et al., 2015) elsewhere in Japan (e.g., Kashiwazaki-Karina, 0.20 g versus 0.32 g recorded) and the United States (at the 1865-MW North Anna Power Station in Mineral, Va, 0.18 g versus 0.26 g recorded in 2011 during a magnitude 5.8 event). In fact, the latter event was the only time an earthquake has forced a U.S. nuclear plant offline and also the first U.S. plant to experience an event that exceeded its design acceleration (within a time window of three seconds).

As the social impact of a possible NPP failure is tremendous as it the case of leakage of radioactive materials, more recent regulations explicitly address the issue of nonlinear SSI by distinguishing nonlinearities in the site response, large-strain soil material behavior, geometric phenomena at the foundation-soil interface, and nonlinear behavior (i.e., cracking) of structures and mechanical equipment. These documents, like the Idaho National Laboratory (INL) methodology (Spears and Coleman, 2014) and the forthcoming Appendix B of the new version of the ASCE 4 Standard (American Society of Civil Engineers (ASCE), 2015) take a significant step further by introducing new concepts, approaches and tools. However, the nature of these provisions is still non-mandatory.

Given the above emerging need for refined analytical and numerical studies, the objective of this work is to shed some further light on nonlinear seismic soil-structure interaction of NPPs by:

(a) correlating the frequency content of the excitation with geometrically nonlinear interface phenomena (i.e., uplift and sliding) of the containment building, in the form of "rocking spectra" (Makris and Konstantinidis, 2003) for different soil profiles. We note that the geometrically nonlinear soil-structure interaction has been studied in the past, see for instance (Kennedy et al., 1976; Nakamura et al., 2010, 2007). The concept of rocking spectra is used herein and has been extrapolated from other systems exposed to seismic risk such as base-isolated generic structures (Politopoulos, 2010), bridges (Anastasopoulos et al., 2013), masonry walls (Costa et al., 2013) or even laboratory and hospital equipment (Cosenza et al., 2014; Konstantinidis and Makris, 2009), free-standing blocks (Dimitrakopoulos and DeJong, 2012; Voyagaki et al., 2013) and monuments (Makris and Vassiliou, 2013).
(b) identify the frequency range of the seismic excitation, as a function of soft and firm foundation soils, that will provoke nonlinear effects at the soil-foundation interface of a NPP.
(c) use the complex nonlinear response of the soil-containment building system as input for the assessment of the internal equipment seismic demand (presented in Part II of this work).

In sum, the FEM modeling and analysis of this two-stage, complex structural assessment is accomplished using the ABAQUS (2010) software (Dassault Systèmes, 2014). The case studied, the assumptions, the methodological steps and the observations made are presented in the following.

2. Overview of the NPP studied

A typical Westinghouse Pressurized Water Reactor (PWR) containment structure is studied in this work, comprising a circular base slab, an upright cylinder as the main structure and a hemispherical dome, as shown in Fig. 1. The PWR has a height of 85.8 m, wall thickness of 1.5 m and is partially embedded in the supporting ground. The reinforcement of the containment is composed of ∅40 mm bars at 80 mm spacing, running both ways at the inner and outer faces of the cylindrical R/C wall, continuing within the spherical dome with an assumed effective concrete cover of 100 mm (Hu and Lin, 2006). Material properties are summarized in (Hu and Liang, 2000) as well as in Table 1 and they are