IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Design & Nature and Ecodynamics
Vol. 20, No. 5, May, 2025, pp. 999-1006
Journal homepage: http://iieta.org/journals/ijdne

Seismic Response of Pile Group Foundations under Multi-Story Buildings in Sandy Soil: Shaking Table Investigation

Omar K. Ali[1*], Jasim M. Abbas[2], Laith Al-Hadithy[1]

[1] College of Engineering, Al-Nahrain University, Baghdad 10011, Iraq
[2] College of Engineering, Diyala University, Baqubah 32001, Iraq

Corresponding Author Email: omar.civ23@ced.nahrainuniv.edu.iq

https://doi.org/10.18280/ijdne.200505

Received: 2 February 2025
Revised: 17 May 2025
Accepted: 24 May 2025
Available online: 31 May 2025

Keywords:
pile group foundation, number of stories, multi-story building, Kobe earthquake, sandy soil, small-scale laboratory model, shaking table device

ABSTRACT

The present study aims to examine the effects of the number of stories on the dynamic behavior of pile group foundations in multi-story buildings. Experimental tests were conducted using a shaking table on a small-scale building model with 4, 6, 8, and 10 stories. These models were designed and fabricated with a consistent weight and a scale ratio of 1:20. The multi-story buildings rest on 3×3 pile groups with an L/D ratio of 16, and are situated within sandy soil exhibiting a relative density of 70%. The shaking table simulated the effects of the Kobe earthquake with a peak acceleration value of 0.82g. The results showed that the vertical displacement (both peak and residual) increases significantly as the number of stories increases. Specifically, when the number of stories increases from 4 to 6, the peak displacement increases by a factor of 3. As the number of stories is increased further to 8 and 10, the peak displacement increases by a factor of 1.9 and 5, respectively. In terms of residual displacement, increasing the number of stories from 4 to 6, 8, and 10 results in an increase by a factor of 17, 5.5, and 33, respectively. These results suggest that even though the weight is constant across all buildings, increasing the number of stories leads to greater building height and flexibility, resulting in increased seismic displacement. Therefore, it is imperative that pile groups are designed to accommodate this augmented movement to maintain foundational stability and ensure structural safety.

1. INTRODUCTION

In recent years, the rapid growth of urban development has led to a significant increase in the construction of multi-story buildings worldwide, including in Iraq. Many of these structures are built on soft or sandy soils, which require the use of pile foundations to safely transfer superstructure loads to deeper, more stable soil layers. Understanding the behavior of pile foundations under seismic loading conditions is crucial to ensuring the safety and serviceability of such structures.

1.1 Pile foundation behavior in sandy soils

Pile foundations serve a critical role in providing stability to structures built on weak or loose soil conditions, such as sand. Under static and dynamic loads, pile groups interact with surrounding soils in complex ways that affect both vertical and lateral displacements. Numerous studies have employed empirical, semi-empirical, and analytical methods to investigate the dynamic behavior of pile groups in sandy soils, especially under seismic loads.

1.2 Influence of number of stories on pile-soil interaction

The number of stories in a structure significantly influences the behavior of pile foundations, primarily due to variations in structural mass and stiffness. An increase in building height generally results in greater inertial forces during seismic events, thereby altering both lateral and vertical responses of the pile groups.

For example, Boulanger et al. [1] conducted seismic interaction experiments focusing on the impact of axial loads on pile foundations. They observed that in mid-rise buildings, lateral response increased by approximately 30% due to resonance effects, while taller structures exhibited greater settlements. Similarly, Xu et al. [2] analyzed the seismic response of buildings with 3, 6, and 9 stories supported by pile groups in dense sand. Their findings indicated that taller structures exhibited 35% more lateral displacement compared to shorter ones, primarily due to increased inertial forces. Thapa and Karki [3] investigated buildings ranging from 4 to 12 stories and found a 30% increase in vertical settlement in taller structures, with shorter buildings experiencing reduced lateral displacements.

Further, Mohasseb et al. [4] studied the seismic interactions between piles and soil for high-rise buildings situated on dense sand. Their results suggested that increasing the number of stories led to a 30% rise in axial forces, which somewhat stabilized lateral movement but contributed to higher settlements. The work of Singh and Tiwary [5] confirmed that taller buildings exert higher lateral and axial loads on pile groups, resulting in increased soil resistance and vertical deformation. Using a combination of numerical simulations and experimental data, they emphasized the importance of considering natural frequency and pile-soil interaction in seismic performance assessments.

Moreover, Meena et al. [6] reported a noticeable rise in vertical settlement as building height increased, linking this to the growing mass imposed on pile groups. They also noted a corresponding reduction in lateral displacements for shorter structures. Finally, Wang and Zhang [7] explored dynamic interactions between pile groups embedded in dense sand and multi-story buildings under seismic loads, finding that taller structures experienced up to 40% greater vertical settlement compared to mid-rise buildings due to elevated inertial forces.

1.3 Seismic response of pile groups for mid-to-high-rise structures

Although previous studies have provided valuable insights into the seismic behavior of pile groups supporting structures with varying heights, most have concentrated on either low-rise or high-rise buildings (typically ranging from 3 to 12 stories). However, there is a lack of focused experimental research specifically investigating mid-to-high-rise buildings in the 4 to 10-story range under seismic conditions, particularly in dense sandy soils. Additionally, limited attention has been given to evaluating how dead loads and increasing mass affect the pile group response during seismic excitation.

1.4 Research gap and objective

In light of the existing literature, there remains a gap in understanding the seismic performance of pile groups supporting multi-story buildings, specifically within the 4 to 10-story range, under both vertical (settlement) and lateral displacements in dense sandy soils.

Therefore, this study aims to address this gap by presenting experimental investigations on the seismic response of pile groups supporting buildings of varying heights (4, 6, 8, and 10 stories) but with equal total weight. The results focus on evaluating both vertical and lateral displacements, contributing to a better understanding of pile-soil-structure interaction in mid-to-high-rise buildings under seismic loading.

2. EXPERIMENTAL SETUP AND TESTING

2.1 Small model-multi-story buildings

To conduct the investigation described earlier, it is essential to first design and construct small-scale multi-story buildings. Four small-scale multi-story structures, comprising 4, 6, 8, and 10 stories, each with identical mass, were fabricated based on a model proposed by Khoshnoudian and Kiani [8]. Each story was designed as a single bay frame oriented in both directions, allowing for an accurate representation of slender structures. The original span width and story height of the prototype were set at 4 meters and 3 meters, respectively. Consequently, the dimensions of the laboratory model buildings (length, width, and height) were proportionally scaled down using a 1:20 scale factor. The beams and columns were fabricated from square steel hollow sections (19.05×200×19.05) mm and (19.05×19.05×150) mm, with a thickness of 1.5 mm. Steel plates of varying thicknesses but with constant dimensions of (200×200) mm served as panels for each building model. Each building was designed to have equal mass across its stories, and the total weight was fixed for all multi-story models for easy comparison of building height. Figure 1 illustrates the four multi-story structures utilized in this study.

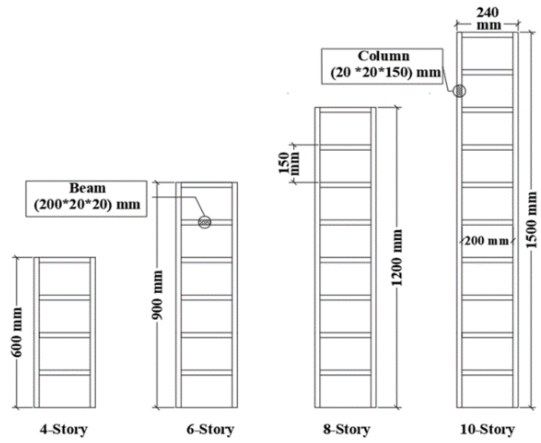
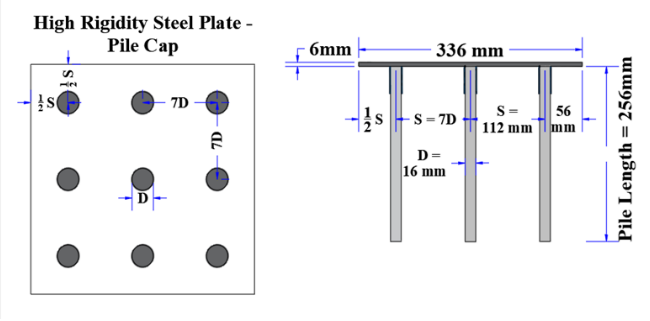


Figure 1. The geometrical properties of the multi-story structures utilized in this study

2.2 Pile group description

In this investigation, the piles employed are made from aluminum pipe tubes, a material frequently chosen for experimental testing in similar types of tests, as noted by studies [9, 10]. These piles consist of closed-end aluminum tubes, characterized by circular cross sections, with an external diameter (*D*) of 16mm and a wall thickness of 1.5mm. The ratio of embedding length to diameter is established at L/D = 16. The configuration of the pile group consists of a 3×3 arrangement, spaced apart by 7*D*, which aligns with recommendations from study [11]. In this study, a high-strength steel plate serves as the pile cap for the group, as illustrated in Figure 2.



(a) Top view (b) Front view

Figure 2. Pile cap details

2.3 Soil used and preparation method

In this investigation, the sandy soil underwent a comprehensive process of cleaning and drying before undergoing testing. The characteristics of the sandy soils examined are detailed in Table 1. The soil was meticulously placed within the laminar soil box utilizing a raining technique method to attain a relative density of 70% as illustrated in Figure 3.

Table 1. Physical and mechanical properties of the soil used

Soil Property	Value	Standard of Test
Relative Density, Dr (%)	70	-
Max. Unit Weight, γmax (kN/m^3)	18.47	ASTM D 4253 (2000)
Min. Unit Weight, γmin (kN/m^3)	15.96	ASTM D 4254 (2000)
Dry Unit Weight, γd (kN/m^3)	17.63	-
Water Content, Wc (%)	19	ASTM D2216 (2010)
Specific Gravity, Gs	2.64	ASTM D854 (2014)
Sand, %	98.4	-
Fine Content, %	1.6	ASTM D422 (2007)
Effective Size, D10 (mm)	0.16	
Mean Size, D30 (mm)	0.26	
Mean Size, D60 (mm)	0.42	
Coefficient of Uniformity, Cu	2.63	
Coefficient of Curvature, Cc	1.01	
Soil Colour	Yellow (Pale yellow)	ASTM D2487 (2010)
Particle Shape	Sub-rounded to sub-angular with low sphericity to high sphericity	
Soil Colour	Yellow (Pale yellow)	
Friction Angle, Ø	39°	ASTM D4767 (2011)
Cohesion, c (kN/m^2)	0	

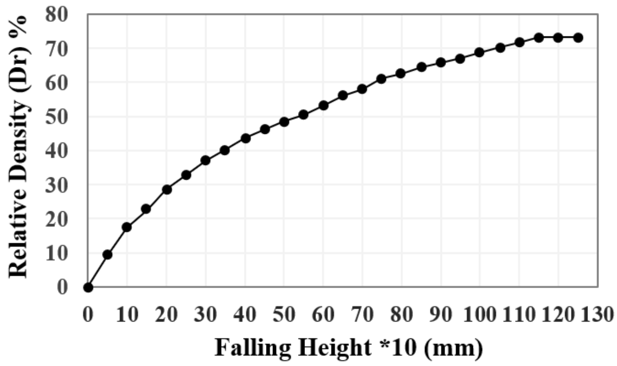


Figure 3. The correlation between relative density and fall height

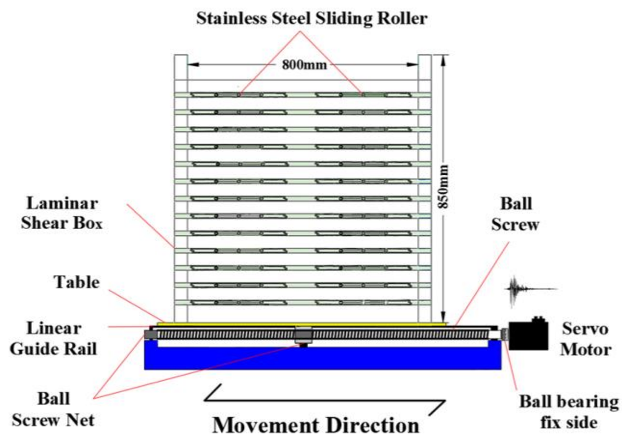
2.4 Laminar soil box description

The laminar soil box (container) has been designed to simulate the propagation of seismic waves through a particular soil layer. The square box of (800 mm×800 mm×850 mm) dimensions consists of 16 aluminum frames, each featuring a cross-section measuring 40×40 mm. These frames are securely joined through bolted connections, as depicted in Figure 4(a). Importantly, the design of these frames enables unidirectional movement while also being constructed to reduce boundary effects by facilitating relative motion among neighboring frames. The container's support structure is composed of 32 ball bearing slides, each featuring a thickness of 12 mm. This design enables a sliding movement of up to ±150 mm between the individual slides, providing significant flexibility and ease of motion.

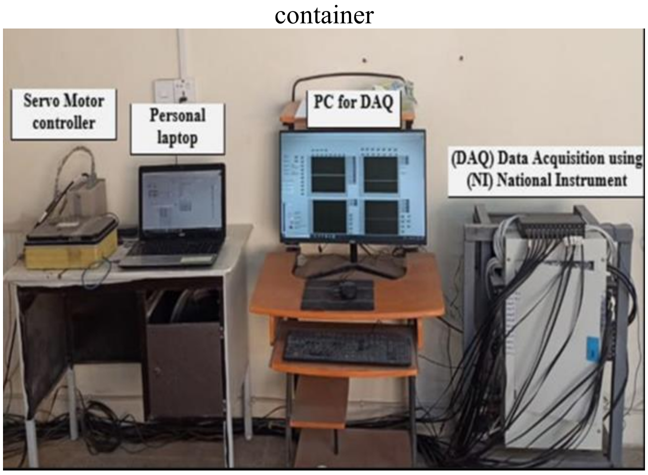
2.5 Shaking table device

The experimental study was carried out utilizing a single-degree-of-freedom shaking table device attached to a data acquisition system (type sampling frequency), located at the University of Diyala [12]. This apparatus was specifically designed to replicate the Kobe earthquakes and is powered by a servo motor capable of achieving a maximum acceleration of 1.8 g while supporting a payload of 10 kN, and reaching 2g when unloaded. The device can generate input wave frequencies ranging from 0.1 Hz to 50 Hz. Figure 4 presents a description of the shaking table model used in this study. Table 2 and Figure 5 present the data and temporal history of the Kobe Earthquake, respectively, that were input into the shaking table device.

To measure both vertical and lateral displacements at the pile cap, three Linear Variable Differential Transformers (LVDTs) sensors were employed, as depicted in Figure 6. WVDT1 (denoted as L1) was tasked with capturing the lateral displacement at the pile cap, while LVDT2 (L2) recorded the vertical displacements on the side of the pile cap directly subjected to seismic loads. Additionally, LVDT3 (L3) was utilized to monitor the vertical displacements on the opposite side of the pile cap. Figure 6 presents a detailed diagram illustrating the testing system.



(a) Details of the shaking table model and the laminar soil container



(b) Details of the digital data acquisition system

Figure 4. Description of the shaking table model

Table 2. Kobe earthquake data

Kobe Earthquake	Details
Geographical Area	Japan
Recorded Date (in UTC)	1995-01-16, (20:46:52)
Magnitude (Mw)	6.9
Duration of Tremors (seconds)	48
Principal Acceleration Axis	North-South
Peak Ground Acceleration (g)	0.82
Depth of Epicenter (km)	7.9
Seismological Station ID	KIMA
Distance to Epicenter (km)	1
Mercalli Intensity Scale Reading	VII – Intensely Strong
Source of Data	www.strongmotion.org

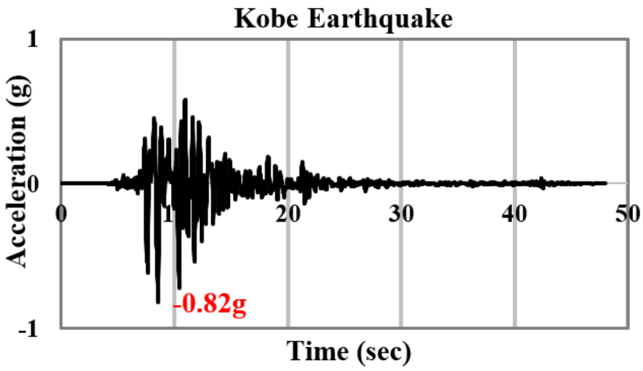


Figure 5. Time history of the Kobe earthquake that was inserted into the shaking table

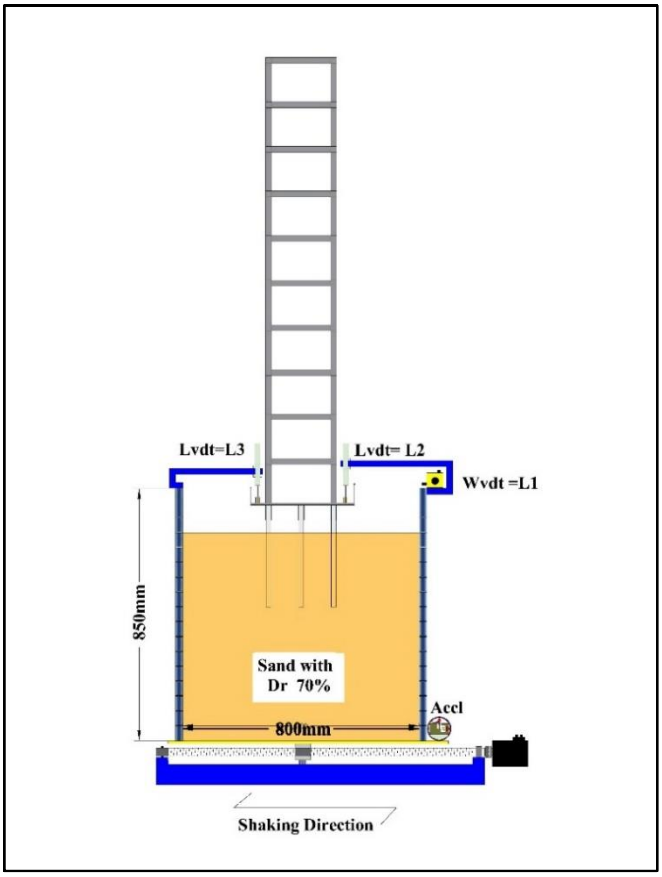


Figure 6. Test system diagram

3. RESULT AND DISCUSSION

In this part, the vertical and lateral displacement at the pile cap for the four multi-story buildings (4-story, 6-story, 8-story, and 10-story) has been represented.

3.1 Vertical displacement at the pile cap

Figure 7 demonstrates the relation between the vertical displacement measured at both sides of the pile cap and the time history for the (4-story, 6-story, 8-story, and 10-story) buildings.

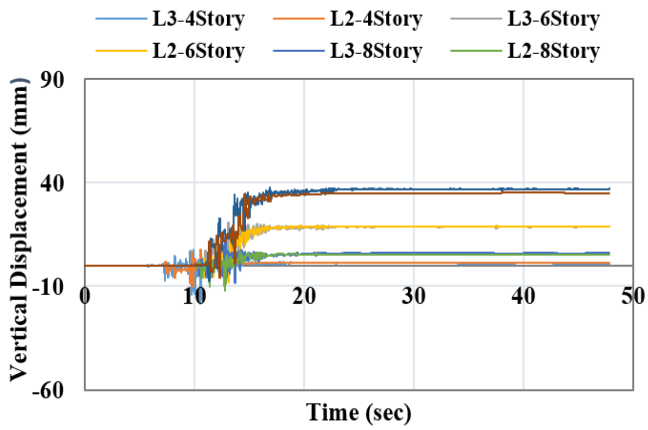


Figure 7. Multi-story vertical displacement of the pile cap Vs. time history for the multi-story buildings (4-story, 6-story, 8-story, and 10-story)

This figure indicates that taller buildings, specifically those with eight and ten stories, undergo considerably greater vertical displacements, with measurements reaching as much as 38 mm. In contrast, other buildings, consisting of four and six stories, demonstrate negligible deformation. In the early stages of a Kobe earthquake, there is a pronounced increase in vertical displacement, especially in taller buildings, as their increased height leads to a greater amplification of seismic forces. This vertical displacement tends to stabilize approximately at the 20-second mark for all types of buildings, suggesting that the system attains a state of equilibrium once the dynamic effects have subsided. In taller buildings, the initial fluctuations are more noticeable due to their increased receptivity to seismic vibrations as well as the internal stress's redistribution. In contrast, shorter buildings exhibit lower and more stable displacements, showcasing a superior ability to withstand deformation caused by earthquakes.

Figure 8 displays the relationship between the value of vertical displacements (residual and peak) recorded at both sides of the pile cap with the number of stories. It can be inferred that the vertical displacement for the four-story building demonstrates a nearly symmetrical pattern, with only a minor difference between the two sides of the pile cap. The peak vertical displacements for the pile cap are noted to be L3 = 7.5 mm and L4 = 7.9 mm, indicating that the peak displacement at the cap side (L4) is 5.3% higher than the peak displacement on the opposite side (L3). Whereas the residual vertical displacements are recorded as L3 = 1.12 mm and L4 = 1.4 mm, yielding a ratio of L4/L3 of approximately 125%. This ratio shows that L4 is 25% higher than L3, indicating slightly more vertical displacement on the side that is directly exposed to seismic loads. Furthermore, these measurements indicate that the relatively low height of the building restricts the redistribution of seismic forces, resulting in a nearly uniform deformation across both pile cap sides. In addition, for the six-story building, the peak vertical displacements recorded at L3 = 20.1 mm increases to 20.9 mm at L4, which yields a ratio of rising approximately equal to 4%, yet the overall displacement remains relatively equitable, indicating that a moderate structural height induces only slight asymmetry in reaction to seismic forces. In the case of residual vertical displacement, the values were 18.64 mm at L3 and 19.1 mm at L4, indicating a more balanced displacement, with only 2.5% higher displacement on L4. For the 8-story building, asymmetry becomes more noticeable, with peak displacement values of 13.9 at L3 and 8.7 at L4, indicating significantly higher displacement on L3 (60%) than L4 during the seismic events. In case of residual displacement recorded at L3 equal 6.14mm decrease to 5.3mm at L4 with a ratio of reduction reaching 16%, showing larger deformation on the pile cap opposite side, probably due to effects of load distribution. The 10-story building exhibits significant vertical displacement, with an equally L4/L3 ratio for peak and residual displacement reaching 6%, indicating noticeable settlement and asymmetry with L3 slightly higher than L4. According to these data, the vertical displacements (both peak and residual) in (4-story and 6-story) buildings, recorded by L4, are generally bigger than L3. This variation can be attributed to the direct exposure to seismic forces. Conversely, in (8-story and 10-story) buildings, the values recorded by L3 surpass those of L4. This phenomenon may be attributed to the redistribution of forces and the asymmetrical responses encountered during soil-structure interaction. An alternative explanation for this result is that energy dissipation mechanisms, including base rocking or sliding, may result in the opposite side (L3) absorbing a greater amount of deformation energy, subsequently leading to increased vertical displacement. These results seem to be consistent with those of the findings [13-15].

Another important finding is that the vertical displacement (both peak and residual) upsurges significantly as the number increases. This trend indicates that taller buildings experience greater loads and heightened seismic responses. For example, from 4 to 6 stories, the L4-peak displacement displays a 154% surge, rising from 7.9 mm to 20.1mm. However, from 6 to 8 stories, a noticeable irregular trend is observed with a 140% reduction in L4-peak displacement, dropping from 20.9 mm to 8.7 mm. A possible explanation for this might be that the 8-story building presumably possesses a natural period of vibration that does not align with the predominant frequencies of the seismic excitation. Consequently, this phenomenon diminishes the dynamic forces' amplitude conveyed to the foundation system, leading to lower vertical displacements, and this agrees with studies [16-18]. Finally, from 8 to 10 stories, the vertical displacement experiences an increase of 306%, escalating from 8.7 mm to 35.3 mm. In summary, the overall trend demonstrates a significant rise in vertical displacement correlated with the increasing number of stories, with the exception of the irregularity noted at the 8-story building. The observed increase in vertical displacement with increasing number of stories would be attributed to that higher buildings possess extended natural periods, which can resonate or align with seismic frequencies. Thereby, enhance the inertial forces that are conveyed to the pile foundation. This phenomenon of resonance induces heightened deformation and stress in the underlying soil, which subsequently leads to an increase in vertical displacement of the pile cap. Furthermore, taller buildings experience higher overturning moments through seismic excitations, resulting in uneven load distribution that further exacerbates the issue of vertical displacement. While shorter buildings experience less vertical displacement during seismic events. This is attributed to a decrease in the dynamic amplification of seismic forces and a lower center of gravity. This effect leads to a reduction in overturning moments and fosters a more even distribution of stress across the building. These results are in agreement with those obtained by studies [19-21].

Another relevant result is the difference between peak and residual vertical displacement (in both L3 and L4). Peak displacements are consistently greater than residual displacements, signifying temporary deformation occurring during seismic excitations. The reduction in percentage from peak to residual displacements is notably more significant in shorter buildings than in taller buildings; for instance, the decline rate in the 4-story building varied between 560% at level L3 to 464% at L4, whereas it was only 1% for the 10-story building.

Several factors could explain this observation. Firstly, the peak vertical displacement observed is generally associated with the intensity and characteristics of the peak ground motion of the earthquake and the building's exposure to fleeting dynamic forces during seismic events that lead to momentary deformations, causing peak vertical displacements. These peak values signify the maximum response of the building-foundation system to seismic loading. Secondly relation between the height of the building and the mechanisms of energy dissipation, the differences between peak and residual displacements emerge from the dynamic effects affected by the height of the buildings. Shorter buildings experience bigger differences because of lower flexibility and fewer mechanisms of energy dissipation, producing heightened transient responses when subjected to seismic forces. Taller buildings show lower differences due to their ratio of height-to-mass and raised flexibility, allowing for better distribution and dissipation of dynamic energy, stabilizing displacements more efficaciously after peak displacement. These findings are in agreement with those obtained by studies [22-24].

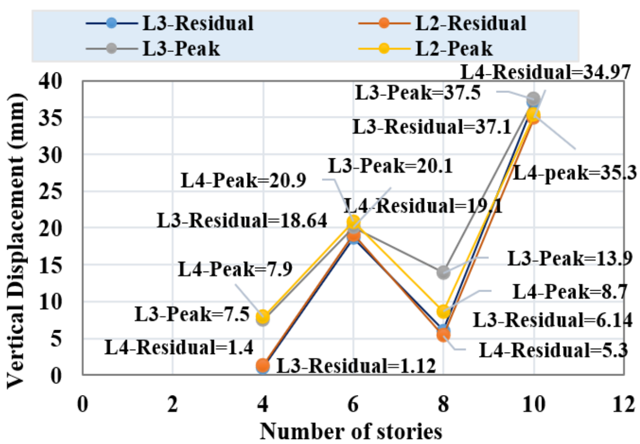


Figure 8. Vertical displacement Vs. number of stories

3.2 Lateral displacement at the pile cap

The peak and residual value of lateral displacement recorded at the pile cap of multi-story buildings have been illustrated in Figure 9. The trends presented in this figure reveal that the 8-story building exhibits the most significant peak lateral displacement, approximately 19mm, suggesting it resonates more intensely with the seismic activity. The 10-story building demonstrates a peak displacement of 15.6mm, which is marginally lower than that of the 8-story building. In contrast, the 6-story building displays a moderate level of peak lateral displacement, approximately 13.5mm, while the 4-story building records the least amount of peak displacement (11.7mm). Subsequent to the peak, the oscillations gradually diminish with time, ultimately stabilizing around a consistent baseline for all buildings. The 6-story structure achieves stability at a faster rate, whereas the 8-story and 10-story buildings require a more extended period to reach equilibrium. These findings suggest that the peak lateral displacement measured at the pile cap of a 6-story building is 15% greater than that of the 4-story building, while the lateral displacement of the 8-story building is 60% greater than that of the 4-story building. This represents the highest recorded displacement, indicating considerable amplification. Additionally, the lateral displacement of the 10-story structure is 33% greater than that of the 4-story building. Although the 10-story building is taller, it exhibits less displacement compared to the 8-story building, as presented in Figure 10. A possible explanation for this might be, the same total mass across differing story numbers indicates that longer buildings, such as those with 8-story and 10-story, would exhibit a lower mass for each story in comparison to lower buildings, like those with 4 or 6 stories. This variation in mass distribution consequently influences the distribution of inertia forces experienced during seismic events. Taller buildings with smaller lower-story masses tend to experience reduced base shears for each floor; however, they may exhibit greater overall displacements. This phenomenon is attributed to their increased flexibility and reduced natural frequencies. This observation aligns with the previously noted trend, which ranks maximum lateral displacement from highest to lowest as follows: 8-story, 10-story, 6-story, and 4-story. On the other hand, shorter buildings exhibit a greater mass per floor, resulting in a stiffer response to dynamic forces. This increased stiffness not only reduces maximum lateral displacement but also amplifies the inertial forces that are directed to the foundation. These results seem to be consistent with studies [25-27].

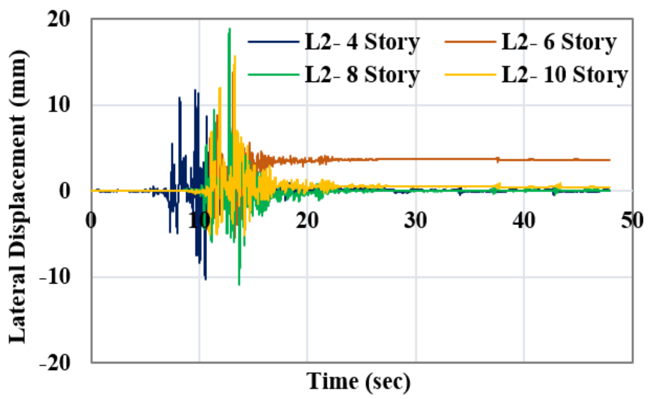


Figure 9. The lateral displacement of the pile cap Vs time history for the multi-story buildings (4-story, 6-story, 8-story, and 10-story)

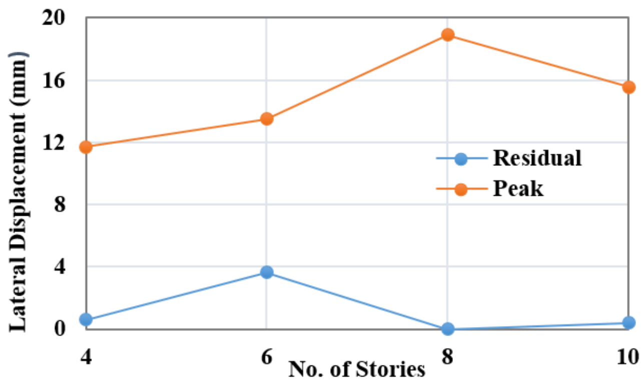


Figure 10. Lateral displacement Vs. number of stories

If we now turn to the residual lateral displacement recorded at the pile cap, the 6-story building displays the utmost residual lateral displacement once the shaking stops, measuring approximately 3.6 mm. This is succeeded by the 4-story building, which records residual displacement of (0.56mm), whereas the 10-story and 8-story buildings display considerably lower residual displacements, ranging from approximately (0.003 to 0.45) mm. This means that the residual lateral displacement observed in the 6-story building is 640% greater compared to that of the 4-story building. In contrast, the residual lateral displacement in the 8-story building is minimal, estimated at around 0.55% of the displacement recorded for the 4-story building, suggesting that it incurs negligible movement. Meanwhile, the 10-story building exhibits a reduction in displacement, registering at 73% of the displacement measured in the 4-story building. It is possible that these results are due to that the equal mass condition does not alter the observed residual lateral displacement trend (6-story > 4-story > 10-story > 8-story), as this performance is primarily determined by factors such as energy dissipation, structural flexibility, and soil-pile interaction rather than mass alone. In other words, residual displacements are influenced more significantly by the lateral stiffness and damping characteristics of the soil-pile-structure system, rather than the distribution of mass within the system. Taller buildings may display greater resonance due to increased flexibility, while shorter structures could endure higher forces concentrated at the pile cap because of their comparatively elevated story stiffness. These results are in agreement with those obtained by studies [28-30]. A non-linear relationship exists between the number of stories and the maximum (peak) as well as the residual lateral displacements of the pile cap. Furthermore, the values of residual lateral displacement may not scale directly with the maximum lateral displacement values due to the mechanism of energy dissipation. Taller buildings with higher damping may show a greater gap between residual and peak lateral displacements, as they dissipate more energy dynamically. This phenomenon is attributable to their enhanced capability for dynamic energy dissipation. In contrast, medium-height buildings, which are more susceptible to resonance effects, often exhibit ratios of peak to final movements that are more closely aligned. This is a result of the continued amplification of displacements experienced in such structures. The residual lateral displacement observed in shorter buildings tends to approximate their maximum lateral displacement more closely, as these structures experience reduced inelastic deformation and soil-pile displacement attributable to their comparatively lower peak displacements. For instance, a four-story building shows a residual lateral displacement of 4.8% when compared to its peak displacement. This ratio rises to 27% for a six-story building. In an eight-story facility, however, the residual lateral displacement is minimal relative to the peak, recorded at merely 0.02%. In contrast, a ten-story building reflects a higher residual displacement at 2.6%. This variation indicates that the residual lateral displacements are significantly influenced by factors such as the flexibility of the structure, its stiffness, and the interaction between the soil and pile, rather than being solely determined by the magnitude of the peak displacements. This finding was also reported by studies [31, 32].

4. CONCLUSION

This research was conducted to examine the influence of the number of stories on the seismic response of pile group foundations installed in sandy soil, focusing on vertical and horizontal displacements, as well as the time period. The ensuing conclusions are derived from the analyses presented above:

1- The vertical displacements at the pile cap show a significant increase with more stories. As the number of stories increased from four to six, eight, and ten stories, the maximum displacement escalates by factors of 3, 1.85, and 5, respectively, relative to the four-story structure. Similarly, the residual displacement also experiences an increase by factors of 17, 5.5, and 33, respectively, compared to the four-story building.

2- The 8-story building exhibits a lesser increase in vertical displacement compared to the 6 and 10-story buildings.

3- In the four-story building, the peak and residual vertical displacements at L4 are higher than those noted at L3 by 14% and 25%, respectively, suggesting a marginally greater vertical displacement on the side exposed directly to seismic forces. Similarly, for the six-story building, the peak and residual vertical displacements at L4 surpass the readings at L3 by 14% and 25%, respectively.

4- The reduction in percentage from peak to residual vertical displacements is notably more significant in shorter buildings than in taller buildings; for instance, the decline rate in the 4-story building varied between 560% at L3 to 464% at L4, whereas it was only 1% for the 10-story building.

5- The 8-story building demonstrates the greatest lateral displacement, measuring 1.62 times that of the 4-story building. Conversely, the 10-story building exhibits reduced displacement, 1.33 times that of the 4-story building. The 6-story building shows a displacement that is 1.15 times greater than that of the 4-story building.

ACKNOWLEDGMENT

The authors are grateful for the financial support towards this research by the Civil Engineering Department, College of Engineering, Al Nahrain University. Postgraduate Research Grant (PGRG) No.: NU. G/2023/HIR/MOHE/ENG/39 (1294-10-2). Also, we would like to thank the University of Diyala for all the technical support.

REFERENCES

[1] Boulanger, R.W., Curras, C.J., Kutter, B.L., Wilson, D.W., Abghari, A. (1999). Seismic soil-pile-structure interaction experiments and analyses. Journal of Geotechnical and Geoenvironmental Engineering, 125(9): 750-759. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:9(750)

[2] Xu, C., Dou, P., Du, X., El Naggar, M.H., Miyajima, M., Chen, S. (2020). Seismic performance of pile group-structure system in liquefiable and non-liquefiable soil from large-scale shake table tests. Soil Dynamics and Earthquake Engineering, 138: 106299. https://doi.org/10.1016/j.soildyn.2020.106299

[3] Thapa, U.J., Karki, R. (2020). Soil-pile-structure interaction effects on high-rise building under seismic shaking. Journal of Innovations in Engineering Education, 2(1): 153-164. https://doi.org/10.3126/jiee.v2i1.36672

[4] Mohasseb, S., Ghazanfari, N., Rostami, M., Rostami, S. (2020). Effect of soil–pile–structure interaction on seismic design of tall and massive buildings through case studies. Transportation Infrastructure Geotechnology, 7: 13-45. https://doi.org/10.1007/s40515-019-00086-7

[5] Singh, H., Tiwary, A.K. (2022). Analysis and effect of piles on raft foundation for high-rise framed structure under seismic loading. Materials Today: Proceedings. https://doi.org/10.1016/j.matpr.2022.11.411

[6] Meena, D., Bansal, A., Bharathi, M. (2024). Seismic analysis of low rise and high rise building and its foundation design. Asian Journal of Civil Engineering, 25: 5215-5226. https://doi.org/10.1007/s42107-024-01108-7

[7] Wang, H., Zhang, R. (2021). Dynamic structure-soil-structure interaction of piled high-rise buildings under earthquake excitations I: Influence on dynamic response. Latin American Journal of Solids and Structures, 18(3). https://doi.org/10.1590/1679-78256223

[8] Khoshnoudian, F., Kiani, M. (2012). Modified consecutive modal pushover procedure for seismic investigation of one-way asymmetric-plan tall buildings. Earthquake Engineering and Engineering Vibration, 11(2): 221-232. https://doi.org/10.1007/s11803-012-0112-6

[9] Abbas, J.M., Hussain, Q.I. (2018). The effect of pile cross section on the lateral behavior of piles under combined loading. Journal of Engineering Science and Technology Review, 11(3): 174-179. https://doi.org/10.25103/jestr.113.24

[10] Aghamolaei, M., Azizkandi, A.S., Abolhasanpoor, A., Hashemi, S. (2024). Influence of soil–pile interface characteristics on the seismic response of single pile foundations: Shaking table testing and numerical simulation. Acta Geotechnica, 19: 417-436. https://doi.org/10.1007/s11440-023-01955-9

[11] El Hoseny, M., Ma, J., Dawoud, W., Forcellini, D. (2023). The role of soil structure interaction (SSI) on seismic response of tall buildings with variable embedded depths by experimental and numerical approaches. Soil Dynamics and Earthquake Engineering, 164: 107583. https://doi.org/10.1016/j.soildyn.2022.107583

[12] Noman, B.J., Albusoda, B.S. (2024). Impact of Vertical vibration on group piles during earthquake loading: Experimental findings. Civil Engineering Journal, 10: 174-208. https://doi.org/10.28991/CEJ-SP2024-010-010

[13] Hang, Y., Chen, X., Zhang, X., Ding, M., Wang, Y., Liu, Z. (2020). Nonlinear response of the pile group

foundation for lateral loads using pushover analysis. Earthquakes and Structures, 19(4): 273-286. https://doi.org/10.12989/EAS.2020.19.4.273
[14] Cheng, Z., Li, S., Wang, J. (2022). Controlled rocking pile foundation system with replaceable bar fuses for seismic resilience. Earthquake Engineering and Engineering Vibration, 21(3): 683-696. https://doi.org/10.1007/s11803-022-2110-7.
[15] Chakraborty, A., Bhattacharya, K., Sawant, V.A. (2025). Soil structure interaction effects on multistorey asymmetric building subjected to earthquake loading. Indian Geotechnical Journal, 55(1): 303-314. https://doi.org/10.1007/s40098-024-00938-1
[16] Abdel Raheem, S.E., Ahmed, M.M., Alazrak, T. (2014). Soil-structure interaction effects on seismic response of multi-story buildings on raft foundation. Journal of Engineering Sciences, 42(4): 905-930. https://doi.org/10.21608/jesaun.2014.111441
[17] Tehaseen, S.G., Kumar, J.C. (2017). Effect of change of storey drift and storey height in multi storey building with varying seismic zones. International Journal of Civil Engineering and Technology, 8(1): 583-590.
[18] Bapir, B., Abrahamczyk, L., Wichtmann, T., Prada-Sarmiento, L.F. (2023). Soil-structure interaction: A state-of-the-art review of modeling techniques and studies on seismic response of building structures. Frontiers in Built Environment, 9: 1120351. https://doi.org/10.3389/fbuil.2023.1120351
[19] Krishna, A.M., Teja, A., Bhattacharya, S., Ghosh, B. (2012). Seismic design of pile foundations for different ground conditions. In 15th World Conference on Earthquake Engineering, Lisbon, Portugal. https://doi.org/10.13140/2.1.3959.9688
[20] Bildik S, Tanrıöver H. (2023). Numerical investigation of the pile–soil interaction problem under dynamic loads. Applied Sciences, 13(21): 11653. https://doi.org/10.3390/app132111653
[21] Beneldjouzi, M., Hadid, M., Laouami, N., Remki, M. (2023). Analysis of coupled site and soil–structure interaction effects on the seismic response of multistory buildings according to EC-8 and ASCE7-16 code provisions. International Journal of Civil Engineering, 21: 1509-1536. https://doi.org/10.1007/s40999-023-00840-6
[22] Hu, D.-Z., Zhang, X.-X., Li, G.-Q., Sun, F.-F., Jin, H.-J. (2021). Application of energy dissipation technology in high-rise buildings. International Journal of High-Rise Buildings, 10(2): 137-147. https://doi.org/10.21022/IJHRB.2021.10.2.137
[23] Bariker P, Kolathayar S. (2022). Dynamic soil structure interaction of a high-rise building resting over a finned pile mat. Infrastructures, 7(10): 142. https://doi.org/10.3390/infrastructures7100142
[24] Jasim, F.A., Jasim, N.A., Al-Hussein, A.A. (2024). Assessment of soil-structure interaction effects on seismic behavior of isolator and mass damper equipped buildings. Mathematical Modelling of Engineering Problems,11(2):325-339. https://doi.org/10.18280/mmep.110205
[25] Dou, P., Xu, C., Du, X., El Naggar, M.H., Su, C. (2021). Experimental study on seismic instability of pile-supported structure considering different ground conditions. Journal of Geotechnical and Geoenvironmental Engineering, 147(11): 04021127. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002632.
[26] Sagdiev, K.S., Yuvmitov, A.S., Egamberdiev, B.O., Toshpulatov, S.U., Toshmatov, E.S. (2023). Simulation of the structure of a multistory building with seismic isolation and the testing technique on a laboratory bench under dynamic (seismic) impacts. E3S Web of Conferences, 402: 07024. https://doi.org/10.1051/e3sconf/202340207024
[27] Gajbhiye, S., Khedikar, A., Abhayankar, S. (2025). Dynamic analysis of a high-rise structure on a deep pile foundation using advanced computational tools: A review. https://doi.org/10.2139/ssrn.5224683
[28] Visuvasam, J., Chandrasekaran, S.S. (2019). Effect of soil–pile–structure interaction on seismic behaviour of RC building frames. Innovative Infrastructure Solutions, 4: 45. https://doi.org/10.1007/s41062-019-0233-0
[29] Rostami, R., Mickovski, S.B., Hytiris, N., Bhattacharya, S. (2020). The dynamic behaviour of pile foundations in seismically liquefiable soils: Failure mechanisms, analysis, re-qualification. IntechOpen. https://doi.org/10.5772/intechopen.94936
[30] Choudhury, D., Maity, A. (2021). Dynamic analysis of pile groups in dense sands under multi-story structures. Geotechnical and Geological Engineering, 39(3): 1057-1075. https://doi.org/10.1007/s11041-021-00553-x
[31] Qu, Z.-M., Sa, S. (2008). Dynamic interaction of soil-pile-structure under seismic action. In the 14th World Conference on Earthquake Engineering, Beijing, China. https://api.semanticscholar.org/CorpusID:18034309.
[32] Thavaraj, T., Finn, L., Wu, G. (2010). Seismic response analysis of pile foundations. Geotechnical and Geological Engineering, 28: 275-286. https://doi.org/10.1007/s10706-010-9311-y

NOMENCLATURE

WVDT	Wire LVDT
L	Embedded length of pile
D	Pile diameter
S	Spacing between piles
Dr	Relative Density, %
γ_{max}	Max. Unit Weight, kN/m^3
γ_{min}	Min. Unit Weight, kN/m^3
γ_d	Dry Unit Weight, kN/m^3
*W*c	Water Content, %
D_{10}	Effective Size, mm
D_{30}	Mean Size, mm
D_{60}	Mean Size, mm
Cu	Coefficient of Uniformity
Cc	Coefficient of Curvature

Greek symbols

Ø	Friction Angle
c	Cohesion, kN/m^2