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Effect of Structure Height on Seismic Response of Adjacent Structures Considering Soil-Structure Interaction

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HIGHLIGHTS

- Seismic tests consisted of three small-scale structural steel models of varying heights on sand soil.
- Structural seismic responses were represented by time-domain behaviors like acceleration and displacement.
- Taller buildings strongly affected shorter adjacent buildings' acceleration and displacement.
- Taller buildings weakly affected the soil pressure of adjacent shorter buildings.

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ABSTRACT

Seismic activity has emerged as a mostly attractive issue for researchers and engineers, particularly in light of the recent occurrence of severe earthquakes worldwide, such as those felt in Turkey and Syria. Most entities prone to seismic damage are the structures. Any type of structure consists of a composite system involving structure, foundation, and soil. Previously, numerical and analytical methods for dynamic seismic analysis of structures ignored the impact of this system during earthquakes. In other words, soil-structure interaction (SSI) was ignored. Moreover, another important factor that was not considered is the interaction between structures and soil, or what is called structure-soil-structure interaction (SSSI), which usually occurs between two adjacent structures. This research aims to comprehensively understand the SSSI by performing a series of dynamic tests using a shaking table system. The tests concentrate on the effect of height on the dynamic behavior between two adjacent steel structures rested on sand soil. This study employed four novel small-scale multi-degree-of-freedom steel structure models: three, four, and five-story steel structures against a three-story steel structure. The results indicated that the tallest building had the maximum effect on the shorter one, especially on the top displacement with a peak value of 3.82 cm, top acceleration with a peak value of about 0.2 g, and foundation rotation with a peak value of around 1 degree. However, the effect of the structure height has a reverse impact on the soil pressure beneath the foundation of the shortest structure since the largest pressure response was recorded for the effect of the shortest similar adjacent building with a peak value of 8.8 kPa. In comparison, the highest building has the lowest effect on the shortest building, with a peak value of 6 kPa.

1. Introduction

The term SSI refers to the interconnection among three basic systems: the structure, the foundation, and the soil media, which is of significant importance to be evaluated so that we can understand the structure's dynamic behavior. In contrast, SSSI refers to mutual influence between neighboring buildings via soil media. According to this field, many factors affect the seismic reaction of the adjacent structures, such as distance between them, height, mass, embedment level, foundation type, and soil type. In many countries around the globe, several crowded residential areas lie within seismic zones; many are old, do not contain safety measures against earthquakes, and are not subjected to seismic design codes. So, these areas need to be considered in the case of seismic activity to avoid the risk of earthquakes because, in many situations, the distance between any two buildings does not exceed a few meters. Furthermore, there are many varieties of building heights, which may lead to serious consequences, some of which are positive and others are negative. Most of the studies done in the domain of SSI and SSSI are theoretical, and some are experimental. Modeling an infinite field is one of the most notable extents when used by the finite element method in case of not taking any action to preclude synthetic reflections at the mesh limits; faults are addressed in the outcomes. Several artificial boundaries have been proposed to manage reflections [1, 2].

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Some researchers worked experimentally on cases of adjacent structures, considering the effects of building height, clear distance between structures, and other variables. Considering the experimental work, Hosseinzadeh and Nateghi [3] investigated the impacts of soil-structure interaction on the dynamic reaction of an individual steel structure model and another adjacent steel structure model using shaking table tests. Aldaikh et al. [4] also conducted a sequence of shaking table examinations on a steel-aluminum building model to study the outcomes of SSSI on its reaction when it was enclosed once by one model building and then by two model buildings while experiencing dynamic excitation. To investigate dynamic SSSI between two adjacent wobble structures, Jabary and Madabhushi [5] repeated nearly spaced housing buildings in an urban ambiance exposed to seismic input motions performed through geotechnical centrifuge tests. They considered structures with and without external damping mechanisms via tuned mass damper (TMD) formations. Kirkwood and Dashti [6] characterized how the building disengagement and ground motion features influence the reaction of adjacent structures founded on a layered, liquefiable soil profile. The dynamic counter actions of adjacent single-degree-of-freedom models were examined by Barrios et al. [7] using a laminar box filled with sand. For the dynamic excitation, they executed impulse loads and simulated ground motions. Their tests included models of variant fundamental frequencies and slenderness.

A series of dynamic geotechnical centrifuge tests on aluminum structure models were performed to check the influences of SSSI interactions on the responses of structures [8]. To evaluate the mechanism and procedures of equipment-adjacent structure-soil interaction (EASSI) under a seismic influence, He and Jiang [9] executed a substructure shake table test (SSTT) based on the branch mode method. Three substructures of the EASSI system were introduced: the equipment-single structure, the foundation soil, and the neighboring structure. Furthermore, they also considered the equipment's mass ratio, frequency ratio, and relative location of the main structure while performing the investigation tests. According to the theoretical work, Behnamfar and Sugimura [10] studied the dynamic behavior of a real-world building beside another structure under earthquake time histories. One of the twin buildings affiliated with Tohoku University in Sendai, Japan, was under inspection. Both structures were prepared to capture the acceleration of the earthquake. The recorded data were utilized to confirm the analytical theory. The acceleration spectrum of the base and roof levels was calculated using the recorded free-field motion as input, and the system of two neighboring buildings was modeled using a 2-dimensional boundary element approach.

Yahyai et al. [11] examined the influence of SSI on seismic performance with period, base shear, and displacements of two nearby 32-story buildings. The investigation included studying the effects of diverse distances between the two buildings and different types of soil, including soft clay, sand, and compacted sand. They modeled the buildings using a 2D frame in ANSYS 5.4. The constructed model consisted of soil, foundation, and structures. Naserkhaki and Pourmohammad [12] performed a numerical study of the effect of SSI and SSSI on the behavior of identical buildings throughout seismic excitations. They represented the buildings as shear structures. According to the soil, they simulated it using a discrete model of a viscoelastic half-space prone to seismic acceleration. Moreover, they created analytically building motion equations with the situations of fixed-based (FB), SSI, and SSSI and solved them numerically. Regarding the investigation of Farghaly [13], two neighboring 3D structures with diverse heights built on different soil types and linked via viscous dampers were assessed with a distinctive layout in the plane to check their structural reactions. He used three different kinds of soil and represented them as a 3D Winkler model to offer a convincing representation of the behavior of the neighboring buildings. He employed SAP2000n to symbolize the system. To examine the dynamic behavior and the interactive effect on the seismic reaction of neighboring surface structure and underground structure, Wang [14] implemented a numerical investigation on the dynamic through-soil interaction between underground station and nigh pile supported surface structure on viscous-elastic soil layer under vertically incident S (shear) wave. He used ANSYS software to conduct this study in the frequency domain. Bybordiani and Arici [15] examined the interactions between neighboring structures in a two-dimensional environment. For this purpose, they built clusters on the viscoelastic half-space throughout, precisely building comprehensive finite element models of 5, 15, and 30-story buildings. They also considered the interaction between the structure and the soil medium.

Ada and Ayvaz [16] observed the effects of the structure-soil-structure interaction on the performance of night frame structures. In their study, they considered the subsurface soil's influence on the structures' activity (3, 6, and 12-story) and likened it to fixed base conditions. Then, they explored the structures' acceleration and basement story drift ratios to discover the significance of the proximity of the diverse neighboring structures. The features considered contained the clear spacing between the structures, the plan of the structures, the stories number in each building, seismic motion, and the soil stiffness. They used the direct methodology of the finite element approach to examine the soil and the structures exposed to seismic motivation. To inspect the dynamic SSSI, Gan et al. [17] numerically investigated three nearby structures with pile-raft foundations ordered in an east–west path in a viscoelastic half-space under seismic provocation. The path of the building's arrangement was parallel to the way of the earthquake stimulation. Their approach included utilizing the Davidenkov model of the skeleton curve of the soil to simulate soil performance, and they also used the viscous-spring artificial boundary. Their tests considered the clear distance between structures, structure classes, structure heights, and the first natural periods of structures.

This research aims to investigate the effect of a building height on the (SSSI) response of an adjacent building, taking into account the shortest distance between the buildings to get the maximum response. The most important part of this study is to examine the level of agreement between our results and the previous studies done in this field.

2. Experimental Work

2.1 Model Preparing

Because of the difficulty and challenge of performing this test using concrete structures, we executed it by designing and constructing carbon steel frame structure models on a similitude factor of 1/46. This factor was chosen due to the limitation of the soil container and shaking table dimensions. These models include a reference 3-story frame structure with a similar 3-story frame structure, a 4-story frame structure, and a 5-story frame structure as shown in Figures 1 which displays the typical scheme of a three-story building frame and Figure 2 (a-c) which displays the manufactured steel building frames used in the study; (a) three-story, (b) four-story, and (c) five story buildings. All details of the frame structure are listed in Table 1. All the structural models were assembled mechanically using carbon steel with a mass density of 7581.76 kg/m^3 and a modulus of elasticity of 185833 MPa.

Table 1: Details of the study models

Member	Cross-section type	Dimensions
Foundation	Plate section	6 mm thickness
Beam	Box section	12.7×12.7 mm^2, 0.8 mm thickness
Column	Pipe section	10 mm diameter, 1 mm thickness
Slab	Plate section	1 mm thickness

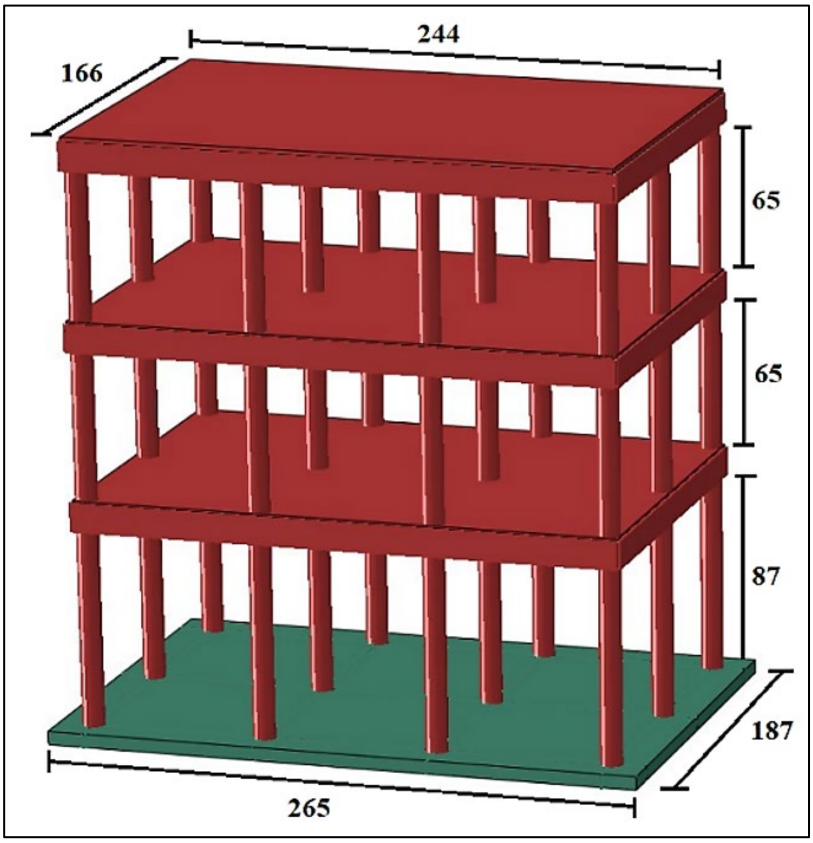

Figure 1: Typical scheme of a three-story building frame (all dimensions are in millimeters)

(a) **(b)** **(c)**

Figure 2: Manufactured steel building frames used in the study: (a) Three-story building (b) Four-story building (c) Five-story building

2.2 Preparation of Soil and Boundary Conditions

Real soil must be used in the investigation to accomplish the principle of (SSSI). So, the soil type utilized here was dry sand taken from Al-Ukhaidir in Karbala, which lies west of Iraq. The values of dry mass density, angle of friction, and cohesion are 1731.2 kg/m^3, 36°, and 0, respectively. According to the boundary conditions, a soil container of dimensions 0.9×0.9×0.6 m^3 was constructed using aluminum sections of dimensions 40×80 mm^2 and a thickness of 3 mm. Most previous studies relating to seismic tests involved the employment of ordinary metal containers filled with rubber or any elastic material to prohibit reflected waves during the dynamic test. According to our research, we used steel sliders of dimensions 12×16 mm^2 between the aluminum sections to avoid the reflecting wave problem and, at the same time, to simulate the real behavior of soil by permitting it to move smoothly in the direction of dynamic excitation.

2.3 Testing Process

A shaking table system was manufactured and assembled to perform a seismic test. This system comprises a shaking table of dimensions 1×1 m^2 with an electric actuator capable of triggering the shaking table with an electric servo valve and a controller. This system is operated by special software in the input computer. It can also provide data on past earthquakes' documented time history through an electrical signal sender connected to the input computer. It is worth noting that the shaking table system requires three-phase electricity to start the actuator. In order to study the structure responses, soil pressure sensors, linear variable differential transformers (LVDT), rotation sensors, and accelerometers will be used. The data obtained from these sensors were collected via a data acquisition collector attached to a data receiver within a desktop computer and then displayed on an output monitor. The process was performed for three cases; the first case includes testing of a three-story building with a similar adjacent building, the second case includes testing of a three-story building with an adjacent four-story building, and the third case includes testing of a three-story building with an adjacent five-story building as indicated in Figure 3 (a-c) which displays the test process for the three cases; (a) three-story versus three-story building, (b) three-story versus four-story building, and (c) three-story versus five-story building. So, the sensors were installed on a three-story building as a reference model for response results. In this study, local time history data of a previous earthquake with a peak ground acceleration (PGA) of about 0.1g that occurred in Ali Al-Gharbi town in Maysan city, which lies in the south of Iraq in 2016, was used as the dynamic excitation as stated in Figure 4.

(a) (b) (c)

Figure 3: Test Process; (a) 3-story vs 3-story building. (b) 3-story vs 4-story building. (c) 3-story vs 5-story building

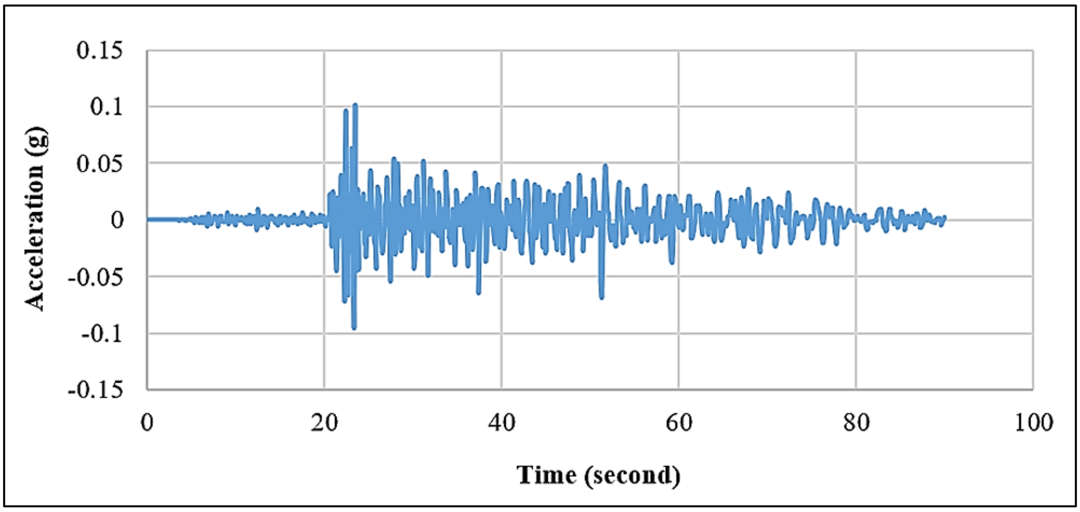

Figure 4: Time history of Ali Al-Gharbi earthquake

3. Results and Discussion

To guarantee accurate and reasonable results and because of the soil type, the soil container was emptied and refilled again after each test to prevent soil density from changing due to seismic activity. Figure 5 compares the building top acceleration response of a three-story building against adjacent buildings with different heights. Throughout observing this Figure, it is obvious that the acceleration responses of the three-story building for all three cases were almost constant with low intensity from the beginning of the earthquake till nearly the first twenty seconds when all of the three cases suddenly raised to their peak ground acceleration (PGA) of 0.172g, 0.187g, and 0.194g for the first case, second case, and third case, respectively. Regarding the first case, as mentioned before, the wave started with low vibrations during the first twenty seconds and reached its peak value at about the second 20. Later, the intensity of the wave vibrations was lowered to settle in an approximate range from 0.12g to -0.14g. After about 60 seconds from the beginning of the excitation and till its end, the wave's behavior changed because the PGA range was diminished from nearly 0.07g to -0.04g. According to the second case, the wave also started with low vibrations during the first twenty seconds when it peaked at second 22.

After that, the intensity of the wave vibrations was just settled in an approximate range from 0.175g to -0.11g. After about 60 seconds from the beginning of the excitation and till its end, the wave's behavior changed because the PGA range was reduced from nearly 0.12g to -0.065g. Referring to the third case, the wave started with low vibrations during the first twenty seconds when it reached its peak value, the highest value among the three cases at second 22. Then, the intensity of the wave vibrations was minimized in an approximate range from 0.08g to -0.13g. After about 60 seconds from the beginning of the excitation and till its end, the wave's behavior changed because the PGA range was lowered from almost 0.04g to -0.055g. To summarize, this outcome is compatible with the study finding of Aldaikh et al. [4], which indicated that a structure seems to experience the most unfavorable interaction influence when bounded by one or two higher buildings by about 10%. This result also agrees with the result of Barrios et al. [7], which showed that whenever the slenderness increases, the resulting acceleration increases also.

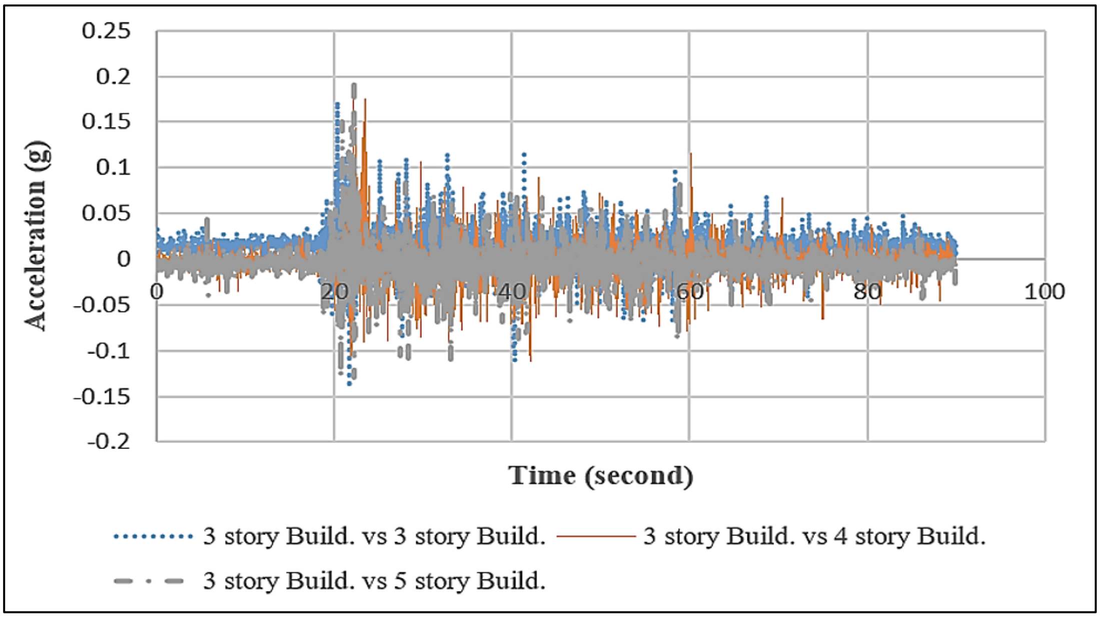

Figure 5: Comparison of building top acceleration response of a three-story building against adjacent buildings with different heights

Figure 6 compares the building top displacement response of a three-story building against adjacent buildings with different heights. By observing this Figure, it is noticed that the tendency of the displacement curves for all three cases is about the same as in Figure 5 for the first twenty seconds. Then, the displacement responses suddenly changed to the first notable values. Regarding the first case, as stated previously, the wave started with low vibrations during the first twenty seconds, when it reached its first raising value of nearly -2.8 cm at about the second 20. Later, the wave vibrations' intensity decreased and became almost stable in an approximate range from 2.7 cm to -2.2 cm till the second 58. After this period, the displacement behavior was maximized from 3 cm to -2.8 cm until the second 87. When the wave was almost finished, it reached its peak value of -3.44 cm at second 89. According to the second case, and just like the previous one, the wave began with low vibrations during the first twenty seconds, reaching its first increasing value of approximately 1.8 cm at the second 20. After that, the wave vibrations' intensity escalated to an estimated range from 2.6 cm to -3.1 cm till about second 41 when the wave reached its ultimate value of 3.65 cm. After this period, the displacement behavior became steady in a near range from 3.6 cm to -3.3 cm until the end of the earthquake. Regarding the third case, which had a similar trend to the former two cases, the wave initiated with low vibrations till the second 19, when it reached its first increasing value of roughly 2.2 cm. Then, the intensity of the wave vibrations was amplified to an estimated constant range from 3.5 cm to -3.4 cm till the second 58 when the wave reached the peak value of -3.82 cm, the highest value among the three cases. Finally, the displacement response continued in an approximate range from 3.4 cm to -3.7 cm until the end of the dynamic excitation. This finding seems to be accepted by the study of Kumar and Mishra [18], which referred to the fact that the displacement reactions of building frame models rise with height.

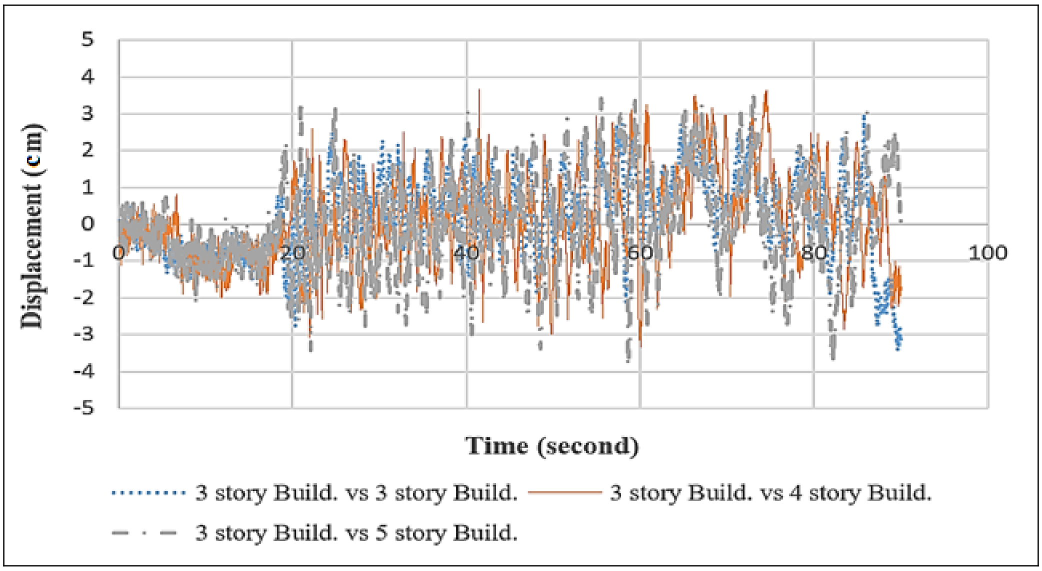

Figure 6: Comparison of building top displacement response of a three-story building against adjacent buildings with different heights

Figure 7 compares the foundation rotation (rocking motion) response of a three-story building against adjacent buildings with different heights. Regarding the first case, during the first twenty seconds from the beginning of the dynamic excitation, it is noticed that the wave started with an approximate range from 0.4 degree to -0.48 degree. Later, the wave vibrations' intensity increased and became almost steady in an approximate range from 0.55 degree to -0.52 degree till the second 60. After this period, the rotation response slightly decreased to an approximate range from 0.52 degree to -0.46 degree until the second 88, when it reached its peak amplitude of 0.59 degree. In the second case, it is obvious that there is a notable increase in the rotation response as compared to the first case, with a near range from 0.73 degree to -0.53 degree during the first twenty seconds. Then, the rotation response decreased with an approximate range from 0.65 degree to -0.4 degree till the second 53, when it reached its ultimate rotation of 0.85 degree. After this period and until the end of the wave, the behavior was in a near range from 0.83 degree to -0.61degree.

Regarding the third case, it is evident that the rotation response here had a similar trend to be maximized as the height increased. The wave started with an approximate range from 0.93 degree to -0.48 degree within the first twenty seconds. After that, just like in the previous case, the rotation behavior was diminished with an approximate range from 0.9 degree to -0.32 degree till the second 53 when it reached its peak rotation value of 0.97 degree, the highest value among the three cases. After this duration and until the end of the wave, the behavior was in a near range from 0.9 degree to -0.46 degree. According to this outcome, there is a harmony with the result of Naserkhaki and Pourmohammad [12], which illustrated that when a structure is of denser mass, it will affect its nearby nimbler structure. At the same time, it is less influenced by its neighboring slighter structure.

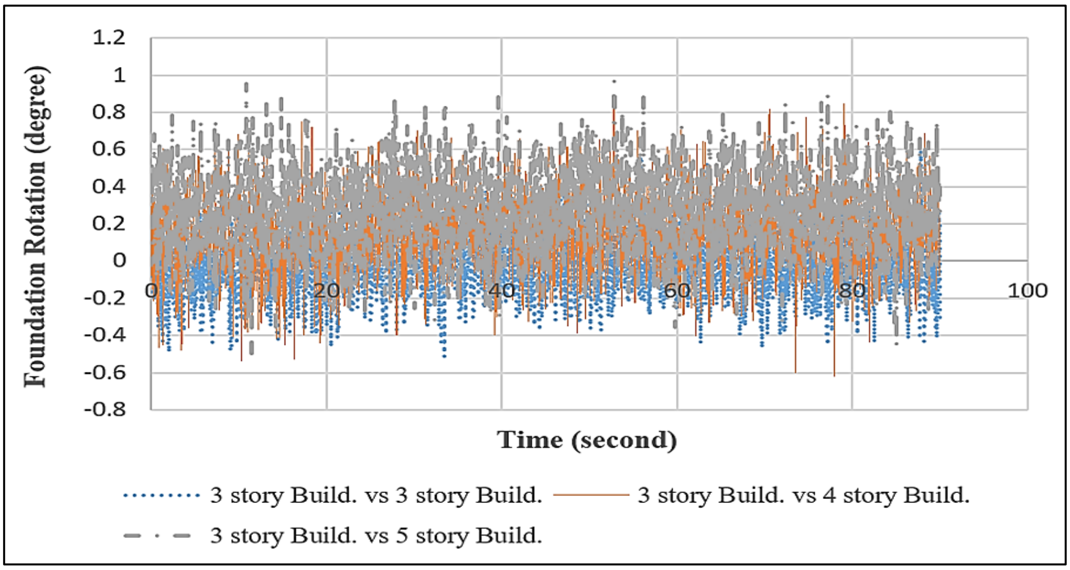

Figure 7: Comparison of foundation rotation (rocking motion) response of a three-story building against adjacent buildings with different heights

Figure 8 compares the soil pressure response of a three-story building against adjacent buildings with different heights. Regarding the first case, during the first twenty seconds from the beginning of the dynamic excitation, it is noticed that the wave started with low intensity. Next, it began to escalate sharply linearly until it reached the first remarkable pressure value of about 6 kPa at the second 23. Later, the wave response continued rising gradually until it reached its peak pressure value of 8.94 kPa at second 62, the maximum value among the three cases. Finally, the wave behavior proceeded frequently till the end of the earthquake and finished with a pressure value of approximately 8.3 kPa. In the second case, it can be seen that there is a similarity in the wave response according to the low intensity during the first twenty seconds, with a minor difference as compared to the first case.

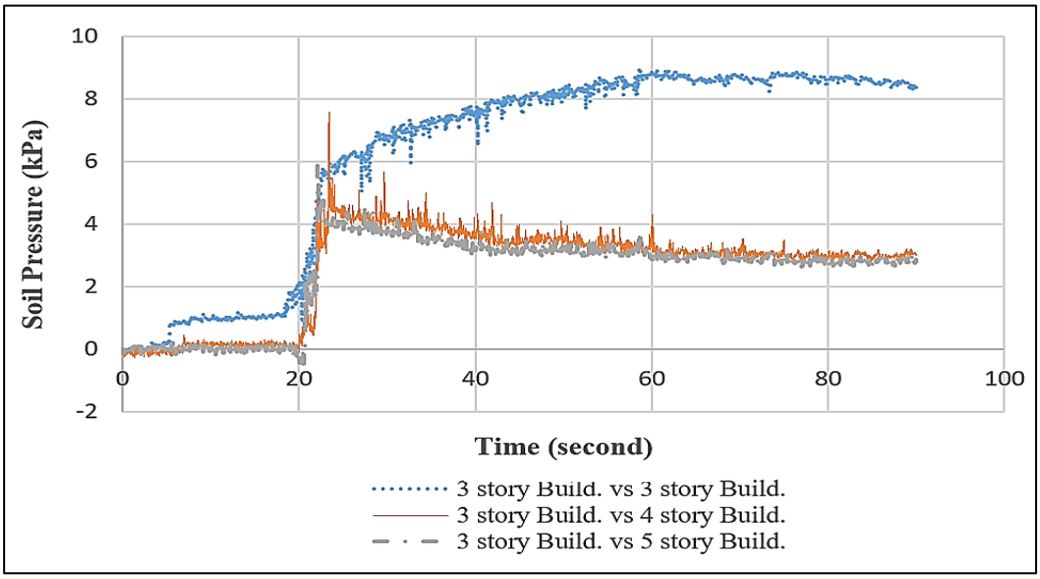

Figure 8: Comparison of soil pressure response of a three-story building against adjacent buildings with different heights

Then, the pressure response experienced an acute leap of about 5 kPa at the second 23 degrees, followed by the peak pressure value of 7.59 kPa after only about two seconds. After this peak, the wave response decreased suddenly to about 4.2 kPa at second 26. After that, the wave continued dropping until it reached a pressure value of 3.2 kPa at the second 60, followed by a constant response until the wave ended at nearly 3 kPa. Regarding the third case, it is clear that the pressure response almost had an identical tendency to the second case during the first twenty seconds, except that the pressure value of this wave had a direct jump to the ultimate value of 6 kPa at the second 23. Subsequently, this response started to reduce gradually to settle approximately on a pressure value of around 3 kPa, and it kept this state constant till the end of the dynamic excitation. To summarize, the pressure response outcomes are unlike the rest of the responses, where the highest building had the least effect on the shorter adjacent building. In contrast, the shortest building had fewer effects on the similar adjacent building. This result seems to be in accordance with the study finding of Hosseinzadeh and Nateghi [3], which stated that there is more influence between identical neighboring buildings than between diverse nigh buildings.

4. Conclusion

Based on the aforementioned results, the following conclusions are listed below:

1) Regarding the acceleration comparison, the effect of SSSI can be sensed here. In contrast, the five-story building affected the three-story building behavior at the highest level of PGA of about 0.2g.
2) According to the building displacement, just like the previous item, the highest building magnified the effect of horizontal movement for the shortest building to be displaced with a maximum value of 3.82 cm.
3) The foundation rotation results gave the same trend as the previous items, which implied the highest influence of the tallest building on the shortest building by a greatest rotation value of approximately 1 degree.
4) Concerning the results of soil pressure, the three-story building had the greatest effect on the soil beneath the similar building of a value of about 9 kPa, while the five-story building had the minimum effect on the three-story building of around 6 kPa.

From the results and conclusion drawn above, which are based on agreement with previous studies, it can be seen that higher buildings have the most critical effect on the behavior of the SSSI of shorter buildings. This effect may be attributed to the fact that any extra height in the building generates extra inertial forces that amplify the responses of acceleration, displacement, and foundation rotation, except for the case of soil pressure, because it seems that similar buildings have more effect on each other than the heavier buildings. This effect may result from the soil type or the close distance between the buildings. So, these issues must be considered in seismic or residential compound design. Furthermore, soil medium must also be considered in dynamic design and analysis.

Author contributions

Conceptualization, M. Abdulaziz., M. Hamood. and M. Fattah.; methodology, M. Abdulaziz., M. Hamood. and M. Fattah.; software, M. Abdulaziz.; validation, M. Hamood. and M. Fattah.; formal analysis, M. Abdulaziz.; investigation, M. Abdulaziz. and M. Hamood.; resources, M. Abdulaziz.; data curation, M. Abdulaziz. And M. Fattah.; writing—original draft preparation, M. Abdulaziz.; writing—review and editing, M. Hamood. and M. Fattah.; visualization, M. Abdulaziz. and M. Hamood.; supervision, M. Hamood. and M. Fattah.; project administration, M. Abdulaziz. and M. Fattah. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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