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ON THE CALCULATION OF THE CLEARANCE TO THE HARD STOP FOR SEISMICALLY ISOLATED NUCLEAR POWER PLANTS

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ABSTRACT

A hard stop will be required for seismically isolated nuclear power plants (NPPs) in the United States to eliminate the seismic isolation system from accidents sequences that could lead to core damage or large release of radiation. The isolation system will be analysed, designed and tested for two levels of seismic hazard: a ground motion response spectrum+ (GMRS+) with a return period of 10,000 years and an extended design basis (EDB) GMRS with a return period of 100,000 years. Response-history analysis for ground motions consistent with these spectra will establish the clearance to the hard stop (CHS), which is required to be the greater than the 99th (90th) percentile displacement for GMRS+ (EDB GMRS) shaking. Alternate representations of seismic hazard (uniform hazard response spectrum, conditional mean spectrum, conditional spectra) are considered for the site of the Diablo Canyon Nuclear Generating Station and distributions of isolation-system displacement are calculated. The 90th percentile displacement for EDB GMRS shaking dictates the calculation of the CHS. Seismic hazard for isolated NPPs should be defined using a uniform hazard response spectrum with due consideration of the differences in the amplitude of the orthogonal horizontal components of ground shaking.

INTRODUCTION

Figure 1 is a schematic of a nuclear power plant (NPP) supported on a seismic isolation system. The isolation system is a singleton because its failure may directly lead to unacceptable performance, measured here by core damage and/or large release of radiation. A hard stop is introduced to prevent failure of the isolation system due to excessive horizontal displacement. The clear distance to the hard stop, along each horizontal axis of the isolated structure, is determined by nonlinear response-history analysis.

Two levels of seismic hazard are considered for analysis and design of seismically isolated NPPs in the United States (see Kammerer *et al.* (forthcoming)): a ground motion response spectrum+ (GMRS+) and an extended design basis (EDB) GMRS. The GMRS is defined as the product of a design factor (equal to 1.0 for isolated nuclear power plants; see Kumar (2015)) and the uniform hazard response spectrum (UHRS) with a mean annual frequency of exceedance (MAFE) of 10^{-4} (return period of 10,000 years). The GMRS+ is the envelope of the GMRS and a regulator-specific minimum response spectrum (e.g., an appropriate spectral shape anchored to a peak ground acceleration of 0.1 g). The EDB GMRS is the UHRS at an MAFE of 10^{-5} (return period of 100,000 years) but can be no less than 1.67 times GMRS+.

The clearance to the hard stop (CHS) is required to be greater than the 99th (90th) percentile displacement for GMRS+ (EDB GMRS) shaking per the forthcoming seismic isolation NUREG (Kammerer *et al.*, forthcoming), where the clear distance is calculated along each horizontal axis of the structure. The isolated superstructure need not be designed for impact on the hard stop if this clear distance is provided because the mean annual frequency of impact and the likely impact velocity are both small.

The distribution of peak isolation-system displacements (and thus the clearance to the hard stop) can be substantially influenced by the definition of the seismic hazard. Four representations of seismic hazard are evaluated in this paper. A macro model of the seismically isolated NPP is subjected to ground motions consistent with the four hazard representations at the site of the Diablo Canyon Nuclear Generating Station in California for two MAFEs: 10^{-4} and 10^{-5}. Distributions of peak isolator displacements are studied to understand the influence of the hazard definition on the calculation of the CHS.

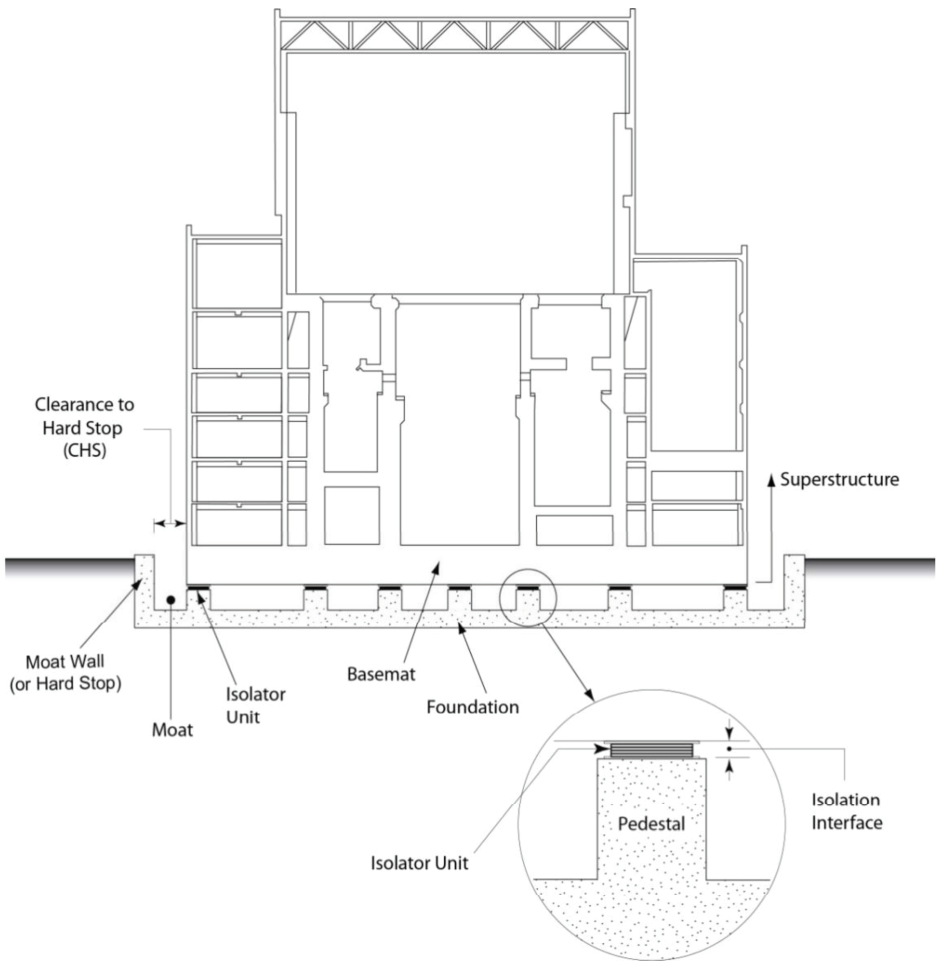


Figure 1: A seismically isolated nuclear power plant (adopted from Kammerer *et al.* (forthcoming))

ALTERNATE REPRESENTATIONS OF SEISMIC HAZARD

The four representations of seismic hazard considered in this study are: UHRS, UHRS with *maximum* and *minimum* components (UHRS-MaxMin), conditional mean spectrum (CMS) and conditional spectra (CS). The UHRS is the traditional representation of seismic hazard for NPPs and other safety-related nuclear structures (e.g., ASCE (2005)). Ground motions matched to the UHRS, which is a geometric mean spectrum for horizontal shaking, have identical response spectra in the two orthogonal horizontal directions despite spectra for recorded ground motions being consistently different from each other (e.g., Boore *et al.* (2006), Beyer and Bommer (2006), Huang *et al.* (2009)). The UHRS-MaxMin is based on the UHRS but acknowledges the differences between the two horizontal components. The spectra for each of the horizontal components can be obtained by scaling the UHRS, up and down, by a set of factors derived from recorded ground motions (e.g., Huang *et al.* (2009)), noting that the geometric mean of two horizontal spectra recover the UHRS.

The CMS is derived from the UHRS using a conditioning period and correlations between spectral accelerations at different periods, which are based on recorded ground motion data (Baker and Cornell, 2006). The CMS ordinate is equal to the UHRS ordinate at the conditioning period and is smaller than the corresponding UHRS ordinate at other periods. The spectral shape of the CMS is more consistent with that of recorded ground motions than the UHRS (NIST, 2011). Conditional spectra address the variability in the CMS ordinates given the spectral ordinate at the conditioning period (e.g., Jayaram *et al.* (2011)).

SEISMIC HAZARD DEFINITION FOR A SITE OF HIGH SEISMICITY

Figure 2(a) presents the 5%-damped UHRS, and CMS and CS with a conditioning period of 2 s for the site of the Diablo Canyon Nuclear Generating Station (latitude = 35.21162 N, longitude = 120.85562 W) at a 2% probability of exceedance in 200 years[1] (return period of 9900 years or MAFE of 1.01×10^{-4}), for an average shear wave velocity in the upper 30 m of soil column of 760 m/s. Conditional mean spectra are obtained from the USGS website http://geohazards.usgs.gov/deaggint/2008/, accessed on June 15, 2014, using the ground motion prediction equation (GMPE) of Campbell and Bozorgnia (2008). A consistent UHRS is obtained from a family of CMS by calculating the CMS at closely spaced conditioning periods, T^*. The software available on the website http://web.stanford.edu/~bakerjw/gm_selection.html is then used to generate conditional spectra (CS). This code uses the Campbell and Bozorgnia (2008) ground motion prediction equation (GMPE) to generate a set of CS. The (M, r, ε) triple at a period of 2 s is (6.66, 5.7 km, 1.88) using the Campbell and Bozorgnia (2008) GMPE. The CMS from the USGS website and the covariance matrix obtained from the software are used to generate the 30 conditional spectra of Figure 2(a). Figures 2(b) and 2(c) present the UHRS, and CMS and CS for T^* of 3 s and 4 s, respectively.

Figure 3 presents the 10,000-year UHRS and a set of 30 uniform hazard response spectra with *maximum* and *minimum* components (UHRS-MaxMin) in two orthogonal horizontal directions (X and Y). The UHRS-MaxMin spectra are obtained by amplitude scaling the UHRS, up and down, by the set of 30 factors derived in Huang *et al.* (2009).

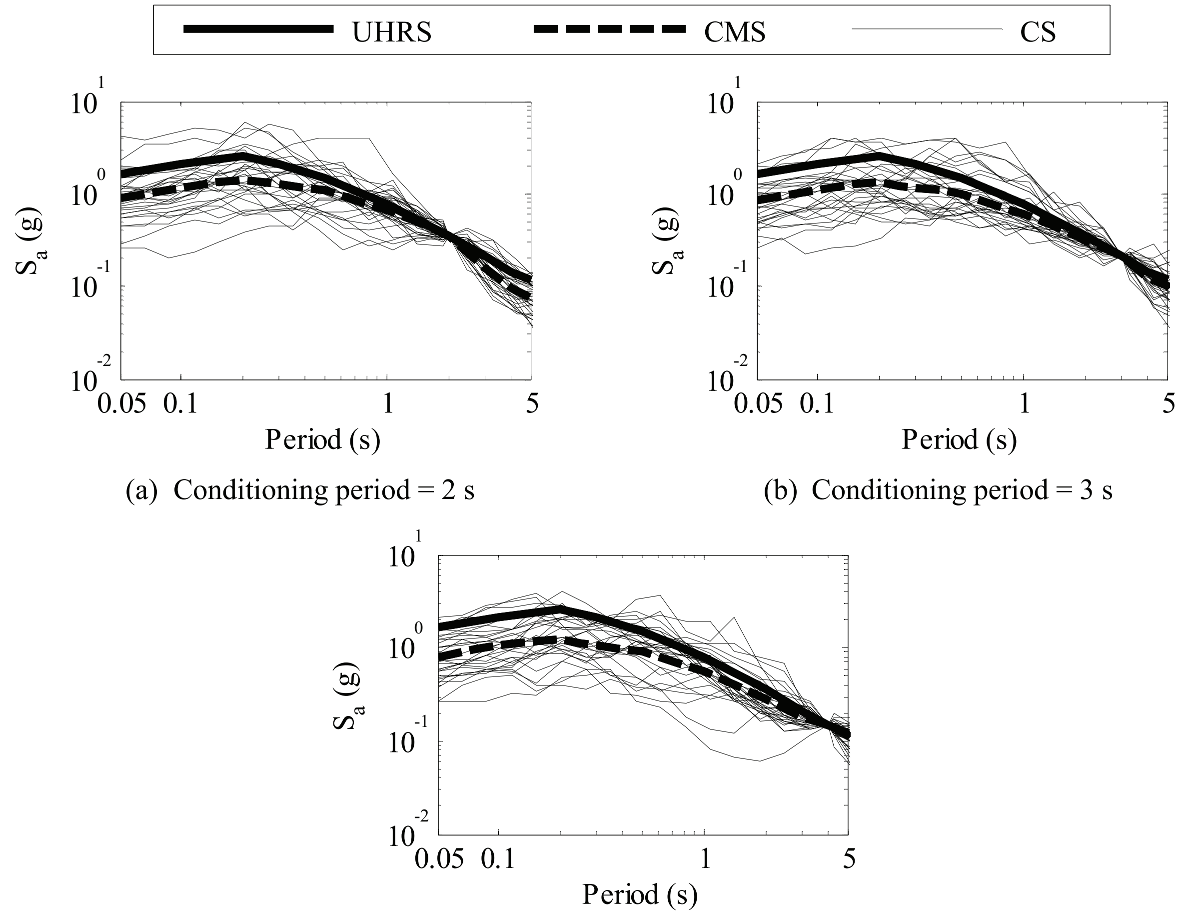
GROUND MOTIONS FOR 10,000-YEAR SHAKING

Sets of 30 ground motions are spectrally matched to the 10,000-year UHRS, UHRS-MaxMin, and CMS and CS with T^* of 2 s, 3 s and 4 s for the Diablo Canyon site. One set of ground motions is matched to each of the UHRS and UHRS-MaxMin spectra, one set of ground motions is matched to each of the three CMSs, and three sets of seed motions are matched to each of the three sets of CS, making a total of 14 sets of 30 ground motions. The seed ground motions are presented in Kumar (2015). Spectral matching is performed over a period range of 0.5 s to 4 s because isolation-system displacements are most influenced by the spectral ordinates in this period range.

The distributions of spectral displacements (SD) of the ground motions matched to the four representations of seismic hazard differ substantially. Figure 4(a) presents the distribution of SD of the 30 UHRS ground motions at 1.5 s in the X direction; the SDs are assumed to distribute lognormally. Also plotted in the panel are the distributions of SDs for UHRS-MaxMin motions, and CMS and CS motions with a conditioning period of 2 s. The median SD for the UHRS (CMS) motions is 0.31 m (0.27 m) and it

[1] The UHRS ordinates are virtually identical to those for 10,000-year shaking (see Kumar (2015)).

differs from the corresponding 99th percentile displacement by only 0.02 m[1] (0.02 m). The median (99th percentile) SD for UHRS-MaxMin motions is 0.41 m (0.55 m). The SD for the three sets of CS-scaled motions distribute similarly because the three sets of motions are matched to the same set of target CS. The median (99th percentile) SD for each of the three sets of CS-scaled motions is 0.26 m (0.49 m).



(c) Conditioning period = 4 s

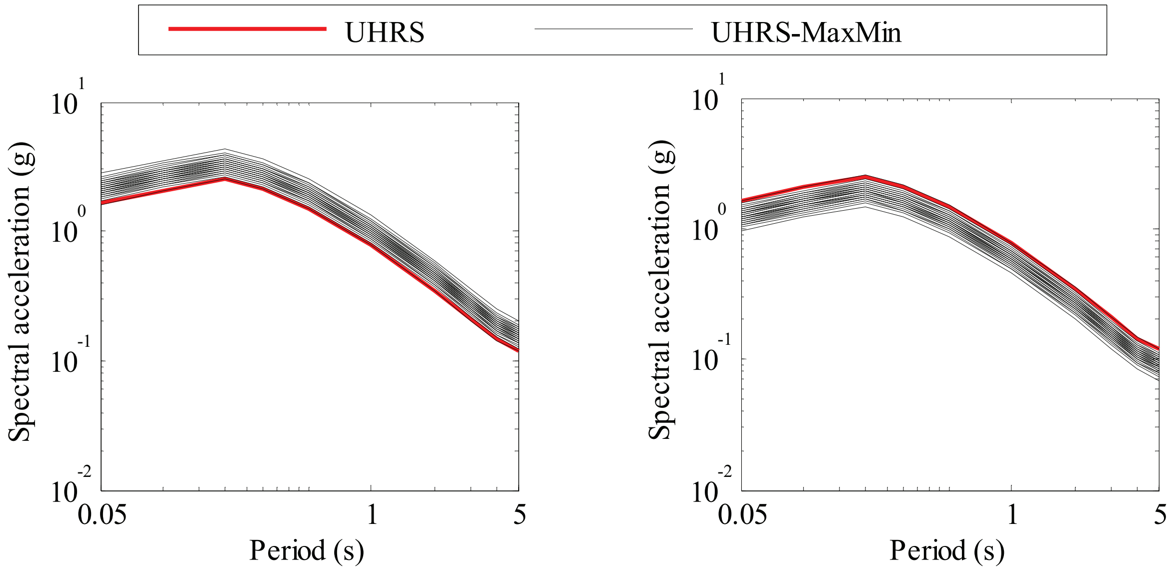
Figure 2: Uniform hazard response spectrum (UHRS), and conditional mean spectra (CMS) and conditional spectra (CS) with conditioning periods of 2 s, 3 s and 4 s at Diablo Canyon at an MAFE of 10^{-4} and 5% damping

Figure 4(b) presents the distributions of spectral displacement at $T = 2$ s with $T^* = 2$ s. There is little difference in the distribution of the SDs for the UHRS, CMS and CS ground motions, since the CMS, CS and UHRS ordiantes are equal at the conditioning period (see Figure 2(a)). A similar observation is made for Figures 4(g) and 4(l) for which $T = T^*$. The distributions of spectral displacement corresponding to the UHRS-MaxMin scaled motions in these three panels are similar to that in Figure 4(a).

For the panels of Figure 4 with $T \neq T^*$, the trends are similar to Figure 4(a), namely, 1) the SDs of the UHRS motions are greater than those of the CMS motions, 2) the distributions of SDs of the three sets of CS motions are virtually identical, 3) the SDs of the UHRS motions exceed those of the CS motions until approximately the 65th percentile, 4) the 84+th percentile SDs of the CS motions are significantly greater

[1] This difference would be zero if the ground motions were *perfectly matched* to the target spectrum.

than those of the UHRS and CMS motions, and 5) the SDs of the UHRS-MaxMin motions exceed those for the other three spectra at percentiles below 90.



(a) X direction (b) Y direction

Figure 3: Uniform hazard response spectrum (UHRS), and uniform hazard response spectra with *maximum* and *minimum* components (UHRS-MaxMin) for the site of Diablo Canyon at MAFE of 10^{-4}

The distributions of spectral displacement in the Y direction are identical to those in X direction, except for the UHRS-MaxMin ground motions because they were amplitude scaled with reciprocal factors for the X direction.

Isolation-system Horizontal Displacement

A seismically isolated NPP is modeled as a single Friction Pendulum™ (FP) bearing with a sliding period of 3 s, a static axial load of 50 MPa, a radius of contact area at the sliding surface of 200 mm and a Coulomb-type coefficient of friction of 0.1 (e.g., Kumar *et al.* (2014)). Sliding is assumed to begin at a lateral displacement of 1 mm. Mass proportional damping of 2% is assigned to the system with the proportionality coefficient anchored to the sliding period of the bearing. This model is subjected to the two horizontal components of ground motions developed in the preceding section. The vertical component is not included in the analysis because isolation-system displacements are not affected by vertical shaking (e.g., Mosqueda *et al.* (2004)).

Figure 5(a) presents the distributions of peak isolator displacement for the ground motions consistent with UHRS, UHRS-MaxMin, and CS and CMS with T^* of 2 s (Figure 2(a)). The peak displacements for the UHRS motions are greater than those for the CMS and CS motions at percentiles smaller than 80; the displacements for the CMS and CS motions are comparable up to the 80th percentile. The displacements for the UHRS-MaxMin motions are greater than those for the other three representations of seismic hazard, at percentiles less than 95. The CS displacements are greatest at 95+ percentile. The ratios of displacements for UHRS-MaxMin (CMS, CS[1]) to UHRS motions are 1.26 (0.73, 0.72), 1.34 (0.85, 1.15) and 1.42 (0.95, 1.67) at 50th, 90th and 99th percentiles, respectively.

[1] The greatest of the three values (one for each of the three sets of CS-scaled motions) is used.

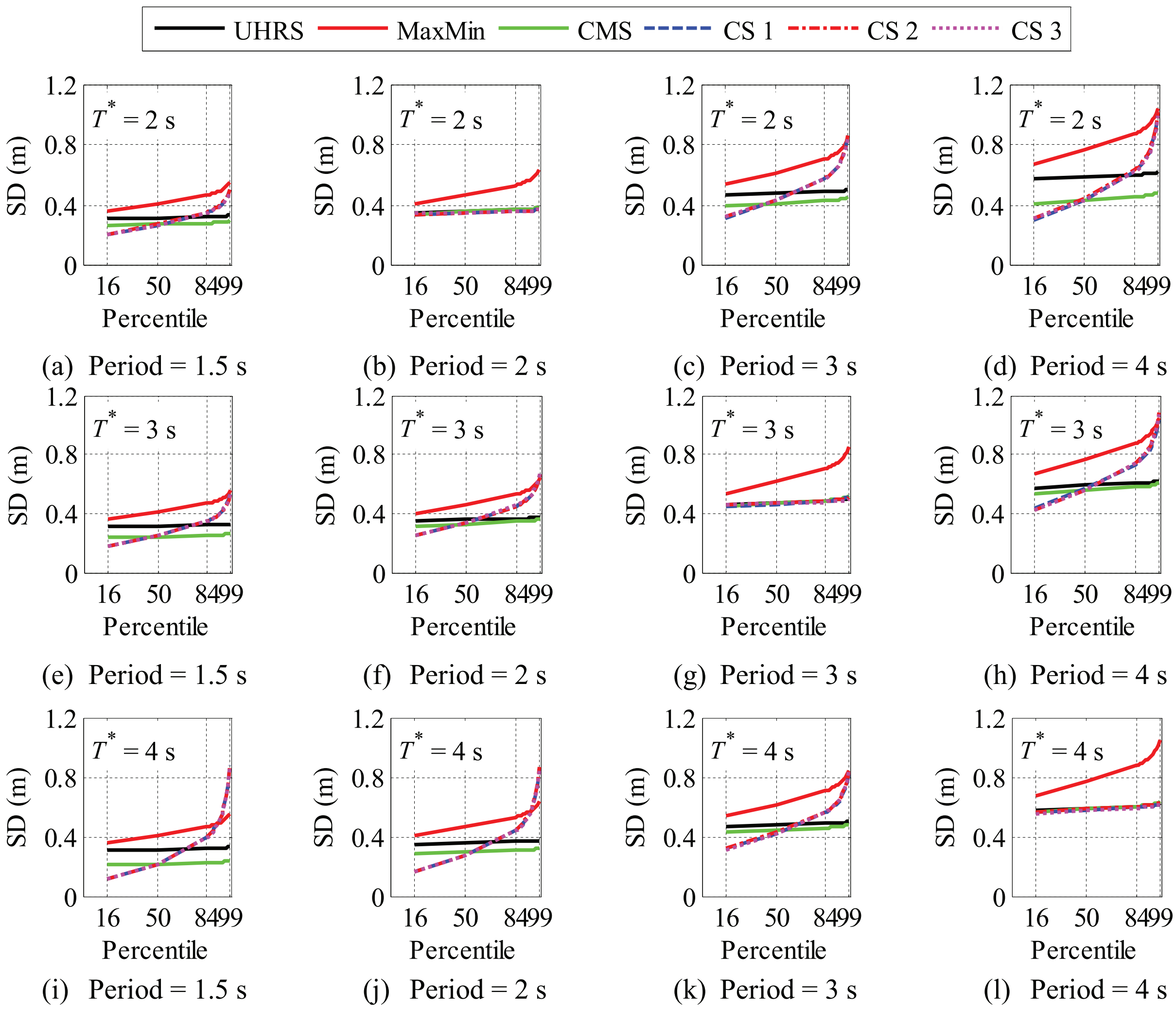


Figure 4: Distributions of spectral displacement in the X direction

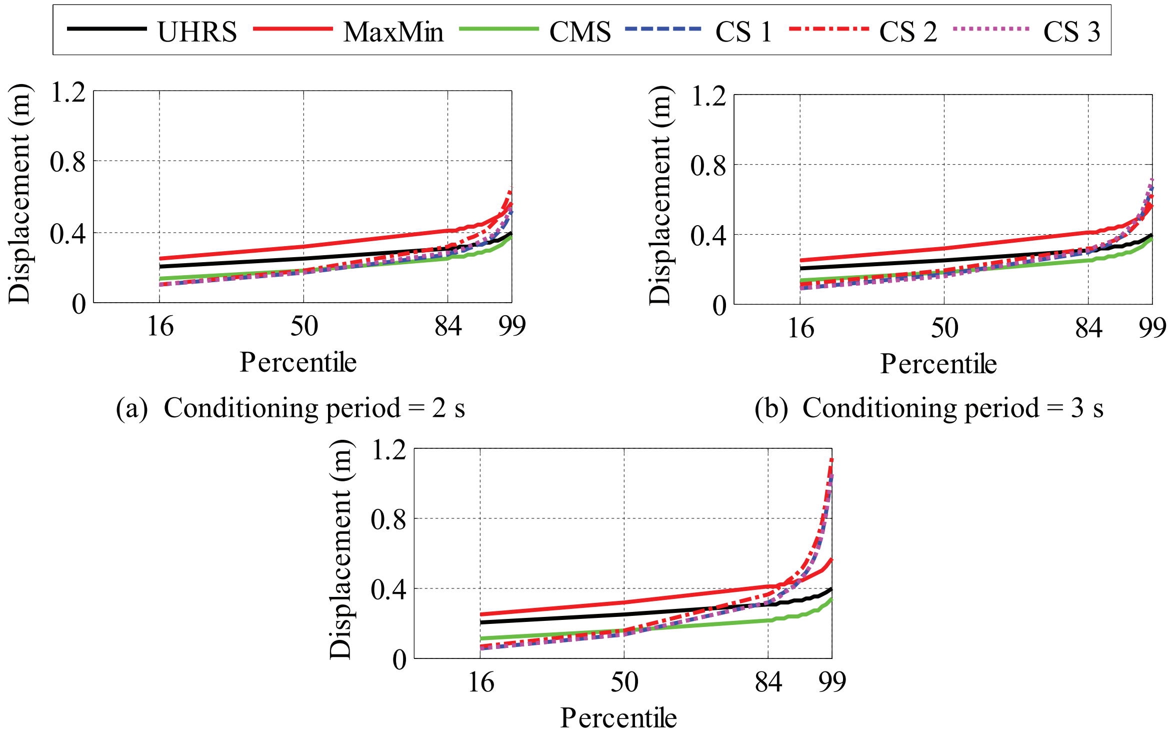
Data for conditioning periods of 3 s and 4 s are presented in Figures 5(b) and 5(c), respectively. The general trends are the same as those for a conditioning period of 2 s. The 95+ percentile peak displacements are greatest for the CS-scaled motions. The ratios of peak displacements for the UHRS-MaxMin (CMS, CS) to UHRS motions are 1.26 (0.73, 0.79), 1.34 (0.84, 1.14) and 1.42 (0.95, 1.81) at the 50th, 90th and 99th percentiles, respectively, for a conditioning period of 3 s, and 1.26 (0.62, 0.60), 1.34 (0.73, 1.43) and 1.42 (0.84, 2.89), respectively, for a conditioning period of 4 s.

GROUND MOTIONS FOR 100,000-YEAR SHAKING

The ratio of 100,000-year to 10,000-year UHRS spectral ordinates at the Diablo Canyon site vary between 2.0 and 2.2 over a period range from 0.5 s to 4 s. The 100,000-year UHRS is adequately calculated by amplitude scaling the 10,000-year UHRS by a factor of 2.1. The UHRS-MaxMin spectra consistent with the 100,000-year hazard are also obtained by amplitude scaling the 10,000-year UHRS-MaxMin spectra[1] by a factor of 2.1. Data for 100,000-year CMS and CS are not available at the USGS website and the 100,000-year CMS are obtained here by amplitude scaling the corresponding

[1] The distributions of amplitude scaling factors in the two directions are assumed to be identical for the two return periods.

10,000-year CMS by 2.1, which is a conservative representation of the seismic hazard for periods other than the conditioning period (see Kumar (2015)).



(a) Conditioning period = 2 s

(b) Conditioning period = 3 s

(c) Conditioning period = 4 s

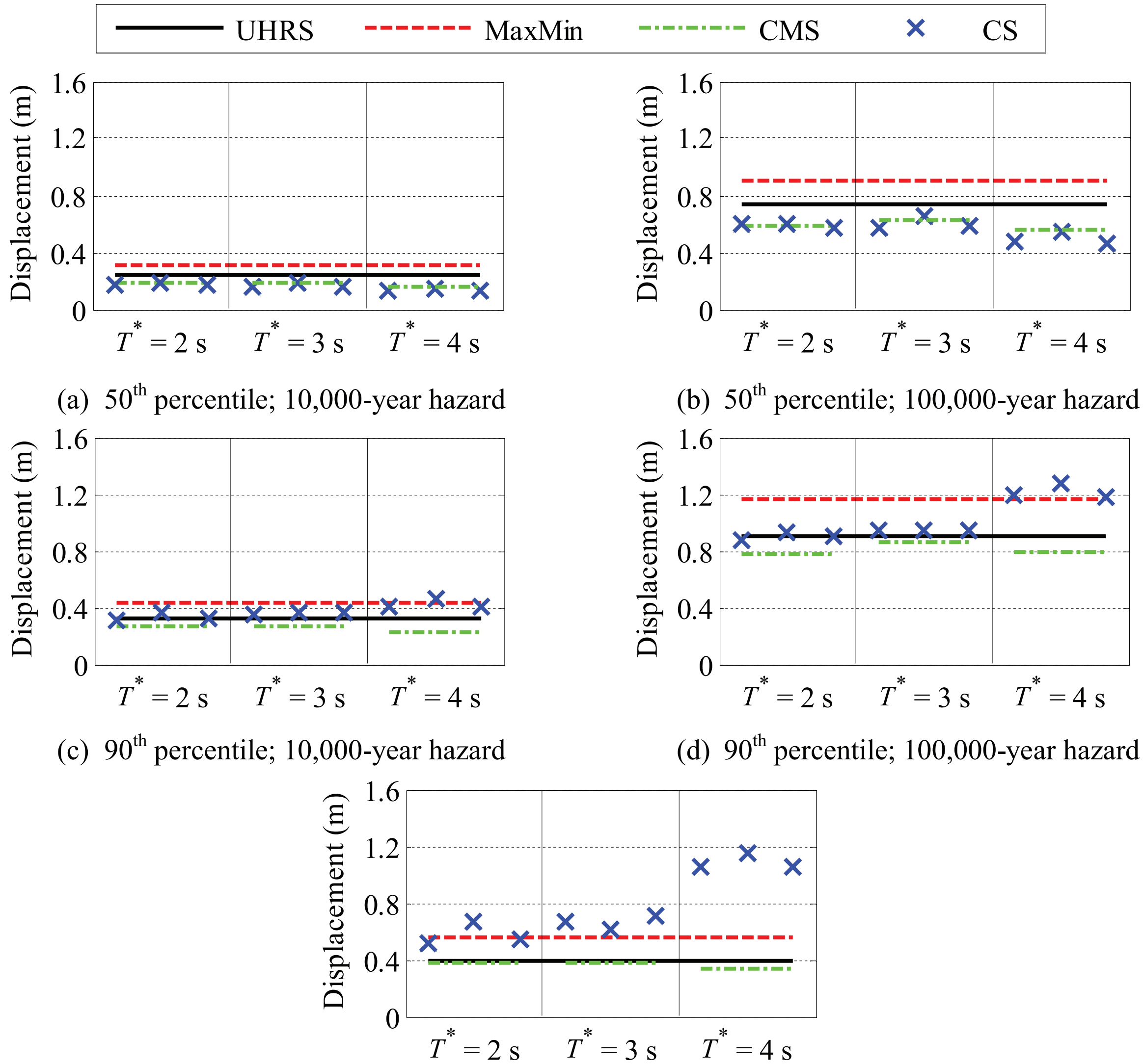
Figure 5: Distributions of maximum displacement of the 3 s FP bearing subjected 10,000-year ground motions for the Diablo Canyon site

COMPARISON OF 10,000- AND 100,000-YEAR ISOLATION-SYSTEM DISPLACEMENTS

The 50th, 90th and 99th percentile displacements for 10,000- and 100,000-year shaking are compared in Figure 6. The median UHRS-MaxMin displacements are greater than those for the corresponding UHRS, CMS and CS at the two hazard levels (Figures 6(a) and 6(b)). The CMS and CS displacements are comparable at this percentile for T^* of 2 s, 3 s and 4 s.

Figures 6(c) and 6(d) present the 90th percentile displacements for 10,000- and 100,000-year shaking, respectively. The UHRS-MaxMin displacements (and CS displacements with T^* of 4 s) are the greatest at this percentile. For T^* of 2 s and 3 s, the CS and UHRS isolator displacements are comparable, and CMS displacements are smaller than those for other three representations of seismic hazard. The CS isolator displacements for T^* of 2 s and 3 s are comparable to the UHRS-MaxMin isolator displacements, and greater than the UHRS and CMS isolator displacements at the 99th percentile (Figure 6(e)). The 99th percentile UHRS and CMS displacements are virtually identical for T^* of 2 s and 3 s.

The forthcoming seismic isolation NUREG requires the CHS to be greater than the 99th (90th) percentile displacement for 10,000-year (100,000-year) shaking. For a given definition of seismic hazard (e.g., UHRS), the 90th percentile EDB GMRS isolator displacement is greater than the 99th percentile displacement and it will dictate the clear distance between the isolated superstructure and the hard stop.



(a) 50th percentile; 10,000-year hazard
(b) 50th percentile; 100,000-year hazard
(c) 90th percentile; 10,000-year hazard
(d) 90th percentile; 100,000-year hazard
(e) 99th percentile; 10,000-year hazard

Figure 6: Median, 90th and 99th percentile peak displacement responses of the FP bearing subjected to 10,000- and 100,000-year ground motions

SUMMARY AND CONCLUSIONS

Seismically isolated nuclear power plants (NPPs) in the United States will include a hard stop to eliminate the seismic isolation system from accidents sequences that could lead to core damage or large release of radiation. The isolation system will be analysed, designed and tested for two levels of seismic hazard: a ground motion response spectrum+ (GMRS+) with a return period of 10,000 years and an extended design basis (EDB) GMRS with a return period of 100,000 years. Response-history analysis for ground motions consistent with these spectra will establish the clearance to the hard stop (CHS), which is required to be the greater than the 99th (90th) percentile displacement for GMRS+ (EDB GMRS) shaking. Calculations performed for the site of the Diablo Canyon Nuclear Generating Station show that the 90th percentile EDB GRMS isolator displacements are greater than the 99th percentile GMRS isolator displacements: the clear distance between the isolated superstructure and the hard stop, along each horizontal axis of the structure, will be determined by response-history analysis using EDB GMRS ground motions.

The GMRS for nuclear power plants has traditionally been attached to a UHRS, although it is widely accepted that this geometric mean spectrum does not well represent the effects of shaking from individual earthquakes. Alternate representations of seismic hazard were considered for the Diablo Canyon site: the conditional mean spectrum (CMS) and conditional spectra (CS). Ground motion sets were scaled to the UHRS, and to the CMS and CS for conditioning periods of 2 s, 3 s and 4 s. Isolation-system displacements for CMS and CS motions were sensitive to the choice of conditioning period and no advantage, in terms of reduced isolator displacements, can be easily taken because the effective period of the isolation system varies by ground motion and intensity, leaving the UHRS as the simplest choice for a target spectrum. The UHRS-MaxMin ground motions, which better represent reality than ground motions spectrally matched to a UHRS, produce consistently greater isolator displacements than the UHRS motions, and so should be used to analyse seismically isolated nuclear power plants.

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