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Behavior of partially connected piled raft foundation under seismic loading

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Keywords: partially connected piled raft, disconnected piled raft, seismic loading, piled-raft, cushion layer

Abstract. A partially connected piled raft foundation is a new modification for the fully connected or disconnected piled raft foundation. The characteristics of the connected piles could transfer loads from the superstructure to the underlying soils. The disconnected piled raft foundation has an effective advantage for reducing the dynamic motion that is transmitted to the high-rise superstructures. However, the dynamic behavior of the partially connected piled raft foundation system under a strong earthquake in medium sand soil has not been thoroughly understood. In this study, the effect of the distribution of piles patterns, number of connected piles (CP), and number of disconnected piles (DP) through a series of seismic experimental model tests have been investigated. These tests were performed with 1, 4, 5, and 9 piles under different static loads. Vertical and horizontal displacements, acceleration, and variation of bending moment of soil and piles are monitored through the experimental tests. The results showed that increasing the number of CP compared with DP contributed to an effective way to reduce the horizontal displacement of the piled raft foundation system. The advantage of DP in resisting seismic loading appears when the number of DP is more than the number of CP. Due to the structural connection of the raft-pile-soil system, the CP was subjected to high values of the seismic acceleration and bending moment. The reduction in the bending moment of DP within the partially connected piles group depended on the number of CP and increasing the thickness of the cushion layer.

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1. *Introduction*

Among different types of foundations, piled raft foundation has been of great importance to practical researchers and studies. Heavy building construction on weak soils required the model piled raft foundation technique [1–4]. According to the connection behavior between pile and raft, connected and disconnected piled raft foundations are studied which will be responsible about sharing the load to the underlying layers [5]. Most of the previous works studied the effect of the cushion layer on the behavior of piles under static loads using experimental modeling. The disconnected piled raft is efficient in reducing the axial stress along the pile compared with that related to the connected piled raft [6]. Two cushion mechanisms could be observed through loading, the negative friction for the upper part and positive friction for the lower part of a pile. The stiffness of the disconnected piled raft foundation system depends on the stiffness of the cushion layer [7].

The performance of the piled raft system under seismic loading is of great concern to geotechnical practitioners to avoid probable damage in the piled raft system [3, 4]. Different researchers and studies explained the behavior of piled raft foundation under large and heavy structures subjected to earthquake loadings. Earthquake usually creates additional loading situations on the piled raft which need special attention [1, 8, 9]. In addition, the piled raft foundation becomes an alternative in cases where soil layers are incapable to carry the applied loads and prevent excessive settlement [10, 11]. Earthquakes or seismic loading make a complex interaction for the pile-raft-soil-foundation components system. Saadatinezhad et al. [12] concluded that different factors could affect the response of the disconnected piled raft foundation such as L/D (slenderness ratio).

Through the centrifuge test was clarified that the disconnected pile located at the edge of the foundation can reduce the effect of the bending moment under seismic loading. At the same time, it was explained that one of the limitations of using disconnected piles is that it cannot provide sufficient tensile force of the raft foundation. On the other side, using a disconnected pile is one of the effective and economical design factors [13]. According to reference [14], it was concluded that using a connected piled raft system under increasing the excitation to 0.15 g and 0.32 g compared to 0.05 g will increase the total settlement of piled raft system by 30 % and 85 %, respectively. Similar to total settlement, differential settlement increases with increasing excitation. One of the disadvantages of using a fully connected piled raft foundation is that higher excitation produces higher irregular forces leading to irregular motions resulting in higher differential settlement.

Rasouli and Fatahi [15] investigated the behavior of disconnected piled raft foundation to protect high-rise buildings under the effect of the normal fault rapture. In this study, there was a comparison between connected and disconnected piled raft foundation systems. The results assessed different parameters such as permanent inter-story drifts, raft displacement, rocking, forces, and bending moments in piles and raft. As expected from this study, the piles near the hanging wall have not avoided the bending effect with 0.5 m differential settlement. Also, it experienced a maximum bending moment of about 7.3 MN.m that passed the maximum design bending moment 3 MN.m. The maximum differential settlement of the raft foundation was 0.292 m that reduced to 0.1 m when the disconnected piled raft foundation had been used.

From the literature data, it can be established that the provision of the partially connected piled raft foundation system reduces the vertical settlement for disconnected piles and increases the vertical settlement and reduces the horizontal settlement for connected piles. It was observed also that the highest value of bending moment for connected one and lowest value for disconnected one at the top part of piles head below the cushion layer. Only a very few studies deal with partially connected piles. Therefore, it is essential to evaluate partially connected piled raft foundation systems under seismic loading with different parameters such as thickness of cushion layer, no. of piles, L/D ratio for connected piles, and different distribution patterns of piles. The covered dynamic response parameters include vertical settlement of the foundation, horizontal displacement of the foundation, acceleration distribution inside the soil media, and a bending moment of piles for different cases.

2. Methods and Materials

2.1. Earthquake Loading System

To simulate the earthquake loading in the laboratory, there are several techniques and methods, one of them being using a shaking table. The shaking table is essential laboratory equipment that simulates the loading that occurs during dynamic excitation as in an earthquake [16]. In this study, the uniaxial sinusoidal motion was adopted by applying a suitable frequency using a shaking table device shown in Fig. 1. The dimension of the shaking plate is 1 × 1 m and 1 ton loading capacity. According to [17], the scale factors are important to select the suitable dimensions of experimental modeling. The motion was executed by using a 3-phase electrical motor connected to a mechanical gearbox to change the rotating direction, and regulate the motor speed and this motor was also connected to an AC-drive regulator. The motor operated to make a slow-motion rotation, then the gearbox operated the motion arm. Many options could be changed such as minimum, maximum, fixed, acceleration, and deceleration frequencies. All these factors affect the motion type and behavior, the range of available frequency is 0–20 Hz. In addition to the AC drive, there were time governor and protection devices shown in Fig. 1 by which the shaking time could be selected and the emergency circumstances could be avoided.

Figure 1. Shaking table and soil box with complete setup.

2.2. Recording Data and Instrumentation

To adjust the exact applied acceleration magnitude a calibration process must be done, this process was executed as follows: for a specific period, the number of back-and-forth cycles was recorded and compared with the results of the software, the result of the software was the acceleration obtained by changing the velocity speed of the motion as shown in Fig. 2. Thus, for a specific value of velocity, it is easy to select the correct number value of the acceleration in the software. The applied value of acceleration was selected and compared with the data from El Centro earthquake history. These data were calibrated using an accelerometer (Acc1) fixed on the base plate of the model after filling the steel model box with soil. Fig. 3 illustrates the calibration results of the applied speed of the electrical motor and the resulting acceleration. Different sensors were used in this study to get the actual behavior of a partially connected piled raft foundation system. These sensors were: 5 accelerometers, 3 strain gauges along each pile length to calculate bending moments values, and 3 LVDTs to calculate the horizontal, vertical, and base displacements.

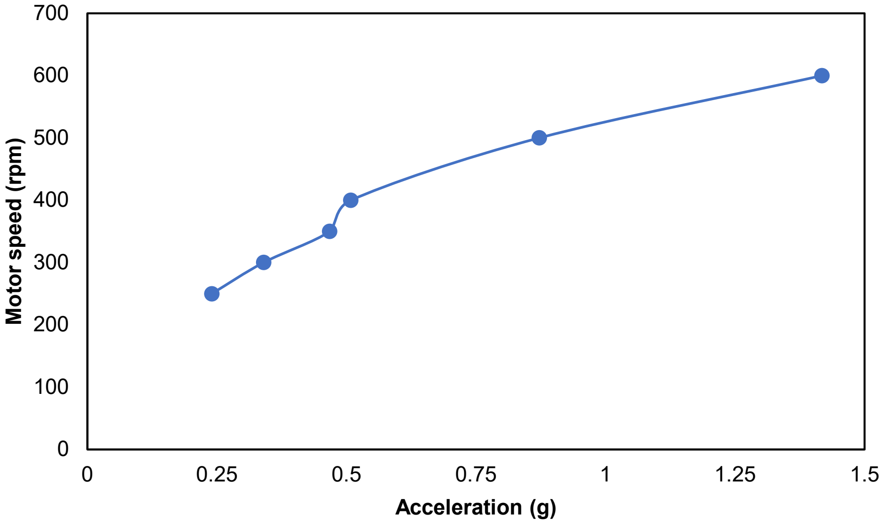

Figure 2. The calibration of motor speed (rpm) and acceleration.

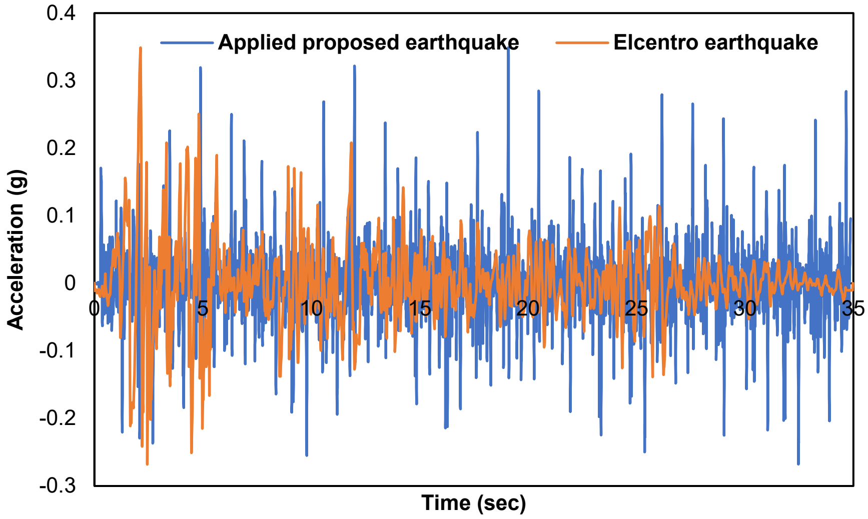

Figure 3. Time history of the applied acceleration on the base of the model compared with El Centro earthquake.

2.3. Materials

2.3.1. Bed Soil

The bed soil used in the model was dry sand obtained from Al-Najaf city (Iraq). A summary of the test results with standard specifications are presented in Table 1. According to the grain size distribution results, it can be seen that the sand consists of fine grains. This sand is categorized as poorly graded sand (SP) according to the Unified Soil Classification System (USCS), while the cushion layer soil is classified as well-graded sand soil (SW).

Table 1. Laboratory tests for model and cushion sand soil.

Property	Standard	Value (Cushion soil)	Value (Model soil)
Specific gravity	ASTM D854	2.68	2.64
Maximum dry unit weight (kN/m^3)	ASTM D4253	18.65	17.20
Minimum dry unit weight (kN/m^3)	ASTM D4254	14.45	13.89
Experimental dry unit weight (kN/m^3) (at Dr =50%)	------	16.28	15.36
D_{10} (mm)		0.13	0.5
D_{30} (mm)		0.44	0.65
D_{60} (mm)	ASTM D422	1.18	0.76
Coefficient of uniformity (Cu)		9.07	1.52
Coefficient of curvature (Cc)		1.26	1.11
Angle of internal friction (Ø) (Direct shear test)	ASTM D3080	35.4	29

2.3.2. Pile and Raft Models

The pile model used in the current study was made of aluminum alloy and had a hollow square cross-section of 14 mm outside dimension and a wall thickness of 1.5 mm. The embedded pile length was 350 mm used to model the disconnected pile and 370 mm to model the connected pile. For connected piled raft model tests a bolt of diameter 10 mm and 30 mm long was provided at the top head of each pile to fix the piles with raft and fastened with a nut. While the piles end was closed with a square aluminum piece of side dimension 14 mm and 2 mm thickness. A square steel plate, of side dimensions (210 × 210) mm and a thickness of 10 mm was used as a raft. The values of the poison's ratio and modulus of elasticity for soil, raft, and piles are displayed in Table 2.

Table** 2. **Mechanical properties for soil, pile, and raft foundation.

Property Name	Soil	Pile	Raft
Poisson's ratio, v	0.31	0.28	0.31
Modulus of elasticity, E (MPa)	12.3	4.8×10^4	2.3×10^5

2.4. Tests Preparation and Procedure

To reconstitute or prepare the sand samples for experimental model tests, several ways were used such as raining, vibration, or tamping. In general, to provide relatively homogenous sand samples and to get the required relative density, the raining procedure is considered the best among these ways. Many trials were performed to draw a relationship between the falling height and the corresponding dry density as shown in Fig. 4. From the curve, it is clear that the falling height should be about 20 cm to get the required dry density of 16.28 kN/m^3 for bedding soil in the physical model and 10 cm to get the density of 15.36 kN/m^3 for the soil of cushion layer. Fig. 5 shows the raining of bedding soil used in this study. The raining technique used in this work consisted of a steel hopper of height 45 cm with a valve at the bottom to control sand raining manually. A sieve of 4.75 mm opening size is attached to the bottom of the funnel and connected to the hopper by a plastic joint to distribute the sand uniformly as shown in Fig. 5. The inside walls of the container were divided into 6 intervals, each of 15 cm thickness, to ensure that the desired dry density was obtained properly. To produce a homogenous sample overall in the container, the required quantity of sand for each layer was weighted such that the designed dry density could be obtained. For conditions of connected and disconnected piled raft model tests, a template provided by the steel mesh method was used. Piles were tied with the steel mesh placed previously inside the container by the plastic tie as shown in Fig. 5. The steel mesh was lifted up when the level of raining sand reached it.

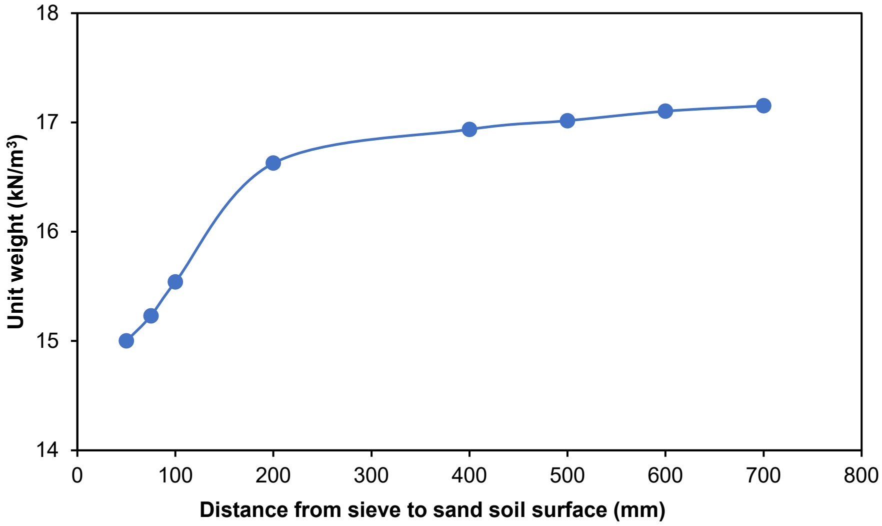

Figure 4. The relationship between the height of falling and the dry density of sand.

Figure 5. Raining tool and positions of the piles within steel mesh.

Several conditions of piles with raft were studied in this work to show the effects of partially connected piles on the behavior of building foundation under seismic loading. The proposed technique of partially connected piles mixes the advantages of both connected piled raft systems and disconnected piled raft systems. The studied patterns are shown in Fig. 6. The notations used in Fig. 6 are defined in Table 3.

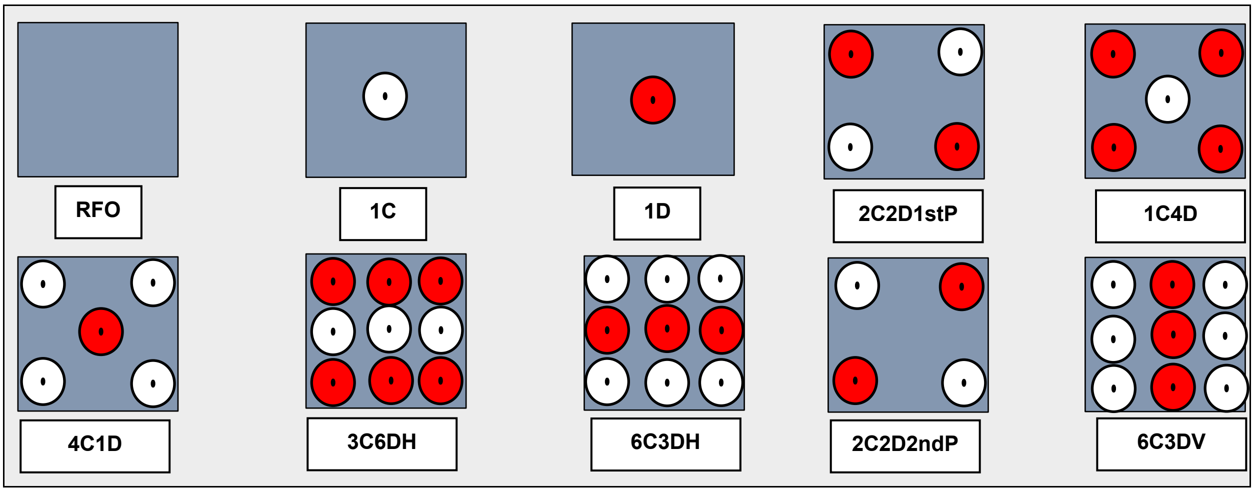

Figure 6. Patterns of piles and raft studied in this work.

The total settlement (horizontal and vertical) of the raft resulting from earthquake excitation was measured using LVDTs connected to the raft model supported on the shaking table. This variation was studied for single and group piles conditions under different static loads. Table 3 shows the details and notifications of conducted experimental tests. The loading was applied on the piles in two stages, the first stage referred to the vertical static axial load on the raft-pile surface with different values depending on the calculated ultimate capacity of the foundation as a guide. During the second stage the horizontal seismic load was applied with constant static loads.

Table 3. Details and notations of the conducted experimental tests.

Test No.	Symbol		Details		No. of dis-connected piles (D)	No. of connected piles (C)	Max vertical displacement failure ratio (δ_{rf})	Static load (kg)
1	RFO		Raft foundation only		----------	----------	1.06D	21.69
2	1C	37cmV*or H**	1 pile connected	L/D1=23.41	----------	1	1.04D	2.41
3		39cmV or H		L/D2=24.68			0.87D	
4		41cmV or H		L/D3=25.94			0.81D	
5	1D	C2cmV or H	1 pile disconnected	Cushion 2cm	1	----------	0.94D	2.41
6		C6cmV or H		Cushion 6cm			0.945D	
7	2C2D	1stP***V or H	2 piles connected	Cushion 2cm	2	2	0.3D	9.64
8				Cushion 6cm			0.7D	
9		2ndP****V or H	2 piles disconnected	Cushion 2cm			0.15D	
10				Cushion 6cm			0.67D	
11	1C4D	C2cmV or H	1 pile connected	Cushion 2cm	4	1	0.52D	12.05
12		C6cmV or H	4 piles disconnected	Cushion 6cm			0.31D	
13	4C1D	C2cmV or H	4 piles connected	Cushion 2cm	1	4	0.33D	12.05
14		C6cmV or H	1 pile disconnected	Cushion 6cm			0.41D	
15	3C6DH	C2cmV or H	3 piles Connected	Cushion 2cm	6	3	0.47D	21.69
16		C6cmV or H	6 piles Disconnected	Cushion 6cm			0.38D	
17	6C3DV	C2cmV or H	6 piles Connected	Cushion 2cm	3	6	0.35D	21.69
18		C6cmV or H	3 piles Disconnected	Cushion 6cm			0.30D	
19	6C3DH	C2cmV or H	6 piles Connected	Cushion 2cm	3	6	0.59D	21.69
20		C6cmV or H	3 piles Disconnected	Cushion 6cm	3	6	0.79D	

V*– Vertical displacement, H*– Horizontal displacement, V – Vertical distribution of piles, H – Horizontal distribution of piles, 1stP***–First pattern, 2ndP****–second pattern.

3. *Results and Discussion*

Fig. 7–12 show the variation of raft settlement with time for a different number of piles (1, 4, 5, and 9) in the piled raft system. Fig. 7 shows that the maximum vertical displacement of the raft foundation without piles is 16.76 mm under 21.69 kg as static building load. Increasing in length to diameter ratio of piles from 23.41 to 24.68 and 25.94 mm decreases the displacement amplitude of the piled-raft system by 19.83 % and 22.59 %, respectively. This reduction is related to the effect of the shaft and lateral resistance of piles. Using of disconnected piled raft produced good stability and resistance for vertical displacement till 15–20 sec from the start of the effect of earthquake excitation as shown in Fig. 8. Using one disconnected pile instead of one connected pile and increasing the thickness of the cushion layer from 2 to 6 cm had a small effect in reducing the vertical displacement. Fig. 9 shows the benefit of using 2C2D1stP instead of

2C2D2ndP by dropping the vertical displacement with 2 cm cushion layer from 4.85 to 2.47 mm. For 6 cm cushion thickness, the displacement was dropped from 11.13 to 10.57 mm. Generally, using of 6 cm cushion thickness is useless to reduce the displacement. 1C4D1stP with 6 cm cushion layer reduced the vertical settlement compared with using 1C4D1stP with 2 cm cushion layer from 8.29 to 4.84 mm. In the same time, the results of 4C1D2ndP for 2 cm and 6 cm cushion layers were equivalent. From these results, it could be concluded that increasing the number of connected piles within a well-compacted cushion layer increases the vertical displacement.

The variation of vertical displacement with time for the pattern of five piles is shown in Figю 10, the vertical displacement was reduced from 8.29 to 5.33 mm when the patterns were changed from 1C4D to 4C1D with 2 cm cushion layer respectively. Increasing the thickness of the cushion layer to 6 cm was not efficient in reducing the vertical displacement of the foundation system. It can confirm for the 9 piles condition that increasing the numbers of connected piles compared with disconnected piles could increase the vertical displacement. This appeared clearly by reducing the displacement from 9.38 to 7.52 mm with changing the pattern from 6C3DH to 3C6DH with 2 cm cushion layer, respectively. Increasing the thickness of the cushion layer to 6 cm slightly affected the vertical displacement of 3C6DV and 6C3DV due to the seizing of the connected piles to the cushion material on the top of the disconnected piles. According to Fig. 11, by increasing the thickness of the cushion layer from 2 to 6 cm, the maximum vertical displacement was reduced from 5.60 to 4.83 mm for the pattern 6C3DV. Also, the maximum vertical displacement of 3C6DV decreased from 7.52 to 6.04 mm by increasing the thickness of the cushion layer from 2 to 6 cm. This reduction in displacement could be attributed to the role of the 6 disconnected piles in the same direction of earthquake vibration. Fig. 12 illustrates the variation of the maximum displacement for all patterns as discussed in Figs. 7–11. Also, in Table 3, the maximum vertical displacement failure ratio (δ_{rf}) compared with the equivalent diameter of the pile (D) is displayed for each test.

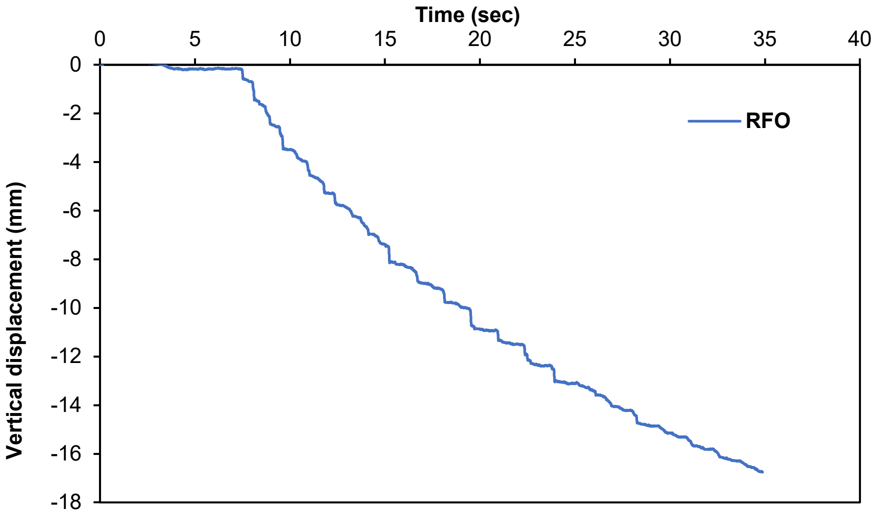

Figure 7. Variation of vertical displacement time for raft foundation only (RFO).

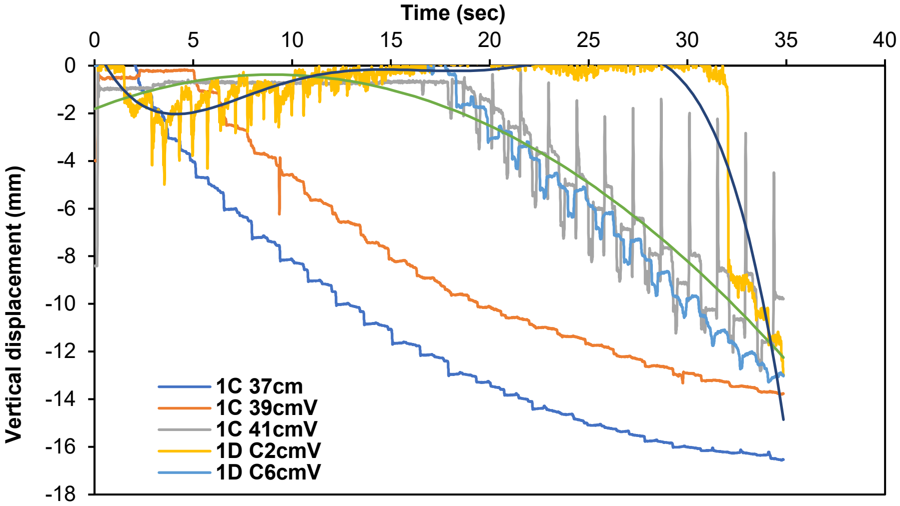

Figure 8. Variation of vertical displacement time for the system of one connected and one disconnected piled-raft.

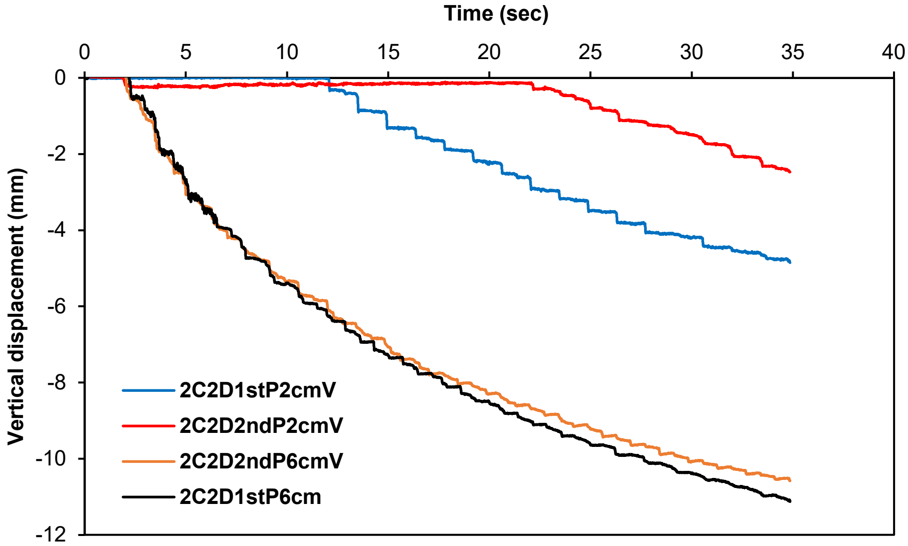

Figure 9. Variation of vertical displacement time for 1st and 2nd patterns of 2 connected and 2 disconnected piled-raft systems.

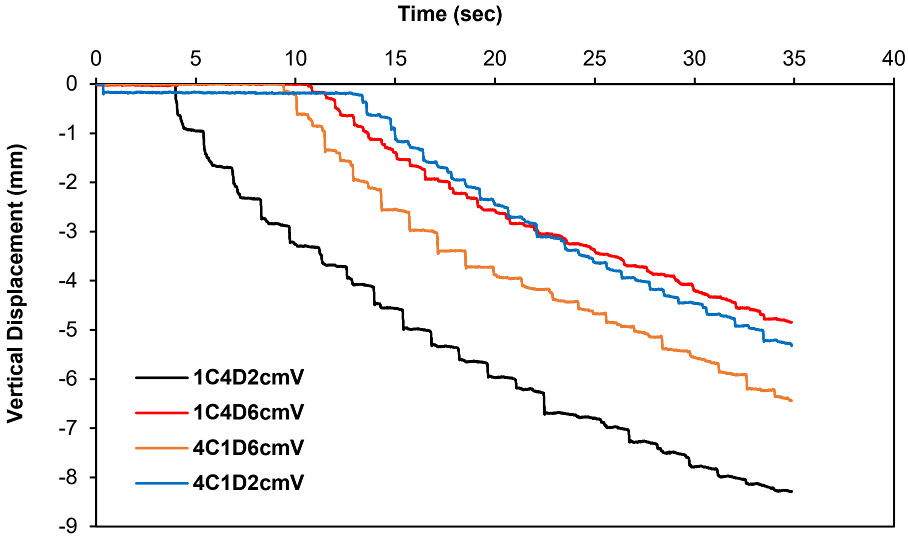

Figure 10. Variation of vertical displacement time for 1 disconnected, 4 connected, and 1 connected, 4 disconnected piled-raft systems.

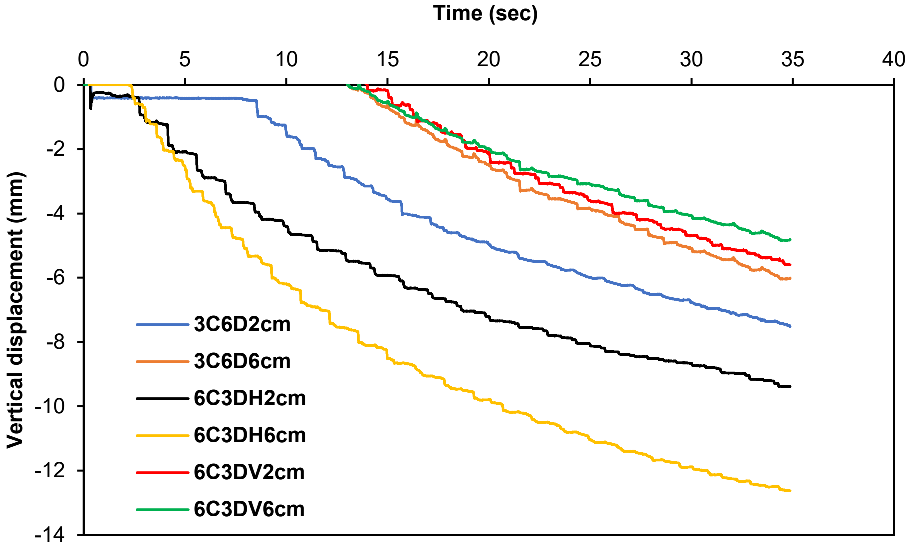

Figure 11. Variation of vertical displacement time for 3 disconnected, 6 connected, and 3 connected, 6 disconnected piled-raft systems.

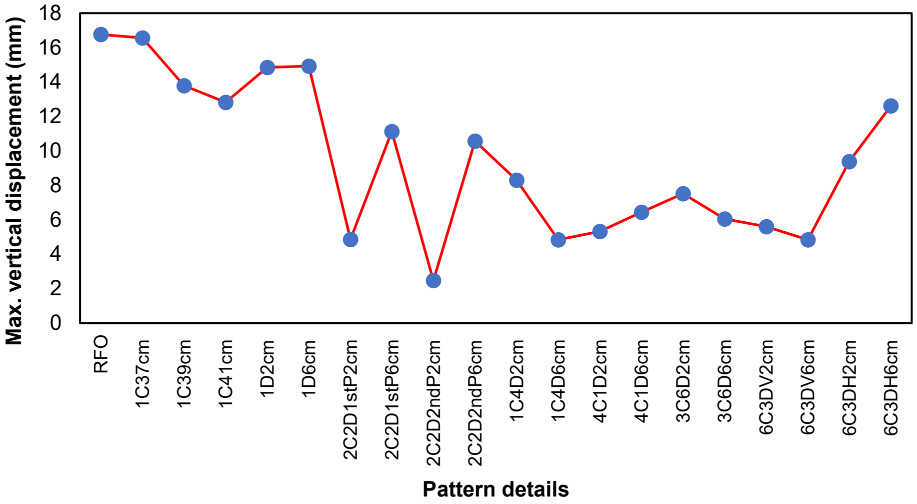

Figure 12. Variation of maximum vertical displacement for tested models.

Fig. 13–15 show the variation of the horizontal displacements measured at the raft foundation with time for several tested models. Increasing the number of connected piles compared with the number of disconnected piles increased the overall stiffness of the piled raft foundation system [12]. The lowest negative and positive horizontal displacements are 22.813 and 38.598 mm measured for the soil model 6C3DV with cushions 2 cm and 6 cm thickness, respectively. It can also be seen that the highest value of the horizontal displacement was 78.372 mm for 3C6DH with a cushion of 6 cm thickness. Generally, the small number of connected piles causes less stiffness as mentioned above. The summary of the lowest and highest horizontal displacements for all patterns of tested models is displayed in Fig. 16.

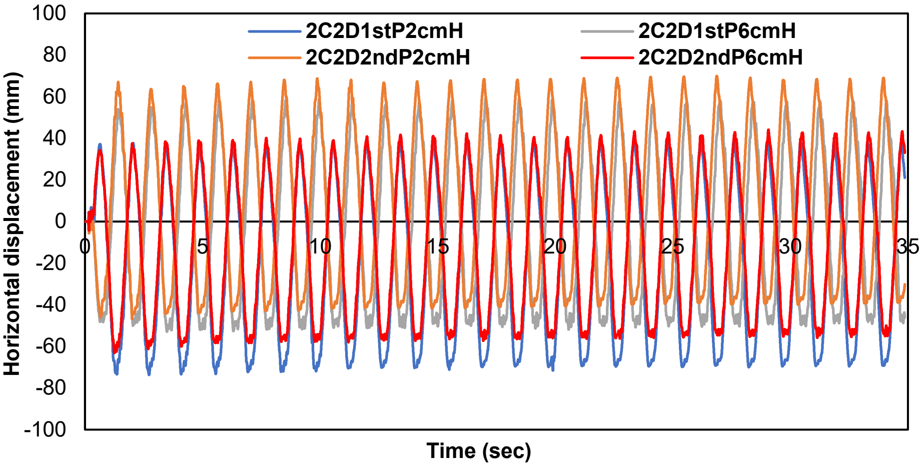

Figure 13. Variation of horizontal displacement with a time of 1st and 2nd patterns of 2 connected and 2 disconnected piled-raft systems.

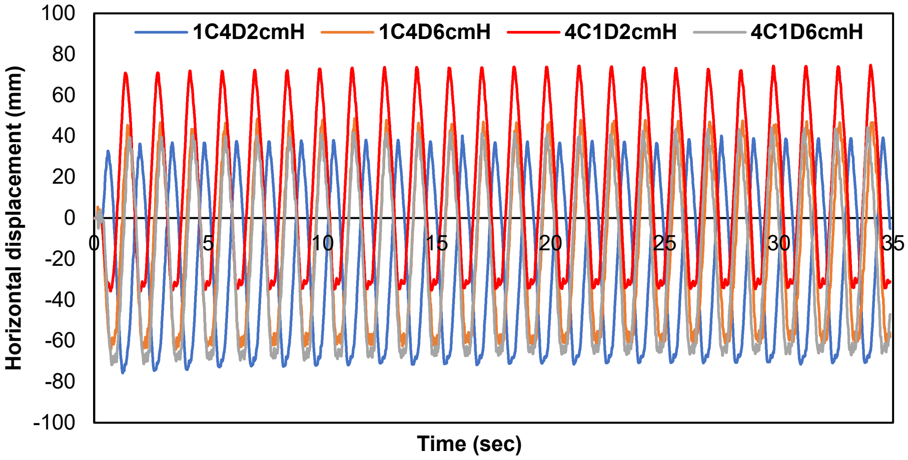

Figure 14. Variation of horizontal displacement with a time of 1 disconnected, 4 connected, and 1 connected, 4 disconnected piled-raft systems.

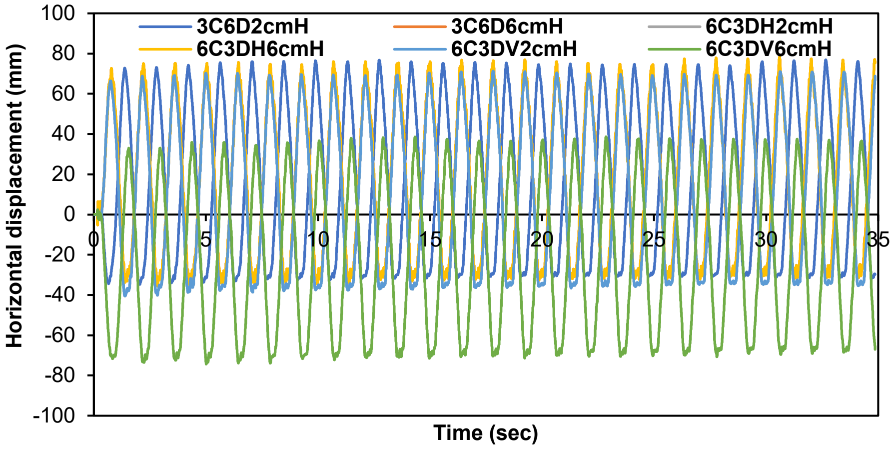

Figure 15. Variation of horizontal displacement with a time of 3 disconnected, 6 connected, and 3 connected, 6 disconnected piled-raft systems.

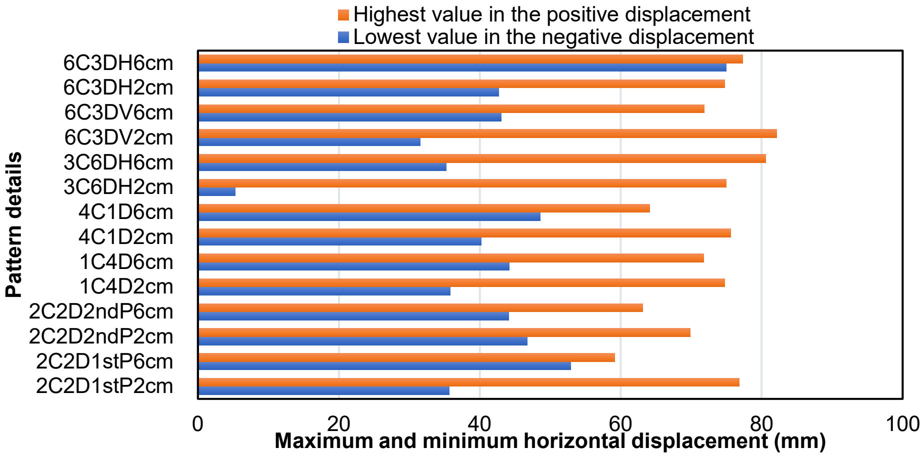

Figure 16. Maximum and minimum horizontal displacements for all patterns of tested models.

The bending moment caused in the piles depends on the pile's connection with the raft foundation, cushion thickness, and locations of the piles within the raft foundation. The profiles of bending moment along the pile length due to earthquake loading for one connected (CP) and one disconnected pile (DP) are clarified in Fig. 17 and 18. It is observed with a strong earthquake (0.35 g), the maximum bending moment occurred at the middle and top of the connected piles. In this study, the maximum bending moment increased when the length of the CP increased. The maximum bending moments were – 425, – 460, and – 486.68 N.mm for pile lengths of 37, 39, and 41 cm, respectively. The maximum bending moment was observed in the top part of the connected pile due to fixed-free ends, on the contrary, when the cushion thickness increased from 2 to 6 cm, the maximum bending moment had changed from + 335.76 N.mm to + 184.54 N.mm. All the maximum bending moments occurred at the top-middle part of the DP due to free-free ends at the top-tip ends respectively. For the pattern 2C2D, the highest reduction in the maximum bending moment was achieved when the pattern 2C2D2ndPC2cm had been used and the lowest reduction was achieved when the pattern 2C2D2ndPC6cm had been used as indicated in Fig. 18. This is more prominent for DP with a higher thickness of the cushion layer, where the stiffness of DP decreases the overall stiffness of the foundation-pile system.

For two patterns 1C4D and 4C1D, in Fig. 19, the bending moment of the CP (center) in the pattern 1C4DC6cm was less than the bending moment of the CP (center) in the pattern 1C4DC2cm. Also, the bending moment of the DP (corner) in the pattern 1C4DC2cm proved to be more bending compared with the DP (corner) in the pattern 1C4DC6cm. With increasing the number of the connected piles, it can be observed that the bending moment increased from + 403.63 N.mm to – 558.35 N.mm for the CP (corner) and it decreased from +105.69 N.mm to – 83.106 N.mm for the DP (center). This observation can be pronounced as a “shadowing phenomenon”. This phenomenon is used to contract the effect of the interaction of the inner piles compare with the outer piles of the pile group under static or dynamic loads. As an important factor in the design of a partially connected piled raft foundation, the location and number of the connected pile's CP can be considered for the patterns 3C6DH, 6C3DH, and 3C6DH. As displayed in Fig. 20, in the pattern 3C6DH, the number of CP is less than the number of DP, and the CP (center) shows more bending moment than the CP (edge). On the contrary, the DP (edge) shows more bending moments than the DP (center). Here, the effect of shadow phenomena has more effect on disconnected piles compared with connected piles depending on the number of piles. For the pattern 6C3DH, the number of CP is more than the number of DP, therefore increasing the number of connected piles will increase the stiffness of the system. In this pattern, the bending moment of the CP (edge) is more than the bending moment of the CP (corner). In the patterns 6C3DHC2cm and 6C3DHC6cm, the DP (center) sustained a small bending moment due to the shadow effect of the surrounding connected piles. For the last patterns 6C3DVC2cm and 6C3DVC6cm, the CP (edge) and CP (corner) show the highest values of the maximum bending moment. As expected, the DP (center) appeared the least values of the bending moment for the same reason as the pattern 6C3DH. It is preferable to mention here, for the DP, during a strong earthquake, must be compared between the destructive and designed bending moment. It is necessary to prepare suitable reinforcement according to the arrangement of the DP in the group.

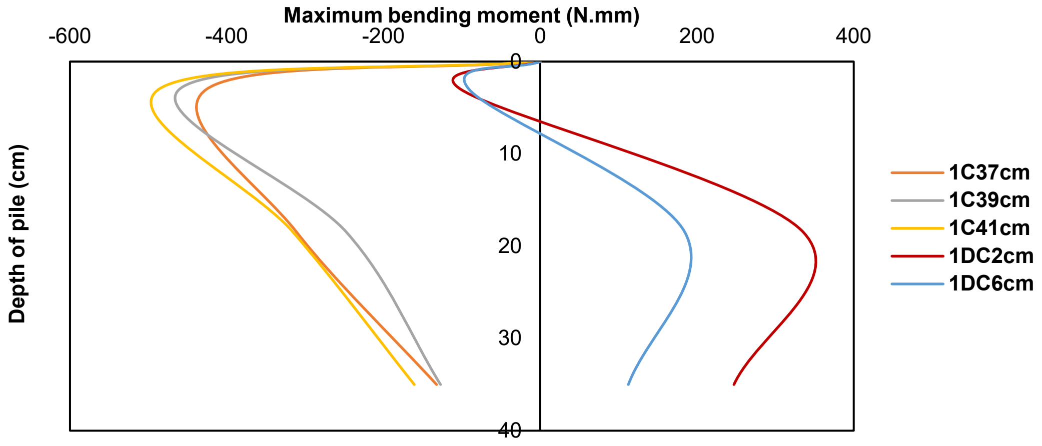

Figure 17. Variation of bending moment with the depth of pile for the single pile patterns (connected and disconnected).

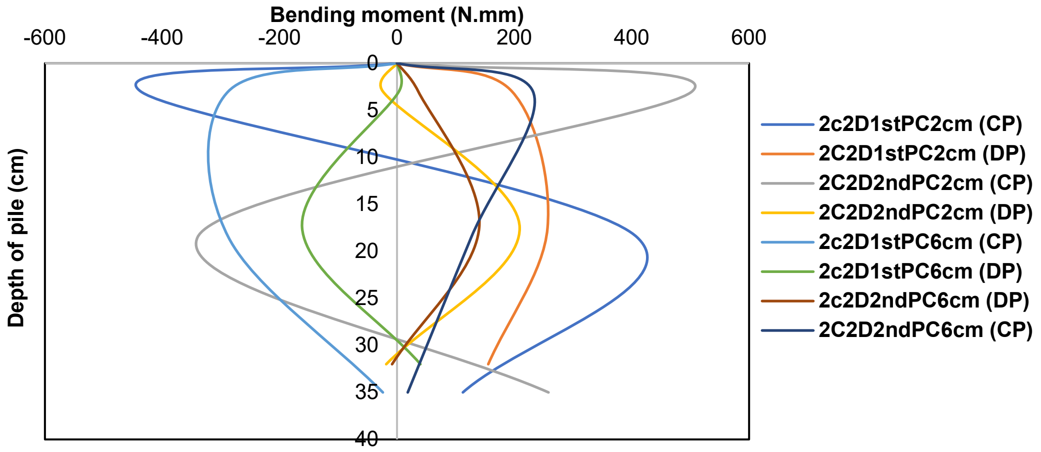

Figure 18. Variation of bending moment with the depth of pile for 2C2D1stP and 2C2D2ndP patterns (connected and disconnected).

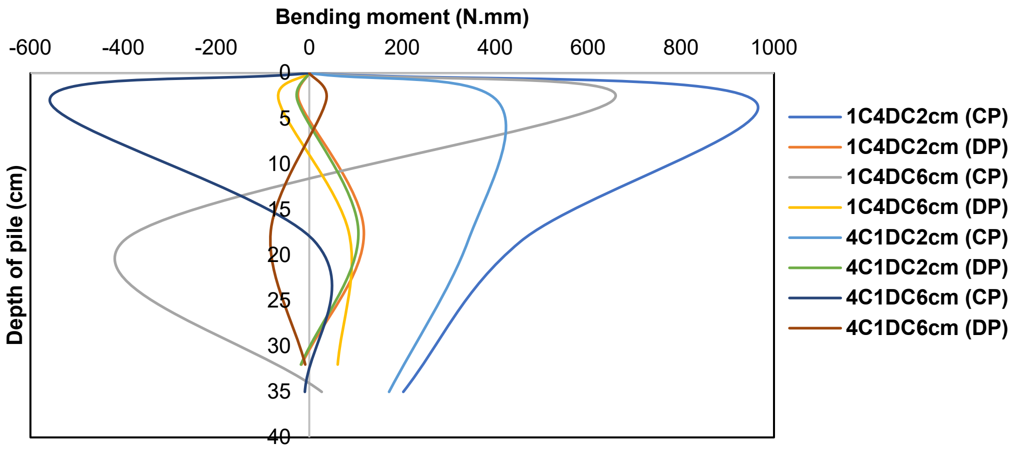

Figure 19. Variation of maximum bending moment with the depth of pile for 4C1D and 1C4D patterns (connected and disconnected) piles.

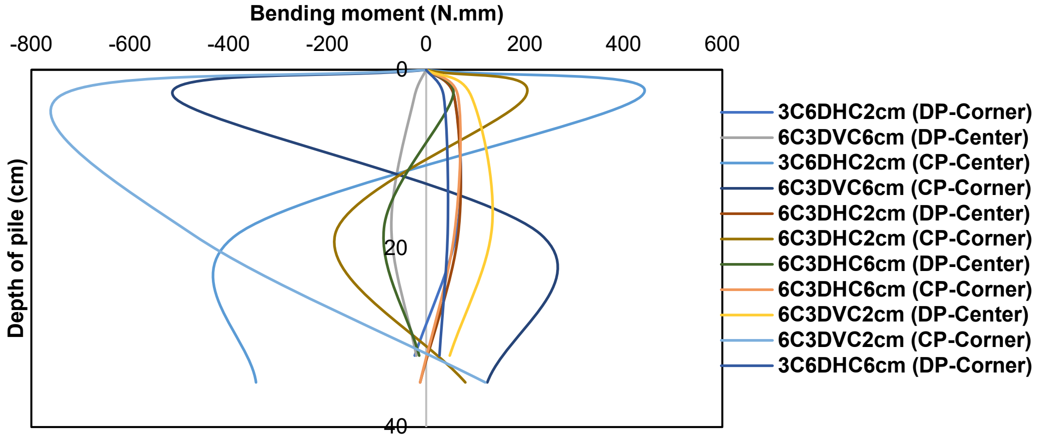

Figure 20. Variation of maximum bending moment with the depth of pile for 3C6DH, 6C3DH, and 6C3DV patterns (connected and disconnected) with RFO.

The acceleration induced by earthquake input motions on the base of the shaking table (Acc1) and within soil layer strata were measured using three digital accelerometers: Acc4 at a depth of 20 cm, Acc5 at a depth of 30 cm, one accelerometer at a cushion layer (Acc3). Also, additional accelerometer was placed on the top of the foundation surface (Acc2). The experimental results of the acceleration variation along the pile depth are presented in Fig. 21–24. For the single pile condition as shown in Fig. 21, the applied acceleration on the base of the shaking model is ranged from 0.31 to 0.38 g. For the CP, the model 1C39cm is recognized as the lowest value of acceleration 0.34 g on the top surface of the foundation.

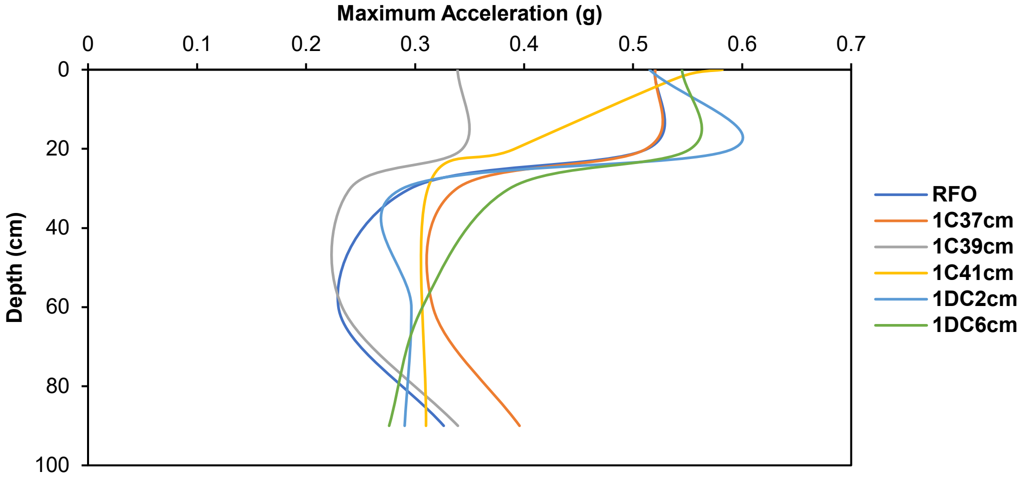

Figure 21. Variation of acceleration with the depth of pile for single pile patterns (connected and disconnected) compares with RFO.

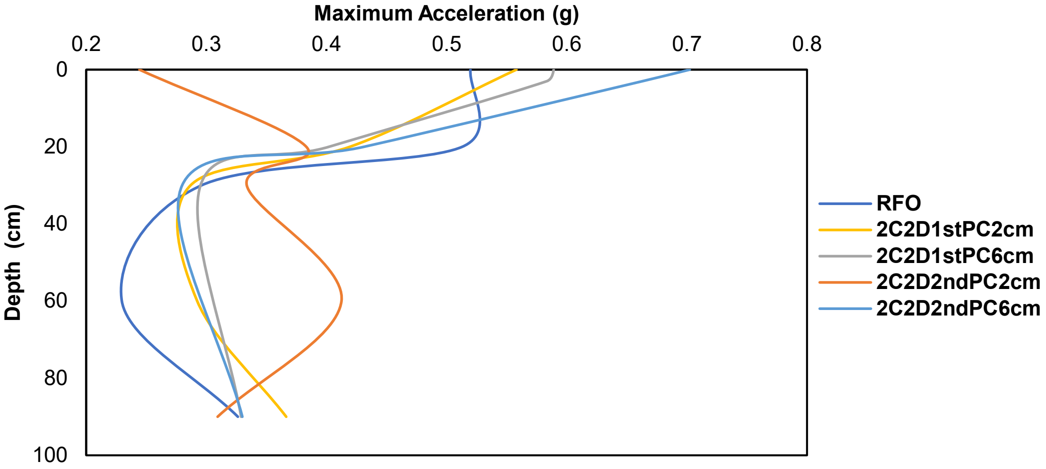

Figure 22. Variation of acceleration with the depth of pile for 2C2D1stP and 2C2D2ndP patterns (connected and disconnected) piles compared with RFO.

The DP 1DC6cm is recognized as the highest value of acceleration 0.544 g. Increasing the thickness of the cushion increased the stiffness of the system, which caused an increase in the value of the acceleration through the cushion layer. For DP conditions, the seismic response of the DP raft foundation system decreased the acceleration as the thickness of the cushion layer increases. This is due to the de-amplification of the raft motion to the free-field ground response. Here, two behaviors of the raft foundation (sliding and kinematic behavior) were observed [18–25]. As shown in Fig. 21 and 22, the seismic acceleration response below the soil depth of 30 cm is less than the acceleration at depth of 20 cm below the soil surface due to the effect of soil pressure. The pattern 2C2D2ndPC6cm showed the highest acceleration on the top of the foundation. At the same time, the pattern 2C2D1sPC6cm with the same cushion thickness had the same acceleration 0.589 g through the cushion and top surface of the foundation.

For the five piles patterns, it is observed from Fig. 23, the reduction in the seismic response (acceleration effect) of the raft (Acc3) for the pattern 1C4D with a cushion thickness of 2 cm and less reduction with cushion thickness of 6 cm. During a strong earthquake (peak ground acceleration of more than 0.35 g), the main reason to reduce the acceleration of the raft foundation is due to the kinematic interaction than due to the sliding behavior of the raft foundation. The patterns 1C4D and 4C1D with a cushion thickness of 6 cm showed less variation between the acceleration of the cushion layer and raft foundation surface. For the nine pile patterns, as shown in Fig. 24, the results were in reasonable agreement. It is confirmed that, when the number of connected piles was more than the number of disconnected piles in the system, there was less variation between the acceleration recorded in the cushion and raft foundation surface. This variation also depended on the cushion thickness. The higher thickness of the cushion layer showed more reduction as noted with the patterns 6C3DH and 6C3DV. The pattern 3C6DHC2cm displayed the lowest value of acceleration in the cushion layer. The pattern 6C3DVC2cm displayed the lowest value of acceleration on the surface of the raft foundation. This is due to a straight relationship between the thickness of the cushion layer and the stiffness that relates to the number of connected piles.

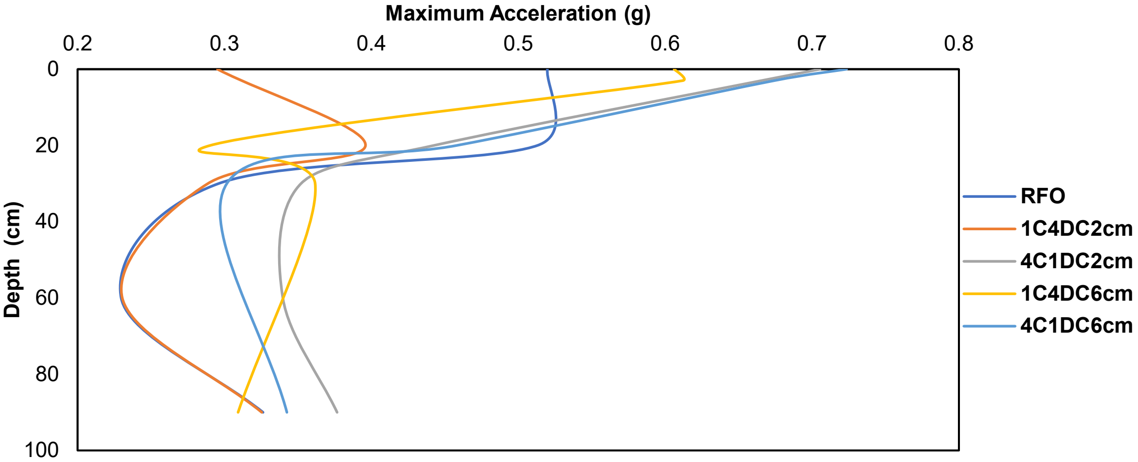

Figure 23. Variation of acceleration with the depth of pile for 4C1D and 1C4D patterns (connected and disconnected) piles with RFO.

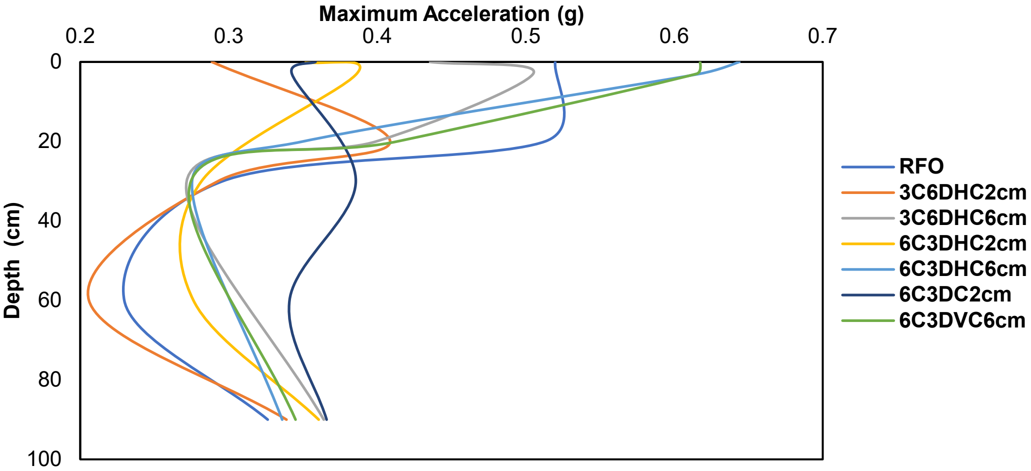

Figure 24. Variation of acceleration with the depth of pile for 3C6DH, 6C3DH, and 6C3DV patterns (connected and disconnected) piles.

4. Conclusions

In this study, the seismic response of the partially connected single and a group of piles under different static loads was evaluated using shaking table centrifuge tests. An experimental model was designed to depend on a virtual prototype dimension. Single and groups of 1, 4, 5, and 9 piles under different patterns for connected and disconnected piles were made from aluminum material. Two thicknesses of cushion layer were used in this study. Earthquake model tests were conducted by calibration depending on data of peak ground acceleration (0.35 g) of El Centro earthquake. Based on the results of the horizontal and vertical displacements, and acceleration of the piled raft foundation system with the seismic bending moment analyses, the following findings and observations were summarized:

- The DP as a single pile or group of piles can appear with less seismic acceleration and bending moment during strong earthquakes. Due to the structural connection of the foundation-pile-soil system, the CP appeared high values of the seismic acceleration and bending moment.
- The connection between the pile's head and the raft foundation was controlling the values of the bending moment. The CP appeared a larger bending moment at the top of the pile while the DP always appeared the maximum bending moment at the mid part of the pile length within partially connected piles. This is depending on the structural connection for each pile, whether it is fixed-free or free-free ends. For single DP conditions, increasing the cushion thickness reduced the variation of the bending moment. For single CP conditions, increasing the length of the pile increased the variation of the bending moment. The reduction in the bending moment of the DP within the partially connected piles group depended on the number of CP within partially connected piles group when the thickness of the cushion layer was increased. The CP in the center and corner had larger bending moments for the patterns 1C4D and 4C1D, respectively. For the pattern 3C6DH, the CP in the center had a larger bending moment than the CP in the edge. On the contrary for the same pattern, the DP in the edge had a larger bending moment than the DP in the corner. The DP in the center and edge and the CP in the corner and edge of the pattern 6C3DH showed less difference in the peak bending moment. Also, The CP in the edge and corner presented little difference from the pattern 6C3DV.
- Using a raft foundation only presented a high value of vertical displacement. Increasing the length of a single connected pile decreased the vertical displacement. When the number of connected piles is equal to disconnected piles, increasing the cushion thickness is useless. The advantages of DP for seismic design are concluded in foundation behavior when the number of disconnected piles is more than the number of connected piles.
- The pattern 2C2D2ndP showed less variation in the horizontal movement. For the other patterns, increasing the number of connected piles compared with disconnected piles contributed as an effective way to reduce the horizontal variation of the piled raft foundation system.

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