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Seismic Response of Adjacent Unequal Buildings Subjected to Double Pounding Considering Soil-Structure Interaction

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Abstract: Various cases of two adjacent multi-story buildings with different numbers of floors and equal or unequal foundation levels under earthquake loading and considering soil-structure interaction (SSI) are investigated. A two-dimensional model for each case of the two adjacent unequal buildings without separation distance is used and a special arrangement of contact elements in the contact zone is employed to fulfil all possible deformation contact modes which take place under seismic loading. The soil is modelled by two-dimensional 4-node elements which are in contact with the foundations of the two adjacent buildings. This paper studies the earthquake-induced double pounding that takes place between the two adjacent unequal height buildings in some upper points at superstructure in the contact zone and also at foundation level, considering soil-structure interaction (SSI). The double pounding and the soil-structure interaction (SSI) effects should be taken into consideration in the seismic analysis of adjacent buildings especially those with different heights and different foundation levels.

Keywords: seismic response; adjacent buildings; pounding; foundation collision; soil-structure interaction; FEM

1. Introduction

Impacts due to earthquake-induced 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 different story heights of the adjacent buildings resulting in slab-column impacts) or collision at the foundation level.

Herein double pounding denotes the pounding which may take place between superstructure levels and foundation levels of the two adjacent buildings.

Pounding between adjacent buildings during earthquakes has attracted considerable interest, see, for example: Anagnostopoulos [1,2], Anagnostopoulos and Spiliopoulos [3], Karayannis and Favvata [4,5], Anagnostopoulos and Karamaneas [6], Efraimiadou et al. [7,8]. Investigation on the effects of the mass distribution on pounding structures (Cole et al. [9]), pounding of seismically isolated buildings (Polycarpou and Komodromos [10]), 3D pounding of buildings (Polycarpou et al. [11,12]), torsional building pounding (Wang et al. [13]), pounding of buildings with different dynamic properties (Jankowski [14]), mid-column building pounding and corner building pounding (Papadrakakis et al. [15]) are also some important examples. However, the above significant studies, they did not account for the influence of the underlying soil on building pounding.

Hao et al. [16] and Hao and Gong [17] investigated the seismic responses of the adjacent buildings subjected to pounding due to spatially varying earthquakes. Rahman et al. [18] studied the effects of foundation compliance of the conventional structures and the importance of soil flexibility has been highlighted. Shakya and Wijeyewickrema [19] analysed unequal story height buildings considering the underlying soil effects to study the mid-column pounding of the adjacent buildings. Naserkhaki and Pourmohammad [20] presented a numerical study of soil-structure interaction (SSI) and structure-soil-structure interaction (SSSI) effects on the response of twin buildings during earthquake excitations using the discrete model concept. Naserkhaki et al. [21] concluded that 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. Mahmoud et al. [22] investigated the coupled effect of the supporting soil flexibility and pounding between neighbouring, insufficiently separated equal height buildings under earthquake excitation. Qin and Chouw [23] presented a numerical investigation of the seismic gap between adjacent structures with structure-foundation-soil interaction (SFSI). Naserkhaki et al. [24] investigated the earthquake induced building pounding problem for various separation gaps and for two foundation conditions, fixed-based and structure-soil-structure interaction (SSSI). Behnamfar and Madani [25] studied the effects of mutual cross interaction and pounding on the nonlinear seismic response of adjacent sample buildings. Alam and Kim [26] studied the spatially varying ground motion effects on the seismic response of adjacent structures considering soil-structure interaction (SSI). Pawar and Murnal [27] concluded that consideration of soil-structure interaction (SSI) increases the 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. Madani et al. [28] studied the effects of pounding and structure-soil-structure interaction on the nonlinear dynamic behaviour of selected adjacent structures. Ghandil et al. [29] studied the dynamic responses of structure-soil-structure systems with an extension of the equivalent linear soil modelling and investigated the problem of cross interaction of two adjacent buildings through the underlying soil.

Recently, Farghaly [30] studied the double pounding of two specific adjacent buildings under seismic load considering SSI. Kharazian and Lopez-Almansa [31] presented an overview of research on seismic pounding between buildings with aligned slabs. Ghandil and Aldaikh [32] investigated the probable seismic pounding effects on the response of adjacent symmetric buildings considering inelastic structure-soil-structure interaction. Li et al. [33] investigated pounding phenomena considering structure-soil-structure interaction (SSSI) under seismic loads and found that pounding and SSSI effects worsen the adjacent buildings' conditions because their acceleration and shear responses are amplified after pounding considering SSSI.

This paper studies the seismic response of various cases of two adjacent buildings with different numbers of floors and equal or unequal foundation levels subjected to double pounding and considering soil-structure interaction (SSI). FEM 2D models were created for the soil and the two adjacent buildings of different heights and foundation levels without separation distance in order to study the phenomena of double pounding, which may take place in some upper points at superstructure in the contact zone and also at foundation levels, between the two buildings subjected to earthquake and considering SSI.

2. Impact Elements

Impacts between two colliding structures are simulated using special purpose contact elements that become active when the corresponding nodes come into contact. In this work, the adjacent buildings were connected by a combination of the gap element and the Kelvin-Voigt model. Figure 1 shows the impact element for each point between the two adjacent buildings, from foundation level to top point of the lower adjacent building.

To model impact between the two colliding buildings, the linear spring-damper (Kelvin-Voigt model) element is mostly used, where K_L is the stiffness and C_L is the damping coefficient (Anagnostopoulos [1], Shakya and Wijeyewickrema [19]). Numerical simulation performed by Jankowski [34] showed that for concrete to concrete impact, K_L = 9350 t/m provides good correlation between experimental results provided by Van Mier et al. [35] and theoretical results. In the present study, the same value of K_L is used.

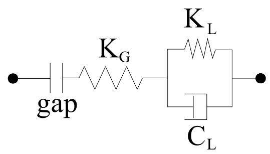


Figure 1. Impact element composed of a gap element and a Kelvin-Voigt element.

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.

3. Model Description

The used earthquake excitation was the 1940 El Centro earthquake accelerogram (Figure 2) with peak ground acceleration (PGA) of 0.50 g and the time history analysis was about 40-s duration consisting of 4000 steps.

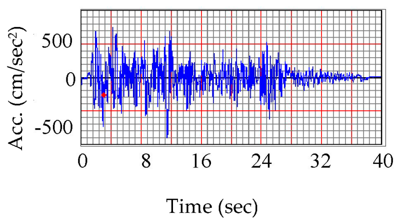
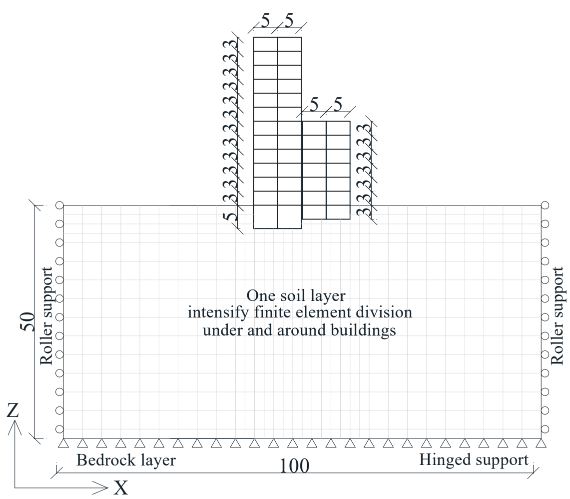


Figure 2. The El Centro earthquake accelerogram.

Herein the SAP2000 (Computers and Structures, Inc., Walnut Creek, CA, USA) [36] software was used to model the adjacent buildings and the underlying soil. The model of the two adjacent buildings with contact elements in the contact zone and the underlying soil is shown in Figure 3.



(**a**)

Figure 3. *Cont.*

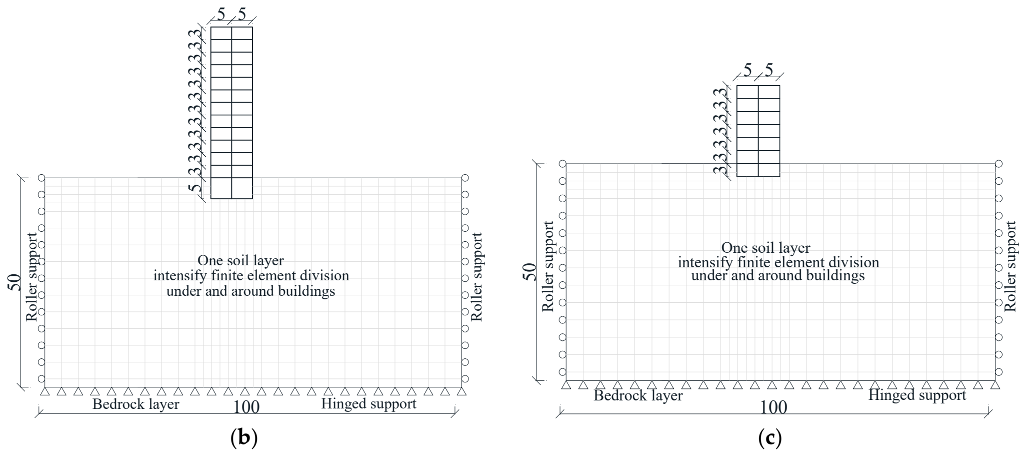


Figure 3. The buildings with soil mesh of modelled representation. (**a**) The two adjacent buildings with unequal foundation levels; (**b**) Single 12-floor building (with foundation at −5 m); (**c**) Single 6-floor building (with foundation at −3 m).

This model incorporates the main buildings (modelled using beam and slab elements), the foundations (modelled as single footings) and the soil mesh which is of quadrilateral shape. 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, the soil is assumed homogeneous and its properties are as shown in Table 1.

Table 1. Soil Properties.

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

As shown in Figure 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 buildings) which were proven to be small enough to transmit all the frequency components of the input motions.

The shown (in Figure 3) buildings are of 12 floors with basement floor (5 m from ground level) and of 6 floors with shallow (3 m from ground level) foundation, with 3 m height of each floor. The gap size between the two buildings is zero. Columns and beams are modelled as frame elements and vertical distributed total (dead and live) load acting on beams of each floor is assumed 2.5 t/m. The foundations (single footings) are also modelled using frame elements. In this paper, the Egyptian Codes of Practice (ECP-203, ECP-201) [37,38] were used. The soil is modelled 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 v.17 computer program [36]. Herein, the fine mesh option was used; furthermore, some other techniques in modelling have been developed as those by Nascimbene [39,40] to effectively solve problems like locking phenomena that may appear in meshing. The assumption of constant damping (5% for all modes) for the numerical model is incorporated in SAP2000 [36].

The sub-grade is modelled with plane strain elements with nonlinear elastic isotropic material. The interaction between the superstructure and the sub-grade is modelled with friction in 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.

4. Results and Discussion

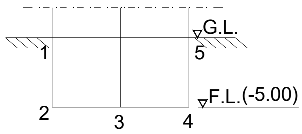
Table 2 shows the definition of the symbols used in the following Figures.

Table 2. Symbol definitions.

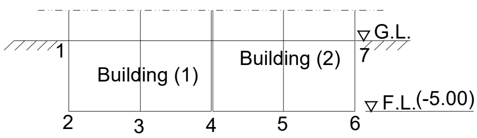
Symbol	Definition	Symbol	Definition
F.L.	Foundation Level.	s	Building considering SSI.
G.L.	Ground Level.	S	Single building considering SSI.
12-12	Two adjacent buildings: both with 12 floors.	f	Fixed base building.
12-10	Two adjacent buildings: one with 12 floors and the other with 10 floors.	F	Fixed base single building.
12-8	Two adjacent buildings: one with 12 floors and the other with 8 floors.	U	Displacement.
12-6	Two adjacent buildings: one with 12 floors and the other with 6 floors.	a	Acceleration.
12-4	Two adjacent buildings: one with 12 floors and the other with 4 floors.	Q	Base shear force.
12-2	Two adjacent buildings: one with 12 floors and the other with 2 floors.	M	Base bending moment.
h	High (tall) building with 12 floors.	N	Base normal force.
s	Short (low) building.	Sx	Lateral soil stress.
alone	Single building.	Sz	Vertical soil stress.
SSI	Soil Structure Interaction effect.	N L	Lateral normal force at foundation.

4.1. Adjacent Buildings with Equal Foundation Levels

Figure 4 shows the distribution of the soil points around the foundation of the single and the two adjacent buildings, where the soil stresses in the x (horizontal) and z (vertical) directions will be calculated.



(**a**) Single building.



(**b**) Two adjacent buildings.

Figure 4. Points distributed around the foundations of the single and two adjacent buildings.

Figure 5 shows the top lateral displacements of the two adjacent buildings with and without SSI and the single buildings with SSI and without SSI (with dash lines). The top displacements of the adjacent short (low) buildings and single buildings in the SSI case are nearly similar; the top displacements of the tall building are nearly constant, in contrary to the gradually lower adjacent building in which the top displacements are gradually decreasing as its height is decreasing. The lateral top displacements in the cases of fixed adjacent buildings are smaller than the corresponding values taking into consideration the effect of SSI. For the single buildings with SSI, the lateral top displacements are smaller with respect to the corresponding values of the two adjacent buildings with SSI effect.

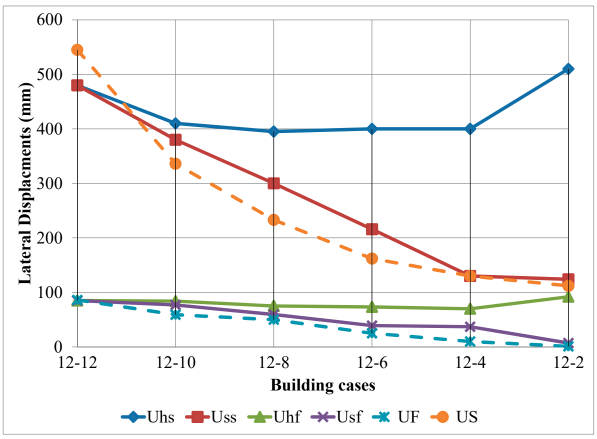


Figure 5. Top lateral displacements in buildings with different configurations.

Figure 6 shows the top acceleration in the *x* direction (top lateral acceleration) of the buildings in different cases. The maximum values of the top acceleration were found in the case of fixed base single buildings, the values of accelerations of the single buildings with the effect of SSI were smaller than the corresponding values of acceleration with fixed base and the top acceleration of the adjacent buildings with fixed base shows the smallest values with respect to the corresponding values of the other cases.

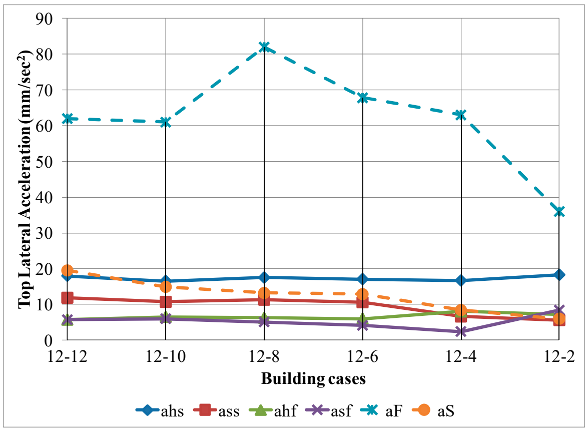


Figure 6. Top acceleration in *x* direction in buildings with different configurations.

Figure 7 shows the base shear force of the buildings with and without SSI, taking also into consideration the pounding effect between the two adjacent buildings with different heights. The maximum values of base shear force, for all the different configuration cases of the buildings, were found as constant values for the single buildings with SSI, while the lowest values of base shear force were found in the fixed base for single and adjacent building cases. The pounding effect appears with SSI in the cases of adjacent buildings with 12 and 8, 12 and 4 and 12 and 2 floors.

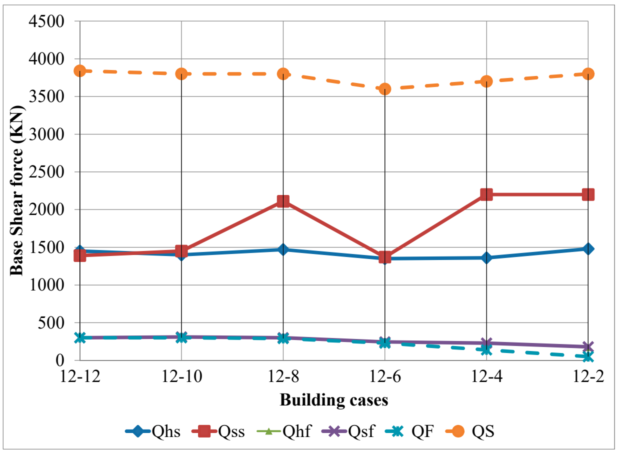


Figure 7. Base shear force in buildings with different configurations.

Figure 8 shows the base bending moment of the buildings with and without SSI, taking also into consideration the pounding effect between the two adjacent buildings with different heights. The maximum values of base bending moment, for all the different configuration cases of the buildings, were found for the single buildings with SSI, while the lowest values of base bending moment were found in the fixed base for single and adjacent building cases. The pounding effect at foundation level appears with the effect of SSI in the adjacent building cases of 12 and 8, 12 and 6 and 12 and 2 floors.

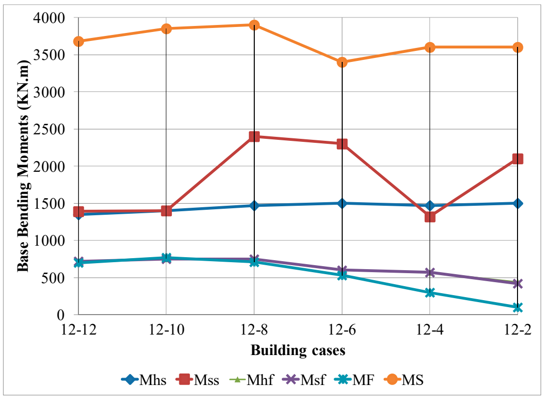


Figure 8. Base bending moment in buildings with different configurations.

Figure 9 presents the base normal force of the buildings with and without SSI. The base normal force is decreased with the decrease of the building height for the short building in the adjacent buildings with SSI but it is constant in the high building with and without SSI. The base normal force in the case of the single building with SSI effect is decreased gradually with the decrease the building height. The base normal force appears to have nearly constant values in the high building of the adjacent buildings with and without the effect of SSI.

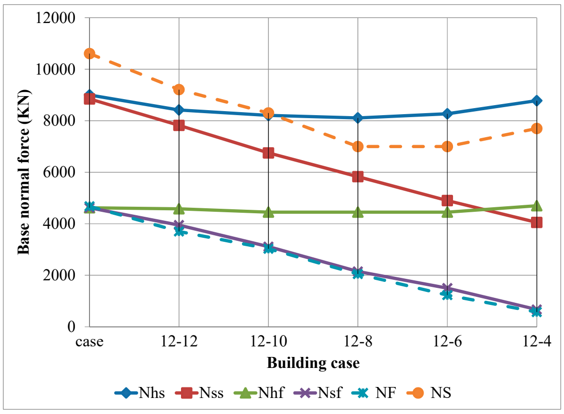
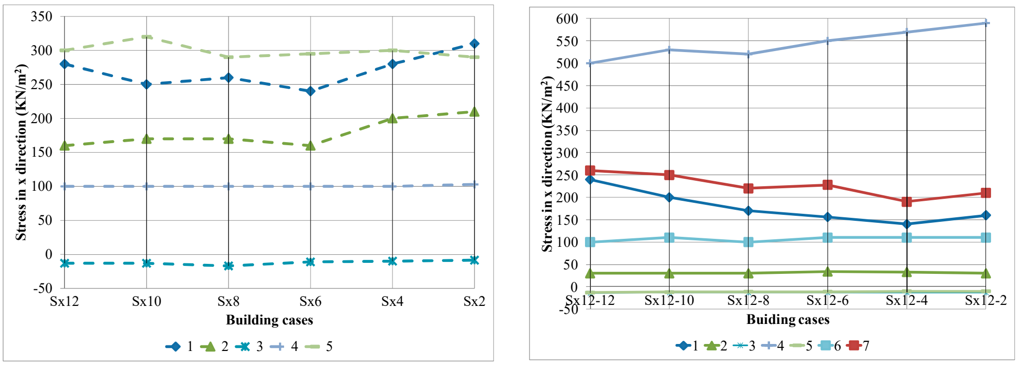


Figure 9. Base normal force in buildings with different configurations.

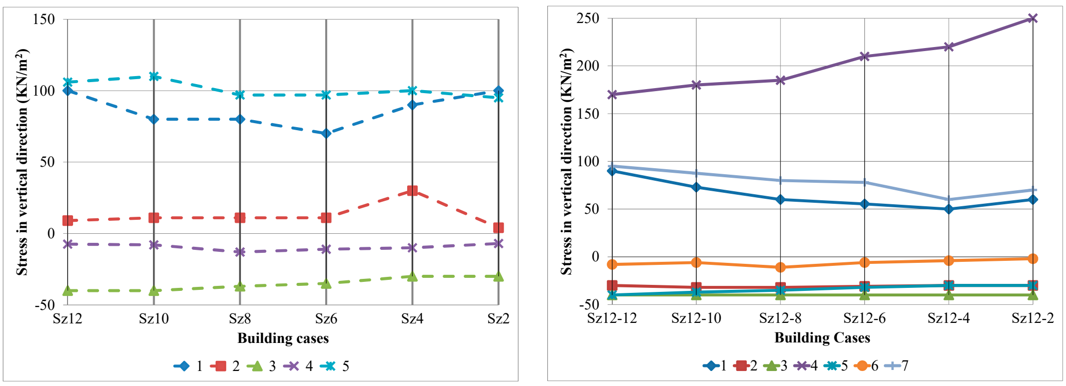
Figure 10 represents the stress in the soil around the foundation of the single and the two adjacent buildings in the lateral direction (at the shown in Figure 4 contact points between the soil and the buildings). Figure 10a shows the stress in the soil around the foundation in x direction for a single building with different heights, where all points are subjected to tensile stress in the soil around the foundation of the single building for all heights but the point 3 (under the building) is subjected to compressive stress in the soil. Figure 10b represents the stress in soil in x direction around the foundation of the two adjacent buildings, where all stresses are tensile around the buildings except for the point 5 (under the building) and the maximum tensile stress was found at point 4; the stresses are decreased in the case of two adjacent buildings especially for points 1, 2, 3, 6 and 7 having positive values (i.e. tensile stresses in the soil) but point 5 is subjected to compressive stress. The pounding effect, especially the foundation pounding, affects the values of stress in the soil around the foundation of the two adjacent buildings with respect to the single building case.



(**a**) Single building with different heights. (**b**) Two adjacent buildings with different heights.

Figure 10. Stress in the soil in *x* direction around the foundation of the single and adjacent buildings.

Figure 11 shows the vertical stress in the soil around and under the buildings (at the shown in Figure 4 contact points between the soil and the buildings) for different configurations. Figure 11a shows the vertical stress in the soil for the single building case with different heights, where vertical stresses are tensile in points 1, 2 and 5 when the building is subjected to earthquake but points 3 and 4 show compressive stress in the soil. Figure 11b shows the vertical stress in soil around the foundations of the two adjacent buildings, where the points 2, 3, 5 and 6 (the points on foundation level at one line) are subjected to compressive stress but the points 1, 4 and 7 are subjected to tensile stress in the soil around the basement floors of the two buildings. The maximum tensile stress appears in point 4 (i.e. the point between the two adjacent buildings) and this stress is increased gradually with the decreasing of the height of the adjacent building by 2 floors every time; that means the decreasing of the height of the adjacent building will subject the short building to overturning under earthquake load. The points 1 and 7 are nearly similar to the corresponding values in single building case.



(**a**) Single building with different heights. (**b**) Two adjacent buildings with different heights.

Figure 11. Stress in the soil in *z* direction around the foundation of the single and adjacent buildings.

Figure 12 represents the lateral normal force at the foundation for different configurations of buildings. The lateral normal force at the foundation was created as a result of the earth pressure on the basement floor at foundation level. Two cases were studied: the first case was the single building (alone) with the SSI effect and the second case was the two adjacent buildings with the SSI effect. The values of lateral normal forces at the foundation in the case of the single building were constant (less than 3000 KN) for all height levels of the building (12, 10, 8, 6, 4 and 2 floors). The lateral normal forces at the foundation for the two adjacent buildings were computed and the low height building shows high values of lateral normal forces by nearly 2.7 times more than the single building and the tall building lateral normal force values increased by nearly 1.5 times than the single building case with different heights. The lateral normal force values in the short building in the two adjacent buildings increased by nearly 1.66 times than the corresponding values in the tall building and the high value of the pushing forces of the tall building on the short building increased the value of the lateral normal forces at the foundation of the short building, which is an evidence of pounding between the two foundations.

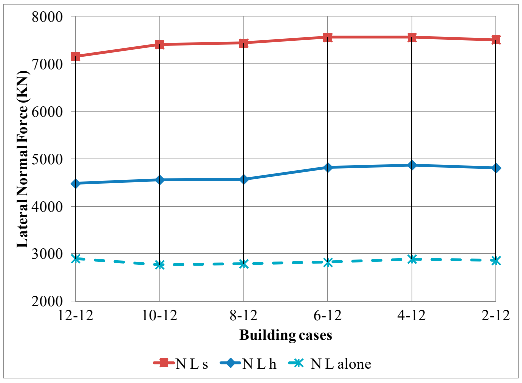


Figure 12. Lateral normal force at the foundation for the two adjacent and single buildings with SSI.

Figure 13 shows the shear forces in the columns of the tall building of 12 floors in the case of the two adjacent buildings with different heights for the short building. The maximum shear force in column occurred at basement floor (indicated by 0). For the two adjacent buildings with the same height, the shear force at basement floor decreased by 1.6 and 1.88 times than the corresponding values in the cases of the two adjacent buildings with 12 and 2 floors and the single building respectively. The shear force at basement floor increased with the decrease of the height of the adjacent building (this means that the foundation pounding increases the shear force gradually as the adjacent building height decreases). The pounding with the top of the adjacent short buildings increases the shear force in that top level and whatever the height of the adjacent building is, the tall building with 12 floors height shows an increase in shear force, e.g. for the two adjacent buildings with 12 and 2 floors, the shear force in column increased by 2 times than the single building case.

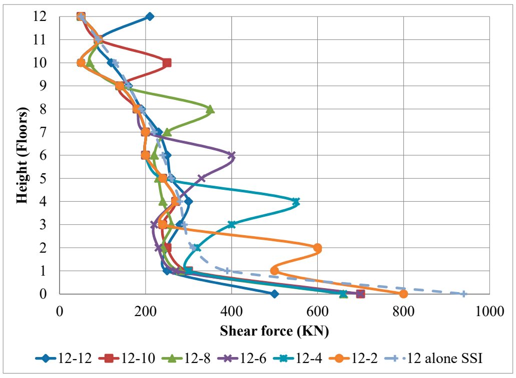


Figure 13. Shear force in the tall building in the case of the two adjacent buildings with SSI.

4.2. Adjacent Buildings with Unequal Foundation Levels

In order to confirm and extend the concept of the dual collision of the buildings, another case is also tested, which is the case of two adjacent buildings but with different (i.e. unequal) foundation levels. Figure 14b shows the difference in foundation levels between the two buildings. The points from 1 to 5 will be checked for soil stresses around and under the single building (with basement floor) (Figure 14a), while for the case of the two adjacent buildings, the points from 1 to 8 will be checked

(Figure 14b). In Figure 14b, the building (1) indicates the tall building (with basement floor shallow foundation) which has a constant height of 12 floors in all the cases of analysis, while the building (2) indicates the short building (with shallow foundation) which is shortened by two floors each time.

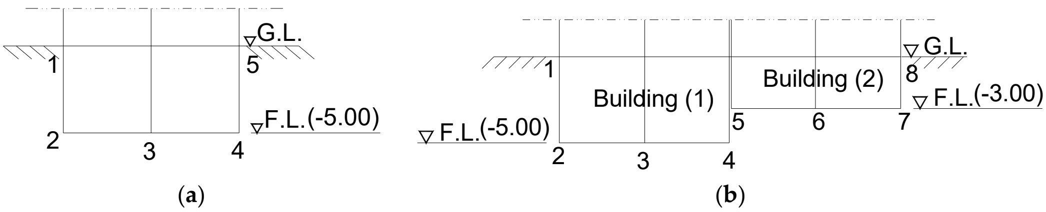


Figure 14. Points distributed around the foundations of the single building and the two adjacent buildings with unequal foundation levels. (**a**) Single building basement foundation; (**b**) The foundations with unequal levels of the two adjacent buildings.

Figure 15 shows the top lateral displacements and accelerations of the two adjacent buildings founded on soil with unequal foundations levels. Figure 15a shows the lateral top displacement of the two adjacent buildings and single buildings with SSI, where the displacement increased in the tall building more than the corresponding values in the case of equal foundation level but for the short building cases the values were similar. Figure 15b shows the lateral top acceleration for the single and the two adjacent buildings.

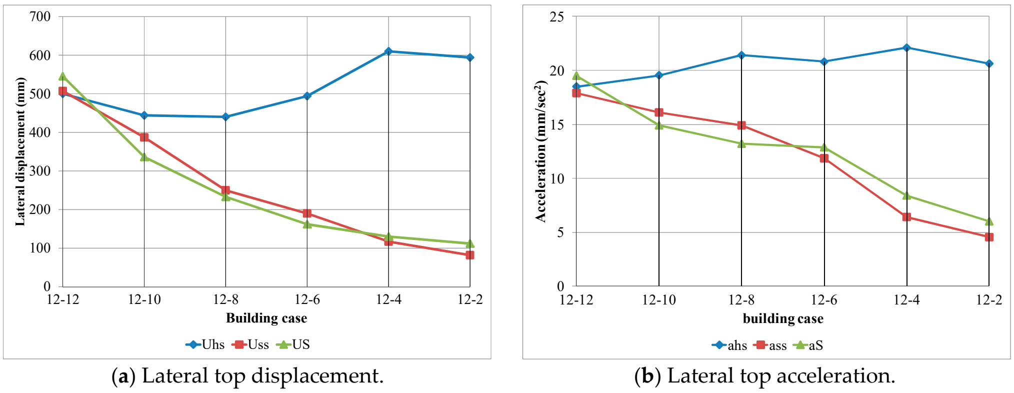
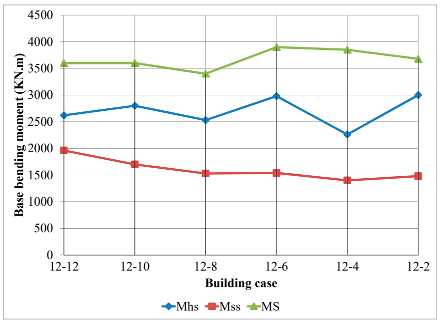
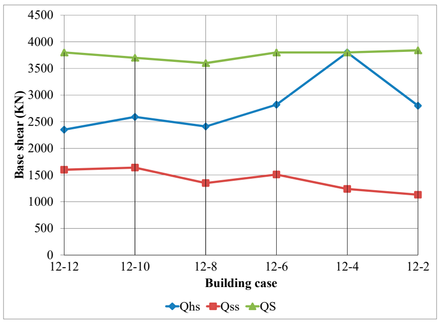


Figure 15. Comparison for top displacement and acceleration between the single and the two adjacent buildings with unequal foundation levels and SSI.

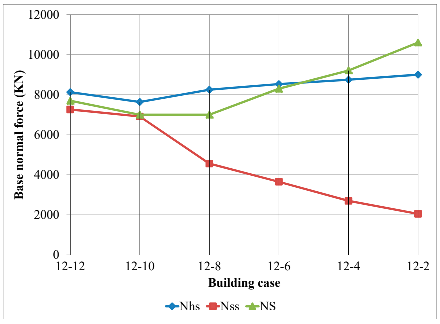
Figure 16 represents the straining actions in the single and the two adjacent buildings with the effect of SSI under seismic load. Figure 16a shows the base bending moment in the two adjacent and single buildings, where the base moment in the short building is smaller than the tall building by nearly 1.6 times and the single building bending moment increased by 2.3 and 1.4 times than the short and tall of the two adjacent buildings respectively. The base bending moment in the case of equal foundation level in the short building is bigger than the corresponding values in the case of unequal foundations levels. Figure 16b shows the base shear force in the two adjacent and single buildings, where the base shear force in the short building is smaller than the tall building by 1.4 times and by 2.3 times than the base shear force in the single building. Figure 16c represents the base normal force in the single and two adjacent buildings, where the base normal force in the short building of the two adjacent buildings decreased with the decreasing of its height.



(**a**) Base bending moment.



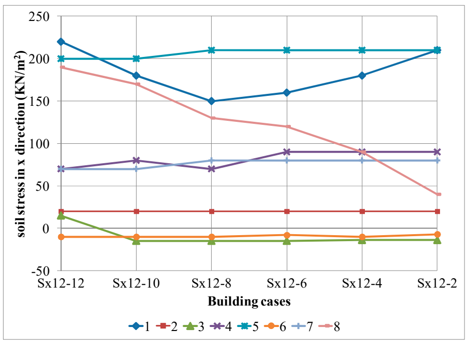
(**b**) Base shear force.



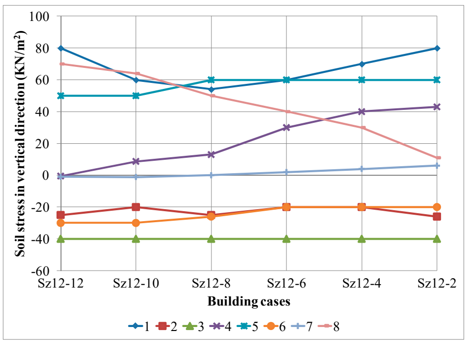
(**c**) Base normal force.

Figure 16. Straining actions at the base of the single and the two adjacent buildings with unequal foundation levels and SSI.

Figure 17 represents the lateral and vertical stresses in the soil around the foundation of the two adjacent buildings at the shown in Figure 14b contact points between the soil and the buildings. Positive stress values denote tension while negative stress values denote compression. Figure 17a represents the stress in the soil in x direction around the foundation of the two adjacent buildings. Figure 17b shows the vertical stress in the soil around the foundations of the two adjacent buildings. As shown in Figure 17b, the points 1, 4, 5, 7 and 8 are subjected to tensile vertical stress in the soil around the basement floors of the two buildings. The pounding effect, especially the foundation pounding, affects the values of stress in the soil around the foundation of the two adjacent buildings.



(**i**) Soil stress in x direction.



(**ii**) Soil stress in z direction.

Figure 17. Stresses in the soil around the foundation of the two adjacent buildings.

Figure 18 shows the lateral normal force at the foundation of the single and the two adjacent buildings. The lateral normal force at the foundation, in general, is less than the corresponding value in the case of equal foundation levels. The lateral normal force in the short building in the unequal foundation level case is less than the corresponding value in the equal foundation level case by nearly 1.3 times and also the lateral normal force in the tall building in the unequal foundation level case is less than that in the equal foundation level case by nearly 1.5 times.

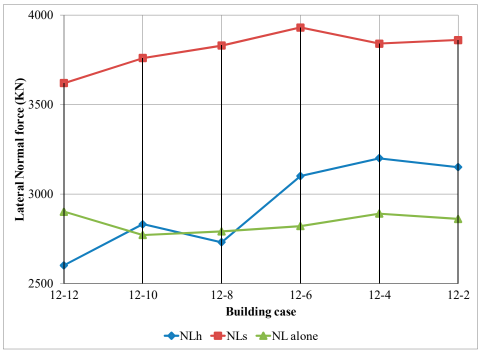


Figure 18. Lateral normal force at the foundation of the single and the two adjacent buildings with unequal foundation levels and SSI.

Figure 19 shows the shear force over the height of the tall building in the two adjacent buildings with unequal foundation levels. The shear force along the height of the building shows high values in the level of the basement of the tall building (as the short building hits the basement column and so pounding occurs) resulting in an increase of the shear force much greater than the corresponding values in the case of equal foundation levels.

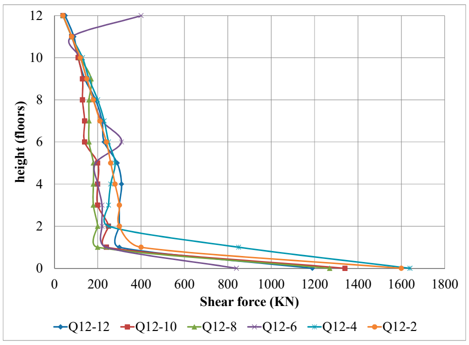
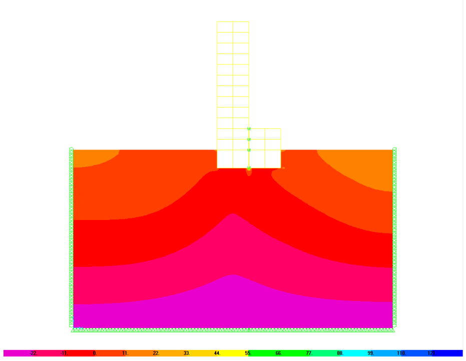


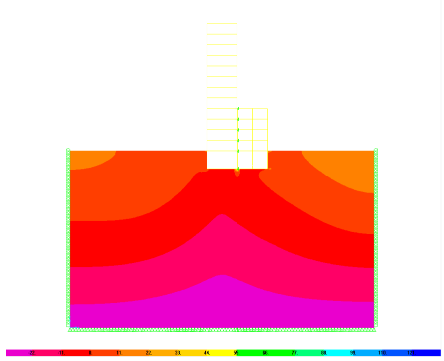
Figure 19. Shear force over the height of the tall building in the two adjacent buildings with unequal foundation levels and SSI.

4.3. Soil Response

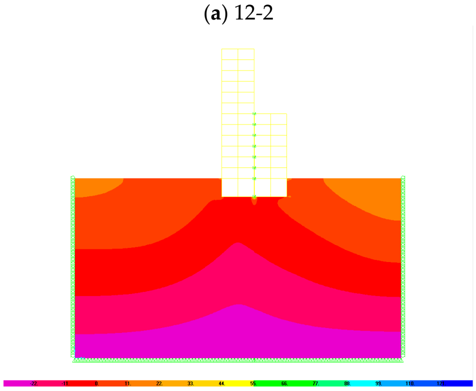
Figures 20 and 21 show the stresses in the lateral and vertical direction respectively in the soil underneath the two adjacent buildings with equal foundation levels. Figure 20a–f represents the lateral stresses in soil under and around the foundation of the two adjacent buildings with equal foundation levels, where lateral stresses increased in the side of the short building in the opposite direction of the earthquake. Figure 21a–f represents the vertical soil stresses underneath and around the equal foundation of the two adjacent buildings; when the two buildings are close or equal in height, the vertical stresses under the buildings are nearly normally distributed. The pounding effect, especially the foundation pounding, affects the values of stress in the soil around the foundation of the two adjacent buildings.



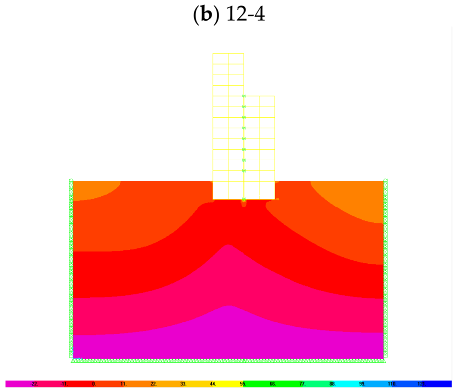
(**a**) 12-2



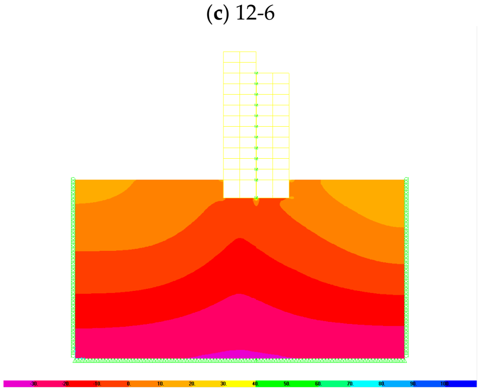
(**b**) 12-4



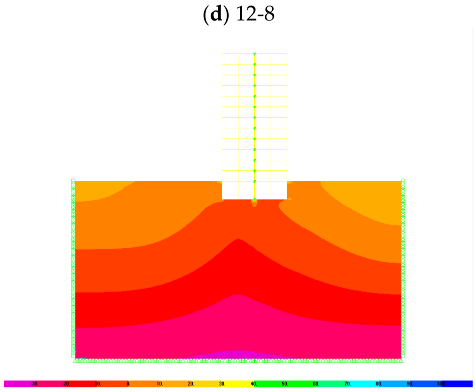
(**c**) 12-6



(**d**) 12-8

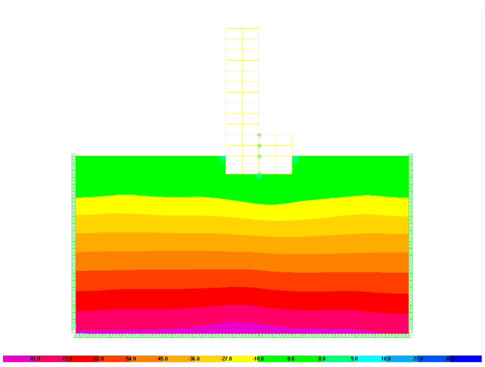


(**e**) 12-10

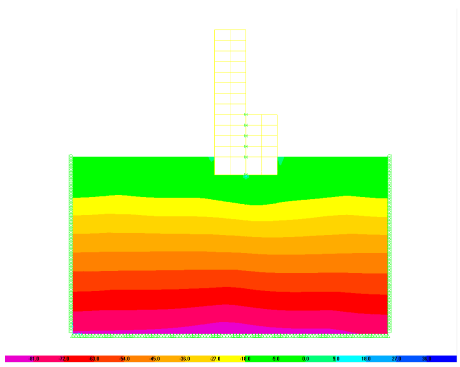


(**f**) 12-12

Figure 20. Lateral soil stresses (KN/m^2) for the two adjacent buildings with equal foundation levels.

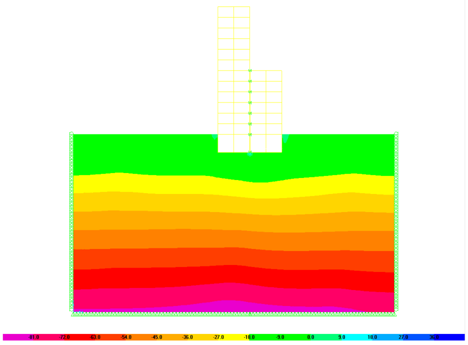


(**a**) 12-2

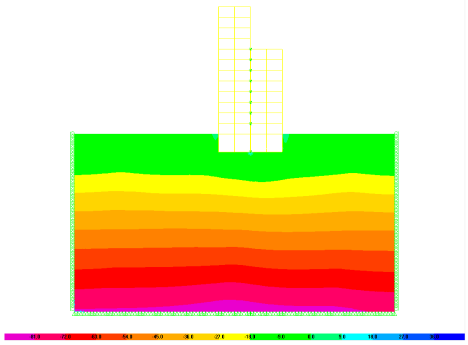


(**b**) 12-4

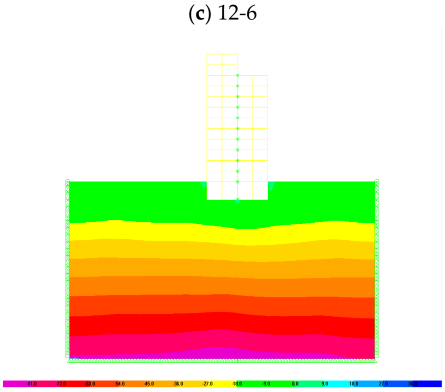
Figure 21. *Cont.*



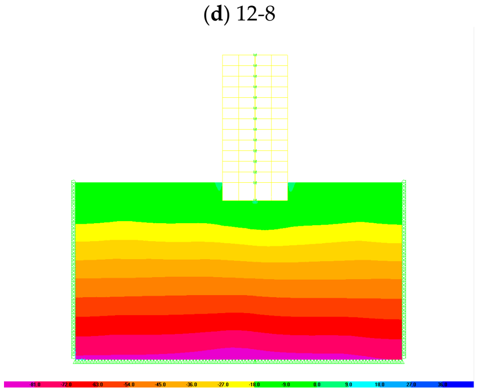
(**c**) 12-6



(**d**) 12-8



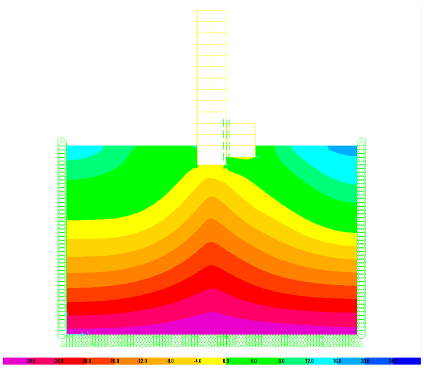
(**e**) 12-10



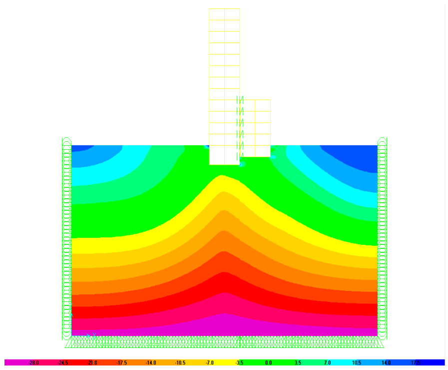
(**f**) 12-12

Figure 21. Vertical soil stresses (KN/m^2) for the two adjacent buildings with equal foundation levels.

Figures 22 and 23 show the stresses in the lateral and vertical direction respectively in the soil underneath the two adjacent buildings with unequal foundation levels. Figure 22a–f represents the lateral stresses in the soil under and around the foundation of the two adjacent buildings with unequal foundation levels, where the lateral stresses increased in the side of the short building in the opposite direction of the earthquake. Figure 23a–f represents the vertical soil stresses underneath and around the unequal foundation of the two adjacent buildings; when the two buildings are close or equal in height, the vertical stresses under the buildings are nearly normally distributed. The pounding effect, especially the foundation pounding, affects the values of stress in the soil around the foundation of the two adjacent buildings.

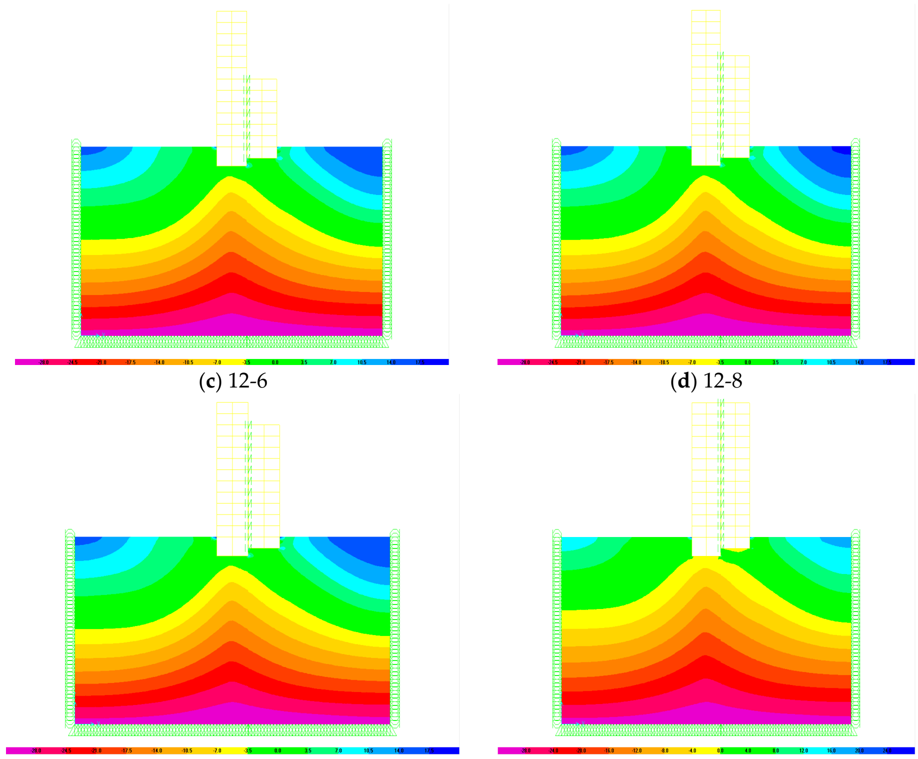


(**a**) 12-2



(**b**) 12-4

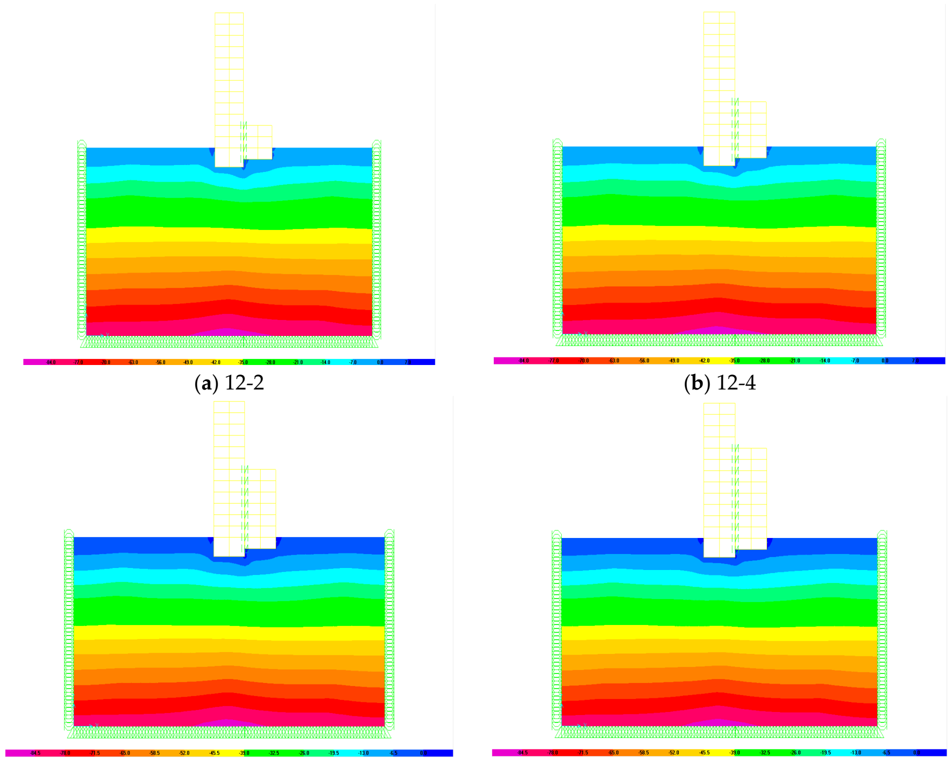
Figure 22. *Cont.*



(**c**) 12-6 (**d**) 12-8

(**e**) 12-10 (**f**) 12-12

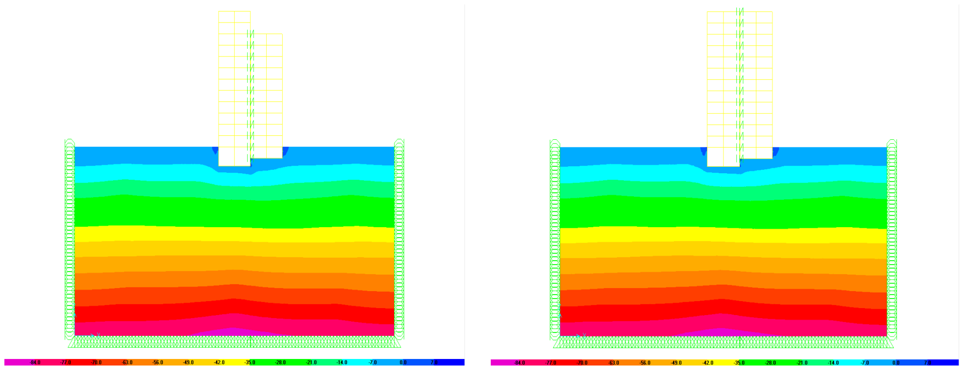
Figure 22. Lateral soil stresses (KN/m^2) for the two adjacent buildings with unequal foundation levels.



(**a**) 12-2 (**b**) 12-4

(**c**) 12-6 (**d**) 12-8

Figure 23. *Cont.*



(**e**) 12-10 (**f**) 12-12

Figure 23. Vertical soil stresses (KN/m^2) for the two adjacent buildings with unequal foundation levels.

5. Conclusions

Various cases of two adjacent buildings with different numbers of floors and equal or unequal foundation levels under earthquake loading were tested with and without the SSI effect to demonstrate the pounding at the top level of the low building and the pounding at foundation level. FEM 2D models were created for the soil and the buildings in order to study the phenomena of double pounding (at the top of the low building and at foundation level) which occurred in the two adjacent buildings subjected to earthquake. Top displacement and acceleration, base normal force, base shear force, base moment and lateral normal force at the foundation were calculated for different configurations of the buildings under earthquake load and comparisons were made between the two adjacent buildings and the single buildings with and without the effect of SSI. From the above comparisons, the following conclusions can be drawn:

- The top lateral displacement in the single and the two adjacent buildings is bigger in the SSI effect case than in the fixed base case.
- When considering the SSI effect, the top acceleration of the short building in the two adjacent buildings decreases with the decrease of its height, while the top acceleration in the tall building is not strongly affected by the height of the short building.
- The base shear forces, the bending moments and the base normal forces in the two adjacent buildings are bigger when considering the SSI effect than in the fixed base case.
- The shear force in the column in the basement level is bigger than in the floor levels for the different heights of the two adjacent buildings.
- The results of the straining actions on the two adjacent buildings subjected to earthquake considering SSI reveal the double pounding at top of the low building and at foundation level.
- The importance of equal foundation levels should be considered for adjacent buildings even if they have not the same number of floors.
- The soil-structure interaction (SSI) and the double pounding effects should be taken into consideration in the building design and the seismic analysis of adjacent buildings especially those with different heights and different foundation levels.

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Conflicts of Interest: The authors declare no conflict of interest.

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