ABSTRACT

The current paper investigates parametrically, through a large number of numerical simulations, the effect of the angle of seismic incidence on the response of adjacent buildings, which are subjected to pounding phenomena due to insufficient or no separation distance between them. The buildings are simulated in three dimensions (3D), using simple structural modelling, considering shear-type behaviour in the horizontal direction, while taking into account the geometry of the buildings in plan. A simple but efficient impact model is used that does not require the ‘a priori’ determination of contact points, taking also into account the geometry at the vicinity of impact when calculating the magnitude and the direction of the impact forces during pounding. In the frames of the current research work, various parametric analyses have been performed, by conducting large numbers of simulations, while varying automatically a certain predefined parameter, in order to assess its effect on the overall structural response during pounding. Specifically, the effect of the excitation angle on the dynamic response is parametrically examined in combination with other determinant factors, such as the accidental eccentricity of the floor masses and the earthquake characteristics.

Keywords: Seismic pounding; Excitation angle; Ground motion directionality; Impact; Numerical analysis

1. INTRODUCTION

Several numerical and analytical studies have shown that the orientation of the seismic action, i.e. the angle in which the horizontal seismic components will be applied in respect to the structural axes affects significantly the response of the simulated structure during a dynamic analysis procedure. Studies have shown that the critical angle of seismic incidence, i.e. the angle in which the response has its maximum value, is, in most of the times, different from 0 or 90 degrees in respect to the structural axes of the building (Lopez and Torres 1997, Lopez et al 2000, Rigato and Medina 2007, Lagaros 2010). In addition, it was found that each response quantity has its own critical angle of seismic incidence and the critical value for a response quantity can be up to 80% larger than the response produced when the seismic components are applied along the structural axes (Athanatopoulou 2005).

It is also widely known that during strong earthquakes, pounding may occur between buildings that are constructed very close to each other with small or no gap between them, resulting in local light damage or, under certain circumstances, in more severe structural damage. The detrimental effects of pounding of adjacent buildings during strong earthquakes, which have been reported in the last few decades (Bertero 1987, Anagnostopoulos 1995, Cole et al. 2012), have motivated many researchers to investigate this phenomenon through numerical simulations and parametric studies, with their majority simulating the problem in two dimensions (2D). However, the effect of bidirectional horizontal excitation of the buildings, as well as the direction of the ground motion cannot be considered when...
using 2D simulations. Moreover, the limited number of numerical studies that included simulation of the adjacent structures in three dimensions did not take into account the effect of the direction of the seismic excitation in respect to the structural axes of the buildings.

The aim of the current paper is, primarily, to investigate parametrically, through numerical simulations, the effect of the angle of seismic incidence on the response of two adjacent buildings, which are subjected to pounding due to insufficient or no separation distance between them and, secondly, to point out the importance of using 3D modelling of structures when investigating such pounding phenomena. The buildings are simulated in three dimensions (3D) using simple structural modelling, considering shear-type behaviour in the horizontal direction while taking into account the geometry of the buildings in plan. A simple but efficient impact model is used that does not require the ‘a priori’ determination of contact points, taking also into account the geometry at the vicinity of impact when calculating the magnitude and the direction of the impact forces during pounding.

2. INTRODUCTION

2.1 Structural modelling

The numerical simulation of the problem is based on a new, simple and efficient methodology that has been recently published (Polycarpou et al. 2013). In the proposed methodology the buildings are considered as three-dimensional multi-degree-of-freedom (MDOF) systems with shear-type behaviour for their stories in the horizontal direction. The slab at each floor level of the superstructure is represented by a rigid diaphragm that is mathematically simulated as a convex polygon, while the masses are considered to be lumped at the floor levels, having three dynamic degrees of freedom (DOFs), i.e. two translational, parallel to the horizontal global axes, and one rotational along the vertical axis. Therefore, considering ground excitations only in the horizontal directions, which is the most important in the current case, no displacement occurs in the vertical direction, since the translational dynamic DOF of the structure refer only to horizontal planes. Accordingly, it is assumed that the impact forces occur only in horizontal planes. The global stiffness matrix of each building is composed, based on the 3×3 stiffness matrices of its storeys, which are, formerly, composed by superposing the 3×3 stiffness matrices of all the columns of the corresponding storey. For the composition of the global mass matrix of each structure, potential mass eccentricities from the centre of gravity of each floor are considered. Finally, the damping matrix of the building is composed from the stiffness and mass matrices, assuming Rayleigh damping.

The equations of motion of each simulated building can be expressed in matrix form as follows:

$$ \ddot{\mathbf{U}} + \mathbf{C} \cdot \dot{\mathbf{U}} + \mathbf{K} \cdot \mathbf{U} = \mathbf{F} + \mathbf{F}_{\text{imp}} $$

(1)

where \( \mathbf{U}(t) \) is the vector of displacements in global coordinates at time \( t \), \( \mathbf{F}_{\text{imp}} \) is the vector of the computed impact forces, acting on each DOF, \( \mathbf{L} \) and \( \mathbf{T} \) are the influence vectors coupling the DOFs of the structure to the two ground motion components \( \mathbf{F}_L(t) \) and \( \mathbf{F}_T(t) \) in the longitudinal and transverse directions, respectively. The influence vectors for the two horizontal components are provided by the following expressions:

$$ \mathbf{L} = [\mathbf{L}^1, \mathbf{L}^2, \mathbf{K}, \mathbf{L}^n] \quad \text{and} \quad \mathbf{T} = [\mathbf{T}^1, \mathbf{T}^2, \mathbf{K}, \mathbf{T}^n] $$

(2)

where:

$$ \mathbf{L}^1 = I_x \cdot \cos \theta + I_y \cdot \sin \theta \quad \text{and} \quad I_x = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}^T $$

$$ \mathbf{L}^2 = -I_x \cdot \sin \theta + I_y \cdot \cos \theta \quad \text{and} \quad I_y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}^T $$

(3)

\( \theta \) is the excitation angle in respect to the system’s principle axes. The differential equations of all simulated structures are directly integrated simultaneously using the Central Difference Method (CDM), which computes the resulting displacements at time \( t + \Delta t \). This characteristic of the method is
an advantage in performing the automatic check by the algorithm for the detection of potential impacts between structures at each time-step of the analysis, based on the deformed position of each floor diaphragm in space. For this reason, the time-step size, $\Delta t$, is selected to be small enough (usually in the range of $1$ to $2 \times 10^{-5}$ sec) to ensure the stability of the numerical method and maximize its accuracy. When an interaction between adjacent structures is detected, the resulting impact forces $F_{imp}$ are computed according to the impact model and the methodology that is presented in the next section.

### 2.2 3D Impact modelling

Most of the force-based impact models that are available in the literature calculate the impact force as a function of the interpenetration depth between the colliding bodies. This method is widely known as the ‘penalty method’ in contact mechanics, because an overlapping is allowed between the two bodies in order to calculate the arising impact forces. However, the use of the interpenetration depth as the key variable entails a significant drawback in the case of 3D impact modelling. Specifically, that approach assumes that the calculated impact force depends only on the indentation, regardless the overall geometry at the contact region. For example, the method assumes that the impact force between two floor slabs, which collide with a specific impact velocity, increases in magnitude in the same way for both cases of side-to-side and corner-to-side impact, which is not true. Therefore, based on the above observation and in order to take into account the geometry at the contact region, it was considered crucial and more appropriate to use the area of the overlapping region, instead of the interpenetration depth, as the key variable in the calculation of the impact forces. Figure 1 describes schematically how the proposed impact model works. When two slabs, which in the proposed methodology are modelled as polygons, come in contact they form an overlapping region, which in most of the cases is either a triangle (Figure 1(a)) or a quadrilateral (Figure 1(b)). The developed algorithm uses the geometry of the overlapping region at each time-step, defined by the coordinates of its nodes, in order to determine: (i) the location of the action point of the impact forces, (ii) the direction of the impact forces and (iii) the magnitude of the impact forces.

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**Figure 1:** Schematic representation of the proposed impact model. (a) The overlapping region forms a triangle; (b) the overlapping region is a quadrilateral.

**2.2.1 Location of the action point of impact forces**
The location of the action point of the impact forces is a very important issue in the case of simulating poundings of buildings in 3D. While in the case of 1D impact models the location of the resultant force vector clearly is at the point of contact, in the case where contact conditions exist over a finite surface area on both bodies, the exact point where the contact force should be applied is not so obvious. For the specific problem of modelling impact between rigid diaphragms, the contact forces in the normal and tangential directions are assumed to act on the centre of the overlapping region, and applied at the corresponding position of the bodies in contact (see Figure 1).

2.2.2 Direction of the impact forces (contact plane)

The normal and tangential directions for the corresponding normal and tangential impact forces are defined using the line that is determined by the two nodes P1 and P2 of intersection between the boundaries of the two colliding bodies (see Figure 1). The normal impact force is perpendicular to this line, which is symbolically called ‘contact plane’, while the tangential impact force is parallel to it. As mentioned above, both impact forces are applied at the centre C of the overlapping region.

2.2.3 Magnitude of the impact forces

An impact stiffness coefficient is used along with the area, $A_c$, of the overlapping region to calculate the elastic impact force in the normal direction, while the tangential impact force is computed in terms of the relative displacement in the tangential direction, $u_{rel,T}$, as follows:

$$
(t+\Delta t) F_{imp,N} = (t) A_c \cdot k_{imp,N}
$$

$$
(t+\Delta t) F_{imp,T} = (t) F_{imp,T} + (t) u_{rel,T} \cdot k_{imp,T}
$$

The indices $N$ and $T$ in the above equations indicate the normal and the tangential directions, respectively, as indicated in Figure 1. $k_{imp,N}$ (in kN/m$^2$) and $k_{imp,T}$ (in kN/m) are the impact stiffness coefficients in the normal and tangential directions, respectively. The time instance $(t+\Delta t)$ represents the current time-step, since the Central Difference integration method is used, while $(t)$ represents the previous time-step. Moreover, the Coulomb friction law is used to limit the tangential impact force below a certain magnitude taking into account the magnitude of the normal impact force and the static and kinetic friction coefficients of the contact surface:

If 

$$
| (t+\Delta t) F_{imp,T} | \leq | (t+\Delta t) F_{imp,N} \cdot \mu_s |
$$

use Equation (5)

If 

$$
| (t+\Delta t) F_{imp,T} | > | (t+\Delta t) F_{imp,N} \cdot \mu_s |
$$

$$
(t+\Delta t) F_{imp,T} = (t+\Delta t) F_{imp,N} \cdot \mu_k
$$

where $\mu_s$ and $\mu_k$ are the static and kinetic friction coefficients, which are applied in the ‘stick’ and ‘slide’ mode of contact, respectively.

As in the case of 1D impact models, a viscous dashpot can be used, in parallel with the impact spring to represent the dissipation of energy during impact (e.g. thermal and acoustic energy) and along with the relative velocity of the bodies in contact can provide the damping impact force. However, for simplicity, in the frames of the current paper only the elastic impact forces are considered in the performed simulations, since the viscoelastic impact model has been followed in the case of studying the effects of pounding in 2D, where it has been found that the specific parameter determines the magnitude of the impact force and affects mainly the acceleration response at the pounding floors (Polycarpou and Komodromos 2010, Komodromos et al. 2007).

3. PERFORMED ANALYSES

Two regular and symmetric reinforced concrete buildings of three and four stories, respectively, have been selected and used. Although the methodology supports the simulation of more complicate
structures with irregularities both in plan and height, the selection of the particular buildings has been made in order to more easily identify the effects of the various parameters on the response during pounding.

3.1 Structural properties

The typical floor-plan and the side view of the simulated adjacent buildings are illustrated in Figure 2. All the columns sections have dimensions 35×35 cm except from the corner columns of the right 3-story building C1, C3, C13 and C15 which have dimensions 100×30 cm. The elastic modulus of concrete has been taken equal to 21 GPa with a Poisson’s ratio equal to 0.2. A uniformly distributed mass of 1000 kg/m² has been considered for all floors that resulted to a 64 tons concentrated floor mass for the left building and a 128 tons floor mass for the right building. A constant viscous damping ratio of 0.05 was considered for all modes for both buildings.

The seismic gap, i.e. the separation distance between the two buildings, is taken to be 0.1 cm, which corresponds practically to the zero gap case (i.e. the buildings are constructed with no gap between them). The value of 0.1 cm was selected instead of 0 cm in order to avoid potential numerical errors at the first step of integration. The normal impact stiffness $k_{imp,N}$ is $2.09 \times 10^7$ kN/m², while the corresponding tangential impact stiffness $k_{imp,T}$ = $4.59 \times 10^6$ kN/m. The static and kinetic friction coefficients are taken to be $\mu_s$ = 0.8 and $\mu_k$ = 0.6, respectively.

![Figure 2: The model of simulated adjacent buildings that have been considered in the numerical example. (a) Plan view; (b) Side view.](image)

3.2 Ground motions

The seismic records from two major earthquakes of medium intensity, which occurred in the South-east Europe, are used for the performed analyses, including both horizontal seismic components of each ground motion. Details about the selected seismic records used are provided in Table 1.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Date</th>
<th>Mw</th>
<th>Station</th>
<th>Component</th>
<th>PGA (m/sec²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens, Greece</td>
<td>07/09/1999</td>
<td>6.0</td>
<td>Kallithea</td>
<td>N46</td>
<td>2.602</td>
</tr>
<tr>
<td>Kocaeli, Turkey</td>
<td>17/08/1999</td>
<td>7.5</td>
<td>Duzce-Meteoroloji</td>
<td>SN</td>
<td>3.039</td>
</tr>
</tbody>
</table>
3.3 Effect of the excitation angle without considering mass eccentricity

In order to investigate parametrically the effect of the excitation angle on the structural response during pounding, large numbers of simulations involving the two adjacent buildings have been performed. Specifically, the two structures have been dynamically analysed simultaneously under each ground motion of which the incidence angle was varied from 0 to 180 degrees, with a step of 4 degrees (i.e. 46 simulations for each earthquake). The buildings have been analysed for two different cases; (i) without pounding and (ii) with pounding, resulting from a limited seismic gap of 1mm between the two buildings. The interstory deflections are selected as the monitor response quantity, since they can be more easily related with the seismic performance and potential structural damage of a building during an earthquake.

Figure 3 presents the peak interstory deflections in the X and Y directions of the corner columns C9 and C3 of the Left and Right building, respectively (see Figure 2), for the case without pounding and considering the Athens Earthquake as ground excitation. The maximum responses for each storey are plotted in terms of the excitation angle, \( \theta \) (see Equation 3). In accordance with previous similar studies, the results reveal that the response is highly depended from the incidence angle, especially in the case of the more flexible left building. Specifically, the peak interstory deflections of column C9 range from 0.4cm (storey drift=1.1‰) for the case of \( \theta=150^\circ \) to 1.1cm (storey drift=3.1‰) for the case of \( \theta=50^\circ \), a discrepancy of about 175%. It is also observed that the critical excitation angle (i.e. the angle where the maximum response occurs) for the deflections in the X direction is nearly common among all floors (about 50°), but is different from the corresponding critical angle for the deflections in Y direction (about 140°), which is also the same for all storeys. Specifically, the difference between the two critical angles is 90 degrees (i.e. complementary angles), since the Left building is symmetrical in both directions.

While in the ‘no pounding’ case the trends in the plots are smooth (Figure 3), when pounding occurs the trends become more rough and the behaviour is more complicated, as shown in Figure 4. Especially in the case of interstory deflections of column C9 (Left building) in the X direction, which is the direction where impacts occur, the effects of pounding are more pronounced. Specifically, the plots in Figure 4 show that for a \( \theta \) between 0 to 90 degrees there is no substantial change in the shape of the trends besides a small increase in the peak responses for all floors. For higher values of \( \theta \) it is observed that the interstory deflections at the top storey of the Left building become larger than the ground floor’s deflections, which are normally the highest among all floors. That is clearly due to pounding and, particularly, the excitation of higher modes of deformation after experiencing impacts. The change in the response is more intense for angles near 90 degrees, probably because the N136 seismic component, which is initially applied in the Y direction, has the largest PGA between the two components. Furthermore, the change in the response-angle relationship is not so obvious in the deflections in Y direction, since pounding occurs only in X direction.
Figure 3: Peak interstory deflections of the buildings’ corner columns in terms of the excitation angle, considering the ‘no pounding’ case under the Athens Earthquake.

Figure 4: Peak interstory deflections of the buildings’ corner columns in terms of the excitation angle, considering the case of pounding under the Athens Earthquake.
The peak interstory deflections during pounding are divided by the corresponding values obtained from the case without pounding, resulting to the so called ‘amplification ratio’. The amplifications of the interstory deflections of columns C9 and C3 of the Left and Right buildings, respectively, are plotted in Figure 5. It is observed that the top storey’s deflections of the Left taller and more flexible building can be amplified up to 3.5 times, depending on the excitation angle. That denotes a substantial increase in the ductility demands of the upper storeys’ columns, not only due to pounding but also due to the arbitrary orientation of the ground excitation in respect to the structural axes of the buildings, which may further increase that demands. Moreover, the angle in which the amplification of the response due to pounding with the adjacent building gets its maximum value is different from the response’s critical angle. For example in the case of the interstory deflections of column C9 at the 4th storey, the angle where the maximum amplification due to pounding occurs is 130°, while the corresponding critical angle is 50° in the case without pounding (Figure 3) and 100° in the case of pounding (Figure 4). It is also observed that in the X direction where impacts occur, the columns deflections at the top storeys have higher amplification ratios than those at lower storeys, at both buildings. Moreover, it is obvious that it is important to take into account the arbitrary angle of the excitation since for different angles the response can be amplified (amplification ratio > 1) or reduced (amplification ratio < 1) due to pounding. Finally, Figure 5 shows that the less affected responses of those examined in the current case are the deflections in the Y direction of the corner column C3 of the Right stiffer building.

![Figure 5: Amplifications of the peak interstory deflections due to pounding, in terms of the excitation angle, considering the Athens Earthquake.](image)

In order to examine whether the above observations depend on the earthquake characteristics, the same set of simulations have been performed using the Kocaeli Earthquake records (Table 1). The results are plotted in Figure 6, where the amplification ratios of the interstory deflections of the same columns are presented. It is observed that, as in the case of the Athens Earthquake, the deflections of the corner columns of the top storey are substantially amplified in case of pounding and, especially in the case of the taller and more flexible Left building, the amplifications of the interstory deflections at its top storey are much more amplified (up to nearly 4 times) than the corresponding responses at the lower floors, which for the most excitation angle values seem to be reduced due to pounding. On the
other hand, in the case of the stiffer Right building it is observed that the deflections are amplified at all floors and for all excitation angle values, in contrast to the Athens Earthquake case where for angles larger than 90° no substantial amplification occurs for column C3. Observing both Figures 5 and 6 it can be seen that for the range of angle values where the X-deflections of the Left building amplify, the corresponding deflections of the Right building are reduced and vice versa. This observation complies with similar observation from previous researchers which performed numerical simulations using structural models in 2D (Anagnostopoulos and Spiliopoulos 1992, Mouzakis and Papadrakakis 2004). Moreover, it becomes evident from the plots that the angle where the maximum amplification of the response is observed is not the same for the two earthquakes, while the degree of which pounding affects the response seems to depend on the ground motion characteristics. Finally, it is important to mention that the deflections of column C9 in the Y direction are also significantly affected from pounding, even though no pounding occurs in the Y direction. However, this effect, which also depends on the excitation angle, is not so pronounced as in the case of the same column’s deflections in the X direction.

![Figure 6: Amplifications of the peak interstory deflections due to pounding, in terms of the excitation angle, considering the Kocaeli Earthquake.](image)

3.4 Effect of the excitation angle considering accidental mass eccentricity

Many seismic codes demand the consideration of an accidental mass eccentricity when performing dynamic analysis of buildings. For example, Eurocode 8 (EC8) suggests an eccentricity of the concentrated floor mass from its nominal location equal to 5% of the floor-dimension perpendicular to the direction of the seismic action (Eurocode 8 EN 1998-1:2004). In order to investigate the effect of mass eccentricity on the response during pounding, a case has been considered where, instead of having the floor masses of the Left building lumped at the centre of gravity of each floor, a mass eccentricity is assumed in both directions, equal to 40 cm in both directions (\(e_x = e_y = 0.4 \text{ m}\)), as shown in Figure 7, which is the 5% of the dimension of the building’s side, as suggested by EC8. No mass eccentricity has been considered for the Right building.
The effect of the excitation angle value has been parametrically studied, considering this time the new structural properties of the Left building and the Athens Earthquake records as the ground motion. The plots in Figure 8 present the amplification of the interstory deflections of the corner columns of the two buildings. Note that for calculating the amplifications of the Left building the response during pounding has been divided by the corresponding response without pounding, but taking into account the eccentricities. Comparing the plots with those in Figure 5 (without mass eccentricities), it can be observed that there is a noticeable change in the amplifications of the Left building due to the mass eccentricities of its floors, while the pounding effects for the Right building seem to be unaffected by the mass eccentricities in the Left building. Specifically, in the case of the Left building, the eccentricities of the floor masses seem to increase the effects of pounding since the amplifications become higher than in the case without eccentricities (Figure 5). This increase of the pounding effects
due to the eccentricities is more pronounced for the lower storeys and occurs in a range of excitation angle values between 80-140°, with the peak at 110°. It is interesting to observe that for an excitation angle equal to 110°, the deflections in the X direction of column C9 are amplified from 2 to 4 times, while for the case of 0°, which is the most typical case where the seismic components are applied along the structural axes, there is no amplification of the response due to pounding. Similar behaviour is observed also for the Right building. Therefore, it is very important to consider the effect of the excitation angle on the structural response during pounding. Finally, Figure 8 shows that pounding has negligible effects on the interstory deflections in the Y direction of the columns of both buildings when eccentricities are considered.

4. CONCLUDING REMARKS

The effects of the excitation angle on the response of two adjacent buildings during pounding have been parametrically examined using a simple and efficient methodology to simulate numerically two multi-storey buildings interacting in three dimensions. The methodology involves the use of a 3D impact model that takes into account the arbitrary location of impact points, as well as the random geometry at the vicinity of impact when calculating the magnitude and the direction of the impact forces.

The results of the parametric studies reveal that it is very important to consider the arbitrary direction of the ground motion in respect to the structural axes of the simulated buildings, especially during pounding. Specifically, according to the obtained results:

- The detrimental effects of pounding may become more severe for certain values of the excitation angle, different from 0 or 90 degrees, which is the most typical case.
- The effect of the excitation angle is more pronounced for the more flexible and taller building, where its ductility demands may increase up to 4 times for an arbitrary value of the excitation angle, compared to the case of θ=0°.
- The highest amplifications of the response due to pounding occur at the upper floors of the colliding buildings.
- The detrimental effects of pounding on the response of the taller and more flexible building became more pronounced when mass eccentricities were considered its floors.
- The most sensitive responses to the variation of the excitation angle, as well as to the mass eccentricities are the interstory deflections in the direction of pounding and especially those of the more flexible and taller building.

5. REFERENCES


