Research on Engineering Structures & Materials
www.jresm.org
Research Group

Research Article

Performance of the pile group foundation supporting multi-story building under repeated earthquakes

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

[1]*Department of Civil Engineering, Al-Nahrain University, Baghdad, Iraq*
[2]*Department of Civil Engineering, Diyala University, Baqubah, Iraq*

Article Info

Article History:

Received 22 Oct 2025
Accepted 17 Nov 2025

Keywords:

Pile groups;
Sandy soil;
Small scale model;
Multi-story steel frame;
Shaking table device;
Kobe earthquake;
Multiple earthquakes

Abstract

Most studies on the seismic behavior of group piles have focused on the pile's behavior under a single earthquake. However, low to moderate seismicity zones often experience multiple successive shocks. In this study, the seismic behavior of pile groups supporting a 10-story building was investigated through a series of experiments under the influence of the Kobe earthquake for three consecutive times with a time interval of 15 min. The tests conducted first involved designing and constructing a 1:20 scale model of a 10-story steel building supported by a 3x3 aluminum pile group foundation with L/D of 16. The tests were conducted on dense dry sand with 70% relative density. The results include the performance of piles and structures in terms of vertical and lateral displacements. The findings indicated that the tilting angle of the pile cap diminished gradually with the application of each subsequent earthquake, decreasing by a factor of three following the second earthquake (0.15°) and by a factor of 4.7 after the third shock (0.08°), in comparison to the initial angle (0.46°). Additionally, the residual lateral displacements observed in the 10-story building during successive earthquakes reflected a continuous decline, with the rates of reduction during the second and third earthquakes being 2.5 and 9.4 times, respectively, in relation to the first earthquake. Conversely, the residual lateral displacement measured at the pile cap exhibited a steady increase over the course of the seismic events, recording increases of 10.5 and 20 times during the second and third earthquakes, respectively, with comparison to the first earthquake.

1. Introduction

Earthquakes consider once of the utmost devastating natural adversities, posing a serious threat to life and property. Despite the efforts made in designing earthquake-resistant structures, it is still challenging to cope with the uncertainties regarding the quality of design against seismic loading. Concerns start to rise about the performance of multi-story and high-rise structures, mainly caused by the increase of post-constructed changes and unwanted stresses on structural bases and foundations. Group piles, widely used in multi-story constructions to reduce settlement and increase capacity, are of utmost importance.

In past few years, much investigate has studied the seismic behavior of piles in the case of earthquakes. These studies have served to raise the level of understanding of seismic piles in many aspects. However, so far, little research has been carried out to study the effects caused by multiple or successive earthquakes; this is because the information on the real actions in the structures affected by these conditions is very limited. Previous research such as that performed by [1] examines the impact of earthquake sequences on the seismic behavior of structures, taking into account soil-foundation-structure interaction (SFSI), by shake table experiments. The findings

*Corresponding author: omar.civ23@ced.nahrainuniv.edu.iq
[a]orcid.org/0000-0003-0148-0918; [b]orcid.org/0000-0002-3157-0351; [c]orcid.org/0000-0002-0857-9788
DOI: http://dx.doi.org/10.17515/resm2025-1279ic1022rs

indicate that the mainshock resulted in more significant soil settlement and elevated acceleration relative to the aftershocks, attributable to the densification of the sand following the initial seismic event. Study conducted by [2] using shaking table tests, the soil and foundation interaction significantly affected shaping structural responses under repeating seismic events. The laboratory model reflected soil conditions in shaking table simulations using real ground motion records from the Wenchuan earthquake, capturing site effects like seismic wave amplification. Results showed that as structural damage accumulated, the model's dynamic properties became increasingly sensitive to soil–foundation interaction, revealing a natural frequency reduction of up to 52% across main vibration modes. This indicated degradation of the RC frame's internal stiffness and increased soil flexibility impact. At high seismic intensities, the foundation–soil system failed to restrain large displacements, leading to inter-story drifts as high as 1/43 and posing near-collapse risks. Consequently, the study underscores that the soil–foundation–structure system's flexibility must be factored into seismic performance evaluations, as soil effects amplify vulnerabilities during the successive event

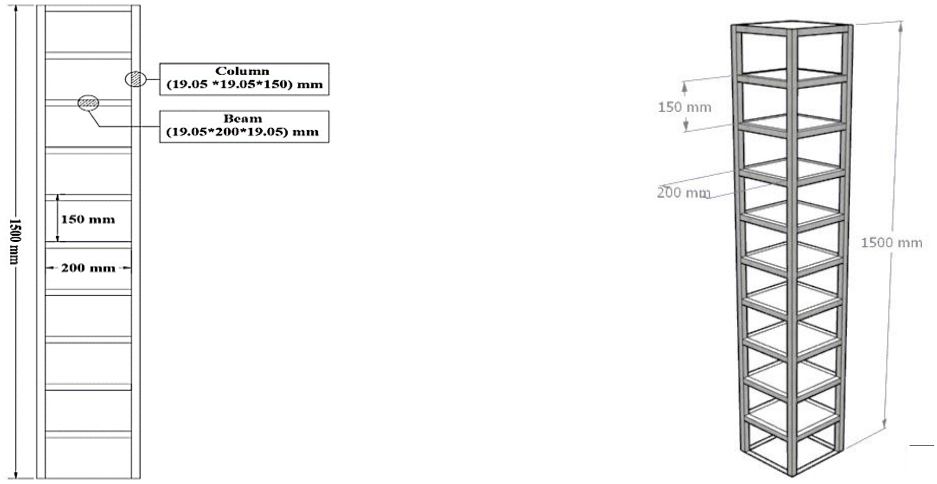
A numerical analysis to explore the nonlinear interactions between soil, piles, and structures for pile foundations subjected to multiple seismic load scenarios in both soil types liquefiable and non-liquefiable [3]. The investigation examined various parameters, including the responses of piles to different seismic intensities and soil conditions. Findings indicated that the performance of piles is notably affected by soil liquefaction, resulting in heightened lateral displacements and bending moments. Sahare et al. [4] examined how sloping ground conditions and following seismic occurrences affect the kinematic behavior of pile groups in soils prone to liquefaction. The research attentive on several parameters such as the spacing between piles, ground slope angles, and the influences of liquefaction during successive shaking events. The results indicated that further seismic activities additional intensify the resulting damage. The study steered by [5] intended to assess the behavior of hybrid foundations in assuaging the effects of liquefaction under strong sequential earthquakes consuming both numerical and experimental modeling methods. The results showed that hybrid foundations pointedly diminished lateral displacement and settlement caused by consecutive seismic action. [6] studied soil–pile–structure interaction (SPSI) and its impact on seismic vulnerability of pile-supported buildings during exposed to successive earthquakes through created nonlinear numerical models. The findings indicated that the sequence earthquakes further elevated the likelihood of structural damage compared to single mainshocks, with results showing significant shifts in fragility curves. The research conducted by [7] examines the processes of liquefaction and re-liquefaction in sand, as well as the response of pile groups to repeated shaking. The study employs centrifuge modeling to analyze factors such as excess pore pressure, soil settlement, lateral displacements, and bending moments in pile group foundations during successive seismic events. The results indicate that each instance of shaking diminishes the potential for re-liquefaction by enhancing soil density and stiffness, which in turn reduces excess pore pressures. Nonetheless, the existence of pile groups has the potential to modify this behavior by augmenting bending moments and lateral displacements as a result of the interactions occurring between the soil and the structures. [8] investigate the response of vertical pile foundations when subjected to a series of seismic activities, including the primary shock and subsequent aftershocks, by simulating the kinematic interaction, which refers to the relative movement between the soil and the pile during repeated seismic inputs. The findings reveal that relative displacements between the soil and foundation, bending moments in the piles, and inertial effects manifest variably across successive seismic events.

Therefore, this research seeks to examine the effect of three consecutive earthquakes on the seismic behavior of group pile foundations embedded in sandy soil. The unique aspect of this investigate is presenting the results of a practical study included test system consist of group piles foundation embedded in sandy soil and supporting 10-story building, while most previous researches approach solely one aspect (foundation or structure).

2. Experimental Setup and Testing

2.1 Ten-Story Building

To carry out the present investigation, it is necessary to first design and build a small-scale multi-story structure. A model consisting of 10 stories was developed based on the design proposed by [9]. Each story was structured as a single bay frame with an orientation in both directions, facilitating an accurate depiction of slender structures. The prototype's original span width and story height were established at 4 meters and 3 meters, respectively. As a result, the dimensions of the laboratory model building (length, width, and height) were proportionately reduced using a 1:20 scale factor. The beams and columns were crafted from square steel hollow sections measuring (19.05×200×19.05) mm and (19.05×19.05×150) mm, with a thickness of 1.5 mm. Steel plates, each with a 6mm thickness and dimensions of (200×200) mm, were utilized as panels for the building model. The structure was designed to maintain uniform mass across its stories. (Fig. 1), depicts the 10-story building employed in this investigation.

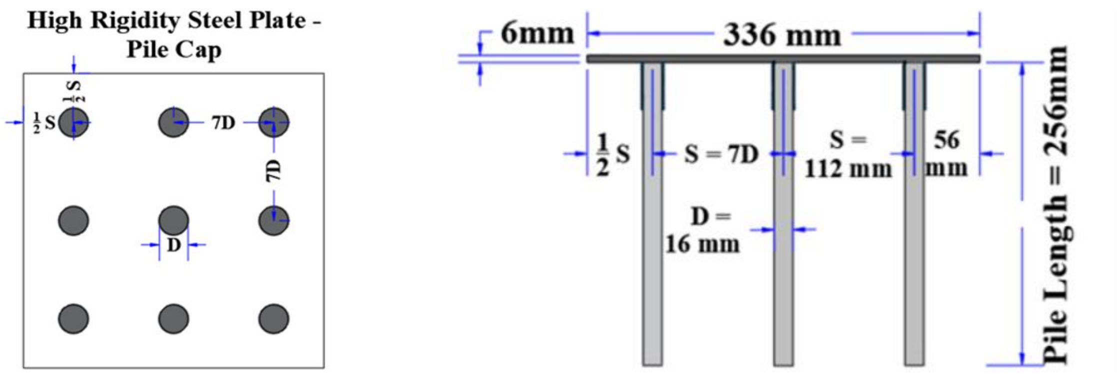


(a) (b)

Fig. 1. Ten-story steel structure details (a- front view b- 3d view)

2.2 Pile Group Description

In the current study, the piles utilized are fabricated from aluminum pipe tubes, a material widely recognized for its suitability in experimental assessments in similar investigations, as referenced by [10,11]. These piles comprised of closed-end aluminum tubes with circular cross sections, featuring an external diameter (D) of 16mm and a wall thickness of 1.5 mm. The embedding length to the diameter ratio is specified as L/D = 16. The configuration of the pile group is arranged in a 3x3 formation, with a spacing of 7D between individual piles, that conforms to the standards established by [12]. A high-strength steel plate is employed as the piles cap in this investigation, as illustrated in (Fig. 2).



(a) (b)

Fig. 2. Pile cap details: a-top view and b- front view

2.3 Laminar Soil Container

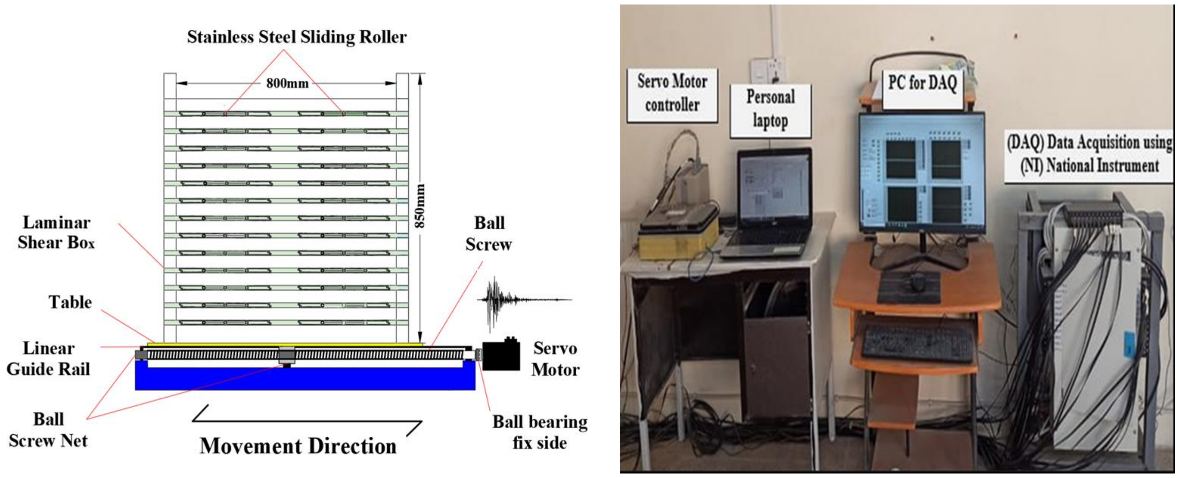
(Fig. 3) illustrates the aluminum laminar soil container, which possesses a cross-sectional dimension of (800 x 800) mm and a height of (850) mm. [13] suggested that to reduce wall side friction, the container's height-to-diameter ratio should be one or lower. As a result, the container height-to-width ratio is considered appropriate. The container is filled with sandy soil of 70% Relative Density (Dr) to depth of 750 mm, divided into five layers, each with a height of 150 mm. The properties of the soil utilized in this research are outlined in Table 1.

Table 1. Physical and mechanical properties of soil used

Soil Property	Value	Standard of Test
Relative Density, Dr %	70	-
Max. Unit Weight, γ_{max} [kN/m^3]	18.47	ASTM D 4253 (2000)
Min. Unit Weight, m_{int} [kN/m^3]	15.96	ASTM D 4254 (2000)
Dry Unit Weight, γ_d [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	-
Effective Size, D_{10} [mm]	0.16	
Mean Size, D_{30} [mm]	0.26	
Mean Size, D_{60} [mm]	0.42	
Coefficient of Uniformity, C_u	2.63	ASTM D422 (2007)
Coefficient of Curvature, C_c	1.01	
Soil Classification (USCS)[1]	(SP), Poorly-graded sand	ASTM D2487 (2010)
Particle Shape	Sub-rounded to sub-angular with low sphericity to high sphericity	-
Soil Color	Yellow (Pale yellow)	-
Friction Angle, Ø	39°	ASTM D4767 (2011)
Cohesion, c [kN/m^2]	0	

2.4 Laminar Soil Container

The experimental study was conducted using a single-degree-of-freedom shaking table device situated at the University of Diyala [14]. This apparatus has been engineered to simulate the conditions of the Kobe earthquakes, and operated by a servo motor that can achieve a maximum acceleration of 1.8 g and accommodating 10 kN payload capacity, and it can reach up to 2g when unloaded. The device is capable of producing input wave frequencies that range from 0.1 Hz to 50 Hz. Fig. 3 shown the details of shaking table model and essential components.



(a) (b)

Fig. 3. Description of shaking table model [14]: a) Details of shaking table model and laminar soil container and b) Details of digital data acquisition system

To assess both vertical and lateral displacements at the piles cap, four Linear Variable Differential Transformers (LVDTs) were utilized, as shown in (Fig. 4). LVDT1 (referred to as L1) employed to measuring the lateral displacement at the top side of the 10-strory building and WVDT2 (L2) employed to measuring the lateral displacement at the piles cap. While LVDT3 (L3) and LVDT4 (L4) used to measuring the vertical displacements at the piles cap side that directly subjected to seismic load and the opposite side, respectively. A comprehensive diagram of the testing system is provided in (Fig. 4). The peak ground acceleration and tremors duration for the Kobe earthquake model inputted was (0.82 g) and (48 sec) respectively [15].

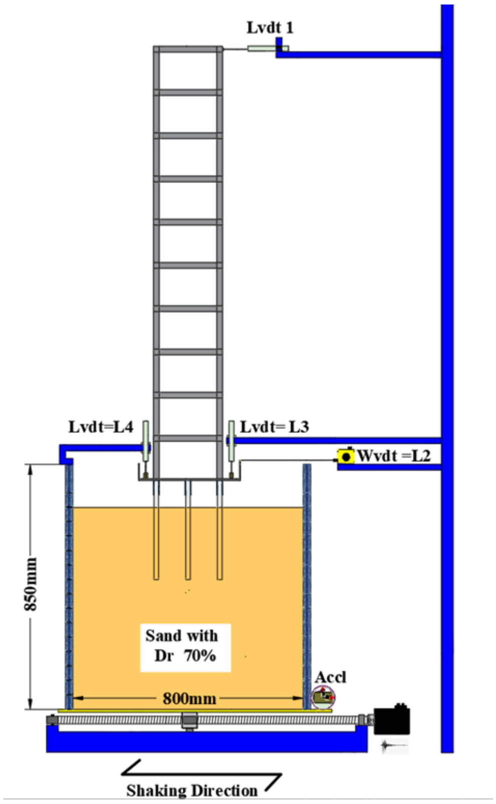


Fig. 4. Test system diagram

3. Result and Discussion

In this part, the vertical and lateral displacement at the pile cap as well as the acceleration in four different locations has been represented and analyzed. The Kobe earthquake was applied on the test model three times in succession with a 15-minute interval between each successive earthquake to give the soil stability after the applied earthquake and before applied the next earthquake (i.e., re-applying the earthquake to the test model). The principal aim of this interval was to permit the soil fabric stabilization via rearrangement of particle and densification subsequent to the first shock, thus ensuring a consistent and quantifiable initial condition for the ensuing event. This approach mitigates the risk of conflating the cumulative effects of progressive fabric alterations with the specific response to each individual shock.

3.1 Vertical Displacement

Fig. 5 demonstrated the relation between the vertical displacement and the time history at both sides of piles cap for the 10-story building during exposing to three consecutive shocks. It can be seen that the waveforms recorded at both sides of pile caps across the three successive shocks have approximately the same trend and show no significant vertical displacement roughly until 7 seconds, indicating that the earthquake impact did not directly affect the piles cap during this initial phase. This stable interval presumably signifies the period prior to the interaction of seismic waves with the foundation piles, wherein considerable forces are exerted. After this point, a noticeable change in vertical displacements which recorded at the pile cap sides were observed in between second ten to second fifteen for the three consecutive shocks, that can be attributed to the increasing intensity of the seismic activity simulated in the laboratory environment. This period is likely aligned with the peak shaking, which exerted maximum stress on the piles cap, resulting in rapid variations (i.e., rotation) in vertical displacement values. This observation indicates that the earthquake's intensity was sufficient to exceed the initial resistance of the piles group foundation. After a duration of 20 seconds, the rates of observed vertical displacements stabilize at each shock of the three consecutive shocks applied.

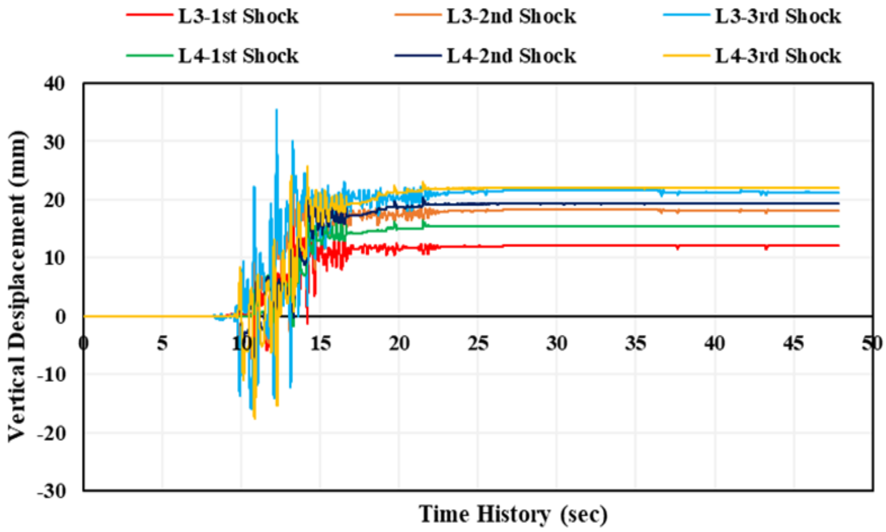
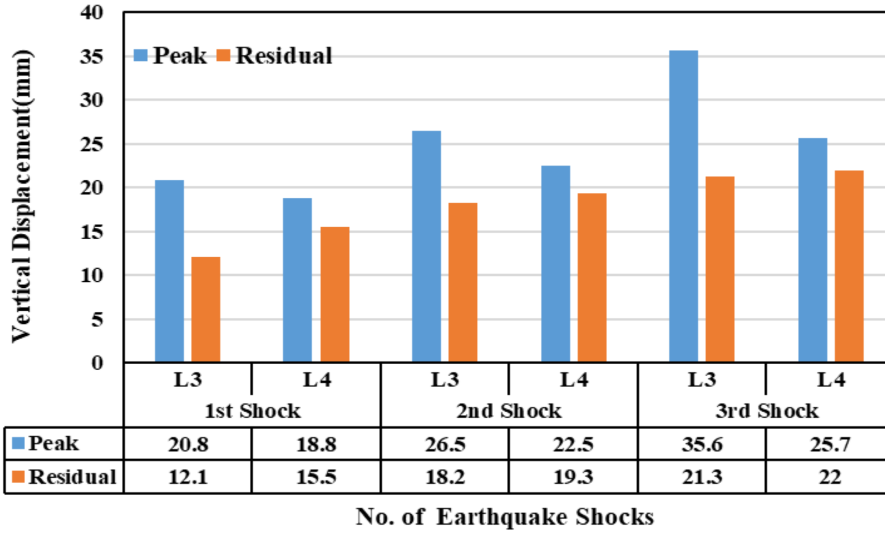


Fig. 5. Vertical displacement of the pile cap vs. time history for the 10-story building under three consecutive earthquakes

Fig. 6 presents the relation between the vertical displacement of the Piles cap (peak and residual values) with number of shocks applied. The data illustrated in this figure clearly indicates that the peak vertical displacement values recorded at the pile cap side that directly subjecting to seismic activity larger than that at the opposite side. In contrast, the residual values show reverse response. This observation holds true for all values recorded during the three consecutive earthquakes that were applied. For instance, during applied the first shock, the peak vertical displacement value recorded at the cap side directly exposing to seismic activity equal to 20.8 decrease to 18.8 mm at the opposite side, indicating a reduction in peak displacement between both side of about 9.5%. Subsequently, a modest elevation in the reduction ratio of peak displacement between the both sides of the pile cap is noted, assessed at around 15.1%, upon the application of the second shock. This ratio experiences an additional rise to reach 27.8% with the application of the third shock. This phenomenon can be attributed to the fact that seismic loading induces an asymmetric interaction between the soil, piles, and building. Specifically, the leading (front) piles row experiences greater horizontal resistance and axial compression compared to the trailing row, particularly when seismic event integrates kinematic drag of soil with the inertial forces exerted by the building. The effect of group pile shadowing causes the cap to rocking towards direction of the seismic load. This results in an increased compression on the leading piles row, while the trailing row experiences reduced compression, and occasionally, transient conditions of tension or gapping may arise among those piles. Concurrently, the process of repeated seismic load results in local densification of the surrounding sand (characterized by volumetric strains of ratcheting), thereby amplifying down-drag (negative skin friction) along the greater sheared leading-pile shafts. This combination of higher cyclic densification and greater compressive axial force, leads to a more substantial vertical displacement. This observation is consistent with the findings of [16,17]. With respect to the observed values of residual vertical displacement, it can be noticed that the residual displacement increased from 12.12 mm at the direct side to 15.54 mm at the opposite pile cap side, indicating an inflation rate of approximately 28.1% during applied the first shock event. Moreover, a comparison of the residual vertical displacement between both sides of pile cap during applying the second and third shocks revealed increasing rates of (6 and 3.3) % respectively. The potential explanations for the increased residual displacement observed at the side of the pile cap opposite to the seismic load possibly due to the cumulative finding of its distinct stress trajectory experienced during seismic loading. While the cap side directly subjected to seismic load shows high vertical displacement due to several direct pulses at the earthquake's peak, the opposite side undergoes fully-reversed, more symmetric cyclic shear. This change in shear strain, coupled with the cap rocking that diminishes confining stress on the opposite side during forward motion, renders the soil in that area more vulnerable to cyclic compaction across numerous cycles. Consequently, the opposite side accrues a more substantial amount of residual displacement from a greater number of effective stress cycles, ultimately surpassing the peak vertical displacement experienced at the pile cap side exposed directly to the seismic shock, and this agree with [17,18].



	1st Shock L3	1st Shock L4	2nd Shock L3	2nd Shock L4	3rd Shock L3	3rd Shock L4
Peak	20.8	18.8	26.5	22.5	35.6	25.7
Residual	12.1	15.5	18.2	19.3	21.3	22

Fig. 6. The relation between the vertical displacements of the pile cap and the number of earthquakes applied

Another important finding is that the effect of multiple earthquakes on the piles cap tilt. It can be seen that the vertical displacement measured at both piles cap sides show increasing values with each subsequent earthquake applied. That can be inferred clearly, when applied the second earthquake, the peak vertical displacements measured on the pile cap side directly subjected to seismic load, and the opposite side, increased by 27.4% and 19.7% respectively, relative to the values obtained during the first shock event. After applying the third shock, the peak values witnessed an additional increase, reaching 71.2% on the direct side and 36.7% on the opposite side when contrasted with their original values at the first shock. Furthermore, similar behavior was observed in case of residual vertical displacement. Following the second shock, the value of residual vertical displacements measured on both direct and opposite cap sides exhibited increases of 50.4% and 24.5%, respectively, relative to the data acquired during the first earthquake. Subsequently, after the third earthquake application, the residual displacements surged to even higher levels, reaching 76% on the direct side and 42% for on the opposite side, when compared to its values recorded during the first seismic event. It seems possible that these results of increase in vertical displacements observed following each earthquake may be attributed to factors such as cumulative plastic deformation. Dense sand exhibits plastic deformation when subjected to multiple seismic loading. Although dense sand initially demonstrates a degree of resistance to deformation owing to its stiffness, each successive earthquake induces further rearrangement of soil particles. Consequently, this phenomenon results in a cumulative reduction in soil volume, which in turn contributes to the observed increases in vertical displacements. and this agree with [19, 20 and 21]. Another possible explanation for this result is that it is due to stress redistribution, and the effects of soil-pile interaction. These mechanisms gradually diminish the soil's capacity to withstand vertical displacement, leading to increased deformation and pile cap tilting with each seismic occurrence and this agree with [17].

3.2 Lateral Displacement

The results of lateral displacements measured at the piles cap and at the top side of 10 story building under the three successive earthquakes are shown in Fig. 7. It can be noticed that the resulting measurement lines for both pile cap and 10-story building show approximately the same trend with a difference in behavior describe the directional response of structural elements during seismic loading as they experience oscillations due to the dynamic forces especially for the period between 8-22 seconds which represent the peak excitation of the earthquake. After a duration of 22 seconds, the rates of observed lateral displacements stabilize at each earthquake of the three consecutive earthquakes applied.

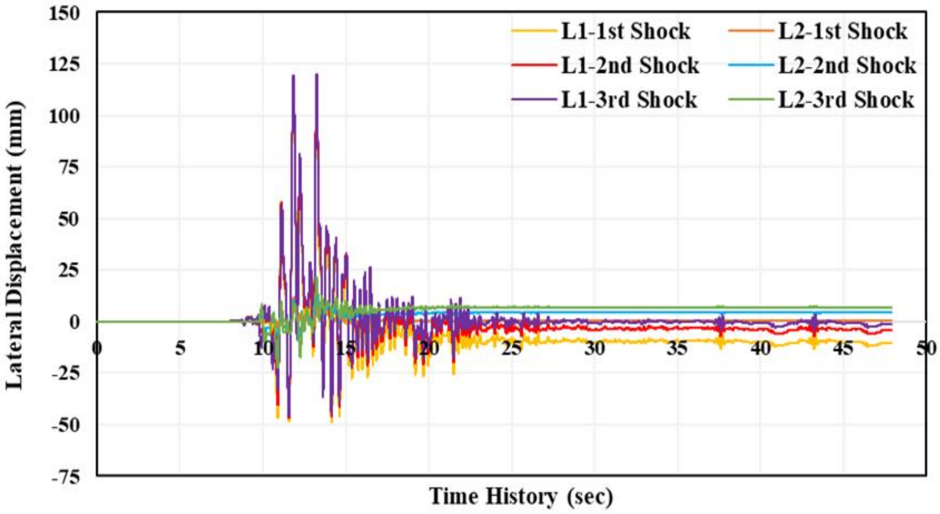


Fig. 7. The relation between lateral displacement vs time history forthe-10 story building under three consecutive earthquakes

Fig. 8 presents the relation between the lateral displacement (peak and residual values) measured at the top side of 10-story building, as well as the pile cap by (L1 and L2) respectively, during applied of the three successive earthquakes. As shown in Figure 8, the peak lateral displacement for the 10-story building which recorded by (L1) increases slightly across the three earthquakes: 114 mm in the first, 117.5 mm in the second, and 120.1 mm when the earthquake is applied for third time. That's mean that the ratio of increasing in value of peak lateral displacement for 10-story building during the second and third earthquakes greater than that recorded at the first earthquake by 3.1% and 5.4% respectively. This trend suggests an accumulation effect, likely due to minor degradation or residual displacement in the building after each seismic event. As for the peak lateral displacement for piles cap measured by (L2), its increases progressively: 15.6 mm at the first earthquake, 18.5 mm at the second earthquake, and 21.7 mm at the third earthquake. This designate that the increasing ratio in peak lateral displacement value for piles cap throughout the second and third earthquake events larger than that noted at the first shock by (18.61 and 39.14) % respectively. The observed upward trend designates in the peak values of lateral displacement that the pile-soil system is undergoing a gradual increase in response, with improvement in energy dissipation over time producing lower values of residual lateral displacements recorded at the end of each shock.

Moreover, these findings show that the 10-story building displays higher peak lateral displacements when compared to those measured at the piles cap. This performance can be attributed to several factors, including dynamic amplification effects, geometric influences and energy transmission. The building height amplifies the seismic forces that it encounters, producing greater lateral displacements occurring at the higher stories of building. Conversely, the piles cap undergoes a relative decrease in lateral displacement, which can be attributed to mechanism of energy dissipation occurring during interactions between soil and piles, in addition the effects of damping by the adjacent soil. The diminished lateral displacements at the piles cap designate its closeness to the source of seismic event in addition to the soil capacity to energy dissipate. Alternatively, the 10-story building shows larger lateral displacements, associated with the increase in the arm of moment and reduced lateral stiffness in the building higher storis and this accord with [22-24]. Moreover, the increase in peak lateral displacements during multiple earthquake events can be explained by a combination of factors, such as residual deformations in the interaction between the soil and pile, nonlinear behavior of the soil, and dynamic amplification effects within the structure. These factors lead to a reduction in stiffness of pile foundations and an escalation of seismic forces at the upper stories of building, which in turn results in increased lateral displacements. This observation aligns with the conclusions drawn [25,26].

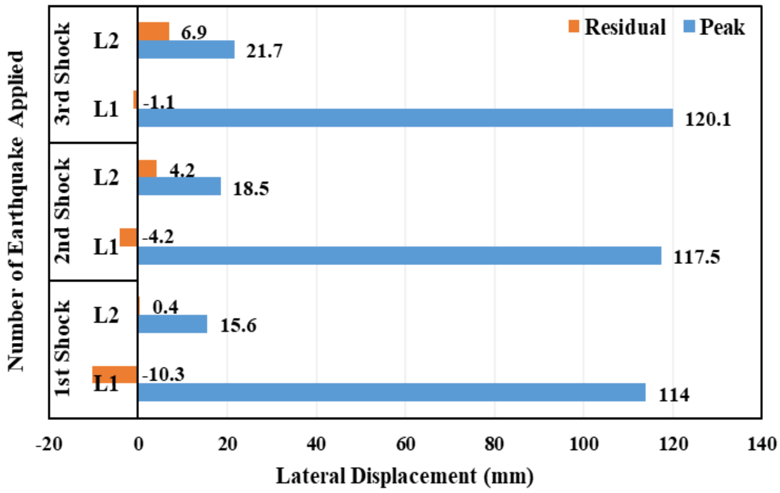


Fig. 8. The relation between the lateral displacements and the number of earthquakes applied

Another observation is that the residual lateral displacement of the 10-story structure during consecutive earthquake events showed a progressive decline, reducing from -10.43 mm in the first earthquake event to -4.21 mm in the second, and further to -1.11 mm in the third event (the negative values indicate that the structure is inclining in the direction of the earthquake). This trend reveals that the reduction rate in the residual lateral displacement of the 10-story structure, during the second and third earthquake events were (147.62 and 845.54) % respectively, compared to the first earthquake event. This behavior suggests that the building exhibits improved stabilization over time, as indicated by the decrease in residual displacements as the system adapts to the effects of successive seismic loading. Conversely, the value of residual lateral displacement noted at the pile cap, demonstrated a progressive increase during applying the earthquake events, 0.41 mm through the first seismic event, reach to 4.19 mm through the second seismic event and 7.99 mm through the third seismic event.

This behavior indicates that the rise in the residual lateral displacement observed at the pile cap through the second and third earthquakes was 10.5 and 20 times greater, respectively, than that recorded during the first earthquake. A potential reason for this phenomenon may be attributed to the nonlinear characteristics, which significantly influences the seismic response of the pile group foundations. As seismic events continue, the soil-pile interaction can result in greater lateral displacements, attributed to a reduction in group pile stiffness due to soil-pile interaction. Furthermore, the cyclic loading from successive seismic events may enhance the cumulative impacts on the response of pile's group, resulting in increased residual lateral displacements at the piles cap as time progresses. The overall behavior of the building is primarily determined by dynamic and geometric factors. Such behavior is consistent with well-recognized theories of soil-structure interaction and the principles underlying seismic dynamics and this agree with [27,28]. Another interesting result is that the measurements of residual lateral displacement noted at the piles cap increased during the three consecutive earthquakes, while decreasing at the 10-story structure. This performance is linked to the cumulative effects of energy dissipation and residual deformation taking place within the soil. As each earthquake occurs, the sand around the piles can undergo densification or minor plastic deformation, leading to a decrease in stiffness and allowing for increased lateral displacement at the piles cap. Moreover, the piles cap experiences greater displacements as a result of the lateral forces impacting it, in conjunction with the restricted lateral displacement of the adjacent soil, which contributes to an increase in the residual lateral displacement at the cap. In case of 10-story building, the inertia of the building aids in dissipating seismic forces, thereby leading to diminished displacements observed at the top side of building. These findings this consistent with [29, 30].

4. Conclusions

This research intended to investigating the impact of applying multiple earthquakes on the seismic performance of the pile group supporting 10-Story building in terms of vertical and horizontal displacement. The following conclusions are drawn from the above analyses:

- Multiple sequential earthquakes notably increases both the peak and residual vertical displacements on piles cap supported multi-story structure. The repeated occurrence of seismic events leads to a deterioration of the soil's stiffness, resulting in progressive vertical displacements, especially on the piles cap side directly exposure to seismic waves.
- The tilting angle observed in the pile cap demonstrated a gradual decrease with each consecutive shock experienced, measuring 0.46° immediately following the first ground motion event, 0.15° after the occurrence of the second motion, and finally reaching 0.1° after the third shock event. This notable decline in the tilt observed after the first earthquake strongly indicates a a redistribution of forces or soil densification. Such changes in tilt can provide crucial insights into the dynamic responses of pile group- structure systems to repeated seismic activity.
- Comparing the pile cap tilting angles against the serviceability limit of Bjerrum (1/150) for angular distortion, the results indicated that the tilting angle during the first shock (0.46°) unacceptable and exceeds the allowable limit, suggesting that the pile group-structure system may experience serviceability issues. In contrast, the tilting angle measured during the second and third shocks within the acceptable limit, this can be attributed to the fact that the first shock produce larger uneven settlement with compare to the subsequent shocks.
- The values of residual lateral displacements observed for the 10-story building model during successive seismic events exhibited a progressive reduction, the rate of decrease during applying the second and third shocks were about 2.5 and 9.4 times respectively, in comparison to the value measured at the first shock event. In contrast, the residual lateral displacement values recorded at the pile cap, exhibited a gradual increase throughout the seismic events, recording (10.5 and 20) times during the application of the second and third shocks, respectively, with compare to the value noted during applying the first shock.

Acknowledgement

The authors are grateful for the financial support towards this research by the Civil Engineering Department, College of Engineering, Al Nahrain University, as a Ph.D. student, in accordance with university order (6710/2/3ر.ج) dated 4/7/2022.

References

[1] Qin X. Shake table study on the effect of mainshock-aftershock sequences on structures with SFSI. Shock Vib. 2017; 2017:9850915. https://doi.org/10.1155/2017/9850915
[2] Qiao YM, Lu DG, Yu XH. Shaking table tests of a reinforced concrete frame subjected to mainshock-aftershock sequences. J Earthquake Eng. 2022; 26 (4): 1693 1722. https://doi.org/10.1080/13632469.2020.1733710
[3] Maheshwari B, Sarkar R. Seismic behaviour of piles in non-liquefiable and liquefiable soil. Bull Earthq Eng. 2021;19(12):5515-32. https://doi.org/10.1007/s10518-021-01244-4
[4] Sahare A, Ueda K, Uzuoka R. Influence of the sloping ground conditions and the subsequent shaking events on the pile group response subjected to kinematic interactions for a liquefiable sloping ground. Soil Dyn Earthq Eng. 2022; 152:107036. https://doi.org/10.1016/j.soildyn.2021.107036
[5] Kumar R, Takahashi A. Efficacy of a hybrid foundation to mitigate liquefaction-induced effects under strong sequential ground motions. In: Earthquake Engineering and Disaster Mitigation. Singapore: Springer; 2023. https://doi.org/10.1007/978-981-99-0081-7_10
[6] Souheyla S, Yahiaoui D, Demagh R. Seismic fragility evaluation of soil-pile-structure interaction effects subjected to mainshock-aftershock records. Int J Comput Civil Struct Eng. 2023;19(3):92-113. https://doi.org/10.22337/2587-9618-2023-19-3-92-113
[7] Padmanabhan G, Ueda K, Maheshwari BK, Uzuoka R. Reliquefaction behavior of sand and response of pile group subjected to repeated shaking sequence using centrifuge model experiments. Soil Dyn Earthq Eng. 2024; 182:108741. https://doi.org/10.1016/j.soildyn.2024.108741

[8] Rajeswari, J.S. Kinematic response of vertical pile foundation under multiple earthquakes. In: Sarkar R, Kumar A, Maheshwari B, editors. Foundation Dynamics. ICRAGEE 2024. Lecture Notes in Civil Engineering, vol 572. Singapore: Springer; 2025. p. 10-20. https://doi.org/10.1007/978-981-96-1417-2_10
[9] Khoshnoudian F, Kiani M. Modified consecutive modal pushover procedure for seismic investigation of one-way asymmetric-plan tall buildings. Earthq Eng Eng Vib. 2012;11(2):221-32. https://doi.org/10.1007/s11803-012-0112-6
[10] Ali A, Karkush M, Aljorany A. Numerical modeling of connected piled raft foundation under seismic loading in layered soils. J Mech Behav Mater. 2023;32. https://doi.org/10.1515/jmbm-2022-0250
[11] Mahdi K, Alaa A, Karrar A, Ahmed AS. Behavior of partially connected piled raft foundation under seismic loading. Mag Civ Eng. 2024;17(4):1280.
[12] El Hoseny M, Ma J, Dawoud W, Forcellini D. The role of soil structure interaction (SSI) on seismic response of tall buildings with variable embedded depths by experimental and numerical approaches. Soil Dyn Earthq Eng. 2023; 164:107583. https://doi.org/10.1016/j.soildyn.2022.107583
[13] Garnier J. Size effect in shear interfaces. In: Proceedings of a Workshop on Constitutive and Centrifuge Modelling: Two Extremes, Monte Verita; 2002; Monte Verita, Switzerland. p. 335-46.
[14] Noman BJ, Albusoda BS. Impact of vertical vibration on group piles during earthquake loading: Experimental findings. Civ Eng J. 2024; 10:174-208. https://doi.org/10.28991/CEJ-SP2024-010-010
[15] Center for Engineering Strong-Motion Data (CESMD). Kobe 1995 Earthquake Strong Motion Data. Sacramento and Menlo Park (CA): CESMD; 2024. Available from: https://strongmotioncenter.org/.
[16] Visuvasam JA, Chandrasekaran SS. Effect of spacing and slenderness ratio of piles on the seismic behaviour of building frames. Buildings. 2022;12(12):2050..https://doi.org/10.3390/buildings12122050
[17] Esmaeili-Falak M, Katebi H, Pourjafar A. Pile-soil interaction determined by laterally loaded fixed head pile group. Geomech Eng. 2021;26(1):13-25.
[18] Zheng G, Sun J, Zhang T, Diao Y. Settlement of a pile under cyclic lateral loads in dry sand. Geotechnique. 2022;73(7):561-71. https://doi.org/10.1680/jgeot.21.00107
[19] Chanda D, Saha R, Haldar S. Seismic behaviour of RC framed building supported on combined piled raft foundation in sandy soil. Arab J Sci Eng. 2024;49(5):145-58. Available from: https://link.springer.com/article/10.1007/s13369-024-09105-3
[20] Zhang HY, Qian DL, Shen C, Dai QQ. Experimental investigation on the dynamic response of pile group foundation on liquefiable ground subjected to horizontal and vertical earthquake excitations. Rock Soil Mech. 2020;41(3): Article 6.
[21] Lu C, Doan M, Chen S, Lin Y. Effective stress analysis for repeated shake-consolidation process of multi-story buildings in liquefiable soils. Comput Geotech. 2024; 134:104-18. https://doi.org/10.1016/j.compgeo.2024.106496
[22] Seed HB, Wong RT, Idriss IM, Tokimatsu K. Moduli and damping factors for dynamic analyses of cohesionless soils. J Geotech Eng. 1986;112(11):1016-32. https://doi.org/10.1061/(ASCE)0733-9410(1986)112:11(1016)
[23] Mylonakis G, Gazetas A. Seismic soil-structure interaction: Beneficial or detrimental? J Earthq Eng. 2000;4(3):277-301. https://doi.org/10.1080/13632460009350372
[24] Chopra K. Dynamics of Structures: Theory and Applications to Earthquake Engineering. 4th ed. Upper Saddle River (NJ): Prentice Hall; 2012.
[25] Kramer SL. Geotechnical Earthquake Engineering. Upper Saddle River (NJ): Prentice Hall; 1996.
[26] Tolentino D, Flores RB, Alamilla JL. Probabilistic assessment of structures considering the effect of cumulative damage under seismic sequences. Bull Earthq Eng. 2018; 16:2133. https://doi.org/10.1007/s10518-017-0285-5
[27] Siri Reddy K, Harini GVS K, Vijayasri T. Nonlinear analysis of soil-pile interaction under seismic loads. In: Proceedings of the International Conference on Advanced Structural Technologies. Singapore: Springer; 2023. p. 331-45. https://doi.org/10.1007/978-981-19-6998-0_30
[28] Hasan MM, Hore S, Al Alim M, et al. Numerical modeling of seismic soil-pile-structure interaction (SSPSI) effects on tall buildings with pile mat foundation. Arab J Geosci. 2024; 18:10. https://doi.org/10.1007/s12517-024-12155-4
[29] Jia K, Xu C, Du X, Cui C, Dou P, Song J. Seismic response comparison and sensitivity analysis of pile foundation in liquefiable and non-liquefiable soils. Earthq Eng Vib. 2023; 22:87-104. https://doi.org/10.1007/s11803-023-2160-5
[30] Zhao H, Zhang F. Seismic response of pile-supported structures considering the coupling of inertial and kinematic interactions in different soil sites. Front Struct Civ Eng. 2024; 18:1350-61. https://doi.org/10.1007/s11709-024-1113-z