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# Investigating the Effect of Pounding on Seismic Response of Isolated Structures

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**Abstract:** *Some investigations have been conducted on pounding phenomenon in fixed base buildings and results showed that most sever damages are pertaining to adjacent buildings with different (unequal) heights or different structural systems [1,3]. But few investigations have been carried out for poundings of isolated buildings. In a case study about Fire Command and Control (FCC) building in Los Angeles which collided with its adjacent structure during Northridge earthquake, it was shown that peak ground acceleration in pounding direction increased from 0.22 g to 0.35 g while in other direction, in which no pounding occurred, the ground acceleration reduced from 0.18 g to 0.07 g which demonstrates good performance of seismic isolation when a pounding occurs.*

**Key words:** *seismic isolation, pounding, earthquake, seismic gap*

## I. introduction:

In recent years, there has been a growing demand for both reducing structural and non-structural damages and preventing any failure in performance and protection of equipments and costly sensitive components of buildings during earthquake. Seismic isolation as a new approach in design and one of practical methods for reduction of seismic damages has grown considerably during the last two decades [1-6]. In the most common method of seismic isolation, by insertion of flexible abutments at foundation level of building, the system time period increases to a value more than predominant earthquake energy containing time periods. Therefore, since the isolated structure has lower fundamental frequency than both frequency of fixed base buildings and predominant frequencies of ground motions, in the first vibrational mode of isolated building displacement s only occur at isolation level and abutments and superstructure approximately remains rigid and consequently acceleration of the floor reduces considerably. Hence, seismic isolation is considered as an appropriate approach for reducing damages of internal non-structural components [4]. Nevertheless, one of practical limitations in implementation of isolation is required seismic gap around the structure to accommodate large displacements at isolation level. In some cases of seismic isolations, this provided gap at isolation level is not sufficient during earthquake event. Therefore, there is possibility that the isolated structure collide with adjacent structure during one strong earthquake [3-5].

## II. Modeling:

The isolated building has been modeled as a shear model with masses lumped at the floors level and it has been assumed that superstructure remains within elastic limit [1, 3, 4], because one purpose of seismic isolation is preventing non-elastic displacements in the structure. Damping and elastic forces of isolation level depend on isolation system characteristics which are modeled linearly in this study. Pounding has also been modeled by introducing $k_{imp}$ and $c_{imp}$ which are used for calculating both elastic and damping forces of impact (figure 1). Damping ($c_{imp}$) was introduced for modeling dissipated energy during the impact. The point of impact is assumed exactly at base mass level and isolation level diaphragm. Effects of interactions between soil and structure are ignored [1-5]. Also since energy dissipation mechanism of the isolated building is not uniformly distributed and it considerably differs from isolation system to superstructure, damping is considered to be non-classic. Damping matrix $\underline{C}$ for the isolated building is calculated by assembling (اسمبل کردن) the provided damping by isolation system $c_{iso}$ and damping matrix $c_{\text{sup}}$ which is corresponding to superstructure damping [1, 3].

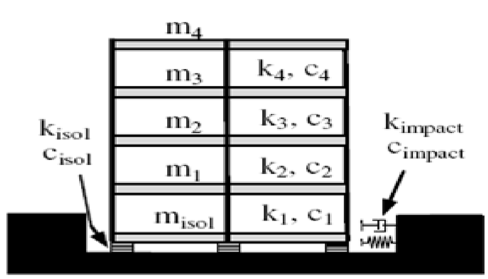


Figure 1. The isolated building, seismic gap [3].

In order to demonstrate effects of pounding on structure behavior, one four-story building was considered under below conditions:

- Fixed base
- Isolated without impact
- Isolated with 15 cm seismic gap at isolation level (about 15% less than required amount)

The fixed base building has four stories, each has mass and stiffness of 500 tons and 1000 MN/m, respectively. Its time period is also equal to 0.4 sec. In the case of isolated building, the mass of each floor is the same as the fixed base building and only one additional rigid diaphragm with mass of 500 tons is considered at isolation level. Time period and effective stiffness of isolators in this case are 1.44 sec and 50 MN/m, respectively. Classical Rayleigh damping has been used for the fixed base building whereas non-classical damping has been considered for the isolated building. The fixed base building damping ratio is considered to be 5%. Superstructure and isolation system damping ratios for energy dissipation are equal to $\xi_{\sup} = 5\%$ و $\xi_{iso} = 15\%$ . In the case of pounding, impact damping coefficient and impact stiffness coefficient are equal to $c_{imp} = 2000\, MNs/m$ and $k_{imp} = 2500\, KN/mm$ . Impact stiffness coefficient is obtained using finite element methods and by analysis of the impact between concrete wall (دال) of isolation level and concrete wall of adjacent structure having height of 2.5 m and thickness of 25 cm. [1, 3]. Then for all above cases, one dynamic analysis was performed using 1994 Northridge earthquake, as a known strong earthquake, record. Maximum displacement of isolation level under this earthquake was obtained to be $U_{\max}^{iso} = 179mm$ which shows assuming 15 cm gap around the structure an impact with isolation level wall occurs. Also the results showed that for the case of poundings interstory displacements, floor shear forces and floor accelerations increase considerably.
Below table lists the obtained results from analysis of this structure.

Table 1. Maximum response values of the fixed base building and the isolated building in case of pounding and no pounding, under Northridge earthquake.

| | Fixed base building | Isolated building (without impact) | **Isolated building (with impact)** |
|---|---|---|---|
| Time period (sec.) | 0.4 | 1.44 | 1.44 |
| Peak interstory displacement (mm) | 20 | 7 | 12 |
| peak floor acceleration **/s$^2$)** | 13.67 | 4.14 | 9.85 |
| peak base shear force (MN) | 20.3 | 8.9 | 12.2 |

Based on obtained results, absolute floor acceleration under Northridge earthquake remarkably is influenced by impact and its value for the isolated building is about two times more than the value in the case of no impact and it is almost the same as absolute floor acceleration in the fixed base building. According to the fact that one of main purposes of seismic isolation is reduction of floor acceleration and consequently protection of internal equipments, the results show that when an impact occurs, the performance of seismic isolation significantly reduces. Effect of some parameters on behavior of the isolated building during pounding was also investigated and the results are discussed in the following sections.

## III. Effect of isolation system softness (horizontal stiffness)

In order to investigate effect of isolation system softness, time period of four-story isolated building was varied in the range of 1.0-4.0 sec and each system was analyzed under Northridge earthquake and with gap widths of 15 cm, 20 cm, 30 cm and ∞ (without impact). Figures 2 and 3 demonstrate results of these analyses for maximum floor displacement (drift), maximum floor acceleration and maximum base shear force.

The maximum floor acceleration and maximum base shear force for the fixed base building with time period of 0.4 sec are equal to $13.7\, m/s^2\,(2.3 \times PGA)$ and 20.3 MN, respectively. This value of maximum base shear force is almost the same as weight of the structure (24.5 MN). According to the results, it can be concluded that pounding of an isolated structure can increase the floor acceleration and reach it to a value several times more than PGA (peak ground acceleration) and increase the structure response to the values experienced in the case of fixed base or even more. This can be very destructive for components of the structure. The results showed that in some cases, peak floor acceleration can be experienced despite larger gap sizes.

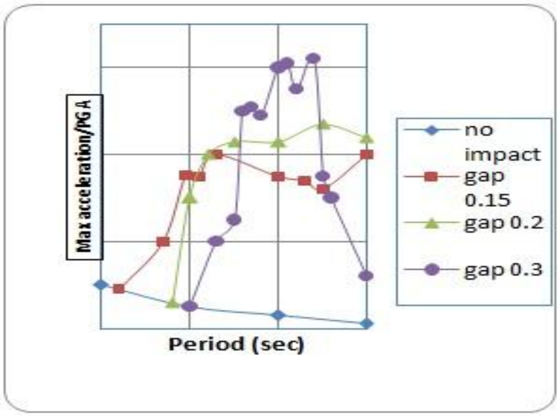


Figure 2. Variation of maximum floor acceleration
Versus time period [3].

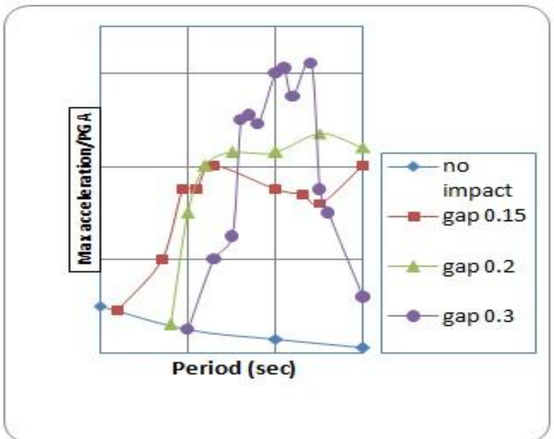


Figure 3. Variation of maximum relative displacement versus time period [3].

## IV. Effect of superstructure stiffness

In this section the effect of superstructure stiffness on the isolated building response during impact is investigated. For this aim, flexibility of the studied four-story building is varied and the responses are studied for four different seismic gap sizes of 10 cm, 13 cm, 16 cm and $\infty$ using Northridge earthquake record (Figures 4,5 and 6). The results are presented in below figure for maximum interstory displacement, maximum floor acceleration and maximum base shear. The results of maximum acceleration and maximum floor shear are normalized with respect to PGA and weight of the structure, respectively and normalized responses are presented as a function of ratio of superstructure stiffness to isolation system stiffness. The results indicate that with increasing superstructure flexibility, interstory displacements increase remarkably but a minor increase occurs in floor acceleration. It is obvious that increasing interstory displacements is very important for damages of structural and non-structural components and they should be controlled. In this study it was found that interstory displacement and floor acceleration reduce as seismic gap around the structure becomes larger.

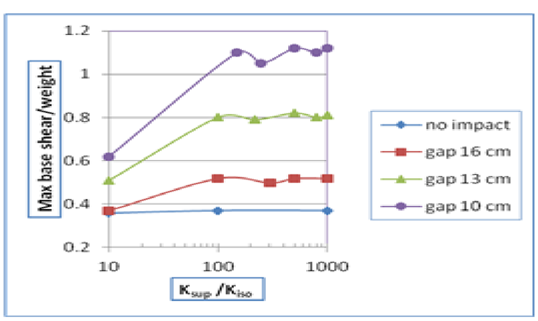


Figure 4. variation of relative displacement versus changes in superstructure stiffness.

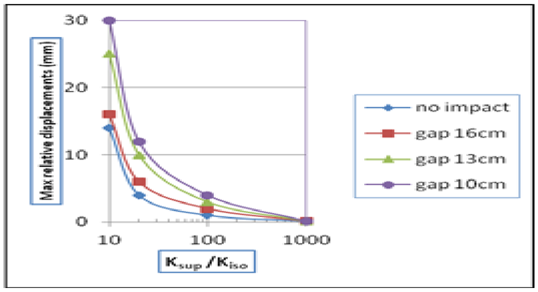


Figure 5. Variation of acceleration versus changes in superstructure stiffness

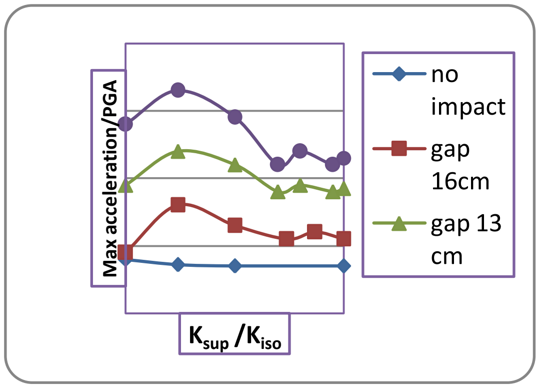


Figure 6. Variation of base shear versus changes in superstructure stiffness.

## V. Effect of damping:

Recent researches has shown that employing supplemental damping devices such as viscous dampers can reduce relative displacement of base level in the isolated building under strong ground motions and earthquake near fault [6]. Hence, in order to investigate effect of damping on reduction of destructive effects of impact some analyses were conducted. For this aim, the isolated building was analyzed using different earthquake records and the results showed that relative displacement of isolation level reduces as damping ratio increases (figure 7). Consequently the possibility of pounding with adjacent structure is reduced. It was also found that impact velocity reduces with increasing damping ration (figure 8). Therefore, employing supplemental damping devices at isolation level can be useful for reducing destructive effects of pounding. But anyway increasing damping has some limitations because it leads to an increase in both interstory displacement and absolute floor acceleration.

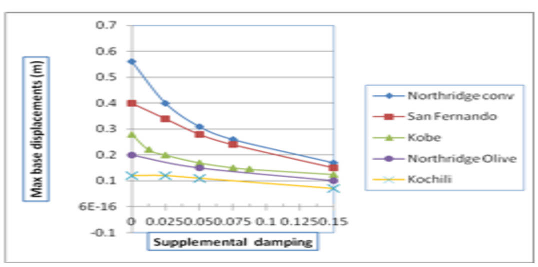


Figure 7. Variation of maximum base displacement versus changes in damping [1].

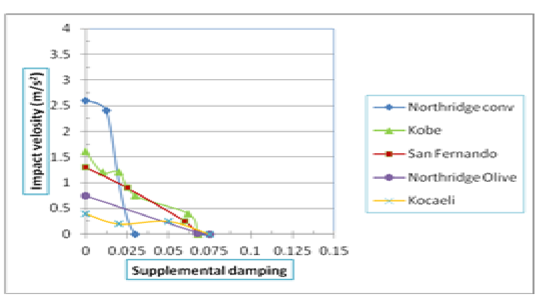


Figure 8. Variation of maximum impact acceleration versus damping [1].

In order to reduce destructive effects of pounding on the isolated building behavior, sudden changes of stiffness can also be avoided by insertion of flexible materials with damping properties, such as bumpers, at certain points at isolation level expected to experience impact. In this way, sudden increases in acceleration due to sudden impact to some extent can be prevented.
For this aim, the studied four-story building was studied under below conditions using Northridge earthquake record to determine advantages of using bumpers:

a) A seismic gap equal to 10 cm without using bumper
b) A seismic gap equal to 10 cm with using a 5 cm thick bumper
c) A seismic gap equal to 15 cm
d) Base condition

Interstory displacements, floor acceleration, inertia and elastic forces are listed in below table. The results indicate that employing bumper at isolation level have positive effects on the structure behavior. It also must be mentioned that using damping devices (bumper) always does not lead to improvement of structure response. For example in the case where pounding may occur slightly, insertion of such devices may cause structure response to increase.

Table 2. Response values of the structure for different conditions of seismic gap with and without employing bumper at isolation level [3].

| | (a) | (b) | (c) | (d) |
|---|---|---|---|---|
| Interstory displacement (mm) | 18.6 | 11.5 | 12.2 | 17.9 |
| Maximum floor acceleration (PGA) | 3.28 | 1.17 | 1.66 | 2.31 |
| Maximum inertia force (MN) | 9.7 | 3.47 | 4.9 | 6.8 |
| Maximum elastic forces ( MN) | 18.6 | 11.5 | 12.2 | 20.3 |
| Maximum impact force (MN) | 13.3 | 5.2 | 5.6 | - |

## VI. Conclusion:

In this paper, it was tried to indicate destructive effects of pounding on isolated structures behavior relying on pervious researches and effects of some parameters on structure behavior were also investigated. The results showed that performance of seismic isolation may reduce significantly under the influence of pounding phenomenon. This phenomenon leads to an increase in acceleration and intersory displacements as well as excites higher modes of deformation of isolated building and causes the superstructure to behave no longer like a “rigid body”. Therefore, taking into account the possibility of pounding in seismically isolated structures which experience large displacements is essential. Also it should be tried prevent pounding phenomenon specially in softer isolation systems because it immensely reduces performance of isolated building and in some cases floor accelerations become much higher than those for the fixed base building while the main purposes of seismic isolation are reducing floor acceleration and protecting internal components of structure. In order to reduce the intensity of pounding, it is also recommended to employ impact reducing devices such as bumper and flexible materials at isolation level. This leads to prevention of sudden changes in stiffness as well as reduction of destructive effects of impact.