Int J Adv Struct Eng (2017) 9:51–62
DOI 10.1007/s40091-017-0148-y

ORIGINAL PAPER

Seismic analysis of adjacent buildings subjected to double pounding considering soil–structure interaction

Ahmed Abdelraheem Farghaly[1]

Received: 4 February 2015 / Accepted: 24 January 2017 / Published online: 3 February 2017

Abstract A 2D model of two adjacent buildings with different heights (6 and 12 floors) and foundation levels without separation distance under seismic load and considering SSI is investigated. A special arrangement of contact elements (gap elements) each 1 m of the low height building in the contact zone is taken into consideration to fulfill all possible deformation contact modes which take place under seismic load (earthquake). Soil is modeled by 2D shell elements in contact with foundations of the two adjacent buildings. This paper focuses on the study of double pounding that takes place between the two adjacent buildings in some upper points at superstructure in the contact zone and also at foundation level. The forces of double pounding between the two adjacent buildings, which increase by softening of the soil, give a valuable assessment of straining actions of the two adjacent buildings and change the behavior of soil under the foundations and around basement floor.

Keywords Seismic analysis · Adjacent buildings · Pounding · Foundation collision · SSI · FEM

Introduction

Impacts due to structural pounding transmit short duration, high-amplitude forces to the impacting structures and may occur at any level of the colliding structures and at any location along the impacting levels (in the case of disparate story heights of the adjacent buildings resulting in slab–column impacts or collision at the foundation level). These effects are of high amplitude, short duration local acceleration, localized degradation of stiffness and strength in affecting members and cause modification to the overall dynamic response of structures. Double pounding means that it can take place between superstructure levels and foundation level of the two adjacent buildings. The effect of soil–structure interaction (SSI) on the dynamic response of a building is on the free field excitation and on the response characteristics of the oscillation system.

The most significant effect of the presence of an adjacent foundation is the introduction of certain modes of response that are not present in the single foundation case, and some of the degrees of freedom will be coupled. The extent of this interaction is dependent mainly on the mass ratio of the adjacent structures, their (compliant foundations) natural frequencies, and the predominant frequency of the excitation.

Pounding between neighboring buildings during earthquakes is an issue that has attracted considerable interest, see, for example: Anagnostopoulos (1988, 2004), Anagnostopoulos and Spiliopoulos (1992), Karayannis and Favvata (2005a, b), Anagnostopoulos and Karamaneas (2008), Efraimiadou et al. (2013a, b). Studies on the effect of the mass distribution on pounding structures (Cole et al. 2011), pounding of seismically isolated buildings (Polycarpou and Komodromos 2010), 3D pounding of buildings (Polycarpou et al. 2014, 2015), eccentric building pounding (Wang et al. 2009), heavier adjacent building pounding (Jankowski 2008), mid-column building pounding, and corner building pounding (Papadrakakis et al. 1996) are also some important examples. Although these studies significantly contribute to the field, they did not account for the influence of the underlying soil on building pounding.

✉ Ahmed Abdelraheem Farghaly
khodary20002000@yahoo.com

[1] Civil and Architectural Constructions, Faculty of Industrial Education, Sohag University, Sohag, Egypt

Hao et al. (2000) and Hao and Gong (2005) investigated the seismic responses of the adjacent buildings subjected to pounding due to spatially varying earthquakes. The attenuation of waves propagating through the soil and the associated time lag caused the buildings to experience different seismic responses. However, the influence of the spatial variation of earthquake ground motions is of secondary importance compared to the SSI, because the adjacent buildings are close to each other.

Rahman et al. (2001) studied the effects of foundation compliance of the conventional structures and the importance of soil flexibility has been highlighted. These authors concluded that the seismic response of the structure increased with consideration of soil flexibility due to the increases in the natural periods of the adjacent buildings, compliance effects must also be taken into account when determining the location of sensitive equipment and appurtenances due to the localized effects of the large amplitude impacts.

Shakya and Wijeyewickrema (2009) analyzed unequal story height buildings considering the underlying soil effects to study the mid-column pounding of the adjacent buildings. They used the SAP2000 (2015) software to model the adjacent buildings and the underlying soil. The buildings were connected by a combination of the gap element and the Kelvin–Voigt model. These authors asserted that pounding forces, inter-story displacements and normalized story shears were generally decreased when the underlying soil was considered.

Naserkhaki et al. (2012) concluded that pounding causes smaller displacements but larger story shears in the flexible building, while the displacements and story shears are increased in the stiff building due to pounding. The underlying soil (SSSI) increases the displacements and story shears produced in both buildings due to pounding compared to those seen under the fixed-base condition. Pounding worsens the adjacent buildings' conditions, which is amplified by the underlying soil, and ignoring the effects of the underlying soil may result in unrealistic and un-conservative designs with detrimental consequences.

Mahmoud et al. (2013) investigated the coupled effect of the supporting soil flexibility and pounding between neighboring, insufficiently separated equal height buildings under earthquake excitation.

Qin and Chouw (2013) presented a numerical investigation of seismic gap between adjacent structures with structure–foundation–soil interaction (SFSI).

Naserkhaki et al. (2013) investigated the earthquake-induced building pounding problem for various separation gaps and for two foundation conditions, fixed-based (FB) and structure–soil–structure interaction (SSSI).

Behnamfar and Madani (2014) studied the effects of mutual cross-interaction and pounding on nonlinear seismic response of adjacent sample buildings.

Alam and Kim (2014) studied the spatially varying ground motion effects on seismic response of adjacent structures considering soil–structure interaction (SSI) and found that the responses of adjacent structures have changed remarkably due to spatial variation of ground motions.

Pawar and Murnal (2014) concluded that consideration of SSI increases number of impacts at impact level, floor-to-column impact is more vulnerable than floor-to-floor impact, and SSI phenomenon may be sometimes responsible for pounding phenomenon due to increase in displacement, so neglecting SSI may lead to erroneous conclusion regarding possibility of pounding.

Madani et al. (2015) studied the effects of pounding and structure–soil–structure interaction on the nonlinear dynamic behavior of selected adjacent structures.

Ghandil et al. (2016) studied the dynamic responses of structure–soil–structure systems with an extension of the equivalent linear soil modeling and investigated the problem of cross-interaction of two adjacent buildings through the underlying soil.

This paper studies the seismic analysis of two adjacent buildings with different heights subjected to double pounding considering SSI and includes into consideration the pounding in the level of foundation especially for different levels of the adjacent building foundations, where the forces in the contact elements between the two foundations get bigger when the soil gets softer, so the double pounding (which may take place in some upper points at superstructure in the contact zone and also at foundations level) between two adjacent buildings of different heights and foundation levels without separation distance under seismic load and considering SSI will have an important effect on the design procedure of such buildings.

Soil–structure interaction (SSI) model

The building and the underlying soil are connected through interaction forces with equal magnitudes but opposite directions. These interaction forces come from the inertial forces that correspond to the masses of the building and the underlying soil, called the inertial interaction. Moreover, the adjacent buildings are coupled through the underlying soil, and the response of each building affects the other because they are located in near proximity, termed the "structure–soil–structure interaction" or "SSSI" effect. The equation of motion for two adjacent buildings with the SSSI effect consideration due to earthquake acceleration of $\ddot{u}_g(t)$ is proposed by Naserkhaki and Pourmohammad (2012) as:

$$\begin{aligned}&\mathbf{M}_{\text{bsb}}\ddot{\mathbf{U}}_{bsb} + \mathbf{C}_{\text{bsb}}\dot{\mathbf{U}}_{\text{bsb}} + \mathbf{K}_{\text{bsb}}\mathbf{U}_{\text{bsb}}\\ &\quad = -(\mathbf{M}_{\text{bsb}}\boldsymbol{v}_{\text{bsb}} + \boldsymbol{v}_{\text{fbsb}})\ddot{\text{u}}_{\text{g}}(\text{t}),\end{aligned} \tag{1}$$

where $\mathbf{M_{bsb}}$, $\mathbf{C_{bsb}}$ and $\mathbf{K_{bsb}}$ are the mass, damping and stiffness matrices, respectively, $\ddot{\mathbf{U}}_{\mathbf{bsb}}$, $\dot{\mathbf{U}}_{\mathbf{bsb}}$, $\mathbf{U_{bsb}}$, $\boldsymbol{v}_{\mathbf{bsb}}$ and $\boldsymbol{v}_{\mathbf{fbsb}}$ are the acceleration, velocity, displacement and the influence vectors of the buildings and underlying soil, respectively. This equation consists of two sets of equations corresponding to the two buildings, while these two sets of equations are coupled by the off-diagonal SSSI components of stiffness and damping matrices. The first set includes $n + 2$ coupled equations; n for the NDOF for the left building and 2 for the 2DOF for the underlying soil. Similarly, the second set includes $m + 2$ coupled equations; m for the MDOF for the right building and 2 for the 2DOF for the underlying soil ($n > m$).

Impact elements

Collisions are simulated using special purpose contact elements that become active when the corresponding nodes come into contact. This idealization is consistent with the building model used and appears adequate for studying the effects of pounding on the overall structural response for the pounding cases under examination. Local effects such as inelastic flexural deformations, yield of the flexural reinforcement and ductility requirements of the columns in the pounding area are taken into consideration through the special purpose elements employed for the modeling of the columns.

To model impact between two colliding structures, the linear spring-damper (Kelvin–Voigt model) element is mostly used. K_{L} is the stiffness and C_{L} is the damping coefficient and is given by:

$$C_L = -2\ln e_r\sqrt{\frac{K_L m_1 m_2}{[\pi^2 + (\ln e_r)^2](m_1 + m_2)}}, \tag{2}$$

where e_{r} is the coefficient of restitution, m_1 and m_2 are masses of structural members (Anagnostopoulos 1988). Numerical simulation performed by Jankowski (2005) showed that for concrete-to-concrete impact, $K_{\text{L}} = 9350$ t/m and $e_{\text{r}} = 0.65$ provide good correlation between experimental results provided by Van Mier et al. (1991) and theoretical results. In the present study the same values of K_{L} and e_{r} are used.

The stiffness of gap element K_{G} is considered as 100 K_{L} to avoid errors in convergence and to ensure that it works as nearly rigidly when the gap is closed. Figure 1 shows the impact element for each point between the two adjacent buildings (from foundation level to top point of the 6-floor building).

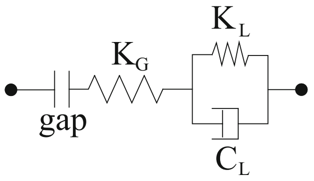


Fig. 1 Impact element composed of a gap element and a Kelvin–Voigt element

Earthquake record

The time history analysis was about 40-s duration consisting of 4000 steps under an actual earthquake accelerogram and a free vibration segment of 0.01 s duration. The used earthquake excitation was the 1940 El Centro earthquake (Fig. 2). The El Centro earthquake record has peak ground acceleration (PGA) of 0.50 g and is representative of a benchmark excitation, commonly used in structural dynamics.

Model description

The analytical model of the two adjacent buildings with gap elements resting on the soil is shown in Fig. 3.

All foundations were designed as rigid surface foundations since the required embedment depth is considered negligible in comparison with the layer thickness. Perfect bond is assumed to exist between the footings and the surface of the supporting soil. Herein, soil is assumed homogeneous and its properties are as shown in Table 1.

As shown in Fig. 3, the dimensions of the soil medium were taken to be 50 m × 100 m, the soil under the buildings consists of one layer with 50 m thickness and this medium was divided into small (fine) grids (under the structures) which were proven to be small enough to transmit all the frequency components of the input motions. The sizes and the characteristics of the structure are also presented in Fig. 3. The model incorporates the main buildings (modeled using beam and slab elements), the foundations (modeled as single footings), and the soil mesh which is of quadrilateral shape; see Fig. 3.

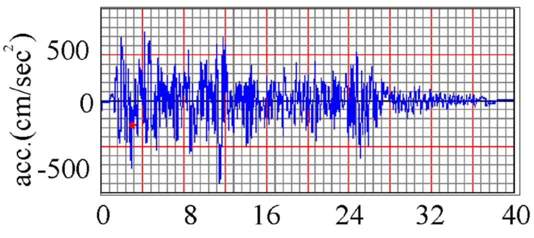
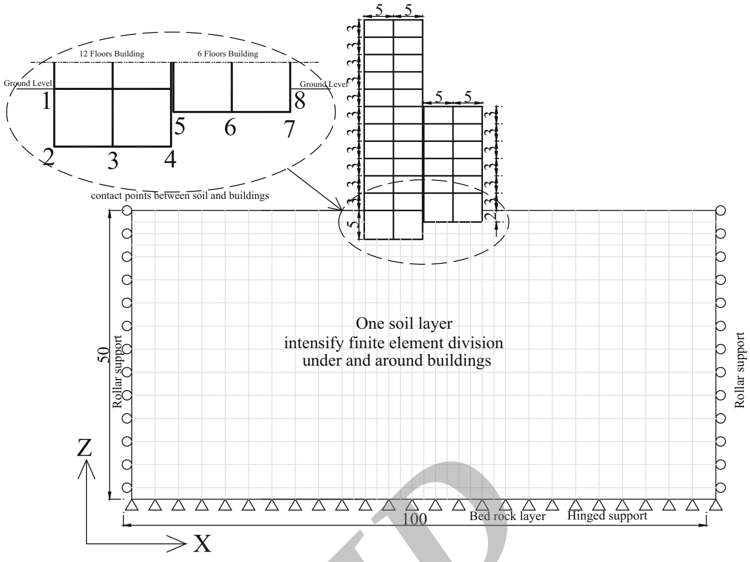
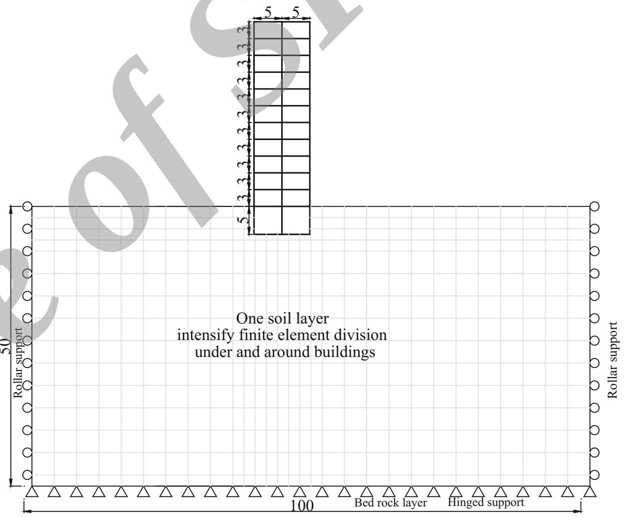


Fig. 2 Earthquake excitation: the El Centro earthquake

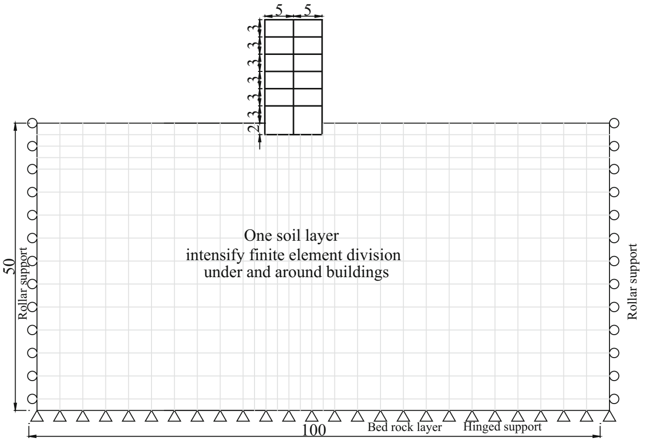
Fig. 3 The structural buildings with soil mesh of modeled representation



(a) The two adjacent buildings with soil representation



(b) 12 floors building



(c) 6 floors building

Table 1 Soil properties

Elastic modulus, E (KN/m^2)	30,000
Soil shear modulus, G (KN/m^2)	14,350
Poisson's ratio, v	0.40
Weight per unit volume, γ (KN/m^3)	16

The buildings are of 6 floors with shallow (2 m from ground level) foundation and of 12 floors with basement floor (5 m from ground level), with 3 m height of each floor. The gap size between the two buildings is 2 cm. Columns and beams are modeled as frame elements, and vertically distributed dead load acting on beams of each floor is assumed 2.5 t/m′. Soil is modeled by 2D shell elements with definition of the curve of soil under cyclic load taking in consideration the nonlinearity of soil during earthquake in SAP2000 computer program (SAP 2015). The assumption of constant damping (5% for all modes) for the numerical model is incorporated in SAP2000 (2015)

The sub-grade is modeled with plane strain elements with nonlinear elastic isotropic material. Interaction between the superstructure and the sub-grade is modeled with friction in a tangential direction and compression capacity in vertical direction. The bottom surface of the sub-grade is restricted in the vertical and tangential direction. Infinite elements are applied on the sides of the sub-grade, representing endless soil propagation.

In this paper, the Egyptian Code of Practice (ECP) (2007, 2008) was used. Table 2 summarizes the properties of each building.

Results and discussion

A parametric study is performed, and the effects of the underlying soil and internal forces of buildings on the seismic responses of the adjacent buildings subjected to earthquake-induced pounding are investigated.

Buildings response

Deformations

Figure 4 shows the deformed shape of the two adjacent buildings subjected to El Centro earthquake with the effect of SSI underneath the two adjacent buildings. In Fig. 4 the gap size between the two adjacent buildings increased at the top of the 6-floor building and a clear gap appeared between the two buildings at the level of the foundations of the two buildings, which indicates the possibility of a collision between the foundations of the two adjacent buildings.

Table 3 shows the description of the symbols used in the Figs. 5, 6, 7, 8, 9 and 12.

Figure 5 illustrates the lateral displacements vs. heights from foundation level of each building (where "−1" and "−2" are the levels of foundations of the 6- and 12-floor buildings, respectively, and "0" is the ground level), under different conditions (the single 6-floor and 12-floor buildings under earthquake excitation, and the two adjacent buildings under earthquake excitation with and SSI effect). Figure 5a shows the lateral displacements of each floor in the 6-floor building, whereas top displacement in the adjacent buildings case with SSI effect increases by 1.4 times than the single (alone) 6-floor building with SSI effect, and by 4 times than that adjacent case without taking into consideration SSI. At foundation level lateral displacement in adjacent building case increases by 1.38 than single building with SSI effect. Figure 5b shows the lateral displacements in the 12-floor building under different considerations, whereas the 12-floor building top displacement with SSI effect decreases in adjacent building case by 1.78 times than the single 12-floor building with SSI effect, and the adjacent 12-floor buildings top displacement with SSI effect increases by 3.27 times than those without taking into consideration SSI, and finally in the alone with SSI effect case, top displacement increases by 5.3 times than those without taking in consideration SSI under seismic load, and at foundation level adjacent building increases by 1.2 times than single building with SSI effect.

Figure 6 shows top lateral accelerations of the two buildings in different cases. Figure 6a shows top acceleration of the 6-floor building, whereas top acceleration of the 6-floor adjacent buildings with SSI effect increases by 1.87 times than adjacent buildings without SSI effect. Also top acceleration of adjacent buildings with SSI effect decreases by 1.67 times than single (alone) building with SSI effect. Figure 6b shows top acceleration of the 12-floor building, whereas top acceleration of the 12-floor adjacent buildings with SSI effect increases approximately by 1.6 times than adjacent buildings without SSI effect. Also top

Table 2 Dimensions and reinforcements of the structural elements of the 6- and 12-floor buildings

Building	Columns		Beams		Foundation	
	Dim. (mm)	Reinf. (mm)	Dim. (mm)	Reinf.	Dim. (mm)	Reinf. (mm)
6 floors	450 × 450	16Ø16	250 × 500	3Ø12 (top)–5Ø16 (bottom)	2000 × 800	13Ø18
12 floors	800 × 800	26Ø18	250 × 500	3Ø12 (top)–5Ø16 (bottom)	3500 × 1200	21Ø25

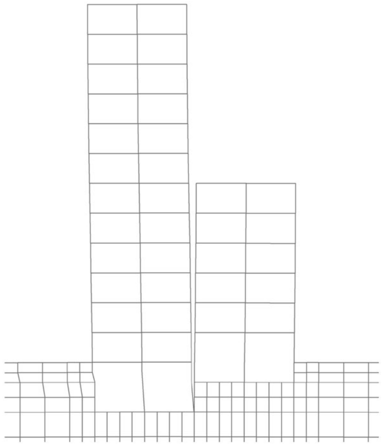


Fig. 4 Lateral deformations of adjacent buildings subjected to El Centro earthquake

acceleration of adjacent buildings with SSI effect decreases by 1.64 times than single (alone) building with SSI effect.

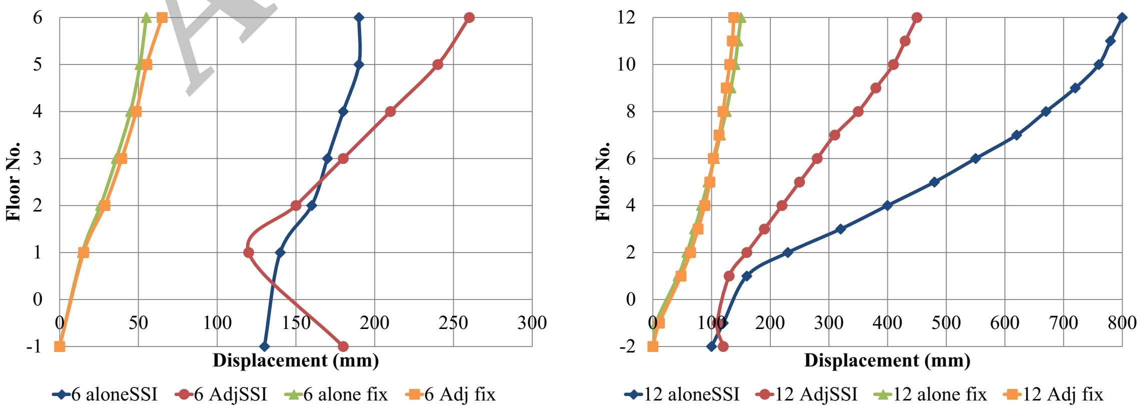
Straining actions

Figure 7 shows shear forces vs. heights for the two adjacent buildings and the single buildings taking in consideration the effect of soil–structure interaction (SSI).

Figure 7a shows shear forces in a 6-floor building with different cases, where for the 6-floor building adjacent to 12-floor building with SSI, shear force at top floor increases by 1.62 and 17.5 times than the 6-floor adjacent building case without SSI and single building case with SSI effect, respectively, and these big values of shear forces at top of the 6-floor building are because of the pounding between this building and the adjacent one, since the effect of pounding increases top shear of the building, whereas at foundation level shear force increases by 2.57 times in adjacent buildings taking into consideration SSI than the corresponding value without SSI, but at foundation level shear force in adjacent building with SSI decreases by 1.6 times than the corresponding value for single building with SSI. Figure 7b illustrates shear forces vs. heights of the 12-floor building under different conditions. Pounding occurs at 6th floor (height of the 6-floor adjacent building), shear force increases by 1.92 times in case of adjacent with SSI than the case without SSI and shear force at foundation level (−2) in adjacent case with SSI increases by 11.4 and 1.4 times than the adjacent case without SSI and single building with SSI, respectively, but at foundation level (−1, foundation level of 6-floor building) shear force in adjacent case with SSI increases by 7.88 times than

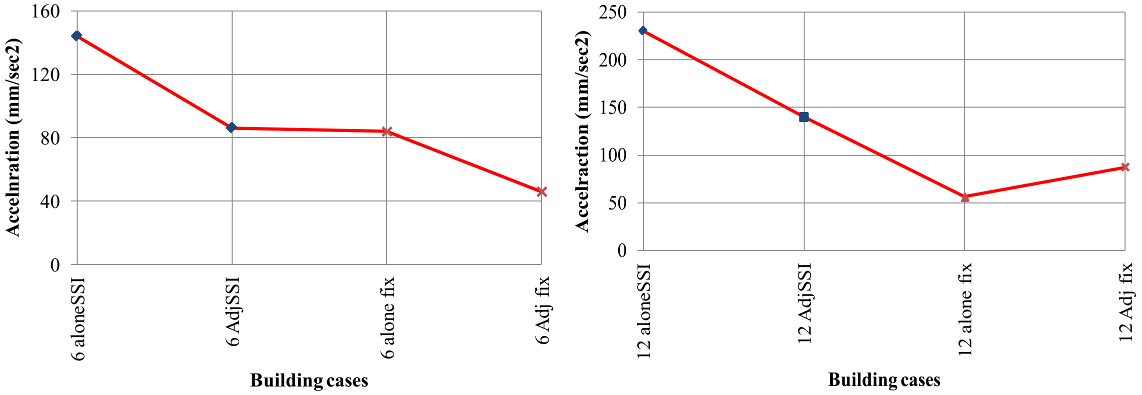
Table 3 Description of symbols in Figs. 5, 6, 7, 8, 9 and 12

Symbol	Definition
6 alone *SSI*	6-floor building alone with effect of SSI under earthquake
12 alone *SSI*	12-floor building alone with effect of SSI under earthquake
6 Adj *SSI*	6-floor building adjacent to 12-floor building with effect of SSI under earthquake
12 Adj *SSI*	12-floor building adjacent to 6-floor building with effect of SSI under earthquake
6 alone *fix*	6-floor building alone without effect of SSI under earthquake
12 alone *fix*	12-floor building alone without effect of SSI under earthquake
6 Adj *fix*	6-floor building adjacent to 12-floor building without effect of SSI under earthquake
12 Adj *fix*	12-floor building adjacent to 6-floor building without effect of SSI under earthquake



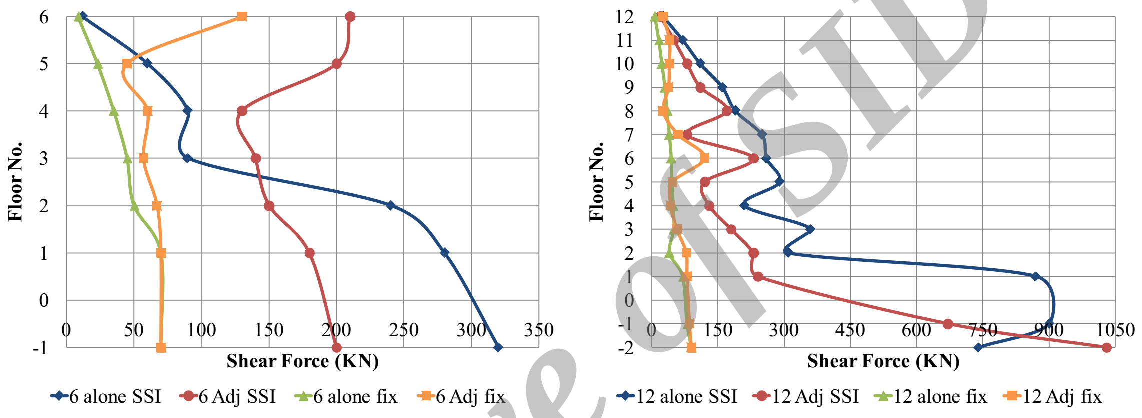
(a) 6 floors building **(b)** 12 floors building

Fig. 5 Lateral displacements of the 6- and 12-floor buildings under different conditions



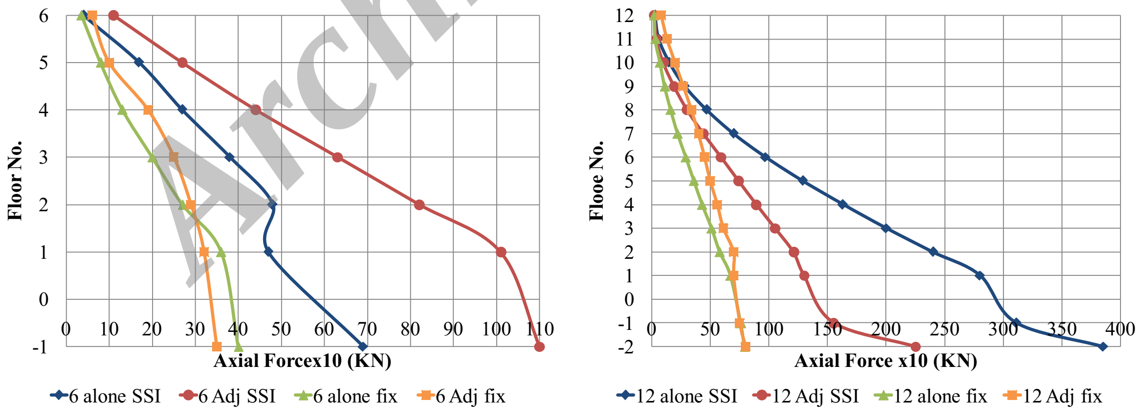
(a) 6 floors building **(b)** 12 floors building

Fig. 6 Top lateral accelerations of the 6- and 12-floor buildings under different conditions



(a) 6 floors building **(b)** 12 floors building

Fig. 7 Shear forces vs. heights

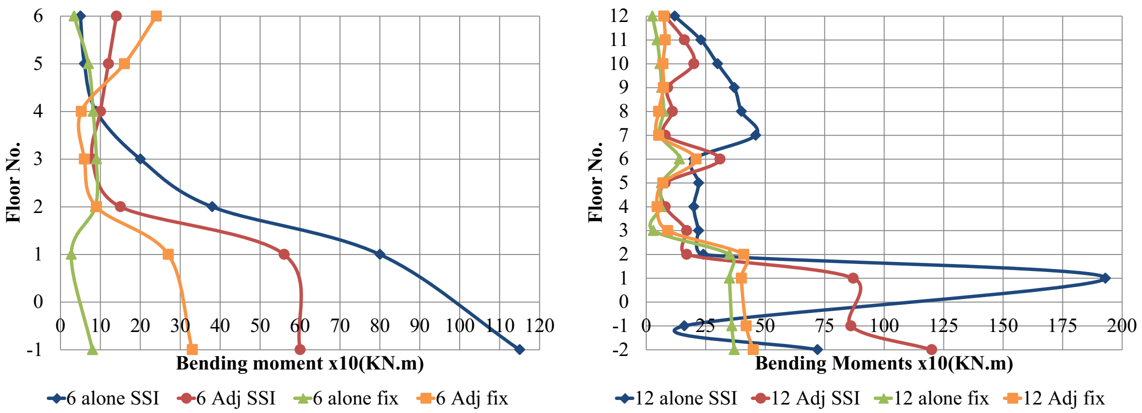


(a) 6 floors building **(b)** 12 floors building

Fig. 8 Axial forces vs. heights

adjacent case without SSI and decreases by 1.3 times than single building with SSI effect.

Figure 8 shows the axial forces in columns of the buildings with different cases. Figure 8a shows axial forces in the 6-floor building under different conditions, where in adjacent buildings case with SSI effect axial normal force increases by nearly 3.14 times than case without SSI, and increase by 1.6 times than single building with SSI effect,



(a) 6 floors building **(b)** 12 floors building

Fig. 9 Bending moments vs. heights

respectively. Figure 8b shows the axial forces in the 12-floor building, where in case of adjacent with SSI axial normal force increases by 2.8 times than the corresponding case without SSI, but it decreases by 1.7 than single building with SSI effect. The effect of SSI magnifies normal force in buildings, whether alone or adjacent buildings cases.

Figure 9 shows bending moments vs. heights of the 6- and 12-floor buildings under different conditions. Figure 9a shows bending moment in the 6-floor building under different conditions, bending moment in single building at foundation level increases by nearly 1.92 times than the adjacent building with SSI effect, but adjacent building with SSI effect bending moment increases by nearly 1.82 times than the corresponding case without SSI effect at foundation level. Figure 9b shows bending moments of the 12-floor building under different conditions. At 6th floor (adjacent building height) bending moment increases nearly by 1.48 times in adjacent case with SSI than that without SSI effect. Bending moment at −1 level in adjacent building with SSI increases by 2.02 times than adjacent buildings without SSI effect. At 2nd foundation (−2) level bending moment in adjacent building with SSI increases by 2.67 times than the corresponding case without SSI effect.

Soil response

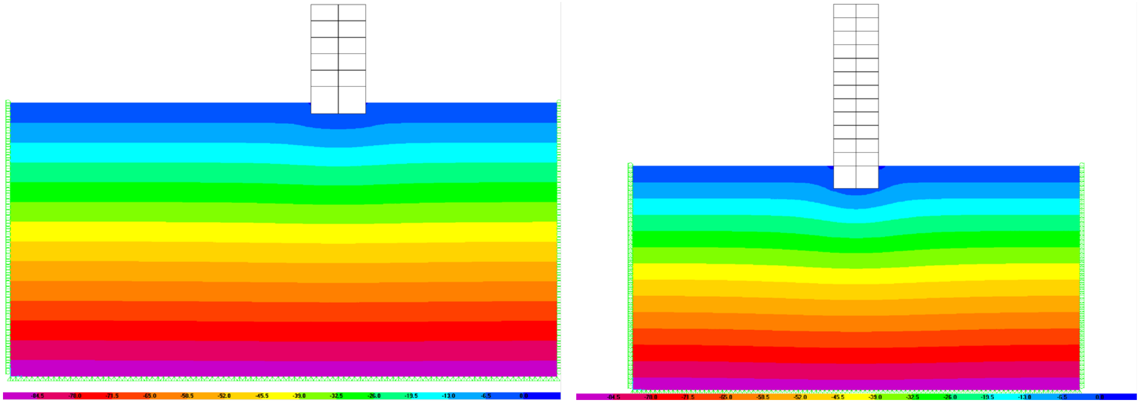
The contact points (as shown in Fig. 3a) between soil and the two adjacent buildings were checked against vertical stresses which have taken place because of different cases of loading (static and earthquake).

Vertical stresses

Figure 10 displays the color contour plots of vertical stresses S_{22} (in *Z*-direction) under static condition for the single buildings (of 6 and 12 floors) and the two adjacent buildings with the effect of soil–structure interaction (SSI), where vertical stresses under and around the buildings in the static case (without earthquake effect) are negative (compression values) and that means that the soil does not suffer from tension collapse under and around the buildings.

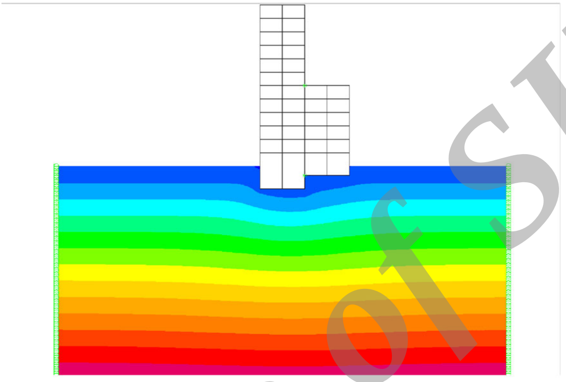
Figure 11 displays the color contour plots of vertical stresses S_{22} (in *Z*-direction) due to the El Centro earthquake for the single buildings (of 6 and 12 floors) and the two adjacent buildings with the effect of soil–structure interaction (SSI), where vertical stresses under and around the buildings under seismic load are positive (tension values) at almost contact points between the buildings and soil (except at the middle under the buildings) and that means that the soil suffers from tension collapse under and around the buildings as appears in the dark blue zones around and under the buildings.

Figure 12 shows the vertical stresses S_{22} (in *Z*-direction) under and around the buildings in different cases. The contact points between the soil and the buildings are shown in Fig. 3a. Figure 12a depicts vertical stresses underneath and around the 6-floor building for different cases, under static load (dead load) only gives compression stresses. In the alone 6-floor building subjected to earthquake, all points between buildings and soil are subjected to tension stresses except point 6 which is in compression at all cases, whereas for points 5 and 7 tension stresses in adjacent buildings cases increase by 1.6 and decreases by 1.3 times than single building under seismic load. Figure 12b illustrates vertical stresses underneath and around the 12-floor building in different conditions. The vertical stresses underneath the 12-floor building did not change for different cases, except the contact points around the building suffer from tension stresses (where small values means separation between soil and the building), but the points



(a) S_{22} for single building with 6 floors

(b) S_{22} for single building with 12 floors



(c) S_{22} for the two adjacent buildings

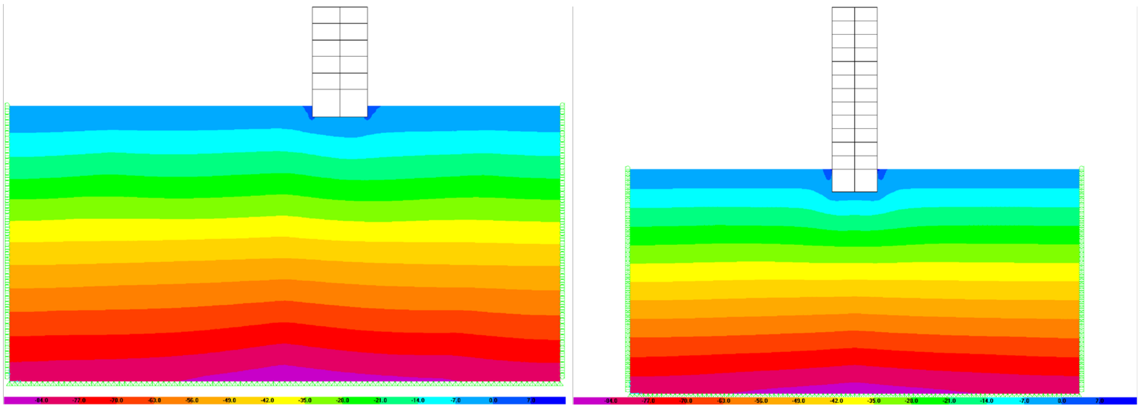
Fig. 10 Selective color contour plots of vertical stresses S_{22} (KN/m^2) only under dead load (static)

under building still in compression state because of the deep foundation level of the building (basement floor) and its heavy weight. Stresses in points 1 and 5 for the adjacent buildings case decrease by 1.6 and 2.3 times than single building under seismic load (since the collision effect between the two buildings increases bearing stresses and reduces tension stresses at these points). The evidence of collapse is the tension stresses that appeared between the soil and the selected points under and around the foundations of the buildings especially under seismic loads.

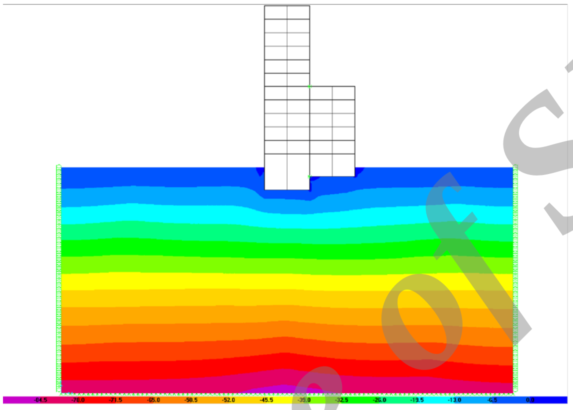
Conclusions

This study was conducted to clarify the extent and the force of the collision between the two adjacent buildings and its impact on the internal forces of the two buildings and the soil under them. A 2D model was investigated with a 6-floor building with shallow foundation and a 12-floor building with basement floor and with contact elements between the two buildings, each 1 m of the height of the 6-floor building, in order to transfer all the movements and pounding forces of the two buildings during the earthquake affecting the system. The results are summarized as follows:

- Collisions between the two buildings can occur at anywhere along the height of the 6-floor building, including its shallow foundation and the basement floor of the higher 12-floors building and not only at its top.
- Pounding increases top lateral displacement of the short (6 floors) building by 1.4 times, and for the tall (12 floors) building decreases it by 1.78 times (in adjacent building cases) than the single building cases when taking in consideration SSI, rather than fixed-base system, but at foundation level the short and tall building lateral displacement increase by 1.38 and 1.2 times than the corresponding values in single buildings with SSI effect.
- Because of the pounding of foundation, base shear decreases by 1.6 and increases by 1.4 times for short (6 floors) and tall (12 floors) buildings (in adjacent building cases) than single building cases with SSI effect, respectively, giving the short building the possibility in collision with basement floor columns

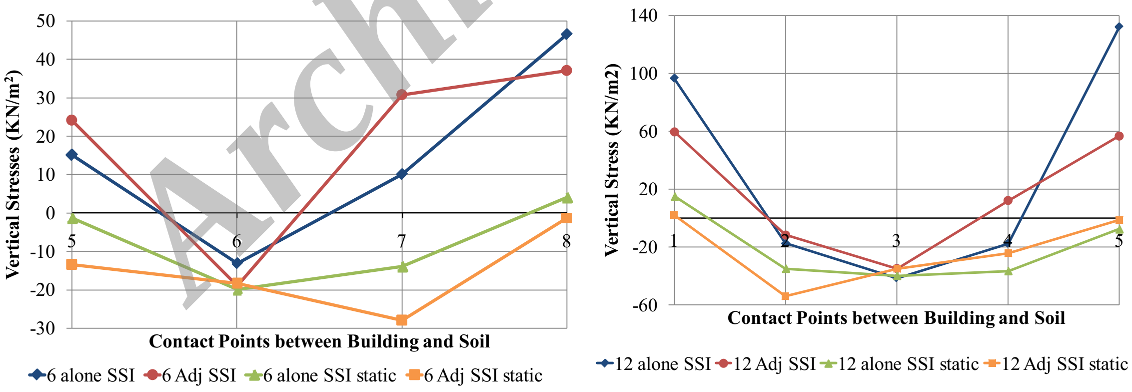


(a) S_{22} for single building with 6 floors **(b)** S_{22} for single building with 12 floors



(c) S_{22} for the two adjacent buildings

Fig. 11 Selective color contour plots of vertical stresses S_{22} (KN/m^2) under earthquake



(a) 6 floors building **(b)** 12 floors building

Fig. 12 Vertical stresses S_{22} (KN/m^2) between soil and buildings under different conditions

and increasing the total base shear values with respect to single building case.

- In short (6 floors) and tall (12 floors) buildings in adjacent building cases with effect of SSI, axial normal forces increases by 3.14 and 2.8 times than the adjacent cases without SSI effect.
- Soil–structure interaction effect magnifies the straining actions on adjacent buildings.
- Vertical stresses in soil underneath and around the two adjacent buildings under seismic load are tensed, especially in the short building, which indicates a separation of soil, whereas the tension stresses

decreases in adjacent buildings for short and tall buildings than the single buildings taking in consideration SSI.

- The force of collision increases by the softening of the soil especially at the foundations level.
- Basement floor of buildings improves the seismic performance considering SSI of the two adjacent buildings.
- Adjacent buildings must be founded in the same level; even they are of different heights.
- SSI effect must be taken into consideration in the seismic analysis of adjacent buildings especially those with different heights and different foundation levels.

References

Alam MI, Kim D (2014) Spatially varying ground motion effects on seismic response of adjacent structures considering soil structure interaction. Adv Struct Eng 17(1):131–142

Anagnostopoulos SA (1988) Pounding of buildings in series during earthquakes. Earthq Eng Struct Dyn 16:443–456

Anagnostopoulos SA (2004) Equivalent viscous damping for modeling inelastic impacts in earthquake pounding problems. Earthq Eng Struct Dyn 33(8):897–902

Anagnostopoulos S, Karamaneas CE (2008) Use of collision shear walls to minimize seismic separation and to protect adjacent buildings from collapse due to earthquake-induced pounding. Earthq Eng Struct Dyn 37(12):1371–1388

Anagnostopoulos SA, Spiliopoulos KV (1992) An investigation of earthquake induced pounding between adjacent buildings. Earthq Eng Struct Dyn 21:289–302

Behnamfar F, Madani B (2014) Effects of mutual cross interaction and pounding on nonlinear seismic response of adjacent buildings. In: Proceedings of the second European conference on earthquake engineering and seismology, Istanbul, pp 1–10

Cole G, Dhakal R, Carr A, Bull D (2011) An investigation of the effects of mass distribution on pounding structures. Earthq Eng Struct Dyn 40:641–659

ECP (2007) ECP-203, Egyptian code for design and construction of reinforced concrete structures, ECPCS-203, Housing and Building National Research Center, Ministry of Housing, Utilities and Urban Planning, Cairo

ECP (2008) ECP-201, Egyptian code for calculating loads and forces in structural work and masonry, Housing and Building National Research Center, Ministry of Housing, Utilities and Urban Planning, Cairo

Efraimiadou S, Hatzigeorgiou GD, Beskos DE (2013a) Structural pounding between adjacent buildings subjected to strong ground motions. Part I: the effect of different structures arrangement. Earthq Eng Struct Dyn 42(10):1509–1528

Efraimiadou S, Hatzigeorgiou GD, Beskos DE (2013b) Structural pounding between adjacent buildings subjected to strong ground motions. Part II: the effect of multiple earthquakes. Earthq Eng Struct Dyn 42(10):1529–1545

Ghandil M, Behnamfar F, Vafaeian M (2016) Dynamic responses of structure–soil–structure systems with an extension of the equivalent linear soil modeling. Soil Dyn Earthq Eng 80:149–162

Hao H, Gong L (2005) Analysis of coupled lateral-torsional-pounding responses of one-storey asymmetric adjacent structures subjected to bidirectional ground motions, part II: spatially varying ground motion input. Adv Struct Eng 8(5):481–496

Hao H, Liu XY, Shen J (2000) Pounding response of adjacent buildings subjected to spatial earthquake ground excitations. Adv Struct Eng 3(2):145–162

Jankowski R (2005) Non-linear viscoelastic modelling of earthquake-induced structural pounding. Earthq Eng Struct Dyn 34:595–611

Jankowski R (2008) Earthquake-induced pounding between equal height buildings with substantially different dynamic properties. Eng Struct 30:2818–2829

Karayannis CG, Favvata MJ (2005a) Earthquake-induced interaction between adjacent reinforced concrete structures with non-equal heights. Earthq Eng Struct Dyn 34:1–20

Karayannis CG, Favvata MJ (2005b) Inter-story pounding between multistory reinforced concrete structures. Struct Eng Mech 20(5):505–526

Madani B, Behnamfar F, Tajmir Riahi H (2015) Dynamic response of structures subjected to pounding and structure–soil–structure interaction. Soil Dyn Earthq Eng 78:46–60

Mahmoud S, Abd-Elhamed A, Jankowski R (2013) Earthquake-induced pounding between equal heights multi-storey buildings considering soil–structure interaction. Bull Earthq Eng 11:1021–1048

Naserkhaki S, Pourmohammad H (2012) SSI and SSSI effects in seismic analysis of twin buildings: discrete model concept. J Civil Eng Manag 6(18):890–898

Naserkhaki S, Abdul Aziz Farah NA, Pourmohammad H (2012) Earthquake induced pounding between adjacent buildings considering soil–structure interaction. Earthq Eng Eng Vibr 11(3):343–358

Naserkhaki S, El-Richa M, Abdul Aziz FNA, Pourmohammad H (2013) Separation gap, a critical factor in earthquake induced pounding between adjacent buildings. Asian J Civil Eng (BHRC) 14(6):881–898

Papadrakakis M, Apostopoulou C, Zacharopoulos A, Bitzarakis S (1996) Three dimensional simulation of structural pounding during earthquakes. J Eng Mech (ASCE) 122(5):423–431

Pawar PD, Murnal PB (2014) Effect of seismic pounding on adjacent blocks of unsymmetrical buildings considering soil–structure interaction. Int J Emerg Technol Adv Eng 4(7):391–395

Polycarpou PC, Komodromos P (2010) Earthquake-induced poundings of a seismically isolated building with adjacent structures. Eng Struct 32(7):1937–1951

Polycarpou PC, Papaloizou L, Komodromos P (2014) An efficient methodology for simulating earthquake-induced 3D pounding of buildings. Earthq Eng Struct Dyn 43(7):985–1003

Polycarpou PC, Papaloizou L, Komodromos P, Charmpis DC (2015) Effect of the seismic excitation angle on the dynamic response of adjacent buildings during pounding. Earthquakes Struct 8(5):1127–1146

Qin X, Chouw N (2013) Numerical investigation of seismic gap between adjacent structures with SFSI. In: Proceedings of the 2013 world congress on advances in structural engineering and mechanics (ASEM13), ICC-Jeju, pp 4179–4189

Rahman AM, Carr AJ, Moss PJ (2001) Seismic pounding of a case of adjacent multiple-story buildings of different total heights considering soil flexibility effects. Bull N Z Soc Earthq Eng 34(1):40–59

SAP2000® (2015) Version 17, linear and nonlinear static and dynamic analysis and design of three-dimensional structures. Computers and Structures, Inc., California

Shakya K, Wijeyewickrema AC (2009) Mid column pounding of multi-story reinforced concrete buildings considering soil effects. Adv Struct Eng 12(1):71–85

Van Mier JGM, Preuijssers AF, Reinhardt HW, Monnier T (1991) Load-time response of colliding concrete bodies. J Struct Eng (ASCE) 117:354–374

Wang LX, Chau KT, Wei XX (2009) Numerical simulations of nonlinear seismic torsional pounding between two single-story structures. Adv Struct Eng 12(1):87–101