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Earthquake-Induced Pounding of Medium-to-High-Rise Base-Isolated Buildings

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Abstract: During earthquakes, out-of-phase vibrations in adjacent buildings with limited distance may cause pounding between them. In recent years, the use of seismic isolation has expanded considerably as an effective approach to reduce seismic damage. However, the isolated building experiences large displacements during earthquakes, and there is a possibility of collisions with adjacent structures. The research on earthquake-induced pounding of base-isolated buildings has been mainly focused on interactions between low structures. In this paper, the influence of structural pounding on the response of medium-to-high-rise base-isolated buildings is investigated under different ground motions. The analysis has been focused on collisions between two insufficiently separated five-story and eight-story base-isolated and fixed base buildings aligned in three different configurations. The results of the study indicate that structural pounding may significantly increase the response of medium-to-high-rise base-isolated buildings during earthquakes. Moreover, substantial dependence of the structural behavior on the gap size between structures has been observed. The general trend shows the reduction in the pounding-involved response with the increase in the gap size value. The results indicate that the increase in the response of the base-isolated building is larger when the height of the structure is bigger. They also show that larger amplifications of peak accelerations of the upper stories can be expected due to collisions. On the other hand, the amplifications of the story shears have not shown any specific trend for different stories of the analyzed base-isolated building.

Keywords: seismic isolation; structural pounding; seismic gap; non-linear analysis

1. Introduction

Earthquakes may cause pounding between adjacent buildings having limited gap and different dynamic properties [1–4]. This phenomenon, known as seismic pounding (see [5,6]), often causes damage and, in some cases, may even lead to the collapse of the buildings. Many pounding-induced damages have been observed in past earthquakes, including the Mexico City earthquake in 1985, the Loma Prieta earthquake in 1989, the Northridge earthquake in 1994, and the Kocaeli (Izmit) earthquake in 1999 (see [7,8] for example). In order to prevent structural collisions during ground motions, it is required to consider a minimum gap for adjacent buildings according to the seismic codes [9]. However, in the case of the large number of existing buildings, which have not been designed according to the current seismic codes, or in the case when the gap between structures has been filled by inappropriate materials, structural pounding has to be mitigated [10].

In recent years, there has been an increasing demand to minimize structural and non-structural damages so as to avoid functionality disruption and to protect sensitive and expensive equipment in buildings, even under extreme earthquake excitations. One of the possibilities is the application of seismic isolation at the base of buildings, which is considered as an effective earthquake resistant design method [11–14]. The application of this type of protection system leads to the elongation of the natural period of a structure. Additional damping is also often provided so as to increase the amount of energy dissipation during vibrations of a building. As a result, the structural response under seismic excitations is substantially reduced [15,16]. Generally, base isolators can be divided into two groups, i.e., laminated rubber bearings and sliding bearings. The first type of isolators is usually represented by high damping rubber bearings (consisting of hard rubber and steel plates, constructed in alternating layers) and lead rubber bearings (with the lead core inside) [17]. In turn, the friction pendulum bearing is a popular sliding system in which low frictional interfaces are applied [18]. Different types of base isolators have wide practical applications in many structures all over the world. Their effectiveness has already been confirmed during a number of seismic events (see [19] for example).

The base isolation systems introduce flexibility at the isolation level of relatively stiff buildings, which results in avoiding resonance with the predominant frequencies of the ground motion. Floor accelerations are substantially reduced and deformations are observed mainly at the seismic isolators, which are specifically designed to accommodate large relative displacements, withstanding several cycles of deformation. However, a kind of limitation for the implementation of seismic isolation is the seismic gap that must be provided around the building to facilitate the expected large relative displacements. The results of the numerical simulations conducted by Das et al. [20], for example, indicate that the minimum gap size can be as large as 50 cm in the case of major ground motions. Fallah and Zamiri [21] obtained the value of 43.7 cm required to prevent collisions of the base with the surrounding moat wall in the case of 10-story base-isolated steel building exposed to the Kobe earthquake of 1995. The peak base displacements for different base-isolated reinforced concrete frame structures with masonry infill walls were also investigated by Jain and Thakkar [22]. The results of the study for the El Centro earthquake of 1940 show that the minimum gap size should be larger than 20 cm. The situation can be somewhat improved by the application of some methods of reduction of excessive displacements at the isolation level. Zelleke et al. [23], for example, proposed to use the supplemental dampers in order to reduce the structural displacements without significant increase in the forces transferred to the superstructure. A structural vibration control system composed of rubber bearing with magnetorheological damper was considered by Fu et al. [24]. The results of the study indicate that the system is capable to reduce the structural response considerably, both at the superstructure and at the isolation level. Also, a new hybrid composite isolation system for the base of structures was proposed by AlMusbahi and Güngör [25]. The system, based on the application of multi-layered laminated rubber bearing along with steel reinforcement, has been found to be effective in improving the seismic behavior of buildings.

Considering the practical restrictions to the size of the seismic gap, the possibility of pounding of a seismically isolated building with adjacent structures during ground motions should be considered. The example of such a situation concerns the case of the Fire Command and Control base-isolated building that had been pounded with adjacent structures during the Northridge earthquake, causing the increase in the peak acceleration from 0.22 to 0.35 g (see [26]). Therefore, it is important to investigate the problem and understand how the maximum floor accelerations and inter-story deflections of seismically isolated buildings are affected by various design parameters and conditions during impacts with adjacent structures.

Collisions in base-isolated buildings during seismic excitations may take place at the level of foundation (base), or at the story level in the case when structures are not sufficiently separated one from another. Most of the studies on earthquake-induced pounding in base-isolated buildings have been focused on collisions at the structural bases. Tsai [27] studied the response of an isolated building bumping against a rigid barrier using a shear beam model of the structure. Based on the results obtained, he underlined the extreme acceleration response due to collisions of the structure. The study on the effects of pounding between the base of an isolated building and the retaining wall was conducted by Malhotra [28]. The results of investigation showed that the shear forces would be increased mainly due to the increase in the stiffness of superstructure or rigidity of retaining wall. Dimova [29] studied earthquake-induced collisions of a base-isolated structure which was modeled as a rigid block. Matsagar and Jangid [30] evaluated the seismic performance of multi-story isolated building with the effect of pounding against the retaining wall. Pounding between the seismically isolated structure and the surrounding moat wall was also studied by Komodromos et al. [31] and Komodromos [32], so as to evaluate the influence of different design parameters and conditions on the peak accelerations and displacements. Further investigations were carried out for earthquake-induced pounding between different stories of two or three adjacent base-isolated buildings. Agarwal et al. [33] considered the case of collisions between two-story structures. The analysis for few-story isolated and non-isolated buildings was also conducted by Mahmoud and Jankowski [34], as well as by Polycarpou and Komodromos [35]. The results of these studies show that pounding may considerably change the response of a base-isolated structure.

The above literature review indicates that the research on earthquake-induced pounding of base-isolated buildings has been much advanced. However, the studies have been mainly focused on collisions between low structures, and the effects of pounding on such structures have been relatively well recognized (see [27–35]). Meanwhile, the number of medium-rise and high-rise buildings equipped with seismic isolation devices is growing rapidly. Therefore, the aim of the present paper is to investigate the influence of pounding on the response of medium-to-high-rise structures under different earthquake excitations. According to the authors' knowledge, such investigation has not been conducted so far. Meanwhile, it can be expected that collisions between such buildings can also be very dangerous.

2. Materials and Methods

2.1. Analyzed Cases of Pounding between Buildings

The study described in this paper has been focused on collisions between two adjacent five-story and eight-story base-isolated and fixed base steel frame buildings aligned in three different configurations (see Figure 1). The first one represents the situation of collisions between five-story isolated and non-isolated structures. Interactions between a base-isolated five-story building and a fixed base eight-story structure have been considered in the second case. Finally, the third case concerns pounding between an isolated eight-story building and a fixed base five-story structure.

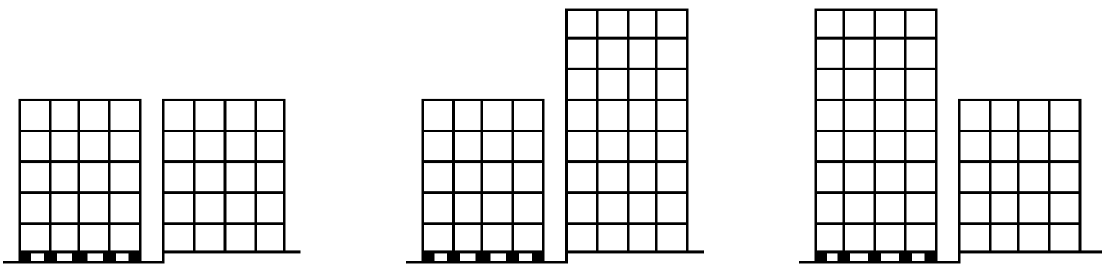

Figure 1. Schematics of 2D structural component models of medium-to-high-rise buildings.

2.2. Description of Buildings

The five-story and eight-story buildings have been designed according to AISC360-05/IBC2006 standard (see Figure 2 for details on cross sections of particular members). The height of each story is equal to 3.2 m, which gives the total height of 16 m and 25.6 m in the case of five-story and eight-story building, respectively. Together, with the dead load resulting from the weight of all structural members, the live load of 350 kg/m^2 has been considered for each floor of both structures. The natural vibration period of the five-story building is equal to 0.64 s, while the corresponding value for the eight-story building has been calculated as equal to 0.91 s.

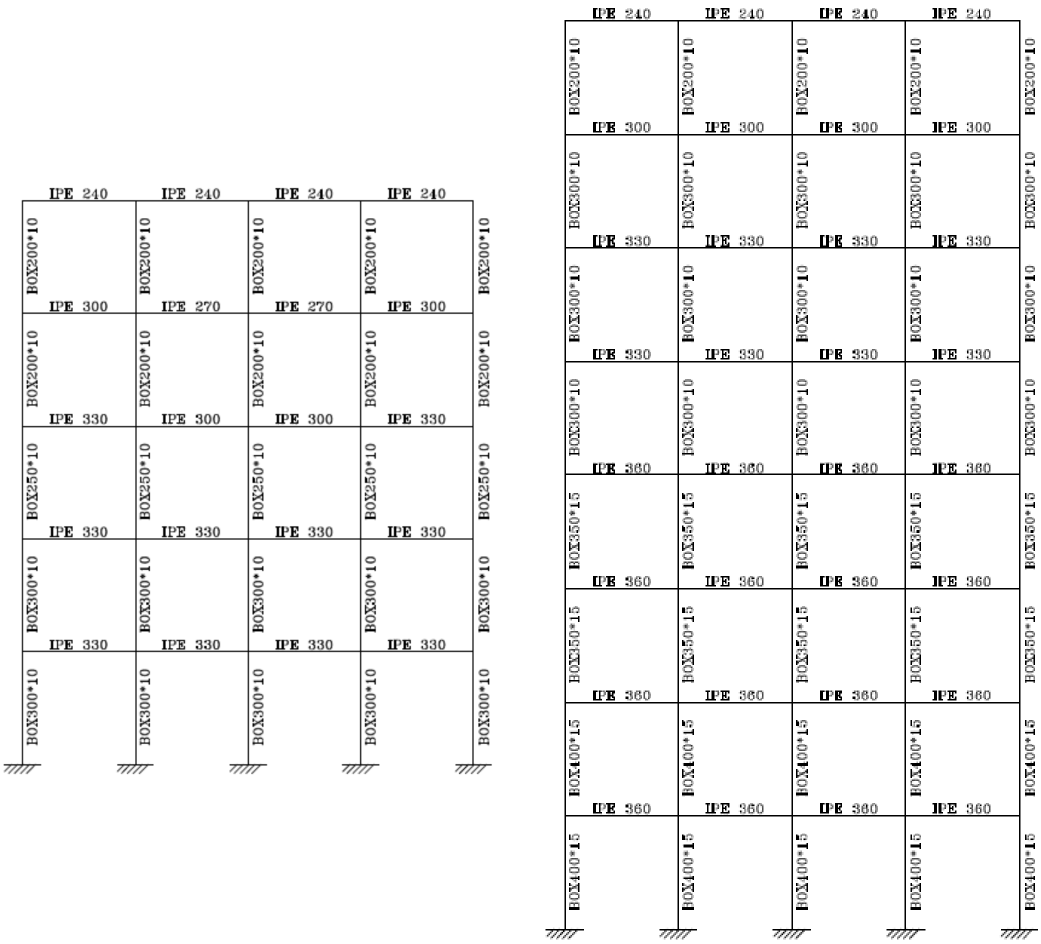

Figure 2. Cross sections of structural members of five-story and eight-story buildings.

2.3. Numerical Models

The detailed 2D structural component numerical models of both buildings have been created and applied in the analysis. The discretization was conducted by dividing each structural member into 20 beam-column elements. Therefore, the total number of 900 and 1440 finite elements has been used in the numerical model of five-story and eight-story steel frame buildings, respectively. All connections between the structural members have been defined as fixed. The linear elastic behavior has been adopted for both frame structures. The Rayleigh damping has been applied in the numerical analysis, considering the damping ratio of 3% for both steel buildings.

The utilized isolation system is composed of elastomeric isolators with lead core inside. Their behavior has been simulated in the analysis by multi-linear non-elastic model (see [12,23]), which is defined by the following parameters: Effective stiffness (K_{eff}), effective damping (C_{eff}), initial stiffness (K_1), and yield force (f_y). The values of these parameters for the structural models of five-story and eight-story buildings are presented in Table 1. These values have been computed based on the natural period of each seismically isolated structure and the hysteresis loop of the isolation system considered.

It should be underlined that appropriate values of mechanical parameters of seismic isolators are very important for simulations and design of base-isolated buildings. Usually, nominal parameters available in technical data sheets suggested by the manufacturers of seismic isolators are taken into account in such cases. However, actual mechanical properties (especially stiffness) of these isolators are strain-rate sensitive and can be considerably different from nominal values available in data sheets. The results of the in-situ tests show that the real, experimentally obtained stiffness value of the particular isolator can be even 2.2 times larger than the nominal design value (see [36]).

Table 1. Parameters of the seismically isolated structural models.

Isolator Characteristics	Building	
	Five-Story	Eight-Story
Effective stiffness, K_{eff} (kN/m)	208.6	313.81
Effective damping, C_{eff} (kN·s/m)	49.9	75.15
Initial stiffness, K_1 (kN/m)	1351.85	2039.7
Yield force, f_y (kN)	23.54	35.5

2.4. Modeling of Pounding

In the analysis, pounding has been modeled by special link elements connecting two opposite nodes located at the same floor level of two adjacent buildings. Six link elements have been used for each of the cases, considering the fact that collisions may also take place at the base level. These elements have been programmed in such a way that they do not show any resistance until the time when contact is detected, i.e., when the initial distance between two nodes is reduced to zero (see [37,38]). Then, the nodes are fully fixed together, preventing from penetration and leading to deformation of both buildings as the result of collision. The nodes are fixed until the end of contact, which is recognized by the fact that buildings have the tendency to separate from each other. After collision, the link elements do not retain any tension resistance, and they are not active until the next impact is detected between particular floors of both buildings. In this way, collision observed in one story does not immediately affect the collision in another story, since link elements act independently. However, it is possible that contact is observed in a few stories simultaneously at the same time.

The approach of using the special link elements described above allows the analysis to be conducted in two phases. In the first one, buildings vibrate independently without interactions, while they are connected in the second phase during the time of collision. Changing from one phase to another makes the analysis to be geometrically non-linear.

2.5. Details of Dynamic Analysis

For the purposes of the dynamic analysis, seven different earthquake records, summarized in Table 2, have been considered. For the comparison purposes, all records have been scaled so as to attain the peak acceleration value of 0.5 g (g is the acceleration of gravity). The pounding-involved seismic response has been determined using the time-stepping Newmark method (see [39]). Based on the preliminary computations, the time step of 0.001 s has been found to be small enough to satisfy the numerical stability and accuracy conditions during collisions between analyzed buildings. Therefore, this time step has been applied in the non-linear time history dynamic analysis. A large number of results for different ground motions have been obtained. Due to the limitation of space, the representative examples are presented in the paper.

Table 2. Earthquake records considered in the study.

Year of Occurrence	Earthquake	M_W	Station	Duration (s)	PGA (g)	PGD (cm)
1992	Big Bear	6.4	Desert Hot Spr. (New Fire Stn.)	60	0.23	4.53
1994	Northridge	6.7	Century CCC	60	0.26	7.85
1994	Northridge	6.7	Saturn Street School	32	0.43	23.04
1971	San Fernando	6.6	Castaic, Old Ridge Route	30	0.27	4.87
1994	Northridge	6.7	Buena-Park	35	0.14	1.62
1992	Landers	7.3	Baker	50	0.11	5.76
1994	Northridge	6.7	Moorpark (Ventura Fire Stn.)	60	0.29	5.48

PGA—Peak Ground Acceleration; PGD—Peak Ground Displacement.

3. Results and Discussion

3.1. Response for Different Gap Sizes

The influence of the gap size between buildings on the response of base-isolated medium-to-high-rise structures has been firstly studied. Figures 3–5 show the peak accelerations of the 5th story of the isolated building with respect to different gap size values for various configurations and ground motion records.

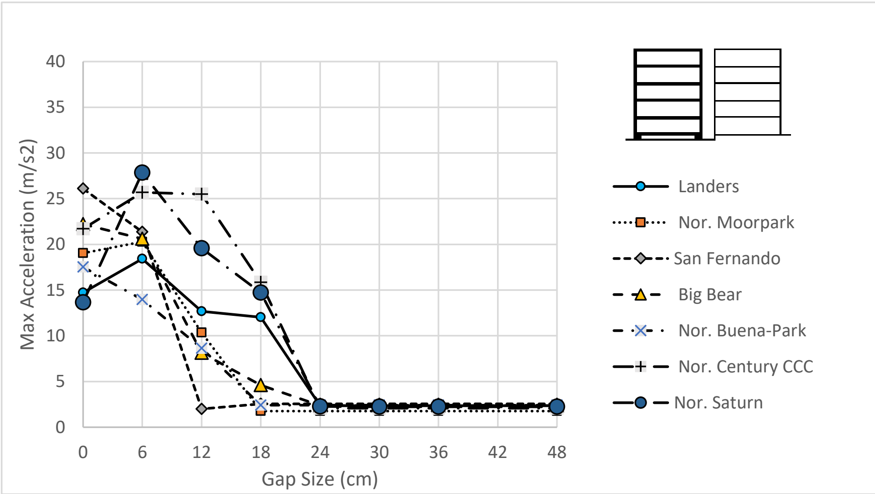

Figure 3. Peak accelerations of the 5th story of the base-isolated building with respect to different gap sizes for the first configuration under various earthquakes.

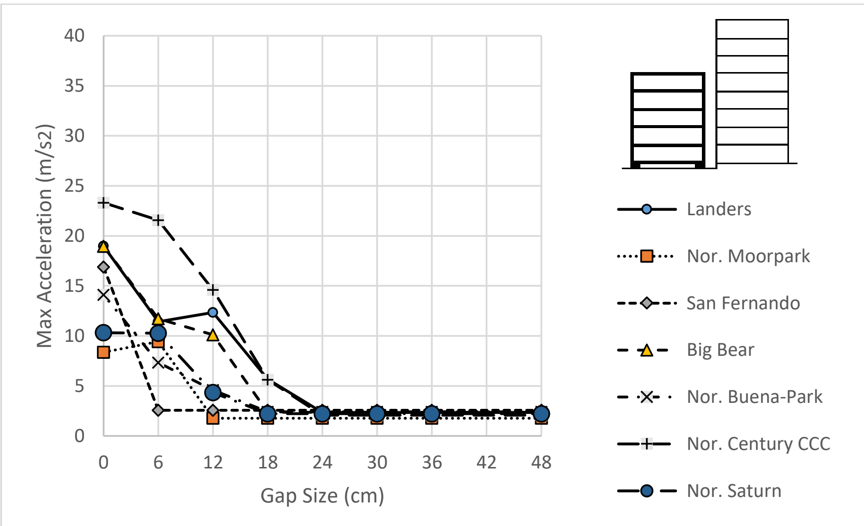

Figure 4. Peak accelerations of the 5th story of the base-isolated building with respect to different gap sizes for the second configuration under various earthquakes.

The results presented in Figures 3–5 clearly indicate that pounding between the isolated and non-isolated buildings may significantly increase the response of the medium-to-high-rise isolated structure in the case of all earthquake records considered. It can also be seen from the figures that the response of colliding base-isolated building depends very much on the gap size between structures. The results indicate that with the increase in the gap size, the response becomes smaller and this trend is observed up to the gap size big enough to prevent pounding. It should be underlined that the size of the gap preventing collisions depends on a number of parameters, including the earthquake intensity, its particular frequency content, the dynamic characteristics of buildings, their configuration, etc.

For the cases analyzed, for which all earthquake records have been scaled so as to attain PGA = 0.5 g, its maximum value has been found to be as large as 30 cm (see Figure 5).

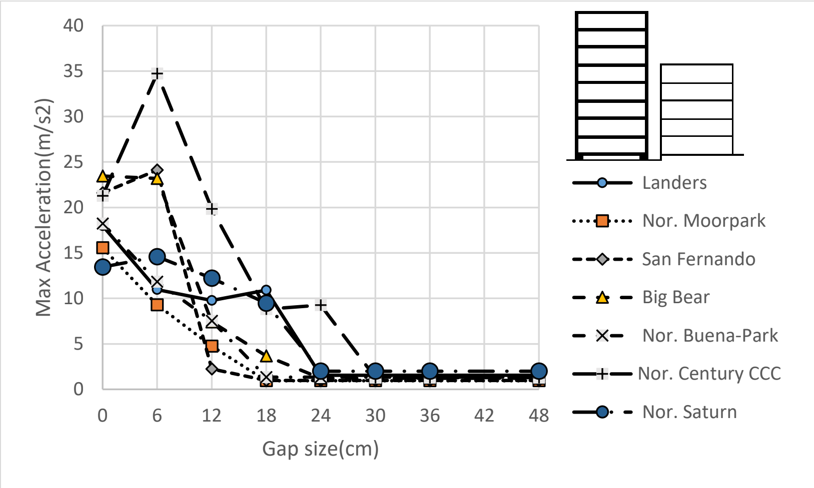

Figure 5. Peak accelerations of the 5th story of the base-isolated building with respect to different gap sizes for the third configuration under various earthquakes.

Moreover, the results of Figures 3 and 4 indicate that the increase in the peak acceleration due to pounding can be as large as 1140% for interactions between the five-story isolated building and the five-story fixed base structure, while it is equal to 828% when the five-story isolated building collides with the eight-story fixed base structure. It should be underlined, however, that the effects of pounding can be even more pronounced when the height of the base-isolated medium-to-high-rise building is bigger, and the increase in the peak acceleration due to pounding between the eight-story isolated building and the five-story fixed base structure can be as large as 2529% (see Figure 5).

It can also be seen from Figures 3–5 that, except for the Buena-Park station record of the Northridge earthquake where the stability in the response is observed from 6 to 18 cm gap size, the remaining records result in structural response modifications due to collisions for gaps as wide as 12 to 30 cm. Moreover, the peak acceleration responses are quite similar for each case of two different buildings interacting under seismic excitation. This is an interesting result, given the fact that the earthquake records are very dissimilar, with PGD of 4.53 to 23.04 cm (see Table 2). It should be underlined, however, that scaling the earthquake records to the same PGA value resulted in reduction in differences between PGD values for various scaled ground motions. It should also be added that PGD is not the only factor influencing structural displacements, and the dynamic parameters of the structure itself have a significant influence on its response, especially when the natural structural period falls within the range of the predominant frequencies of excitation. Moreover, the pounding-involved response is much different comparing to the regular response without collisions (see also [5,35] for example). Therefore, the above reasons caused the situation observed in Figures 3–5 so that different records provided quite similar results.

3.2. *Amplification Factors*

In the second stage of the investigation, for each of the cases studied, the amplification factor has been calculated as a ratio between the peak response parameter when pounding takes place and the peak response parameter without pounding when a large gap size preventing collisions is considered. The acceleration amplification factors for different stories of the isolated building during various earthquakes are presented in Figures 6 and 7. Also, the story shear amplification factors for different stories of the isolated building during various earthquakes are shown in Figures 8 and 9. The previously underlined dependence of the pounding-involved response of medium-to-high-rise isolated building on the gap size is also visible at Figures 6–9. It can be clearly seen from the figures that both parameters analyzed (peak accelerations and peak story shears) for all stories of the base-isolated building are much influenced by structural pounding under different values of gap size between structures. The results also show that larger amplifications of accelerations can be expected for the upper stories which undergo pounding, while they are substantially smaller for the stories above pounding level (see the results for the third configuration at Figures 6 and 7). On the other hand, Figures 8 and 9 indicate that the amplifications of the story shears do not show any specific trend and they can be either increased or decreased for different stories of the base-isolated medium-to-high-rise building.

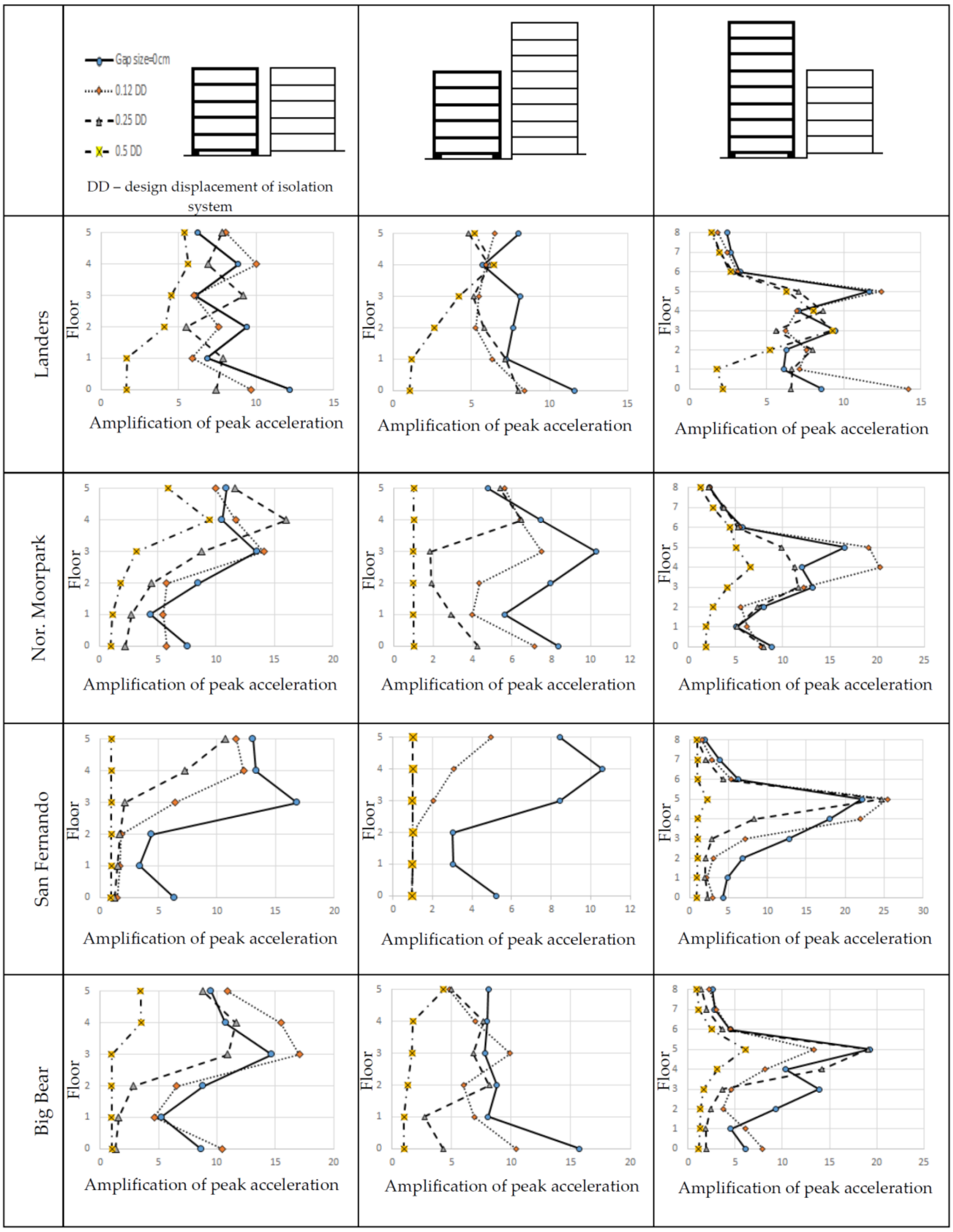

Figure 6. Acceleration amplification factors due to pounding for different gap sizes and various stories of the base-isolated building during the Landers, Northridge (station: Moorpark), San Fernando, and Big Bear earthquakes.

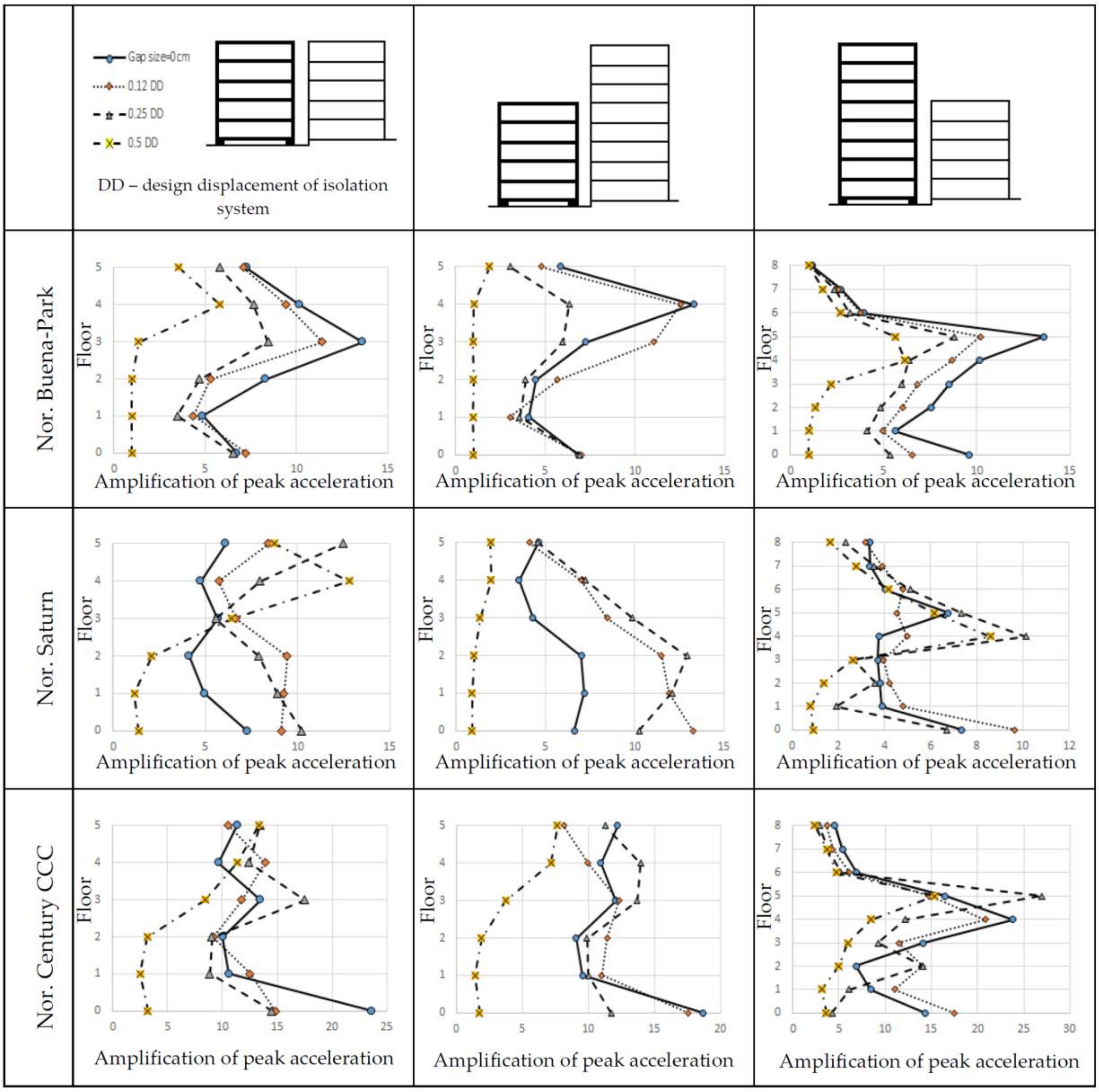

Figure 7. Acceleration amplification factors due to pounding for different gap sizes and various stories of the base-isolated building during the Northridge earthquake (stations: Buena-Park, Saturn Street School, and Century CCC).

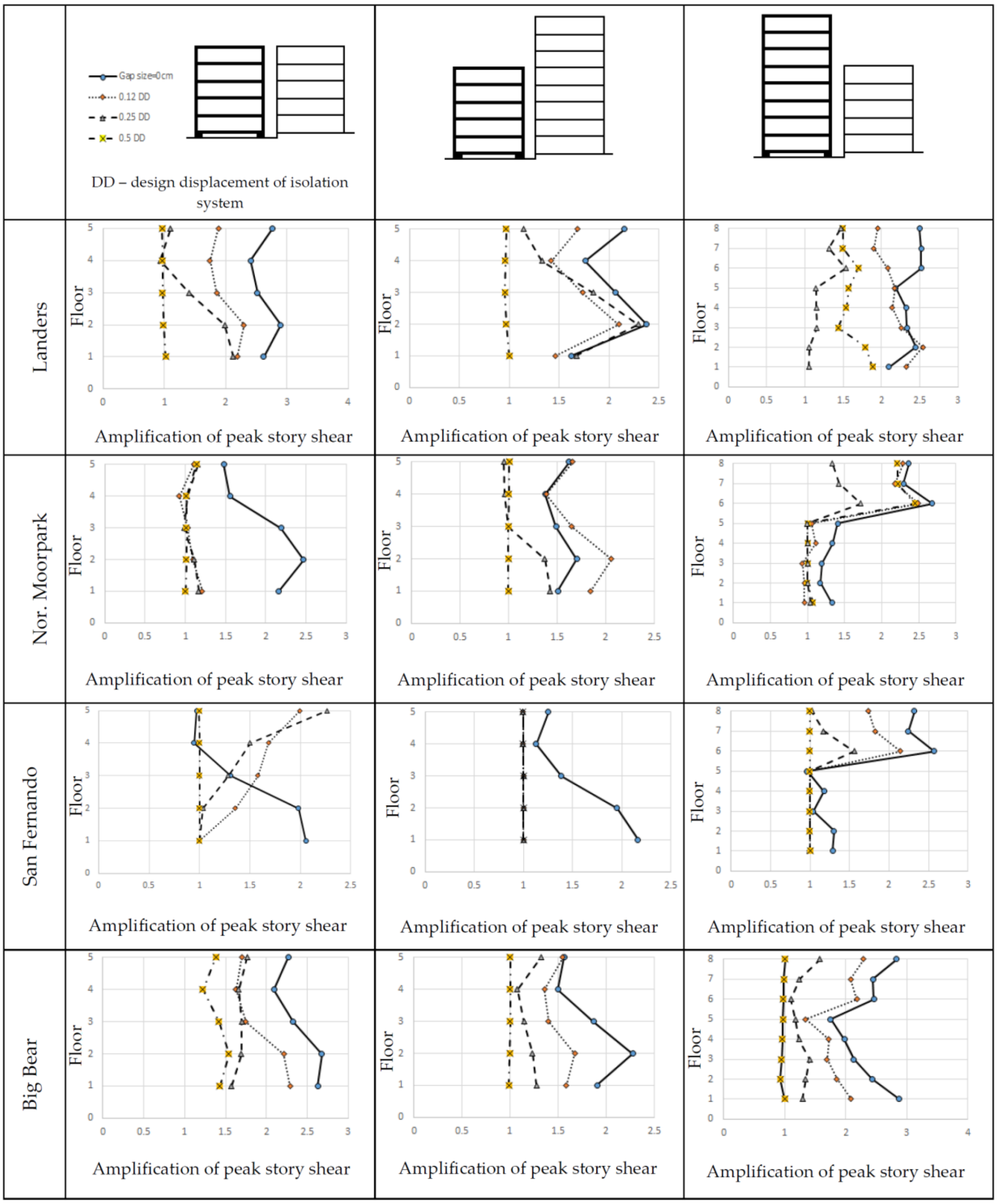

Figure 8. Story shear amplification factors due to pounding for different gap sizes and various stories of the base-isolated building during the Landers, Northridge (station: Moorpark), San Fernando, and Big Bear earthquakes.

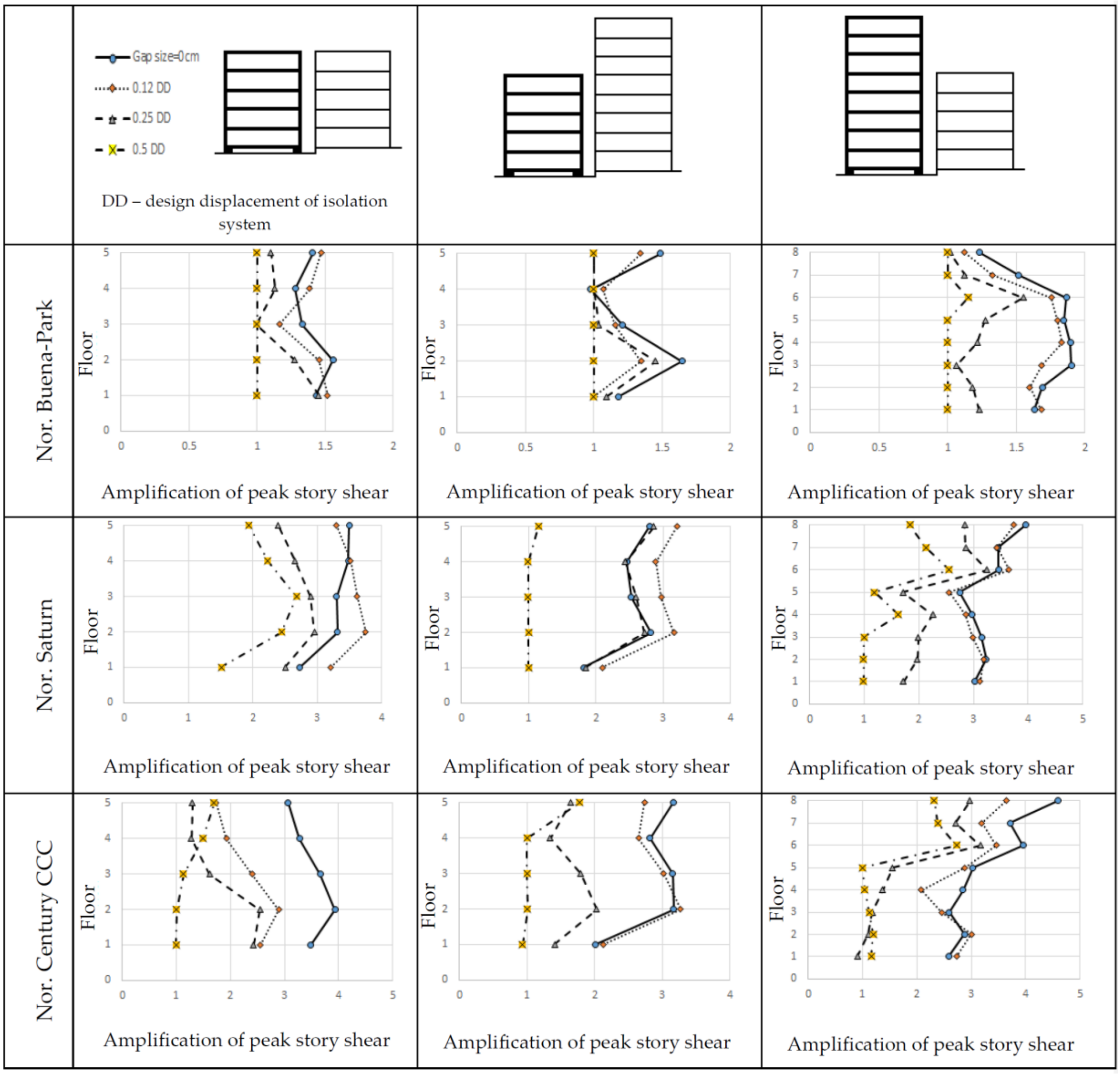

Figure 9. Story shear amplification factors due to pounding for different gap sizes and various stories of the base-isolated building during the Northridge earthquake (stations: Buena-Park, Saturn Street School, and Century CCC).

3.3. Hysteresis Curves

Additionally to previous results, the examples of the hysteresis curves for isolators of the base-isolated building for the case of pounding (zero gap size between buildings) as well as for the case when pounding does not take place (large gap size preventing collisions) during different earthquakes are also presented in Figures 10 and 11. The figures show the relations between shear forces and displacements for the slabs just above the isolation devices. It can be seen from Figures 10 and 11 that collisions have also significant influence on displacement responses as well as on the shapes of the hysteresis curves themselves. From this point of view, the results confirm findings described above concerning the fact that the response of medium-to-high-rise base-isolated building may substantially increase as the effect of pounding with adjacent fixed base structure.

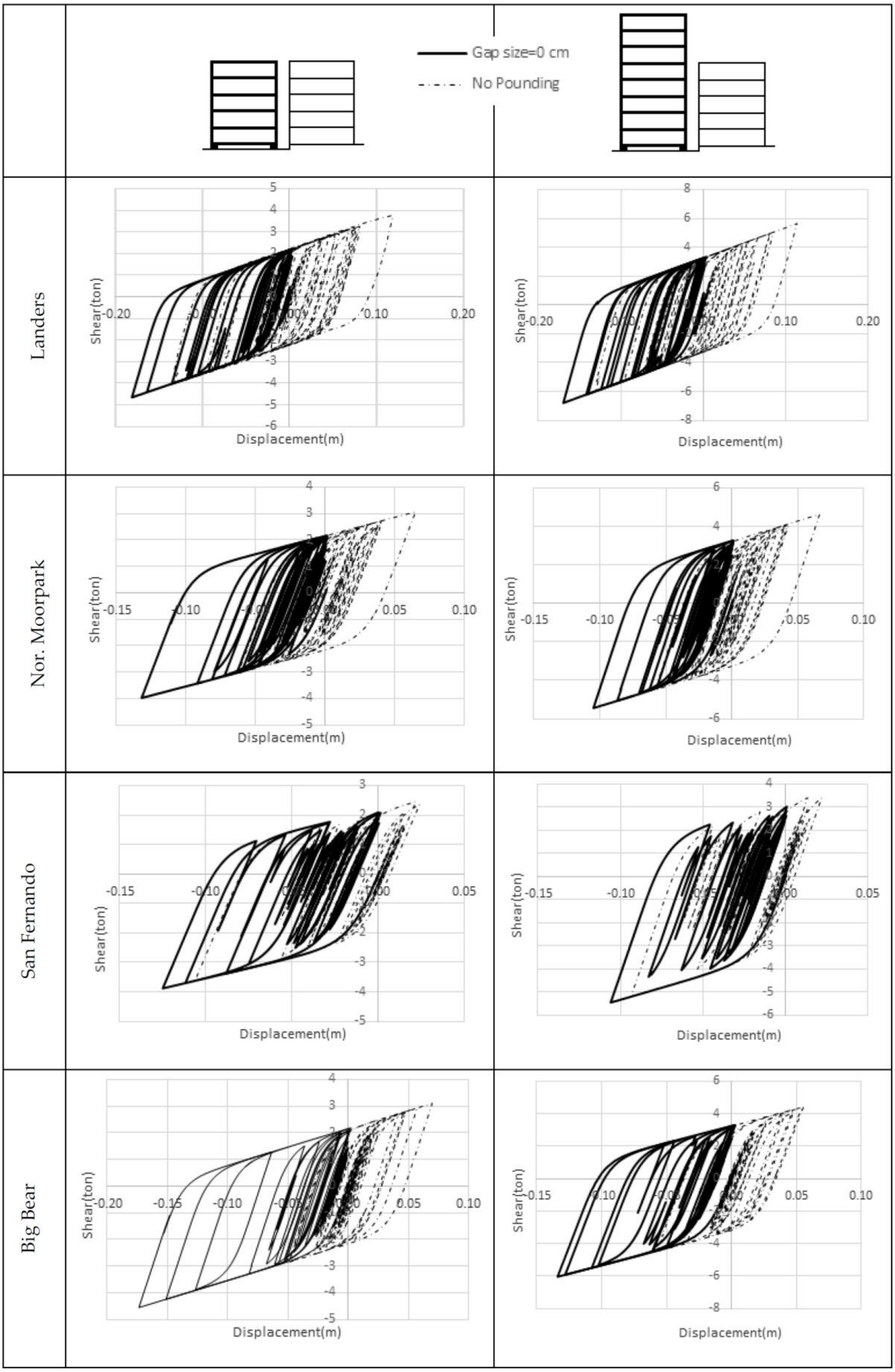

Figure 10. Hysteresis curves for isolators of the base-isolated building for pounding and no pounding cases during the Landers, Northridge (station: Moorpark), San Fernando, and Big Bear earthquakes.

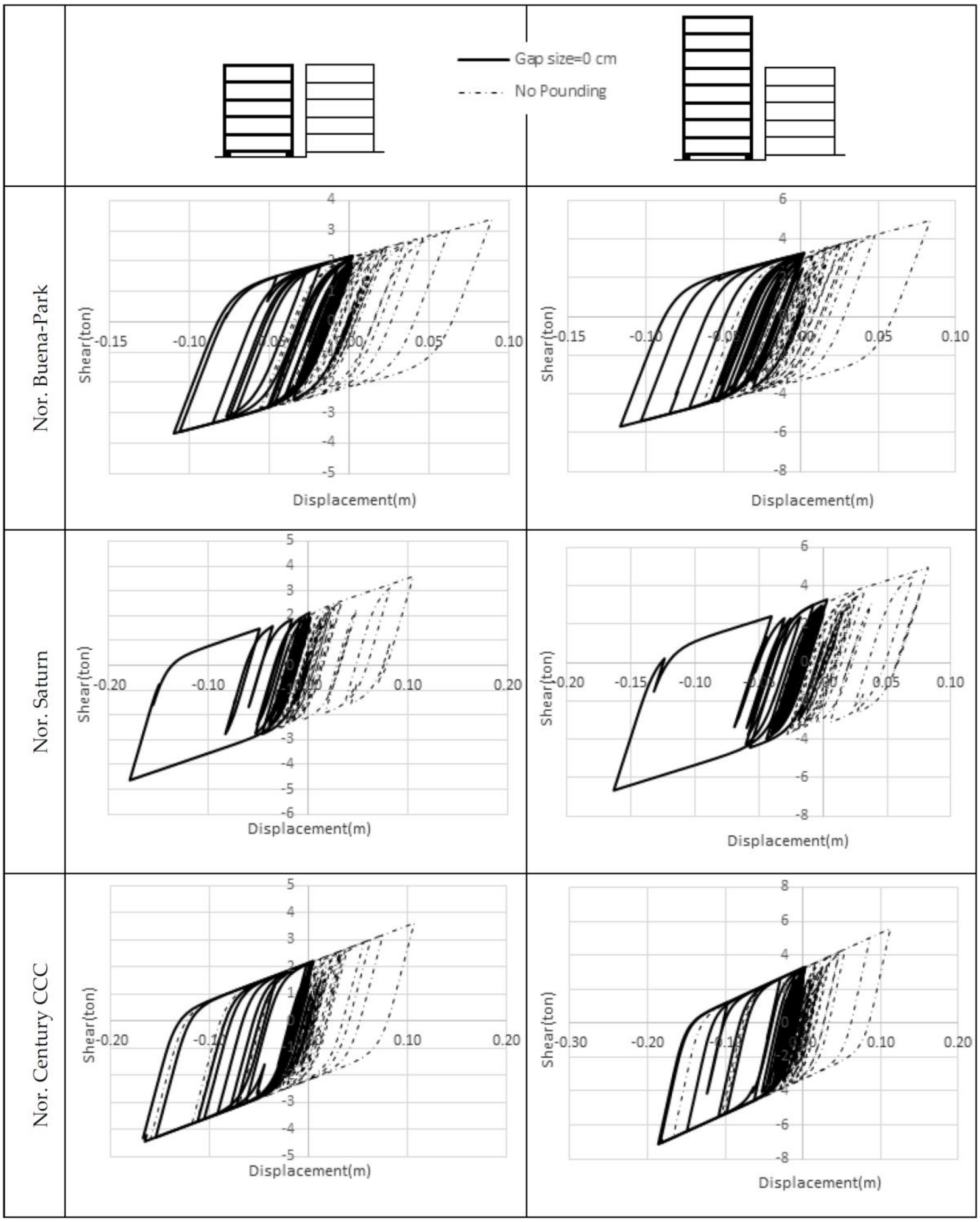

Figure 11. Hysteresis curves for isolators of the base-isolated building for pounding and no pounding cases during the Northridge earthquake (stations: Buena-Park, Saturn Street School, and Century CCC).

4. Concluding Remarks

The influence of earthquake-induced structural pounding on the response of medium-to-high-rise base-isolated buildings has been investigated in this paper. The analysis has been focused on collisions between two insufficiently separated five-story and eight-story base-isolated and fixed base buildings aligned in three different configurations.

The results of the study clearly indicate that structural collisions may significantly increase the response of medium-to-high-rise isolated buildings during ground motions. They show that the structural behavior depends very much on the gap size between structures. The results indicate that with the increase in the gap size, the response of the base-isolated building becomes smaller, and this trend is observed up to the gap size large enough to prevent pounding. The significant influence of the gap size on the pounding-involved structural response underlines the importance of this parameter for all possible structural configurations under different earthquake excitations.

Moreover, it has also been observed from the analysis that the increase in the structural response is larger when the heights of both colliding buildings are close to each other, as compared to the case when the isolated building is smaller than the adjacent fixed base structure. It should be underlined, however, that the effects of pounding can be even more pronounced when the base-isolated building has more stories. That makes the analysis concerning closely-spaced medium-to-high-rise structures quite difficult, especially that the number of stories in buildings is designed based on the needs of the owner, and should rather not be restricted by requirements of earthquake-induced structural pounding.

The results of study also indicate that the response amplification factors due to pounding are much different for different stories of the isolated building. Larger amplifications of accelerations can be expected due to collisions in the case of the upper stories which undergo pounding, while they are substantially smaller for the stories above pounding level. On the other hand, the amplifications of the story shears have not shown any specific trend, and they can be either increased or decreased for different stories of the analyzed isolated structure.

Finally, the obtained hysteresis curves have confirmed that structural pounding during earthquakes has significant influence on displacement responses of the base-isolated medium-to-high-rise building, as well as on the shapes of the hysteresis curves themselves. This conclusion is very important from the point of view of choosing appropriate types of isolation devices with particular characteristics which should be applied in the case of different structural configurations.

It should be underlined that the results of the study described in the paper can be useful for the design of base-isolated buildings adjacent to other medium-to-high-rise structures with the same or different heights. In particular, they can be applied when a new base-isolated building is planned to be constructed close to the existing fixed-base structure and the construction site is very limited (i.e., due to high land prices in highly populated cities). The decision concerning the new structure can be made with relation to its dynamic parameters, number of stories, characteristics of isolation devices, etc. Another example might concern the situation when the seismic retrofitting (by applying base isolation) of one of the existing closely-spaced buildings is planned to be carried out and no change in the in-between gap size can be considered. In any case, the analysis described in the paper can be successfully used to assess the minimum gap size so as to prevent structural pounding between both buildings during an earthquake. It can also be applied to verify the harmfulness of the negative effects of collisions, and possibly to consider some pounding mitigation methods if collisions between two adjacent medium-to-high-rise buildings cannot be prevented.

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