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Seismically induced uplift effects on nuclear power plants. Part 2: Demand on internal equipment

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HIGHLIGHTS

- As a continuation of Part I where rocking spectra for the containment structure of a nuclear power plant under earthquake-induced vibrations were derived, the second part of this work focuses on the dynamic response of the nuclear power plant mechanical sub-systems (i.e., main cooling system, steam generators, emergency cooling injection tanks and piping) that are housed within the containment structure and are associated with power generation.
- The internal equipment configuration is then excited by the ground motion numerically predicted in Part I by considering geometrically nonlinear soil-structure interaction effects.
- Following extensive parametric studies, the seismic demand imposed on the internal equipment is assessed on the basis of dynamic stress analysis of the critical components.

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ABSTRACT

This work focuses on the dynamic response of nuclear power plant mechanical sub-systems (i.e., main cooling system, steam generators, emergency cooling injection tanks and piping) that are housed within the containment structure and are associated with power generation. More specifically, the numerical modeling procedure focuses on the internal R/C wall structural system used for supporting the mechanical equipment. Next, the complex grid of the mechanical components is modeled with shell finite elements. This internal equipment configuration is then excited by the ground motion numerically predicted in Part I of this work by considering geometrically nonlinear soil-structure interaction effects. Following extensive parametric studies, the seismic demand imposed on the internal equipment is assessed on the basis of dynamic stress analysis of the critical components. Depending on frequency content of the incoming seismic motion, it is shown that abrupt uplift may take place. This is true even for moderate earthquake intensity, particularly when the containment structure rests on soft soils and the vertical component of ground motion is not negligible. This situation may produce peaks in the pipe elbow strains that could potentially affect serviceability, operation and under extreme conditions, the safety of the entire nuclear power plant.

1. Introduction

As mentioned in Part I, nuclear power plants (NPP) are a reliable and efficient source of power in general and electricity in particular for modern, industrialized societies that pursue both economic growth and reduced CO_2 emissions (Cho et al., 2016). There is, of course, much skepticism in the general public regarding the consequences of even a minor nuclear accident. This would result in the release of radioactive materials in the atmosphere, as well as in the surrounding environment, with catastrophic consequences for both urban centers and for the surrounding countryside (Housner, 1960). For this reason, many precautionary measures are routinely taken and limit states are assessed in the design of the NPP containment structure in order to minimize risk even for extreme events, such as earthquake induced ground motions with associated soil-structure-interaction (SSI) phenomena (see ASCE 1998, 2005) and the forthcoming ASCE 4 revised standards (American Society of Civil Engineers (ASCE) 2015). In the second part of this work, we study the response of internal sub-systems within

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a NPP containment structure that are associated with power generation. More specifically, the safety systems that are critical for normal NPP operations, such as the main cooling system, the steam generators and the emergency cooling injection tanks along with the connecting piping network.

Keeping the (mechanical, electrical, instrumentation and control I&C) equipment functional and safe is a performance objective of paramount importance and is met by providing (a) seismic adequacy (capacity, proper function) of component and pipe supports and (b) anchorage of pipe and equipment component supports, while avoiding equipment seismic interactions (falling, pounding, spray and flooding). Damage to these equipment is not frequent, but has been reported in cases of ground motion excitations exceeding the Design Basis Earthquake (Fujita et al., 2014).

Even though the equipment qualification in nuclear power plants has evolved since the basic recommendations of the 1980s to the more detailed latest Regulatory Guide of the US Nuclear Regulatory Commission (NRC, 2009), there is still very limited guidance on specific mitigating measures that can improve the resiliency of the NPPs to Beyond the Design Basis Earthquake. Also, the fragility assessment of critical NPP equipment is rather limited to date (Iijima et al., 2004). Most important, to the best of the author's knowledge there is no comprehensive numerical study on the effect of nonlinear SSI phenomena at the foundation-soil interface such as sliding and uplift, on the seismic demand imposed on the internal equipment. As shown in Part I of this work, these phenomena are noticeable for moderate to low frequency ground motions (0.5–1.0 Hz) even at relatively low (i.e., comparable to the design) ground shaking intensities (0.2–0.4 g) for the case of NPP foundation of soft soil profiles.

The objective of this part is therefore (a) use of the nonlinear *response* of the containment building derived through refined 3D analysis of the SSI system presented in Part I, as the *input* for the base excitation of the same building inclusive of the mechanical equipment duly modeled with 2D and 3D finite elements, and (b) quantification of the additional seismic demand that may be imposed on the internal piping system due to the aforementioned sliding and/or rocking of the containment building when founded on soft soil formations.

In general, utility companies make every effort to build NPP on rock outcrop, or at least on firm soils. This is engineering common sense, given that NPP comprise heavy structures such as the containment building, so that foundation settlement is avoided under routine operating conditions and site amplification effects are absent in seismically-prone regions (Kramer, 1996) Occasionally, it is not possible to abide by these guidelines, especially in heavily-populated countries and/or countries where the major urban centers are concentrated along the coastline (Bougaev et al., 1996; Takada, 2012). For cases such as these, the presence of a heavy and stiff structure founded on soft soil may trigger undesirable SSI phenomena.

2. Numerical analysis of the NPP internal structure and equipment

Following the detailed finite element method (FEM) modeling of the containment building and its surrounding soil domain presented in Part I, the internal structure and equipment is further modeled in detail in this section. Notably, the seismic analysis of the various NPP subsystems is usually conducted using the equivalent beam model (Huang et al., 2010; Lee et al., 2014) to represent their stiffness, with all mass lumped at a reduced number of degrees-of-freedom (DOF) as compared to their original number. This modeling procedure is broadly used as it produces a simple mechanical model that is efficient in representing the basic eigenmodes of the structure and its components at an affordable computational cost. Along these lines, the seismic input for the secondary systems is implemented in terms of in-structure response spectra or in-structure time histories. This modeling procedure has its benefits, but also its limitations considering the inherent difficulties in an accurate representation of these complex subsystems.

In this approach, a 3D computer-aided, blueprint-type model of the main mechanical components of the NPP pressurized water reactor (PWR) under study was first created, using published information from the Atomic Energy Commission of Canada (Atomic Energy of Canada Limited (AECL) 2004). This 3D CAE model was then imported in the FEM software using advanced translation techniques (Nakamura et al., 2006) for generating the mesh, assigning the mechanical properties, and solving. Following this procedure, the FEM model produced was developed in ABAQUS CAE (Dassault Systèmes, 2014) and, due to its associated high computational cost, it was solved in parallel. Multiple load cases, such as fluid-structure-interaction, constrained thermal expansion, etc., can be separately analyzed and were not studied herein.

The internal structure of the containment building of Fig. 1 is an R/C wall structural system that is 40 m high (see Fig. 2, left). It is nearly circular in plan and supports the reactor, two steam generators, four circulation pumps and the connecting piping network, plus the emergency injection cooling tanks. This support structure is symmetrical about the Y-axis and nearly so about the X-axis. It has two distinct, tower-like structures that house and support the steam generators. The walls range from 1.5–3.0 m thick in order to support the mechanical components, but also for radiation shielding purposes. As a consequence, this structural system is quite stiff despite its large dimensions and mass. The R/C walls are modeled using 3D solid, ten-node tetrahedral, second order finite elements (C3D10). The largest element edge length in the FEM mesh was set to 2.5 m, getting progressively smaller, in order to follow the wall geometry. The FEM mesh was extended so as to model the mechanical components by using linear shell, four-node with reduced finite element (FE) integration (S4R). An appropriately high value for the shell FE thickness was assigned so as to approximate the large stiffness in components such as the reactor, the steam generators and the circulation pumps. These components are anchored into the walls with connecting steel beams for operational safety reasons. Finally, the piping system represents a two stage mechanical system, with stage one comprising small piping networks that pass through the reactor, while stage two is for large diameter steel pipes that circulate the accumulated

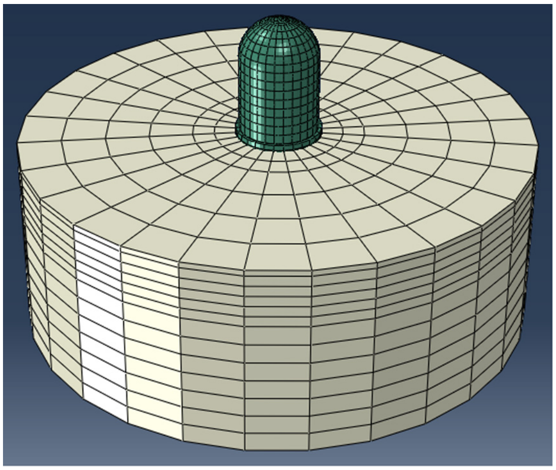

Fig. 1. FEM mesh of NPP containment structure and supporting soil deposits.

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