Impact of Structural Pounding on Structural Behaviour of Adjacent Buildings Considering Dynamic Soil-Structure Interaction

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ABSTRACT

The structural behaviour of adjacent buildings during a structural pounding and the impact of which has been a subject of discussion for many years and soil-structure interaction (SSI) has been ignored in the design due to its complexity. However, recent research showed that SSI effects can increase the lateral deflections in structures founded on soft deposits. SSI can also affect the inter-storey drifts on a similar founding soil, causing inelastic behaviour and subsequently severe damages. This study attempts to conduct a comprehensive review and comparison of the past and present studies with and without soil-structure interaction effect to show the significance of SSI on structural pounding and hence the need for a new seismic design approach by considering the detrimental influences of SSI on structures, in particular on adjacent buildings at proximity of each other. The displacement and inter-storey drifts are compared with future predictions to better understanding of pounding effect on these building and subsequently improve the design to mitigate the impact.

Keywords: *Structural Pounding, Adjacent Buildings, Soil-Structure Interaction, Seismic Response, Load Carrying Capacity*

1. Introduction

Earthquakes around the world have shown their destructive powers to cause severe damage to man-made structures (Far, 2019a). Among those, tall buildings are no exception. Tall buildings are eminent in large cities (Far, 2019b). As the land value increases, these buildings are constructed closer and closer to each other which, in turn, are a recipe for pounding. El-Centro (1940), Northridge (1994), and Kobe (1995) are among those earthquakes that had high effect on adjacent structures. An overturning event is inevitable due to the height of these buildings during a large earthquake, the degree of which pending on the type of the soil that these buildings are resting on, gap distance, etc. Hence, there is a need to assess the soil-structure interaction effects due to seismic behaviour of the structures. These soil-structure interaction effects can be observed in adjacent buildings built on similar foundations which can cause severe pounding.

The main question remains with pounding impact and the way it should be dealt with. The effect of SSI on structures, however, has been noted in several studies in recent years (e.g., Tabatabaiefar, 2016; Tabatabaiefar, 2017). This study, though, tries to explain the significance of SSI on pounding impact within adjacent buildings, and most importantly, derive a relationship between SSI, pounding and structural behaviour of these building types. To achieve this goal, a comparison of study cases was adopted to establish a relationship between these phenomena and eventually derive a method to mitigate the effect of pounding.

Furthermore, this paper is a steppingstone to reach the final goal which is a practical solution to mitigate the impact of structural pounding on adjacent buildings and to see the significance that SSI can offer. Previous researchers concentrated mostly on separation gap. This study attempts to develop

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a new method to reduce the effect of pounding while considering SSI without emphasising on separation gap. Strictly speaking, the comparison kills two birds with one stone, meaning showing the significance of SSI in earthquake pounding analysis and at the same time introducing a new strategy, mitigating the pounding impact by studying the structural behaviour of adjacent buildings.

In recent years, Gazetas and Mylonakis (1998), Maheshwari and Sarkar (2011), and Far & Flint (2017) demonstrated that the SSI effects on structural systems have become increasingly significant when the structures are founded on soft soils. Veletsos and Meek (1974) and Tabatabaiefar et al. (2012) suggested that SSI effects are substantial when the soils' average shear wave velocity is less than 600 m/s in un-braced buildings. Factors like site conditions, earthquake source, and travelling waves can affect the structures during an earthquake excitation which are all part of free-field ground motion, and are influenced by SSI (Fatahi et al., 2011; Samali et al. 2011; Fatahi & Tabatabaiefar, 2014). A foundation corresponds to a half-space field for a building founded on a solid rock during a seismic response. In the free field motion, however, the influence of building on the rock surface is minimal. This is not valid as the presence of the structure can alter the soil surface in soft soil underlayer (Tabatabaiefar et al., 2015; Tabatabaiefar & Clifton, 2016; Tabatabaiefar et al., 2017).

Pounding impact, on the other hand, has been an obvious effect on adjacent buildings for quite some time. The effect of pounding has been a subject of research since California earthquake in 1906. However, the previous research has been premature as lack of knowledge on SSI did not allow the researchers to include this effect in their efforts. Simplest method of avoiding pounding that has been around for years is to calculate the maximum gap distance between the adjacent structures safety and hence making those large enough to prevent future collisions. This method has been reviewed by many researchers such as Kluge et al (2020) and Khatami et al (2020). Further to these, researchers attempted to include the effect of SSI during an earthquake excitation in adjacent buildings. A variety of procedures were implemented for the analysis. Mahmood et al (2012) investigated the coupled effect of the supporting soil flexibility and pounding using Kobe (1995). Their results showed a decrease in lateral displacement but an increase in acceleration which indicates lower pounding effect. Other effects such as structure-soil structure interaction (SSSI) was also considered by few researchers in structural pounding. Ghandil and Aldaikh (2016) investigated the effect of SSSI in pounding problem of two adjacent buildings resting on a soft soil profile excited by earthquake loadings. The results showed that the minimum clear distance stated in the standard was required in three occasions to prevent the occurrence of seismic pounding.

Researchers have been involved in various solutions, considering separation gap while considering the influence of soil-structure interaction and structure-soil-structure interaction. Pounding impact issue appeared at latter stage when researchers realise the connection of these. Separation gap was the only concern in early years. These studies show the significance of SSI on pounding regardless of gap distance, hence bringing the gap distance calculated in most standards under the microscope. It also demonstrates the effect of SSI in the inelastic analysis, mitigating the significance of separation gap in comparison to SSI effect during a pounding impact in adjacent buildings and their structural behaviour.

Structural pounding that was observed during previous earthquakes generally generated large impact forces and high acceleration pulses during a short duration, which causes lateral deflection. A comparison of the results from previous research is the subject of this study. In that, the structural response of a few adjacent multi-storey buildings and significant effect of SSI in their lateral deflection and inter-storey drifts are discussed. The results are an overall view of the impact of SSI on structural pounding, and the requirements to mitigate this effect. Finally, a prediction is concluded to indicate the importance of SSI inclusion in current design and developing future procedures.

2. Background

Researchers have been involved in various solutions, considering separation gap, and connection between the adjacent buildings using rubber-dampers, etc. However, these became rather standard solutions to resolve structural pounding in most countries in which the influence of soil-structure interaction was ignored. In the 1964 Alaskan earthquake, the 14-storey Westward Anchorage Hotel building was damaged because of pounding to a shorter 6-storey adjacent building. With a gap of only 100mm, the impact was strong enough to displace the steel girder roof of the shorter building (Naeim F. 1989). In the 1985 Mexico City and 1989 Loma Prieta earthquakes, a large share of seismic damage was also due to pounding.

2.1 Separation Gap

Separation gap has been a discussion over many years and was considered the solution to prevent pounding impact in adjacent buildings. As such, providing flexible members in between adjacent buildings became a popular and reasonable solution to mitigate pounding impact. Having said that, resolving the pounding effect by calculating the minimum separation gap appeared to be a good approach.

Zhi-wu Yu, et al (2017) proposed a new general spectral difference method (gSDM) to calculate the minimum safe distance of adjacent buildings. The results showed that the gSDM method reasonably considered the non-proportional damping of the structure and yielded a more accurate result. It also revealed that the gSDM method agreed better with the time history analysis solution compared to the coupled damping method and can be used to calculate and predict an adequate safety distance between adjacent buildings to avoid pounding during earthquakes. Favvata (2017) studied two adjacent RC building with one shorter than the other to determine a minimum separation gap with potential inter-story seismic pounding. Her work showed a relationship between the separation gap, shear level of the column, seismic loading and hazard used in the evaluation. Gan et al (2019) studied the effect of dynamic SSSI on three adjacent tall building, determining separation gap to be the main factor.

Miari et al (2019) analysed a seismic pounding between adjacent buildings to identify the parameters, soil interaction issues by considering aspects of a sufficient separation gap to introduce mitigation measures for structural pounding. Abhina and Nair (2016) evaluated the seismic pounding effect on two adjacent buildings (a 5 and 8-storey with fixed base) using structural software ETABS without consideration of SSI. It was determined that the pounding increased in those cases without sufficient separation gaps. Zhang et al (2018) analysed pounding between adjacent structures based on a transfer matrix method without consideration of SSI, using structural software MS-TMM and ANSYS. The results showed an increase in pounding force and the number of poundings when there was a decline in separation gap size. Farahani et al (2019) considered seismic ponding impact between adjacent coupled buildings in torsion without the effect of SSI, in which separation gap size was the critical finding.

2.2 Previous Research on Effects of Soil-Structure Interaction regarding Pounding

Soil-structure interaction effects on structural pounding was studied in early 90's by Schmid & Chouw (1992). They examined the pounding of two adjacent buildings during the Montenegro earthquake to see the effect of SSI on the vibration behaviour of the buildings using a partial differential equation numerical method. The results showed that the SSI changes the dynamic characteristics of the soil-structure system. The buildings vibrated lower frequencies on higher amplitudes. Mahmoud et al (2013) investigated pounding impact between equal height multi-storey buildings by considering SSI. The results indicated that the SSI had significant response on pounding during an earthquake, especially on smaller structure. It also showed the soil flexibility can decrease the lateral deflection and the pounding impact forces. Zou et al (2013) took the matters further by studying the pounding of adjacent buildings with SSI effect on pile foundation. The results showed that the soil property (shear-wave velocity) and foundation parameters (e.g., pile stiffness) had influential effect on structural pounding.

Xue et al (2016) analysed structural pounding force using viscoelastic materials in a damper model and compared the results to the experimental duplicate. The results showed the damper model with low effect. This was expected as the SSI was not considered. Kluge et al (2020) studied non-linear structural pounding under stochastic excitation. Changhai et al (2015) studied the seismic pounding response of adjacent multi-degree-of-freedom (MDOF) buildings with bilinear inter-story resistance characteristics. Results show that the maximum response of the building is amplified because of pounding and pounding force is affected by mass difference. Gattulli et al (2019) conducted a procedure with damper coupling of adjacent structures to reduce pounding effect.

Viccencio and Alexander (2018) explored the dynamic effect of SSSI on adjacent unsymmetrical buildings during a seismically induced torsional motion. The findings showed the smaller building have influential effect on the taller building by considering SSSI. Mavronicola et al (2020) analysed the seismic response of the ground motion directionality effect on base isolated buildings during pounding in adjacent structures. Their work indicated that the effect depended on the incidence angle, the width of the seismic gap, the flexibility of the superstructure and potential accidental mass eccentricities on the peak seismic response. He et al (2018) considered polymer bumpers to mitigate the pounding effect in adjacent building with different heights. They showed that polymer bumpers can reduce pounding forces and shearing forces between adjacent buildings. Factors such as viscoelastic properties of polymer bumpers, separation gap distance sizes of bumpers can also influence the pounding responses between buildings.

Jankovski and Mahmood (2016) and then Mohsenian et al (2021) conducted an experiment using adjacent three-storey building with different dynamic characteristics to mitigate the pounding effect. The results indicated that the provided link was only beneficial to the lighter structure. Kontoni and Farghaly (2018) studied seismic response of adjacent unequal buildings subjected to double pounding by considering SSI. Their results showed the significance of SSI when analysing the seismic double pounding.

Moghadasi et al (2011) analysed the effect of soil-foundation-structure on structural response of adjacent buildings using Monte Carlo earthquake excitation. Their work showed a direct link between soil-foundation-structure effect on structural response by increasing it. Qi and Knappett (2020) considered a variety of foundation type on liquifiable soil to the influence of SSSI, the results of which showed an increase in pounding impact as the ground motion occurs more near the surface when the foundation is on liquifiable soil. Liolios et al (2015) did a computational analysis on adjacent RC buildings connected by cable elements under multiple earthquakes to determine the pounding damage response without SSI effect. It was concluded that pounding had significant effect on the earthquake response. Darbandsari and Kashani (2018) reviewed several computational methods which considered the effect of SSSI on pounding on closely spaced adjacent buildings. It was determined that all showed the detrimental alteration seismic pounding response and the necessity to consider soil structure interaction under static and dynamic loading conditions. Therefore, inclusion of SSSI in the analysis was necessary.

Tubaldi et al (2020) attempted a fluid viscous damper system in two adjacent buildings to mitigate pounding without considering the effect of SSI. They concluded that this method was not practical as it required variable changes to the building features. Petronijević et al (2014) used computer simulation method to analyse potential pounding in adjacent buildings without considering SSI but use of expansion joints. The dynamic analysis in their work showed that installation of expansion joints was necessary but at a cost. Rahgozar and Ghandil (2011) worked on several adjacent building cases, 15 and 30 storey buildings under the influence of SSI. It was determined the pounding response was reduced where in a shorter and taller building combination. Suhas and Prakash (2017) compared the effect of SSSI and SSI on adjacent 10-storey buildings. It was concluded the effect of SSSI on lateral deflection and base shear was approximately 61% and 42% more than SSI, respectively.

Passoni et al (2014) used damper coupling in between adjacent building without SSI effect. They concluded that dissipative connection was an improvement compared to rigid links. Elwardany et al

(2019) studied SSI effect on structural pounding of adjacent steel-frame building where the infill concrete panels were used. The results showed that SSI significantly increase pounding through vibration and natural period of the buildings. Naderpour et al (2016) did a numerical study on pounding between two adjacent buildings without the influence of SSI. The results indicated that the peak impact forces during collision was much dependent on impact velocity and force time history, gap size, coefficient of restitution, and stiffness of impact spring element. Chouw and Hao (2011) did an observation experiment on pounding behaviour of adjacent structures during the 2011 Christchurch Earthquake. They determined that large openings in walls and inadequate separation distance were main factors of pounding damage in 1 and 2 storey buildings, especially in end buildings. Soil liquefaction was another major reason for pounding.

Dobre et al (2014) conducted a research on pounding effects during an earthquake, with and without consideration of SSI of buildings in Romania. The effects of pounding on dynamic response consist generally in high amplitude in a short duration local acceleration with high shear to cause degradation of structural elements when SSI was considered. The case was reversed in the case without SSI. Shahbazi et al (2020) determined the high effect of SSI on steel frame building that were subjected to near-field earthquakes with forward directivity. Uz and Hadi (2011) conducted a seismic history analysis of asymmetrical adjacent buildings while considering the effect of SSI who showed a substantial increase in values of the pounding force and the number of impacts, while a reduction in deformation with an increase of shear wave velocity and increase in the SSI forces at the foundation level. A review by Chinmayi H. K. (2019) on pounding of structures with SSI effects found dramatic alterations to the adjacent buildings dynamic responses when SSI effect is considered.

Mohammadi et al (2015) worked on structural reliability index versus behaviour factor in RC frames with equal lateral resistance. They proved the ultimate lateral resistance of structures which causes an increase to a certain level of redundancy can enhance behaviour factor of structures relating to pounding. Monavari and Massumi (2012) did a study on estimating of the displacement in concrete buildings using elastic and inelastic analysis. Their results identified inelastic analysis had significant effect on displacement of levels, especially in upper levels. Massumi et al (2015) did a research on seismic response of RC building with earthquake-resisting reinforced masonry infill panels. Their study showed that the infill panels can stiffen the buildings, while reducing the displacement which in turn minimising the pounding effect.

Analysing the pounding between adjacent structures by using a spring–damper flexible link contact element or the gap element have been used by researchers around the world. This was combined with applying the impact between rigid structures while using restricting elements. Anagnostopoulos SA. (1988) and Pant & Wijeyewickrema (2012) investigated the seismic behaviour of pounding between adjacent buildings considering gap elements by using lumped mass which showed a negligible effect with SSI ignored. Favvata et al. (2009) investigated the behaviour of external connections in relation to the storey-level impact between adjacent structures. It was shown that the localised nonlinear behaviour of such connections could be beneficial for the framing and subsequently reduce the pounding effect.

The pounding of base-isolated structures was studied by Komodromos 2008 using a nonlinear Hertz element for modelling an inelastic impact. The pounding results showed an increase in accelerations and lateral displacements. In another work, it was reported that the period ratio of two adjacent structures determines the probability of occurrence of pounding (Aydin 2010).

Mahmood et al (2013), Behnamfar and Madani (2014), and Pawar and Murnal (2014) showed an increase in pounding force in smaller clear distances. Soil flexibility reduced the displacements and decreased the storey shear in all storeys. The displacements and storey shear were reduced by soil flexibility while it indicated an increase in those factors when a non-linear time history analysis was performed. Rahman et al. (2001) and Madani et al. (2015) discussed the effects of the SSI on the inelastic response of adjacent steel structures with a number of storeys varied between 3 and 12. The study showed that the SSI considerably increased the values of pounding forces and leads to collisions even for larger gap distances.

Sołtysik et al (2017), Jankowski and Mahmoud (2016) conducted analysis of pounding between two adjacent structures using a detailed nonlinear finite element (FE) procedure of adjacent structures in series to study the effect of the pounding behaviour and their effects with considering SSI and SSSI who concluded an increase while Kharazian (2017) studied the influence of the SSI on pounding between 3 and 5 storey RC structures. The results showed that SSI has significant influence on the pounding-involved structural response during earthquakes.

In this study, Rahman et al (2001), Goltabar et al (2008), Naserkhai and Pourmohammad (2011), Karamadi and Togarsi (2017), Ghaedi et al (2018), Kantoni and Farghaly (2018) and Khatami et al (2020) were chosen for comparison to studies by Tabatabaiefar et al (2012). Tabatabaiefar et al (2012) proved that the accelerations of ground motion within structures are affected by factors such as the flexibility within the foundation supporting system and variations between foundation and free-field motions. Hence, an assessment of intermediate loadings of inter-storey drift and increase in deflection was established by considering a rational effect of soil-structure interaction.

This study attempts to confirm these findings as well as proving the significance of taking into account the effect of SSI into the design of the structure and analysis of the pounding impact on adjacent buildings. The results are interpolated off the original graphs prepared by these researchers and then extrapolate to a new graph which include the results by Tabatabaifar et al (2012). A comparison is carried out upon establishing graphs based on those results. A philosophical analysis is conducted to indicate the importance of SSI on structural behaviour of adjacent buildings and pounding impact during a seismic excitation.

2.3 A Critical Review

This section attempts to critically review the previous research components carried out on the effects of structural pounding and then highlights the benefits and advantages of the current study.

Firstly, both the current and previous studies have two major aims in common. Those are to mitigate pounding effect and to understand the effect of SSI on pounding. In the process, all researchers had their own theory, from which attempted to derive an approach or technique. However, just about 89% were concerned about separation gap and using means of separation links such as dampers to determine a minimum required gap (e.g., Zhi-wu Yu, et al 2017). This has been a common practice in the past, has come under scrutiny because of the limitation this solution offers (e.g., practicality limitation in large cities due to the price of land). This is not the case in the current study as separation gap is not considered as a major factor because of the limitations discussed and also the current study considers other factors such as lateral deflection and/or inter-storey drifts more significant which can affect pounding more seriously.

Other major issue with previous researches is the fact that on many SSI effect has been omitted or has not been addressed properly because of lack of knowledge, limitation of resources, etc. On many that included SSI effect, the point was approached by means of numerical and computational methods rather than experimental for verification. The current study attempts the verification of findings by comparison to the practical models for accuracy.

3. Case Studies

Tabatabaiefar et al (2012) performed computational and numerical analyses of 5-storey, 10-storey, and 15-storey buildings on fixed-based and soft soils of C_e, D_e and E_e types under various depths. El Centro 1940, Hachinohe 1968, Northridge 1994 and Kobe 1995 excitations were applied, the deflections of average response under elastic and inelastic behaviour along with inter-storey drifts were tabulated and graphed for comparison and verification using a practical model, built on a shake table.

In this study, the above results are compared to the ones obtained by the researchers mentioned in introduction in order to magnify the significance of SSI on foundations during an earthquake excitation and the effect of SSI on structural behaviour of adjacent buildings. On that note, the focus is mainly the reflective effect of SSI and SSSI on pounding impact of these buildings. To simplify the task, the average values of all four earthquakes on both lateral deflection and inter-storey drift are used for comparison. It is to be noted that those results include an average value of bedrock depth of 10m, 20m and 30m. These lateral and deflections and inter-storey drifts are considered the major sources of pounding during an earthquake and hence the comparison can provide an important tool towards understanding of the events leading to the final pounding between the adjacent buildings, their behaviour and the steps that are required to mitigate such impact.

3.1 Case Study No. 1

Rahman et al (2001) who did an earlier research on a 6-storey and 12-storey adjacent buildings with a fixed base, coupled and non-coupled foundations. As elucidated by many studies (e.g. Far, C. & Far, H., 2019; Saleh et al., 2018; Walsh et al., 2018; Haydar et al., 2018; Far & Far, 2019a,b), structural material and properties plays a significant role in simulating the actual behaviour of building frames. They incorporated the effects of soil flexibility on the inelastic dynamic response of these building which have moment-resisting frames. The 5-storey building from Tabatabaiefar et al (2012) and 6-storey building from Rahman et al (2001) are compared and graphed as depicted in Figures 1 and 2.

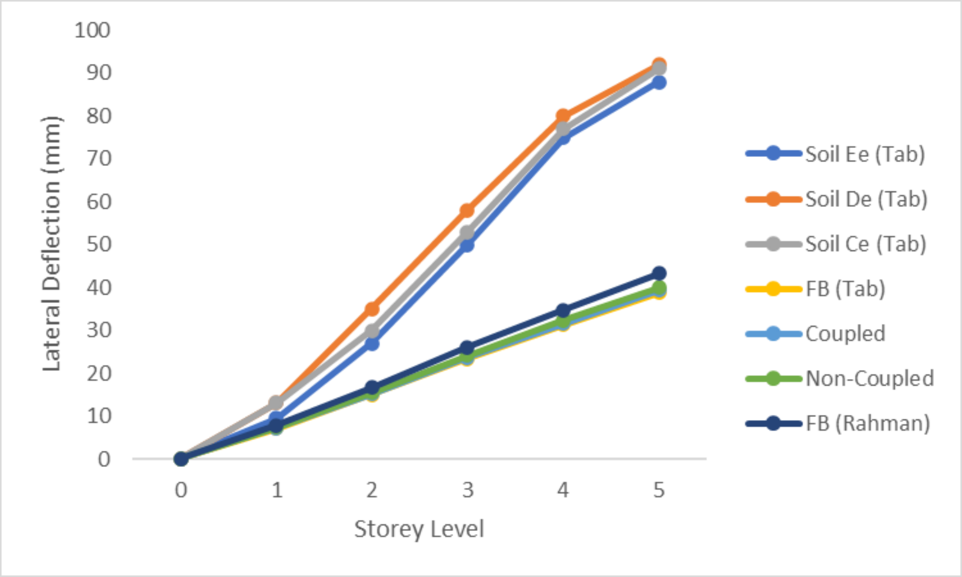

Figure 1 – Comparison of the results by Tabatabaiefar et al (2012) for 5-Storey building (elastic) and Rahman et al (2001) for 6-Storey building

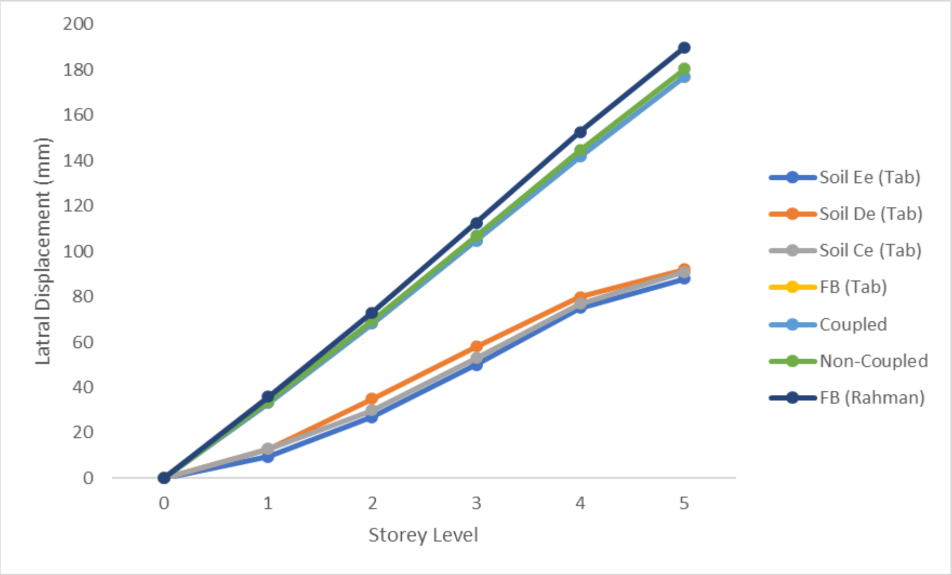

Figure 2 – Comparison of the results by Tabatabaiefar et al (2012) for 5-Storey building (inelastic) and Rahman et al (2001) for 6-Storey building

These buildings were subjected to a combination of three (3) actual earthquake excitations of El Centro in 1940, Mexico City in 1985 and Northridge in 1994. The records were evaluated by means of a structural analysis using a structural software called Ruaumoko. One of their results showed a graph with displacement at every level for both buildings. An average value of those three foundation types was graphed. This graph was interpolated, and the results were extrapolated against the results obtained by Tabatabaiefar et al (2012).

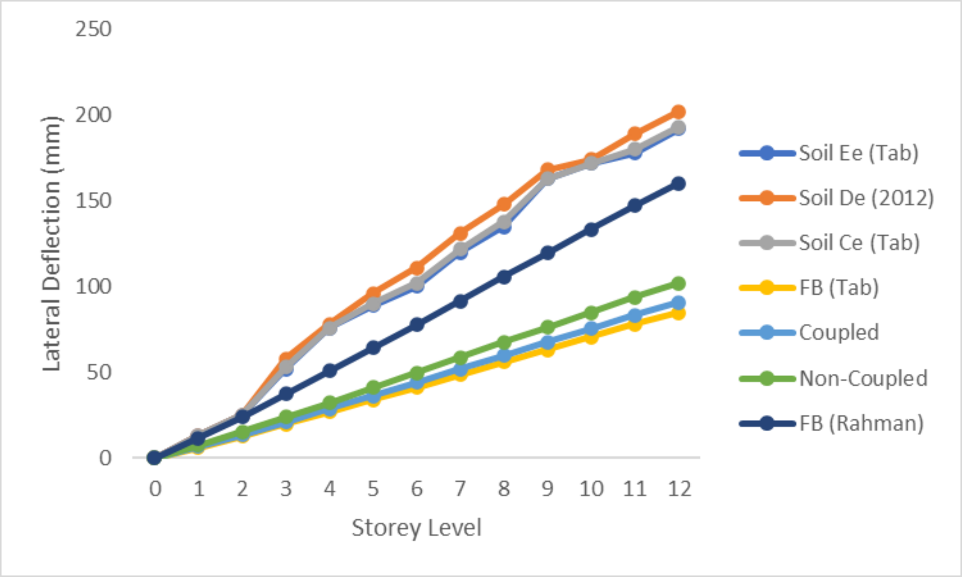

Figure 3 – Comparison of the results by Tabatabaiefar et al (2012) for 15-Storey building (Elastic) and Rahman et al (2001) for 12-Storey building

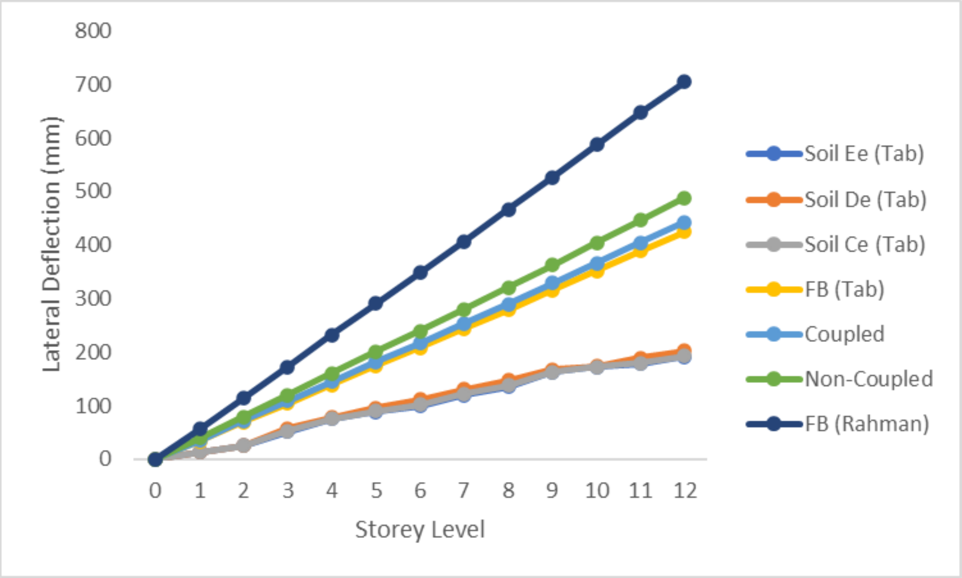

Figure 4 – Comparison of the results by Tabatabaiefar et al (2012) for 15-Storey building (Inelastic) and Rahman et al (2001) for 12-Storey building

The comparison clearly indicates that the figures by Tabatabaiefar et al (2012) are much higher with the influence of various soil type and increases in soft soils. Rahman et al (2001) incorporated three types of base connections without considering the relevant soil effects. The graphs show that although the earthquake excitation values slightly differ in those cases (i.e., Kobe (1995) and Hachinohe (1968) vs Mexico City (1985), for instance), the outcome can still reflect the differential in deflection values and hence the significance of SSI effect is apparent by considering the values with SSI and without SSI effect being rather large. Increase in deflection is a good indication of higher lateral movement which causes pounding of the adjacent buildings. The effect of pounding is higher which means SSI had a higher effect on the behaviour of these adjacent buildings.

Figures 3 and 4 are related to 12 -Storey building by Rahman et al (2001) and 15-Storey building by Tabatabaiefar et al (2012). Similar results can be seen for the 12-storey building. However, the effect is more apparent in the inelastic behaviour than elastic, which indicates the buildings behave inelastically at pounding stage which causes higher impact.

More noticeable is the high value of deflection for fixed-based foundation provided by Rahman et al (2001) compared to Tabatabaiefar et al (2012) results which is more than twice as much. Part of this massive difference can be related to miscellaneous and human error along with lack in equipment accuracy, etc. However, majority belongs to the effect of SSI that was not incorporated in Rahman et al (2001) research. Most significantly, the higher value indicates the high pounding impact that theoretically occurred in between these adjacent buildings. It is apparent that inelastic condition has a much higher impact in the overall pounding effect which shows the highest increase in the lateral movement,

3.2 Case Study No. 2

Goltabar et al (2008) analysed the effective parameters in pounding impact of the three (3) different pairs. A 5-Storey and 2-Storey, a 5-Storey and 7-Storey, and a 5-Storey and 12-Storey were considered in the study. The results are compared to the results by Tabatabaiefar et al (2012) which are depicted in Figures 5 and 6:

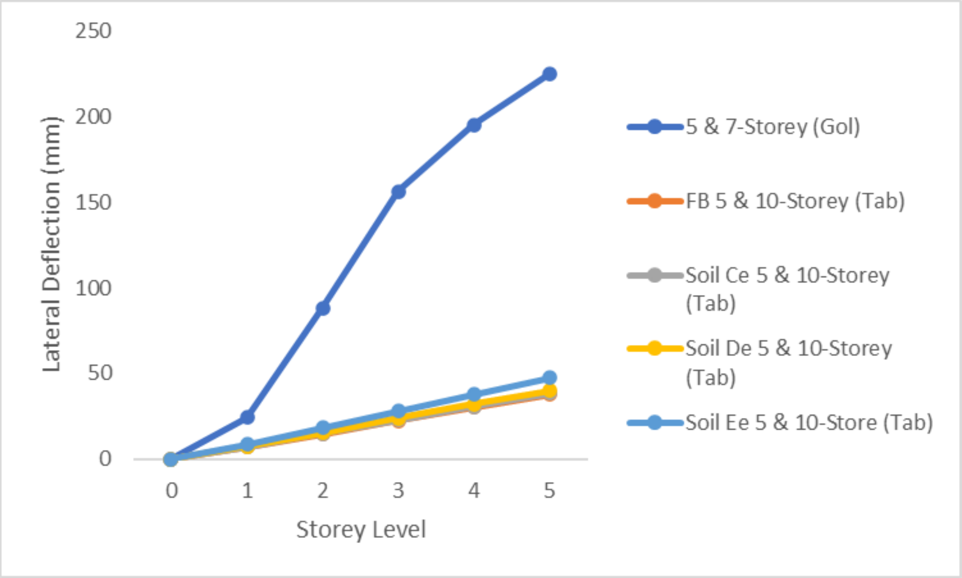

Figure 5 – Comparison of the results by Tabatabaiefar et al (2012) for 5 & 10-Storey building (Elastic) and Goltabar et al (2008) 5 and 7-Storey building

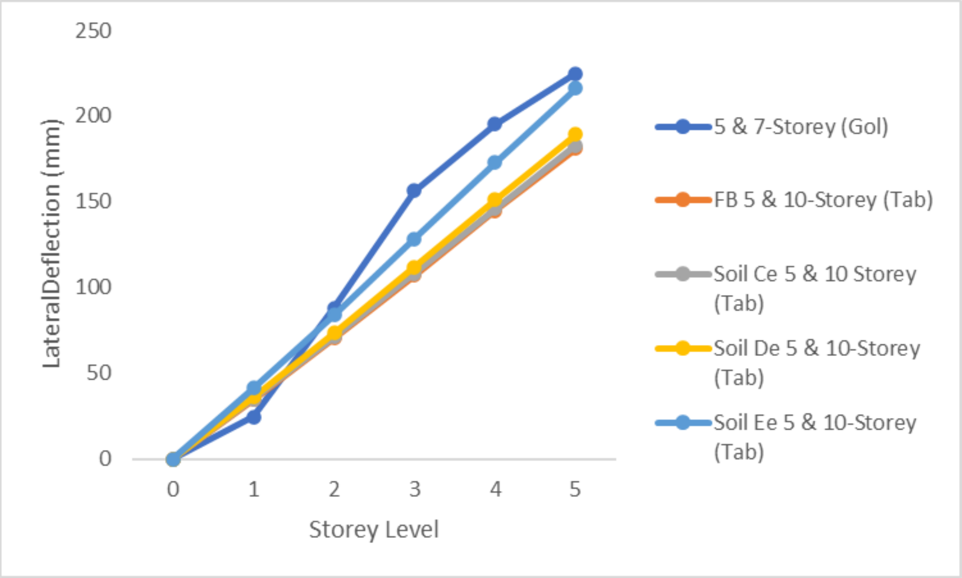

Figure 6 – Comparison of the results by Tabatabaiefar et al (2012) for 5 & 10-Storey building (Inelastic) and Goltabar et al (2008) for 5 and 7 Storey building

Accelerographs readings of three (3) separate earthquakes, Elcentro (1940), Tabas (1978) and Sakaria (1999) were used to perform a non-linear time history analysis on these adjacent buildings, the results of which were graphed.

An average value of 5 and 7 storey (Goltabar et al 2008) was compared to an average value of 5 and 10-storey by (Tabatabaiefar et al 2012). Goltabar et al (2008) carried out the analysis using GAP joint element on soil type II whereas Tabatabaiefar et al (2012)'s buildings were founded on bedrock type Ce, De, and Ee.

The results show a close relationship with similar values for inelastic behaviour. However, there is a enormous gap between Tabatabaiefar et al (2012) and Gotabar et al (2008) values. Goltabar et al (2008) have emphasized their research with a limited gap separation.

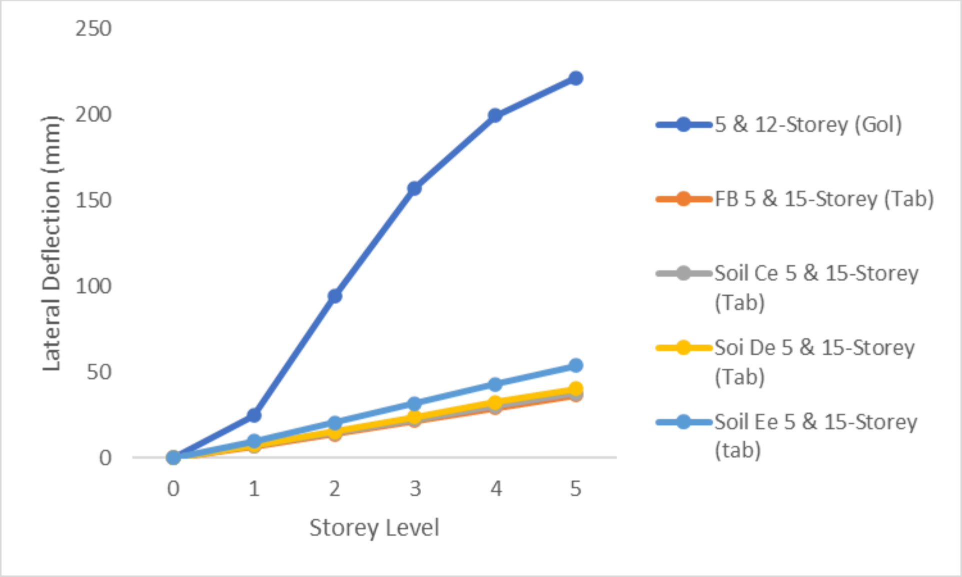

Figure 7 – Comparison of the results by Tabatabaiefar et al (2012) for 5 & 15-Storey building (Elastic) and Goltabar et al (2008) 5 and 12-Storey building.

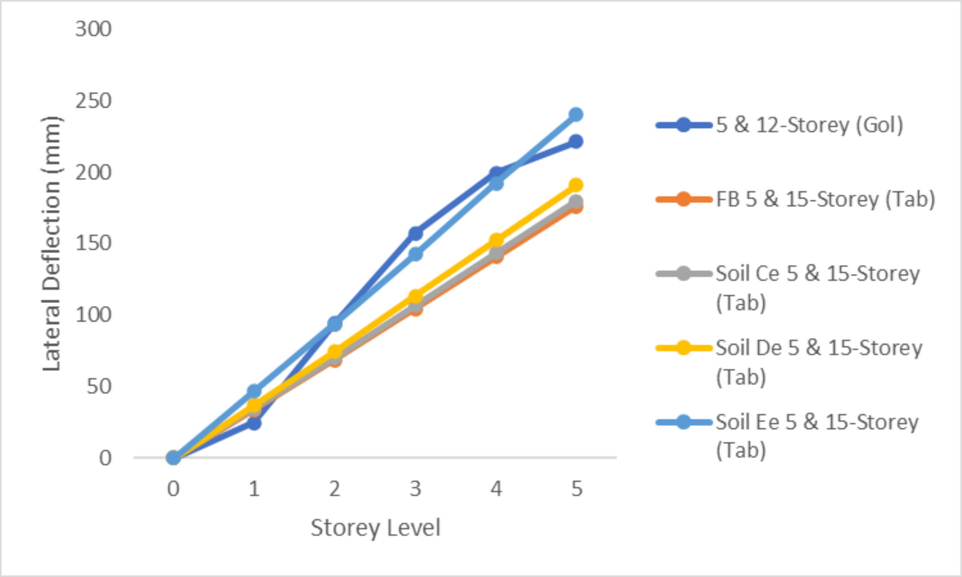

Figure 8 – Comparison of the results by Tabatabaiefar et al (2012) for 5 & 15-Storey building (Inelastic) and Goltabar et al (2008) for 5 and 12 Storey building

The major gap in values can be explained in elastic graph as Tabatabaiefar et al (2012) show the results of Fixed-Base (FB) along with bedrock soil as a continuous but gradual increase in deflection which appeared to be more realistic than Goltabar et al (2008) because of the difference in soil type that was implemented. Inelastic results are consistence between the two (2) researchers which is an indication of SSI effects on pounding impact being more serious in elastic region. Furthermore, the SSI affected the structural behaviour of the adjacent buildings during the elastic analysis. The results are consistent with an increase in lateral movement which increases the pounding effect.

Figures 7 and 8 represent results for comparing the 5 and 12-Storey buildings in Goltabar et al (2008) model with Tabatabaiefar et al (2012)'s 5 and 15-Storey model. The values are averaged as before, and they appeared to be fairly similar to the results obtained for 5 and 7-Storey by Goltabar et al

(2008) and 5 and 10-Storey by Tabatabaiefar et al (2012). The finding indicates that the deflection is not affected with a presence of a taller building up to a certain storey level which is the 5th storey, in this case. Therefore, the pounding is unaffected. On the hand, the SSI influence lifts in inelastic analysis especially in upper levels and hence it is a concern for a pounding impact.

3.3 Case Study No. 3

This case study is about the work by Naserkhaki and Pourmohammad (2011) who analysed two (2) 7-storey buildings, modelled on a visco-elastic half-space soil which were subjected to an earthquake excitation under three (3) conditions of fixed base (FB), soil-structure interaction (SSI) and structure-soil-structure interaction (SSSI). These were developed under analytical procedure and solve numerically. In their study, both lateral deflection and inter-storey drift were graphed which are interpolated and used for comparison to those obtained by Tabatabaiefar et al (2012) which are depicted below:

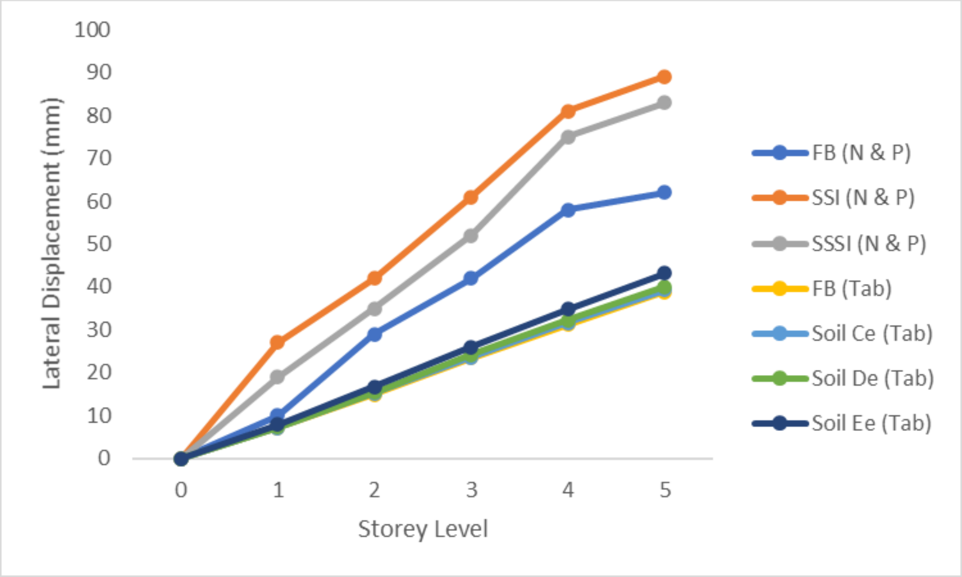

Figure 9 – Comparison of the results by Tabatabaiefar et al (2012) for 5-Storey building (Elastic) and Naserkhaki and Pourmohammad (2011) for 7-Storey building.

The values produced by Naserkhaki and Pourmohammad (2011) are relatively higher than Tabatabaiefar et al (2012). Fixed base (FB) analysis by Naserkhaki and Pourmohammad (2011) show slightly higher values. However, the main difference is in the values shown for soil-structure interaction (SSI) and structure-soil-structure interaction (SSSI).

Increase in values speak of higher pounding impact. This is more apparent with SSI and SSSI effects which means the pounding occurs with a higher frequency and within a shorter period. Figure 9 shows the elastic analysis done by Tabatabaiefar et al (2012). The main difference is in shear wave velocities chosen by the two researchers. Naserkhaki and Pourmohammad (2011) considered a 400 m/s and 700 m/s for a regular soil and a hard soil, respectively whereas these values were reduced to 300 m/s and 600 m/s in the work by Tabatabaiefar et al (2012).

The following Figure 10 is for inelastic analysis. Higher values are expected from Tabatabaiefar et al (2012) according to the results that have been shown so far in other cases.

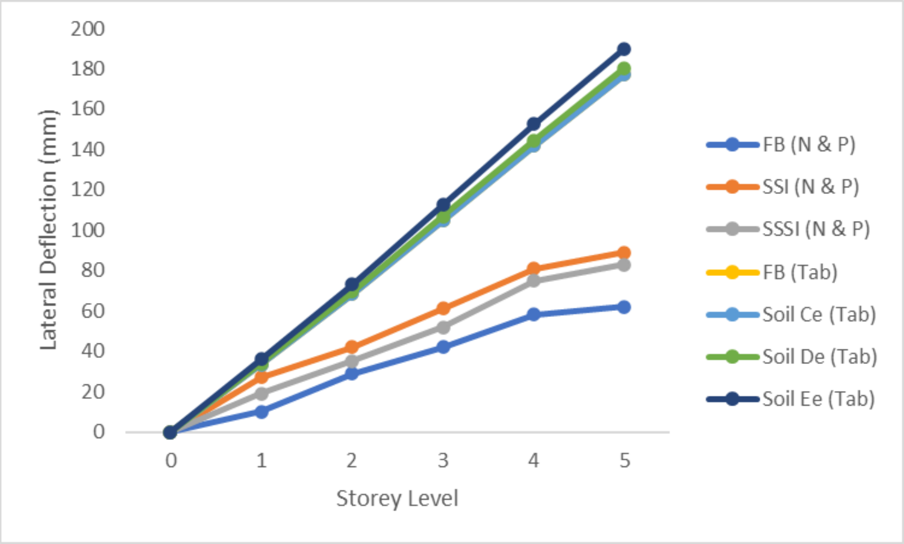

Figure 10 – Comparison of the results by Tabatabaiefar et al (2012) for 5-Storey building (Inelastic) and Naserkhaki and Pourmohammad (2011) for 7-Storey building.

As predicted, Tabatabaiefar et al (2012)'s values are increased slightly in comparison to Naserkhaki and Pourmohammad (2011)'s. This may be due to the fact their results also include the effects of SSSI which suggests a higher pounding impact (Far et al., 2017; Far & Far, 2017).

In this case study, the inter-storey drifts are also analysed in comparison. The following figures show this comparison:

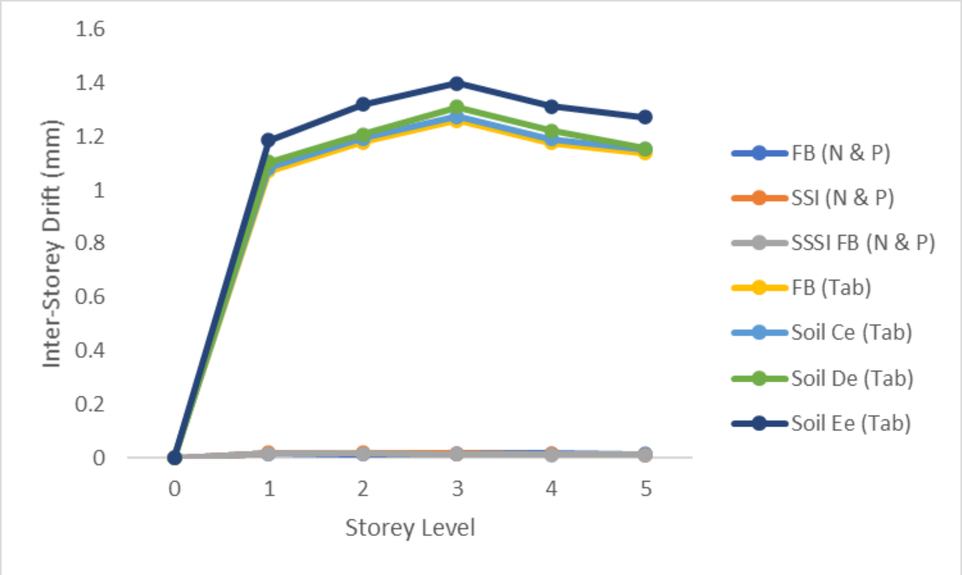

Figure 11 – Comparison of the inter-storey drifts by Tabatabaiefar et al (2012) for 5-Storey building (Elasti) and Naserkhaki and Pourmohammad (2011) for 7-Storey building.

Results by Tabatabaifar et al (2012) show a clear pattern that appears to be more accurate. The inter-storey drifts shown in Nasekhaki and Pourmohammad (2011) work do not reflect a real value as these are all in micro-millimetre range.

These were extracted from the elastic analysis done by Tabatabaiefar et al (2012). The following figure is the comparison in inelastic analysis:

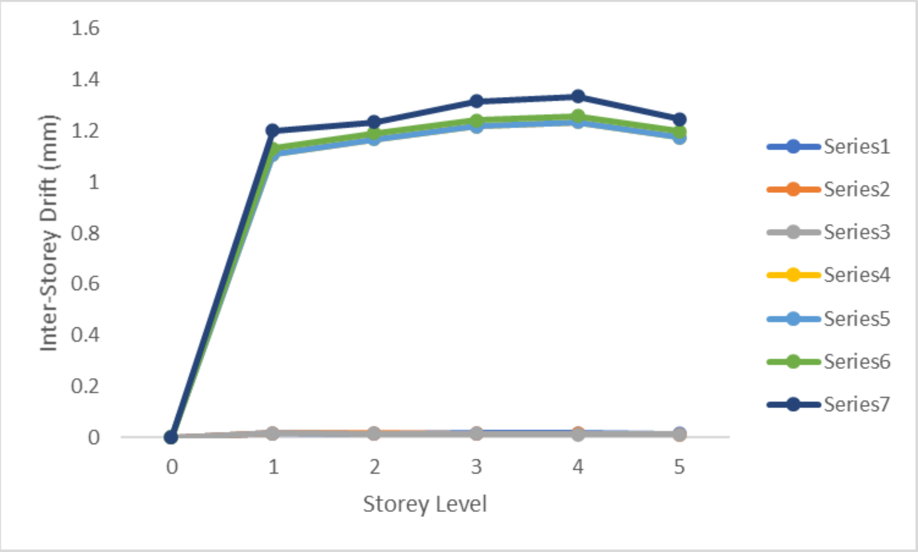

Figure 12 – Comparison of the inter-storey drifts by Tabatabaifar et al (2012) for 5-Storey building (Inelastic) and Naserkhaki and Pourmohammad (2011) for 7-Storey building.

These graphs speak of extreme similarity in values. The elastic and inelastic analysis appeared to have produced proximate values, suggesting that the elasticity had a negligible effect on the lateral movement. The effect on pounding is clear from the lateral deflection results as the results show an obvious jump in values while considering the SSI effect. Both elastic and inelastic behaviour indicate effects of SSI on pounding impact, clearly whereas this is not apparent in each level drifts.

3.4 Case Study No. 4

This case study regards the work done by Karamadi and Togarsi (2015) who used a standard live Load of 3kPa and a superimposed dead load of 1kPa on a 10-Storey and 15-Storey adjacent concrete moment-resisting frame buildings with fixed base (FB). The analysis was carried using the structure software ETABS, results of which were graphed.

These results were interpolated and graphed in comparison with Tabatabaiefar et al (2012). In this case, inter-storey drifts are also considered and compared from the two research and are depicted in Figures 13-16.

From the graphs, there is a significant difference in the lateral deflection values, especially in the inelastic analysis. This is a valid indication of confirming SSI effect on the pounding impact. The analysed modelled by Karamadi and Torgesi (2015) was simply based on structure's analysis without considering the SSI effect. Tabatabaiefar et al (2012) took this further in their analysis by considering these effects in variety of soil deposits and bedrocks.

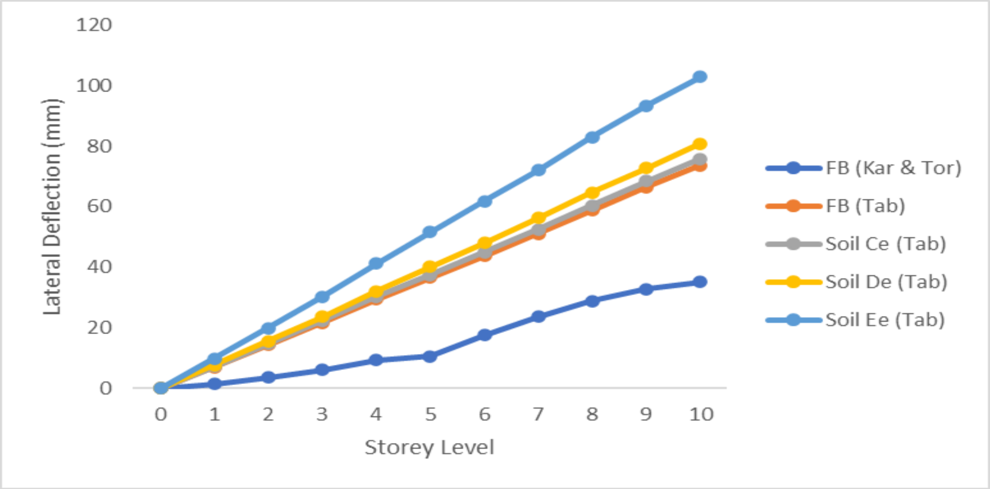

Figure 13 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Elastic) and Karamadi and Torgesi (2011) for 10-Storey building.

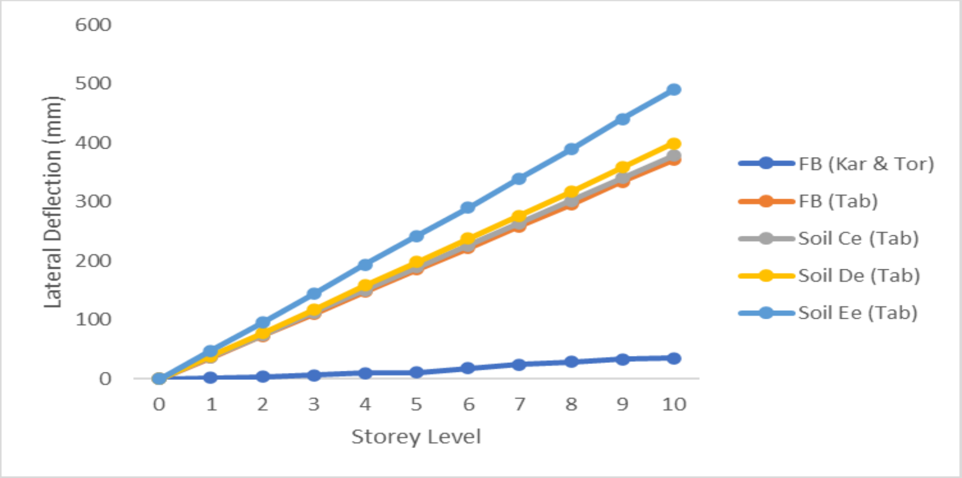

Figure 14 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Inelastic) and Karamadi and Torgesi (2011) for 10-Storey building.

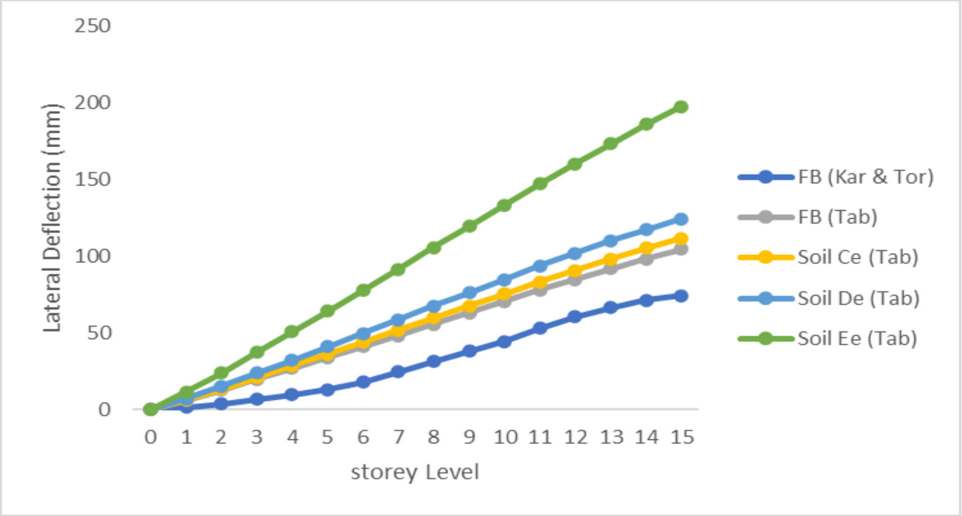

Figure 15 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 15-Storey building (Elastic) and Karamadi and Torgesi (2011) for 15-Storey building.

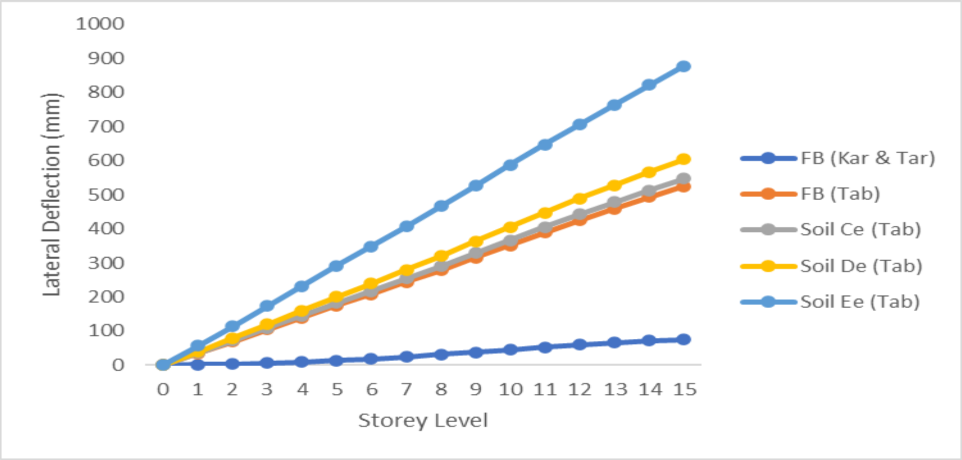

Figure 16 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 15-Storey building (Elastic) and Karamadi and Torgesi (2011) for 15-Storey building.

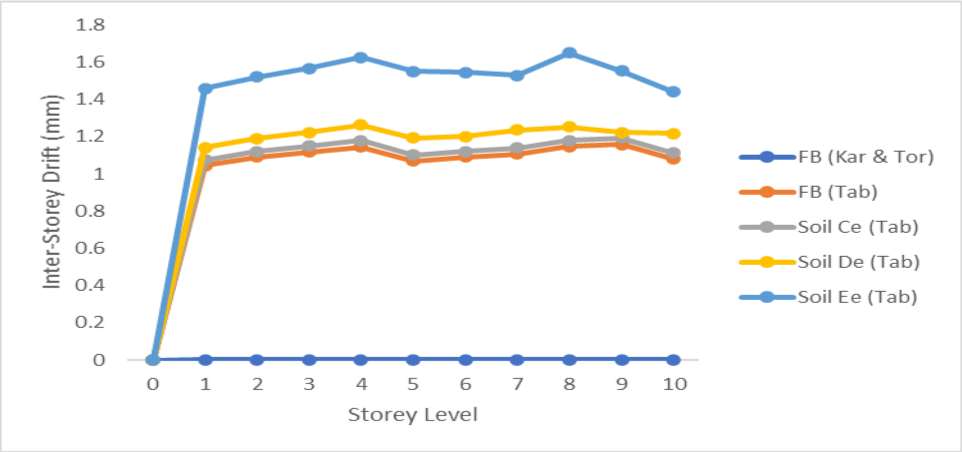

Figure 17 – Comparison of the inter-storey drift by Tabatabaiefar et al (2012) for 10-Storey building (Elastic) and Karamadi and Torgesi (2011) for 10-Storey building.

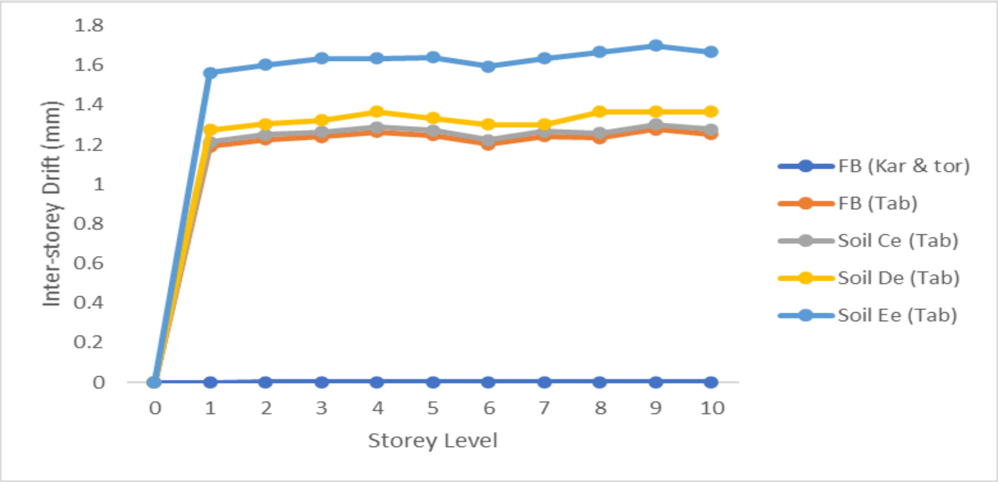

Figure 18 – Comparison of the inter-storey drift by Tabatabaiefar et al (2012) for 10-Storey building (Inelastic) and Karamadi and Torgesi (2011) for 10-Storey building.

There are noticeable differences in inter-storey drift values of the two research. This observation indicates the high accuracy of the work by Tabatabaifar et al (2012). It shows the high effect of SSI on the structures that has been ignored in Karamadi and Torgesi (2015)'s. The accuracy of the software and reliability of numerical-based results has gone under the microscope, too.

The effect of SSI on pounding impact is apparent in the lateral deflection results, regardless of storey height. This effect is much higher in Tabatabaifar et al (2012) as SSI effect was implemented and hence increased the effect on structural behaviour and subsequently pounding impact.

The following figures are for the 15-storeys and their comparison:

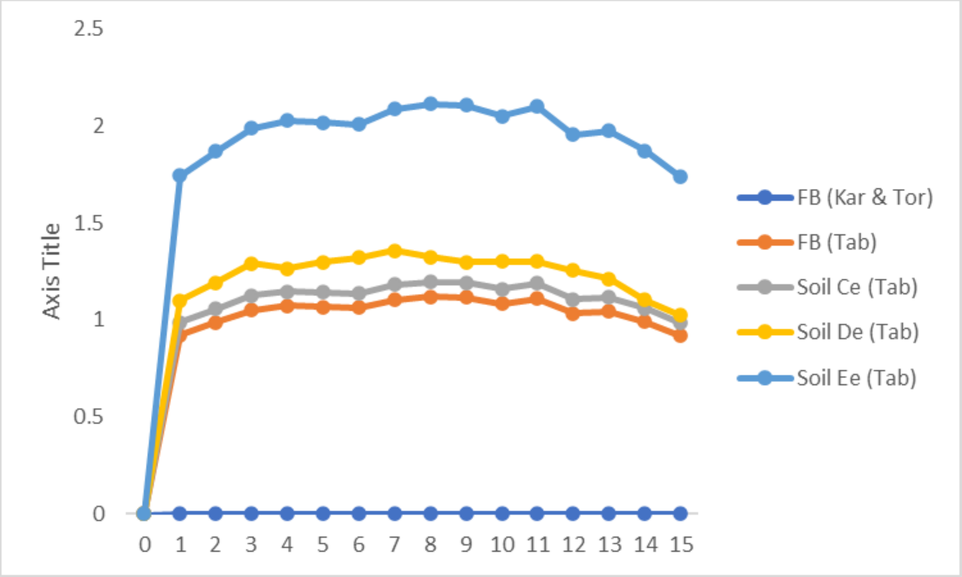

Figure 19 – Comparison of the inter-storey drift by Tabatabaiefar et al (2012) for 15-Storey building (Elastic) and Karamadi and Torgesi (2011) for 15-Storey building.

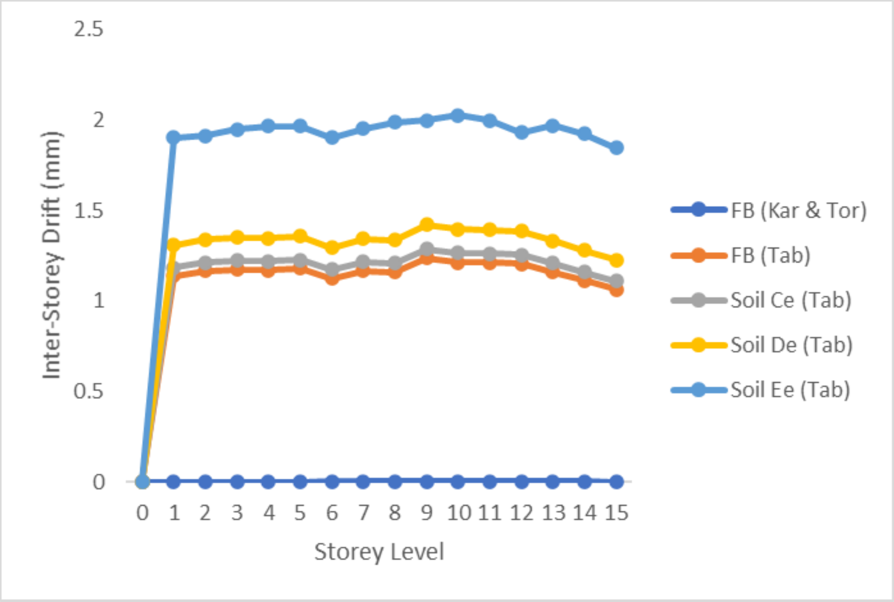

Figure 20 – Comparison of the inter-storey drift by Tabatabaiefar et al (2012) for 15-Storey building (Inelastic) and Karamadi and Torgesi (2011) for 15-Storey building.

The results of 15-storey are similar to 10-storey ones. It is to be noted that these results resemble those from case study No. 3. Numerical methods were used to solve for the results and hence can be assumed that these methods are similar to structural analysis done on a software such as ETABS. Furthermore, the results do not appear to be realistic, with the values in micrometre range. As such, comparing these results to that of Tabatabaiefar et al (2012) do suggest another reason other than computer or human error. This assumption can leave only one other more realistic explanation which goes back to incorporation of SSI effect into the mix. Tabatabaiefar et al (2012) has included SSI effect by considering three (3) soil types Ce, De, and Ee. Even in the fixed base (FB) scenario, the basis of fixed-base (FB) in Tabatabaiefar et al (2012) case is on the underlying soil which is none-existent in the analysis by Karamadi and Toresi 2015).

All these results point to the proportional effect of SSI on structural pounding. That is, the higher the lateral movement, the worst the pounding impact. This effect is difficult to see in inter-storey drifts comparison as the values obtained from Karamadi and Toresi (2015) are not compatible to those of Tabatabaiefar et ala (2012) and therefore cannot be distinguished. As such, Tabatabaiefar et al (2012) results suggest a pattern that indicate a clear effect of SSI on pounding impact.

3.5 Case Study No. 5

Goankar and Savoikar (2016) did a review study on the work by Yahyai et al (2008), Rahgozar and Ghandil (2011) and Nateghi and Tabrizi (2011). Among these, the work by Nateghi and Tabrizi (2011) was an analysis by ETABS with a consideration of two (2) types of soil, namely clay and sand. In their analysis, they have considered two (2) adjacent buildings of various height which was a combination of 15-15 storey, 15-30 storey and a single 15 storey building.

The single 15-storey and 15-15 storey combination on two (2) different types of soil (clay and sand) are considered in this study, the results of which are graphed against Tabatabaiefar et al (2012) for a comparison as shown below:

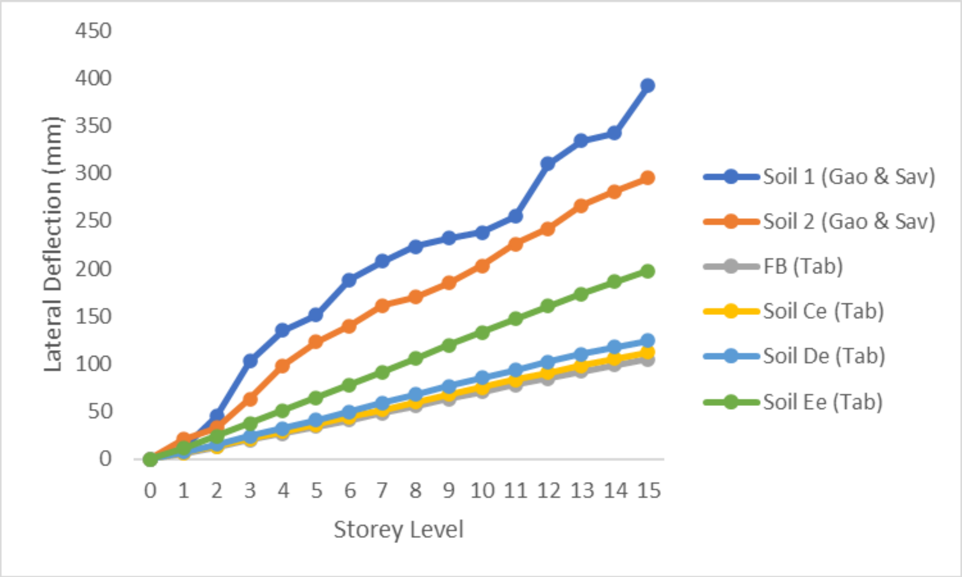

Figure 21 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 15-Storey building (Elastic) and Gaonkar and Savoikar) for 15-Storey building.

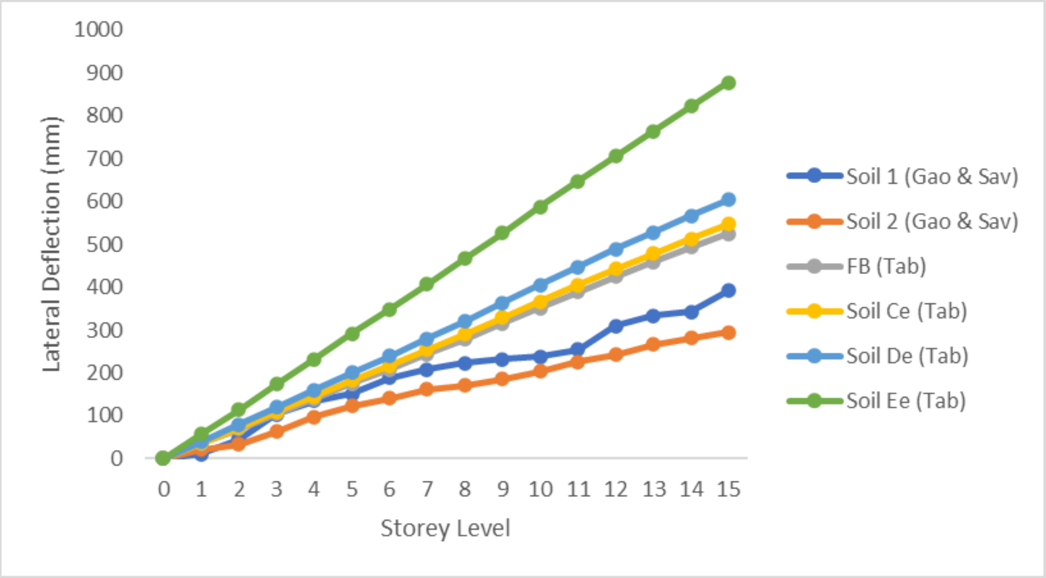

Figure 22 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 15-Storey building (Inelastic) and Gaonkar and Savoikar) for 15-Storey building.

In elastic case, the results shown by Gaonkar and Savoikar (2016) are higher than those indicated by Tabatabaiefar et al (2012). The relationship is reversed in inelastic region with the values obtained by Tabatabaiefar et al (2012) are more than twice as much as those calculated by Goankar and Saviokar (2016) and as a result the effect of pounding impact is doubled.

It is to be noted that this inconsistency can be due to the different soil types used in these case studies. These are not only different but perhaps considered to be dynamically quite opposite of one another. with Gaonkar and Savoikar (2016) having clay and sand types, the characteristic of these types completely differs to the bedrock Ce, De and Ee used by Tabatabaiefar et al (2012). Another main difference will be the differential shear velocity values through the soil deposits in Gaonkar and Saviokar (2016)'s case in comparison to the rocky nature of the underlayer soil in Tabatabaiefar et al (2012)'s. This is also apparent in the 15-15 storey results depicted below:

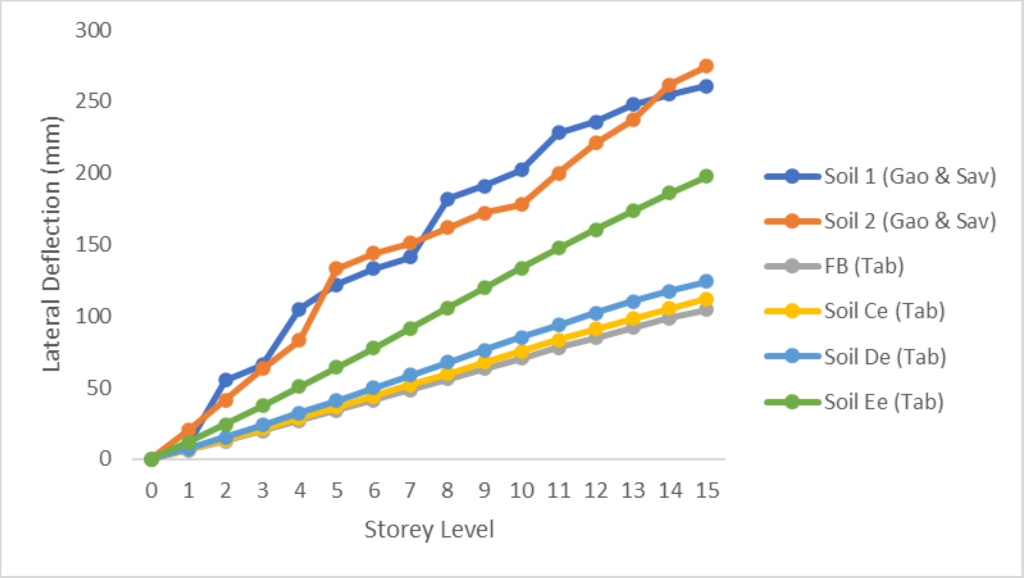

Figure 23 – Comparison of the lateral deflections by Tabatabaifar et al (2012) for 15-Storey building (Elastic) and Gaonkar and Savoikar) for 15-15 Storey building.

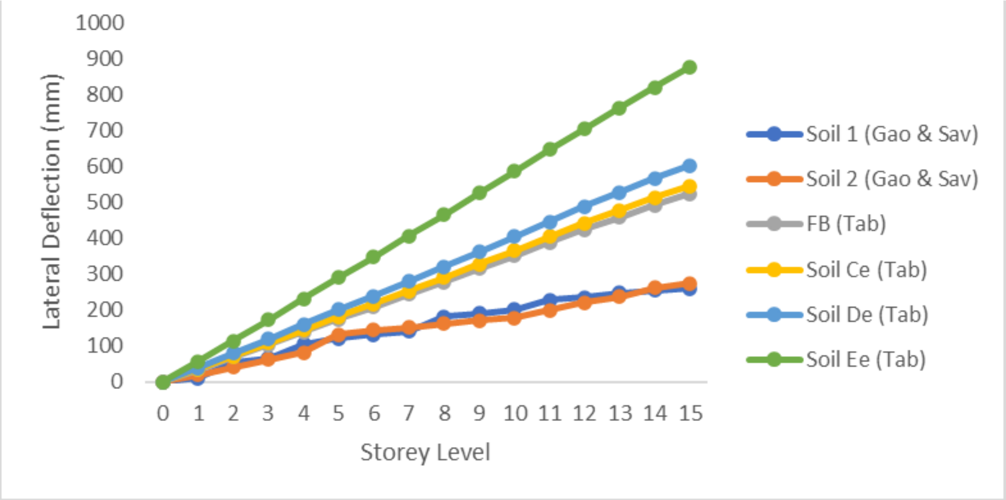

Figure 24 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 15-Storey building (Inelastic) and Gaonkar and Savoikar) for 15-15 Storey building.

The comparison of adjacent 15-15 storey of Gaonkar and Savoikar (2016) to 15-storey by Tabatabaiefar et al (2012) reveals a slight difference in results with values steadily fluctuating but still consistent to those achieved in single storey analysis. This finding indicates that the pounding impact in adjacent building was influenced by SSI, but the effect was minimal.

3.6 Case Study No. 6

Ghaedi et al (2018) did a study on four (4) California suburban areas and analysed lateral deflection during an earthquake motion. These sites were Cape (1992), El-Centro (1940), Santa Monica (1994) and Los Angeles City Central (1994). Among the results obtained from their work, the lateral deflections at each level were calculated and graphed which were interpolated and used to compare to Tabatabaiefar et al (2012)'s results from 10-storey building which are depicted below:

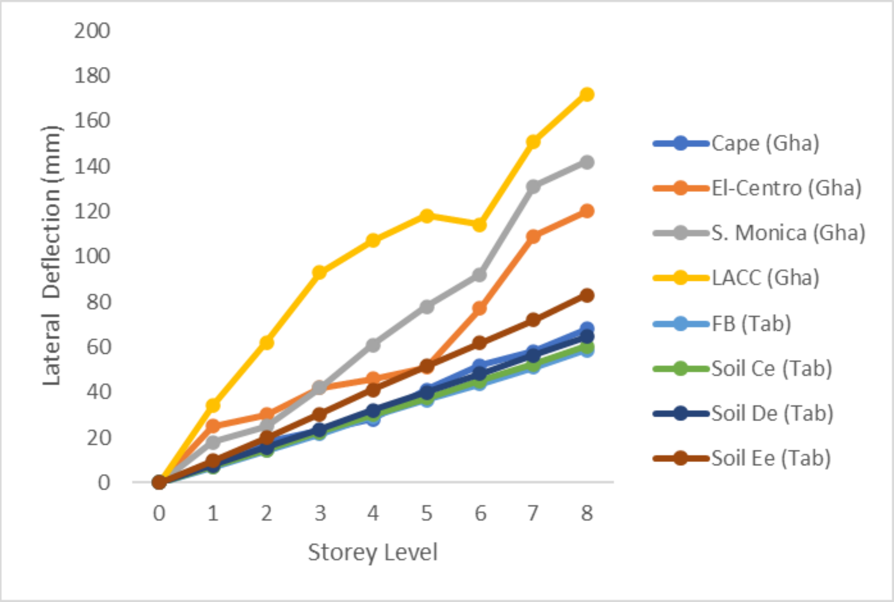

Figure 25 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Elastic) and Ghaedi et al (2018) for 4 & 8 Storey building on a Fixed-Base (FB) foundation

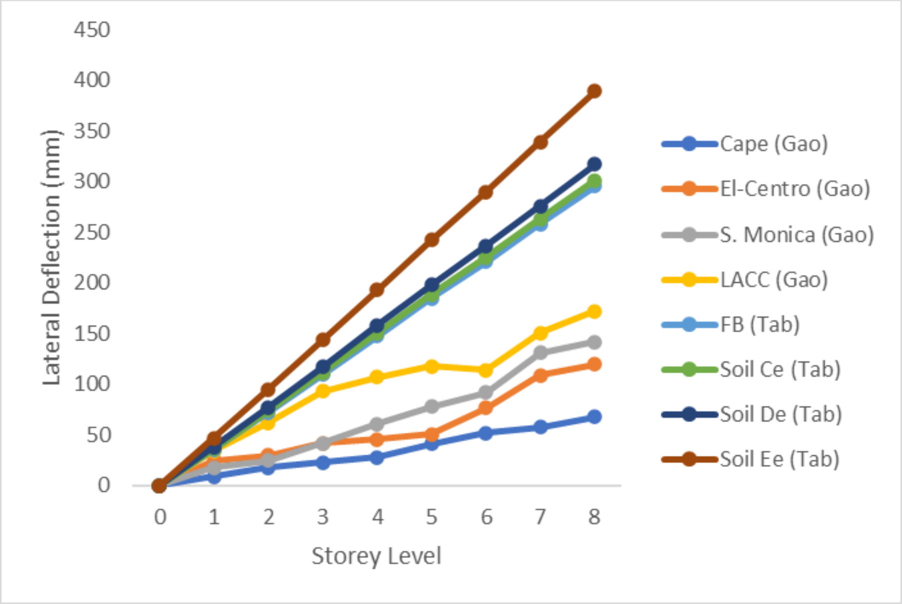

Figure 26 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Inelastic) and Ghaedi et al (2018) for 4 & 8 Storey building on a Fixed-Base (FB) foundation

Two (2) adjacent buildings with different heights (i.e., a 4-storey and 8-storey) were modelled and analysed on a structural software SAP2000. The foundations for these buildings were considered as a Fixed-Base (FB) at one instance and changed to (BI) for the second trial. Both of these buildings were subjected to the ground motion of those above-mentioned earthquakes. Figures 25 and 26 represent comparison results for a Fixed-Base (FB) foundation while the following figures are for Base-Isolated (BI) condition:

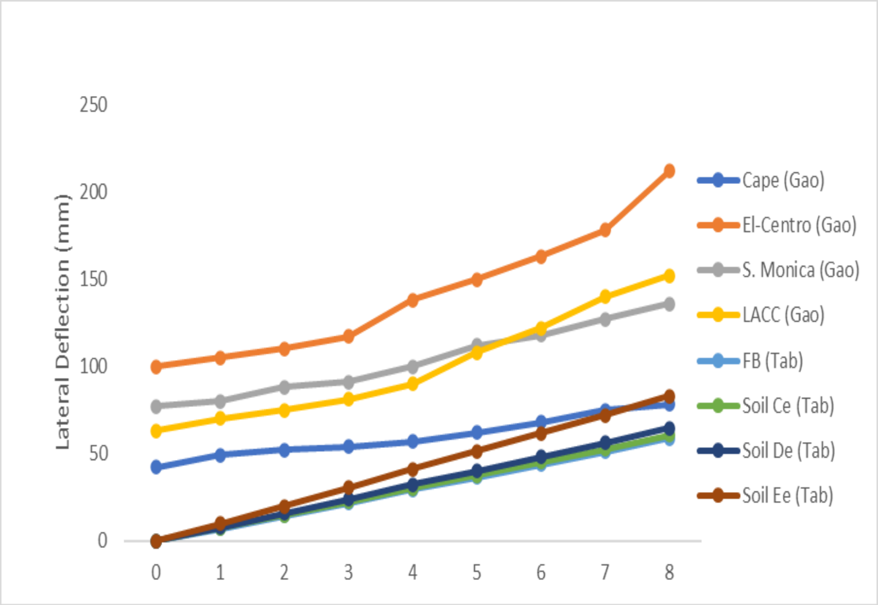

Figure 27 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Elastic) and Ghaedi et al (2018) for 4 & 8 Storey building on a Base-Isolated (BI) foundation

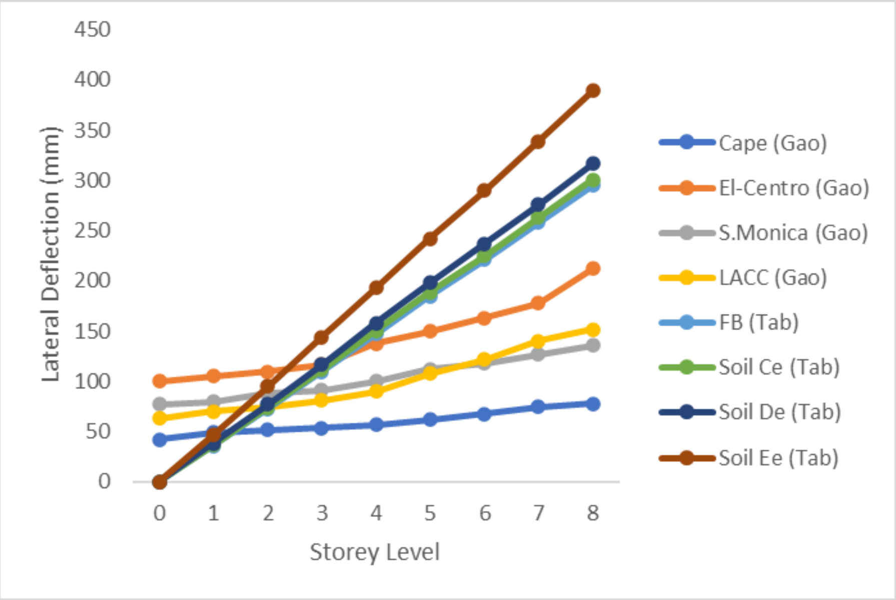

Figure 28 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Inelastic) and Ghaedi et al (2018) for 4 & 8 Storey building on a Base-Isolated (BI) foundation

In this case, the effect of SSI on pounding impact is clearly demonstrated in inelastic analysis with the high deflection ratio in Base-Isolated (BI) conditions. However, the results for the Fixed Based (FB) foundation have a reversed effect which favoured the analysis without the consideration of SSI.

This is contradicting the previous results in other cases, meaning the SSI had no effect on structural pounding or behaviour of the neighbouring building. Although, the comparison is not supporting the significance of SSI effect, it does not necessarily criticise the importance of SSI to the foundation. Furthermore, the effect of SSI on pounding phenomena is clearly negligible in the elastic behaviour which is not the case in any of the previous cases. However, it must be noted that the impact has always been to a lesser effect in elastic region.

As these studies have considered several different parameters and tools, it is not abnormal to obtain results that are not consistent with the SSI effect. There are other factors that made the comparison difficult and subsequently producing contradicting results, some of which are listed below:

1. Usage of different software - Finite Difference Software, FLAC2D was used in Tabatabaiefar et al (2012) whereas Ghaedi et al (2018) employed SAP2000 for analysis
2. Soil Type – Soil type C_e, D_e and E_e were considered by Tabatabaiefar et al (2012) that were not included in Ghaedi et al (2018)'s work. However, the major difference in type of rock formation and the depth which is clearly demonstrated as up to 30m in Tabatabaiefar et al (2012)'s work, but not mentioned in Ghaedi et al (2018)'s, which would have enormous impact on results.
3. The most significant difference lies on variety of seismic excitations that were considered in both cases. Tabatabaiefar et al (2012) chose El Centro 1940, Hachinohe 1968, Northridge 1994 and Kobe 1995 excitations for their study with El Centro being the only common one. This is considered the main factor influencing the results that eventually causing contradicting the theory behind the SSI effect. Different earthquake excitations, therefore, would mean various parameters, resulting contradicting outcome.

3.7 Case Study No. 7

Khatami et al (2020) study focused on using an artificial neural network (ANN) method to determine a sufficient seismic gap to avoid collisions between two adjacent 6-storey buildings during a series of seismic excitations. Once the model was established, the parametric analysis was carried out for various earthquakes scaled to different values of the peak ground acceleration (PGA). The lateral deflections were graphed which were interpreted and manually interpolated for a comparison to Tabatabaifar et al (2012)'s. The result is depicted below:

Six different earthquake records were used in the analysis. These were Tabas (1978), Imperial Valley (1979), Loma Pietra (1989), Landers (1992), Kobe (1995), and Kocaeli (1999) earthquakes. The analysis was conducted using a Matlab-based software. The earthquake characteristics and the parameters of buildings have been defined as inputs in the ANN analysis. Among all different methods to predict differential movement, statistics and random algorithm was selected.

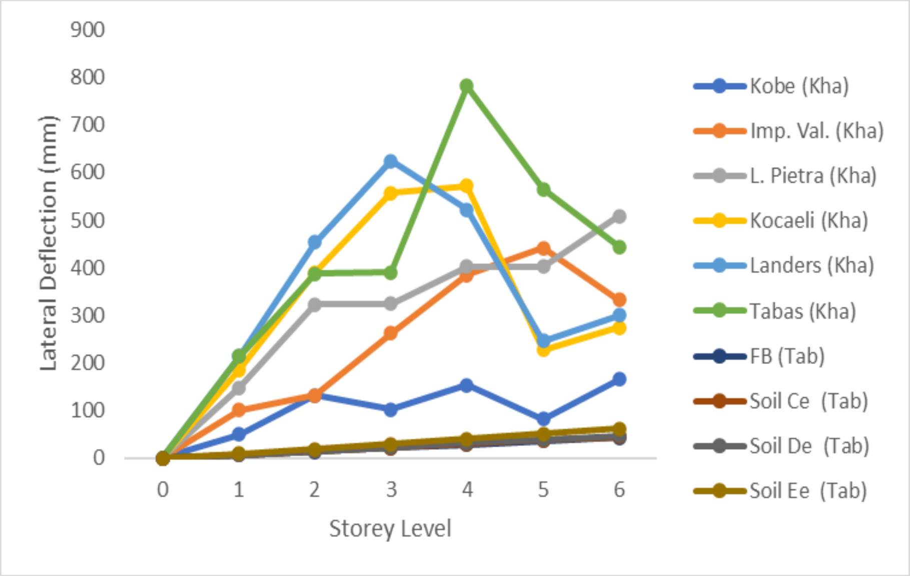

Figure 29 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Elastic) and Khatami et al (2020) for 2 x 6-Storey buildings (Inelastic)

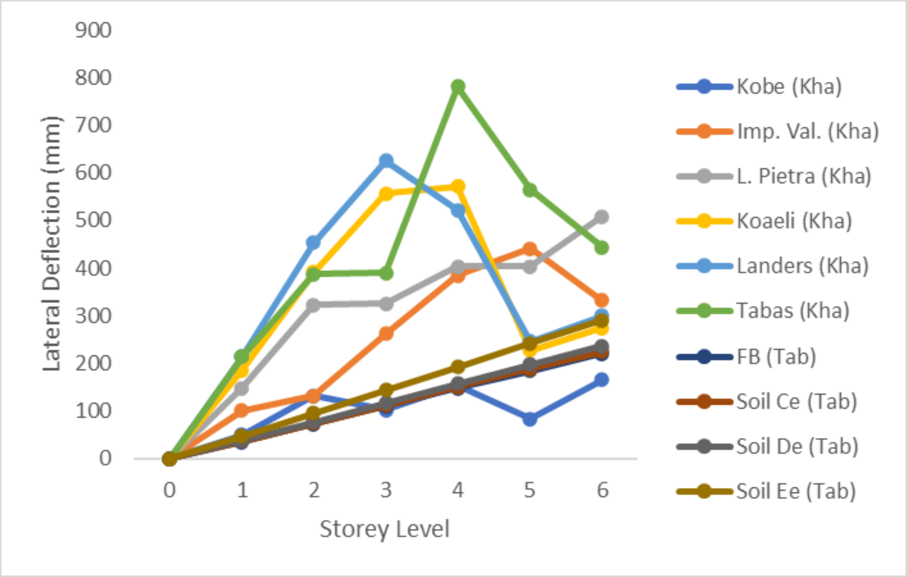

Figure 30 – Comparison of the lateral deflections by Tabatabaiefar et al (2012) for 10-Storey building (Inelastic) and Khatami et al (2020) for 2 x 6-Storey buildings (Inelastic)

Khatami et al (2020) study show a higher value for all earthquake excitations. The elastic values by Tabatabaiefar et al (2012) are much lower and even the inelastic values do not reach the values by

Mehrabi et al (2017). This could be due to the fact that a variety of earthquakes were used by Khatami et al (2020) and hence the parameters and characteristics differ to the ones used by Tabatabaiefar et al (2012). In any case, Khatami et al (2020) work was without the effect of SSI and yet showed a much higher values of structural pounding effects and an increase in the required gap between the adjacent buildings. These results suggest that the pounding effect can also be related to the structure itself and that SSSI can have a higher effect on pounding impact in certain earthquake excitations.

4. Discussion

In Section 3, seven case studies were considered and compared to the results obtained by Tabatabaiefar et al (2012). The results were mostly consistent showing the degree of SSI effect on structural pounding through lateral deflection and inter-storey drifts. For all nonlinear elastic models, the lateral movement was much lower. However, it still showed that pounding occurs but with a lesser impact. The effect was much higher in inelastic behaviour with higher values, especially in upper levels which was a clear indication of a much larger pounding effect and subsequently more damage. This is also valid in moment-resisting frames with Fixed-Base (FB).

The effect of SSI on pounding is apparent in most cases. Case study 1 shows this effect in 5-storey and 6-storey case with much larger values in elastic and inelastic a lot more than the 12-storey and 15-storey case. There is a reasonable reduction in values in inelastic region for 12-storey and 15-storey buildings which indicate a high pounding impact in low-rise buildings than the mid-rise buildings, in general.

Case study 2 indicates enormous difference in values of elastic behaviour but not a large gap in inelastic behaviour. This is due to the difference in soil type. However, the cases both showed a large effect of SSI on pounding impact as the results are high during the inelastic behaviour.

Case studies 3 and 4 are good example of SSI and SSSI effect on structural pounding of adjacent buildings while considering both elastic and inelastic behaviour. These cases clearly demonstrate the negative effect of SSI and SSSI on the lateral movement, showing large values which in turn indicate a large pounding impact during an earthquake excitation. The effect on pounding is also visible on inter-storey drifts' results.

The SSI effect on pounding impact is not so apparent in elastic behaviour comparison for case studies 5 and 6 but shown quite a jump in values when inelastic behaviour was considered. This has shown that inelasticity analysis has a large impact on pounding impact and should be considered in the design.

Case study 7 is a contrary to the rest of the cases showing larger values for without considering SSI. Although, the values do not reflect the purpose of SSI in the design, they can support the theory but a lesser effect.

A final comparison of Naserkhaki et al (2012) and Ghaedi et al (2018) is presented in Figures 31:

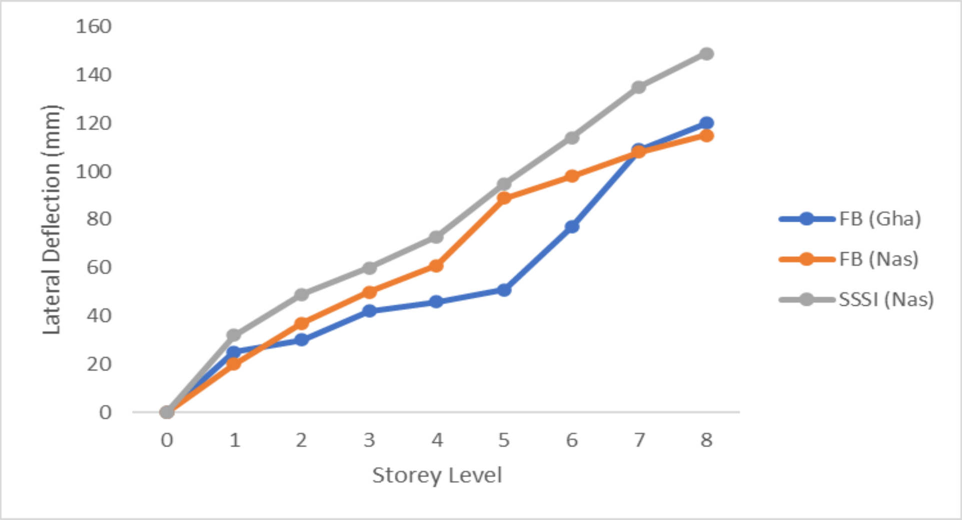

Figure 31 – Comparison of the lateral deflections by Naserkhaki et al (2012) for 10-Storey building and Ghaedi et al (2018) for 8-Storey building

On these, earthquake parameters during El-Centro Kobe (1940) were used in both researches, the result of which was compared. A Fixed Base (FB) foundation without the effect of SSI or SSSI was assumed in the model by Ghaedi et al (2018) whereas SSSI and fixed base conditions were considered by Naserkhaki et al (2012).

The result is conclusive showing a large effect on structural pounding impact once SSSI is considered. The effect of SSSI is inevitable which increases the pounding impact through lateral movement.

The effect of SSI on pounding is clearly demonstrated by considering the inelastic characteristic in all cases. A remarkable increase in values can be observed in comparison to the elastic. It emphasises the significance of SSI on pounding and its enormous effect on structural behaviour of the building. This effect is quite apparent in a single building as well as adjacent buildings. However, there is also higher effects where adjacent buildings are considered in most cases.

5. Conclusion

This study aimed to demonstrate the significance of considering soil-structure interaction effects on structural pounding by comparison of case studies developed by recent and modern researchers. Higher values obtained in these cases while considering SSI and SSSI supported this theory, against those without SSI effect.

Most significant factor was the lateral deflection. The deflection was increased as the building got taller. The proportionality varied in each case with an average range of 1:2.5. This indicates the pounding force increases at higher level and hence SSI can increase the pounding impact in taller buildings more than others, for instance. Overall, the effect of SSI is regarded as significant, even more than SSSI. Direct influence of SSI on pounding impact was clearly established by highlighting the effect of SSI on structural behaviour of adjacent building. This was quite apparent in just about 86% of the cases which showed the significance of SSI inclusion in pounding impact analysis.

The results of this investigation focused on showing the significance of SSI in earthquake analysis during pounding of adjacent buildings. All the cases that were discussed during the course of this study had results that were interpolated and compared with Tabatabaiefar et al (2012)'s.

The comparison proved in all cases that SSI effect can increase the sway in low to mid-rise buildings which can cause pounding. It can also affect the inter-storey drifts which is considered an additional force for larger pounding impact. Higher values of both lateral deflection and inter-storey drifts were apparent in those cases that considered the effect of SSI and SSSI which support the theory behind pounding effect.

There was a clear message regarding elastic and inelastic analyses. The values produced by inelastic analysis are by far higher in all cases, indicating that this analysis is most effective and should be taken into account in the design while calculating the pounding impact. It suggests that inelastic is more appropriate to use in earthquake excitation analysis as it provides a better and more accurate results in relation to the pounding impact and structural behaviour of adjacent buildings.

On that note, the significance of inelasticity can be observed in all cases studied in this paper. An enormous increase in values during the inelastic analysis speaks volume of the effect of SSI on pounding during this analysis. One thing is for sure that the effect of SSI while during the inelastic analysis is apparent and cannot be ignored. High values of lateral deflections and inter-storey drifts while considering the inelastic analysis mean higher pounding forces. It is to be noted that these high values are due to the SSI effect and hence emphasise the importance of SSI inclusion along in the inelastic analysis of earthquake excitations.

As shown by several case studies outlined so far, the SSI effect is visible, causing an increase in lateral deflection and subsequently the pounding impact. These findings support the need for a new approach that must implement the SSI effect in the current seismic design to mitigate structural pounding impact.

This study proved the significance of the dynamic SSI on structural pounding. It also showed that the effect of pounding significantly increases under inelastic analysis. Based on these findings, a practical method will be developed using these effects. The practical method will include a relationship between a combined effect of SSI and inelastic behaviour of the adjacent building to mitigate structural pounding. The results had shown the direct proportion of the SSI and inelastic behaviour to the structural pounding as they both notably increase the effect.

Based on the outcomes of this study, it is highly recommended to the practicing engineers and engineering companies take into account the effects of soil-structure interaction and structural pounding simultaneously in seismic analysis and design of adjacent buildings to ensure the safety and integrity of the structures against earthquake action.

6. References

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