Study on Pounding of Structures with Soil–Structure Interaction Effects: A Review

H. K. Chinmayi^{1,2}

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Abstract In metropolitan cities, due to high land value structures are built very close to each other. During strong earthquakes, adjacent buildings with insufficient clear distances collide with each other causing architectural and structural damage or collapse of the whole structure. In addition to pounding, the interaction effects exchange the vibration energy between buildings making the problem further complicated. This paper attempts to provide a state-of-the-art review on the pounding of structures considering soil–structure interaction effects.

Keywords Pounding · Soil–structure interaction · Numerical modeling · Buildings · Earthquake

Introduction

Due to urbanization in recent days, cities are constructed with many closely spaced buildings with very less or no gap. During strong quakes, the sudden ground movement is transferred from the ground to the superstructure through foundation resulting in different structural dynamic characteristics and out-of-phase lateral vibrations. Due to an insufficient separation distance between adjacent buildings, the buildings cannot vibrate freely, thus leading to pounding. Buildings vibrating out of phase collide with each other causing severe damage to the structure, life, and

economy. The phenomenon in which two buildings strike due to their lateral movements is known as pounding.

Buildings are generally constructed on soil; local soils overlying the bedrock at the site modify the characteristics of the motion as it passes through the strata to reach the ground surface. Hence, consideration of the interactions between the buildings and the underlying soil is essential as soil plays a significant role in modifying the seismic motions which in turn affects the behavior of buildings. This paper attempts to present the current state of the art of building pounding, with the emphasis on soil–structure interaction (SSI) effects.

Literature Review

The collision of adjacent buildings because of some form of excitation, generally seismic excitation, is known as building pounding. Over the last 20 years, this phenomenon has been widely researched. Due to the high complexity, illustrating pounding necessitates a thorough knowledge of the dynamic performance of multiple buildings along with knowledge of how the buildings will react to different magnitude, but small duration impulsive forces. Representing pounding analytically is very complicated and physically is very exclusive. In general, pounding building scenarios can be categorized as either floor-to-floor or floor-to-column pounding (Fig. 1).

Numerous studies have been carried out by various researchers on the pounding of structures with soil–structure interaction effects. Earlier research concerning structural pounding between structures during the earthquake was done by Bertero [4]. The study aimed to identify and converse the primary causes of pounding of adjacent engineered buildings, and to evaluate their observed

✉ H. K. Chinmayi
chinmayi.moorthy@gmail.com

¹ Department of Civil Engineering, B.M.S. College of Engineering, Bangalore, India

² Bangalore, India

Fig. 1 Pounding categorization [7]

performance regarding improving the earthquake-resistant design and construction of new adjacent buildings and retrofitting existing ones where separation appears to be inadequate.

Later in the year 1988, Anagnostopoulos [1] carried out a research where a simplified model of several adjacent buildings in a block was used to study the pounding of such buildings during strong earthquakes. The results of the study showed that the end structures almost always experience the substantial increases in their response while in the interior structures the opposite often happens which explains why high percentages of corner buildings collapse in some earthquakes. The same author in the year 1992 along with Spiliopoulos K.V. [2] performed research on the response of adjacent buildings in city blocks under strong earthquakes taking into account the mutual collisions, or pounding, resulting from insufficient or non-existing separation distances. The buildings were idealized as lumped mass, shear beam type, multi-degree-of-freedom (MDOF) systems with bilinear force–deformation characteristics and with bases supported on translational and rocking spring-dashpots. Collisions occurring between adjacent masses at any level were simulated using viscoelastic impact elements with five real earthquake motions. The outcome of the study exhibited that pounding causes high overstresses, mainly when the colliding buildings have significantly different heights, periods or masses. Authors also recommended to introduce a set of conditions into the codes, combined with some special measures, as an alternative to the seismic separation requirement. Pounding response of adjacent buildings subjected to spatial earthquake ground excitations was carried out by Hao et al. [12]. The adjacent structures in the study were modeled as two single-degree-of-freedom (SDOF) oscillators with multiple supports. Pounding effects were simulated by spring-dashpot pounding elements. Linear elastic and nonlinear inelastic responses were considered in the analysis. The outcome of the study showed that a larger damping is required to mitigate seismic pounding effect if ground motion spatial variation effect is considered and spatially varying ground excitations result in a greater number of pounding events between adjacent structures. Cole et al. [6] carried out a study on the effect of diaphragm wave propagation on the

analysis of pounding structures. Here, author extended the work of Watanabe and Kawashima [22] “Numerical simulation of pounding in bridge decks” to consider multiple collisions between three different configurations of adjacent buildings with distributed masses. Wave theory was extended, and an ‘instant wave’ model was proposed to govern whether the lumped mass assumption causes significant loss of accuracy in the displacement response of the structure. In the framework of distributed mass collisions, the characteristics of the impact force were also investigated. The results found provide the guidance to researchers in selecting the collision element stiffness.

A parametric study on buildings pounding response in addition to proper seismic hazard mitigation practice for adjacent buildings was carried out by Raheem [18]. An analytical model and methodology for the formulation of the adjacent building-pounding problem based on the classical impact theory were developed to evaluate the effects of structural pounding on the global response of building structures. Study shows that pounding amplifies the building displacement demands beyond those typically assumed in design. Hence, existing design procedure should account for dynamic impact and adjacent building period ratio should be carefully selected to reduce the pounding effects.

The study on pounding of two neighboring buildings during the Montenegro earthquake was performed by Schmid and Chouw [20]. The effect of interaction between the structure and the soil on the vibration behavior of the buildings was analyzed using finite element method, where the structure and the soil were modeled using finite elements and boundary elements and the nonlinear calculation was performed in the Laplace and time domains. The results of the study disclosed that SSI changed the dynamic characteristics of the structure–soil system; the building vibrated with higher amplitude and lower frequencies causing reduced internal forces leading to pounding. Another research to evaluate the effect of SSI on seismic behavior of two adjacent 32 story buildings for variable distances between the buildings and three soil types such as soft clay, sandy gravel and compacted sandy gravel was carried out by Yahyai et al. [23]. The result of the study states that considering the SSI effects increases time

period, base shear, and displacements, and this increase depends on the distance of two adjacent buildings. Shakya et al. [21] also performed a study on seismic pounding between three typical reinforced concrete moment resisting frame buildings in a row using finite element analysis software SAP2000. A 10-story building was located between two identical 9-story buildings, considering the effects of underlying soil on the structural response. To contemplate the effect of mid-column pounding the story height of 10-story building was kept different from those of the two 9-story buildings. The underlying soil was taken into account through the discrete model at the foundation level and the contacts between the buildings were incorporated through impact elements consisting of a gap element and a Kelvin-Voigt element. To investigate the response of buildings such as interstory displacements, impact forces and normalized story shear two far-field earthquakes and two near-field earthquakes were used as input motions. Outcomes of the analyses exhibited reduced interstory displacements, impact forces and normalized story shear when underlying soil was considered. Same author in year 2009 along with Wijeyewickrema performed a study on mid-column pounding of multi-story reinforced concrete buildings considering soil effects where an analysis on seismic pounding of reinforced concrete buildings with non-equal story heights including soil–structure interaction was performed. Two building configurations, 10-story and 9-story buildings and two 5-story buildings, were considered. The maximum impact forces and inter-story displacements were observed in buildings considered for the near-field earthquakes in both fixed foundation and flexible (soil) foundation cases. When the underlying soil effect is considered a significant reduction in impact forces were observed and the maximum interstory displacements occurred when there was no pounding.

A study to determine the seismic responses in building, due to the interaction between adjacent buildings owing to pounding and the interaction between the buildings through the soil for two conditions: fixed-based (FB) and structure–soil–structure interaction (SSSI), was carried out by Naserkhaki et al. [17]. Numerical model developed for the study consists of adjacent shear buildings resting on a discrete soil model and a linear viscoelastic contact force model that connects the buildings during pounding. The results of the study show that pounding worsens the building's condition because their seismic responses are amplified after pounding. The ratio of seismic response under SSSI conditions with pounding to those without pounding is greater than that of the FB condition.

An attempt to introduce the concept of structure–soil–structure interaction and a literature review on the study of structure–soil–structure interaction effects for two adjacent buildings was carried by Gaonkar and Savoikar [9]. Case

history on dynamic structure–soil–structure interaction analysis that considers adjacent tall buildings was also provided as a reference. A three-dimensional finite element numerical simulation using ANSYS was carried out by Li et al. [16] as per Chinese design code for Shanghai soft soil with the rigid foundation, box foundation, and pile foundation. For simulation, the Davidenkov model of the soil skeleton curve was assumed for soil behavior, and the contact elements with Kelvin model were adopted to simulate pounding phenomena between adjacent structures. The results of the study show that the seismic separation requirement for adjacent buildings as per Chinese design code is insufficient to avoid pounding effect and pounding and SSSI effects worsen the conditions of the adjacent buildings because the acceleration and shear responses are amplified after pounding considering SSSI.

Kasai et al. [15] carried out pounding damages survey and analytical pounding studies which included a pounding survey from the 1989 Loma Prieta earthquake, development of pounding dynamic analysis computer program, actual case studies to determine required building separations to exclude pounding, and a possible pounding mitigation technique. The experimental validation for analytical studies on seismic pounding was carried out by Filiatrault et al. [8]. The study presented the results (pounding response) of shake table tests of pounding between adjacent three and eight-story single-bay steel framed model structures subjected to various earthquake intensities and initial separations. Modeling the pounding effect by elastic gap elements produced accurate displacement and impact force results. Bertero [3] reviewed the history of observed damage after significant earthquake ground motion due to adjacency hazard, of which pounding of buildings was just one potential source. The author also recommended the need to improve the state of the art and the state of the practice by improving and/or developing new seismic code regulation for the reduction of the seismic risk that can be generated by adjacency hazards. One more experimental study on earthquake-induced pounding between structural elements made of different building materials, such as steel, concrete, timber, and ceramic, was carried out by Jankowski [13]. The experiment focused on the pounding-involved response of two tower models excited on a shaking table. The results of the study showed that the value of the coefficient of restitution depends significantly on the prior-impact velocity as well as on the material used. Based on the results, the author suggested the appropriate formulations to be applied in the numerical simulations.

The assessment of seismic pounding hazard for Taipei city was carried out by Jeng and Tzeng [14]. Taipei City is vulnerable to seismic pounding destruction due to its high seismicity, soft soil condition, and many tall buildings with

improper seismic separation. The study conducted a survey on seismic separation, to reveal the status and identify the buildings susceptible to pounding damage. To obtain the story shear amplification, dynamic pounding analyses of model frame structures were also conducted. From the calculated story shear amplification, the measured gap, and the relative position of the buildings, a damage index was assigned for each building and related with a proposed damage criterion based on story shear amplification to define its damage level. The survey on seismic separations between buildings revealed that 30% of tall buildings studied had separations smaller than that required, and many are prone to the most dangerous pounding damage patterns.

Analysis of coupled lateral-torsional-pounding responses of one-story asymmetric adjacent structures subjected to bi-directional ground motions was performed by Hao and Gong [11]. It is a succeeding paper of Gong and Hao [10], presenting numerical results of a parametric study of seismic-induced lateral-torsional-pounding responses of an asymmetric and a symmetric one-story adjacent structure by the author. The paper states that spatially varying ground motion induces additional torsional and out-of-phase responses between adjacent structures in comparison with uniform ground motion considering the spatial ground motion, resulting in smaller base shears, and smaller torque in an asymmetric structure, but larger torque in a symmetric structure.

Building pounding state of the art: identifying structures vulnerable to pounding damage was carried out by Cole et al. [7] to assist engineers in undertaking either preliminary or in-depth assessment of buildings with pounding potential. The study emphasized on the loadings caused by pounding and identified the fundamental difference between floor-to-column collisions and floor-to-floor collisions. Existing methods of building-pounding assessment are also reviewed to assess each method's applicability and weaknesses along with the current mitigation options in terms of practical application to existing structures. The same author, in the year 2011, carried out a study to investigate the effects of mass distribution on pounding structures by proposing an equivalent lumped mass model against simplified distributed mass models through numerical modeling of two two-story buildings. The study highlighted the significant influence that diaphragm mass distribution may have on the analysis of pounding structures.

Comparison of codal provisions of seismic separation requirement for adjacent structures was carried out by Rajaram and Kumar [19]. The two-linear single-degree-of-freedom oscillators were used to study the impact force for five different ground motions ranging from 0.2 to 0.8 g. The separation distance was calculated from the codal

provisions of different countries. The result of the study shows that when the impact time is same, the separation distance between the two structures decreases and the amount of impact increases. For structures having the same period, no need to provide separation distance. The amount of impact depends on the response of the structures at the particular time, minimum space between the structures, and velocity of the structures.

Case Study: Pounding Damage to Buildings and Bridges in the 22 February 2011 Christchurch Earthquake by Chouw and Hao [5]

Observations on damage incurred by the buildings resulting from relative movements between adjacent structures during 22 February 2011 Christchurch Earthquake are presented in the study. Pounding-induced damage occurs when the relative response is larger than the gap between adjacent structures. The relative structural response is often initiated by the different dynamic characteristic of the participating structures.

On September 4, 2010, at 4.35 AM New Zealand Standard Time (NZST) in the South Island of New Zealand a strong earthquake of magnitude 7.1 occurred. The epicenter of which was approximately 37 km west of Christchurch. A strong aftershock of magnitude 6.3 occurred in Christchurch City on 22 February 2011 at 12.51 NZST after several thousand aftershocks for which the epicenter was located about 6 km from the Christchurch Central Business District (CBD) in the Port Hills near the town of Lyttelton. Even though the aftershock was of a smaller magnitude than the main event, it caused severe destruction to Christchurch City, especially to buildings in the CBD. Because the aftershock had a shallow focal depth of approximately 5 km, with the hypocentre very close to the CBD which resulted in strong shaking not only in the horizontal but also in vertical direction causing widespread soil liquefaction. One of the most severely damaged structure during the event is the Christchurch Cathedral in CBD. Damage in building occurred due to the insufficient gap between the buildings to cope with the closing relative movements during the shaking. The out-of-phase responses of adjacent structures were caused mostly by the different dynamic properties of the participating structures.

During 22 February 2011 Christchurch Earthquake, all columns of under construction building along Lichfield Street were impacted against the floor and separated. Damage occurred in the column due to pounding is shown in Fig. 2. Damage due to pounding between two adjacent buildings is shown in Fig. 3. Damage to all lower sections between the openings has been observed. It is observed that

Fig. 2 Damage due to relative movement between columns and floor in the CBD

Fig. 3 Pounding-induced damage to structures with large wall openings in the CBD

the stiffer building on the right-hand side experienced less damage.

Figure 4 shows end buildings in the CBD, damaged by relative movements. The loss of the entire parapet of the right-hand side building and large crack at the interface between the perpendicular walls and in the end wall due to lack of anchorage was observed.

The damage to the upper wall of the left unreinforced masonry (URM) building is shown in Fig. 5. The entire floor was almost completely destroyed. The severe damage was mainly due to the large number of openings and brittleness of URM.

Fig. 4 Pounding-induced damage to end building

Fig. 5 Loss of top floor due to pounding with adjacent building

The observation made from the study states that damage due to relative movement induced pounding can occur not only to tall buildings but also to one- and two-story buildings and brittle unreinforced masonry (URM) buildings with the large window or door openings are very vulnerable.

Conclusions

An elaborate study on the pounding of structures with soil–structure interaction effects has been carried out considering the work carried out by numerous researchers as a reference. The pounding phenomenon appears to be detrimental and is more intense for the tallest buildings. Further, considering the effect of soil, amplify the cause. Hence pounding between adjacent buildings considering SSI is of vital significance to the sustainability.

Pounding phenomena considering SSI effect change the adjacent buildings dynamic responses. Buildings usually vibrate with higher amplitudes and lower frequencies. There is also increase in other seismic responses such as base shear and lateral displacement of the structure due to interaction, and it depends on the distance between two adjacent buildings. Pounding degenerates the building's condition because the seismic responses are amplified after pounding. Corner buildings always experience significant increases in their response in comparison with interior structures. The effect of pounding is more pronounced when the differences in the masses of two adjacent structures are huge.

To avoid damage to adjacent buildings during the earthquake, it is necessary to provide the adequate separation along with proper design and detailing. Existing design procedure should account for dynamic impact. Adjacent building period ratio should be carefully selected to reduce the pounding effects.

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