

**Research Note****Torsional Earthquake-Induced Pounding between Adjacent Buildings Founded on Different Soil Types****Mahmoud Miari^{1*} and Robert Jankowski²**

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Received: 12/02/2024**Revised:** 08/06/2024**Accepted:** 26/06/2024**ABSTRACT**

This paper investigates the effect of the soil type on the torsional response of buildings experiencing torsional pounding due to earthquake excitations. Six buildings (one 4-storey building and five 6-storey buildings) with different configurations have been considered. First, pounding between different structures has been analysed for a specified soil type and the effect of the torsional pounding and the contact asymmetry on the torsional response of colliding buildings has been investigated. Then, these pounding cases have been considered for different soil types to study the effect of the soil type on the torsional response of buildings experiencing torsional pounding. Five soil types have been considered, i.e. hard rock, rock, very dense soil and soft rock, stiff soil and soft clay soil. The results of the study indicate that the earthquake-induced torsional pounding causes an increase in the peak storey rotation of the colliding buildings as compared to the symmetric pounding in all cases. Higher peak storey rotations have been experienced for colliding buildings founded on the soft clay soil, then for buildings founded on the stiff soil, then for buildings founded on very dense soil and soft rock, and finally for buildings founded on the rock and hard rock.

Keywords:

Structural pounding;
Irregular buildings;
Torsional response;
Soil type; Earthquakes

1. Introduction

Earthquake-induced pounding is defined as the collisions that occur between adjacent buildings during earthquakes. These collisions have a significant effect on the response of the colliding structures (Anagnostopoulos, 1988; Favvata, 2017; Rezaei et al., 2020; Mavronicola et al., 2020; Miari & Jankowski, 2022a; b). Earthquake-induced pounding has been experienced in several earthquakes, such as in the Mexico earthquake where 40% of the buildings experienced collisions and in 15% of buildings with severe damage or collapse pounding was found (Rosenblueth & Meli, 1986), and in 20-30% of them pounding was the major reason of damage (Anagnostopoulos, 1996). Also,

the effects of pounding were observed in 200 out of 500 surveyed buildings after the Loma Prieta earthquake (Kasai & Maison, 1997). Indeed, pounding was also found in some recent earthquakes, such as in Christchurch (New Zealand 2010 and 2011) (Cole et al., 2010; 2011; 2012a; 2012b) and Gorkha (Nepal 2015) (Sharma et al., 2016). Also, pounding between irregular structures was experienced in the Puebla-Morelos earthquake (Mexico 2017) (Preciado et al., 2022).

Earthquake-induced pounding has been extensively studied in the past (see Miari et al., 2019; 2021, for details). Pounding was found to significantly increase the acceleration, shear forces and

impact forces of colliding buildings while the displacement may increase or decrease (Soltysik & Jankowski, 2013; Raheem, 2006; Soltysik & Jankowski, 2015; Rojas & Anderson, 2012; Raheem, 2014; Inel et al., 2014; Efraimiadou et al., 2013; Soltysik et al., 2017). This amplification is experienced in the principal direction of collisions and unaffected in other directions (Jameel et al., 2013). The amplification significantly depends on the dynamic properties of the colliding structures (mass, ductility, damping ratio, period, etc.) (Jankowski, 2006; 2005; Hosseini et al., 2022). The frequency ratio has the largest influence on the maximum impact force and ductility demands, while the frequency and mass ratios have the largest influence on the impact impulse (mass ratio is predominant for low frequency range) (Crozet et al., 2018; 2017). However, most of the previous studies on structural pounding during earthquakes considered only symmetric pounding. Meanwhile, the asymmetrical behaviour of buildings may take place during ground motions, either due to contact asymmetry or structure asymmetry (e.g. irregular structures, soft storeys, etc.). The asymmetry leads to torsional pounding which may have a substantial effect on the colliding structures (Chau et al., 2004; Wang & Chau, 2008; Wei et al., 2009; Fiore et al., 2013; Karayannis & Naoum, 2018; Ozer, 2024; Raheem et al., 2019). Torsional pounding is more significant than translational pounding because of the torsional effect. Torsional pounding is more complex than the solely translational pounding. Torsional pounding leads to a significant increase in the number of collisions, building displacements, shear demands, torsion demands, and ductility demands (Chau et al., 2004; Wang & Chau, 2008; Wei et al., 2009; Fiore et al., 2013; Karayannis & Naoum, 2018). Indeed, the building irregularity has a significant influence on the peak displacement, impact forces, shear forces, and ductility demands (NK & Nair, 2016). However, the peak torsional impact velocity is insensitive to the changes in the eccentricity as well as the separating distance during pounding (Wei et al., 2009). The impact force increases as the setback degree increases (Rajaram & Kumar, 2012). The torsional demands depend on the number of storeys of the shorter structure, and the torsional demands

increase as the number of storeys of the shorter building increases (Karayannis & Naoum, 2018). Also, higher asymmetry leads to higher torsional responses (Karayannis & Naoum, 2018, 2017). Indeed, the torque demands increase due to torsional pounding of buildings and the effect is more substantial for the stiffer structures (Gong & Hao, 2005).

Fixed-base buildings were considered in most of the aforementioned studies. However, the natural frequency of the building considering the Soil-Structure Interaction (SSI) is less than that without considering the SSI due to the flexible base/soil (Stewart et al., 1999; Kamgar et al., 2021). This means that the SSI may have a substantial effect on the response of the vibrating buildings experiencing collisions during earthquakes (Uz et al., 2023, Ahmed & Farghaly, 2023; Raheem et al., 2021). This influence of soil on the pounding-involved structural response was analysed not only in the case of SSI (Naserkhaki et al., 2014) but also in the case of soil-pile-structure interaction (Fatahi et al., 2018). Flexible building experiences higher damages than the stiffer one due to collisions in the case of SSI (Ghandil & Aldaikh, 2017; Naserkhaki et al., 2012; Madani et al., 2015; Mahmoud et al., 2013). However, the effect of pounding considering SSI on the response of colliding buildings is still not clear, as contradictory results about the effect of pounding considering SSI on the colliding buildings were obtained in previous studies. Pounding with SSI was found to increase the displacements, impact forces and shear forces in some studies (see Naserkhaki et al., 2014; Ghandil & Aldaikh, 2017; Naserkhaki et al., 2012; Farghaly, 2017; Kontoni & Farghaly, 2018; Naserkhaki et al., 2013; Li et al., 2017, for example) while it was found to decrease the displacements, impact forces and shear forces in other studies (see Mahmoud et al., 2013; Shakya & Wijeyewickrema, 2009; Shakya et al., 2008; Elwardany et al., 2019, for example). These contradictory results are referred to several factors, mainly due to the soil types and foundation types used in different analyses. The effect of the soil type on the response of buildings experiencing collisions has been studied recently, and it was found that the soil type has a significant effect on the response of

colliding buildings (Miari & Jankowski, 2022c-g; 2021). In all these studies, only symmetric pounding was considered. Five different soil types defined in the ASCE 7-10 code have been considered in these studies, i.e. hard rock, rock, very dense soil and soft rock, stiff soil and soft clay soil. The soil type has been found to have significant influence on the accelerations, displacement and storey shears for buildings experiencing floor-to-floor pounding (Miari & Jankowski, 2022c). Also, the soil type effects on buildings experiencing floor-to-floor pounding have been studied using incremental dynamic analyses and fragility assessment methods (Miari & Jankowski, 2022d). Five performance levels have been considered which are operational performance, immediate occupancy, damage control, life safety and collapse prevention. It was found that the soil type significantly affects the performance levels of the colliding buildings. The colliding buildings are more vulnerable to damage when they are founded on soft clay soil, then when they are founded on the stiff soil, then when they are founded on very dense soil and soft rock, and finally when they are founded on the rock and hard rock. The soil type has also confirmed that it significantly affects the response of the colliding buildings using shaking table tests (Miari & Jankowski, 2022e). Also, the soil type has been found that it significantly affects the value of the seismic gap that should be provided between adjacent buildings to eliminate collisions (Miari & Jankowski, 2022f). Moreover, the effects of the soil type on buildings experiencing floor-to-column pounding have been studied (Miari & Jankowski, 2022g). The shear response of the column experiencing collisions from the top storey of the shorter building have been investigated. It was found that the impacted column experience higher shear demands when the colliding buildings are founded on the soft clay soil, then when they are founded on the stiff soil, then when they are founded on very dense soil and soft rock, and finally when they are founded on the rock and hard rock. Indeed, Miari and Jankowski (2023) proposed effective equations to eliminate collisions between adjacent buildings considering different soil types. However, in all these studies, only symmetric pounding was considered while

asymmetric pounding was ignored. Moreover, the torsional response of buildings founded on soft soil (site class D) have been studied and compared with the fixed-base case. This study didn't compare the torsional response of this case (when the building is founded on site class D) with other cases (when the building is founded on different site classes).

The previous studies were focused on the effect of the soil type on the earthquake-induced response of colliding buildings considered symmetric pounding while the asymmetric pounding was ignored. It means that the effect of torsional pounding was neglected and only symmetric/translational pounding was considered in the analyses. However, studying the effects of torsional pounding is apparent as it is a common case in the special buildings with unique architectural or structural characteristics (irregular structures/ soft storeys). Therefore, the aim of this paper is to study the effect of the soil type on the response of colliding buildings experiencing torsional pounding. Buildings with different number of storeys and configurations have been considered in this study. First, pounding between different structures has been analysed for a specified soil type and the effect of the torsional pounding and the contact asymmetry on the torsional response of colliding buildings has been investigated. Then, these pounding cases have been considered for different soil types to study the effect of the soil type on the torsional response of buildings experiencing torsional pounding. Five different soil types defined in the ASCE 7-10 code have been considered in this study, i.e. hard rock, rock, very dense soil and soft rock, stiff soil and soft clay soil.

2. Numerical Models of Buildings

Six buildings (one 4-storey building and five 6-storey buildings) with different configurations were considered in the study. These buildings are reinforced concrete buildings with 3 m storey height. The numerical models of structures were created using ETABS software (Computers and Structures, 2018). The columns and beams were defined as frame elements, while slabs were modelled as shell elements. The structures considered in this study are 3-D buildings because the

slabs have a very high contribution in pounding, referred to their very high in-plane axial stiffness relative to the flexural column/wall stiffness (see Ehab et al., 2014). The material properties used in the models are as follows: concrete with the compressive strength of 35 MPa and the modulus of elasticity of 27.8 GPa, steel (grade 60) with the yield strength of 420 MPa and the modulus of elasticity of 200 GPa. The live load was considered to be equal to 4 kN/m², while the superimposed dead load was equal to 2 kN/m². The finite element models of the buildings are shown in Figure (1). The 4-storey building has 16 m length and width (the bays are 4×4 m in each direction). The other five structures are 6-storey buildings with different

configurations in the x- and y-directions. The five buildings are denoted as 6-storey building type 1, 2, 3, 4 and 5. The bays of the 6-storey buildings are as follows: 16 m length and 12 m width (the bays are 4×4 m in the x-direction and 3×4 m in the y-direction), 16 m length and 8 m width (the bays are 4×4 m in the x-direction and 2×4 m in the y-direction), 12 m length and 12 m width (the bays are 3×4 m in each direction), 12 m length 8 and width (the bays are 3×4 m in the x-direction and 2×4 m in the y-direction) and 16 m length and width (the bays are 4×4 m in each direction), for type 1, 2, 3, 4 and 5, respectively. Table (1) presents the natural period, frequency and mass for each building.

Table 1. Natural periods, frequencies and masses of buildings.

Building	Period (s)	Frequency (Hz)	Mass (ton)
6-Storey Building Type 1	0.806	1.241	1366.866
6-Storey Building Type 2	0.781	1.281	940.115
6-Storey Building Type 3	0.803	1.245	1044.508
6-Storey Building Type 4	0.778	1.285	718.709
6-Storey Building Type 5	0.82	1.22	1792.470
4-Storey Building	0.544	1.837	1193.450

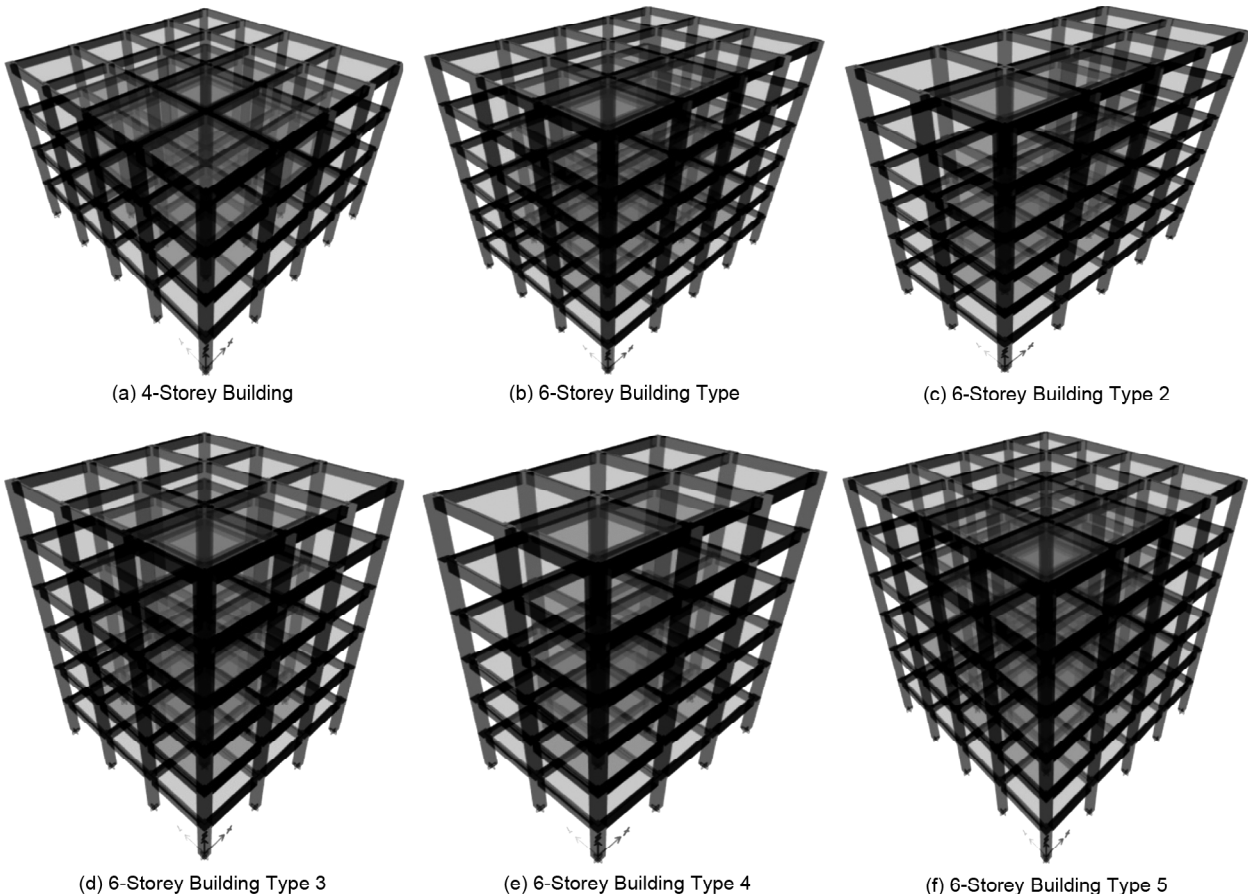


Figure 1. Models of buildings considered in this study.

Then, earthquake-induced pounding between the 4-storey building and five types of the 6-storey building has been studied. Different pounding cases (i.e. case 1, 2, 3, 4 and 5) have been correlated with the type of the 6-storey building (i.e. type 1, 2, 3, 4 and 5). The finite element models of these pounding cases are shown in Figure (2) (3-D and plan views). It can be noticed from the figure that the pounding cases 1, 2, 3 and 4 induce torsional pounding while case 5 results in the symmetric

translational pounding (considered for the comparison purposes). Table (2) presents the respective ratios of natural periods, frequencies and masses for the two colliding buildings for different pounding cases. It is the ratio of the natural period, frequency and mass of the 6-storey building in the case of vibrating independently to that of the 4-storey building. The seismic gap has been considered as equal to 4 cm for all cases. In this study, pounding was modelled by the use of special gap elements.

Table 2. Ratios of natural periods, frequencies and masses for the two colliding buildings for different pounding cases.

Pounding Scenario	Period Ratio (-)	Frequency Ratio (-)	Mass Ratio (-)
4-6 Pounding Scenario Case 1	0.675	1.480	0.873
4-6 Pounding Scenario Case 2	0.697	1.434	1.269
4-6 Pounding Scenario Case 3	0.677	1.476	1.143
4-6 Pounding Scenario Case 4	0.699	1.430	1.661
4-6 Pounding Scenario Case 5	0.663	1.506	0.666

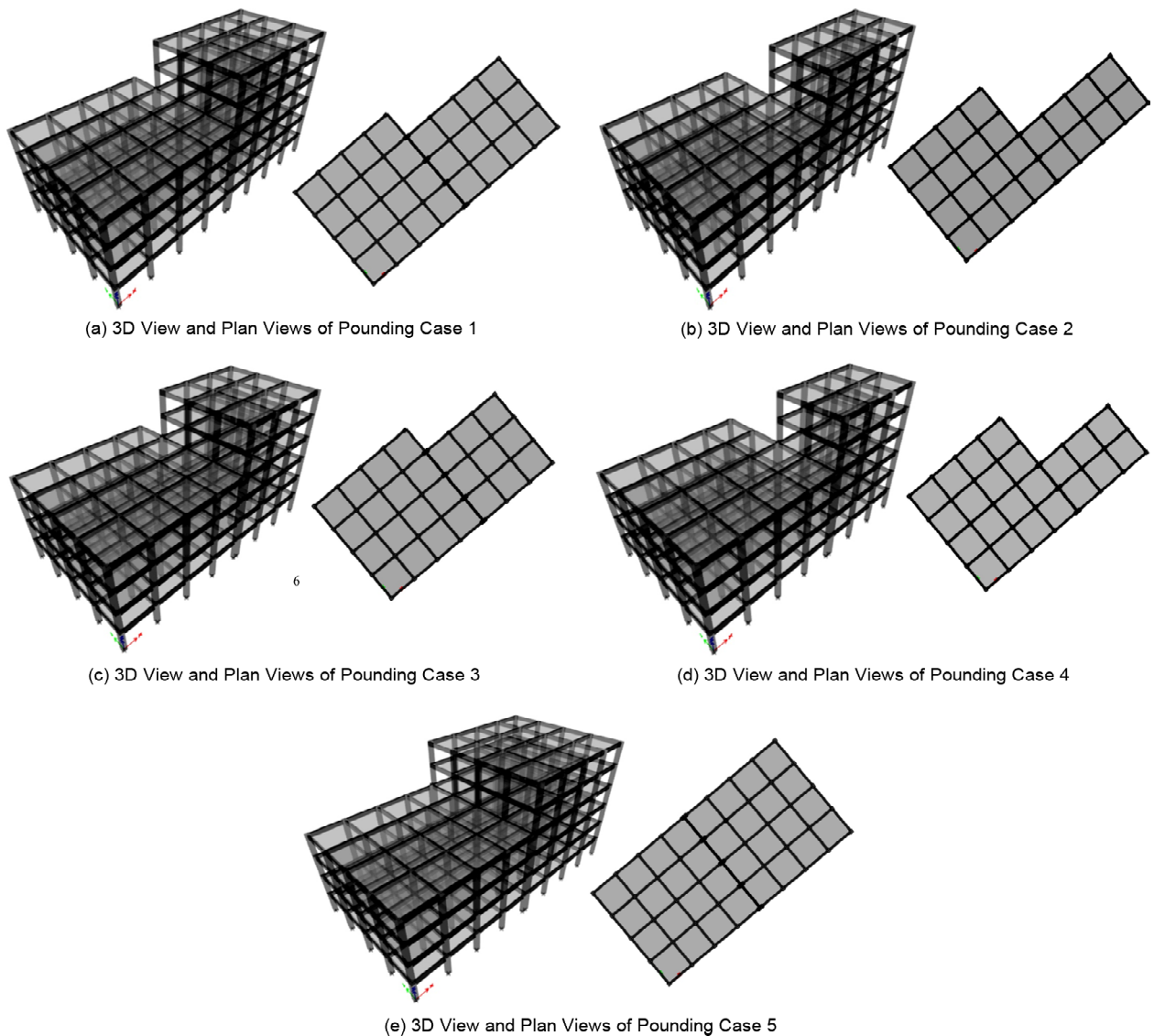


Figure 2. 3D views and plan views of pounding cases considered in this study.

These elements were placed every 4 m along the collision length at all storeys. The gap elements are two-node compression-only link elements (they are activated when adjacent buildings are in contact and deactivated elsewhere - see Computers and Structures reference manual for details). The activation of each gap element was implemented in the numerical model with the support of a spring having relatively high stiffness. In the numerical simulations of this study, the stiffness value of each spring was taken as equal to 1010 N/m. This value was found to be large enough so as to obtain high precision of pounding-involved response of structures considering SSI by the ETABS software. Indeed, Ghandil and Aldaikh (2017) found that the response of colliding buildings during earthquakes was insensitive to the impact stiffness when its value was higher than 1010 N/m.

The detailed non-linear analysis was carried out for different earthquake records. The most representative results, obtained for the Kobe earthquake of 1995 (station: Kobe University, peak ground acceleration (PGA): 0.275766g - see Figure (3) and PEER website for details), are presented in this paper. The structural response was obtained applying the fast nonlinear analysis method developed by Ibrahimbegovic and Wilson (1989). Jaradat and Far (2021) have shown that this method provides results with acceptable accuracy. In this method, the nonlinearity is considered for the gap and support elements. The dynamic equilibrium equation of the vibrating structure is shown in Equation (1).

$$K_L u(t) + C \dot{u}(t) + M \ddot{u}(t) + r_N(t) = -M \ddot{u}_g(t) \quad (1)$$

where K_L is the stiffness matrix for the linear

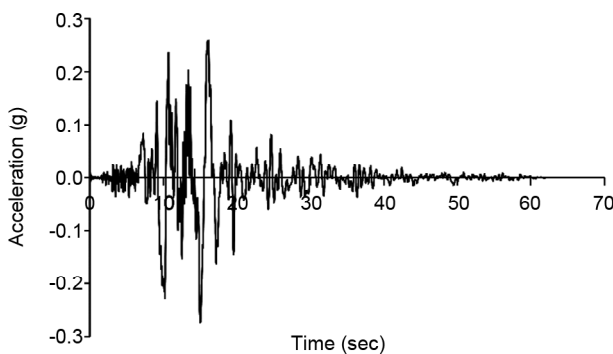


Figure 3. Time history of the Kobe earthquake of 1995 (station: Kobe University).

elastic elements (all elements except for the gap and support elements); C is the proportional damping matrix; M is the diagonal mass matrix; $r_N(t)$ is the vector of forces from the nonlinear degrees of freedom (gap and support elements); $u(t)$, $\dot{u}(t)$, and $\ddot{u}(t)$ are vectors of the relative displacements, velocities, and accelerations with respect to the ground; and $\ddot{u}_g(t)$ is the vector of ground motion accelerations. The time step of 0.001 s was found to be small enough to satisfy the conditions of numerical stability and accuracy during collisions between adjacent buildings. Therefore, this time step was applied in the non-linear seismic analysis.

Table 3. Definition of the site classes.

Site Class	Description	Site Class Definition
A		Hard Rock
B		Rock
C		Very Dense Soil and Soft Rock
D		Stiff Soil
E		Soft Clay Soil
F		Soils Requiring Site Response Analysis in Accordance with Section 21.1 in the ASCE 7-10 Code

The soil was considered in this study by defining the response spectrum and then by matching the target response spectrum with the earthquake record. In the definition of the response spectrum, the soil type and the site parameters are required. After defining the response spectrum, the earthquake record was scaled to it and the detailed time history analyses were performed. Five soil types were considered in the study based on the ASCE 7-10 code which are soil types A, B, C, D and E (see Table 3). The site parameters were selected as follows: 0.5 for S_1 (mapped risk-targeted MCER spectral response acceleration parameter at 1-s period), 1.25 for S_s (mapped risk-targeted MCER spectral response acceleration parameter at short period), and 8 s for T_L (the long-period transition period) (Miari & Jankowski, 2022c; d).

3. Torsional Pounding between Buildings Founded on the Same Soil Type

In this section, the effect of the torsional pounding on the response of colliding buildings is investigated and compared with the translational pounding (symmetric pounding). Special attention is

Table 4. Peak storey rotations for the 4-storey building for different pounding cases and the ratios between the peak storey rotation of the pounding cases 1, 2, 3, and 4 to that of the symmetric pounding case (case 5).

Storey Number	Peak Storey Rotation for Case 5 – Symmetric Pounding Case (rad)	Peak Storey Rotation for Case 1 (rad)	Ratio	Peak Storey Rotation for Case 2 (rad)	Ratio	Peak Storey Rotation for Case 3 (rad)	Ratio	Peak Storey Rotation for Case 4 (rad)	Ratio
0	0	0	-	0	-	0	-	0	-
1	0.00326	0.00339	1.04	0.003606	1.11	0.003486	1.07	0.003673	1.13
2	0.002891	0.003052	1.06	0.003261	1.13	0.003148	1.09	0.003259	1.13
3	0.002072	0.002114	1.02	0.002274	1.10	0.002195	1.06	0.002559	1.24
4	0.00151	0.001529	1.01	0.001756	1.16	0.001766	1.17	0.002127	1.41

paid to the torsional response, and in particular, to the peak storey rotations. Soil type A is considered in this part of the study. Table (4) presents the peak storey rotations of the 4-storey building for the pounding cases 1, 2, 3 and 4 as well as for the symmetric pounding case (case 5). The table shows also the ratios between the peak storey rotation of the 4-storey building for cases 1, 2, 3 and 4 to that of the symmetric pounding case (case 5). Additionally, the graphical presentation of the results is presented in Figure (4). It can be clearly seen from Table (4) and Figure (4) that the peak storey rotations have

been increased in the torsional pounding cases, as compared to that of the translational pounding. For instance, the peak storey rotation of the 4th storey of the 4-storey building is 0.002127 rad in case 4, while it is only 0.00151 for the case of the symmetric pounding (case 5). The ratios between the peak storey rotation of the pounding cases 1, 2, 3, and 4 to the that of the symmetric pounding case (case 5) have ranged from 1 to 1.5. Therefore, it can be concluded that the torsional pounding causes an increase in the peak storey rotations for all cases as compared to the symmetric pounding case.

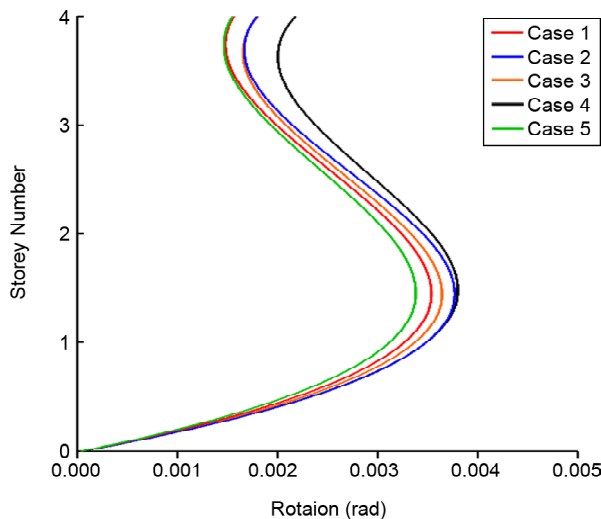


Figure 4. Peak storey rotations for the 4-storey building for different pounding cases.

4. Torsional Pounding between Buildings Founded on Different Soil Types

In this section, the effect of the soil type on the torsional response of buildings experiencing torsional pounding is investigated. The peak storey rotations of the 4-storey building founded on different soil types for the cases 1, 2, 3, 4 and for the symmetric pounding case (case 5) are presented in Tables (5) to (9). The graphical presentation of the results is also shown in Figures (5) to (9).

It can be clearly seen from Tables (5) to (9) and Figures (5) to (9) that the 4-storey building has experienced higher peak storey rotations when the colliding buildings were founded on soil type E,

Table 5. Peak storey rotations for the 4-storey building for case 1 founded on different soil types.

Storey Number	Peak Storey Rotation (rad)				
	Soil Type A	Soil Type B	Soil Type C	Soil Type D	Soil Type E
0	0	0	0	0	0
1	0.00339	0.004261	0.004817	0.005793	0.007424
2	0.003052	0.003818	0.004277	0.005229	0.007029
3	0.002114	0.002579	0.003645	0.003832	0.005529
4	0.001529	0.001919	0.002215	0.0024	0.003709

Table 6. Peak storey rotations for the 4-storey building for case 2 founded on different soil types.

Storey Number	Peak Storey Rotation (rad)				
	Soil Type A	Soil Type B	Soil Type C	Soil Type D	Soil Type E
0	0	0	0	0	0
1	0.003606	0.004546	0.004862	0.005947	0.006858
2	0.003261	0.004088	0.00426	0.005436	0.006739
3	0.002274	0.002875	0.003486	0.003876	0.005394
4	0.001756	0.002209	0.002787	0.003157	0.003444

Table 7. Peak storey rotations for the 4-storey building for case 3 founded on different soil types.

Storey Number	Peak Storey Rotation (rad)				
	Soil Type A	Soil Type B	Soil Type C	Soil Type D	Soil Type E
0	0	0	0	0	0
1	0.003486	0.004449	0.004679	0.005878	0.006588
2	0.003148	0.00399	0.00424	0.005216	0.006498
3	0.002195	0.002802	0.003418	0.003767	0.005429
4	0.001766	0.002203	0.002154	0.002518	0.003438

Table 8. Peak storey rotations for the 4-storey building for case 4 founded on different soil types.

Storey Number	Peak Storey Rotation (rad)				
	Soil Type A	Soil Type B	Soil Type C	Soil Type D	Soil Type E
0	0	0	0	0	0
1	0.003673	0.004568	0.004856	0.006121	0.00637
2	0.003259	0.004068	0.004278	0.005507	0.006374
3	0.002559	0.003207	0.003479	0.003857	0.00514
4	0.002127	0.002679	0.003122	0.003505	0.003302

Table 9. Peak storey rotations for the 4-storey building for the symmetric pounding case (case 5) founded on different soil types.

Storey Number	Peak Storey Rotation (rad)				
	Soil Type A	Soil Type B	Soil Type C	Soil Type D	Soil Type E
0	0	0	0	0	0
1	0.00326	0.004091	0.004858	0.005139	0.007353
2	0.002891	0.003623	0.004405	0.004666	0.007213
3	0.002072	0.002655	0.003644	0.003607	0.005529
4	0.00151	0.001891	0.002279	0.002533	0.003739

Table 10. Peak storey rotations for the 4-storey building for different pounding cases founded on different soil types.

Pounding Case	Peak Storey Rotation (rad)				
	Soil Type A	Soil Type B	Soil Type C	Soil Type D	Soil Type E
Case 1	0.00339	0.004261	0.004817	0.005793	0.007424
Case 2	0.003606	0.004546	0.004862	0.005947	0.006858
Case 3	0.003486	0.004449	0.004679	0.005878	0.006588
Case 4	0.003673	0.004568	0.004856	0.006121	0.006374
Case 5	0.00326	0.004091	0.004858	0.005139	0.007353

then on soil type D, then on soil type C, then on soil type B, and finally on soil type A. For instance, the peak storey rotation of the 2nd storey of the 4-storey building for case 1 is equal to: 0.007213 rad for soil type E, 0.004666 rad for soil type D, 0.004405 rad for soil type C, 0.003623 rad for soil type B and

0.002891 rad for soil type A. Moreover, Table (10) presents the peak rotations (among all storeys) for the 4-storey building for cases 1, 2, 3, 4 as well as for the symmetric pounding case (case 5). The graphical presentation of the results is also shown in Figure (10). It can be seen from Table (10) and

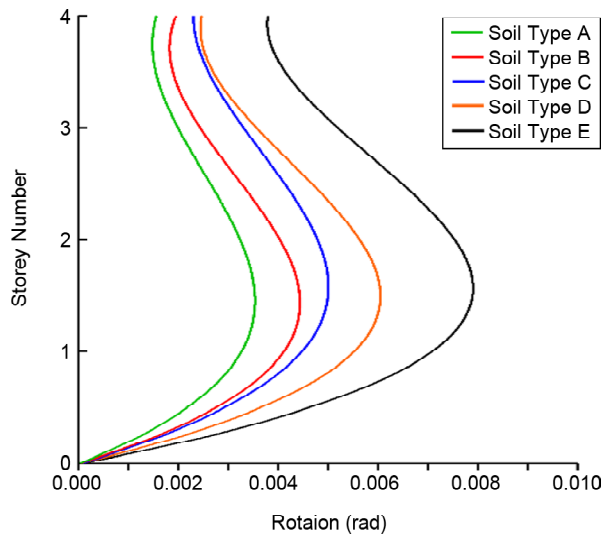


Figure 5. Peak storey rotations for the 4-storey building for case 1 founded on different soil types.

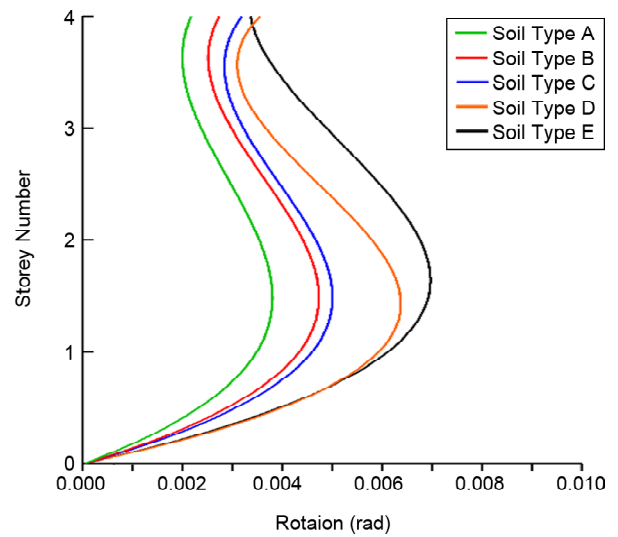


Figure 8. Peak storey rotations for the 4-storey building for case 4 founded on different soil types.

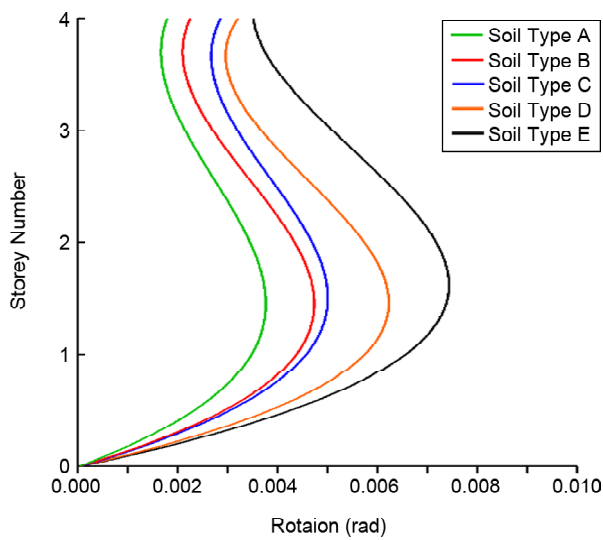


Figure 6. Peak storey rotations for the 4-storey building for case 2 founded on different soil types.

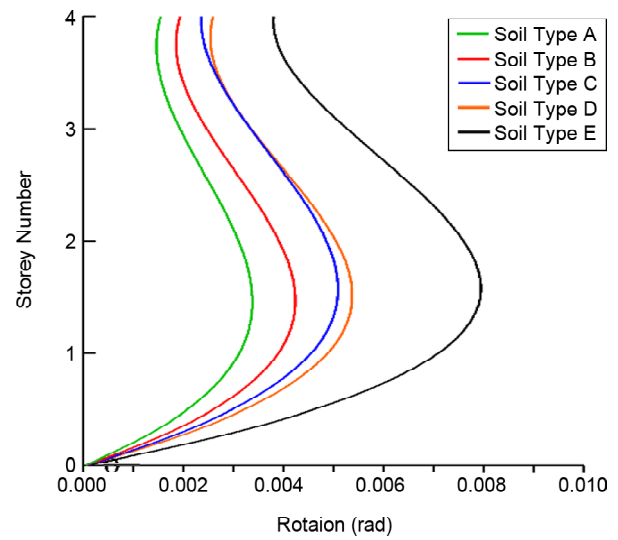


Figure 9. Peak storey rotations for the 4-storey building for the symmetric pounding case (case 5) founded on different soil types.

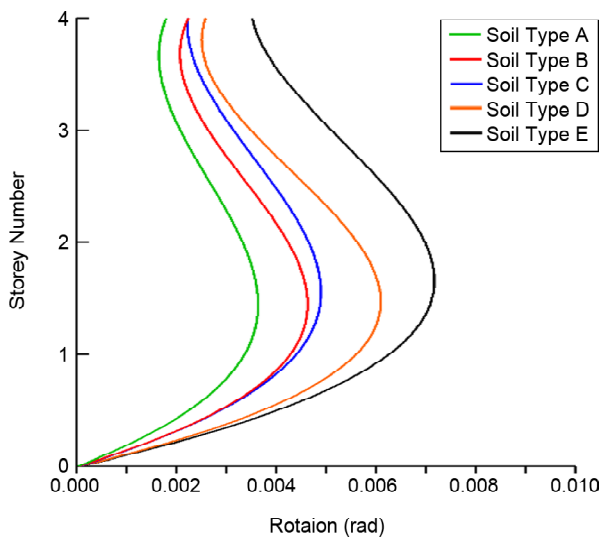


Figure 7. Peak storey rotations for the 4-storey building for case 3 founded on different soil types.

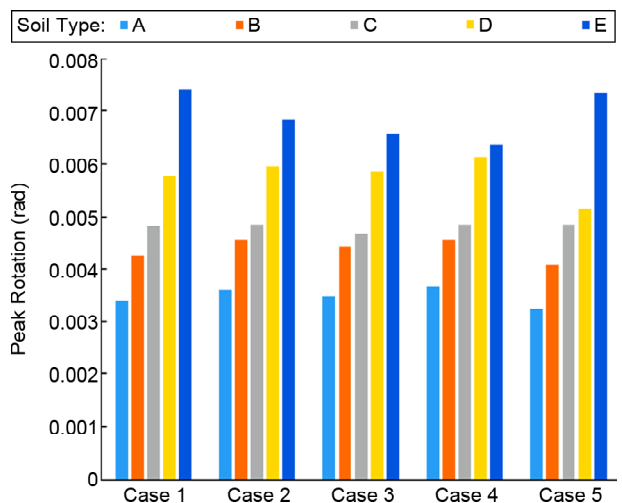


Figure 10. Peak rotations for the 4-storey building for different pounding cases founded on different soil types.

Figure (10) that also the peak rotation has been significantly affected by the soil type and that the 4-storey building has experienced higher peak rotations for soil type E, then for soil type D, then for soil type C, then for soil type B, and finally for soil type A.

5. Conclusions

The effect of the soil type on the torsional response of buildings experiencing torsional pounding due to earthquake excitations was studied in this paper. Six buildings (one 4-storey building and five 6-storey buildings) with different configurations were considered. Five pounding cases were analysed, four of them had asymmetric contact leading to torsional pounding and one had symmetric contact leading to symmetric translational pounding (considered for the comparison purposes). First, pounding between different structures has been analysed for a specified soil type and the effect of the torsional pounding and the contact asymmetry on the torsional response of colliding buildings has been investigated. Then, these pounding cases have been considered for different soil types to study the effect of the soil type on the torsional response of buildings experiencing torsional pounding. Five different soil types defined in the ASCE 7-10 code have been considered in this study, i.e. hard rock, rock, very dense soil and soft rock, stiff soil and soft clay soil. The results of the study indicate that the earthquake-induced torsional pounding causes an increase in the peak storey rotation of the colliding buildings as compared to the symmetric pounding in all cases. The ratio between the peak storey rotation for the torsional pounding cases and the symmetric pounding case were ranged between 1 and 1.5. Indeed, it can be concluded that the soil type has a significant effect on the peak storey rotations and the peak rotation. Higher peak storey rotations and higher peak rotations were experienced for colliding buildings founded on the soft clay soil, then for buildings founded on the stiff soil, then for buildings founded on very dense soil and soft rock, and finally for buildings founded on the rock and hard rock. Therefore, it is necessary to take into account the effects of torsional collisions in studies considering soils, especially soft soils.

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Compliance with Ethical Standards

Conflict of interest: The authors declare that they have no conflict of interest.

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