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# Damage-based Seismic Planar Pounding Analysis of Adjacent Symmetric Buildings Considering Inelastic Structure-Soil-Structure Interaction

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## Abstract

In cities and urban areas, building structures located at close proximities inevitably interact under dynamic loading by direct pounding and indirectly through the underlying soil. Majority of the previous adjacent buildings pounding studies that have taken the Structure-Soil-Structure Interaction (SSSI) problem into account have used simple lumped mass-spring-dashpot models under plane-strain conditions. In this research, the problem of SSSI-included pounding problem of two adjacent symmetric in plan buildings resting on a soft soil profile excited by uniaxial earthquake loadings is investigated. To this end, a series of SSSI models considering one-directional nonlinear impact elements between adjacent co-planar stories and using a method for direct FE modeling of 3D inelastic underlying soil volume have been developed to accurately study the problem. An advanced inelastic structural behavior parameter, the seismic damage index, has been considered in this study as the key nonlinear structural response of adjacent buildings. Based on the results of SSSI and fixed-base cases analyses presented herein, two main problems are investigated, namely, the minimum building separation distance for pounding prevention and seismic pounding effects on structural damage in adjacent buildings. The final results show that at least three times the IBC 2009 minimum distance for building separation recommended value is required as a clear distance for adjacent symmetric buildings to prevent the occurrence of seismic pounding. At the IBC recommended distance, adjacent buildings experienced severe seismic pounding and therefore significant variations in storey shear forces and damage indices.

*Keywords:* Seismic planar pounding, storey damage index, storey shear force, adjacent symmetric buildings, structure-soil-structure interaction, IBC 2009 minimum distance for building separation provision.

## 1. Introduction

An increasing human population and the existence of a limited available habitable urban space has resulted in densely located buildings in most busy places. The concentration of tall buildings and skyscrapers in metropolises located in high seismic activity regions has made the occurrence of a special seismic phenomenon possible, i.e. the seismic pounding of adjacent structures. In the 1964 Alaskan earthquake, the 14-storey Westward Anchorage hotel building was damaged because of pounding to a shorter 6-storey adjacent building. Despite a 10 centimeter gap, the impact was strong enough to displace the steel-girder roof of the shorter building [1]. In the 1985 Mexico City and 1989 Loma Prieta earthquakes, a large share of seismic damage was also due to pounding. Pounding between adjacent structures has been generally modeled using a special spring-damper contact element, or the gap element, applying the principles of impact between rigid bodies and making use of a restitution factor [2]. An examination of the pounding of single-degree-of-freedom (SDF) systems showed that the response was not overly sensitive to the restitution coefficient [2]. Also, the intensity of impact was larger for adjacent systems with different heights. The risk of seismic pounding for buildings in Taipei was studied using contact spring elements [3]. The study showed that in 30% of the cases (708 cases out of a total of 2,359), the gap between buildings was not sufficient to prevent pounding. They predicted that in the case of a strong earthquake, 17% of studied buildings (403 cases) would be damaged, out of which 46 cases would collapse and 76 cases would be heavily damaged. Liolios [4] studied the problem of one-sided impact for adjacent buildings including friction. A numerical procedure based on an incremental

1  
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3 51 problem formulation was utilized and a discretization in space and time was performed.  
4 52 Favvata et al. [5] investigated the storey-level impact between adjacent multi-storey buildings  
5 53 concentrating on the behavior of exterior steel beam-column connections. It was shown that,  
6 54 in certain cases, the localized nonlinear behavior of such connections could be beneficial for  
7 55 the associated columns by reducing their pounding damage. The pounding of base isolated  
8 56 structures was studied using a nonlinear Hertz element for modeling an inelastic impact [6].  
9 57 The observation was that even for the base isolated buildings, pounding results in increased  
10 58 floor accelerations and displacements and activation of higher modes. Similar research was  
11 59 carried out on other base isolated structures focusing on the acceleration response of floors  
12 60 [7]. The seismic behavior of pounding buildings was investigated using lumped parameter  
13 61 gap elements [8,9]. In another work, it was reported that the period ratio of two adjacent  
14 62 structures determines the probability of occurrence of pounding [10]. For increasing period  
15 63 ratios, the risk of pounding was shown to be higher. Seismic pounding has been also  
16 64 extensively observed in bridges. In earthquakes such as San Fernando (1971), Loma Prieta  
17 65 (1989), Northridge (1994) and Kobe (1995), severe damage occurred due to pounding [11,  
18 66 12]. However, in comparison to buildings, the problem of pounding for bridges has evidenced  
19 67 less consideration. The inclusion of a sufficient gap and the enlargement of expansion joints  
20 68 in bridges are expensive and usually impractical due to current traffic usage [12]. Pounding  
21 69 between adjacent structures having different structural properties during earthquakes has been  
22 70 the subject of other various research work [13-21], in which either the base has been taken to  
23 71 be rigid or through-the-soil interaction has been ignored. From these studies, some new  
24 72 findings have been obtained. For example, similarity in the frequencies of adjacent structures  
25 73 reduces the probability of pounding. Also, in order to avoid the incidence of pounding  
26 74 between adjacent buildings in base isolation cases, a greater distance is needed than that  
27 75 usually set out in non-isolated cases. In addition, it has been seen that column-to-floor  
28 76 pounding is more critical than floor-to-floor cases, and the pounding phenomenon is  
29 77 detrimental rather than beneficial and this is more intense for the taller adjacent building.  
30 78 Structure-soil-structure interaction (SSSI) is another important seismic phenomenon  
31 79 occurring in closely spaced buildings [22]. According to early findings, SSSI increases the  
32 80 vibration period, and damping and lateral displacement results in a rocking motion in  
33 81 adjacent buildings [23]. When damping does not increase to the extent that it alleviates the  
34 82 effects of the increased period and the induced rocking motion, this combinatory  
35 83 phenomenon can result in an increased displacement response and a higher possibility for  
36 84 pounding even if the code prescribed distance is observed between buildings. Considering  
37 85 pounding and cross interaction concurrently is not usual in seismic analysis because high-  
38 86 accurate modeling of SSSI problems is particularly complicated. In recent works, researchers  
39 87 have tried to simplify the modeling of SSSI problems whilst preserving a sufficient level of  
40 88 accuracy, such as simple discrete models for the interaction of adjacent buildings [24-27] or  
41 89 the near-field method for the inelastic modeling of SSSI problems [28]. The interested reader  
42 90 may refer to the reference [29] where a comprehensive list of SSSI included studies could be  
43 91 found.  
44 92 As discussed above, the complexity of simultaneously studying the seismic pounding of  
45 93 adjacent buildings and SSSI problems has resulted in a limited number of relevant research.  
46 94 The pounding of two adjacent structures on flexible foundations during the Montenegro  
47 95 earthquake was studied in [30]. It was shown that the foundation flexibility effects on  
48 96 pounding could not be ignored. Chouw [31] analyzed two adjacent buildings linked by a  
49 97 pedestrian bridge taking into account soil flexibility by employing the boundary element  
50 98 method. The majority studies on pounding-included structural adjacency cases has been  
51 99 carried out on bridge structures. For example, in a study on a bridge on soft soil with soil-  
52 100 structure interaction (SSI), it was concluded that the minimum distance at the expansion joint

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2  
3 101 was a function of the shear wave velocity in soil [32]. In another work [33], it was observed  
4 102 that SSI can considerably increase the number of impacts between bridge girders under the  
5 103 effect of non-uniform ground motions. In two concurrent experimental works, SSSI effects  
6 104 on pounding were studied considering small scale bridge models resting on stiff, medium and  
7 105 soft soils using shake table tests [34, 35]. It was shown that pounding was more probable  
8 106 when the soil was softer and the two structures were more different in terms of fundamental  
9 107 period. The nonlinear behavior of the soil was observed to have an essential effect on  
10 108 pounding in bridges [36]. On such soils, the lateral displacements of adjacent decks were  
11 109 amplified and resulted in a larger impact. In another study [37], it was shown that the code-  
12 110 prescribed width of the separation joint is not sufficient on soft soils especially when the  
13 111 fundamental periods of the soil and structure were close to each other and also to the  
14 112 excitation frequency due to resonance phenomenon. Naserkhaki et al. [38] developed a model  
15 113 consisting of adjacent shear buildings responding in elastic range resting on equivalent  
16 114 springs and dampers. They observed that pounding and SSSI together resulted in a more  
17 115 severe response in terms of maximum shear and displacements of top floor.

18 116 The evident importance of cross-interaction between adjacent structures effects on pounding  
19 117 in addition to the scarcity of relevant literature on the subject constitute the main motivation  
20 118 behind the current research. The main importance of the current work stems from the  
21 119 emphasis on two major topics: (1) more accurate modeling of the problem geometrically as  
22 120 well as in terms of material nonlinearity; and (2) more reliable and quantitative investigation  
23 121 of the problem which would lead to more practical results. A series of numerical analyses on  
24 122 the SSSI-included seismic pounding of adjacent building structures has been carried out. The  
25 123 analysis is conducted on two symmetric building structures having various heights and  
26 124 considering the inelasticity of underlying soft soil profile and the nonlinearity in impact  
27 125 elements. To prevent the plane-strain assumption of the complicated SSSI study, 3D  
28 126 geometrical models have been developed in this study including underlying soil volume and  
29 127 two adjacent buildings subjected to uniaxial earthquake excitations.

30 128 Based on the aforementioned limitations (i.e. planar pounding between symmetric adjacent  
31 129 buildings), the torsional effects triggered by the pounding have not been taken into account.  
32 130 Therefore, the main goals of this research are: (i) Study the minimum distance for building  
33 131 separation recommended by the International Building Code (IBC) [39]; and (ii) Investigate  
34 132 the seismic pounding effects on damage distribution along the height of adjacent buildings, in  
35 133 both of SSI and fixed base (FB) conditions.

36 134

## 37 135 **2. Design of structural systems**

38 136 Four 3-dimensional (3D) buildings are considered here for developing various adjacency  
39 137 cases, two short (5 and 10 stories) and two tall (15 and 20 stories) buildings. The inter-storey  
40 138 height is equally 3 meters ( $m$ ) which results in total heights of the buildings of 15, 30, 45 and  
41 139 60  $m$ , respectively. For each building, four bays (with length equal to 5  $m$ ) have been  
42 140 assumed in each direction in the stories and therefore the plan dimensions in all buildings are  
43 141 considered to be  $20 \times 20$   $m$ . The structures are located in a very high seismicity area.  
44 142 According to the ASCE7-2010 standard [40], the gravitational loads are  $DL = 7.60$   $\text{kN/m}^2$   
45 143 and  $LL = 2.00$   $\text{kN/m}^2$ , where  $DL$  denotes dead load and  $LL$  denotes live load. The load  
46 144 bearing system is a special steel moment frame designed based on AISC360-10 [41]. The  
47 145 diaphragms are RC rigid in plane slabs with a thickness of 0.15 to 0.20  $m$ , with thicker slabs  
48 146 for the taller buildings. The structural sections used for the buildings are summarized in Table  
49 147 1. Strip and mat foundations are used for the 5 and 10-storey buildings, respectively;  
50 148 however, for the tall 15 to 20-storey buildings pile group foundations are selected. The above  
51 149 foundation systems are all assumed to have a boundary area of  $21 \times 21$   $m$ . The length of each  
52 150 pile is 20  $m$ . Table 2 shows the characteristics of the pile groups designed for each building



151 and soil type D. Additionally, values of the first four natural vibration modes periods of each  
152 designed building in fixed base condition are presented in the Table 3.

153  
154 Table 1. The typical sections of 5 to 20-storey buildings (units in mm, IPE $a$  is an I section,  $a$  mm  
155 deep).

<i>No. of Stories</i>	<i>Beam Sections</i>	<i>Column Sections</i>
5	IPE300 and 330	Box240x12.5, 260x12.5 and 280x12.5
10	IPE300, 330 and 360	Box260x20, 280x20 and 300x20
15	IPE300, 300O, 330, 330O, 360 and 360O	Box180x20, 240x20, 300x20 and 340x20
20	IPE300, 300O, 330, 330O, 360, 360O, 2IPE300 and 2IPE330	Box200x20, 240x20, 260x20, 320x20 and 340x20

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Table 2. Characteristics of the pile groups designed.

<i>No. of Piles for Each Building</i>		<i>Pile Diameter for Each Building (m)</i>		<i>Pile Cap Thickness (m)</i>
<i>15S</i>	<i>20S</i>	<i>15S</i>	<i>20S</i>	
16	16	0.5	0.6	1.0

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Table 3. In-plane natural periods of the designed buildings (fixed base conditions).

<i>No. of Stories</i>	<i>T (sec)</i>			
	<i>Mode 1</i>	<i>Mode 2</i>	<i>Mode 3</i>	<i>Mode 4</i>
5	0.98	0.33	0.20	0.14
10	2.01	0.64	0.41	0.29
15	2.92	1.11	0.60	0.42
20	3.48	1.31	0.71	0.50

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### 3. Site profiles considerations

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A common site of soft soil is considered for the dynamic analysis. This soil profile consists of three clay layers with a total depth of 45 m on a bedrock [23, 28]. The properties of the soil profile are presented in Table 4. The effective values of the shear modulus  $G$  and the damping ratio  $\zeta$  are taken into account for each soil layer.

Table 4. Properties of the soil layers ( $Z$ =depth,  $E$ =modulus of elasticity,  $G_{max}$ = static shear modulus,  $V_s$ = shear wave velocity,  $T_s$ = fundamental period,  $C_u$ = undrained cohesion) [23, 28].

<i>Z (m)</i>	<i><math>C_u</math> (kPa)</i>	<i><math>E</math> (kPa)</i>	<i><math>G_{max}</math> (kPa)</i>	<i><math>V_s</math> (m/s)</i>	<i><math>T_s</math> (s)</i>
0 - 10	148	166,334	61,605	185	
10 -25	206	204,242	75,645	205	0.84
25 - 45	365	333,578	123,548	255	

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Figure 1 shows the amplification curves of the above site obtained from ground-level earthquake records deconvolution procedures using the SHAKE2000 program [42]. As can be observed, the selected site will amplify the bedrock motions for the common frequency range of earthquakes at bedrock of 0.1-1 Hz. The dynamic characteristics of the sites presented in Table 4 and Figure 1 show that the selected soil profiles are general enough within the soil type D as per ASCE7 site classification provisions [40].

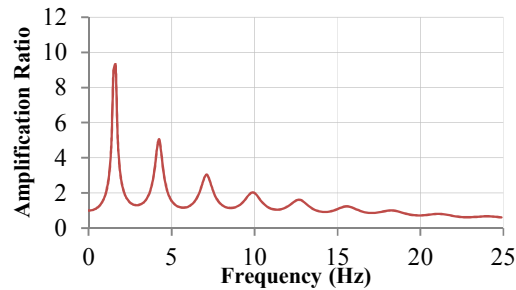


Figure 1. Amplification curves of the site.

#### 4. Seismic records

A set of at least seven pairs of consistent earthquake records are necessary for dynamic analysis [40], if the average response is to be used. For consistency, the following conditions were taken into account in the selection of ground motions: site classification D, magnitude 6-7, source distance 20-50 kilometers (km) and strong motion duration  $\geq 12$  sec. The database of PEER NGA [43] was explored with the above constraints, and earthquakes cited in Table 5 were selected.

Table 5. Characteristics of the earthquake records selected [43].

Event	Year	Station	PGA (g)	Scale Factor			
				5 Storey	10 Storey	15 Storey	20 Storey
Imperial Valley-06	1979	El Centro Differential Array	0.431	1.36	1.44	1.51	1.58
Loma Prieta	1989	Hollister Diff. Array	0.264	1.80	1.89	1.99	2.08
Kocaeli, Turkey	1999	Duzce	0.326	1.35	1.42	1.49	1.57
Duzce, Turkey	1999	Duzce	0.427	0.97	1.02	1.07	1.12
Chi-Chi, Taiwan	1999	CHY036	0.260	1.60	1.69	1.77	1.86
Erzican, Turkey	1939	Erzincan	0.489	1.20	1.26	1.33	1.39
Imperial Valley-06	1979	El Centro Array #7	0.463	1.22	1.28	1.34	1.41
Loma Prieta	1989	Foster City - APEEL 1	0.291	1.76	1.85	1.95	2.04
Northridge-1	1994	Northridge -17645 Saticoy St.	0.411	1.33	1.40	1.47	1.54
Northridge-1	1994	Rinaldi Receiving St.	0.634	0.89	0.94	0.98	1.03

The scaling of the ground motions has been done based on the ASCE7-10 code design spectrum. The code recommends that the scaled mean acceleration response spectrum (at 5% damping) should not be less than the design spectrum over the periods ranging from  $0.2T$  to  $1.5T$ , where  $T$  is the fundamental period (fixed base) of each building. Figure 2 shows the spectral accelerations of soil type D records after scaling for the 10-storey building ( $T=2.03$  seconds). Moreover, a comparison with Figure 1 reveals that the selected earthquakes are powerful enough within the governing frequency range of the sites.

In this SSSI-included study, the earthquake records are input at the bedrock to the structure-soil-structure system. Therefore, in order to compute the ground motion at the bedrock, a free-field response analysis using SHAKE2000 program has been conducted beforehand where the above ground surface motions are input at the top of a 1-D free-field soil column. The considered column consists of the whole vertical profile of soil.



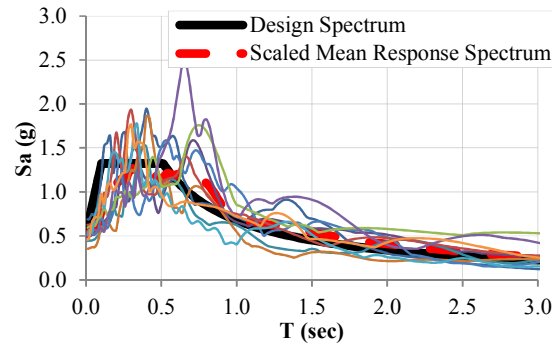


Figure 2. Design and scaled response acceleration spectra (5% damping) for the 10-storey building on soil type D.

## 5. Modeling considerations

The SSSI system is modeled in SAP2000 [44] for dynamic analysis. In the following subsections, the modeling considerations of the structure and the soil are presented.

### 5.1. Structural considerations

To comply with real behavior under large earthquake loading, the structures designed in Section. 2 are modeled nonlinearly for dynamic analysis of the SSSI. The nonlinearity is introduced in the structural members by placing elasto-plastic zero length hinge elements at the ends of the frame elements. These hinges are rigid before yielding and their moment-rotation behavior is schematically shown in Figure 3. This is a generic figure in which the quantities on the vertical and horizontal axes are normalized using appropriate scale factors (SFs). These scale factors are yield rotations of plastic hinges according to equation 5-2 in FEMA 356 [45] for steel structural members automatically defined in the SAP2000 program. The diaphragms and the pile caps are modeled by linear shell elements. The diaphragms are assumed to be rigid in plane.

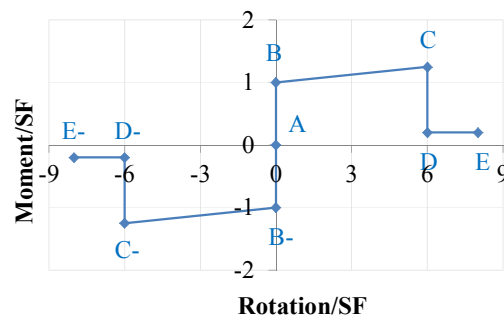


Figure 3. Schematic of the moment-rotation diagram of elasto-plastic frame hinges.

In Figure 3, B is the yield point and C is the capacity point after which the moment capacity drops sharply due to local failures (rupture or buckling). The length of line B-C is proportional to the rotation ductility of the hinge. The ordinates of the anchor points on the moment-rotation diagram in Figure 3 are extracted from ASCE41 [46]. The damping value of each structure is assumed to be of Rayleigh type with 5% material damping. For the soil media, the damping is considered using Near-Field Method presented in section 5.2. According to this method, the effective properties (effective damping and shear modulus) of soil are used in the far-field zone. In the near-field zones, modified values of the effective properties are used.

233 The damage index ( $DI$ ) is the key parameter for the quantitative investigation of seismic  
 234 pounding effects of nonlinear structural response. For an assessment of this parameter, a  
 235 simple deformation-based non-cumulative equation (Equation 1) is presented as follows [47]:

$$DI = \frac{\Delta_t - \Delta_y}{\Delta_u - \Delta_y} = \frac{\frac{\Delta_t}{\Delta_y} - 1}{\frac{\Delta_u}{\Delta_y} - 1} = \frac{\mu_t - 1}{\mu_u - 1} \quad (1)$$

236 Where  $\mu_t = \Delta_t / \Delta_y$  and  $\mu_u = \Delta_u / \Delta_y$  are ductility demand (target displacement  $\Delta_t$  to yield  
 237 displacement  $\Delta_y$ ) and ultimate ductility (ultimate displacement  $\Delta_u$  to yield displacement  $\Delta_y$ ),  
 238 respectively. The values of  $\Delta_y$  and  $\Delta_u$  can be determined from pushover analysis separately  
 239 for each storey. In this study, the pushover analyses have been carried out with the  
 240 parameters defined according to FEMA 440 displacement modification [44] in SAP2000  
 241 software. The target displacements of the stories of each adjacent building ( $\Delta_t$ ) can be  
 242 calculated from direct integration time history inelastic analyses using the scaled earthquake  
 243 records presented in Table 5. In order to account for probable underlying soil effects, these  
 244 pushover and dynamic analyses have been carried out on SSSI models including impact  
 245 elements. From these defined parameters the value of  $DI$  for each storey can be determined  
 246 according to Equation 1. The soil modeling considerations in the SSSI models are reviewed  
 247 in the next sub-section.

## 5.2. Geotechnical considerations

250 The direct method of analysis of a system consisting of soil and structures is adopted in  
 251 analyses of this study. In such analyses, the suitable plan dimensions of a certain volume of  
 252 soil under structures limited to the bedrock must be selected. The plan dimensions of the soil  
 253 ( $L$  and  $B$  in Figure 4) were determined by trial and error, as presented in reference [28].  
 254 Adequate values for these dimensions have been obtained to be as:  $L = (100 m + d)$ , where  $d$  is  
 255 the clear separation distance, and  $B = 40 m$ . In fact, it has been observed that for at least  
 256  $D_x = 2.5a$  in  $x$ -direction and  $D_y = 0.5a$  in  $y$ -direction, the structural responses are numerically  
 257 stable and independent of soil medium dimensions. Figure 5 shows a sample convergency  
 258 analysis result.

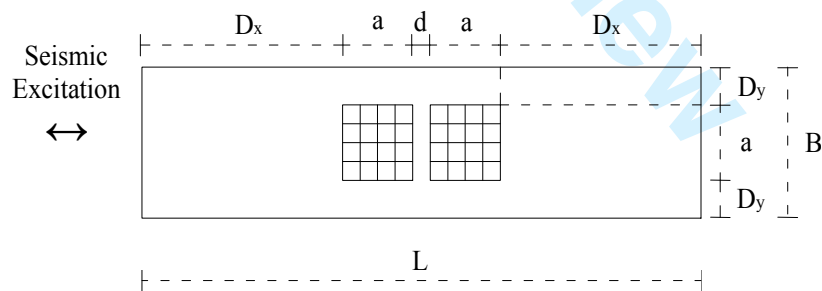


Figure 4. The geometrical dimensions in the site plan of adjacency model.

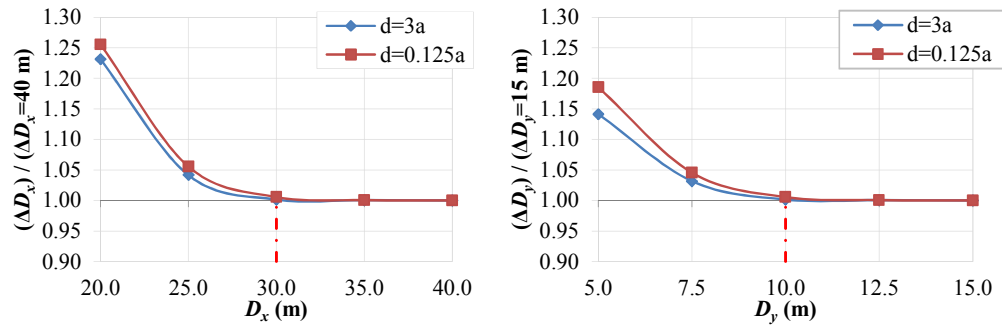


Figure 5. The lateral roof displacement for the case of the 30-storey adjacent buildings versus the dimensions introduced in Figure 4 (responses are normalized to the ones at the dimensions shown as indices) [28].

An extended equivalent linear method has been used for the modeling of nonlinearity and inelasticity soil material in site volumes called the Near-Field Method (NFM) [28]. The fundamental basis of NFM is presented in Figure 6. This figure presents an SSSI system containing two 15-storey adjacent buildings with a clear distance of 10 m resting on a soil medium. According to the NFM, this medium is divided into two separate soil zones called “Near-field” and “Far-field” that are in the vicinity of and far from the superstructure, respectively. In modeling the Far-field zone, the effective (initially reduced) soil properties determined in a free-field dynamic response analysis are used. For the Near-field zone, a secondary reduction is required to be applied on soil shear modulus, due to structural vibrations and inelastic soil-foundation interaction under earthquake excitation, which increase the cyclic soil shear strain values in the Near-field zone. A rigorous numerical model has been presented in reference [28] to determine the near-field dimensions and also the effective properties of the soil medium.

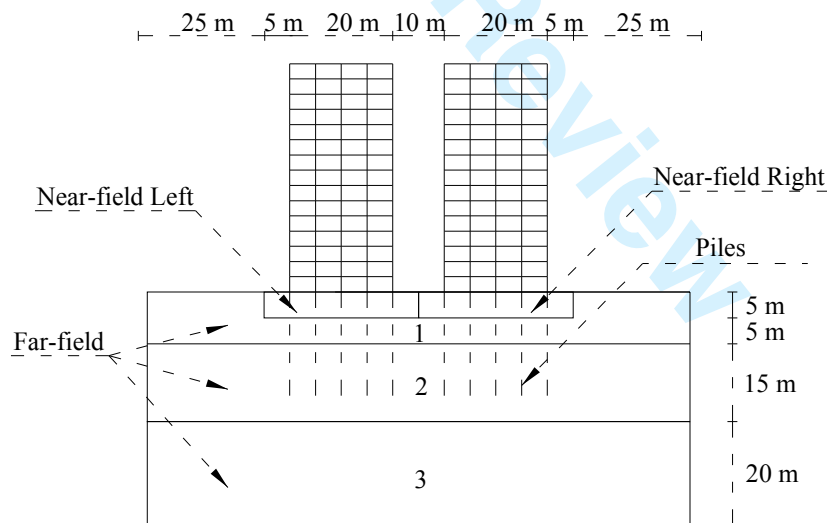


Figure 6. The near-field soil zone for two adjacent 15-storey buildings on the underlying soil medium.

### 5.3. Adjacency distance considerations

In the study of seismic pounding between two adjacent buildings that simultaneously including SSSI effects, it is required that the structures are close enough to each other to increase the seismic pounding occurrence probability. On the other hand, two adjacent buildings should not be so far away from each other that the SSSI effects are eliminated. An adequate clear distance between two adjacent buildings ( $d$ ) must be limited to a minimum

value equal to the minimum distance for building separation ( $\delta_{MT}$  according to IBC 2009 standard) and also a maximum value equal to half of the greater adjacent building width in plan ( $a/2$  where  $a$  is the greater adjacent building width [28]), which can be expressed as in Equation 2 below:

$$\delta_{MT} \leq d \leq \frac{a}{2} \quad (2)$$

According to IBC 2009 standard,  $\delta_M$  shall be determined at critical locations using Equation 3 [39]:

$$\delta_{MT} = \sqrt{(\delta_{M1})^2 + (\delta_{M2})^2} \quad (3)$$

$$\delta_{M_i} = \frac{C_d \delta_{max}}{I} \quad (i = [1,2] \text{ is the number of each adjacent building})$$

in which  $C_d$ ,  $\delta_{max}$  and  $I$  are deflection amplification factor (as in Table 12.2-1 of ASCE7), maximum displacement (section 12.8.4.3 of ASCE7) and importance factor (section 11.5.1 of ASCE7) respectively for each building. In this study,  $\delta_{M1}$  and  $\delta_{M2}$  are taken as the linear lateral displacements of adjacent buildings at the probable collision storey level. These values can be determined from linear time history analyses of the considered buildings in two SSI (according to chapter 19 provisions of ASCE7 standard [40]) and fixed base conditions. For comparison,  $\delta_{M1}$  and  $\delta_{M2}$  calculated in both of SSI and FB cases, are presented in Table 6. The labels of 5S, 10S, 15S and 20S denote the 5, 10, 15 and 20-storey buildings, respectively. The collision storey is taken as the location of the first probable collision between adjacent buildings; usually this is the top floor of the shorter building (as a result of this study can be seen in Sec. 6).

Table 6. Minimum distances for separation of considered adjacent buildings according to IBC 2009 provision in FB and SSI base conditions.

Adjacency Case	Collision Storey No.	FB		SSI		Differences in % (SSI to FB)
		$\delta_{MT}$ (cm)	$\delta_{MT}/a$	$\delta_{MT}$ (cm)	$\delta_{MT}/a$	
5S with 10S	5	35.3	0.018	39.2	0.020	11
5S with 15S	5	31.2	0.016	34.6	0.017	11
5S with 20S	5	30.0	0.015	33.6	0.017	12
10S with 15S	10	56.6	0.028	65.1	0.033	15
10S with 20S	10	49.0	0.024	57.3	0.029	17
15S with 20S	15	79.8	0.040	96.6	0.048	21

As can be seen from Table 6, the variation of recommended minimum distances in SSI and FB conditions (SSI/FB %) is rather noticeable, especially as the adjacent buildings heights increase. However, for consistency and for the results to be comparable, the same separation distances have been used in both of FB and SSI conditions. As the SSI condition is the main case and the FB condition is the secondary (i.e. for comparison purposes) case, the SSI column values from Table 6 are selected to be used for all of the models developed in this study. Hence, the adjacency distance values are as follows:

$$\begin{aligned} 0.02a \leq d \leq 0.5a & \quad (\text{for all cases that include adjacency to the 5-storey building}) \\ 0.03a \leq d \leq 0.5a & \quad (\text{for "10S with 15S" and "10S with 20S" cases}) \\ 0.05a \leq d \leq 0.5a & \quad (\text{for "15S with 20S" case}) \end{aligned} \quad (4)$$

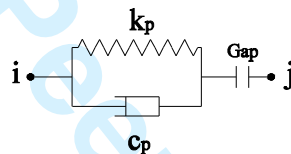
These distance ranges for various adjacency cases stated in Equation 4 have been discretized to a sufficient number of interval values (5 values) as shown in Table 7.

322 Table 7. Minimum distances for separation of considered adjacent buildings according to IBC 2009  
 323 provision.

Adjacency Type	Non-dimensional spacing intervals ( $d/a$ )
5S with 10S	[0.02, 0.04, 0.08, 0.25, 0.50]
5S with 15S	[0.02, 0.04, 0.08, 0.25, 0.50]
5S with 20S	[0.02, 0.04, 0.08, 0.25, 0.50]
10S with 15S	[0.03, 0.06, 0.09, 0.25, 0.50]
10S with 20S	[0.03, 0.06, 0.09, 0.25, 0.50]
15S with 20S	[0.05, 0.10, 0.15, 0.25, 0.50]

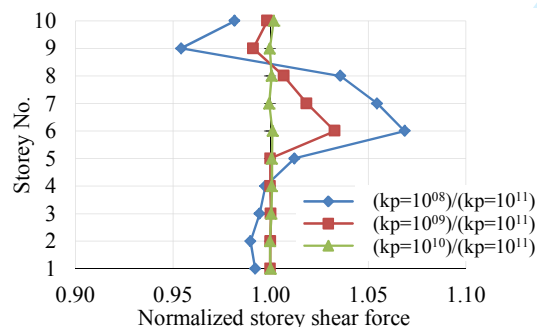
#### 5.4. Pounding considerations

324  
 325 The impact element model is shown in Figure 7 and consists of three sub-elements. In the  
 326 middle part, a linear spring  $k_p$ , and a dashpot  $c_p$  are present. On the right, there is a predefined  
 327 gap. The spring  $k_p$  is used for modeling elastic deformations at impact. The viscous damper  $c_p$   
 328 defines a linear source of energy dissipation (due to heat and sound) at impact. The element is  
 329 activated when the gap is closed. In Figure 7,  $i$  and  $j$  signify the two nodes of the element.  
 330 This element has an extension (contraction) degree of freedom at each node.  
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 Figure 7. The pounding (impact) element.

341 The value of  $k_p$  depends on the stiffness of colliding bodies. As the pounding considered here  
 342 is planar, adjacent rigid diaphragms of collision stories (having the same height) are assumed  
 343 as the adjacent impacting bodies. The collision can be assumed between two adjacent rigid  
 344 bodies and therefore  $k_p$  must be taken to be very large. The results of time history analysis  
 345 conducted were insensitive to values  $k_p \geq 10^{10}$  N/m, therefore  $k_p = 10^{10}$  N/m is assumed. Figure 8  
 346 shows the effect of  $k_p$  variation on storey shear force for the case of two 10 and 20-storey  
 347 adjacent buildings on soil with  $d=0.03a$ .



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 Figure 8. Storey shear force distribution in structural height in a 10-storey building adjacent to a 20-storey building with  $d=0.03a$  (i.e.  $d=1.0$  m) (the values in each case have been normalized to the case of  $k_p=10^{11}$  N/m).



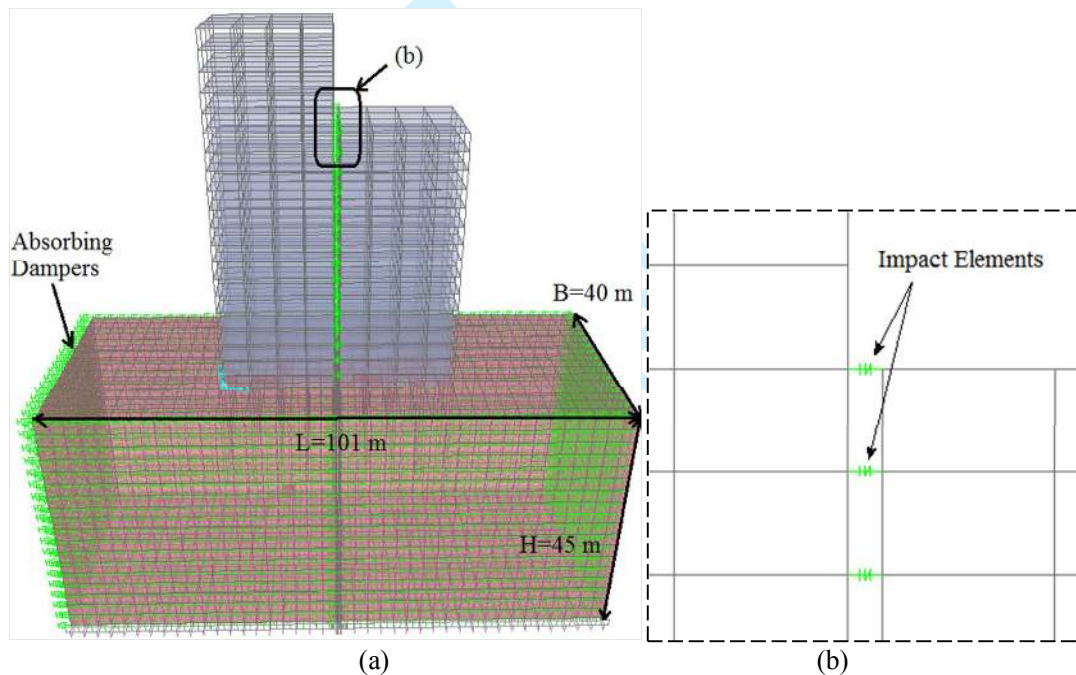
354 The value of damping coefficient  $c_p$  can be calculated from the literature (equation 5 in Ref.  
 355 [2]) according to the damping ratio ( $\zeta$ ). For the applications herein, a value of the damping ratio  
 356  $\zeta=0.14$  has been assumed [2]. Also, the gap values are determined from Table 7.

357

### 358 5.5. Numerical modelling

359 The numerical models for the study of seismic planar pounding effects considering SSSI  
 360 presented herein are 3D geometrical models developed with one-directional seismic pounding  
 361 and assembling the two adjacent symmetric buildings, soil medium and impact elements  
 362 between stories with the same heights subjected to uniaxial earthquake excitations. The  
 363 impact elements have been considered in all of the adjacent stories (from bottom to top along  
 364 the structural height of lower adjacent building). An example of the finite element (FE)  
 365 model of the pounding case including two 15 and 20-storey buildings on flexible base with  
 366  $d=0.05a$ , abbreviated as 15S-20S-SSSI-0.05a case, made in SAP2000 software is depicted in  
 367 Figure 9. The bottom of the model is rigidly fixed at the bedrock surface. The vertical side  
 368 boundaries are selected to be of the transmitting type, where use is made of absorbing viscous  
 369 dampers perpendicular to the boundary with damping factors  $\rho V_s A$  in which  $A$  is the area  
 370 shared by one damper,  $V_s$  is the shear wave velocity and  $\rho$  is mass density of soil [26, 48].  
 371 The earthquake records are only input at the bedrock to the structure-soil-structure system.

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375 Figure 9. 15S-20S-SSSI-0.05a case, (a) 3D FE model made using SAP2000 (Soil boundary elements  
 376 are energy absorbing dampers [26, 48]), (b) Cross section of impact elements between adjacent stories  
 377 (These elements are located between two buildings at all adjacent stories along the height of  
 378 buildings).

379

### 380 6. Results

381 As aforementioned, the current research aims to investigate two main issues considering  
 382 SSSI-included pounding namely:

- 383 1) Minimum distance of adjacent buildings for pounding prevention.
- 384 2) Pounding effect on structural seismic damage.

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3 385 In the following sections, the distribution of impact elements forces and the seismic response  
4 386 of adjacent buildings are presented. In this study, The dynamic analyses were conducted for  
5 387 10 earthquake excitations but only mean values of the results will be presented In this section.  
6 388

### 7 389 **6.1. Minimum distance of adjacent buildings for pounding prevention**

8 390 During an earthquake, it is possible that two adjacent buildings extremely approach each  
9 391 other without a significant impact. Therefore, the investigation of envelop values of seismic  
10 392 gap time history of impact elements cannot be an adequate indication for the occurrence of  
11 393 strong seismic pounding. The pounding phenomenon can be directly investigated according  
12 394 to envelop values of spring force time histories of impact elements. In order to study these  
13 395 forces, the best method is to investigate the storey shear force distribution along the height of  
14 396 one of the adjacent buildings (for example, the taller building) with and without the presence  
15 397 of impact elements (Figure 9) in various adjacency cases. The observation of considerable  
16 398 change in storey shear forces in the presence of impact elements in comparison to the case  
17 399 without these elements would mean a severe seismic pounding occurrence. In addition, an  
18 400 investigation of probable pounding effect on storey shear force is provided hereinafter.  
19 401 Figures 10-12 show results for all adjacency cases including SSSI effects and FB conditions.  
20 402 In these figures, the horizontal axes indicate normalized storey shear force in the presence of  
21 403 pounding elements ( $V$ ) to their values in the absence of these elements ( $V_0$ ) and the vertical  
22 404 axes indicate the number of stories. Reviewing these figures, some important observations  
23 405 can be made:  
24 406

25 407 1- As expected, the most critical adjacency distance is the minimum value recommended by  
26 408 the IBC 2009 standard (i.e. minimum value of  $d$  in Eq. 4) and leads to maximum variations in  
27 409 storey shear forces.

28 410 2- Due to pounding, the maximum variation in shear forces of the taller building is always  
29 411 observed in the inter-storey above the top-floor of the shorter adjacent building. This floor is  
30 412 always the location of the first probable collision between the two adjacent buildings and  
31 413 therefore (in this study) is considered as the *collision storey* (this has been previously  
32 414 presented in Table 6). The above inter-storey in taller buildings experiences the maximum  
33 415 variation in shear force during seismic pounding and can be considered as the *critical storey*.  
34 416 This outcome has been confirmed for shorter buildings through similar results including the  
35 417 distribution of storey shear forces in each adjacency case; however, for the sake of brevity  
36 418 their results are not presented in this paper.

37 419 3- If a significant pounding is quantitatively taken as the pounding with more than 10%  
38 420 variation in collision storey shear force, significant seismic pounding can be observed in all  
39 421 SSSI-included adjacency cases taking into account IBC 2009 recommended distance.  
40 422 Although soil-structure interaction has been taken into account as per ASCE7 in calculating  
41 423 the IBC 2009 recommended minimum distance for building separation, it is clear from the  
42 424 results presented herein that considerable pounding is easily possible during a strong  
43 425 earthquake for buildings on soft soils.

44 426 4- It seems that the “adjacency type” is an important issue in the study of seismic pounding  
45 427 effects on the response of adjacent buildings. For example, for each taller building as a target  
46 428 building, the critical effect of pounding with maximum variation in storey shear forces is  
47 429 observed in the case of adjacency with a shorter building having half the height of the target  
48 430 building (10S next to 20S and 5S next to 10S). For shorter adjacent buildings with heights  
49 431 less than this value, the seismic vibrations reduced considerably; consequently, the severity of  
50 432 the probable pounding is reduced (e.g. 5S or 10S next to 20S). For shorter adjacent buildings  
51 433 with heights more than this value, the pounding occurrence probability is significantly

reduced (e.g. 15S next to 20S and 10S next to 15S), possibly due to similarities in the vibration frequencies and mode shapes to the taller building.

Based on the observations above, a more reliable recommendation for minimum distance of adjacent buildings to prevent probable seismic poundings can be suggested. The recommended adjacency distance can be selected as a conservative value of a variation boundary in shear forces of the critical storey in SSSI-included cases, Figure 13. This value is called the “baseline variation” and is selected to be 2.5% and its boundary has been highlighted as a vertical black line in the figure. According to Figure 13, the separation distance ( $d_{min}$ ) must be selected in the range of  $0.06a$  to  $0.13a$ , depending on adjacency type. These distance values with IBC recommended minimum values are comparatively presented in Table 8. For each adjacency type, a minimum distance of more than 3 times the IBC/ASCE7 recommended value is required to prevent the seismic pounding of adjacent buildings resting on soft soils, Table 8. Also, it is necessary that the ASCE7-2010 chapter 19 soil-structure interaction provisions are considered when the IBC provision is used.

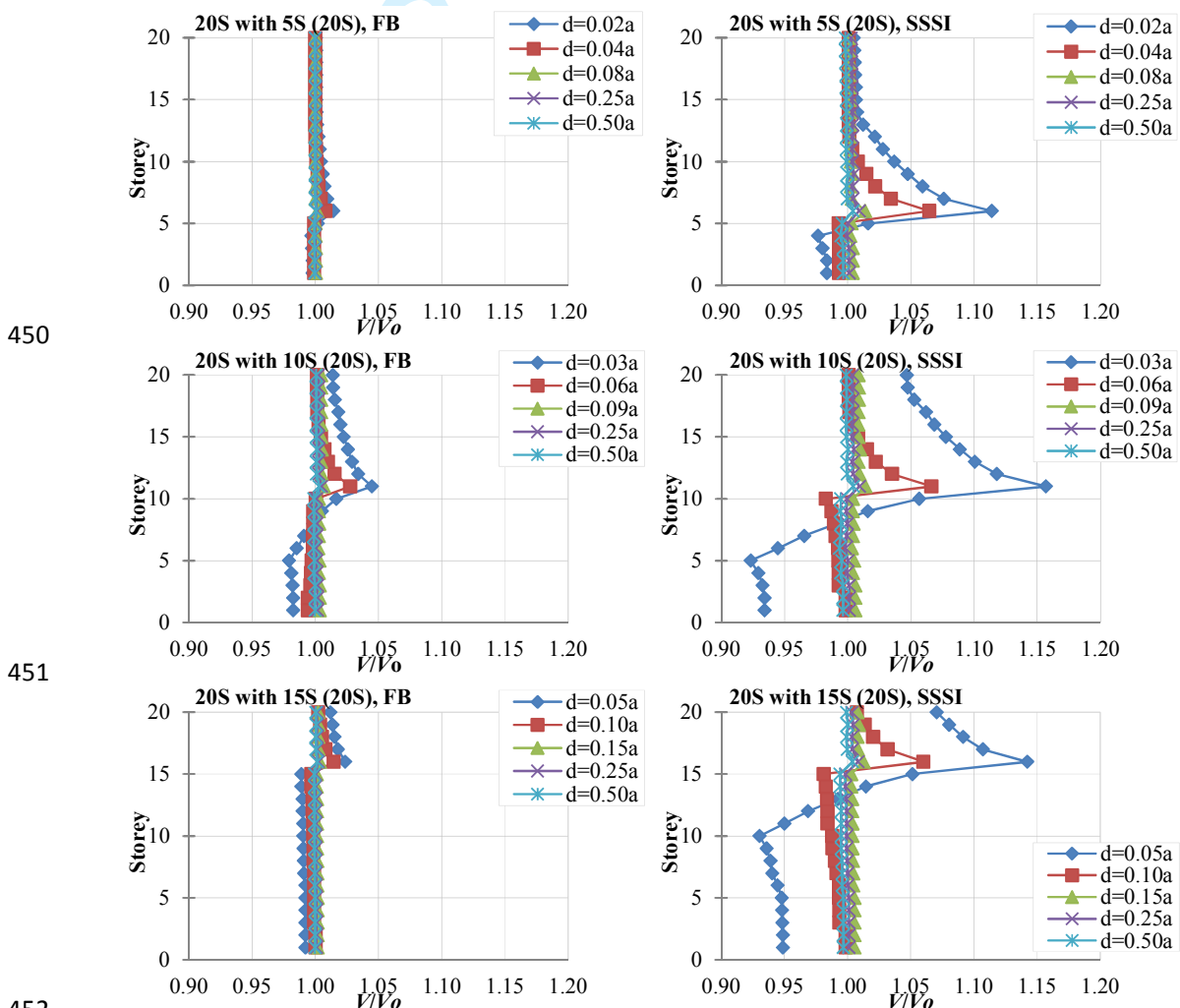


Figure 10. Normalized storey shear force in presence of pounding elements ( $V$ ) to their values in absence of these elements ( $V_0$ ) in 20-storey building adjacent to shorter buildings with various clear distances and base conditions.

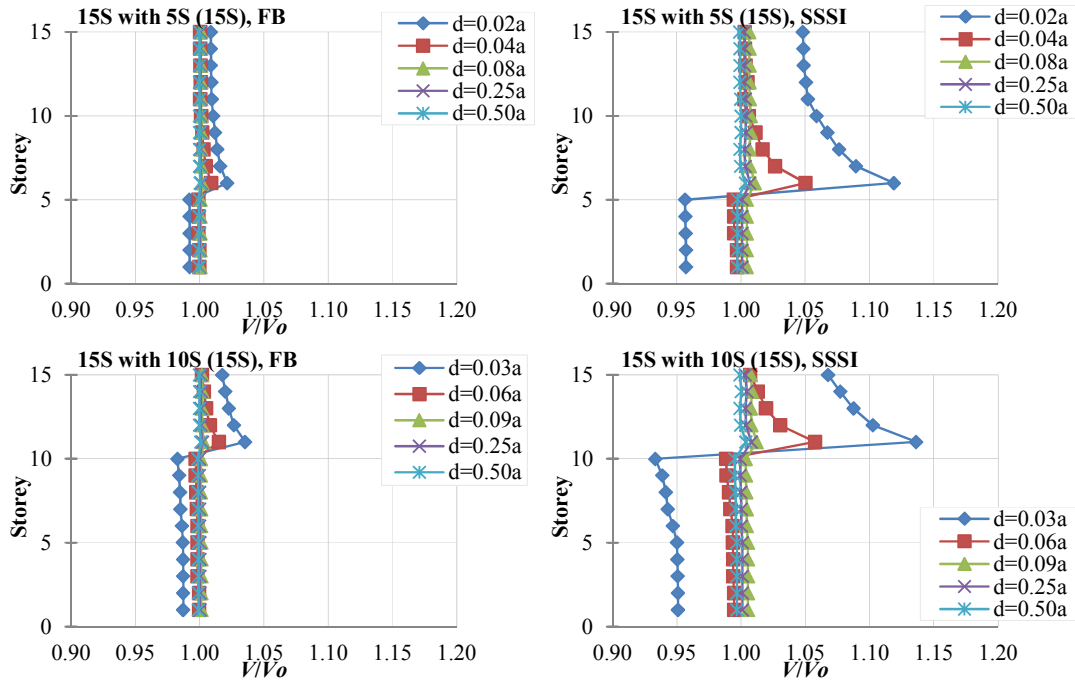


Figure 11. Normalized storey shear force in presence of pounding elements ( $V$ ) to their values in absence of these elements ( $V_0$ ) in 15-storey building adjacent to shorter buildings with various clear distances and base conditions.

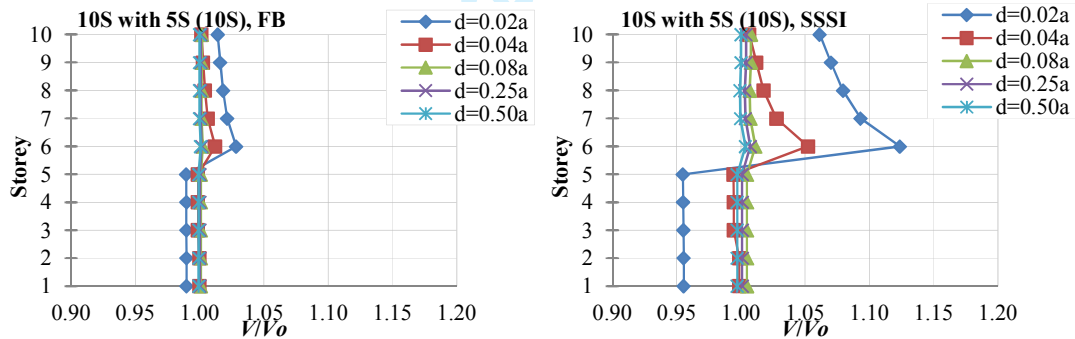


Figure 12. Normalized storey shear force in presence of pounding elements ( $V$ ) to their values in absence of these elements ( $V_0$ ) in 10-storey building adjacent to shorter buildings with various clear distances and base conditions.

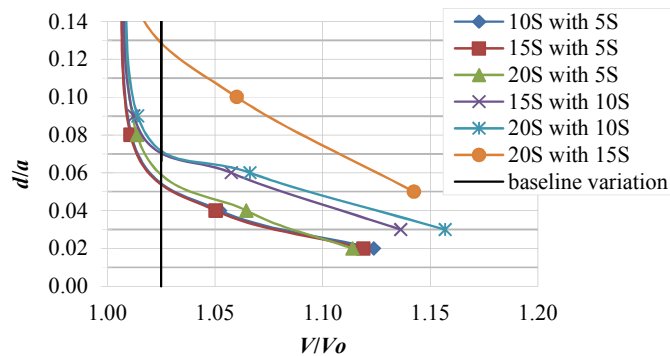


Figure 13. The variations of the normalized shear forces of the critical storey in presence of pounding elements to their values in absence of these elements in various SSSI-included cases.

472 Table 8. Minimum required distance for building separation and seismic pounding prevention on soft  
473 soils according to analyses in this study and IBC/ASCE7 standards.

Adj. Type	$d_{min}/a$		
	Current Analysis	Codes (IBC & ASCE7)	Percentage of difference (%) (Analysis-Codes)/Analysis x 100.
5S with 10S	0.0550	0.0200	64
5S with 15S	0.0550	0.0200	64
5S with 20S	0.0600	0.0200	67
10S with 15S	0.0725	0.0300	59
10S with 20S	0.0750	0.0300	60
15S with 20S	0.1300	0.0500	62

474

## 475 6.2. Pounding effect on structural seismic damage

476 In this subsection, the local and global effects of seismic pounding on the distribution of the  
477 damage index parameter ( $DI$ ) along the height of adjacent buildings are investigated. The  
478 damage indices in the presence of impact elements have been normalized to their values  
479 without the presence of these elements ( $DI/DI_0$ ). The clear distances equal to the minimum  
480 value recommended by the IBC/ASCE7 standards (Table 6 in the SSI case) were selected.  
481 The results including seismic damage distributions in all stories are presented in Figures 14-  
482 16. Reviewing Figures 14-16 and Table 9 the following interpretations could be stated:

483

484 1- The overall trend in the variation of seismic storey damage indices along the structural  
485 height is generally similar to that of storey shear forces. Also, as can be seen from Table 9 the  
486 variation in  $DI$  values during seismic pounding can be up to 48% and therefore is more  
487 significant than variation in  $V$  values, up to 16% (Figures 10-12). This result clearly indicates  
488 that the seismic damage index is a more sensitive parameter than the other conventional  
489 seismic structural response parameters and should be taken into account.

490 2- As would be expected, the inclusion of SSSI in studying the effect of pounding on seismic  
491 damage is considerable. The variation of normalized  $DI$  values due to this effect is up to 23%  
492 and 14% in taller and shorter building, respectively. Comparing the SSSI and FB curves in  
493 Figures 14-16, it can be observed that the SSSI increases the power and severity of the  
494 seismic impact and makes its effects more intense on structural seismic damage.

495 3- According to variations of  $DI/DI_0$  especially at the critical storey for the fixed-base  
496 conditions, the IBC 2009 minimum separation distance was insufficient to prevent the  
497 occurrence of severe seismic pounding.

498 4- As previously stated, the *critical storey* always experiences the most variations in the  
499 seismic damage index (up to 48% and 20% in SSSI and FB conditions, respectively) due to  
500 the pounding effect in both of the adjacent buildings. For the shorter building, the maximum  
501 variation is observed at the top floor (up to 34% and 17% in SSSI and FB conditions,  
502 respectively). These significant variations have taken place when the IBC/ASCE7  
503 recommended adjacency distance was selected.

504 5- During pounding the taller building experiences more seismic damage than the other  
505 building. Therefore, the pounding phenomenon is more critical for the taller adjacent  
506 building. The results observed for the tallest building (20-storey) considered in this study are  
507 summarized in Figure 17. For a tall building (with a total height of  $H$ ) within close distances,  
508 it seems that the most critical case is adjacency to a shorter building with the height equal to  
509  $H/2$ . A justification similar to that mentioned in item#5 in the previous section, can be

510 presented for this observation. For shorter adjacent buildings with heights less than this value,  
 511 the seismic vibrations reduced considerably; consequently, the severity of the probable  
 512 pounding is reduced (e.g. 5S or 10S next to 20S). Also, for shorter adjacent buildings with  
 513 heights more than this value, the pounding occurrence probability is significantly reduced  
 514 (e.g. 15S next to 20S and 10S next to 15S), possibly due to similarities in the vibration  
 515 frequencies and mode shapes to the taller building.

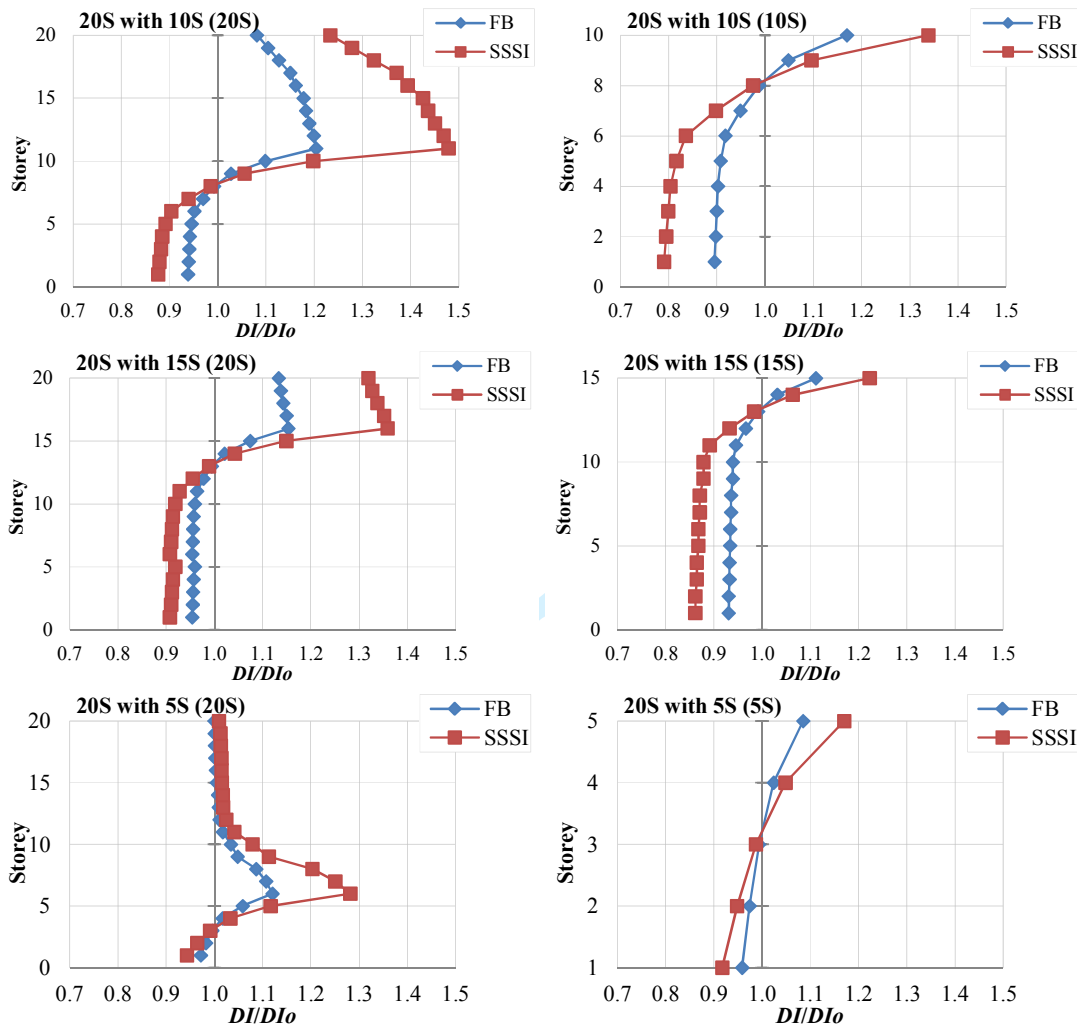
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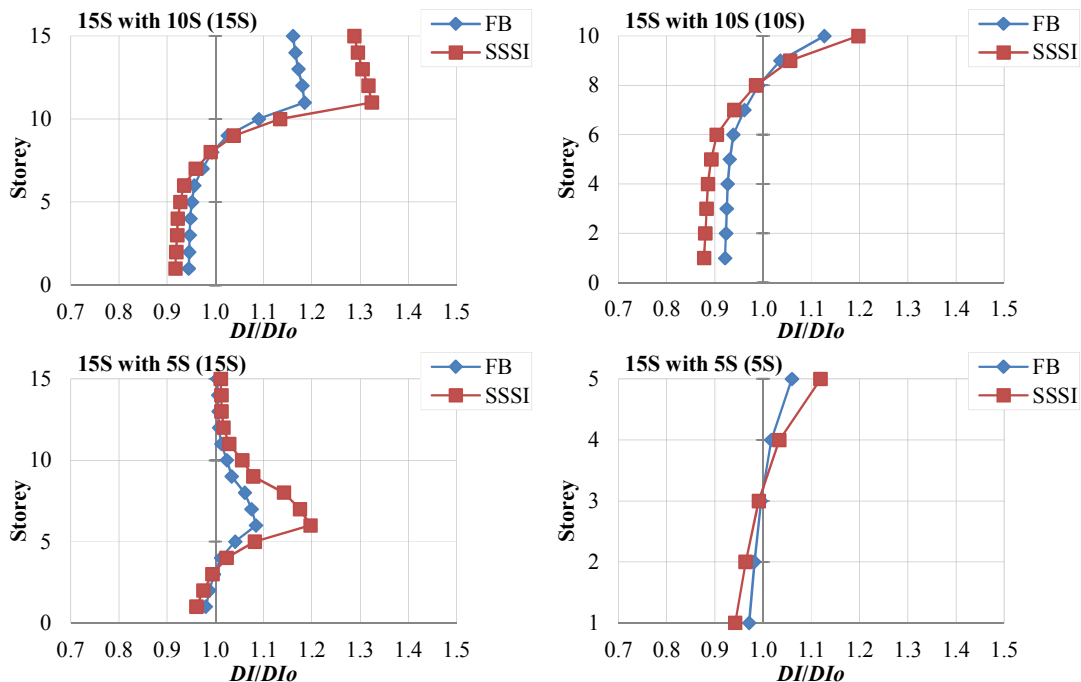
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520 Figure 14. Normalized storey seismic damage index values in presence of pounding elements ( $DI$ ) to  
 521 their values in absence of these elements ( $DI_0$ ) in two adjacent buildings of all 20-storey adjacency  
 522 cases with  $d=IBC/ASCE7$  recommended value in two FB and SSSI base conditions.  
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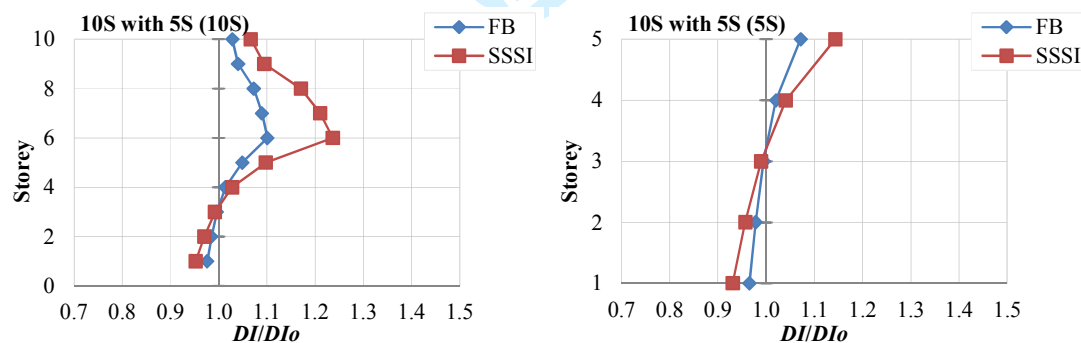
Figure 15. Normalized storey seismic damage index values with presence of pounding elements ( $DI$ ) to their values with absence of these elements ( $DI_0$ ) in two adjacent buildings of 15-storey building adjacency cases with shorter buildings with  $d=IBC/ASCE7$  recommended value in two FB and SSSI base conditions.

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Figure 16. Normalized storey seismic damage index values with presence of pounding elements ( $DI$ ) to their values with absence of these elements ( $DI_0$ ) in adjacent buildings in adjacency case of two 10- and 5-storey buildings with  $d=IBC/ASCE7$  recommended value in two FB and SSSI base conditions.

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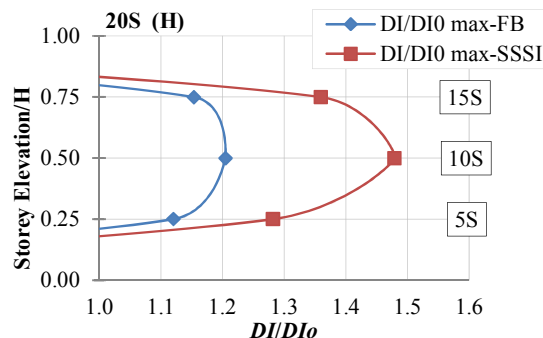
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Table 9. Details of maximum variations of normalized storey seismic damage indices (observed in the critical storey) in presence of pounding elements to their values in absence of these elements in all adjacency cases with  $d=IBC/ASCE7$  recommended distance for building separation.

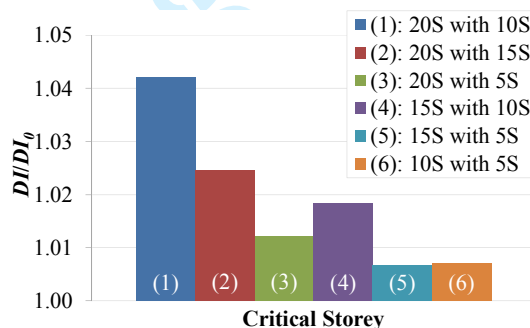
Adj. Case	Taller Adjacent Building		Differences in % (SSSI to FB) (%)	Shorter Adjacent Building		Differences in % (SSSI to FB) (%)
	FB $DI/DI_0$ max	SSSI $DI/DI_0$ max		FB $DI/DI_0$ max	SSSI $DI/DI_0$ max	
20S with 10S	1.20	1.48	23	1.17	1.34	14
20S with 15S	1.15	1.36	18	1.11	1.22	10
20S with 5S	1.12	1.28	14	1.09	1.17	8
15S with 10S	1.18	1.32	12	1.13	1.20	6
15S with 5S	1.08	1.20	10	1.06	1.12	6
10S with 5S	1.10	1.24	12	1.07	1.14	7





545 Figure 17. The envelope of the maximum seismic damage index variations at critical storey in 20-  
 546 storey building based on the various impact locations due to adjacency to 5, 10 and 15-storey  
 547 buildings.  
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 549

550 6- If the clear distance between two adjacent buildings on soft soil is selected to be at least 3  
 551 times that of the IBC/ASCE7 recommended value, it can be expected that the maximum  
 552 effect of seismic pounding on storey shear forces will be less than 2.5%. This observation can  
 553 be investigated based on the seismic  $DI$  values as a more sensitive parameter in inelastic  
 554 structural response. In Figure 18, the variation of the  $DI/DI_0$  ratio at the critical storey in all  
 555 SSSI-included adjacency cases with  $d=[3 \times (\text{IBC/ASCE7 recommended distance})]$  are  
 556 presented. As can be seen from Figure 18, negligible variations of seismic damage indices  
 557 values are observed at this adjacency distance (up to 4%).  
 558



559 Figure 18. Variation in  $DI/DI_0$  ratio at the critical storey in all SSSI-included adjacency cases with  
 560  $d=[3 \times (\text{IBC/ASCE7 recommended distance})]$ .  
 561  
 562

563 **7. Conclusions**

564 In this study the probable seismic pounding effects on the response of adjacent symmetric  
 565 buildings considering structure-soil-structure interaction have been investigated. This was  
 566 carried out by taking into consideration two adjacent symmetric in plane buildings excited by  
 567 earthquake loadings on a soft soil profile representing the flexible base conditions. The  
 568 inelasticity of structures and soil medium were taken into account by means of plastic hinge  
 569 elements and the near-field method, respectively. The seismic damage index and shear force  
 570 of stories were considered as the main structural system response measures. The pounding  
 571 and SSSI phenomena as primary and secondary factors causing variations of structural  
 572 seismic response in various adjacency cases were modeled both simultaneously and  
 573 separately. Finally, within the assumptions considered in this study, some major observations  
 574 can be made:  
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3 577 1-At least three times the IBC 2009 minimum distance for building separation recommended  
4 578 value is required as a clear distance for adjacent in-plane symmetric buildings (with identical  
5 579 architectural plan and dimensions) on soft soils to prevent the occurrence of seismic  
6 580 pounding. Within this distance, the maximum effects of the phenomenon are not more than  
7 581 2.5% and 4% in terms of storey shear forces and seismic damage indices, respectively.  
8 582 2-Seismic damage index ( $DI$ ) is a more sensitive and critical parameter than conventional  
9 583 seismic storey shear and therefore should be given more significance.  
10 584 3-In accordance with the IBC 2009 recommended minimum distance, buildings experienced  
11 585 severe seismic pounding and therefore significant variations in storey shear forces and  
12 586 damage indices of up to 16% and 48%, respectively, were observed at the *critical storey* in  
13 587 SSSI cases. The corresponding variations for the FB cases are 4% and 20%, respectively, for  
14 588 storey shear forces and damage indices.  
15 589 4-The taller adjacent building experienced more severe seismic damage due to pounding than  
16 590 the shorter building. The location of the occurrence of this damage is not at the collision  
17 591 storey but at an inter-storey above that in the taller building termed the *critical storey*. The  
18 592 *collision storey* is the location of the first probable seismic pounding and is always the top  
19 593 floor of the shorter building.  
20 594 5-For each tall building with a total height of  $H$ , during seismic pounding within a close  
21 595 adjacency distance, the most severe impact is powered by a shorter adjacent building with a  
22 596 height of  $H/2$ . For shorter buildings of height more than  $H/2$ , the similarity in vibration  
23 597 frequencies and mode shapes of buildings decreases the probability of the seismic impact.  
24 598 While for shorter adjacent building with the height less than  $H/2$ , a weak impact was  
25 599 observed. It is necessary to note that the architectural plan and storey height of adjacent  
26 600 buildings are assumed to be similar in this study and the only difference between the two  
27 601 considered adjacent buildings is the number of stories and therefore their total height. In  
28 602 general, the problem of “the effects of the vibration modes and frequencies on the pounding  
29 603 response of adjacent buildings” is an important issue that deserves further study. For such  
30 604 studies, it is suggested that more various types of buildings adjacency be considered and the  
31 605 effects of a parameter such as “adjacency frequency ratio” (the fundamental frequency ratio  
32 606 of adjacent buildings) on the seismic pounding response of taller adjacent building be  
33 607 investigated.  
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