Proceedings of 9th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2021 Month: March Volume: 9

Seismic Separation Requirement to Reduce Pounding

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Abstract
Adjacent or closely spaced buildings may be subjected to pounding when subjected to strong ground motions. Pounding between closely spaced building structures can be a serious hazard in seismically active areas. Pounding of adjacent buildings could have worse damage as adjacent buildings with different dynamic characteristics which vibrate out of phase and there is insufficient separation distance or energy dissipation system to accommodate the relative motions of adjacent buildings. A large separation is controversial from both technical (difficulty in using expansion joint) and economical (loss of land usage) views. Different codes seem to suggest different values for the minimum separation distance between buildings. In order to study the optimum requirement of seismic separation gaps adjacent buildings are analyzed to calculate the code required separation gaps as well as analyzed in order to study response of the adjacent structures when subjected to strong ground motions from real earthquakes(time histories).

Keywords
Seismic Separation, Pounding

1. Introduction

The 2015 Gorkha Earthquake had a significant effect on the built structures in Kathmandu and nearby hilly districts in Nepal. Although a significant number of building stocks vulnerable to pounding were present in the capital city, only limited cases of pounding were observed but this could be attributed to an unusual characteristic of ground motion recorded in Kathmandu, which was dominated by energy for periods significantly longer than the resonant periods for structures throughout the valley (Shrestha and Hao, 2018) [1]. But, this may not always be the case. The earthquake that struck Mexico City in 1985 has revealed the fact that pounding was present in over 40 percent of 330 collapsed or severely damaged buildings surveyed and in 15 percent of all cases it led to collapse (Rosenblueth and Meli, 1986:Kasai et al., 1992) [2]. Similarly, it is always a possibility that Kathmandu valley could be subjected to an earthquake with predominant periods much lesser than the 2015 Gorkha Earthquake resonating with much shorter buildings.

When earthquake occur in areas where the buildings are constructed very close to each other without proper separation gap, the buildings may vibrate in out-of-phase motion that lead to hammering of adjacent buildings (Reddy et al., 2014)[3]. Thus a certain amount of separation is mandatory. But, a large separation is controversial from both technical (difficulty in using expansion joint) and economical (loss of land usage) point of views (Raheem, 2006)[4].

The most simplest and effective way for pounding mitigation and reducing damage due to pounding is to provide enough separation but it is sometimes difficult to be implemented due to detailing problem. An alternative to the seismic separation gap provision in the structure design is to minimize the effect of pounding by decreasing lateral motion which can be achieved by joining adjacent structures at critical locations so that their motion could be in-phase with one another or by increasing the pounding buildings damping capacity by means of passive structural control of energy dissipation system or by seismic retrofitting.

2. Methodology

The methods and procedures used for the purpose of this study are briefly discussed in the following sections.

2.1 Finite Element Modeling

Two different plans of buildings are considered that represent the plans of typical low rise residential buildings being built in and around Kathmandu. Plan A is a three bay by two bay plan and Plan B has three bays in both diections . These two plan are selected for the purpose of this study because these types of structures can be abundantly found in and around Kathmandu valley and are being constructed in confined small land portions. The first plan represents a structure built in confined piece of land for the residence of a small nuclear family consisting of two bedrooms, a kitchen and a living room. The second plan represents a structure built for renting purpose in confined condition. All structures having Plan A and Plan B have been called Block A and Block B respectively in the study from this section onwards.

All buildings are considered as bare frame structures, hence no infill wall is considered for simulation in the model but is considered for the loading. All the columns are assumed to be restrained in all directions and for all rotations at the base of the structure (i.e. fixed base). The floor slabs are characterized as thin shell elements of thickness 125 mm and modeled as rigid diaphragms. Building geometry and material properties used in this study are listed in Table 1 below.

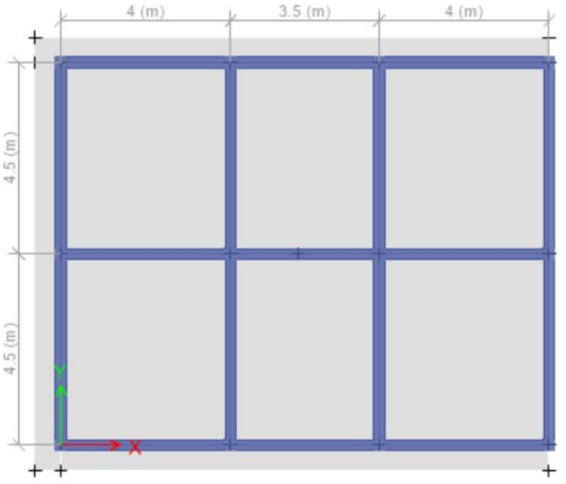

Figure 1: Plan of Block A

Four sets of 5 buildings each are modeled in finite element based software ETABS 2018. The sets are 2, 3, 4, 5 and 6 story buildings with Plan A and all floor heights 3.0 m for the first set and all floor heights 2.7 m for the second set. The other two sets are 2, 3, 4, 5 and 6 story buildings with Plan B with all floor heights 3.0m and 3.3m respectively buildings. In total 20 different models were created using finite element software ETABS 2018.

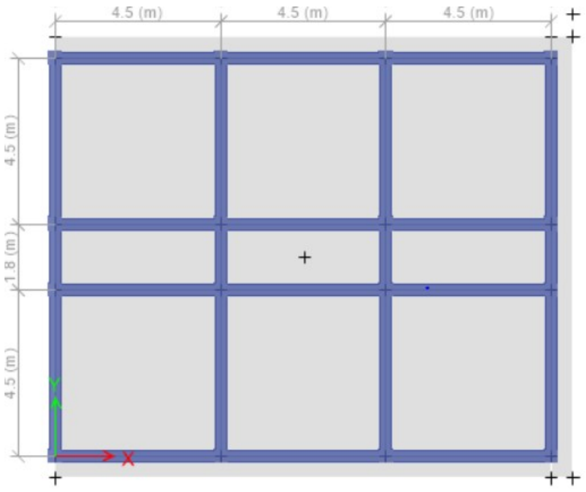

Figure 2: Plan of Block B

Table 1: Building Geometry and Material Properties (Block A)

Properties	Block A
Height of story	2.7 m and 3.0m
Plinth Area	109.74 m^2
Grade of Concrete	M25
Column Size	300mm x 300mm
Beam Size	250mm x 400mm
Density of RC Members	25 kN/m^3
Density of Brick Masonary	19.2 kN/m^3

Table 2: Building Geometry and Material Properties(Block B)

Properties	Block B
Height of story	3.0 m and 3.3 m
Plinth Area	155.68 m^2
Grade of Concrete	M25
Column Size	400mm x 400mm
Beam Size	300mm x 450mm
Density of RC Members	25 kN/m^3
Density of Brick Masonary	19.2 kN/m^3

The structures were then analyzed using linear static equivalent force method and response spectrum procedures and the forces, displacements and then the seismic separation were calculated using the IS 1893:2002, IS 1893:2016 and NBC 105:2020 codes based procedures.

As per NBC 105:2020 code, the seismic zone factor (Z) for Kathmandu is 0.35 and the importance factor of the residential buildings are taken to be 1. The soil type is taken as very soft soil (Type D) as suggested by the code for most places in Kathmandu valley. The response reduction factor (Rμ) and the over strength factor were taken as 4 and 1.5 respectively as suggested by the code for Reinforced Concrete moment resisting frame. The damping for all cases is taken as 5 percent of critical.

As per IS 1893:2002 and IS 1893:2016 codes, all of the structures are residential buildings assumed to be located in Zone V. Thus, the seismic zone factor (Z) is taken as 0.36 and the Importance Factor (I) is taken as 1. The soil type is taken as soft soil (Type III) and since the structure is modeled as special moment resisting frame the response reduction factor is taken as 5. The damping for all cases is taken to be 5 percent of critical.

The models were then analyzed using the software ETABS 2018 for the loads described bythe IS 1893:2002, IS 1893:2016 and NBC 105:2020 codes based procedures for separate cases for equivalent force method and response spectrum method of respective codes. Minimum seismic separation were then calculated as per Clause 5.6.2 of NBC 105:2020 code and Clause 7.11.3 of IS 1893:2002 and IS 1893:2016 respectively.

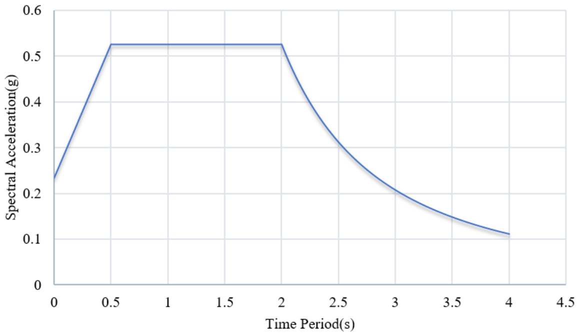

Figure 3: Target Spectrum defined in PEER Ground Motion Database

2.2 Time History Analysis

The design acceleration response spectra defined by NBC 105:2020 for Kathmandu with Seismic Zone Factor (Z) = 0.35, Importance Factor (I) = 1, and Over strength Factor = 1.5 as shown in Figure 3 was defined as the target spectrum in the Pacific Earthquake Engineering Research Centre (PEER) Ground Motion Database search engine. The parameters range of magnitude (Mw 6.5 to 8), source to site distances (0 km to 150 km) and shear velocity (50 to 200 m/s) were specified in the search engine and based on of the similarity of their response spectrum to that of the target spectrum, 1979 Imperial Valley earthquake (Mw = 6.5) strong motion data recorded at EC County Centre FF station, 1995 Kobe (Japan) Earthquake(Mw = 6.9) strong motion data recorded at Port Island station and 1999 Kocaeli (Turkey) Earthquake (Mw = 7.5) strong motion data recorded at Ambarli station were selected for the purpose of this study. The selected ground motion were then spectrally matched in the time domain for a range of time periods of 0.05 to 2.0 seconds using (Hancock et al., 2006)[5] defined procedures of spectral matching by addition of wavelets using Seismomatch 2018 software. The spectrally matched time histories of the selected earthquakes are shown in Figure 4, Figure 5 and Figure 6 respectively.

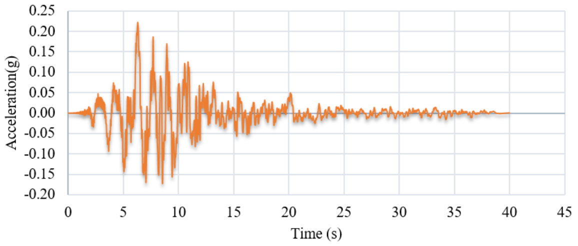

Figure 4: 1979 Imperial Valley Earthquake Acceleration Time History after spectral matching

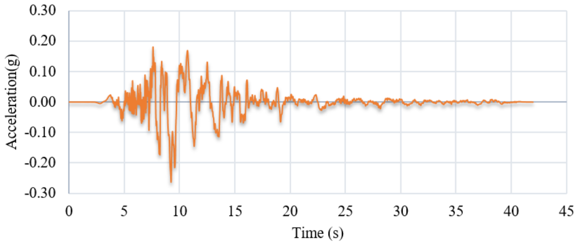

Figure 5: 1995 Kobe Earthquake Acceleration Time History after spectral matching

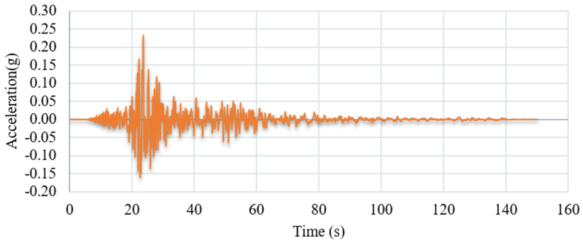

Figure 6: 1999 Kocaeli Earthquake Acceleration Time History after spectral matching

The models were then analyzed using the software ETABS 2018 for the three time histories using Linear Direct Integration Time History method. Minimum seismic separation requirement to preclude pounding was then calculated by overlapping the displacement time histories of the top of the shorter building and the corresponding level at the taller buildings. The minimum seismic separation of the two structures are then calculated by finding the response for which the arithmetic difference between the two displacements time histories is maximum, i.e. maximum (u_A(t) - u_B(t)).

3. Results and Discussion

In order to calculate minimum seismic separation requirement using different procedures, 4 different combinations of Block A and Block B buildings adjacent to each other for number of story varying from 2 to 6 were considered, which are as follows:

- Case I - Block A with all story height 3.0m and Block B with all story height 3.0m
- Case II - Block A with all story height 2.7m and Block B with all story height 3.0m
- Case III - Block A with all story height 3.0m and Block B with all story height 3.3m
- Case IV - Block A with all story height 2.7m and Block B with all story height 3.3m.

The number of story for both the blocks were kept the same for all combinations and cases. The results of the study are discussed in the following sections for the above mentioned combinations.

3.1 Case I - Block A (Story Height 3.0m) and Block B (Story Height 3.0m)

The minimum separation requirement at the top floor level of 2, 3, 4, 5 and 6 story Plan A (Story Height 3.0m) and Plan B (Story Height 3.0m) buildings using NBC 105:2020, IS 1893:2002 and IS 1893:2016 codes and the maximum seismic separation requirement among the results from the three time histories are shown graphically in figure 7 and figure 8.

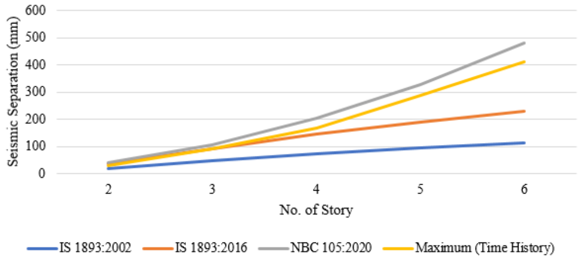

Figure 7: Case I -Comparison of code based seismic separation requirement (Response Spectrum Method) and seismic separation from time history analyses

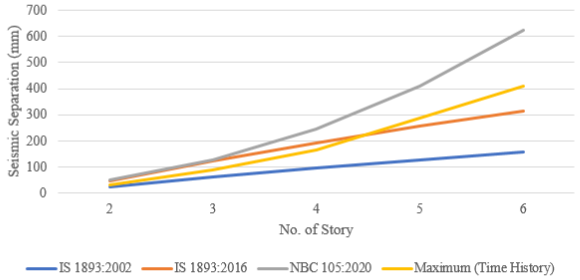

Figure 8: Case I -Comparison of code based seismic separation requirement (Equivalent Force Method) and seismic separation from time history analyses

NBC 105:2020 code requirements for this case of same floor height and same total height of adjacent buildings is much higher than IS 1893:2002 and IS 1893:2016 code requirements for both Response Spectrum method and Equivalent Static Force method. This difference is obvious from the fact that the seismic demand in terms of response spectra described by NBC 105:2020 code is much higher than demand described by the IS codes. The seismic separation requirement given by NBC 105:2020 is slightly higher than the results from time history analysis when response spectrum method is used but is much higher when equivalent force method is used and the difference increases as the number of story i.e. the height increases. Equivalent Force method gives higher response and thus higher seismic separation requirement than response spectrum method because, it assumes that all of the seismic mass vibrates in the fundamental natural period of the building in considered direction.

3.2 Case II - Block A (Story Height 2.7m) and Block B (Story Height 3.0m)

The minimum separation requirement at the top floor level of 2, 3, 4, 5 and 6 story Plan A (Story Height 2.7

m) and corresponding level of Plan B (Story Height 3.0m) buildings using NBC 105:2020 and IS 1893:2016 codes and the maximum seismic separation requirement among the results from the three time histories are shown graphically in figure 9 and figure 10.Since the separation requirement defined by IS 1893:2002 and IS 1893:2016 codes is same when the floor levels of adjacent structures are different, only IS 1893:2016 is stated in this section.

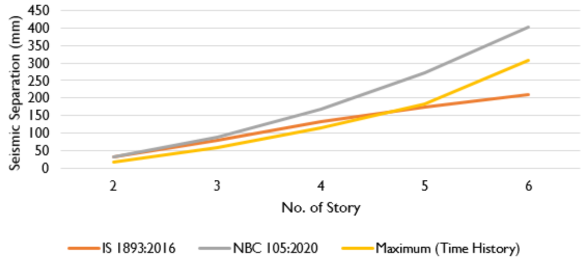

Figure 9: Case II -Comparison of code based seismic separation requirement (Response Spectrum Method) and seismic separation from time history analyses

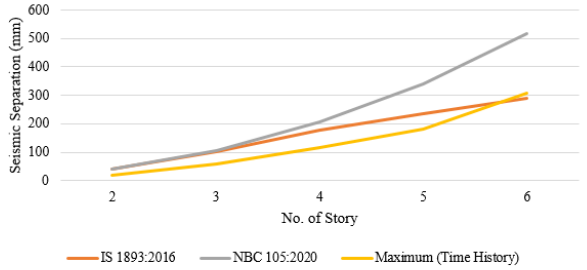

Figure 10: Case II -Comparison of code based seismic separation requirement (Equivalent Force Method) and seismic separation from time history analyses

NBC 105:2020 code seismic separation requirements for this case is much higher than IS 1893:2016 code requirement for both Response Spectrum method and Equivalent Static Force method. The seismic separation requirement given by NBC 105:2020 is relatively higher than the results from time history analysis for both of the methods and the difference increases as the number of story increases i.e. the height increases. The seismic separation requirement given by IS 1893:2016 is somewhat comparable to the results from time history analysis.

The results of Case II also show that the seismic separation requirement for this case of Block A buildings with story height 2.7m and Block B buildings with story height 3.0m, is lower for all of the codes, methods and time history analysis than the cases with both of the blocks having same story height of 3.0 m (Case I). That is because, Block A buildings being the less stiffer structure of the two, the stiffness of block A buildings increase due to decrease in height causing increase in stiffness of the buildings and the maximum displacement of block A buildings decrease and thus the seismic separation requirement decrease. As per time history results, it too decreases because of the decrease in time periods of the less stiffer Block A buildings, which makes the time periods of the two adjacent structures more comparable and more in phase with each other.

3.3 Case III - Block A (Story Height 3.0 m) and Block B (Story Height 3.3m)

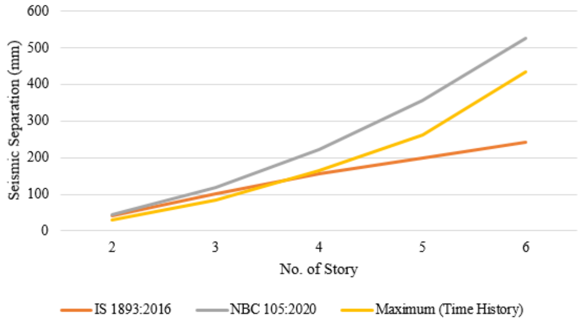

Figure 11: Case III -Comparison of code based seismic separation requirement (Response Spectrum Method) and seismic separation from time history analyses

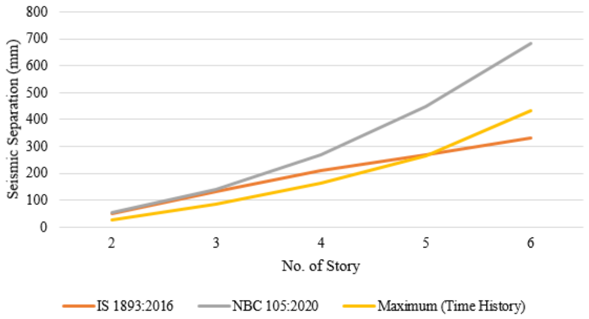

Figure 12: Case III -Comparison of code based seismic separation requirement (Equivalent Force Method) and seismic separation from time history analyses

The minimum separation requirement at the top floor level of 2, 3, 4, 5 and 6 story Plan A (Story Height 3.0m) and corresponding level of Plan B (Story Height 3.3m) buildings using NBC 105:2020 and IS

1893:2016 codes and the maximum seismic separation requirement among the results from the three time histories are shown graphically in figure 11 and figure 12.

The seismic separation requirement, for this case of Block A buildings with story height 3.0 m and Block B buildings with story height 3.3m, is higher for all of the codes and methods than the cases with both of the block having same story height of 3.0 m (Case I). As the height of Block B buildings is increased when compared to the case in section 3.1, the stiffness of the structures have decreased and thus the displacements increased due to which seismic separation distance requirement as per Equivalent Force Method and Response Spectrum Method increase. As for the time history analysis, the seismic separation distances decrease slightly for all number of story except for 6 story buildings. This is because, due to the increase in height of story, time period of Block B buildings increase and for lesser number of stories comes more into phase with the time periods of Block A buildings. The anomaly in the case of 6 story buildings is because the time periods of 6 story buildings are in the region where the response spectra of Kobe earthquake shows a clear peak which is higher than the target spectra owing to high amplitude content in this frequency range.

3.4 Case IV -Block A (Story Height 2.7 m) and Block B (Story Height 3.3m)

The minimum separation requirement at the top floor level of 2, 3, 4, 5 and 6 story Plan A (Story Height 2.7m) and corresponding level of Plan B (Story Height 3.3m) buildings using NBC 105:2020 and IS 1893:2016 codes and the maximum seismic separation requirement among the results from the three time histories are shown graphically in figure 13 and figure 14.

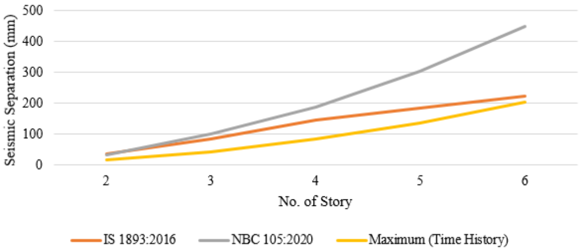

Figure 13: Case IV -Comparison of code based seismic separation requirement (Response Spectrum Method) and seismic separation from time history analyses

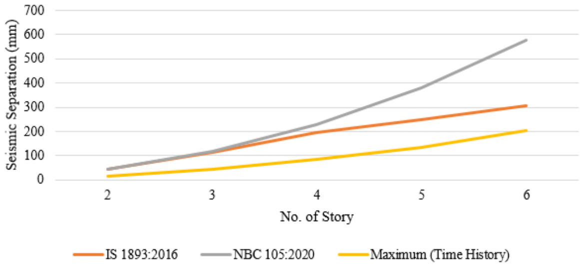

Figure 14: Case IV -Comparison of code based seismic separation requirement (Equivalent Force Method) and seismic separation from time history analyses

The NBC 105:2020 code requirements for this case is much higher than IS 1893:2016 code for both Response Spectrum method and Equivalent Static Force method. The seismic separation requirement given by NBC 105:2020 is nearly double of the results from time history analysis for both of the methods and the difference increases as the number of story i.e. the height increases for response spectrum method. The seismic separation requirement given by IS 1893:2016 is also much higher than the value given by the time history analyses. The seismic separation requirement from these cases (Block A of story height 2.7m and Block B of story height 3.3m) of structures calculated from the codes are nearly similar to the results for the case of same story height of the two blocks(Case I). This is because the displacement response of Block A buildings has decreased due to increase in stiffness and that of Block B buildings has increased due to decrease in their stiffness. But the time history results shows a much lower seismic separation requirement than the code based requirement which is substantially lower than the results in Case I. The low seismic separation requirement from time history analysis is because the stiffness of stiffer Block B buildings have decreased due to increase in story height resulting in increase in its natural time period and the stiffness of less stiffer Block A buildings have increased owing to decrease in story height resulting in decrease in its time period. The combination of increase in time periods of Block B buildings and decrease in time periods of Block A buildings has caused the phase differences between the structures to decrease and be more closer, due to which the seismic separation requirement has decreased substantially.

4. Conclusion

The purpose of this study has been to analyze seismic separation requirement between adjacent structures and to study its variation with height, story levels and the codes. For this, ETABS 2018, a linear and non-linear static and dynamic analysis and design program for three dimensional structures has been used. Dynamic analysis has been carried out to know about the deformations, natural frequencies and time periods, floor responses(displacements) which are required to calculate seismic separation requirements. The NBC 105:2020 code defines a higher level of hazard for use in Kathmandu with a longer constant acceleration region on acceleration spectra than the IS 1893 codes. The highest level of hazard defined by IS 1893 code is that of Zone V which is less than that defined by the NBC 105:2020 codes. Thus analysis with NBC 105:2020 codes results in higher base shears, larger displacement for most of the cases and thus results in higher seismic separation requirement. The specific conclusions made from this study from the analysis of the results are as follows:

1. The results from time history analyses from individual earthquakes show that for two to three story buildings with low fundamental time periods Imperial Valley earthquake requires higher seismic separation requirement, whereas for taller buildings with higher fundamental time periods Kobe Earthquake requires higher seismic separation requirement owing to high amplitude content in the corresponding frequency range.

2. NBC 105:2020 code recommends the absolute sum of the maximum displacement of adjacent structures to calculate seismic separation requirement. But the comparison of code based results to the results of time history analysis show that the seismic separation need not be as high as stated in the codes. The codes seem to have used higher factor of safety when defining seismic separation requirement.

3. NBC 105:2020 code and both of the IS 1893 codes depend on maximum displacement only for the calculation of seismic separation requirement. But from the results of time history analyses, it can be seen that the seismic separation requirement also depends upon the time periods of the two structures. For more closely spaced time periods of the adjacent structures, it can be seen that all of the codes discussed here overstate the seismic separation requirement when compared to the results from time history analysis. Comparison of the results in sections 3.1, 3.3 and 3.4 show that, for a more closely spaced time periods of adjacent structures, the minimum seismic separation distance is more affected by the change in time periods of the adjacent structure than the maximum displacements of the adjacent structures.

4. On the basis that the seismic demand of structures in Kathmandu Valley is the demand defined by the NBC 105:2020 code, the separation requirement provided using IS codes may not be sufficient to preclude pounding when subjected to an actual earthquake matching the demand defined by NBC 105:2020 for taller buildings.

Acknowledgements

The authors are thankful to Department of Earthquake Engineering, Thapathali Campus for providing excellent opportunity to conduct research under their guidance. The authors are also thankful to Mr. Susan Prajapati for his assistance during the course of this research work.

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