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Seismic response of base isolated nuclear power plants considering impact to moat walls

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ABSTRACT

Seismic isolation can be an effective strategy to protect critical facilities including Nuclear Power Plants (NPPs) from the damaging effects of horizontal earthquake ground shaking. The increased flexibility at the base and resulting elongation of the natural vibration period of the structure leads to significant reductions in forces and acceleration transmitted to the structure above the isolation level at the expense of displacements concentrated in the isolation system. Displacement demands can be large at sites of moderate to high seismic hazard and can be accommodated by a horizontal clearance or moat at the isolation level, typically located in the basement of a structure. A surrounding moat wall can function as a stop to limit isolation system displacements and prevent bearing failure under beyond design basis shaking. However, impact of the isolated structure against the moat wall is of concern due to potential amplification in response of the superstructure. Design guidelines aim to prevent impact by specifying a required minimum clearance to stop (CS) with a low annual frequency of exceedance. A CS below the required value can be justified through analysis considering impact to the moat wall or stop. However, little guidance is available on how to model impact to the moat wall and resulting effects on the NPP superstructure. This study proposes a simplified model for impact simulation that captures the impact forces and the effects of impact on the response of seismically isolated NPPs. Variable clearance to the stop and a range of properties for the moat wall and isolation system are considered to identify parameters that influence the response. Results of these studies indicate that large NPP plants as considered here can have significant penetration into the moat wall, and thus not fully limit displacements in the isolation system, while having considerable increases in accelerations throughout the height of the NPP model.

1. Introduction

Seismic isolation can be an effective strategy to protect critical facilities including Nuclear Power Plants (NPPs) from the damaging effects of horizontal earthquake shaking. Seismic isolation is typically achieved by installing a layer of flexible bearings at the base of the structure with a horizontal clearance or a moat at the basement level allowing for the free movement. Application of seismic isolation to NPPs has been considered since the early 1980's (Bhatti et al., 1982; Buckle and Mayes, 1990) with potential benefits including simplification of seismic design, enhanced safety margin, and facilitated standardization (Tajirian et al., 1990). More recent studies (Huang et al., 2010; Frano and Forasassi, 2010; Huang et al., 2013; Wong et al., 2012, Wong et al., 2013) have identified and addressed technical challenges as well as concerns related to application of seismic isolation in NPPs. To improve modeling capabilities of seismic isolation hardware especially for beyond design basis shaking, advanced models of both sliding (Kumar et al., 2015) and elastomeric (Kumar et al. 2014) isolation bearings have been proposed. In addition, Schellenberg et al. (2015, 2016) conducted experimental tests using hybrid simulation of a numerical model of a NPP and full-scale bearing experiments under various loading conditions that directly account for the bearing behavior in the simulation through experimental measurements. These experiments along with tests by Kim et al. (2017) examined the behavior of large seismic isolation bearings designed for NPP applications through failure, providing data and insight on the bearing capacities that can be used to validate bearings models.

In the U.S., design provisions for nuclear facilities limit the displacement of the seismic isolation system by a stop or moat wall, that is intended to prevent failure of the bearings (Kumar and Whittaker, 2015). However, exceeding the gap displacement is also of concern given the potential for impact to the stop and associated amplification

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in structural response. The required minimum clearance to stop (CS) is thus specified to prevent impact. For example, ASCE 4 (2017) requires a CS no less than the 90th percentile displacement demands corresponding to Beyone Design Basis Earthquake (BDBE). Use of a CS below the specified value requires analysis to demonstrate that impact will not result in unacceptable performance of the NPPs. Importantly, the consequences of impact or procedures to mitigate these effects have not been examined for NPPs. Few experimental and numerical studies related to pounding have been conducted for non-nuclear base isolated building structures (Masroor and Mosqueda, 2012; Komodromos et al., 2007). This paper builds on the previous studies to evaluate the effects of impact on the response of seismically isolated NPPs. A moat wall model suitable for parametric studies is proposed to capture the impact forces and effects on the isolated NPP. The moat wall model is applied to simplified isolated plant model and variable characteristics of the isolation hardware and moat wall properties are considered to capture parameters that influence impact response.

2. Simplified model of Nuclear Power plant

This study focuses on modeling the effects of moat wall impact on seismic response of base isolated NPPs. A simplified superstructure model is considered for the NPP, consisting of a lumped-mass stick model for 1-D horizontal earthquake shaking. The model of the NPP and the design of the isolation system is largely based on current design efforts for a standardized isolated APR1400 plant model. The dynamic properties of the model listed in Table 1 are similar to the reactor containment building (RCB) of the APR1400 (Kim, 2005; Schellenberg et al., 2015, 2016). This model was found suitable for these studies as it could capture some higher mode effects in the superstructure that can be excited by the impact force. The mass of the structure and the secondary systems were lumped at discrete locations at select levels (Fig. 1). The weight of the structure consisting of the representative RCB is 70,000 tons and the total weight of the structure is 118,000 tons considering the base mat above the isolation system. The thickness of the base mat foundation is 3 m and assumed to be rigid in this model. The isolation system model includes three isolator elements beneath each of the structural stick model connections to the foundation. For this study considering only the shear behavior of the bearings, each was considered as a bilinear hysteretic horizontal spring. Modeling parameters considered for the isolation system are provided in Table 2.

Throughout this study, the response is evaluated at an elevation near the ground level, which is at an elevation of about 23 m considering the basement depth. This location is examined to compare the various model configurations considered. The structural model was implemented in OpenSees (OpenSees, 2014) to make it more conducive to numerous parametric studies and take advantage of its large element library for modeling complex and nonlinear behavior of the structure including impact.

3. Moat wall model

The seismic design of isolated NPPs with a CS below the specified value will require analysis considering impact to the moat wall or stop. A moat wall model for impact analysis is proposed in efforts towards developing the necessary tools to examine the consequences of impact on the NPP. The stop can be constructed in the form of a moat wall around the basement of the NPP with this study considering only 1-D horizontal response. Modeling of the moat wall as the stop requires consideration of the reinforced concrete wall and soil backfill resistance in the structural model as well as localized impact behavior. While previous studies have examined impact for regular buildings both experimentally (Masroor and Mosqueda, 2012; Sasaki et al., 2017) and numerically (Komodromos et al., 2007; Masroor and Mosqueda, 2013), the impact behavior of a NPP can have different characteristics due to its potential size scale (Sarebanha et al., 2017). The thickness of the base mat and moat walls considered here are loosely based on preliminary designs for the seismically isolated APR1400 with parameters varied to capture a wider range of behaviors. Fig. 2 shows a schematic of the basement isolation level of the considered NPP and the surrounding moat wall with dimensions considered in this study. The approach taken to develop the moat wall impact model is based on past experimental studies on impact at smaller scales, previous analytical work, and supplementary finite element analysis to gain insight on impact between a massive wall and structure as considered here. In this study aimed at studying the effects of seismic pounding in NPPs, different (CS) values were assumed to examine the effect of this parameter.

Studies of pounding in base isolated structures has been mainly analytical with various approaches used to model contact based on small scale experimental verification (Jankowski, 2005). Parameters for modeling the behavior of the moat wall with soil backfill under impact forces at the scale considered here is limited in the literature,

Table 1
Modal frequencies for isolated simplified NPP (2D).

Mode	Frequency (Hz)	Direction
1	0.50	Isolation – Horizontal Translation
2	1.58	Isolation – Vertical Translation
3	4.27	RCB - Horizontal Translation

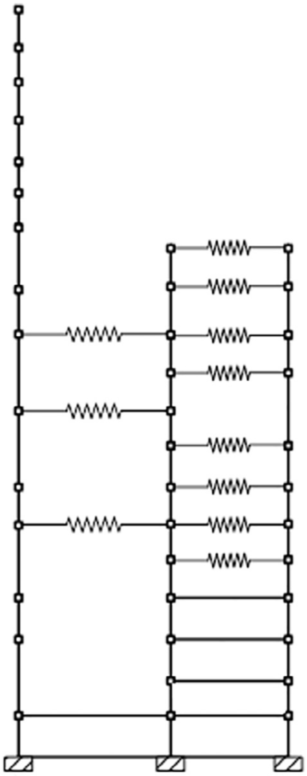

Fig. 1. Lumped mass model for RCB.

Table 2
Properties of the entire isolation system using Lead Rubber Bearings (LRB).

Design variables			
Effective stiffness (K_{eff})	1187.65 tons/cm	Post elastic stiffness (K_2)	572.018 tons/cm
Lead yield force (Q)	12,928.30 tons	Initial stiffness (K_1)	5720.18 tons/cm
Yield disp. (D_y)	2.51 cm	Yield force (F_y)	14,364.8 tons