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Technical Note

# Accounting for soil nonlinearity in three-dimensional seismic structure-soil-structure-interaction analyses of adjacent tall buildings structures

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***Abstract***

*The interactive effects of adjacent buildings on their seismic performance are not frequently considered in seismic design. The adjacent buildings, however, are interrelated through the soil during seismic ground motions. The seismic energy is redistributed in the neighboring buildings through multiple structure-soil-structure interactions (SSSI). For example, in an area congested with many nearby tall and/or heavy buildings, accounting for the proximity effects of the adjacent buildings is very important. To solve the problem of SSSI successfully, researchers indicate two main research areas where need the most attention: 1) accounting for soil nonlinearity in an efficient way, and 2) spatial analysis of full 3D soil-structure models. In the present study, three-dimensional finite element models of tall buildings on different flexible foundation soils are used to evaluate the extent of cross interaction of adjacent buildings. Soil nonlinearity under cyclic loading is accounted for by Equivalent Linear Method (ELM) as to conduct large parametric studies in the field of seismic soil-structure interaction, the application of ELM is preferred over other alternatives (such as application of complicated constitutive soil models) due to the efficiency and reliability of its results. 15 and 30 story steel structures with pile foundations on two sandy and clayey sites are designed according to modern codes and then subjected to several actual earthquake records scaled to represent the seismicity of the building sites. Results show the cross interaction of adjacent buildings on flexible soils, depending on their proximity, increases dynamic displacements of buildings and reduces their base shears.*

***Keywords:*** *Equivalent linear method (ELM), Structure-soil-structure interaction, Adjacent tall buildings structures, Frequency content, High amplitude records, Low amplitude records.*

## 1. Introduction

In the design of low rise structures the effects of soil-structure interaction (SSI) are often ignored. However, these effects are considerable for the tall and/or heavy structures. The existence of this interaction phenomenon can also be extended to the adjacent buildings on the same foundation soil. The adjacent buildings, however, are interrelated through the soil during seismic ground motions. The seismic energy is redistributed in the neighboring buildings through multiple structure-soil-structure interactions (SSSI). For example, in an area congested with many nearby tall and/or heavy buildings, accounting for the proximity effects of the adjacent buildings is very important.

It is well known that SSI affects the seismic response of soil-structure systems, depending on the frequency content of the seismic motion, the soil type and depth, and the properties of the structure. Reports of different SSI effects through actual earthquakes or analytical studies are well documented in the literature (Mylonakis, 2000 [1], Saadeghvaziri et al. 2000 [2], Inaba et al. 2000 [3], Halabian and El Naggar 2002 [4], Tongaonkar and Jangid 2003 [5], Dutta et al. 2004 [6], Nakhaei and Ghannad 2008 [7]).

By accounting for soil nonlinearity in SSI analysis, the seismic ductility demands and the force responses may be reduced significantly (for example for the column shears and bending moments up to 30% and 60% reduction, respectively), and in contrast, the story displacements are increased (Raychowdhury 2011 [8], Saez E. et al. 2011 [9]). These conclusions indicate the importance and the advantages of an adequate SSI effects evaluation. Clouteau et al (2012) [10] carried out a parametric study on the effects of SSI and SSSI on different responses of embedded buildings and showed that the foundation impedance is mainly governed by the stiffness of the soil layer right below the building foundation. In addition, SSSI has a slight influence on the response of both buildings for surface foundations, but this influence maybe higher in the case of embedded foundation with a decrease of the response at the top of the buildings (up to 30% reduction).

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Lou et al (2011) [11] conducted a comprehensive literature review on SSSI, covering over 100 research papers. Comparing different methods of the study of SSSI, such as analytical methods; analytical–numerical methods; numerical methods; experiments and prototype observations, they concluded that most of the studies that rely on analytical methods and/or analytical–numerical methods, are based on the elastic half-space theory, which deemed not suitable for the analysis of the dynamic interaction of structures with deep foundations, because of the exclusion of material damping and radiation damping. Due to the difficulty of the solution for the analysis method and the excessive simplifications of the model for soil and structures, it was far from the real solution for problems of SSSI. The numerical methods including finite element method (FEM); Boundary element method (BEM); and FEM-BEM-combined method, are greatly considered as the most effective tools for the study of SSSI. However, simpler methods such as FEM are imperative for application. FEM can simulate the mechanics of soil and structures better than other methods, deal with complicated geometry and applied load, and determine non-linear phenomena.

Some of future directions of research on SSSI are also given by Lou et al (2011) [11]: 1) To solve the problem of SSSI successfully, nonlinear analysis of both soil and structure must be considered. Currently, there is scarcely any research considering this. 2) Spatial analysis of full model in 3D need to be performed.

Previous studies confirm that SSI and SSSI play an important role in altering the force and displacement demands, indicating an urgent necessity to develop accurate and yet efficient methods of evaluating different responses of soil-structure systems while the soil nonlinearity under cyclic loading is accounted for in a realistic manner. The objective in this study is first to apply Equivalent Linear Method (ELM) in 3D FE modeling of soil-structure systems, and secondly, to assess the impacts of the distance and the relative heights of the adjacent buildings on their cross interactions and different responses of the individual buildings.

In ELM by assuming elastic behaviour for soil, the soil shear modulus and damping are kept constant for all the soil elements in the FE model. By entering the effective shear strain (usually 65% of the maximum shear strain, Kramer 1996 [12]) for all the soil elements in that run to the shear modulus and damping degradation curves for the considered soil, the shear moduli and damping ratios for all soil elements are updated and then a new elastic analysis is performed. This iteration process will go on until the error between shear strains in two consecutive runs is less than say 5%. Usually in 3 to 5 runs this iterative process ends (Kramer 1996 [12]). It is important to note that for the purpose of conducting large parametric studies in the field of seismic soil-structure interaction, the application of ELM is preferred over other alternatives (such as application of complicated constitutive soil behaviour models) as being capable of accounting for soil nonlinearity in an efficient way and yielding reliably accurate results, therefore, serving as a right tool to pursue the future directions set by Lou et al (2011) [11] in SSSI studies.

## 2. Modelling and Analytical Advantages of the Current Study

Some of the common shortcomings in previous SSI and SSSI studies as also pointed by Lou et al (2011) [11] are: 1) their limited scope due to the inherent complexity of the issue, 2) their use of simplifying assumptions such as 2D plane-strain modeling, 3) ignoring the soil nonlinearity under cyclic loading, 4) the use of idealized lumped mass and lumped springs for modeling the soil and/or the structure, etc. For example, assuming plane-strain for a foundation soil model in a 2D FE analysis may be valid; however, for a soil-structure system in which the building structure has limited dimensions in plan, this assumption is erroneous.

Compared to the previous studies, the modelling and analytical superiorities of the current study are as follows: 1) all the soil-structure and structure-soil-structure models considered are full 3D. 2) The nonlinear behavior of the foundation soils under cyclic loading is accounted for by ELM. 3) Due to the importance of the earthquake frequency content on different responses of the structures, seven actual far field earthquake records with different amplitudes, selected and scaled according to ASCE7 (2010) [13]. 4) Rather than using impedance function or substructure methods, the Direct method, is used which is based on the FE modelling of the whole soil-structure as one system and therefore is capable of accounting for the radiation of seismic waves in an unbounded medium, by implementing the transmitting boundaries in the foundation soil.

In 3D FE soil models, the soil is modelled using 8 node Solid elements. In this study, while using ELM, and in the process of iterations on soil shear strains, in order to update the shear modulus and the damping ratio for each element, the average of the shear strains along the excitation direction for the 8 nodes is entered into the degradation curves, even if, the shear strains in the other directions might have been substantial. However, later in this study by a number of verification studies, it is shown that this assumption does not undermine the validity of the results.

## 3. Description of Structural Models

The structural models considered here are 3D special steel moment resisting frames of 15 and 30 stories representing mid-rise and high-rise buildings, designed based on AISC (2005) [14]. They all have 4 bays in each direction in plan. Each bay is 5 meters. Height of the stories is 3 meters. Design gravity floor loads of DL=760 kg/m² and LL=200 kg/m² are applied. Design regulations are in accordance with ASCE7 (2010) [12]. The building site is assumed to be in an area with high seismic hazard risk with a short period design spectral acceleration ($SD_s$) of 1.0g and a design spectral acceleration at the period of one second ($SD_1$) of 0.6g. The site category is assumed as type D where the short period site coefficient ($F_a$) is 1.0 and the long period site coefficient ($F_v$) is 1.5.



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Both structures rest on piles. Pile groups are designed for soil type D (Tomlinson, 1994 [15]). For the 30 story structure, the pile group includes 25 piles and for the 15 story structure, the pile group consists of 16 piles. To prevent interaction of adjacent piles they are located no less than 5 m apart in each direction. Each pile is 20 meters long. Piles are of reinforced concrete with reinforcements differing in its top 8 meters compared to its lower part. The pile cross section is circular with a 0.5 m radius for the 15 story and 0.8 m radius for the 30 story buildings. The pile caps are one meter deep and all design criteria including punching shear controls are implemented.

## 4. Description of the Foundation Soil Properties

Two building sites are considered in this study. Site 1 includes 25 m of sandy soil in two layers, as per Table 1 and Site 2 comprises of 45 m of clay soil in three layers as per Table 2. Both are categorized as type D according to ASCE 7 (2010), with a shear wave velocity of 180-360 m/s, representing moderately soft soils. Since the effects of SSI and SSSI are usually considerable for tall and/or heavy structures, it is important to consider foundations with softer soils, which more likely produce higher responses in such structures. Also, the soil type D is more geographically common, especially in urban areas where tall buildings are more likely to be constructed.

Other relevant properties of these soil profiles are also shown in Tables 1 and 2. Fig. 1 illustrates the variation of shear modulus and damping ratio with shear strain for different soils layers of Sites 1 and 2, as per Seed and Idriss (1970) [16] degradation curves which are more suitable for general foundation soils similar to those considered in this study. The site periods for Sites 1 and 2 are 0.43s and 0.84s, respectively (SHAKE2000 [17]).

**Table 1** Soil properties at Site 1

| *Sand* | | |
|---|---|---|
| Z[1] (m) | G[2] (kPa) | $V_s$[3] (m/s) |
| [0 - 10] | 64503 | 188 |
| [10 - 25] | 152000 | 281 |

[1]depth, [2]shear modulus, and [3]shear wave velocity

**Table 2** Soil properties at Site 2

| *Clay* | | |
|---|---|---|
| Z[1] (m) | G[2] (kPa) | $V_s$[3] (m/s) |
| [0 - 10] | 52070.7 | 164 |
| [10 - 25] | 91530.5 | 205 |
| [25 - 45] | 161874 | 256 |

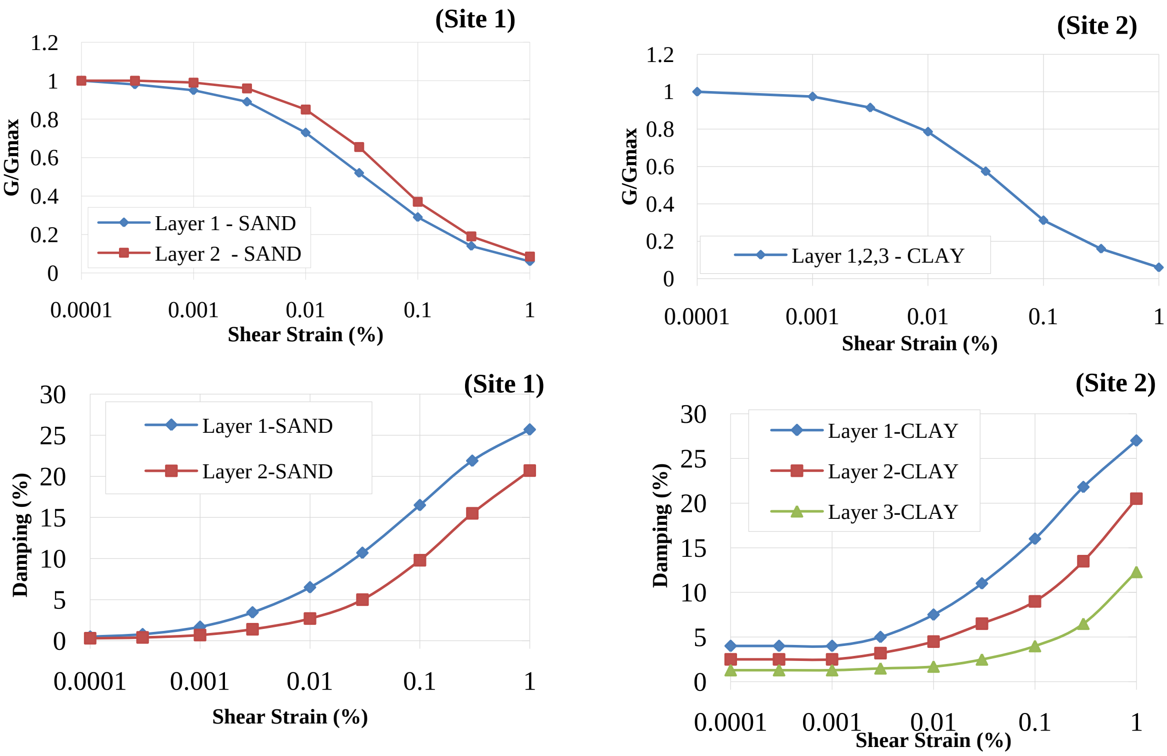


**Fig. 1** Shear modulus and damping degradation curves for different soils (Seed and Idriss, 1970)

## 5. Finite Element Models for Dynamic SSI and SSSI Analyses

OpenSees software is applied to conduct the nonlinear time history seismic SSI and SSSI analyses of the 3D soil-structure systems (University of California, Berkeley, 2009 [18]). These analyses are carried out for three different conditions: 1) one single structure (15 or 30 story building) on rigid support/bedrock, 2) one single structure on Site 1 and/or Site 2, and 3) two adjacent structures (for


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all possible adjacency combinations of 15 and 30 story buildings) on Sites 1 and/or Site 2. Fig. 2, for example, shows the 3D view of a typical FE model consisting of two 30 story adjacent structures on foundation soil, used in this research. For structural modelling, the Beam Element is used for the frame members and the piles. Shell Element is used for the rigid diaphragm and the pile caps. Solid 3D Element with 8 nodes is used to model the foundation soil. This element in each direction is 2.5m. A Rayleigh damping is used for the structures, assuming 5% damping ratio for the first two structural modes. Piles and frame members are assumed to behave in elastic range.

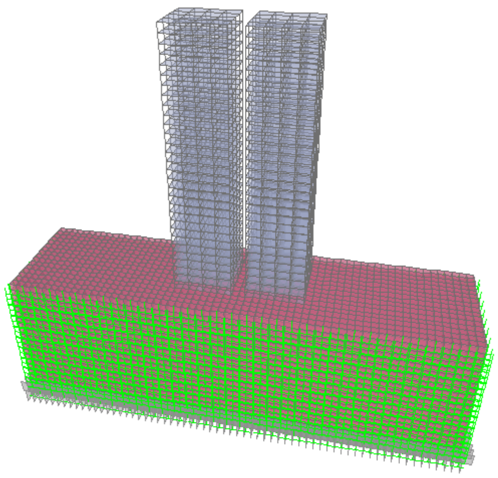

**Fig. 2** A typical 3D FE model of two adjacent 30-story buildings on pile groups on Site 2

## 6. Description of Selected Earthquake Records

Seven actual far-field earthquake records are considered for seismic analysis and design of the structures (PEER, 2014 [19]). The criteria considered for selection of appropriate earthquake records are given in Table 3.

Since the foundation soil considered here is of type D, those earthquake records are selected that are recorded on grounds with soil type D. According to ASCE7-2010, the procedure of scaling earthquake records for seismic analysis is dependent on the structural first mode period. In fact, it specifies that within period range of 0.2T – 1.5T, the 5% damped elastic response spectrum of the record has to set just above its design spectrum. T is the first mode period of the structure in question. For selecting records suitable for both 15 and 30 story buildings, this period range is broadened to $0.2T_{15} – 1.5T_{30}$. A thorough search in PEER Strong Ground Motion Database according to the above criteria led to the selection of seven records listed in Table 4. Fig. 3 shows the 5% damped acceleration response spectra of these records in unit of g. According to this figure, three of the records are of High amplitude and four are of Low amplitude. For each record there are 2 scale factors corresponding to the two structures of 15 and 30 stories, hence, for seven earthquakes, there would be 14 scaled records in total, which all correspond to the ground surface. Table 4 presents the selected earthquakes and the new scaled PGAs of the records for both 15 and 30 story buildings. Also given in this table are dominant periods of the earthquake records.

**Table 3** Criteria for selection of earthquake records

| Seismometer location | Ground Level |
|---|---|
| Period range of strong motions | $0.2T_{15} – 1.5T_{30}$ |
| Site category | D ($V_s$ = 180–360 m/s) |
| Magnitude | 6 – 7 Richter |
| Source Distance | 20 – 50 km |
| Strong motion duration | ≥12 s |

The fourteen earthquake acceleration time histories mentioned above are all recorded on ground surface; however, in SSI studies, the earthquake records must be applied at the bedrock. Therefore, the computer program SHAKE2000 is used to generate the de-convoluted version of the same records, corresponding to bedrock level. There are fourteen records and two foundation soil profiles/sites, therefore, there would be twenty eight acceleration time histories at bed rock level that must be regenerated before any SSI or SSSI analysis can begin.

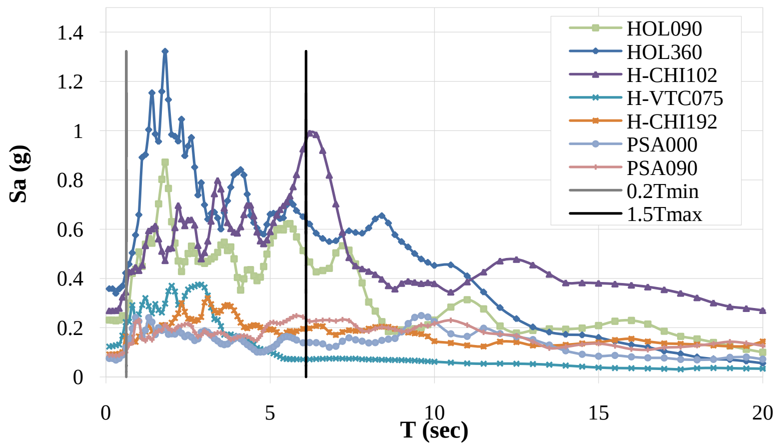


**Fig. 3** Acceleration response spectra (5% damped) for the seven records used along with the period range of interest ($0.2T_{15}$ to $1.5T_{30}$)



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**Table 4** Characteristics of the selected earthquakes

| Earthquake | Component | Dominant period | Scaled PGA (g) | |
|---|---|---|---|---|
| | | | 15 Story | 30 Story |
| **Northridge** | **HOL090** | **0.7** | **0.54** | **0.78** |
| | **HOL360** | **0.8** | **0.64** | **0.93** |
| **Victoria, Mexico** | **H-CHI102** | **0.7** | **0.32** | **0.47** |
| Imperial Valley | H-VTC075 | 0.2 | 0.28 | 0.41 |
| Victoria, Mexico | H-CHI192 | 2.2 | 0.21 | 0.31 |
| Landers | PSA000 | 1.0 | 0.18 | 0.26 |
| | PSA090 | 1.0 | 0.21 | 0.30 |

Regular : Low Amplitude Record
**Bold : High Amplitude Record**

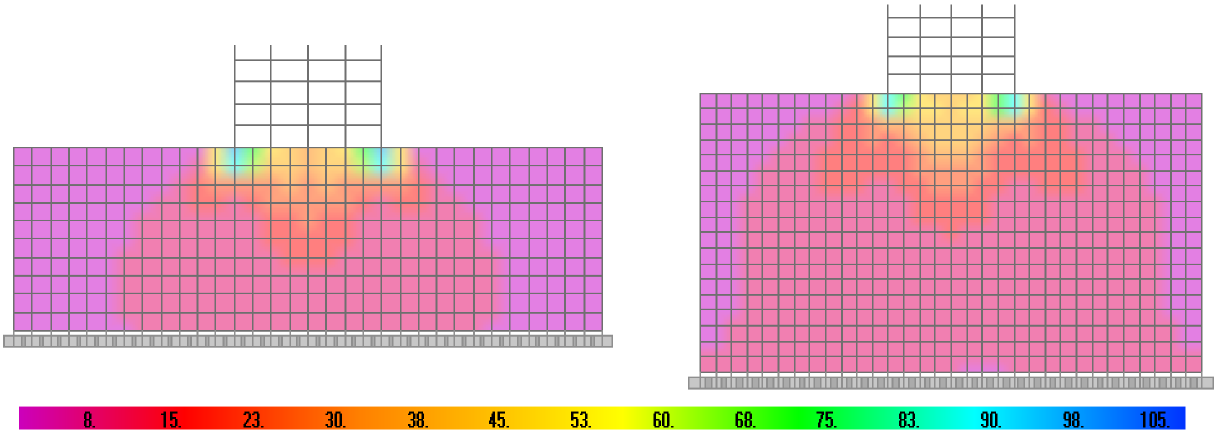
## 7. Implementing Transmitting Boundaries in the Soil-Structure Models

Foundation soil layers are usually unbounded on the sides. FE modelling of an unbounded medium is not possible; therefore, a portion of the foundation soil must be separated by implementing transmitting boundaries. These boundaries must simulate the energy dissipation capabilities of the original unbounded soil medium. According to Wolf (1985) [20], a series of dashpots on the surface of the transmitting boundaries must be considered whose damping coefficient, C is defined as $C = \rho V_s A$, where $\rho$ is the soil density, $V_s$ is the soil shear wave velocity, and A is the tributary area of the node on which the dashpot is placed on the surface of the boundary (Wolf, 1985). Fig. 2 shows typical dashpot elements (in green color) on transmitting boundaries considered in this study.

## 8. The Extent of Soil Nonlinearity in SSI and SSSI Systems

Being subject to lateral seismic motions, it is shown that the soil immediately surrounding the structural foundation will become distressed heavily and undergo nonlinear behaviour the most, compared to the rest of the soil medium (Clouteau et al., 2012). Fig. 4 shows the contours of the maximum shear stress developed in the foundation soil beneath a 30 story building on Sites 1 and 2. It is clear that excessive soil plasticity, due to seismic motions, is mostly concentrated near the building foundation (zones 1 and 2 in Fig. 5), and the rest of the foundation soil (zones 3 to 9) is less affected by the building motions and rather more controlled by the free field motion. The cause of such distress in the soil close to the building foundation can be attributed to the building motions, including its rocking action, since near the footing side ends the shear stresses and strains are higher. Also, for the sites considered here, the extent of where the building-caused-soil-plasticity is spread seems to be independent of the soil type and depth. That is almost 25% of the building base dimension (zones 1 and 2 in Fig. 5).

It is noteworthy that since the regions immediately surrounding the building concrete foundations experience large plastic deformations, they tend to limit or isolate the soil nonlinearity within themselves and filter (not transfer) dynamic vibrations of the superstructure to the lower regions, and/or, filter (not transfer) the earthquake shear waves from bedrock to the superstructure. Therefore, the rest of the regions will behave more or less similar to the free field motion.




(a) (b)

**Fig. 4** Maximum shear stresses (in unit of kN/m$^2$) in foundation soil when supporting a 30 story building and subjected to HOL090 earthquake, (A) Site 1, and (B) Site 2



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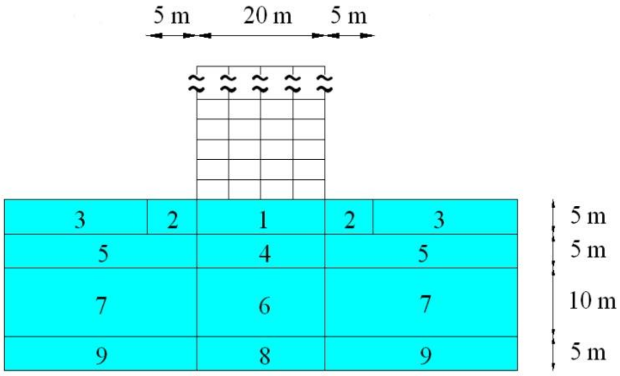


**Fig. 5** Regionalizing foundation soil in 3D FE models: a single building on site 1

## 9. The Optimized Dimensions of the Soil FE Model

Soil media are usually unbounded on the sides. This is usually accounted for by implementing transmitting boundaries in the perimeter of the plan of the foundation soil FE model. These boundaries are also extended downwards to the bedrock. The farther these side boundaries are from the building, the more accurate supposedly the FE analysis results would be. In some previous studies that were based on two dimensional plane-strain modelling and with elastic behaviour for the soil, these side boundaries may have been required to set rather far from the building. However, due to the following three reasons, the soil model dimensions in this study could be smaller: 1) the soil behaviour here is assumed to be nonlinear which in turn allows considerable amount of earthquake energy to be dissipated, 2) since soil nonlinearity is mostly concentrated around the building foundation, most of the earthquake energy will be dissipated there locally and the rest of the FE system would be left with not much of earthquake energy to dissipate, and 3) since the FE mesh here is 3D, the earthquake energy would be dissipated spatially and therefore, more rapidly.

By considering a large soil model, the FE model will become overly large and require extensive computational efforts, on the other hand, by using a very small model, the accuracy of the results may be undermined. Therefore, the optimized locations for the side boundaries in plan must be sought to ensure a fast and efficient analysis with reliable results.

The 3D soil models for SSSI studies in this work are all assumed to have the same dimensions in plan: a length of 160m along the earthquake excitation direction and a constant width of 40m (normal to the excitation direction). In order to control the adequacy of these dimensions two sensitivity studies on the length and width of the models are conducted. Two extreme inner building distance, *d* of two 30 story adjacent buildings of 3*a* = 60m and 0.125*a* = 2.5m (0.125*a* is later shown to be the most critical distance between the two adjacent buildings, where *a* is the building base dimension (*a* = 20m)) are considered on Site 2 with differing soil model lengths and widths (Fig. 6). B is the soil model width and D is the longitudinal distance from the outer face of the building to its adjacent parallel transmitting boundary. The model length therefore would be = 2D + 2a + d, where a is the width of one building, d is the inner buildings distance ). These SSSI models are then subjected to HOL360 which has the highest PGA and Sa in the frequency bandwidth set by ASCE 7(2010) among the records used. Fig. 6 presents the results of these parametric studies on B and D. Fig. 6a provides the variation of the ratio of the maximum roof displacements in these models, to that of the same model, except with B = 60m. It is clear that considering soil model widths beyond B = 40m does not bring any additional accuracy. Considering a model width of B = 40m, Fig. 6b illustrates the variation of the ratio of the maximum roof displacements in these models, to that of the same model, except with D = 60m. It can be seen that models with a minimum distance D of 30m provide accurate enough results. Therefore, from now on in this work the soil model width B = 40m, D = 30m, and its total length (2D + 2a + d) is considered to be constant and equal to 160m.

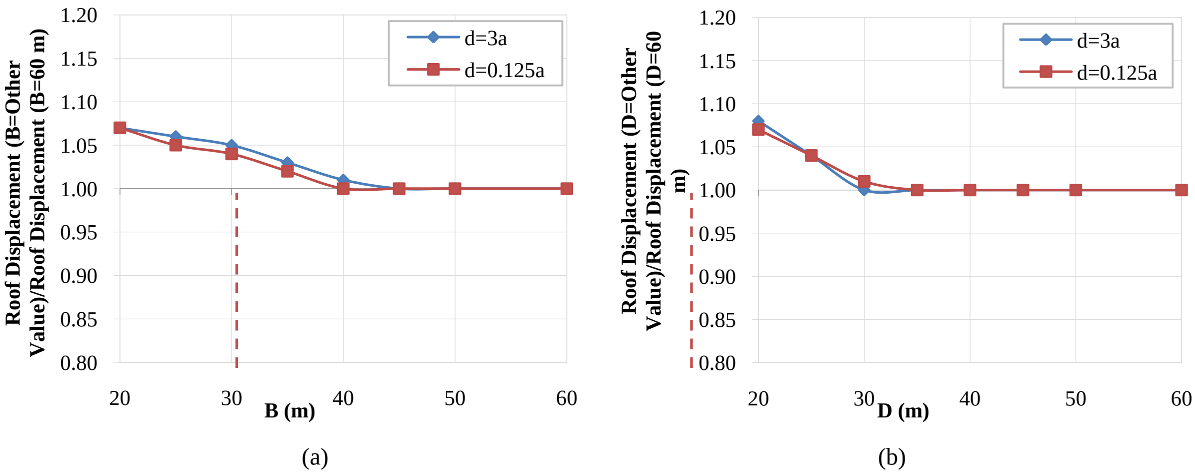


**Fig. 6** Variation of normalized roof displacements of two adjacent 30 story buildings located on soil models with different lengths and widths in plan, normalized with that of the same buildings on soil model with D = 60m and B = 60m, respectively, on Site 2 and subjected to HOL360 earthquake



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## 10. Verification of the 3D FE Modelling and Analysis

Free-field analysis is considered for this verification process. Therefore, for the 3D FE soil models in this study, the dynamic (high shear strain) shear moduli and damping ratios of different soil layers are taken from the results of SHAKE 2000 software, an one dimensional modelling soil media with layers. Hence, such 3D FE Free-field modelling can be analyzed linearly. In order to verify the validity of the 3D FE modelling and analysis by OpenSees program using ELM, the 160m by 40m FE soil models of Sites 1 and 2 are subjected to free-field motion analyses under Elcentro 1940 earthquake record (S00E). Fig. 7 provides comparisons of the 5% damped acceleration response spectra of these soil models for the ground surface (Figs. 7a and 7b), and the profiles of peak horizontal acceleration along the centreline of the soil models for Sites 1 and 2 (Figs. 7c, and 7d), using FE 3D modelling by OpenSees and one dimensional modelling by SHAKE2000. In general the results by the two modelling methods are very close, confirming the validity of the 3D FE modelling and analyses conducted in this study using OpenSees program. However, the responses by the 3D modelling are slightly less than those of one D counterpart. The justification may be that in the 3D modelling the damping radiation is spatial and, therefore, more effective, which leads to lower responses.

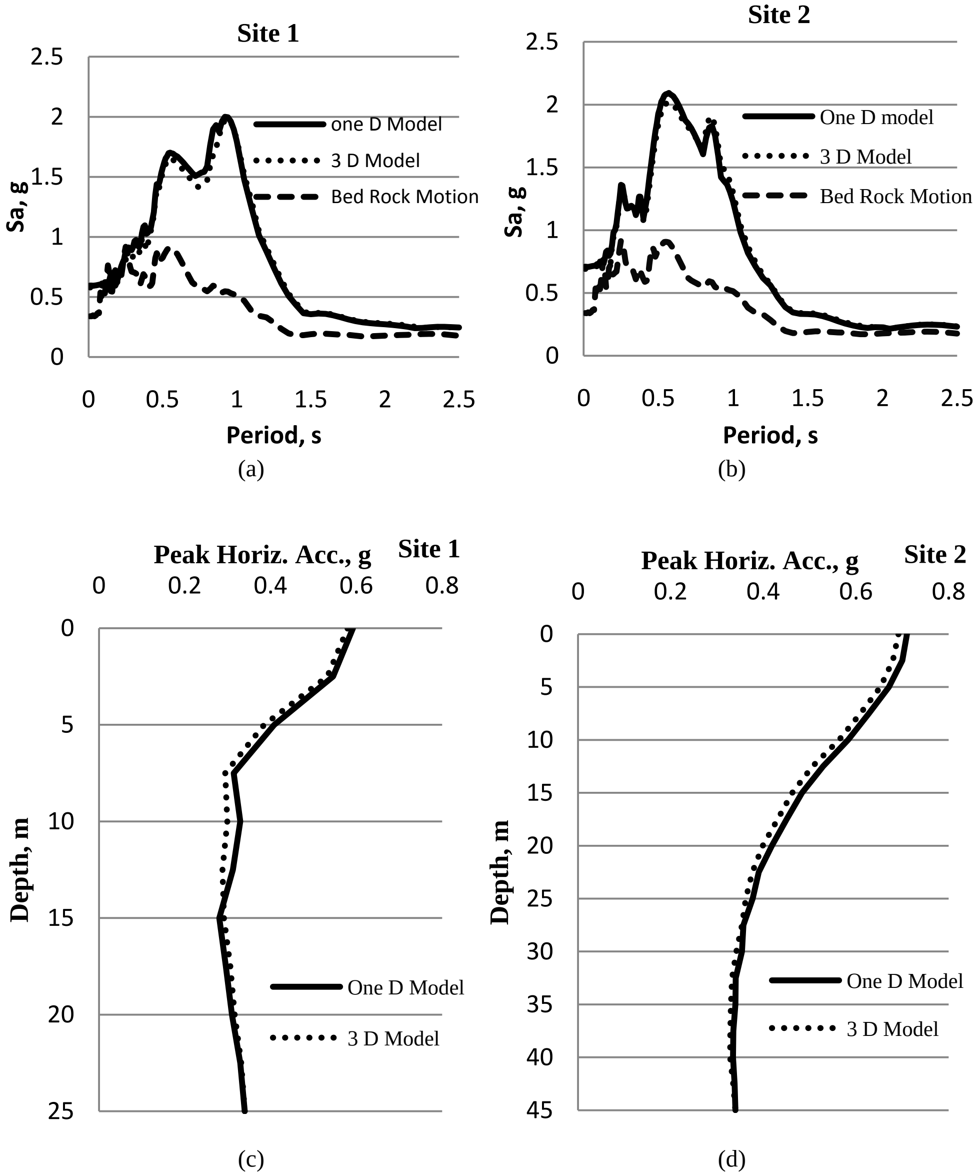


**Fig. 7** Comparisons of 5% damped free-field response spectra and profiles of peak horizontal accelerations for Sites 1 and 2, based on 3D FE modelling by OpenSees and one dimensional modelling by SHAKE2000, subjected to Elcentro earthquake record (S00E)

It is expected that as two adjacent buildings are closer, the chance of their interaction is higher. It becomes more critical if the buildings are tall and/or heavy too. To determine the critical distance of the two adjacent buildings, a sensitivity study on this critical distance is conducted here. Six models of two adjacent 30 story buildings on site 2, subjected to HOL360 record, are developed with variable building clear distances of 0.125*a*,



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0.25*a*, 0.5*a*, 1.0*a*, 2.0*a* and 3.0*a* (i.e., 2.5, 5, 10, 20, 40 and 60 meters). Fig. 8 illustrates the normalized story displacement of a 30 story building for these six different SSSI models to those of the free standing single 30 story building on Site 2 (model 30S-S2). The model names such as 30Svs30S-S2 (d=0.125a) in this figure means a 30 story adjacent to another 30 story on Site 2 (S2) and 0.125a (2.5m) apart. The following conclusions can be made from the results in this Fig. 1) for building distances more than 0.5*a*, SSSI need not be considered and the responses are more or less similar to those of a single building. i.e., SSI analysis will be sufficient. 2) The closer the two adjacent 30 story buildings are, the more the amplification of the story displacements would be. In fact, when the buildings distance is between 0.125*a* to 0.5*a* (2.5 m to 10 m), the increase in the story displacements in model 30Svs30S-S2 (d=0.125a) is the most compared to models where the buildings are farther apart. More importantly, in the latter model, the highest story displacement amplification along the height of the 30 story building occurs in its lower stories, which is up to 80% more compared to that of a single 30 story building on the same site (30S-S2). Therefore, in this study, hereafter, only two critical building distances of 0.125*a* and 0.25*a* (2.5 m and 5 m) would be considered in SSSI analyses.

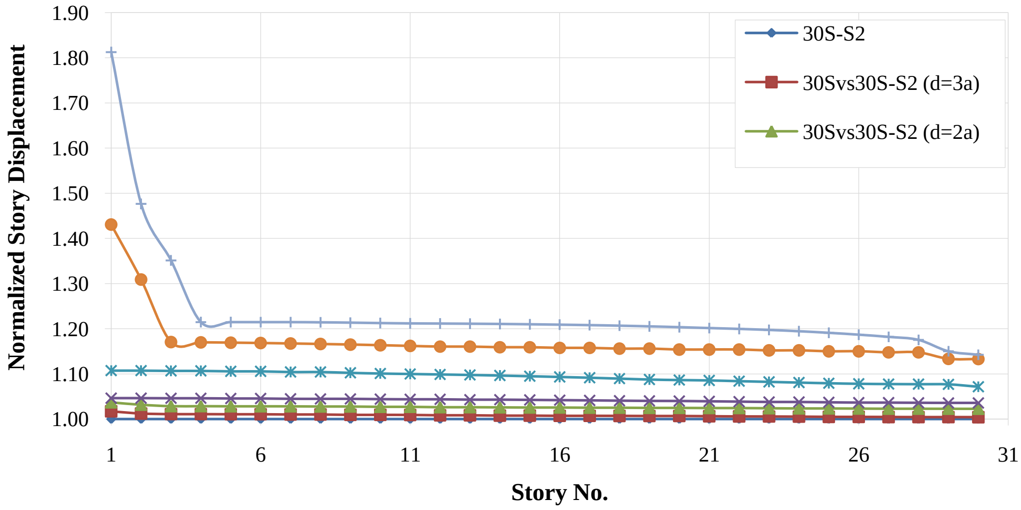


**Fig. 8** The normalized story displacements of a 30 story building in pair, by those of a single free standing 30 story building, for different building clear distances, on Site 2 and subjected to HOL360 earthquake

## 12. Results and Discussions

The main objectives in this research are to evaluate the impacts of: 1) the distance between the adjacent buildings, 2) the type of adjacency (i.e., the relative height of the adjacent buildings), and, 3) the effect of earthquake spectral amplitude, on different responses of the adjacent buildings. Among the responses investigated are the structural local responses (such as story displacements) and the global responses (for example maximum structural base shears) of both the soil-structure and structure-soil-structure systems.

*12.1. The effects of SSSI on story displacements*

Fis. 9 and 10 show the variation of story displacements for all adjacency cases of the 15 story building, and for High and Low amplitude records, respectively. Figs. 11 and 12 show the same results for the 30 story building. The story displacements shown in these figure include structural drift plus foundation rotation. It must be noted that; for example, "30S" stands for a single 30 story on rigid support, and for example, "30S-S1" means a single 30 story on Site 1. Also, “30Swith15S-0.125a-S1(15S)” for example means the FE model includes a 30 story building adjacent to a 15 story, one eighth of the buildings width apart, on Site 1, and the results for the 15 story is being considered. The following observations, in general, can be made from these figures, 1) High amplitude records yield higher story displacements (up to 230% for the 30 story and 80% for the 15 story building) than Low amplitude ones. 2) Shorter building distances cause higher story displacements. 3) For a given site and an earthquake record, the adjacent buildings have higher responses than those of a single free-standing counterpart building, i.e., accounting for SSSI slightly increases the story displacements. 4) A taller building increases the response of a shorter adjacent building, and a shorter building decreases the response of a taller adjacent building. For example, a 15 story next to a 30 story has higher story displacement than when it is next to another 15 story. Also, a 30 story next to a 15 story building has lower responses than when it is next to another 30 story. This is because of the rocking action at the base of the taller building which influences the response of the shorter building and the vibrations of the shorter building do not much impact the response of the taller building.

However, it depends on the frequency content of motion induced by larger building in the presumptive location of smaller building, and dominant natural frequency of soil-structure system for smaller building.

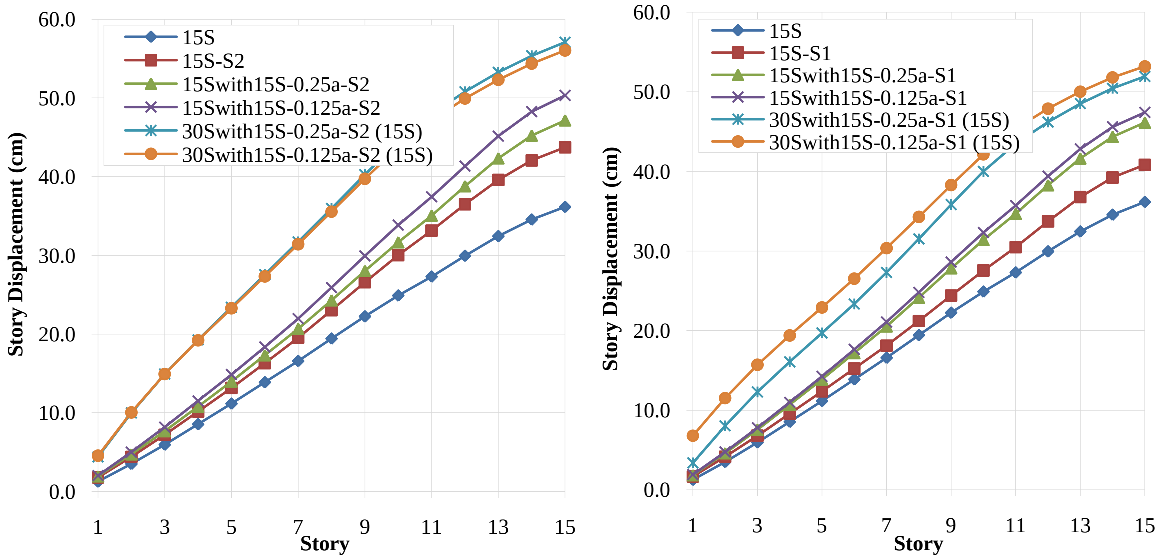


**Fig. 9** Mean story displacements (relative to the base of the building) of a 15 story building on both site 1 (right) and site 2 (left) due to high amplitude records for different adjacency cases

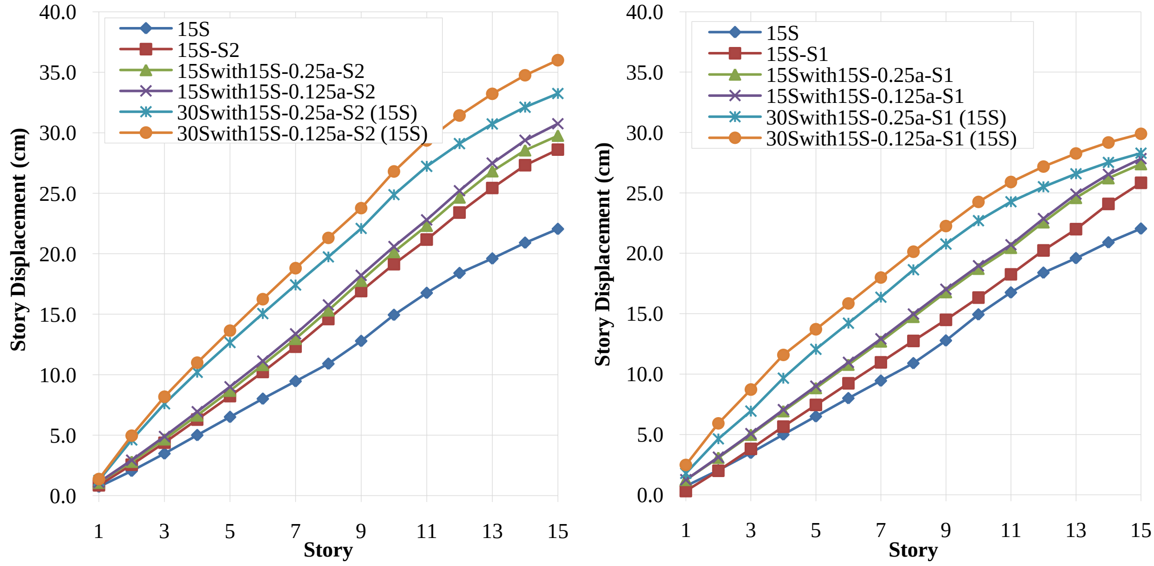


**Fig. 10** Mean story displacements (relative to the base of the building) of a 15 story building on both site 1 (right) and site 2 (left) due to low amplitude records for different adjacency cases

5) Irrespective of the earthquake type, the buildings on Site 2 experience higher story displacements than when they are on Site 1. In fact, the peak story displacements of a 15 story building on Site 2 are higher for the High amplitude records, up to 5%, and for the Low amplitude records, up to 23% than those on Site 1. While for a 30 story building on Site 2 subjected to the High amplitude records the maximum story displacements are higher, up to 3%, and for the Low amplitude records, up to 5% than when the building is on Site 1. The preceding conclusions are perhaps due to the fact that the period of Site 2 (soft-deep clay) is closer to the earthquake predominant period and/or the building fundamental period of the buildings than that of the Site 1 (shallow-dense sand) and this proximity tends to amplify the structural responses.



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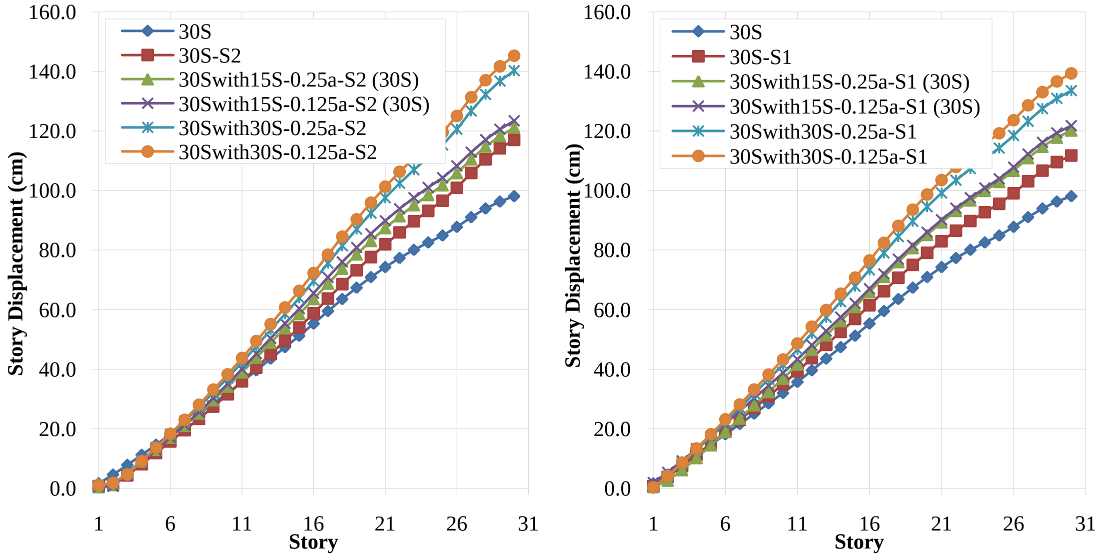


**Fig. 11** Mean story displacements (relative to the base of the building) of a 30 story building on both site 1 (right) and site 2 (left) due to high amplitude records for different adjacency cases

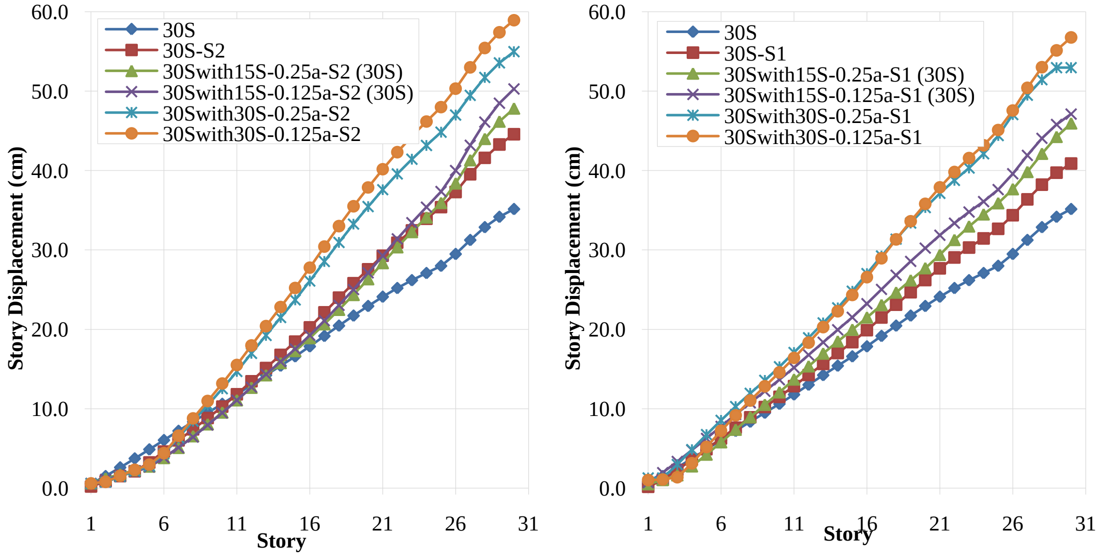


**Fig. 12** Mean story displacements (relative to the base of the building) of a 30 story building on both site 1 (right) and site 2 (left) due to low amplitude records for different adjacency cases

### *12.2. The effects of SSI and SSSI on structural base shear*

Figs. 13 and 14 show the structural base shears and the foundation factors *(FF)* for different conditions for the 15 and 30 story buildings, respectively. The *FF* is defined as the ratio of the maximum base share of a building on a flexible site ($V_{SSI}$ *or* $V_{SSSI}$) to that of the same building on rigid support *(V)* and subjected to the same earthquake record. The first two columns on the left side in Figs. 13 and 14 corresponded to the buildings on rigid support and subjected to the High and Low amplitude records, respectively. The next four columns are for the single buildings on Sites 1 and 2 (SSI). It is clear that the base shears and foundation factors follow a descending trend with a rather large drop at the beginning. This drop in the base shear is due to the SSI. Also, the results for the softer-deeper Site 2 are lower than for the stiffer-shallower Site 1. Interestingly, the base shears due to the High amplitude records are higher (up to 40% for the 15 story and 50% for the 30 story) than those for the Low amplitude records.



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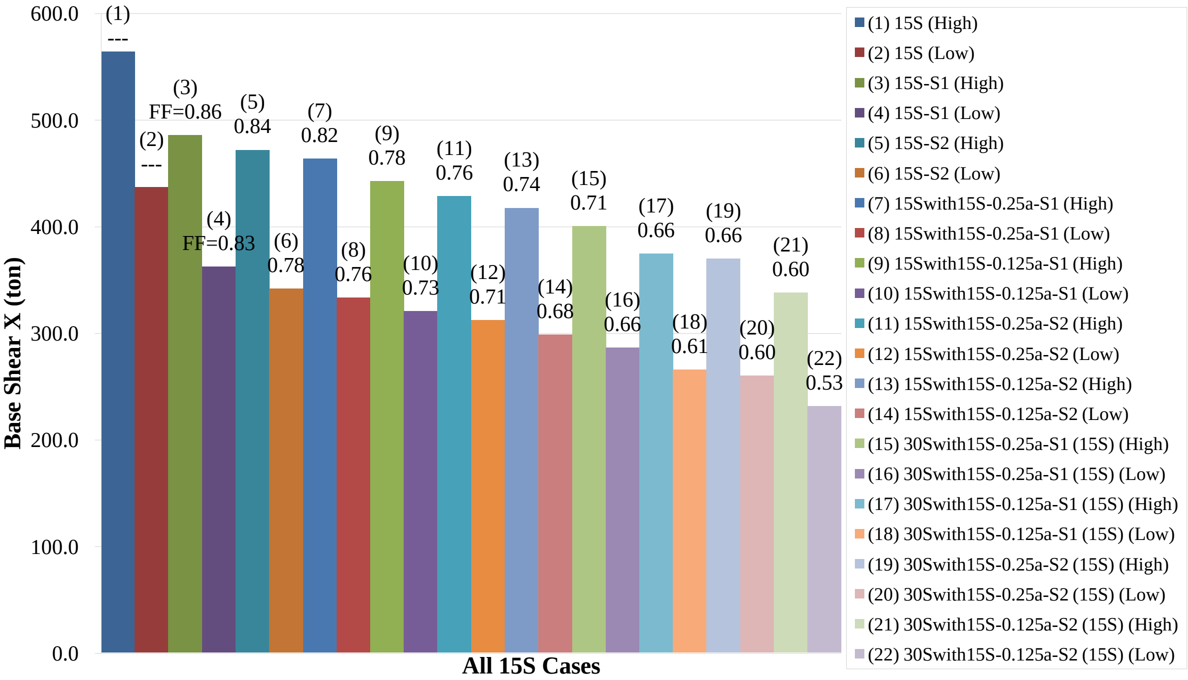

**Fig. 13** The structural base shears for all the 15 story buildings on rigid ground or on Sites 1 and 2; subjected to the high and low amplitude records; and all the adjacency cases

The 7th to 10th columns represent the base shear and foundation factor of the building in question adjacent to a 15 story, on the Sites 1, with the two building distances of one eighth and one fourth of the building width, and for the two earthquake types of High and Low amplitudes. The 11th to 14th columns represent the same information except for the Site 2. Then, the next eight columns, 15th to 22nd represent the same information except that the adjacent building is the 30 story. Irrespective of the number of building stories, the following conclusions can be made from Figs. 13 and 14: 1) in general, accounting for SSI reduces the base shear and foundation factors. 2) Despite the story displacements that were higher for the Site 2, the base shears for this softer-deeper site are lower than those for the stiffer-shallower Site 1. 3) Closer building distances slightly reduces the structural base shear and foundation factor, i.e., SSSI reduces the base shear as well. 4) For any given site or earthquake type, the base shear decreases more when the building in question is next to a 30 story building rather than a 15 story.

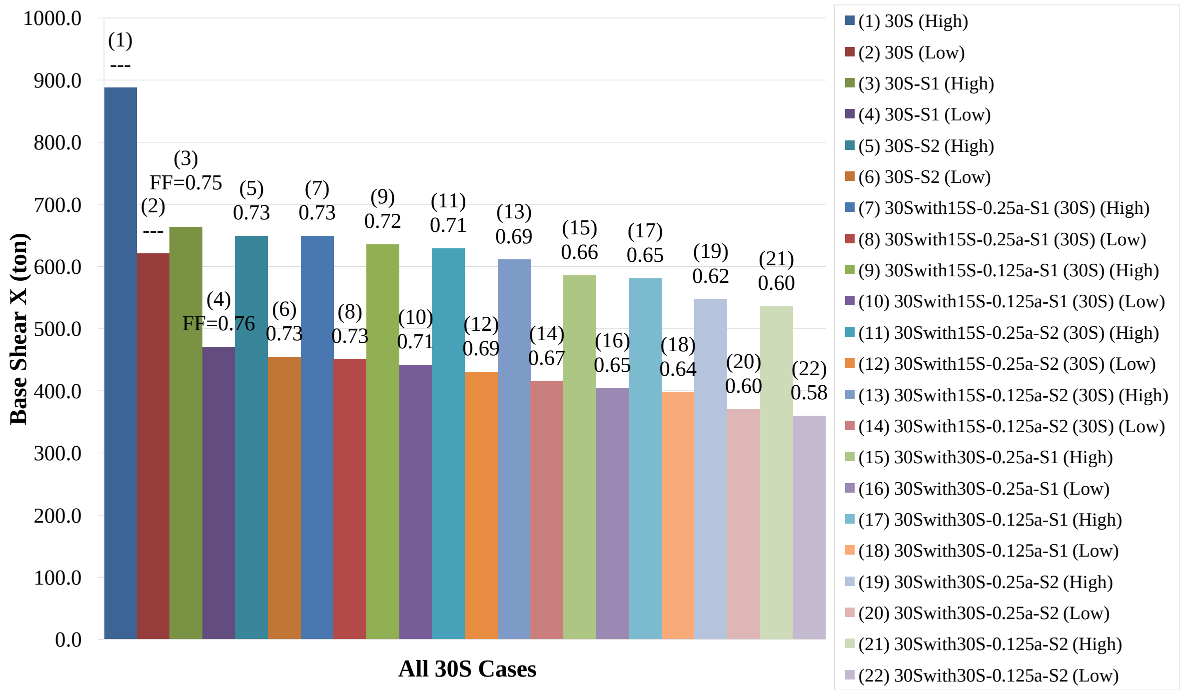

**Fig. 14** The structural base shears for all the 30 story buildings on the rigid ground or on the Sites 1 and 2; subjected to the high and low amplitude records; and all the adjacency cases



[ DOI: 10.22068/IJCE.13.3.213 ]

5) The foundation factors, in general, for a 30 story building are lower than those for a 15 story building. The largest base shear reduction for a 15 story is up to 30% and occurs when it is next to a 30 story. While at the same time the 30 story itself experiences only 7% reduction in base shear. The base shear in the same 30 story when next to another 30 story is reduced by 19%, i.e., the base shear reduction in taller buildings is less than the shorter buildings. In other words, during earthquakes the taller building will be less influenced by the shorter buildings than otherwise.

According to Eq. 19.2-2 in ASCE 7-2010, by considering SSI, seismic design base shear is allowed to be reduced up to 30% (i.e., $V_{SSI}/V \geq 0.7$, where $V$ corresponds to the base shear of a rigid base structure). Table 5 provides a comparison of the ASCE-7 recommended ratio of $V_{SSI}/V$ versus the analytical results obtained in this study for both the SSI and SSSI cases. It should be noted that for each soil-structure model (say 15S-S2), the analytical values in this table represent the average values corresponding to the seven records used here.

Table 5: Comparison of ASCE-7 recommended ratio of $V_{SSI}/V$ versus the analytical results obtained in this study, for SSSI cases: a) the adjacent building is 15 story, and b) the adjacent building is 30 story.

**Table 5a** The adjacent building is 15 story

| *Case* | *$V_{SSI}/V$ (ASCE7)* | *$V_{SSI}/V$ (Analysis)* | *Diff. with ASCE7 (%)* | *$V_{SSSI}/V$ Adj. to 15S d=0.25a* | *Diff. with ASCE7 (%)* | *$V_{SSSI}/V$ Adj. to 15S d=0.125a* | *Diff. with ASCE7 (%)* |
|---|---|---|---|---|---|---|---|
| 15S-S1 | 0.96 | 0.85 | 11.46 | 0.79 | 17.71 | 0.76 | 20.83 |
| 15S-S2 | 0.92 | 0.81 | 11.96 | 0.74 | 19.57 | 0.71 | 22.83 |
| 30S-S1 | 0.86 | 0.74 | 13.95 | 0.73 | 15.12 | 0.72 | 16.28 |
| 30S-S2 | 0.85 | 0.75 | 11.76 | 0.70 | 17.65 | 0.68 | 20.00 |

**Table 5b** The adjacent building is 30 story

| *Case* | *$V_{SSI}/V$ (ASCE7)* | *$V_{SSI}/V$ (Analysis)* | *Diff. with ASCE7 (%)* | *$V_{SSSI}/V$ Adj. to 30S d=0.25a* | *Diff. with ASCE7 (%)* | *$V_{SSSI}/V$ Adj. to 30S d=0.125a* | *Diff. with ASCE7 (%)* |
|---|---|---|---|---|---|---|---|
| 15S-S1 | 0.96 | 0.85 | 11.46 | 0.69 | 28.13 | 0.64 | 33.33 |
| 15S-S2 | 0.92 | 0.81 | 11.96 | 0.63 | 31.52 | 0.57 | 38.04 |
| 30S-S1 | 0.86 | 0.74 | 13.95 | 0.66 | 23.26 | 0.65 | 24.41 |
| 30S-S2 | 0.85 | 0.75 | 11.76 | 0.61 | 28.24 | 0.59 | 30.59 |

The following conclusions could be drawn from the results in Table 5: 1) The design base shear reductions/ratios as recommended by ASCE-7 when SSI is considered are conservative, 2) Close adjacency of the buildings reduces their base shear further when SSSI is considered, 3) The closer the two adjacent buildings, the lower the maximum base shear. 4) The taller the two adjacent buildings, the lower the maximum base shear. However, as explained earlier, as much as inclusion of SSI and/or SSSI is beneficial in reducing the base shears, it is detrimental in increasing the story displacements.

## 13. Summary and Conclusions

The current study intends to evaluate the effects of SSI and SSSI (building adjacency) on the response of structures on flexible sites subjected to earthquakes with different amplitudes by application of ELM and 3D FE of soil-structure models. The conclusions made here are based on the structures, soil models and the earthquake records applied in this research. The following are some of the conclusions drawn from this research:

*a) Verification of the 3D FE modelling and analysis*: The results of a free-field motion analysis by 3D FE modelling by OpenSees and one D dimensional modelling by SHAKE2000 were compared. It was concluded that the results by the two modelling methods are very close, confirming the validity of the 3D FE modelling and analyses conducted in this study using OpenSees program.

*b)The Effects of SSI and SSSI on local responses:* 1) Accounting for SSI and/or SSSI increases the story displacements (the SSSI slightly with higher extent), 2) Shorter building distances cause higher story displacements, and 3) A taller building increases the response of a shorter adjacent building, and a shorter building decreases the response of a taller adjacent building, compared to the response of a free standing structure on the same foundation soil. However, it depends on the frequency content of motion induced by larger building in the presumptive location of smaller building, and dominant natural frequency of soil-structure system for smaller building.

*c) The Effects of SSI and SSSI on global responses:* 1) Accounting for SSI and SSSI reduces the base shear, 2) Despite the story displacements that were higher for Site 2, the base shears for this softer-deeper site are lower than those for the stiffer-shallower Site 1, 3) The base shears and/or foundation factors due to High amplitude records are higher than those for Low amplitude records., 4) Closer building distances slightly reduce the structural base shears and/or foundation factors. 5) The structural base shear decreases more when a building is next to a 30 story building rather than a 15 story, 5) The foundation factors, for a 30 story building are generally lower than those for a 15 story building, 6) During earthquakes, the taller building will be less influenced by the shorter buildings than otherwise.

*d) The Effects of earthquake* amplitude *on the SSI and SSSI responses:* The structural local and global responses are significantly inflenced by the amplitude of the records, so that due to High amplitude records the base shears could be higher, up to 50% and the story displacements, up to to 250% than those for Low amplitude records.

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