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Seismic Response of Next Generation Plants with base isolators to Horizontal and Vertical Accelerations

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ABSTRACT

The goal of this research is to develop an efficient base isolator system to prevent damage to non-structural components in Next Generation Nuclear Plants (NGNPs). NGNPs will operate under very high temperatures and include a passive cooling system to control temperature under disruptive events. The NGNPs may be subjected to strong horizontal and vertical seismic accelerations. Base isolators have been used between containment structures and the foundation to reduce the horizontal seismic response of nuclear facilities. However, the system performance under vertical accelerations is not well understood. This investigation evaluated three-dimensional base isolators to control NGNP vertical seismic accelerations in addition to horizontal accelerations using models developed in OpenSees (2010). The model represented a circular reinforced concrete containment structure resting on different types of elastomeric bearings. To mitigate the effect of vertical accelerations on the NGNP, modified elastomeric bearings with less intermediate steel shim plates were used (i.e., low shape factor bearings). To prevent large vertical and rotational displacements, the systems with modified isolators also included damping devices. The vertical accelerations of the base isolated systems with low shape factor bearings were substantially lower than those of systems using conventional elastomeric bearings. The vertical displacements were initially higher for the LSF bearings, but once the damping devices were incorporated, the displacements were comparable to those of conventional isolator systems. The initial results show that it is possible to mitigate the effect of strong vertical seismic accelerations using simple modifications to conventional base-isolated systems.

INTRODUCTION

Base isolation systems are a promising solution to create resilient systems because relative displacements of the superstructure are minimized. Seismic structural resiliency refers to the building's ability to withstand expected earthquake levels with minor damage or no damage. Current base isolation systems can achieve these high seismic performance objectives when subjected to horizontal accelerations (Morgan and Mahin 2009). Base isolation has been used in several safety-related nuclear structures using different isolator designs (Eidinger and Kelly 1985). Base isolation reduces seismic demands on structural and nonstructural components and systems in nuclear power plants (NPPs). However, nuclear facilities also require efficient seismic isolation under vertical seismic accelerations. In most cases, the critical seismic failure modes are related to failure of non-structural components. Base isolators can reduce the structural horizontal response and the probability of failure by several orders of magnitude (Huang et. al 2010), but the effect of vertical accelerations is not well understood.

The failure probability threshold for NGNP evaluation is likely to be 10^{-8}/year, which will significantly increase accelerations and magnitude of the evaluated seismic events. Moreover, vertical accelerations may be relevant because the vertical-to-horizontal spectral acceleration ratio, V/H, is larger for earthquakes of large magnitude, especially for sites closer to the fault. In most of previous studies, however, only horizontal accelerations are considered in the evaluation (Huang et. al 2010, Eidinger and Kelly 1985). This study assesses the response of different base isolator systems under three orthogonal seismic accelerations. Traditional elastomeric bearings are modified to reduce the vertical stiffness, and supplementary dampers are incorporated to control potential large vertical and rotational displacements caused by the flexible bearings. The results are compared to a conventional base isolation system.

Numerical simulation of NGNP under Extreme ground motions

The seismic performance evaluation includes a circular reinforced concrete (RC) containment structure that may be used in a NGNP (e.g., Blanford et. al 2007). The containment structure has about 30 m. in diameter and 42 m. in height (13). The structure will be placed on a base isolator system consisting of elastomeric bearings. Prior to the numerical evaluation, a study was carried out to determine the main factors affecting the bearings' dynamic properties.

Parameters controlling vertical base isolation

Elastomeric bearings consist of several layers of rubber bonded to intermediate steel shim plates, and modification of their geometric properties can result in horizontal and vertical isolation. To select the characteristics of the elastomeric bearings, the vertical and horizontal stiffness of the bearings can be defined as (Liu et. al 2009, Naeim and Kelly 1999, and Warn and Ryan 2012):

$$K_{V0} = \frac{E_c A_b}{T_r} \tag{1}$$

$$K_H = \frac{GA}{T_r} \tag{2}$$

K_{V0} is the initial vertical stiffness of the isolator, A_b is the bounded rubber area, A is the area of the steel shims, T_r is the total thickness of rubber, G is the rubber shear modulus, and E_c is the compression modulus of composite material. The low horizontal stiffness needed to lengthen the fundamental natural period of the system is provided by T_r, whereas the close spacing of the steel shim plates provides a large vertical stiffness.

The compression modulus for a solid, circular incompressible rubber layer can be expressed as (Naeim and Kelly 1999, Yamamoto et. al 2009, and Liu et. al 2009):

$$E_c = \frac{(6\kappa G S_1^2)E_b}{(6\kappa G S_1^2)+E_b} \tag{3}$$

Where E_b is the bulk modulus of rubber, and κ is a constant related to the rubber hardness. Also, S_1 is the first shape factor. For circular elastomeric bearings, $S_1 = D/4t_r$ (Yamamoto et. al 2009), where t_r is the thickness of rubber layers. Because S_1 factors typically have values between 15 and 25, the vertical stiffness is three orders of magnitude larger than the horizontal stiffness, leading to very short vertical periods of vibration between 0.03 and 0.10 s. Elastomeric bearings with a small number of steel shim plates are also known as low shape factor (LSF) bearings.

Fig. 1 shows the variation of vertical stiffness with respect to rubber layer thickness assuming $D = 1.2$ m, $T_r = 0.5$ m, and $\kappa = 1.0$. For this particular configuration, the shape factor S_1 varies from $S_1 = 1.2$ (for $t_r = 0.25$ m) to $S_1 = 60$ (for $t_r = 0.005$ m).

The effect of S_1 on the vertical stiffness of elastomeric bearings is well documented (e.g., Aiken et. al 1989). Eqns. 1-3 also indicate that other parameters affect in a lesser degree the vertical stiffness, such as the diameter of the isolator, D. The variation on these parameters may be considered a design optimization technique and will not be further discussed in this paper.

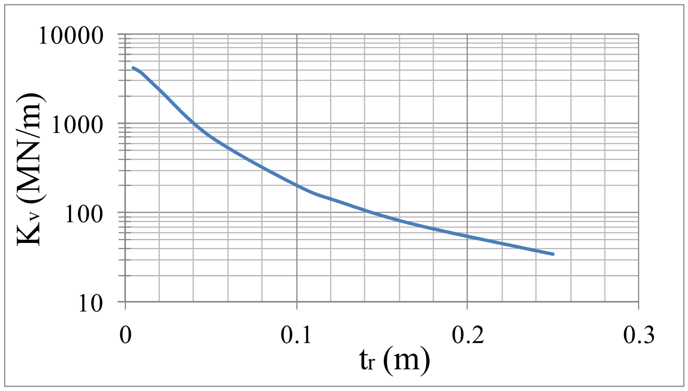
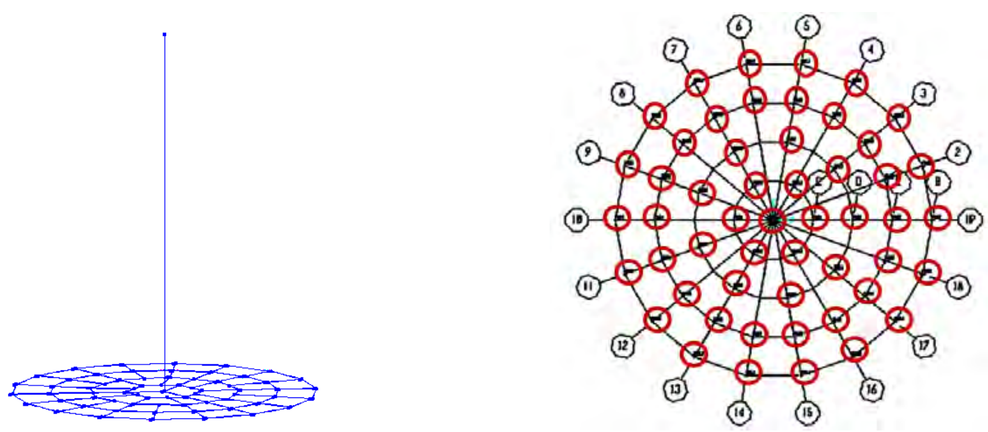


Fig. 1 Rubber layer thickness effect on elastomeric rubber bearing vertical stiffness
(D = 1.2 m, T_r= 0.5 m)

NGNP Modeling and Base Isolator Bearings

To test the effect of the rubber layer thickness on the seismic response of the concrete container, a simplified model was created in OpenSees (2010). The container walls are represented in the model with a beam-column element with a lumped mass at the top, whereas a rigid plate is used to model the foundation mat (Fig. 2). A total of 52 isolators were used, each one supporting a gravitational load of about 640 Ton. The slab is made of shell quad elements, creating a rigid diaphragm. The isolators are modeled by the zero length elements and linear elastic material.

The base isolated system was initially designed using traditional isolators (RB-1) with D = 1.2 m, T_r = 0.5 m, t_r = 0.01 m, and G = 1.8 MPa, rendering a shape factor S_1 = 30, and K_V/K_H = 919 (based on Eqn. 2). The base isolated system damping was assumed as ζ =10%. Also, the target horizontal period of vibration was T_{H1} = 2.5 s., whereas the isolation design led to a vertical fundamental period of vibration T_{V1} = 0.1 s.



(a) (b)

Fig. 2 (a) Simplified Models of Concrete (b) Base-Isolator's Location

Three different elastomeric bearings were considered to generate five different structural models. The first elastomeric bearing (RB-1) is the conventional case with small rubber layer thickness (i.e., high shape factor). To add flexibility in the vertical direction, the rubber layer thickness was increased to t_r = 0.125 m (RB-2) and t_r = 0.25 m (RB-3), which is considered an extreme case. Probably the only system built with a rubber layer thickness of this order was the Pestalozzi school building in Skopje, which consisted of square-shaped rubber bearings with no steel shim plates (Gjorgjiev and Garevski, 2012). The characteristics of the three bearings are presented in Table 1. Note that the S_1 parameter is drastically reduced for bearings RB-2 and RB-3.

Table 1. Rubber bearing characteristics used in the modeling

Bearing parameters	RB-1	RB-2	RB-3
Bearing diameter, D[m]	1.2	1.2	1.2
Total thickness of rubber, T_r[m]	0.5	0.5	0.5
Thickness of a single rubber layer, t_r[m]	0.01	0.125	0.25
Shear modulus, G[MPa]	1.8	1.8	1.8
Horizontal stiffness, K_h [kN/m]	4,009	4,009	4,009
Vertical stiffness, K_v[kN/m]	3,684,042	132,343	33,840
K_v/K_h	919	33	8.44
Shape factor, S_1	29.8	2.4	1.2

The other system parameter evaluated in this study was the system's percentage of critical damping, which for the baseline was assumed as ζ =10% in horizontal and vertical directions, an expected value when using elastomeric bearings. For some cases, however, the damping was increased to ζ = 30% only in the vertical direction, which assumes that supplementary damping devices are installed in this direction. Table 2 presents five evaluated cases based on variations of bearing type and damping parameter. Note that RB-1 bearing is not combined with a damping ζ =30%, because the high vertical stiffness of this bearing should prevent large vertical and rotational displacements, making the use of supplementary damping unnecessary. Table 2 also reports the fundamental period of vibration in horizontal and vertical directions.

Table 2. Description of the different analysis cases

Characteristics	Case I	Case II	Case III	Case IV	Case V
Bearing	RB-1	RB-2	RB-2	RB-3	RB-3
Horizontal damping, ζ_x	10%	10%	10%	10%	10%
Vertical damping, ζ_z	10%	10%	30%	10%	30%
Horizontal period of vibration, T_{H1}	2.5 s.	2.5 s.	2.5 s.	2.5 s.	2.5 s.
Vertical period of vibration, T_V	0.1 s	0.38 s.	0.38 s.	0.86 s.	0.86 s.

Earthquake ground motions

The models were subjected to ground motions with no forward directivity effects, and large PGAs in the three orthogonal directions. The failure probability threshold for NGNP evaluation is likely to be 10^{-8}/year, which increases accelerations and magnitude of the evaluated seismic events. Vertical accelerations are relevant for these seismic scenarios because the vertical-to-horizontal spectral acceleration ratio, V/H, is larger for earthquakes of large magnitude, especially for sites closer to the fault (Gulerce and Abrahamson 2011). The time history analyses performed in the study included the three components of the selected ground motion records. The characteristics of the three ground motions used in the initial study are presented in Table 3. Statistical evaluations were not obtained due to the limited number of records (ASCE 41-06 2006).

Table 3: Ground motions used in this study

Rec. No.	Record/Component	Earthquake	Component	Station	PGA	M_w	R(Km)
Record-1	IMPVALL/H-AGRDWN	Imperial Valley 1979	Vertical	6618 Agrarias	0.835	6.9	12.9
	IMPVALL/H-AGR003		Horizontal-N		0.370		
	IMPVALL/H-AGR273		Horizontal- W		0.221		
Record-2	KOBE/NIS-UP	Kobe 1995	Vertical	0 Nishi-Akashi	0.371	6.9	11.1
	KOBE/NIS000		Horizontal-N		0.509		
	KOBE/NIS090		Horizontal- W		0.503		
Record-3	LOMAP/CAP-UP	Loma Prieta 1989	Vertical	47125 Capitola	0.541	7.1	14.5
	LOMAP/CAP000		Horizontal-N		0.529		
	LOMAP/CAP090		Horizontal- W		0.443		

Fig. 3 shows the horizontal and vertical response spectra for the third record, Loma Prieta 1989 earthquake. For the horizontal direction, the maximum spectral accelerations are located at the 0.3-0.4 s. period interval. However, the vertical direction showed a higher frequency content resulting in most of the energy concentrated in the spectral interval $T_V < 0.2$ s. These observations are common in strong seismic events, although the high spectral acceleration interval in the vertical direction can extend beyond $T_V = 0.2$ s. For this record, the horizontal isolation works well because the spectral acceleration at the elongated horizontal period $T_H = 2.5$ s. is 26% of the peak ground acceleration. That is, the ground motion amplitude is reduced four times at the mass location of a single-degree-of-freedom (SDOF) system. In the vertical direction, however, the vertical ground motion is amplified 2.5 times at the vertical period $T_{V1} = 0.1$ s.

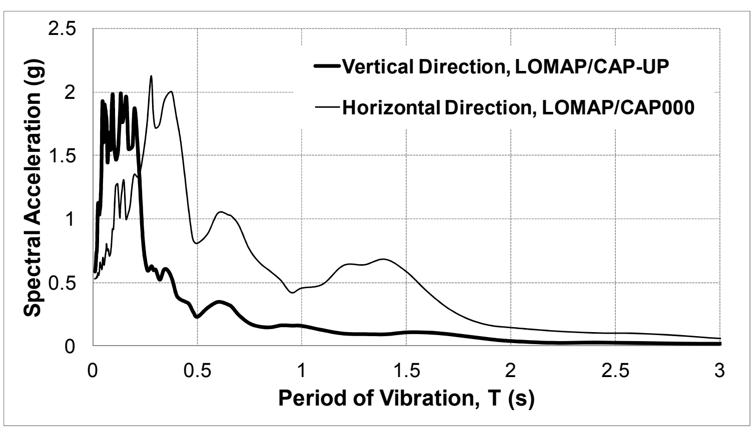


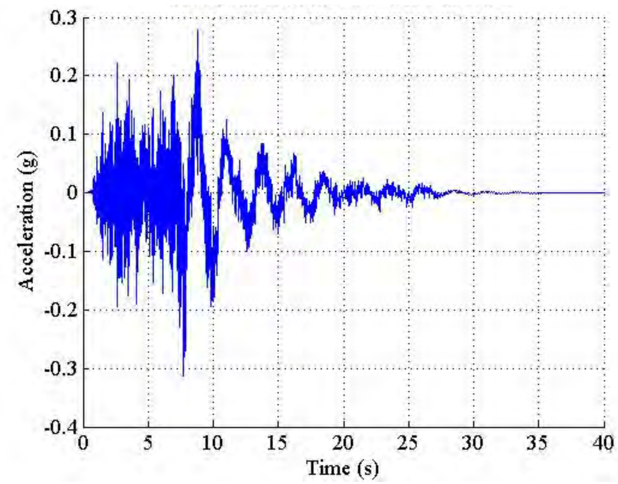
Fig. 3 Horizontal and vertical response spectra for Loma Prieta 1994 Earthquake, Capitola station.

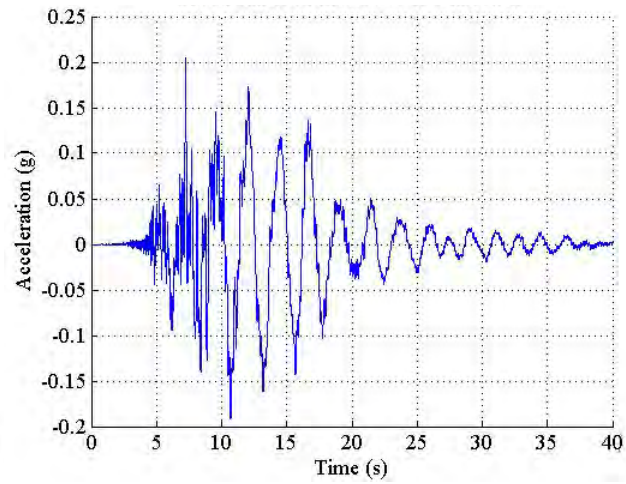
Analysis and results

Experimental tests of elastomeric isolator rubber bearings have shown that the hysteretic loops of these isolators behave almost linearly under cyclic loading (e.g., Abe et. al 2004). Based on these analyses, linear response was assumed for the horizontal direction, and the assumption was extrapolated for the vertical direction. This simplification assumes that lifting of the isolator will not occur, or that the isolator will exhibit relatively linear behavior in tension, an assumption that may be inaccurate for certain conditions (Warn and Ryan, 2012).

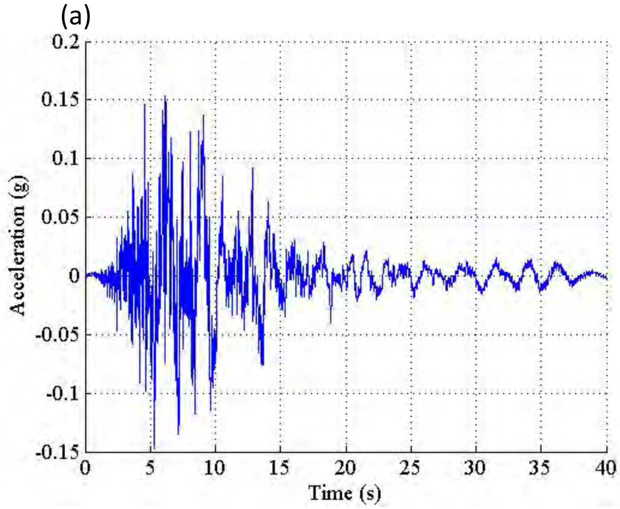
The structural analysis results obtained from OpenSees (2010) using linear time history analysis are presented below. Fig. 4 shows the acceleration of the model at the lumped mass (top of beam-column element) for Case I in the horizontal direction “x”. The horizontal accelerations for the other cases are similar to those of Case I.

Fig. 5 presents the vertical response for the Loma Prieta 1989 earthquake (Record-3) for Cases I and II. As observed, the use of a flexible base isolator (RB-2) in Case II reduced the vertical accelerations more than four times. Fig. 5(c) shows the vertical acceleration response for Case III (i.e., with RB-2 bearings and $\zeta = 30\%$), which has maximum amplitudes similar to those of Case II. That is, for this time history analysis the additional damping did not significantly reduce the vertical acceleration response because at T_{V1} = 0.38 s the response is controlled by the inertial forces, not the damping. This is a consequence of the spectral shape for this particular record (Fig. 3).





(a) (b)



(c)

Fig. 4. Acceleration in “x” direction under (a) Record-1 (b) Record-2 (c) Record-3

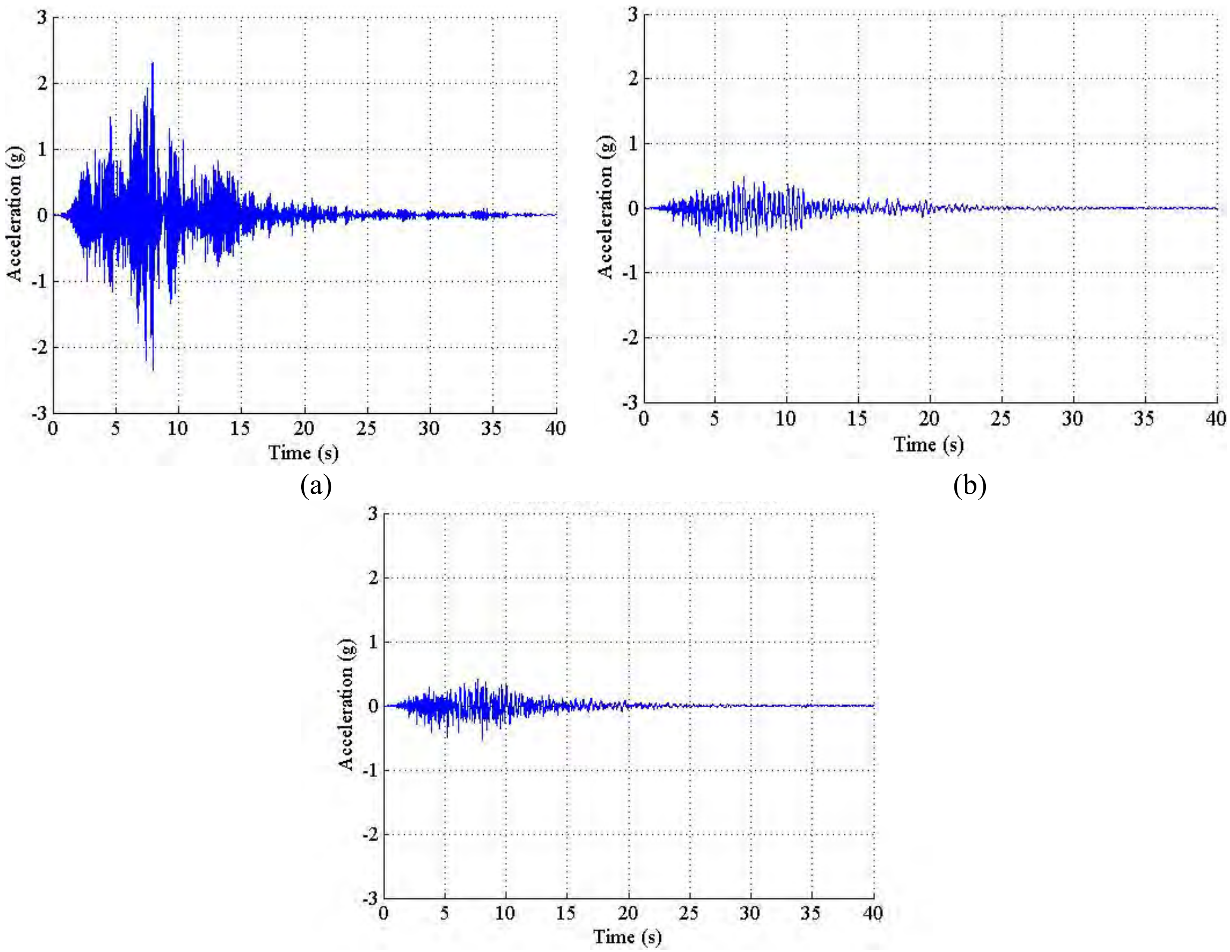
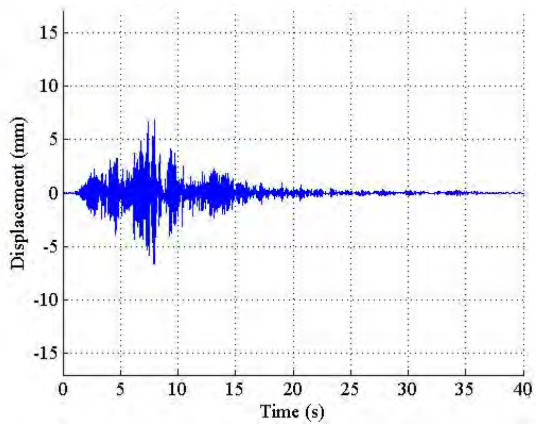


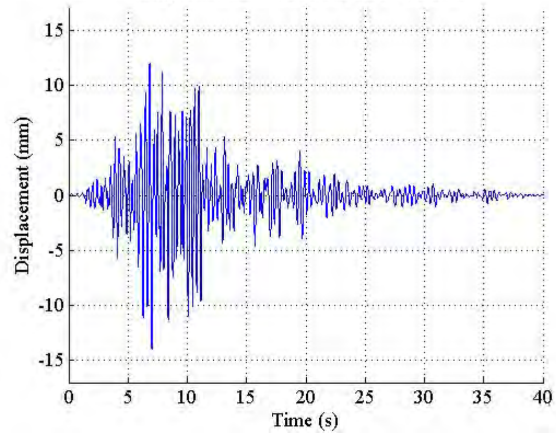
Fig. 5 Vertical acceleration response for (a) Case I, (b) Case II, and (c) Case III Isolation Systems under Record-3

Fig. 6 shows the vertical displacement for Cases I, II, and III. A comparison of Figs. 6(a) and 6(b) shows that vertical displacements of the more flexible isolator resulted are more than twice the displacements of conventional isolator systems. However, the displacements were reduced to the original levels when the damping was increased to $\zeta = 30\%$ (Case III, Fig. 3(c)). Thus, supplementary damping devices are needed because i) the high energy region in the vertical spectral acceleration may extend beyond T_V = 0.2 s. for other records, and ii) because additional damping reduces vertical and rotational displacements, as in this example.

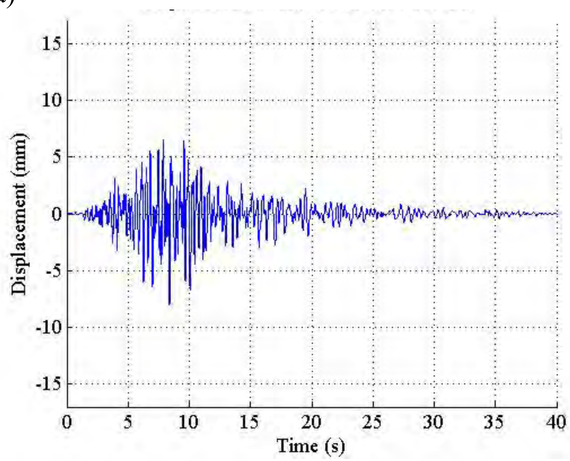
The evaluation of Cases IV and V indicated that the use of RB-3 elastomeric bearings did not lead to significant differences with respect to the results obtained when using RB-2 bearings. The reason is that the three ground motions have high vertical spectral accelerations at periods smaller than T_V = 0.38 s. Thus, the period lengthening from 0.38 to 0.86 s. was not relevant for this set of ground motions. The results indicate that the maximum vertical displacements occur when Record-2 is used in the analysis, but the main trends remain. Finally, the use of elastomeric bearings with less vertical stiffness did not lead to significant differences in torsional displacement, and the rocking response was not significantly affected by the design modifications.



(a)



(b)



(c)

Fig. 6 Vertical displacement response for (a) Case I, (b) Case II, and (c) Case III Isolation Systems under Record-3

CONCLUSIONS

The study presents an initial assessment on the use of modified elastomeric bearings to isolate the vertical response of NGNPs. The elastomeric bearings have less intermediate steel shim plates (i.e., low shape factor bearings), and the base isolation system includes supplementary damping devices to prevent large vertical and rotational displacements. The main findings of the analyses are:

- The rubber layer thickness is the most important parameter to reduce the vertical stiffness of elastomeric bearings. For instance, an increase in the rubber layer thickness from $t_r = 0.01$ m to $t_r = 0.25$ m, reduces the vertical stiffness more than 100 times.
- The base isolator diameter, or side in the case of square-shape isolators, also modifies the vertical stiffness of elastomeric bearings, but in a lesser degree. This is a parameter that can be used to optimize the design of systems isolated in three directions.
- According to the spectral shapes of the selected ground motions, the RB-2 and RB-3 bearings are flexible enough to cause a period lengthening that leads to vertical accelerations. That is, the added flexibility shifts the vertical periods to low spectral acceleration regions. However, the vertical damping of the isolators needs to be increased to reduce the increase in vertical accelerations caused by the more flexible system.

- The use of the more flexible RB-3 bearings did not lead to a significant reduction of the vertical accelerations, when compared to the displacements obtained with RB-2 isolators. The conclusion is that for the small set of ground motions used in the study, the flexibility provided by RB-2 is enough to shift the period from the high vertical spectral acceleration region. Thus, additional period lengthening (from T_V = 0.38 s. to 0.86 s.) does not benefit the system's response.

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