



Seismic Pounding Response of Neighboring Structure using Various Codes with Soil-Structure Interaction Effects: Focus on Separation Gap

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Abstract

Due to the high cost and less availability of land, the buildings are constructed adjacent to each other with a significantly smaller separation gap. Whenever seismic forces act on adjacent structures, they collide and cause significant structural and architectural damage. Soil-Structure Interaction (SSI) effects cause more complications in the adjacent structures. This paper assesses the gap distance between RC bare frame adjacent structures of varying heights in medium and soft soil with and without SSI to avoid the pounding effect of an earthquake. The main objectives are to find the separation distance between adjacent buildings by the provisions of FEMA 356, IS 1893 (Part 1):2002, IS 1893 (Part 1):2016 and EN 1998-1:2004. The separation gap between different codes was then compared to determine the minimum separation required to prevent pounding between the structures. The maximum lateral displacement on the roof and the time period of the adjacent buildings are compared with and without SSI. There is a significant increase in lateral displacement, separation distance, and time period considering SSI. It is found that the Indian code overestimates the separation distance. Thus, this study guides structural engineers to maintain a minimum separation distance between buildings erected on medium and soft soils in high seismic zones of India.

Keywords: Soil-Structure Interaction; Pounding; Codes and Standards; Separation Distance; Adjacent Buildings; SAP 2000.

1. Introduction

Due to the increasing population and the efficient use of land for construction, there is a need to construct closely spaced buildings. However, the vulnerability of building damage due to a strong earthquake remains a problem to be solved entirely. Also, the behaviour of soil structure is partially understood. If the gap between adjacent buildings is insufficient, buildings during earthquakes will not be allowed to vibrate freely and will thus fail due to pounding.

Several seismic pounding studies have been carried out worldwide, but there is still insufficient understanding and provisions in international codes. The corners of the building are subjected to high risk during seismic events [1]. Also, pounding causes stress on buildings of different heights, masses, and periods, and it requires some special measures and provisions for a minimum separation gap in an International Standards [2]. The effect of pounding worsens neighbouring

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shear buildings resting on a discrete soil type, as amplification of seismic responses occurs in the case of pounding [3]. The effects of pounding depend on the vibration between adjacent buildings [4]. The masonry infills affect the response of the steel frame in the case of pounding [5]. In low-rise buildings, consideration of pounding due to adjacent structures can be beneficial as seismic response is reduced. Hence, it is essential to include the effects of pounding while designing the structure of existing buildings to maintain a sufficient separation distance [6].

Ground motions are significantly affected by the soil strata. The interaction and pounding effects exchange the vibration energy and complicate the structure's analysis [7]. As physical modelling of soil is challenging, ABAQUS software helps analyze the behavior of soil strata with inertial effects and damping [8]. Milad et al. represented the dynamic analysis of soil and structure through simplified models [9]. Incorporating nonlinear pounding effects with soil-structure interaction reduced the need for micro piles, buttresses, and boundary elements and reduced the project's construction cost [10]. Direct losses due to seismic excitations are estimated using the performance tool, and the SSI effects are included to avoid underestimation in the case of tall buildings [11]. Because the SSI affects the structural demand of the structure, both the fragility and performance analysis of the structure were unreliable [12]. The structure-soil-structure interaction (SSSI) increased the foundation base shear demands and peak foundation moments irrespective of the geometric shape of the structure [13]. The effects of pounding are greater than SSI in adjacent buildings in the case of a minor clear distance, causing seismic damage to beams [14]. Simple models were used to represent soil-foundation interaction and interaction between neighboring building foundations affected by the number and position of foundations [15]. Anand and Kumar summarized different approaches to considering SSI in analyzing buildings, and there is a need to select the correct method for proper analysis [16]. Due to the coupling effect of pounding between structures and the soil stiffness of insufficiently spaced structures, the response of lighter structures was significantly affected [17]. Nonlinear analysis for both soil and structure is essential [18]. The effect of soil and structure exceeds the linear elastic phase and needs elastoplastic analysis. Shear at the base increases with an increase in the stiffness of the superstructure and the flexibility of soil strata [19].

Various researchers used base isolation techniques to reduce the pounding effect between adjacent structures. In 1987, they presented a simplified method for base-isolated structures over semi-flexible soil with an SDOF oscillator [20]. The link elements between two adjacent buildings reduce the gap size and prevent the pounding effect [21]. Pant et al. studied the pounding impact and found that failure due to flexure governs base-isolated buildings [22]. Eftychia et al. verified the effect of accidental torsion and studied the response of adjacent base-isolated structures [23]. Pounding effects can also be reduced by including a Tuned-Mass Damper in adjacent buildings [24]. There is a need for extensive research, as many mitigation measures have certain disadvantages, like damage to the shear wall, space requirements for the use of damper connectors, etc. [25].

Studies on the structures of homogenous one layer of soil extending up to certain levels were considered in the past. In this paper, the pounding effect between adjacent structures considering SSI layered soil was analyzed. The paper's main aim is to validate the separation gap considering SSI using FEMA 356, IS 1893 (Part 1):2002, IS 1893 (Part 1):2016, and EN 1998-1:2004. Then the separation gap by different codes is compared, and the minimum separation used to avoid pounding between the structures is calculated. This paper compares the maximum lateral displacement, separation distance, and time period of adjacent buildings with varying height and support conditions.

2. Research Methodology

It is found that the type of soil and its nature greatly affect the behavior of the structure. As a result, studies on soil-structure interaction and structural pounding are critical. The step-by-step procedure for this analytical study is as follows:

- Collection of soil data from actual site to simulate real behaviour of soil model.
- Analytical modelling is carried out in SAP 2000 v20 with and without SSI.
- Fixed base is assigned to building supports at base.
- Soil profile is defined in material properties using actual site data.
- Fixed base is removed, and new material is defined as Mat.
- The soil is defined as solid in section properties.
- Geometric model of soil boundary is created and divided into 3 equal parts on both axes. Then, it is extruded in 3 layers up to 10 m below ground.
- In the Y-Z plane, restraint is provided along the X-axis by selecting translation 1 in the support option. Similarly, the X-Z plane provides restraint along the Y-axis by selecting translation 2.
- The edges of the soil model are restrained along both X and Y axes, whereas the soil bottom at 10 m below FFL is fixed.

- The mat foundation is assigned with the solid property as MAT.
- Solid mesh of 0.5×0.5 m is created.
- Contact elements on each floor of adjacent buildings simulate pounding action. It is defined in link property and type of element as a gap.
- The directional property is assigned in one direction with non-linear behaviour.
- The stiffness and gap distance is accordingly provided.

Bhuj Time History data was used for seismic analysis, and Eigenvector analysis was carried out. Pounding load case defined as non-linear time history and load combinations described as per IS 456-2000. The maximum lateral displacements of both adjacent structures were obtained for pounding free separation distance. The separation distance obtained from various international codes FEMA 356:2000, IS 1893:2002, IS 1893 (Part 1): 2016 and EN 1998-1:2004 compared. The time period of the structures is compared to understand the effect of soil-structure interaction. Figure 1 depicts the overall flow of this study to conclude.

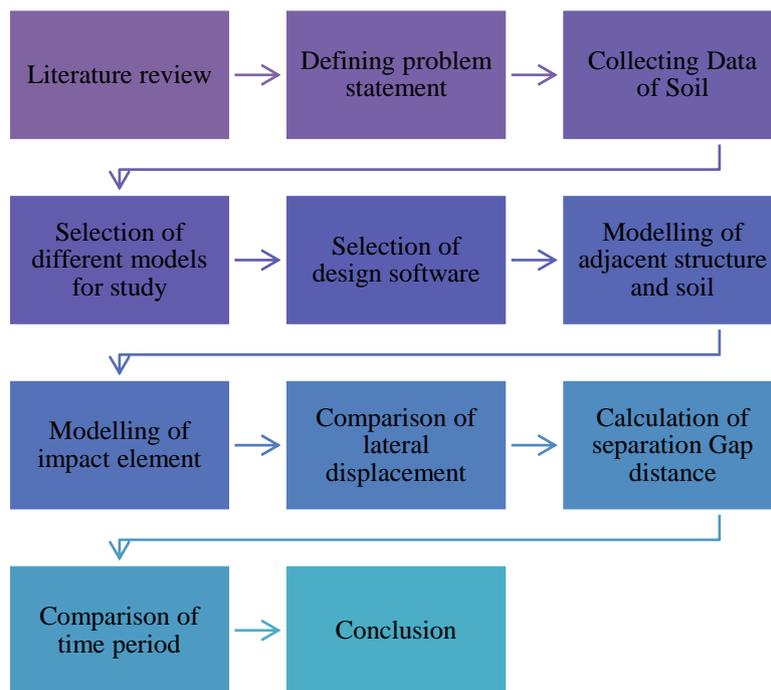


Figure 1. Flowchart of the research methodology

2.1. Soil Data

Subsoil investigation data of the actual project site used in the present study. Such accurate site data have merits over idealized soil data and can capture the actual behaviour of soil. The layered soil consists of 10 m deep with 3 m clayey soil, 6 m residual soil of volcanic rock formation, 1.5 m moderately weathered volcanic rock and 1 m highly weathered volcanic rock. Figure 2 shows the location of actual soil data used in this study. Table 1 summarizes the property of layered soil used in this study.

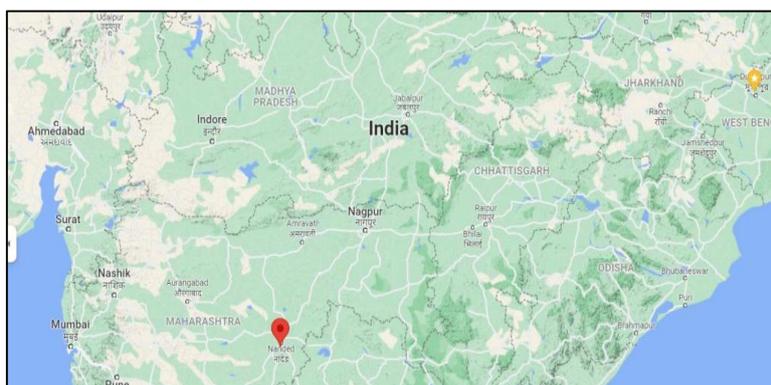


Figure 2. Location of Actual soil used in the study

Table 1. Property of soil

Soil Property	Layer 1	Layer 2	Layer 3	Layer 4
Unit Weight (γ) (kN/m ³)	28.1059	29.7632	38.4225	40.5505
Shear Modulus (G) ((kN/m ²)	12666	150168.08	289611.39	312557.29
Modulus of Elasticity (E) (kN/m ²)	32931.6	390437	289611.39	812649
Soil class type (NHERP)	E (soft Soil)	E (soft soil)	D (stiff soil)	D (stiff soil)

2.2. Numerical Model of Soil and Foundation

The analytical methods are complicated because of the different matrices and vectors used to solve the dynamic equations. Due to this, the finite element modelling method is used to solve the problem. In this paper direct approach of modelling is used in SAP 2000 to model the soil. The mat foundation with soil is defined instead of the fixed base to get the realistic effect of soil. The mat foundation of concrete grade M25 is defined. Figure 3 shows a model of the adjacent structure of the same and different heights with a fixed base. The solid property is depicted for both mat foundation and soil. The solid is divided into smaller parts for finite element modelling by meshing. Figure 4 visualizes the FE model of soil. Boundary conditions consider the infinite soil into finite soil. In the present model, boundary conditions for soil fixed at the bottom, at corners restrained along with X and Y directions and in the middle portion of the X-Z plane is restrained along Y-direction similarly, in Y-Z plane at the edge in the middle portion is restrained along X-direction.

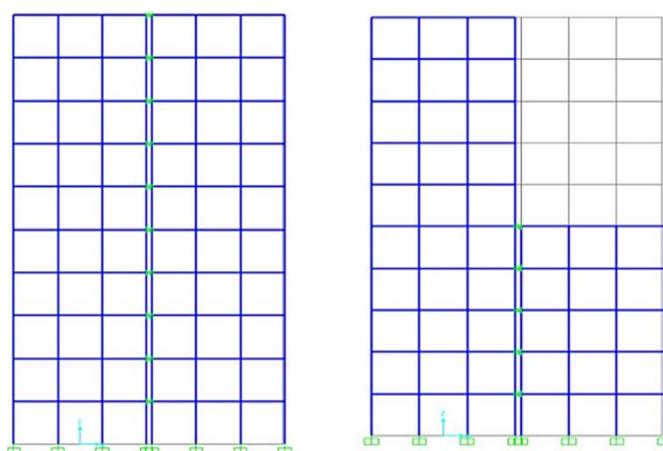


Figure 3. Model of the adjacent structure of same and different heights with a fixed base

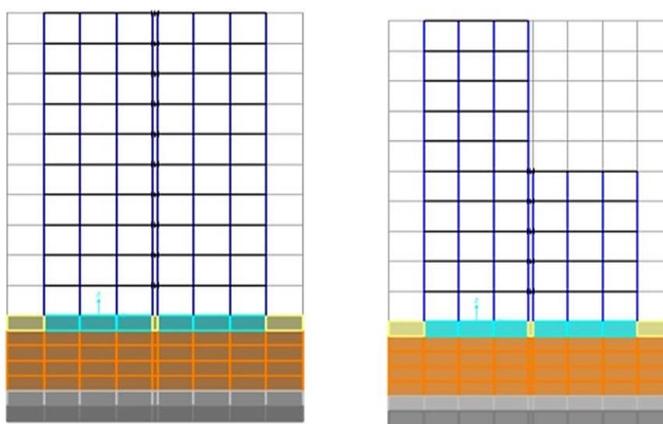


Figure 4. Model of the adjacent structure of same and different heights with mat foundation & layered soil

2.3. Features of Selected Models

In the study, two adjacent RC frames of equal heights and two adjacent RC frames of different sizes were modelled. Models designed as a flexible base to consider the effects of soil-structure interaction. Figures 3 and 4 represents the geometric configuration of models created in the software. Model 1 consists of two adjacent 10-storey 3-Bay RC frames and Model 2 consists of two adjacent one of 10-storey 3-bay and another 5-storey 3-bay frame. Each storey's height and bay spacing are kept the same for all frames, i.e. 3 m. A separation distance of 0.12 and 0.36 m between the adjacent

buildings was considered for investigating the effects of seismic pounding. Loads are applied as per IS 875 (Part 1, 2, and 3) and IS 1893 (Part 1): 2016. Analysis, design and detailing of models are following IS 456:2000 and IS 13920:2016. M30 concrete and Fe 500 rebar grade are used. The moment of inertia for a slab, beam and column was modified by IS 13920:2016.

2.4. Impact Element Modelling

The non-linear link element is used to model the gap between adjacent structures. The adjacent buildings are separated by 0.12 and 0.36 m, represented in SAP 2000 V.20 using link element. The link element at the joint of each structure is activated in case buildings come closer to each other and deactivated when buildings go away from each other. A non-linear link element in this model represents the gap used, as described in Figure 5. The directional property, like open distance, is equal to the gap distance between the adjacent structure, and the stiffness of the link is similar to 100 times the stiffness of the connecting element and no inertial effect is considered.

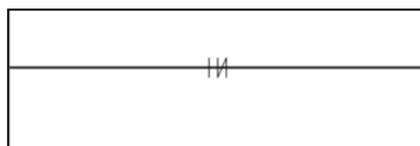


Figure 5. Representation of non-linear link element

3. Results and Discussions

3.1. Lateral Roof Displacement

The Time-History method of analysis is used to study the actual behavior of all models. Time-history data of the Bhuj earthquake has been used to model a more realistic situation in the Indian scenario. The primary aim is to study the effect of soil-structure interaction in terms of maximum roof lateral displacement by variation of separation distance. Figure 6 shows the maximum lateral roof displacement for the separation gap of 0.12 and 0.36 m in similar height adjacent buildings with and without considering SSI. It found that the maximum lateral roof displacement in similar-height structures without SSI was nearly the same for a gap of 0.12 and 0.36 m. But there is a huge difference in the values of lateral displacement when SSI is considered. Table 2 shows the maximum lateral displacement (in mm) values for model 1 with and without considering SSI. There is a 90–95% increase in maximum lateral roof displacement values by considering SSI in adjacent buildings for both separation gaps.

Table 2. Maximum Lateral Displacement (mm) at the roof for same height with and without SSI for different separation gap

Building	Maximum Lateral Displacement (mm)			
	Gap 0.12 (m)		Gap 0.36 (m)	
	Without SSI	With SSI	Without SSI	With SSI
1	112	2288.1	103.3	1063
2	111.9	2281.5	91.6	1461

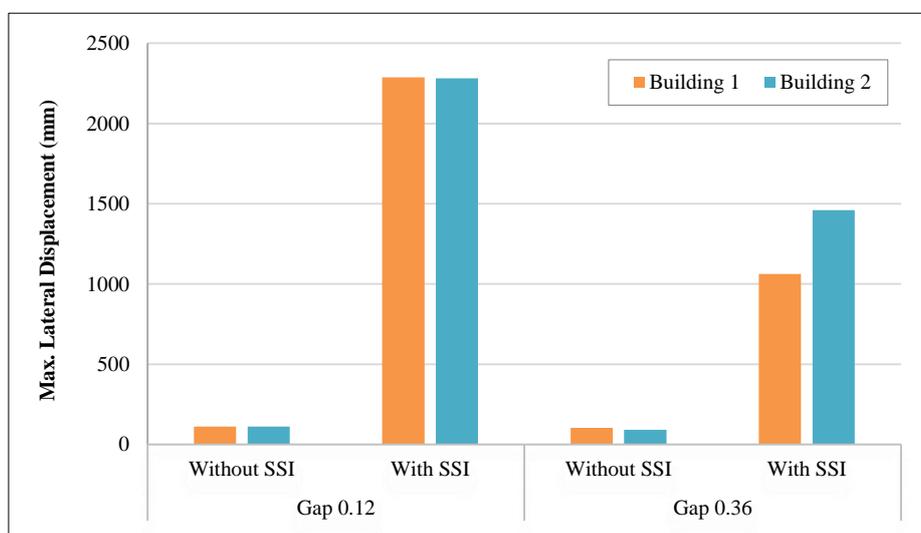


Figure 6. Maximum lateral displacement (mm) at the roof of both buildings with & without SSI for same height

Similarly, Chore found an increase in lateral displacement when the SSI effect was taken into account [26]. Awchat and Monde found that the lateral storey drift increases by 47-87% in seismic zone II and 60-95% in seismic zone III, IV and V considering SSI [27]. Also, by an increase in gap distance, lateral displacement was reduced. The height of the structure affected the lateral displacement of the structure. Considering the buildings as fixed base in design restraint the natural behaviour of soil at site. The soil beneath the buildings depending on the type i.e. hard, medium and soft type affect the base fixity type. The type of soil considered in this study increased lateral displacements of the building.

Figure 7 shows the maximum lateral roof displacement for the separation gap of 0.12 and 0.36 m in different height adjacent buildings with and without considering SSI. It found that in the varying height of structures, the maximum lateral roof displacement is nearly identical for a gap of 0.12 and 0.36 m. A similar trend as in model 1 was observed when the effect of SSI was considered. Table 3 shows the maximum lateral displacement (in mm) values for Model 2 with and without considering SSI.

Table 3. Maximum Lateral Displacement at the roof for different height with and without SSI for different separation gap

Building	Maximum Lateral Displacement (mm)			
	Gap 0.12 (m)		Gap 0.36 (m)	
	Without SSI	With SSI	Without SSI	With SSI
1	148.1	3605	121.7	3354
2	101.8	1597	93.3	1636

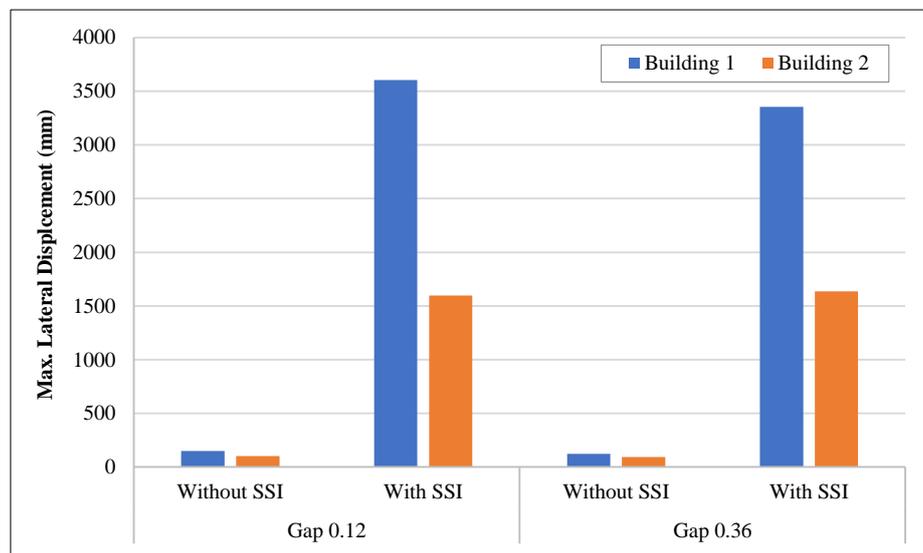


Figure 7. Maximum Lateral displacement at the roof of both buildings with and without SSI for different height buildings

3.2. Separation Distance

The separation distance given by different codes is the minimum distance between the adjacent structures. Table 4 presents the various provisions provided by international regulations for the estimation of separation distance.

Table 4. Separation gap as per international standards

Country and National Code	Provision	Remark
USA - FEMA 356 Clause 2.6.10.1	$\Delta S_i = ((\Delta_{i1})^2 + (\Delta_{i2})^2)^{1/2}$	Δ_{i1}, Δ_{i2} = Lateral displacement under consideration, at i^{th} level with reference to the ground, calculated as per provisions for the selected hazard level.
India-IS 1893:201 Clause 7.11.3	Separation Gap = $R_1 \Delta_1 + R_2 \Delta_2$	R_1, R_2 and Δ_1, Δ_2 = Response reduction factor and displacement corresponding to building 1 and 2 respectively.
India- IS 1893:2002 Clause 7.11.3	Separation Gap = $R/2(\Delta_1 + \Delta_2)$ for similar heights; Separation Gap = $R(\Delta_1 + \Delta_2)$ for different heights.	R and Δ_1, Δ_2 = Response reduction factor and displacement corresponding to building 1 and 2 respectively.
Europe-EN 1998-1:2004 (E) Clause 4.4.2.7	$\Delta S_i = ((\Delta_{i1})^2 + (\Delta_{i2})^2)^{1/2}$	Δ_{ij} = Elastic displacement due to design seismic action computed as per code. Note: For unit or buildings with same elevation S_i will be reduce by factor 0.7.

Figure 8 shows the separation gap as per provisions given in different codes of similar height adjacent buildings with and without considering SSI. It found that in similar height structures, the minimum separation gap provided by IS

1893:2016 follows the Absolute sum method (ABS). The Indian code IS 1893:2002 reduces this distance by 50% for similar height buildings. The FEMA 356 and EN 1988-1:2004 both use the Square root sum of squares (SRSS) method, but EN 1988-1:2004 reduces the separation gap by 70% in similar height buildings. Table 5 shows the minimum separation distance (in mm) values for buildings with the same heights and without considering SSI. There is a nearly 50% increase in minimum separation distance values by considering SSI in both adjacent buildings for both separation gaps. The values suggested by the recent Indian code are 80-90% more than those obtained by FEMA 356 and EN 1998-1:2004 code. The gap distance presented by using the SRSS method was less but sufficient for the Bhuj earthquake. It found that considered separation gap, i.e., 0.12 m was insufficient to avoid pounding according to all considered codes except for EN 1998-1:2004 code without SSI case. But the assumed 0.36 m was safe according to FEMA 356 and EN 1998-1:2004 in both with and without SSI.

Table 5. Comparison of separation distance (mm) calculated using various codes for buildings of similar heights with and without SSI

	Gap	FEMA 356	IS 1893:2016	IS 1893:2002	EN 1998-1:2004
Without SSI	0.12	158.32	1119.50	559.75	110.82
	0.36	138.06	974.50	487.25	96.64
With SSI	0.12	323.12	2284.80	1142.4	226.18
	0.36	278.92	1962.00	981	195.24

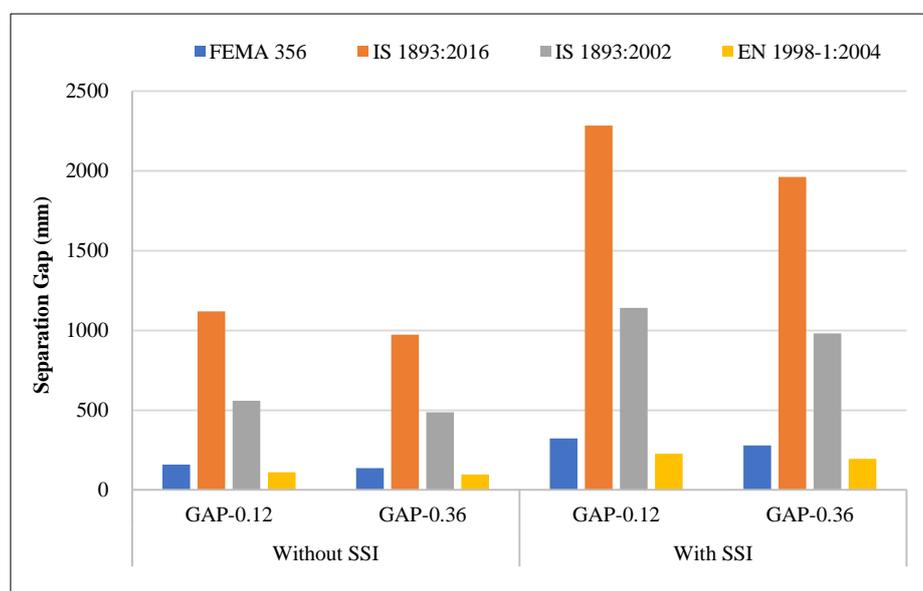


Figure 8. Comparison of separation distance (mm) calculated using various codes without SSI and SSI for buildings of the same height

Figure 9 shows the separation gap as per provisions given in different codes in the varying height of adjacent buildings with and without considering SSI. All codes found that in varying height structures, both 0.12 and 0.36 m gaps were unsafe. There is a nearly 70-75% increase in minimum separation distance values by considering SSI in adjacent buildings of different heights. Table 6 shows the values of minimum separation distance (in mm) for buildings with different heights with and without considering SSI.

Table 6. Comparison of separation distance (mm) calculated using various codes for buildings of different heights with and without SSI

	Gap	FEMA 356	IS 1893:2016	IS 1893:2002	EN 1998-1:2004
Without SSI	0.12	153.79	949	949	153.78
	0.36	125.66	765	765	125.66
With SSI	0.12	580.14	4001.45	4001.45	580.13
	0.36	514.23	3545	3545	514.22

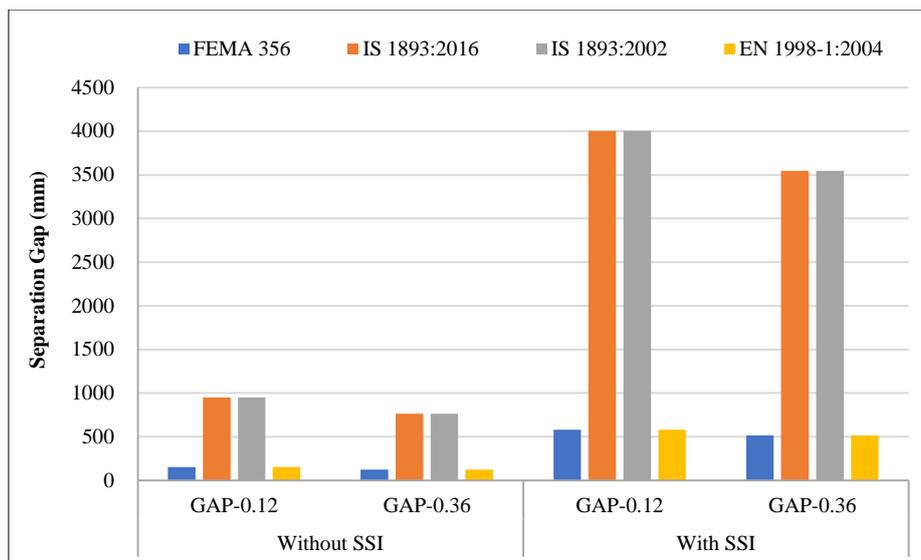


Figure 9. Comparison of separation distance (mm) calculated using various codes without SSI and SSI for buildings of different heights

3.3. Time Period

The time period is an integral property of the structure. It is the time required by the structure to complete the cycle of oscillation. Figure 10 shows the time period in various modes for a separation gap of 0.12 m and 0.36 m in similar height adjacent buildings with and without considering SSI. It is found that in the same-height structures, the time period increases as the gap increases. Similarly, when the effect of SSI is considered, the time period is greater than it would be without SSI. Thus, with time period, the ductility demand of the structure increases for structures with SSI. Similar results were found during a study conducted on G+10 buildings in different seismic zones of India. The time period increased considering the SSI effect [27]. For example, there was a 15–25% increase in time period when the SSI effect was considered. It is essential to include the effect of SSI in the structure as it affects the time period of the structure. The structures with SSI in this model are more ductile than the fixed-base models. Table 7 shows the values of time period (in a sec) for buildings of the same heights without considering SSI. Figure 11 shows the time period in different modes for a separation gap of 0.12 m and 0.36 m in other height adjacent buildings with and without considering SSI. A similar trend was observed in the case of buildings of different heights. Table 8 shows the values of time period (in a sec) for buildings of dissimilar heights with and without considering SSI.

Table 7. Variation of time period (sec) in different modes for buildings of similar heights with and without SSI

Mode	Time Period (sec)			
	Gap 0.12 (m)		Gap 0.36 (m)	
	Without SSI	With SSI	Without SSI	With SSI
1	2.69	3.26	2.85	3.41
2	2.66	3.26	2.84	3.41
3	2.65	3.24	2.72	3.28
4	2.29	3.24	2.71	3.27
5	2.29	2.78	2.42	2.92

Table 8. Values of time period (sec) for buildings with different heights with and without considering SSI

Mode	Time Period (sec)			
	Gap 0.12 (m)		Gap 0.36 (m)	
	Without SSI	With SSI	Without SSI	With SSI
1	2.71	3.25	2.71	3.20
2	2.69	3.25	2.71	3.21
3	2.32	2.78	2.32	2.82
4	1.40	1.90	1.40	1.92
5	1.40	1.90	1.40	1.92

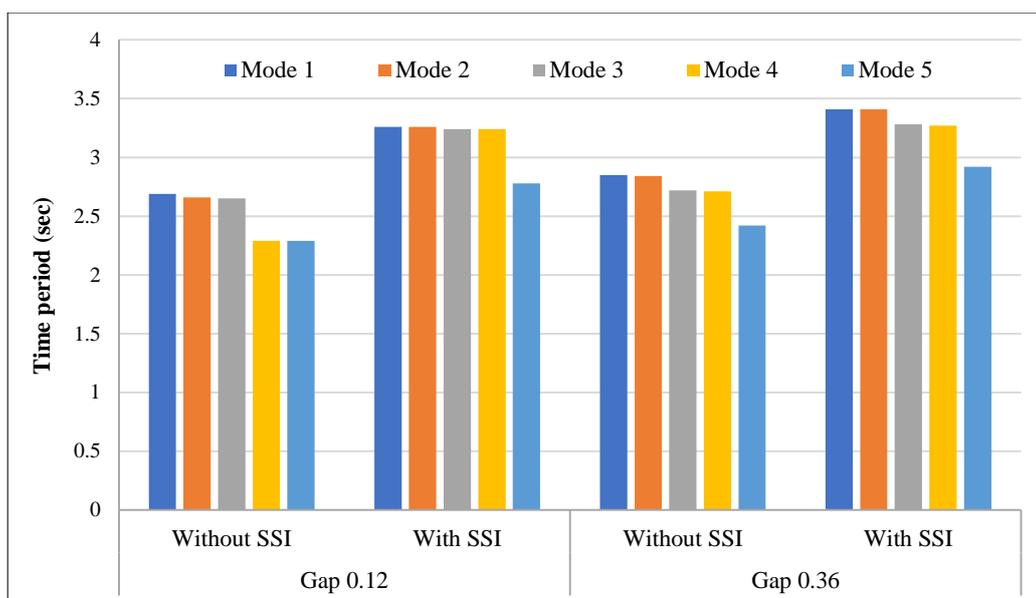


Figure 10. Variation of time period (sec) in different modes for buildings of similar heights with and without SSI

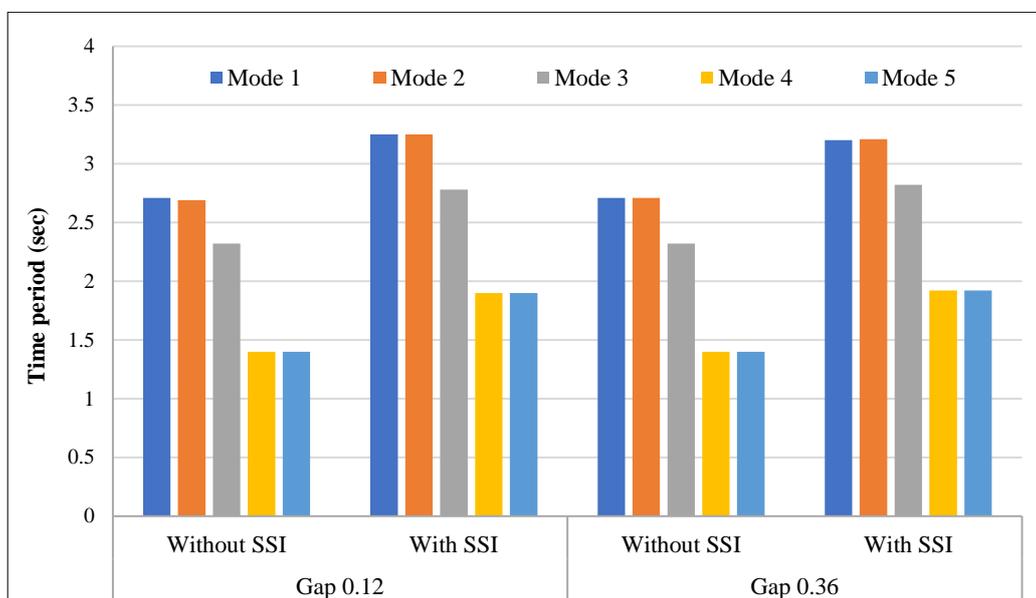


Figure 11. Variation of time period (sec) in different modes for buildings of different heights with and without SSI

4. Conclusions

Considering the SSI effect, the study was conducted to verify the separation distance estimated as per the latest Indian Standard IS 1893 (Part 1):2016. Eight models of adjacent RC frames have been analyzed for different gap distances. Also, the variation in the estimation of gap distance is compared using four different standards. In addition, the effects of lateral displacement and time period on the structure considering SSI are also compared. The results of this study are as follows:

- When the effect of SSI was considered, the maximum lateral displacement values differed significantly, around 90-95%.
- Lateral displacement is reduced when the gap distance is increased from 0.12 to 0.36 m between the structures.
- Indian Standard IS 1893 (Part 1): 2016 overestimates values obtained for separation distance by 80-90% more than those obtained by FEMA 356 and EN 1998-1:2004.
- The minimum separation distance increases by 50% considering SSI in both adjacent buildings for both separation gaps for similar-height buildings, and it increases to 70–75% for different-height buildings.
- The gap distance should be calculated using the SRSS method rather than the ABS method, but it is still sufficient for the Bhuj earthquake.

- The considered separation gap, i.e., 0.12 m, is insufficient to avoid pounding as per all considered codes except for the EN 1998-1:2004 code without SSI case. A separation gap of 0.36 m is safe according to FEMA 356 and EN 1998-1:2004 with and without SSI.
- The SSI effect increases the time period of structures by 15–25%. In addition, the gap between the adjacent structures increases the time period and ductility demand of structures.

From this study, it is clear that in the case of buildings with layered soils, the effect of SSI must be considered in the design of the structures to ensure their safety. For closely spaced structures in seismic regions, at least the minimum gap distance adopted by FEMA 356 and EN 1988-1:2004 should be considered to avoid destruction during earthquakes due to pounding. The study's future scope will include the use of base isolators or other dampers, as well as the effect of SSI. Also, experimental and physical modelling can be done on the same study to validate the results of numerical modelling. A formula for the separation gap can be evaluated to avoid the pounding for different seismic inputs and different soil types. Most of the formulae to evaluate separation gaps by different codes overestimate or underestimate separation gaps and depend only on the height of the structure.

5. Declarations

5.1. Author Contributions

G.A., A.M., R.S., R.D. and G.D. contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the first author. The data are not publicly available because it is original site data available from geotechnical consultant for proposed construction of new departmental buildings of Shri Guru Gobind Singhji Institute of Engineering and Technology, Nanded.

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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