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Effect of seismic hazard definition on isolation-system displacements in nuclear power plants

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ABSTRACT

The effect of seismic hazard definition on the distribution of isolation-system displacements in a nuclear power plant (NPP) are studied in the paper and recommendations are made for design practice. The NPP is considered to be located at Diablo Canyon in California, a site of high seismic hazard, and is horizontally isolated using Friction Pendulum™ (FP) seismic isolation bearings.

Four descriptions of seismic hazard are investigated: uniform hazard response spectrum (UHRS), conditional mean spectrum (CMS), conditional spectra (CS), and UHRS-MaxMin. Uniform hazard response spectra are derived by probabilistic seismic hazard analysis and are the traditional description of seismic hazard in the nuclear industry in the United States. The UHRS is used to characterize the effects of design basis shaking but its ordinates across a wide range of period do not represent shaking associated with one ground motion set. The CMS and CS are derived from a UHRS and better characterize the effects of shaking from one ground motion set. The UHRS-MaxMin definition is also based on the UHRS but explicitly recognizes differences between motions in the orthogonal horizontal directions.

To investigate the utility of alternate descriptions of seismic hazard, the macro model of a seismically isolated NPP is subjected to ground motions consistent with the four definitions and for two intensities of earthquake shaking: design basis (DB) and beyond design basis (BDB) shaking as defined in the forthcoming seismic isolation NUREG. The coefficient of friction at the sliding surface is defined using two models: 1) Coulomb, and 2) *p*-*T*-*v* model that updates the coefficient of sliding friction at each time step as a function of axial pressure, temperature and sliding velocity.

The key results of the study, which are broadly applicable to sites of lower seismic hazard and other nonlinear bearings (e.g., the lead-rubber bearing), are: 1) the seismic hazard definition should account for differences between the amplitude of ground motions in the principal horizontal directions, 2) the displacement capacity of an NPP isolation system is controlled by the 90th percentile BDB shaking displacement, for a given hazard definition, and 3) the coefficient of friction at the sliding surface of a single-concave FP bearing should be defined using a *p*-*T*-*v* model because the standard Coulomb model may be inadequate for high values of axial pressure and nominal coefficient of sliding friction.

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1. Introduction

Seismic isolation is a viable strategy for protecting safety-related nuclear structures, including nuclear power plants, from the effects of extreme earthquake shaking (e.g., Huang et al. [1], Kammerer et al. [2]). For large light water reactors, the isolation system will likely be installed in a horizontal plane, immediately below the basemat and above a foundation, as shown in Fig. 1. (For small modular and advanced reactors, isolators may be used to protect an entire plant but be placed at multiple levels below grade, or protect individual structures, systems and components within the plant; see [3] for details.) The performance of individual isolators is key to the response of a large light water reactor or similar, because a) individual isolator behaviors cannot yet be shown to be weakly correlated, requiring isolator behavior to be used to describe isolation-system behavior, and b) the isolation system is a singleton, with isolation-system failure potentially leading to core damage or large early release of radiation due to a cascading failure of containment. (Both assumptions are extremely conservative but will have to be proven on a project-specific basis. Isolator capacities may be strongly correlated but demands are likely weakly correlated: horizontal displacements may be similar but coexisting axial forces will vary widely, and isolators will be

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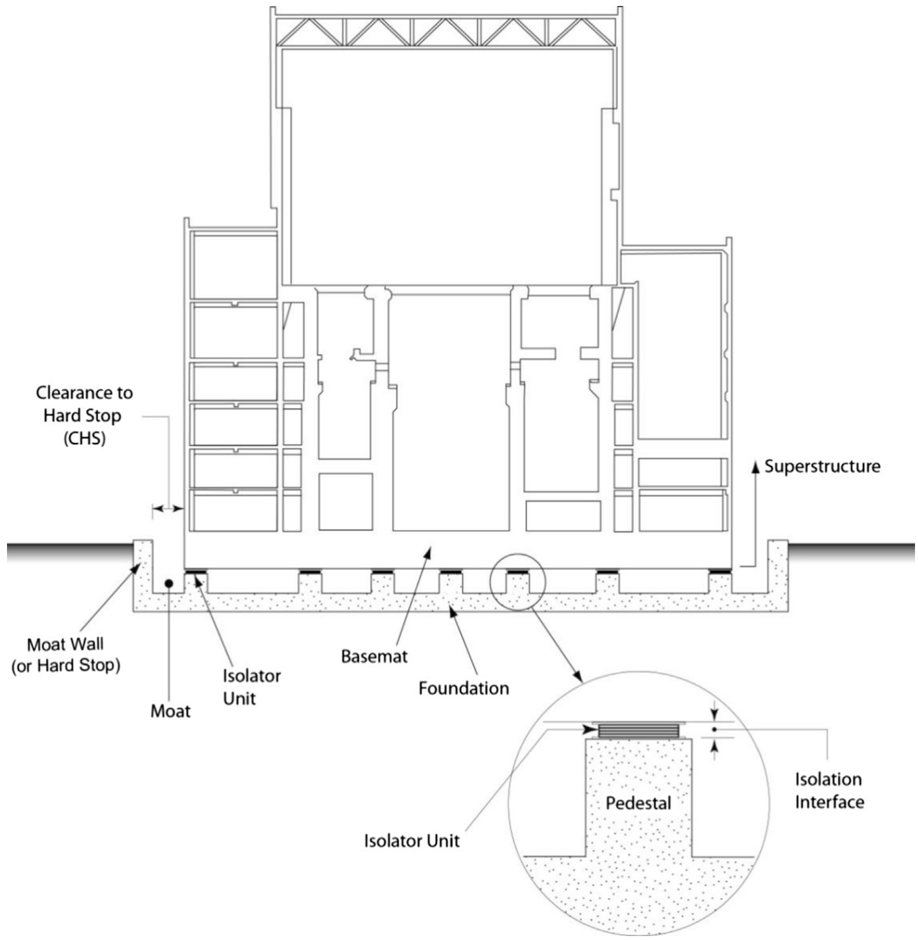

Fig. 1. A seismically isolated nuclear power plant (adopted from [2]).

physically tested for maximum and minimum axial forces. Individual isolator failure will not result in either breach or collapse of the containment vessel: the basemat will be designed to span over multiple lost isolators per ASCE 4-16 [4] and the draft isolation NUREG [2], and pedestals will provide gravity support for the basemat in the event of isolator failure).

The physical testing of prototype isolators will be required in US nuclear practice for axial force and lateral displacement demands consistent with extreme shaking: 90th percentile BDB displacements and the co-existing maximum/minimum axial forces. Assuming the probabilistic seismic hazard calculations are performed correctly, and nonlinear dynamic analysis is used to calculate demands on the isolated substructure, isolators and superstructure, it is important to generate consistent sets of ground motions as input to the analysis. Herein we study three representations of seismic hazard and two interpretations of geometric mean horizontal shaking. Single concave Friction Pendulum™ (FP) bearings are used to isolate the NPP but the results are directly applicable to other nonlinear isolation systems, including lead-rubber bearings and triple concave Friction Pendulum™ (FP) bearings.

Three representations of seismic hazard investigated are: uniform hazard response spectrum (UHRS), conditional mean spectrum (CMS), and conditional spectra (CS). The UHRS is the traditional measure of seismic hazard in the nuclear industry (e.g., [5]). The CMS is based on the UHRS, but has a spectral shape consistent with that of recorded ground motions (see [6]). Conditional spectra account for the variability in the ordinates of CMS at periods other than the conditioning period (e.g., [7]). Given a representation of the hazard (UHRS, CMS or CS), the spectra of the two orthogonal horizontal directions are typically assumed to be identical, even as the correlations between the acceleration histories in the two directions consistent with the spectra are rather weak (Huang et al. [8] note that the median, 90th percentile and 99th percentile correlations between the two recorded horizontal components are approximately 0.15, 0.30 and 0.50, respectively).

Two interpretations of a geometric mean horizontal spectrum are also considered, where the geometric mean ordinate at a specified period is equal to the square root of the product of the spectral accelerations at that period along the orthogonal horizontal axes: 1) both amplitudes are equal at a given period, and 2) the spectral amplitude of the shaking along one horizontal axis is greater (less) than the amplitude of the perpendicular component, UHRS-MaxMin (e.g., Huang et al. [9]), but their product, period-by-period, recovers the geometric mean horizontal spectrum.

As defined in the forthcoming NUREG [2], two levels of seismic hazard are considered for the analysis and risk assessment of base isolated nuclear power plants: ground motion response spectrum+ (GMRS+) and beyond design basis (BDB) GMRS. The two hazard levels correspond to the mean annual frequency of exceedance (MAFE) of 10^{-4} and 10^{-5}, respectively, provided that the GMRS+ spectrum exceeds the regulator-specific spectrum (see Kumar et al. [10]), which in the United States is typically a standard spectral shape anchored to a peak ground acceleration of 0.1 g.

The three hazard definitions and two ground motion interpretations are briefly discussed below. Sets of ground motions consistent with the UHRS, UHRS-MaxMin, CMS and CS, with MAFEs of 10^{-4} and 10^{-5}, are developed for the site of the Diablo Canyon

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