NUMERICAL SIMULATION OF SEISMICALLY ISOLATED BUILDINGS CONSIDERING POUNDINGS WITH ADJACENT STRUCTURES

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ABSTRACT:

Considering a limited seismic gap around a seismically isolated building, in combination with a very strong earthquake excitation, there is always the possibility of poundings either with the surrounding moat wall or with the neighboring buildings. In order to investigate the influence of the impacts on the overall structural response, seismically isolated buildings in series with adjacent structures have been simulated and analyzed numerically under strong earthquake excitations. The effects of certain parameters, such as the size of the separation distance, the earthquake characteristics and the structural properties of the adjacent buildings, have been investigated parametrically using a specially developed software application.

KEYWORDS: pounding, seismic isolation, impact, earthquake, Java programming.

1. INTRODUCTION

Seismically isolated buildings are expected to experience large displacements relative to the ground during strong earthquake excitations, especially when the latter contain long period impulses. In order to accommodate such large displacements a sufficiently wide clearance must be provided around the building, which is known as "seismic gap". Since the width of the provided seismic gap cannot be unlimited due to practical constraints, especially in cases of retrofitting existing structures, a reasonable concern is the possibility of pounding of a seismically isolated building against either the surrounding moat wall or the adjacent buildings during a very strong earthquake.

Pounding incidences between conventional fixed supported buildings during strong earthquakes motivated several researchers to investigate these phenomena numerically and experimentally (Anagnostopoulos 1988, Maison and Kasai 1990, Anagnostopoulos and Spiliopoulos 1992, Davis 1992, Filiatrault et al 1995, Papadrakakis et al 1991, Papadrakakis et al 1996, Chau and Wei 2001, Chau et al 2003). The limited research work that has been carried out for poundings of seismically isolated buildings concerned only the case of impacts at the base of the buildings (Tsai 1997, Malhotra 1997, Dimova 2000, Matsagar and Jangid 2003, Komodromos et al 2007). Tsai H.C. (1997) simulated the superstructure of an isolated building as a continuous shear beam bumping against a stopper at the base in order to investigate the effects of impact on its structural response. Based on wave propagation theory, he observed very high acceleration response during poundings with the surrounding structures at the isolation level. Using a similar approach, Malhotra (1997) has concluded that the base shear force increases with the stiffness of the structure or the retaining wall, while sometimes it becomes higher than the total weight of the building. Matsagar and Jangid (2003) also examined the case of poundings of seismically isolated MDOF structures, for various types of seismic isolation systems using the Newmark time integration method. They concluded that poundings affect more the response of seismically isolated buildings when the latter have a flexible superstructure, an increased number of stories or relatively stiff adjacent structures. Agarwal et al (2007) have examined poundings of a seismically isolated building with other adjacent building. However, the simulation was expressed analytically and involved only two-degree-of-freedom buildings. Thus, there is a scientific and practical need to investigate thoroughly this interesting research problem.

This research work is focused on the effect of having conventional fixed supported buildings adjacent to the seismically isolated building leading to poundings of the superstructures in series. The importance of this investigation, in contrast to the case of fixed supported buildings, is due to the fact that it is more likely to have more rigorous performance requirements and higher expectations for buildings that utilize an innovative earthquake-resistant design, such as seismic isolation, than for conventionally fixed-supported buildings.

2. MODELING AND SIMULATION ASSUMPTIONS

In the current research work, the conventionally fixed supported buildings and the superstructure of the seismically isolated building are modeled as multi-degree of freedom (MDOF) systems with shear-beam behavior and the masses lumped at the floor levels, assuming that the superstructures remain linear elastic during earthquake excitations. For seismically isolated buildings, the dynamic behavior of the isolation system is represented by a bilinear model (Figure 1), which corresponds to that of the Lead Rubber Bearings (LRB). In that case the bilinear behavior is justified by the yielding of the lead core after a certain shear force. In particular, prior to the yielding of the lead core, the isolation system has an initial stiffness K_1, which is much higher than the post-yield stiffness K_2 that corresponds solely to the stiffness of the rubber.

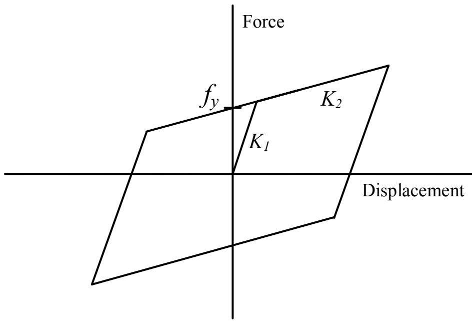

Figure 1: Bilinear modeling of the behavior of the isolation system.

2.1. Impact modeling

The numerical modeling of impact and the estimation of the impact forces acting on the colliding bodies is an essential topic not only for the cases of structural poundings but also for other problems involving numerical simulation of impact. Though, in the case of structural poundings, simple impact models, which estimate the impact forces, are usually used by researchers investigate structural impact (Anagnostopoulos 1988, Jankowski 2005, Muthukumar and DesRoches 2006). In the current study, a force-based impact model is used assuming an impact spring and an impact dashpot in parallel, exerting impact forces to the colliding structures whenever their separation distances are exceeded (Komodromos et al 2007). For the corresponding impact model, the stiffness of the impact spring was assumed to be 2500 kN/mm, while the coefficient of restitution was taken equal to 0.7.

2.2. Location of impacts

In the simulations, the seismically isolated building is considered to be either adjacent to other fixed-supported buildings or alone. In the first case the poundings may occur with the neighboring buildings at the upper floors due to the seismic induced deformations of the structures in series in combination with the limited separation gap. Conversely, in the second case poundings occur only at the base of the building due to the limited separation distance between the seismically isolated building and the moat wall, which is assumed to move with the ground during the excitation. The separation distance between the buildings can be equal or larger than the seismic gap at the base of the seismically isolated building. However, for simplicity, in the presented analyses, the distances of the adjacent buildings and the surrounding moat walls are considered to be equal and the floors of the buildings in series are assumed to be at the same levels (Figure 2).

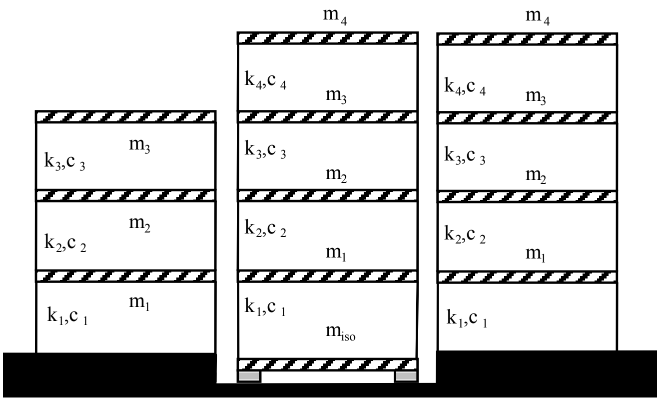

Figure 2: Seismically isolated building in series with other fixed-supported buildings.

3. ANALYSES AND RESULTS

Based on the previously described assumptions, a software application has been specifically developed in order to efficiently perform large numbers of dynamic simulations of seismically isolated buildings in series with other structures taking into account pounding incidences. An Object-Oriented Programming (OOP) approach and the Java programming language have been utilized to design and implement a flexible and extendable software application with effective visualization capabilities that can be used in relevant numerical simulations and parametric analyses.

For the following simulations, a typical 4-story seismically isolated building with the characteristics that are listed in Table 1 is considered. The fundamental period of the 4-story fixed-supported superstructure is equal to 0.404 seconds. The superstructure's characteristics are assumed to be the same for the neighboring fixed supported buildings. In case of poundings, the aforementioned linear viscoelastic impact model with plastic deformations is employed. A set of some of the most catastrophic earthquake records is used, each of them scaled to have a PGA = 1 g (Table 2). The acceleration response spectra of the excitations are shown in Figure 3. Based on the response spectra, all six excitations were selected to have high acceleration response for long periods in order to cause significantly large seismic loads on the seismically isolated building.

Table 1: Characteristics of the seismically isolated building that was considered in the simulations.

Parameter	**Value**
- Superstructure's characteristics:	
Story stiffness (k_i)	1 GN/m
Story mass (m_i)	500 tons
Superstructure's damping ratio (ξ_{sup})	2%
- Isolation system:	
Mass at isolation level (m_{iso})	500 tons
Viscous damping ratio (ξ_{iso})	5%
- Bilinear characteristics of the isolation system:	
Initial stiffness (K_1)	200 MN/m
Post yield stiffness (K_2)	25 MN/m
Characteristic strength (f_y)	$0.1\times W_{tot}^{*}$

* *W_{tot} = total weight of the building*

Table 2: Earthquake records that were used in the simulations

Earthquake	Mw	Station	PGA (g)	Scale Factor (PGA=1g)	Scale Factor (PGA=0.6g)	Duration (sec)
El Centro, 1940	6.9	Imperial Valley	0.348	2.871	1.723	53.76
Kobe, 1995	6.9	0 KJMA	0.821	1.218	0.731	48.00
Northridge, 1994	6.7	Olive View	0.604	1.655	0.993	30.00
Northridge, 1994	6.7	Converter Station	0.897	1.115	0.669	40.00
Kocaeli, 1999	7.4	Sakarya	0.628	1.592	0.955	20.00
San Fernando 1971	6.6	Pacoima Dam, S16	1.170	0.854	0.513	71.12

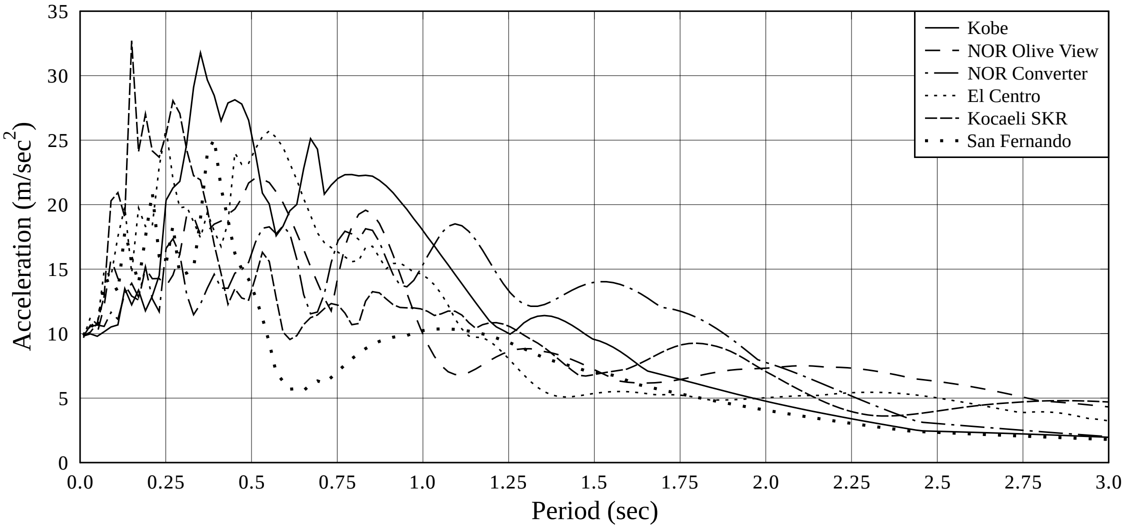

Figure 3: Acceleration response spectra of the six earthquake records, scaled to have a common PGA equal to 1.0 g, considering a damping ratio of 5 %.

A series of dynamic analyses has been conducted in order to investigate the case of having the seismically isolated building adjacent to other fixed supported buildings, compared to the case of the seismically isolated building standing alone surrounded only by the moat wall. In the first case, the 4-story seismically isolated building is considered to be between two 4-story fixed supported buildings with the same structural characteristics and at equal distances. Therefore, impacts may occur at the base of the seismically isolated building or at any floor level. In the second case, the impacts are considered to happen only at the base of the seismically isolated building with the surrounding moat wall which is also standing at equal distances at the left and right of the building. The size of the available clearance between the adjacent structures is varied between the values of 15 and 45 cm with a step of 0.5 cm (60 simulations) for both cases. Two different earthquake records were selected as excitations for this analysis. In order to examine the influence of the excitation's intensity the records were scaled either to have a PGA equal to 1 g or 0.6 g.

Figures 4 and 5 present the results of this parametric analysis, which has been performed in order to examine the different effects of each parameter on the response of the seismically isolated buildings of the two cases. The plots in Figure 4 provide the peak floor accelerations of the seismically isolated building in terms of the size of the available clearance from adjacent buildings and/or the moat wall. The corresponding peak interstory deflections are shown in Figure 5, only for the case of having the excitations scaled to have a PGA equal to 1 g. As it was expected, the response is, in general, decreasing with the increment of the available clearance. However, the variations on the curves indicate that this is not always true, especially for relatively narrow gap sizes in combination with the earthquake characteristics.

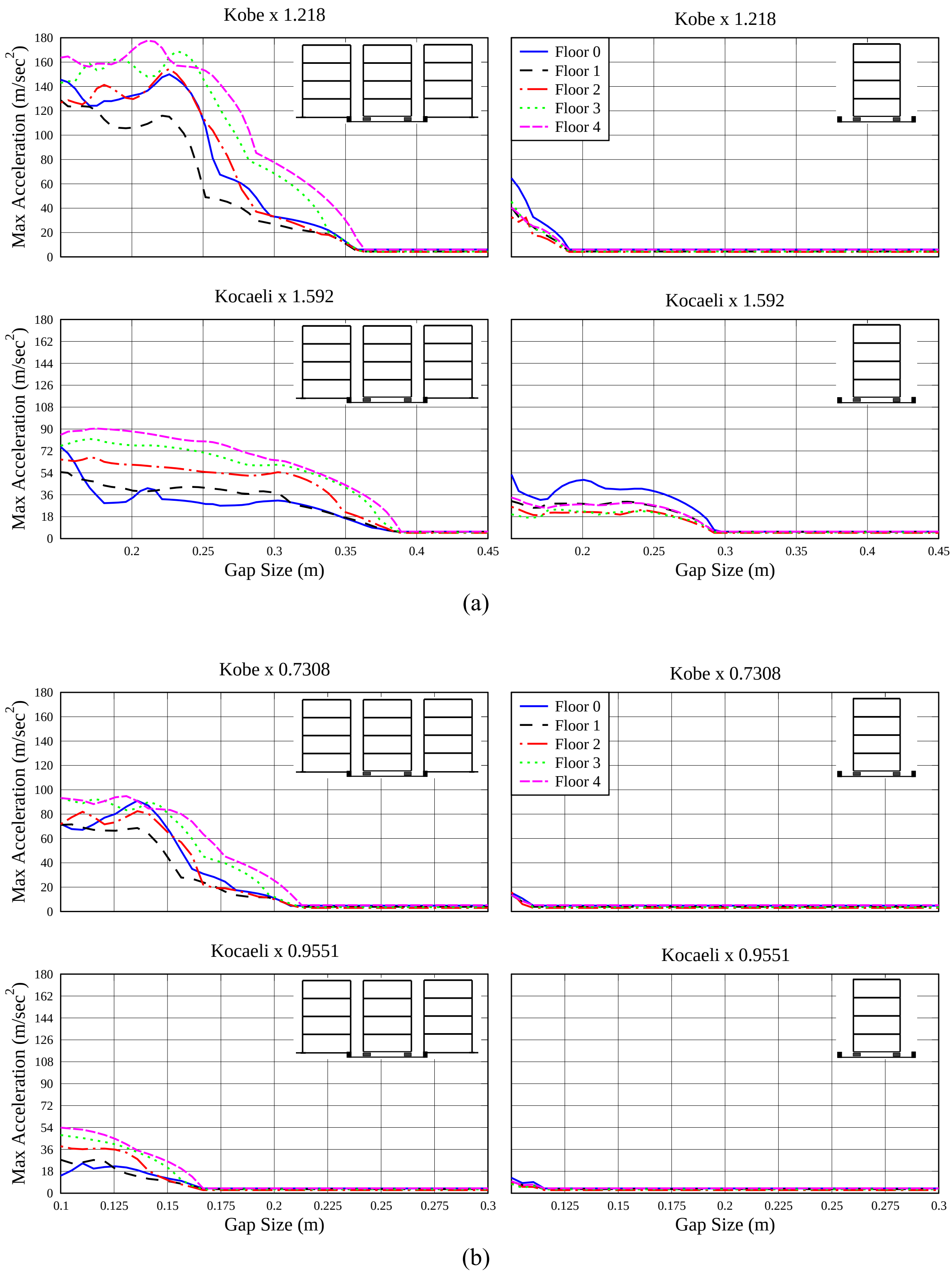

Figure 4: Maximum absolute floor acceleration of the seismically isolated building in terms of the size of the separation distance from the adjacent structures under the Kobe (Japan, 1995) and Kocaeli-Sakarya (Turkey, 1999) earthquakes, both scaled to have a PGA equal to (a) 1 g , (b) 0.6 g.

Comparing the two cases of the seismically isolated building being adjacent either with two fixed-supported buildings or only the moat wall, some significant differences on the response due to poundings are observed. Firstly, it is obvious that the presence of the fixed supported buildings in close distance with the seismically isolated building affects significantly the response of the latter during poundings. Figure 4 shows that the amplification of the peak floor accelerations due to impact is much more pronounced in the case where the seismically isolated building hits against the adjacent 4-story buildings. Poundings may occur for much wider gaps compared to the case of impacts only with the moat wall. In particular, the seismically isolated building may pound against the neighboring building at the upper stories, due to the deformation of the structures in series, before hitting the surrounding moat wall.

Figure 4 also suggests that for the case without adjacent buildings, the highest value of the peak floor acceleration during poundings corresponds to the ground floor, while for the other case corresponds mainly to the top floor. This is due to the location of impacts since the floor acceleration response is highly affected by the presence of impact and the impact velocity, which is higher at the top floors. Additionally, by comparing the corresponding results considering different scale factor of the excitation, a dissimilar influence of the intensity of each earthquake on the response is observed. In particular, for the case of scaling both records to 1 g, a wider gap is needed to avoid poundings with adjacent buildings during Kocaeli record than during Kobe, while when the PGA is scaled to 0.6 g, exact opposite happens. This can be explained from the non-linearity of the isolation system's behavior in combination with the different response of the fixed supported buildings under each earthquake. Specifically, the top floor displacement of the 4-story fixed supported building for Kobe and Kocaeli, scaled at PGA = 0.6 g is 10 cm and 5.5 cm, respectively.

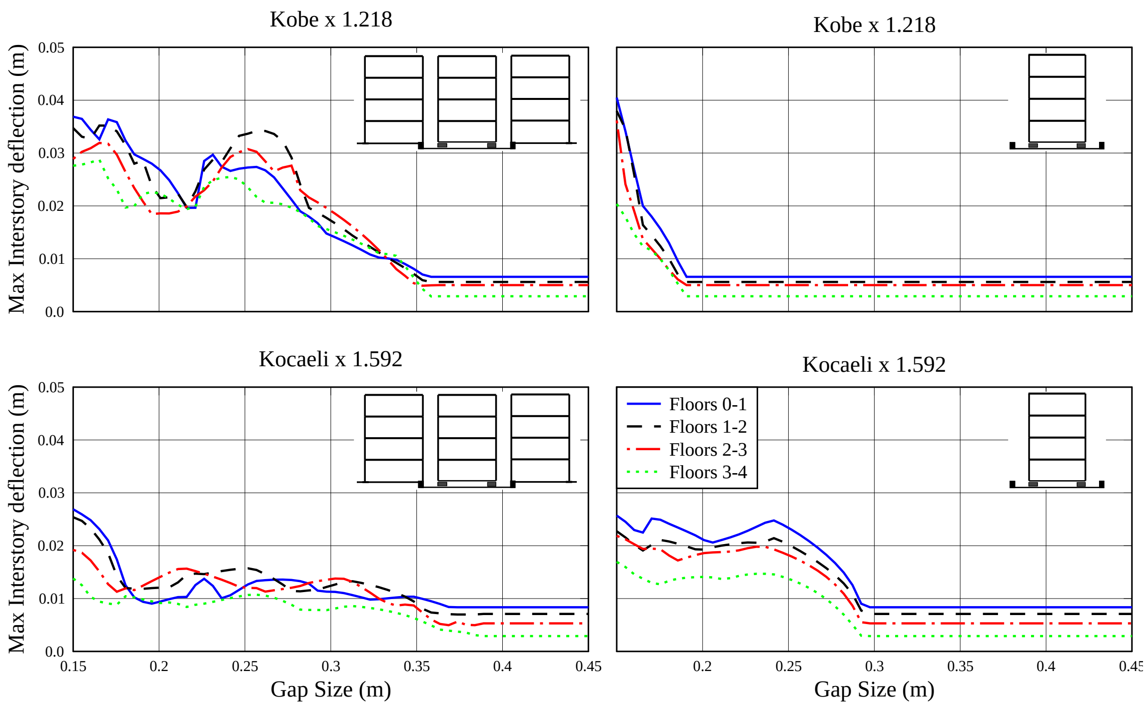

Figure 5: Maximum interstory deflections of the seismically isolated building in terms of the size of the separation distance under Kobe and Kocaeli-Sakarya earthquakes scaled to have a PGA equal to 1g.

In contrast to the acceleration response, the peak interstory deflections during poundings for the case of the buildings in series are not always greater than the case of having impacts only with the moat wall (Figure 5). In fact, the plots for the first case for the Kocaeli ground motion record show smaller interstory deflections for all the gap sizes. This indicates that in the specific case, the adjacent buildings act as constrainers, preventing the large horizontal displacements that happen in the case where the seismically isolated building hits only against the moat wall at the isolation level. The mode of deformation of the seismically isolated building during poundings for the two different configurations can be seen from the plot of Figure 5. In the case of having poundings only at the isolation level, the peak interstory deflection is most of the times decreasing when moving from the ground floor to the top story, while for the case of the three buildings in series this is not happening. This observation indicates that the excitation of higher modes of deformation is much more pronounced for the case of having poundings of buildings in series.

Another set of simulations has been conducted in order to examine the effect of the characteristics of the adjacent building and specifically the number of stories in combination with the earthquake characteristics. In particular, the same seismically isolated building was considered in four different cases: (i) adjacent only to the surrounding moat wall and adjacent with two identical fixed-supported buildings with either (ii) two, (iii) four or (iv) six stories. All six aforementioned earthquake records (Table 2) scaled to have a PGA equal to 1 g were used in the simulations. The separation distance between the structures was considered equal to 25 cm for all cases. The plots of Figure 6 provide the amplification factors of the response of the seismically isolated building due to poundings regarding to the case of unlimited gap, where no poundings occur. In general, the amplification of the peak floor accelerations is much greater than the amplification of peak interstory deflections since the first are much more sensitive to local impact (Komodromos et al, 2007). As expected, the amplification of the response of the seismically isolated building seems to depend on the earthquake characteristics in combination with the number of stories of the adjacent building. For example, the worst case scenario for the Kobe earthquake is when the adjacent fixed-supported buildings have four stories and consequently an eigenfrequency in resonance with the excitation. In addition, the amplification of maximum interstory deflection is higher for the upper stories in the case where impacts occur only at lower floors (case 1 and 2), while just the opposite happens for the amplification of maximum floor accelerations.

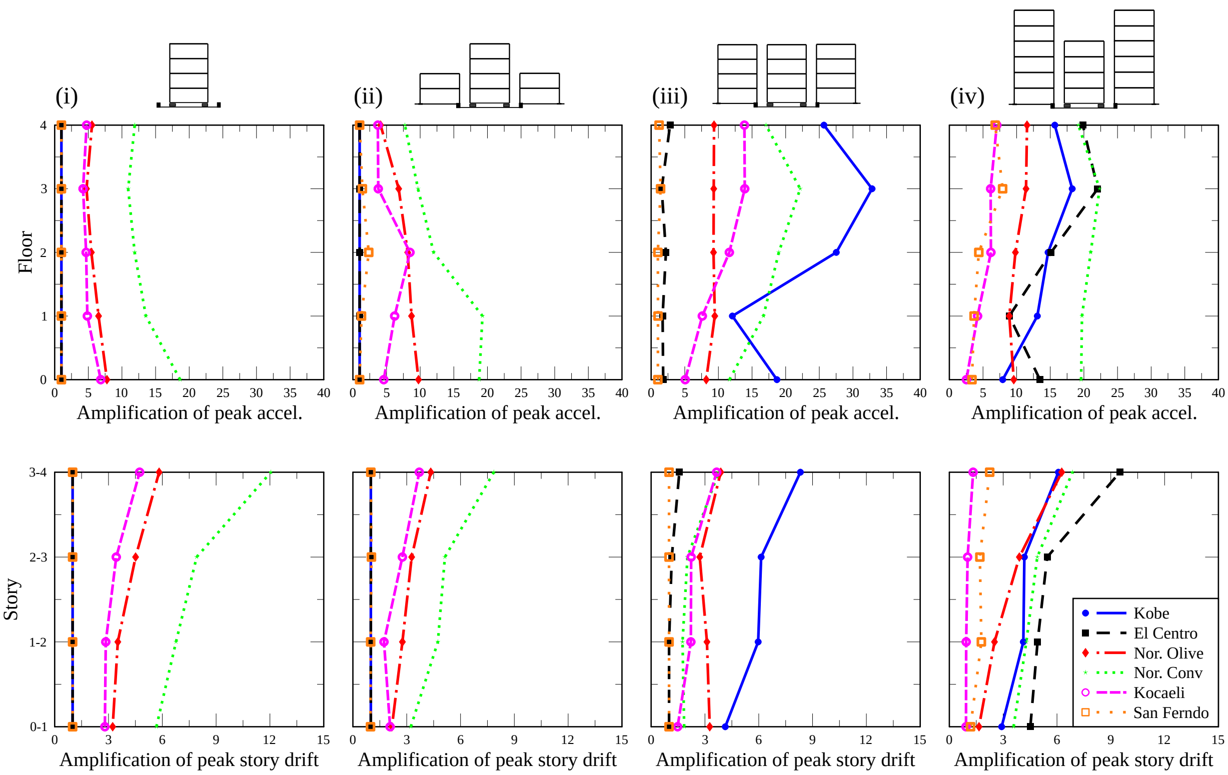

Figure 6: Amplification of the maximum responses of the seismically isolated building adjacent to different structures with separation distance equal to 25 cm under six earthquake records with PGA equal to 1 g.

4. CONCLUSIONS

Some representative results were presented in this paper that were selected from a wide range of simulations, performed in order to investigate the effects of poundings with adjacent structures on the response of seismically isolated buildings during strong earthquakes. The presented results considered only the case of a 4-story seismically isolated building with specific structural characteristics under different cases of neighboring structures and under a range of excitations.

It was found that the presence of a fixed-supported building in close proximity with the seismically isolated building may cause unexpected impact phenomena at upper floors due to the deformation of the buildings in series. The presented results revealed that the seismically isolated building pounds with the adjacent fixed supported buildings for much wider seismic gaps than those that are needed to avoid poundings with the surrounding moat wall at the base. Also, the number of stories of the adjacent fixed-supported buildings seems to play a significant role to the severity of the impact. Therefore, it is important to take into account the presence and the characteristics of the adjacent buildings on the estimation of the gap size around a seismically isolated building, as the design displacement at its base may not be a sufficient sole criterion.

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