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Understanding the Dynamic Behavior of Piled Raft Foundation through Previous Studies

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ABSTRACT

The population increase and construction development witnessed by the world in recent years and the exploitation of areas that may have unsuitable soil for constructing high rise buildings. Hence, it is necessity to develop a special type of foundation that can withstand large static and dynamic loads. The piled raft foundation system that depends on the soil-piles-raft interaction phenomenon is very important which was developed to increase the load carried capacity and reduce the settlement. Many types of weak soil are considered to be problematic which should be taken into consideration in geotechnical engineering. Therefore, the researchers studied the behavior of the pile raft system by experimental and numerical methods under static and dynamic loads to understand the mechanism of the load sharing between the foundation compositions as well as to reach the safe design regarding bearing load and settlement.

Keywords:

Weak soil; Piles; Piled-raft foundation; Load sharing; Seismic load.

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1. INTRODUCTION

When constructing any building, it must first make sure of the validity of the recognized types of foundations such as raft foundation. On the other hand, it must start with shallow foundation and if it does not meet the design requirements, it will be transferred to a deep foundation as piles or combined shallow-deep as a piled-raft foundation system. The main benefits of this system are increasing the applied load capacity and reduction in the total and differential settlement. Furthermore, increases the ability of the foundation to resist the lateral load coming from seismic load [1]. The behavior of piled-raft system is very important to be understood in terms of economics and resists the static and dynamic load, which is very complex. Many things must be taken into consideration, including the interaction that occurs between the piles, the soil, and the raft. In addition, how each part of such foundation system is taking the load, which is known as load sharing [2]. The load-sharing ratio means the load carried by piles divided by the total applied load on the piled raft system. This ratio is very important to find out the efficiency of the system and whether it is suitable for the applied load and the specified cost or not. Simulation and finding this ratio are very complex and difficult, especially in numerical methods. When a seismic load occurs, this ratio is more difficult to estimate because the load directions are vertical from the building while it is horizontal from the earthquake. This means that the load-sharing ratio when seismic occurs is expressed by two values; the first value is vertical dynamic load sharing which is estimated as in the static one. The difference between them is just in the summation of the vertical load carried by the piles is considered the dynamic phase. However, the second is lateral dynamic load sharing which depends on the lateral load carried by piles and the applied total lateral load on the piled raft system that comes from the seismic [3]. The horizontal load that comes from the seismic is also called the base shear. It can be determined either by depending on the number and height of building stories in addition to many coefficients using different codes like Indian code IS 2950-1 (1981) and American code ACI 351.3R-18. Alternatively, by summation of the horizontal shear forces carried by raft and piles which calculated using numerical programs among as PLAXIS, ABAQUS, ANSYS and ETABS. This method is useful when the load of the building is simulated as an equivalent uniform load to study the behavior of the foundation. Without any doubt, this system is expensive compared to other types of foundations (see Fig. 1). This foundation performs well in weak soil and is resilient sufficient to support the massive load of a high-rise building, but its cost goes up when earthquake safety is taken into account. The aim of this paper is to collect a number of important works that studied the piled raft foundation system on various types of soils, including clay, sandy and layered soil using experimental and numerical methods under the static and the dynamic loads.

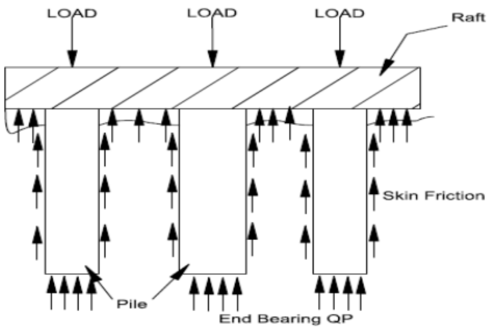


Fig. 1 Load transfer interaction mechanism [4]

2. THE EFFECT OF PILES DIAMETER AND LENGTH IN PILED RAFT FOUNDATION SYSTEM BEHAVIOR

Kamash [5] referred to the effect of pile’s length and was also interested in pile’s diameter using the ASTN III software. The study was about 12 floors of square and rectangular buildings and the total vertical load from the building is 101.265MN in addition to the seismic force. It was found that the increase in the pile’s diameter from 0.6m to 0.8m and from 0.6m to 1m caused a decrease in the settlement at the center of the building by 24% and 43% respectively with the pile’s diameter for square building model and 27% and 49 % for rectangular building model. The effect of the model’s shape on the settlement is negligible. The effect of the pile’s diameter is less than the effect of the pile’s length in reducing vertical settlement and lateral displacement for both square and rectangular shapes. The lateral displacement increases with pile’s diameter decrease. 0.6m diameter has greater lateral displacement compared with 0.8m and 1m by 24% and 40% in square while 30% and 52% in rectangular shape. The rectangular raft has a settlement of more than the square raft about 39%, 32% and 28% for 0.6m, 0.8m and 1m in diameter respectively. The bending moment increases with the increase in the diameter of piles regardless if the model is rectangular or square. The vertical applied load on piles does not only increase by increasing the pile’s diameter but also the positions of piles have a significant effect. About the effect of piles length, it was used 16m, 20m and 24m. It was found that the central, differential and lateral displacement decreases with pile’s length increase. The difference of vertical settlement between rectangular and square is negligible for the different pile’s length.

Juneja et al. [6] studied the asymmetry pile’s length that varied between central piles and outer piles by experimental static load test and theoretical equations. It was found that increasing the length of central piles and number of the piles causes an increase in the load-sharing ratio, where the central pile’s length has a significant effect on the load-sharing. Meanwhile, the increase in the central pile’s diameter has an insignificant effect on the load sharing.

Chang et al. [7] used an explicit finite difference scheme and validated it by MIDAS GTS program to investigate the earthquake effect on the piled raft foundation system. The main three parameters studied were pile’s diameter, pile’s length and pile’s number. The smaller diameter gave a smaller foundation displacement but the relative displacement displayed a large value between the foundation and the soil. By decreasing the embedment of the piles causes a slightly increase in the displacement and decreases the relative displacement between the foundation and the soil.

Bagheri et al. [8] by numerical study, using ABAQUS studied the effect of seismic load on the interaction between piles, soil and structure. The verification was carried out by comparison between ABAQUS results and shaking table test results on soft clay soil. High-rise buildings have 15 and 30-storey with raft simulated as a fixed base foundation and piled raft as asymmetry piles in length and diameter. It was found that the base shear force was 61% larger in the 28m pile length compared to the 10m for the El Centro earthquake and 24% for the Northridge earthquake. In general, the lateral displacement of the 28m pile’s length was lower than that exhibited by the 10m pile length under the El Centro, Hachinohe and Kobe seismic loads but only the Northridge earthquake for 30 story gave convergent values. The 2D and 3D models gave the same values for lateral displacement in fixed base but for the case of shallow foundation, it was found that the lateral displacement depends on the seismic intensity. In high seismic intensity, the lateral displacement gave the same values. Meanwhile, at the low intensity, the values were different. Finally, it concluded that the pile’s configuration, pile’s length, pile’s diameter and the high of super structure have a significant impact on the piled-raft foundation behavior that is subjected to different seismic forces.

Roy et al. [9] studied the piled raft system as an analytical Winkler model by springs with centrifuge test validation to find the effect of harmonic vibration on natural radial frequency. It was found that the natural radial frequency decreases with the increased length of piles due to the effect of pile’s stiffness. The increase in the number of stories caused an increase in the system’s stiffness that caused a decrease in natural radial frequency. The effect of pile’s diameter was indistinguishable as seen in Fig. 2.

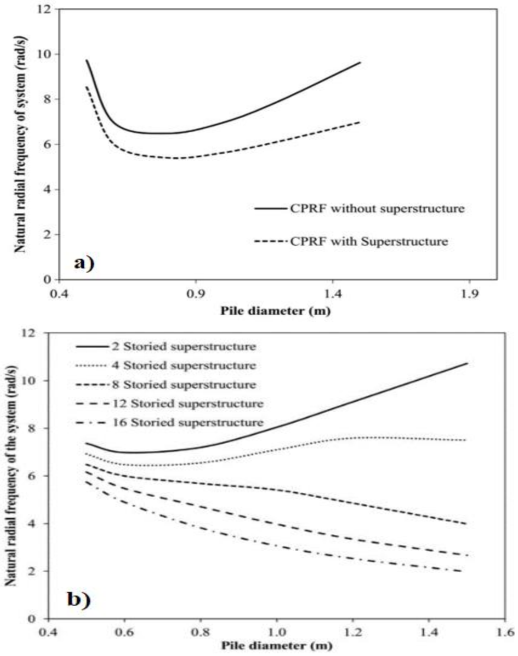


Fig. 2 Influence of pile’s diameter on natural radial frequency a) comparison between with and without superstructure. b) with superstructure of different stories [9].

Beygi et al. [10] focused on the effect of pile’s length on the behavior of PRFS under the static load using PLAXIS 3D program. The water table was variable; the raft dimension was 10mx6mx0.35m and the pile’s lengths were 0, 5, 10, 15 and 20m with 0.5, 0.75 and 1m in diameter. It was found that the bearing capacity increases and the displacement at the center of the raft decreases due to the increase the pile’s length. A higher settlement was obtained when the water table was at the ground surface compared with no water table. The settlement deference has convergent values when increasing the length of the piles up to 15m. In addition, the increase in the pile length of more than 15m, leads to reduce the effect of the changes in water level.

Chaudhuri et al. [11] conducted a 3D numerical study using ABAQUS to examine the effect of seismic load on very soft clay on the steel piled-raft foundation. The length of piles varied between 5m and 20m with different configurations for asymmetry pile’s length. The asymmetry pile’s length caused an increase in lateral shear force in connection piles-raft point compared with symmetry length. This may be due to an increase in force in the asymmetry length of piles that causes a torsional mode of vibration in higher modes. The asymmetry piles length also caused more increase in the lengthening of the fundamental period compared with symmetry piles length. This may be due to a decrease in the lateral stiffness of the asymmetry foundation system compared to the symmetry foundation system.

El Attar [12] studied the effect of pile’s length subjected to the TOHOKU earthquake in addition to vertical load with the aid of the ABAQUS program. The lengths of piles used were 15m, 20m and 25m embedded in layered soil. It was found that the axial load increases with increasing the pile’s length. This system with longer piles and less number was more efficient than a system with more numbers of piles and shorter lengths. Higher bending moment indicated at the connection area of the pile and the raft especially in the longer piles, which attributed to the increase in the carrying load and the shear as well as the higher displacement in the soil in the case of the longer piles under the seismic force.

Xie et al. [13] used ANSYS program to simulate a soil with 35 layers of a different shear modulus and different damping ratio. The piled raft foundation simulated as shown in Fig. 3 with different spacing and different diameter. The model that was used had better design of PRFS by using different diameters compared with using different spacing in the event of an earthquake. The rocking decreases with static optimum design. For example, it changed from 0.0203 to 0.0168 by optimum diameter, while it changed from 0.0203 to 0.0198 by optimum spacing. This results indicated that not only the spacing or diameter have influenced on the rocking but also the irregular resistance of piles distribution under the raft is the reason to decrease the rocking in addition to decrease the effect of rocking on superstructure. The static optimum design of piles caused less acceleration in the base which in turn, decreased the displacement. The optimum design has a small effect on amplification factor of soil on the input earthquake wave but it has a good effect on amplification of the superstructure that affects the acceleration magnification coefficient.

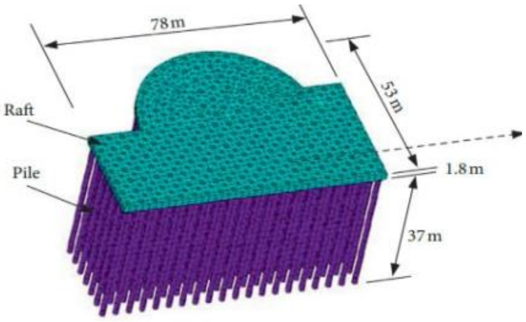


Fig. 3 Dimensions of piles and raft [13]

Moayed et al. [14] investigated the behavior of PRFS by using different dimensions of piles. The load is unequal vertical static load equivalent to a high-rise building with different soil types such as soft clay, medium clay, medium sandy clay, dense gravel and very dense gravel with two layers. In general, the differential settlement occurs might occur due to many factors such as the non-uniform distributed load on the foundation (Fig. 4), different types of soil under the foundation, different dimensions or characteristics of foundation under buildings, etc. It was found that the piles with different diameters under unequal load behaved well regarding in piled raft operation more than uniform piles diameters due to more carried load capacity under larger applied load position that caused lower settlement. In addition to the effect of soil type with different pile diameters as shown in Table 1 that the model with soft clay at the top layer and very dense gravel at the bottom layer was more stable than other types of soil layer. The piles with different diameters are more effective for reducing settlement and differential settlement when dense soil is at the bottom. If the bottom layer of soil is soft clay, the pile's diameters will have an insignificant effect on maximum settlement and differential settlement and using longer piles could be more useful.

3. THE EFFECT OF PILES NUMBER AND SPACING ON PILED RAFT FOUNDATION SYSTEM BEHAVIOR

Fattah et al. [15] studied experimentally the behavior of the piled raft foundation resting on different sandy soils densities. The piles groups were as (1x2, 1x3, 1x4, 2x2, 2x3, 2x4, 3x3, 3x4, and 4x4) under cases of free-standing piles and contact raft. The load failure is greater about one time in PRFS of the contact raft compared with the free-standing piles group when the number of piles is 9. When 16 piles were used, the difference between foundation types increases to four times. When the number of piles is more than 6 the system can be considered as a settlement reducer. The settlement increased to 8 times in group piles compared with PRFS of 1×2 model. When more than 6 piles were used, the effect of piled-raft on the settlement was decreases. As the number of piles increases from 4 to 16, the piled-raft system's bearing increases from 11% to 56% relative to the un-piled system as well as the pile's load sharing increases as its number increases; a pile of 16 has a load sharing that is five times more than a pile of 4 [16].

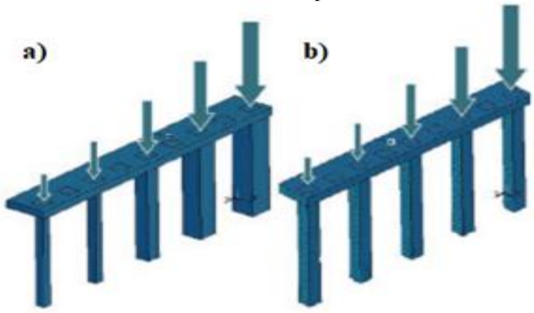


Fig. 4 Unequal applied load on the piles a) different pile's diameter and b) uniform piles diameter [14].

Table 1: Soil layers used [14].

No. of model	Top layer	Bottom layer
1	Soft clay	Very dense gravel
2	Soft clay	Dense gravel
3	Soft clay	Medium sandy clay
4	Soft clay	Medium clay
5	Soft clay	Soft clay
6	Medium sandy clay	Very dense gravel
7	Medium sandy clay	Dense gravel
8	Medium sandy clay	Medium sandy clay

Jayarajan and Kouzer [17] investigated the piled raft foundation behavior by numerical analysis using PLAXIS 3D. The raft is square 12m×12m×0.5m. The piles numbers are 4, 8, 12 and 16 piles of different configurations under static uniform load. It was concluded that the increased number of piles causes an increase in load carried by the piles and a decrease in settlement until the optimum upper limit that no benefit for adding more piles than a specific number. The increase the number of piles caused an increase in the bending moment, especially in piles-raft connection points.

Elsamee [18] studied the effect of pile's spacing on ultimate load capacity and load sharing for PRFS and piles group. The study was done by experimentally and numerically using models with load cell and PLAXIS 3D respectively for dense sand. The pile's spacing that was chosen is 2, 3, 4, 5, 6 and 7 times the pile's diameter (d). The ultimate capacity of the piled raft increases with the increase in the spacing between the piles but for the piles group, the behavior is reversed after the spacing becomes more than 4d. The load carried by skin friction of piles increases with the increase in the pile spacing in the pile group but in piled raft the behavior is the same until the spacing is more than 4d the behavior changes to the opposite. The end-bearing load carried by piles for both piled raft and piles group decreases with increasing the piles spacing.

The work of Sharafkhah and Shooshpasha [19] compared the piled raft, piles group and unpiled raft by physical laboratory tests. The main parameter in this study is the pile number comprised of a single pile, 2x2, and 3x3 for both piled raft and piles group in sandy soil. When the load is uniform on all the raft's area the raft is in higher bearing capacity because of the increase in confining pressure under the center of the raft before failure. When the 2x2 piles are used, the piles bear an equal portion of the load because of the symmetrically distribution. The contact pressure below the raft is uniformly distributed more than the other models. The 3x3 piles have a different behavior; firstly, the piles carry the major portion of the applying load until the piles fail then the raft's contact pressure suddenly increases from the corner to the center. The stiffness of central pile is small due to the interaction effect that causes an increase in pressure at the center of raft. The bearing capacity of piles is larger in piled raft more than the group of piles but the stiffness is smaller. By increasing the number of piles, the settlement decreases and the load-settlement curve in the initial step of loading becomes steep but when the piles fail, more load transverse to the raft causes the load-settlement curve to be similar to the curves of unpiled raft. By increasing the spacing/ diameter ratio from 2.6 to 5.2, the load sharing by piles decreases from 87% to 71%.

Karmakar et al. [3] simulated the combined piled raft foundation system by a 3D finite element model using SAP-2000 in addition to a centrifuge experimental model for validation. The vertical and horizontal load sharing were studied because of its importance especially in the dynamic case. The results revealed that the vertical and horizontal load sharing is not affected by the frequency of superstructure but it increases by increasing the number of piles. In addition, there were some peaks in vertical and lateral displacement with some frequencies due to the approach of the frequency of dynamic site with the frequency of soil-structure. This behavior was in the 24 and 39 piles number but when increasing the number to 77, both displacements showed uniform displacement. It may be that the effect of frequencies closeness decreases with increasing the number of piles as shown in Fig. 5.

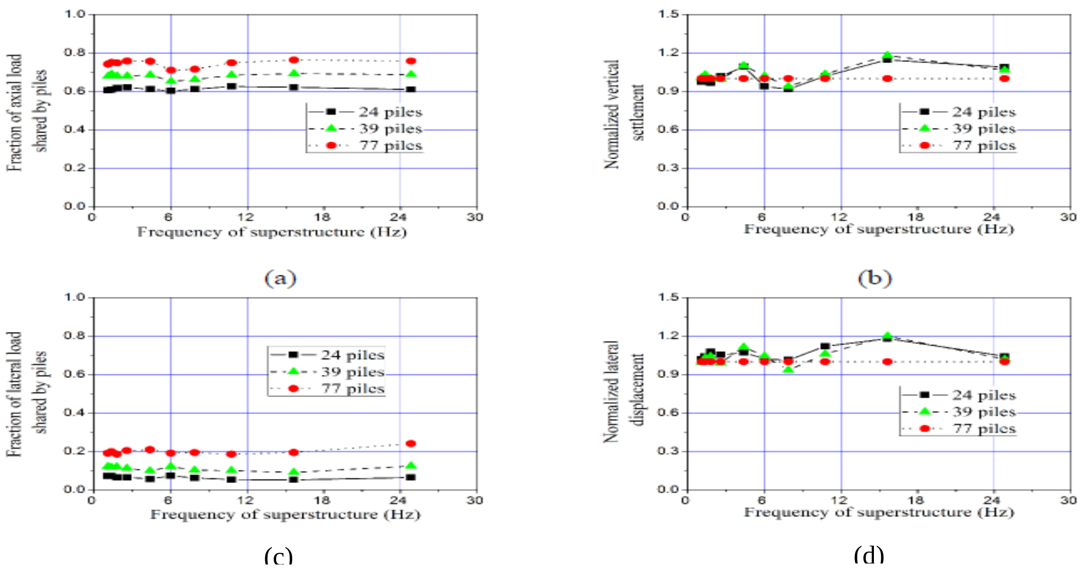


Fig. 5 The effect of frequency of superstructure with different configuration of number of piles on (a) axial load shared, (b) normalized vertical settlement, (c) lateral load shared and (d) normalized lateral displacement [3].

Nguyen et al. [20] performed the analysis of PRFS by numerical analysis using CIS SAFE software. The raft thickness and number of piles were studied and there is a main point that reached about the pile's number. It was found that the average settlement and differential settlement decrease with increasing the number of the piles for the minimum thickness of the raft, however, there are limits to the number of piles, which give no more effect on the differential settlement as shown in Fig. 6.

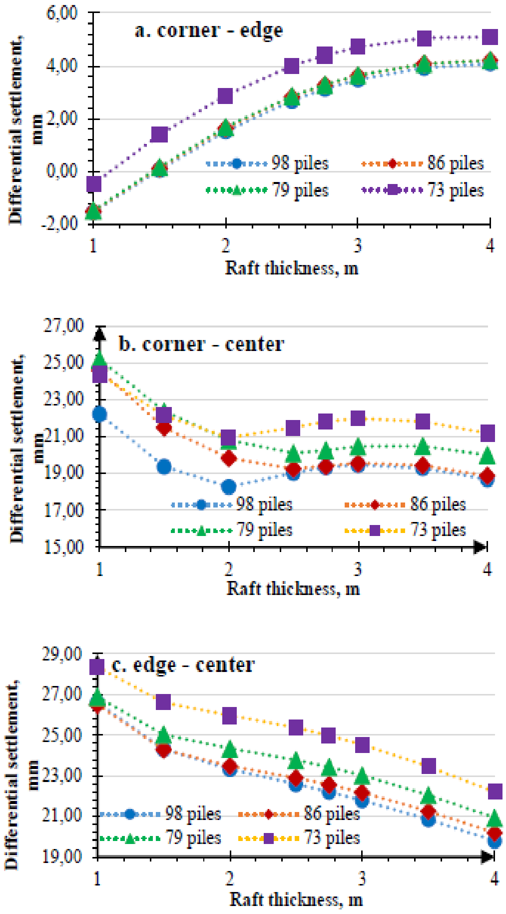


Fig. 6 Variation of differential settlement with raft thickness [20].

A 3D numerical study was carried out by Ferchat et al. [21] on the PRFS in addition to a group of piles and unpiled raft foundation using FLAC^{3D} program considering different spaces between the piles. It was found that the increased in the number of the piles causes an increase in the load-carried capacity of the piled raft system and the spacing between piles has a significant effect on this behavior. The number of piles has a more significant effect on the load-settlement curve and bearing capacity than spacing between piles.

4. THE EFFECT OF PILES POSITION ON PILED RAFT FOUNDATION SYSTEM BEHAVIOR

The behavior of the piles is influences by their position in the PRFS as well as regarding the seismic load direction. The piles at the edge which is opposite to the direction of the earthquake load have carried larger lateral load compared with central piles and edge piles on the other side of the seismic load as shown in Fig. 7.

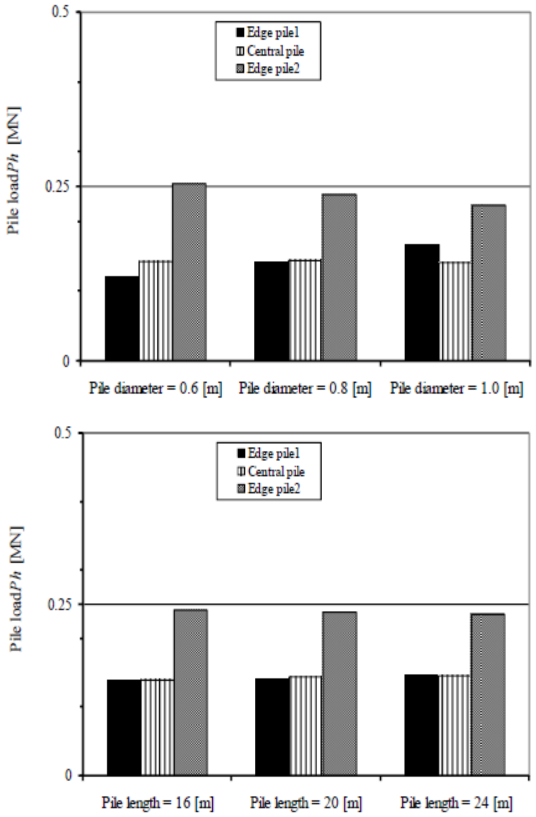


Fig. 7 Variation of pile load resistance with pile diameter and pile length [5].

The earthquake has a big impact on the bending moment but this effect varies with the location of the piles. Shafiqu and Sa'ur [22] studied the effect of pile's position by numerical analysis using PLAXIS 3D considering the effect of the Hallabjah earthquake on different soil types from different sites in Iraq. The largest earthquake to ever strike Iraq happened on November 12, 2017, in Halabjah, Sulaymaniah Province, with a magnitude of 7.3 MW. As shown in Figs. 8 and 9, the piles A, B, C and D are studied, the piles B and D have a significant effect on bending moment especially B because it is opposite to the seismic wave direction. The bending moment is larger at the pile's head (pile-raft connection point) or at 5-15% of the pile's depth measured from the top. The type of soil is a very effective factor because the value of the bending moment in all the piles and the settlement of the raft were larger in cohesion soil compared to the cohesionless. The shear wave velocity had higher values for the cohesion soils compared to the cohesionless.

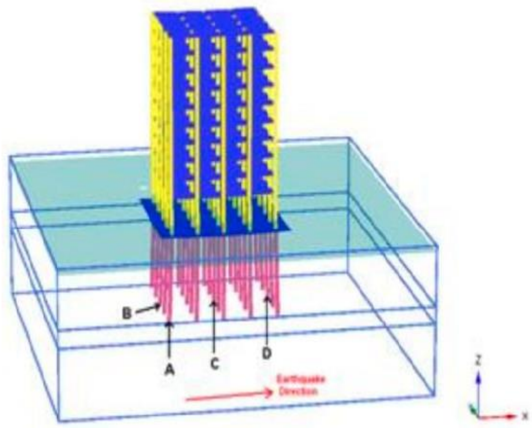


Fig. 8 Model of piled-raft and the piles positions [22].

The mechanism of the piled raft foundation has a significant effect on the behavior of piles. The position of piles and settlement level are very important to study the load carried by piles. The load carried at initial settlement 0.2% Br (width of the raft) was the larger at corner pile compared to the edge piles.

The piles at the center carried the smaller portion of the load. After the load is ultimate at settlement 10% Br, the carried load by all piles increases and be more closely related to each other and is larger at the center piles due to the pressure at the group's center as shown in Fig. 10.

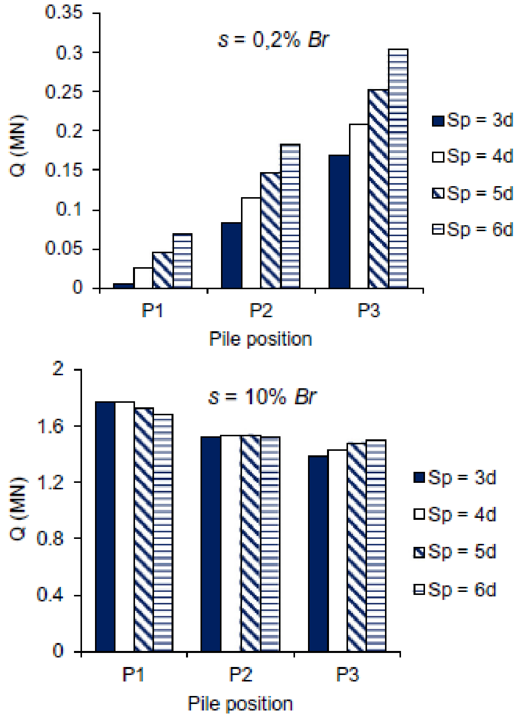


Fig. 10 The load carried by piles according to it is position and percentage of settlement (P1 is the pile at the center, P2 is the pile at the edge and P3 is the pile at the corner) [21].

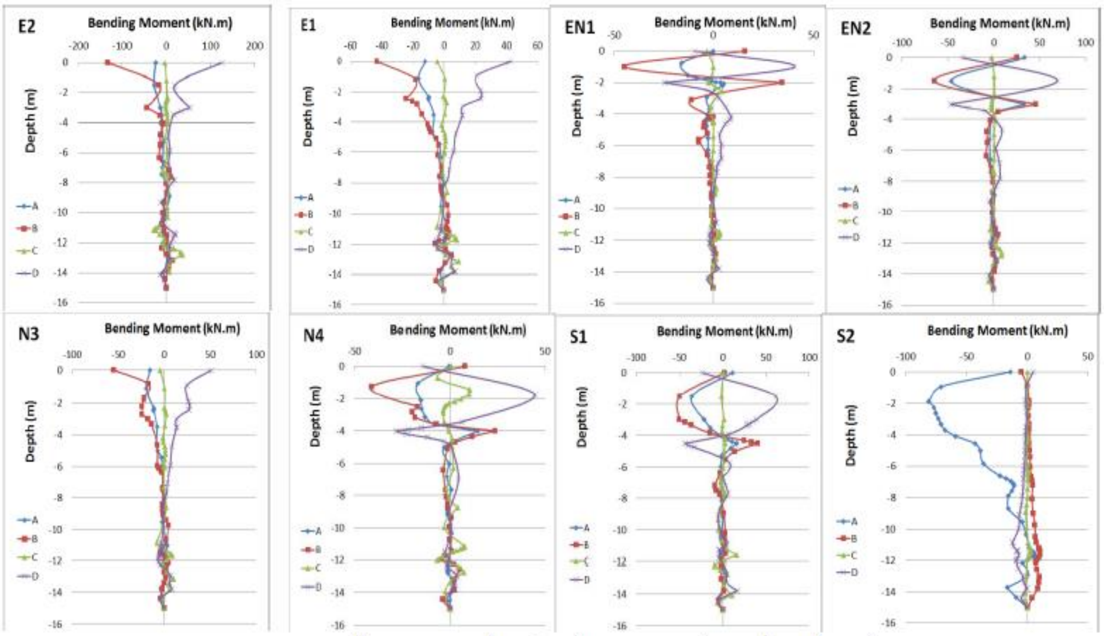


Fig. 9 Bending moment with different pile's position and different sites [22].

5. THE EFFECT OF RAFT SHAPE AND DIMENSIONS ON PILED RAFT FOUNDATION SYSTEM BEHAVIOR

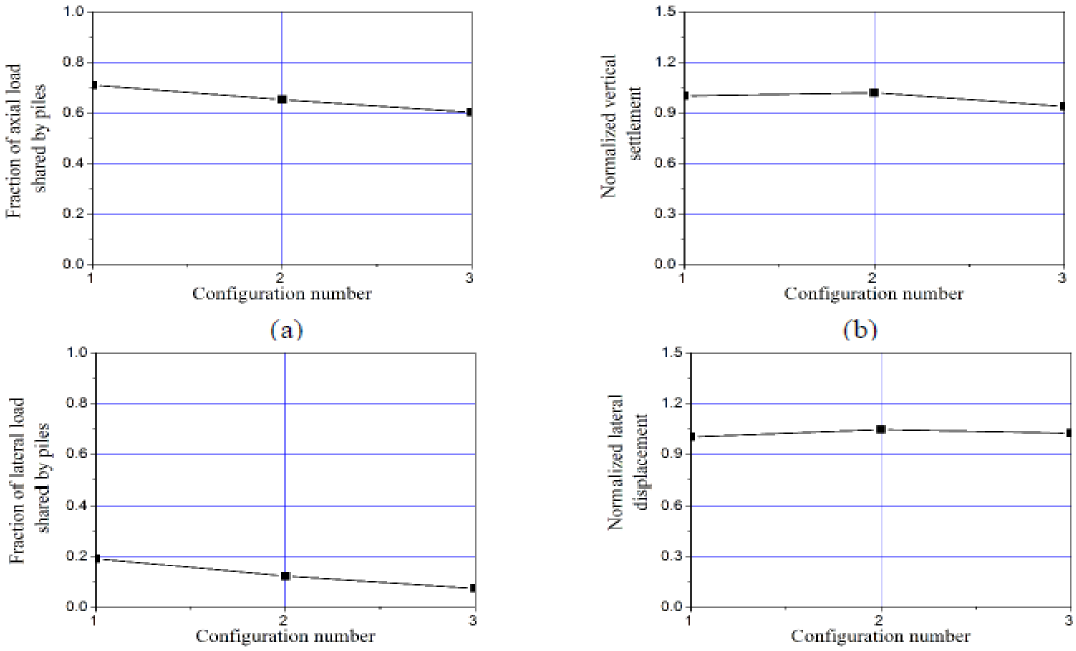
The raft has an insignificant effect on the settlement reducing when the number of piles is greater than 6. For loose, medium, and dense soil, the static ultimate load carrying capacity increases by around 93%, 96%, and 98% respectively, when the raft dimensions and the number of piles is increase from the 3×3 piled raft model to the 4×4 model. The effect of raft dimensions on settlement and failure load was more significant in the PRFS compared with both the unpiled raft and piles group [15].

The raft thickness has slightly affected the average settlement. The differential settlement was recorded at the different locations. The raft thickness has an effect up to the specific value and then has an insignificant effect on the differential settlement as shown in Fig. 6. The raft thickness has does not affect on the load shared between the piles and the raft. The bending moment of the raft increases and the surface pressure at the raft bottom decreases with increasing the raft thickness. In general, the distribution of static load from the structure to the piles is irregular; it was found that by increasing the raft thickness, the piles' reactions at the center area decreases, while it increases at the perimeter and other area. On the other hand, the increase in raft thickness causes a regular redistribution static load from the structure that was carried by the piles [20].

Nashaat [23] used both steel and concrete rafts to examine the impact of raft rigidity on load sharing through numerical and experimental methods. The load shared by piles increased by (28.3-53.67)% and the load shared by soil decreased by (27.3-36.85)% as a result of the rigidity of the raft. It is recommended to use a raft that is at least twice as thick as the pile's diameter. An increase in raft thickness affects the load transferred by piles substantially depending on the type of connection between the raft and the piles. When the piles are not attached to the raft, the raft stiffness has no influence; however, when it is, the load carried by the piles increases with the raft rigidity [24].

As shown in Fig. 11 the raft thickness has an insignificant effect on both the axial and the lateral load sharing. The axial and lateral displacement decreases with increasing the raft thickness to a specific value and it becomes ineffective with the continuing increase in the thickness [3].

In general, the raft thickness is not very effective in PRFS, especially with the minimum spacing between piles. The acceleration, vertical load on the foundation system and lateral displacement do not change obviously with different raft thickness. For the same spacing between piles, the increase in raft thickness caused significant effect on load shared by raft but the load shared by piles and the bearing soil also did not change obviously [12].



(c) (d)

Fig. 11 Variation of the Lateral load share and displacement with raft thickness [3].

Bhartiya et al. [25] used a numerical method to evaluate the nonlinear behavior of the piled-raft foundation as an alternative method for the hand-calculation. An investigation was conducted on the impact of raft shapes, including strip, rectangle, and circle, on the settlement of various types of sand soil. It was found that the choosing raft's shape has an important effect on the static settlement of the piled raft foundation. The circular raft with a circular configuration of the piles below the raft has the a small differential settlement. The differential settlements in rectangular and strip shapes were 10% and 20% respectively of the average settlement. According to Azizkandi and Taherkhani [26], the geometric shape of the foundation has an impact on its settling as well as its bearing capacity. The results showed that square foundations were capable of bearing greater loads than circular foundations. A circular foundation's wedge has a more uniform structure throughout, whereas a square foundation's wedge is formed on the side that carries the eccentric load.

6. THE EFFECT OF WATER TABLE ON PILED RAFT FOUNDATION SYSTEM BEHAVIOR

Meena and Nimbalkar [27] care about the effect of the water table on the PRFS under the seismic load in addition to static vertical load in layered soil using PLAXIS 2D program. The water level was at 6m, 12m and 18m from the ground surface with some cases of arranging the soil layers. In the first case the clay is underlain by sand, it was found that the ultimate settlement was 18.85mm, 23.6mm and 22.8mm respectively with the water level. As shown in Fig. 12 all water levels give the same trend and there is a change in the interface line because of the change in soils property. At the consolidation phase, the settlement was 3.5mm, 4.3mm and 4.4mm. In second case, when sand is underlain by soft clay as shown in Fig. 13 the ultimate settlement was 209.2mm, 198.4mm and 191.6mm respectively with water level. At the consolidation phase, the settlement was 5.3mm, 5mm and 4.8mm. In addition to the effect of water level on ultimate settlement, it also affects the peak ground acceleration. The peak ground acceleration was increased by 20% when the water level at 18m upon that when at 12m and 6m.

The differential settlement decreases with the increase in the ratio D_w/B (the depth of the water level from the surface /width of the raft) from zero to 2 and when the ratio is up to 2 it has an insignificant effect as shown in Fig. 14. The load sharing increases with increase the D_w to its optimum value and then has an insignificant effect and this behavior is clearer by increasing the length of piles as shown in Fig. 15.

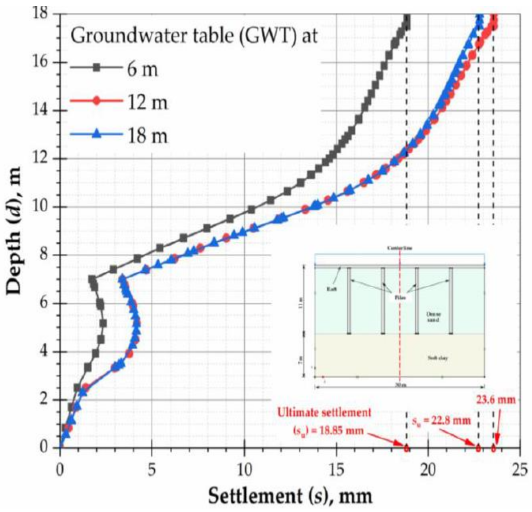


Fig. 12 Ultimate settlement with different water table for sand underlying soft clay [24].

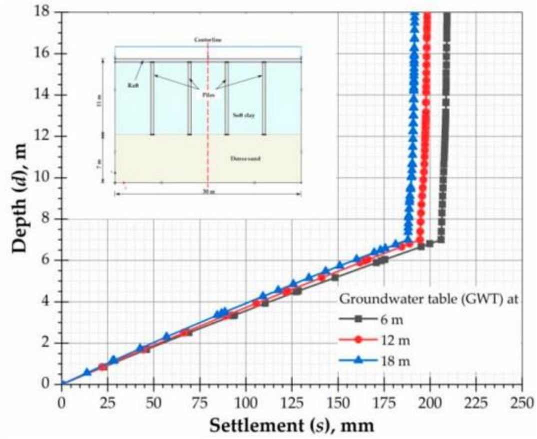


Fig. 13 Variation of settlement with the water table [24].

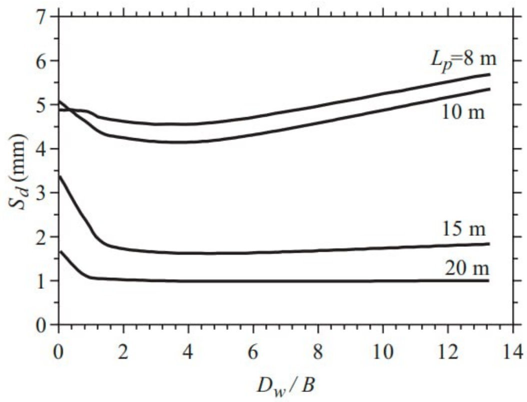


Fig. 14 Effect of water level on settlement for different lengths of piles [10].

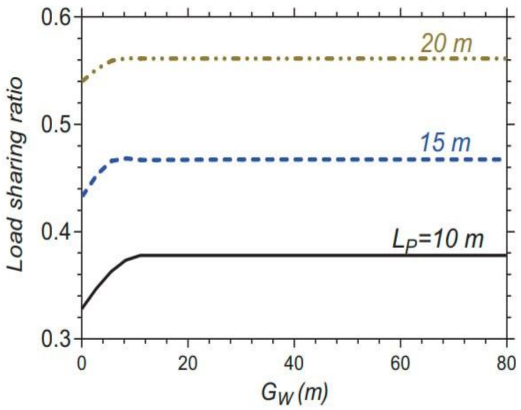


Fig. 15 Effect of water level on load-sharing ratio [10].

7. THE EFFECT OF SEISMIC INTENSITY ON PILED RAFT FOUNDATION SYSTEM BEHAVIOR

Kumar et al. [2] interested in the effect of different seismic loading on both lateral displacement and the bending moment. The El-Centro, Loma Prieta, Bhuj and Sikkim earthquake were used by numerical method analysis using the PLAXIS 3D program. The characteristics of the aforementioned earthquake are presented in Table (2). The verification was carried out by experimental centrifuge test for some models in addition to the numerical study. The piled raft foundation model was 28m×28m×16m for soil media with raft 4mx4m in addition to four piles. The case study was about the Messetrum tower as a complex model that shown in Fig. 16. It is noteworthy that, when compared to all other normalized displacements seen under various input motions, the normalized horizontal displacement acquired during the motion of the Loma Prieta 1989 earthquake was the largest. This can be explained by the resonance condition, which was not present in any of the previous instances. In the case study, the bending moment and normalized lateral displacement gave the maximum values at piles raft connection points (pile head).

Halder and Manna [28] look after the effect of seismic intensity by the pseudo static load for Uttarkashi (1991) and Sikkim (2011) using finite element method by PLAXIS 3D program that was validated by centrifuge test for the literature. The model is homogenous soil with four piles 9m length and 0.5m diameter and 4mx4m raft. It was found that the lateral displacement and bending moment have larger values with the increase in the load intensity. The load shared by the raft decreases with increased load intensity regardless of the piles-raft connections cases if the connection is rigid or hinged. The values of pseudo-static load sharing by piles varied between (25-57) % and pseudo-static load sharing by raft (43-75) % depending on the piles-raft connection case. The lateral displacement is a maximum at the pile's head for fixed and hinged connections. The bending moment is a maximum and zero at the pile's head in rigid and hinged connections respectively. The maximum value of bending moment in a hinged connection occurs at 2m-3m depth from the embedded pile's length.

Table 2: Details of earthquakes [2].

Earthquake strong motion parameters	Earthquakes			
	Bhuj 2001	Sikkim 2011	Loma Prieta 1989	El-Centro 1979
Peak ground acceleration (g)	0.106	0.201	0.279	0.43
Bracketed duration (sec)	12.44	25.35	15.17	17.64
Maximum horizontal load applied to generic CPRF (kN)	621.4	1178.4	1635.6	2520.8
Maximum horizontal load applied to CPRF of Messeturm tower (MN)	192.7	365.5	507.4	782.0

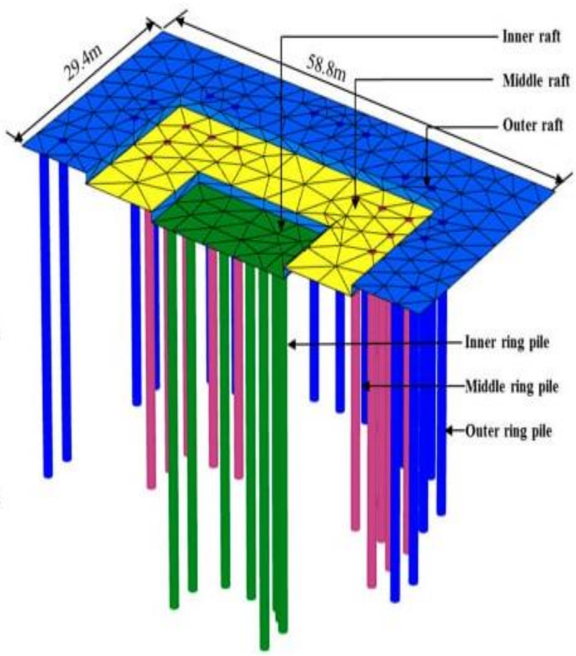


Fig. 16 The piled raft foundation system for Messetrum tower model [2].

8. CONCLUSIONS

This research paper is a collection of previous works that contributed effectively to the development of the piled raft foundation system (PRFS). In general, the studies depend mostly on two methods of analysis and research, either through finite element numerical analysis using important and well-known engineering programs, or through making laboratory models, whether in the case of static or dynamic load. Many parameters have been studied and still need to be developed, including the effect of piles diameter, spacing between piles, and length of piles for symmetry or asymmetry design, raft thickness, raft dimensions, water table, seismic intensity and number of stories. Through these studies, it was concluded that the dynamic loads should be investigated for additional results such as shear strength, moments, differential settlement and average settlement and the most important parameter is the load sharing between piles and raft to get an economical and safe design. The key findings from the previous studies can be summed up as follows:

- Regardless of the raft shape, an increase in the diameter and length of the piles resulted in a decrease in lateral displacement and settling. When it comes to reducing settlement and lateral displacement, pile length has a bigger impact than pile diameter.
- As the diameter and length of the piles increase, so does the bending moment and the axial load.
- The rise in the water table led to an increase in settlement, but this effect may be disregarded if pile length is increased over the upper limit.
- In comparison to the symmetry situation, the asymmetry length of piles has a greater lateral shear force and a longer fundamental period.
- While the number of piles increased, settlement and differential settlement decreased, whereas the vertical and horizontal loads carried by the piles as well as the bending moment increased.
- The load sharing by piles is unaffected by the thickness of the raft; nevertheless, lateral displacement and settlement decline as raft thickness increases.
- It is suggested to use raft thickness that is at least twice the diameter of the piles because the rigidity of the raft increases load sharing.
- The lateral displacement and bending moment have larger values with the increase in the load intensity. The load shared by the raft decreases with increased load intensity.

REFERENCES

[1] J.D. Patil, S.A. Vasanvala, and C.H. Solanki, “A study on piled raft foundation: state of art”, *International Journal of Engineering Research and Technology,* Vol. 2, Issue: 8, pp.1464-1470, 2013.

[2] A. Kumar, D. Choudhury, and R. Katzenbach, “Effect of earthquake on combined pile–raft foundation”, *International Journal of Geomechanics*, Vol. 16, Issue: 5, p.04016013, 2016, doi: 10.1061/(ASCE)GM.1943-5622.0000637

[3] S. Karmakar, R. Ranjan, and V.S. Phanikanth, “Dynamic Load Sharing of Combined Pile Raft Foundation (CPRF) for Reinforced Concrete Structures”, *International Journal of Geotechnical Earthquake Engineering (IJGEE)*, Vol. 11, Issue: 1, pp.17-44, 2020, doi: 10.4018/ijgee.2020010102

[4] S. Ayuluri and B. Vamsi Krishna. “Settlement analysis of Piled Raft Foundation System (PRFS) in soft clay”, *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)*, Vol. 14, Issue: 2, pp. 62-68., 2017, doi: 10.9790/1684-1402086268

[5] W. Kamash, “Analysis of Structures on Piled Raft under Earthquake Excitations”, *Ain Shams Journal of Civil Engineering*, 1, pp.203-2141, 2009.

[6] A. Juneja, A. Tiyagi, and R. Bisht, “Load Sharing in Piled Rafts”, *In Indian Geotechnical Conference*, pp. 1-9, 2013.

[7] D.W. Chang, M.R. Lee, M.Y. Hong, and Y.C. Wang, “A simplified modeling for seismic responses of rectangular foundation on piles subjected to horizontal earthquakes”, *Journal of Geo Engineering*, Vol. 11, Issue: 3, pp.109-121, 2016.

[8] M. Bagheri, M. E. Jamkhaneh, and B. Samali, “. Effect of Seismic Soil–Pile–Structure Interaction on Mid-and High-Rise Steel Buildings Resting on a Group Of Pile Foundations”, *International Journal of Geomechanics*, Vol. 18, Issue: 9, p.04018103, 2018, doi: doi.org/10.1061/(ASCE)GM.1943-5622.0001222

[9] J. Roy, A. Kumar, and D. Choudhury, “Natural frequencies of piled raft foundation including superstructure effect”, *Soil Dynamics and Earthquake Engineering*, *112*, pp.69-75, 2018, doi: doi.org/10.1016/j.soildyn.2018.04.048

[10] M. Beygi, A. Keshavarz, M. Abbaspour, and R. Vali, “3D Numerical Study of the Piled Raft Behaviour Due to Groundwater Level Changes in the Frictional Soil”, *International Journal of Geotechnical Engineering*, Vol. 14, Issue: 6, pp. 665-672, 2020, doi: doi.org/10.1080/19386362.2019.1677326

[11] C.H. Chaudhuri, D. Chanda, R. Saha, and S. Haldar, “Three-dimensional numerical analysis on seismic behavior of soil-piled raft-structure system”, In *Structures*, Vol. 28, pp. 905-922. Elsevier, 2020, doi: doi.org/10.1016/j.istruc.2020.09.024

[12] A. El-Attar, "Dynamic analysis of combined piled raft system (CPRS)", *Ain Shams Engineering Journal*, Vol. 12, Issue: 3, pp.2533-2547, 2021, doi: doi.org/10.1016/j.asej.2020.12.014

[13] Y. Xie, S. Chi, and M. Wang, "Influence of variable rigidity design of piled raft foundation on seismic performance of Buildings," Mathematical Problems in Engineering, vol. 2020, pp. 1–13, Mar. 2020. doi:10.1155/2020/1780197

[14] R. Ziaie-Moayed, M. Kamalzare, and M. Safavian, "Evaluation of piled raft foundations behavior with different dimensions of piles", *Journal of Applied Scientific,* Vol. 10, Issue: 13*: 1320-1325*, 2010.

[15] Y.M. Fattah, M.A. Yousif, and S.M. Al-Tameemi, "Bearing capacity of pile group and piled raft foundations on sandy soil", *Journal of Engineering and Sustainable Development*, Vol. 17, Issue: 2, pp.64-96, 2013, https://www.iasj.net/iasj/article/75372

[16] M.Y. Fattah, M.A. Al-Obayd, and F.A. Al-Jalabi, "Effect of number of piles on load sharing in piled raft foundation system in saturated gypseous soil", *International Journal of Civil Engineering and Technology (IJCIET)*, Vol. 9, Issue 3, pp. 932–944, 2018

[17] P. Jayarajan, and K.M. Kouzer, "Analysis of piled raft foundations. *Indian Journal of Science*", Vol. 16, Issue: 51, pp.51-57, 2015.

[18] W.A. Elsamee, "Effect of pile spacing on ultimate capacity and load shearing for piled raft foundation", *International Journal of Applied Engineering Research*, Vol. 13, Issue: 8, *ISSN*, pp.0973-4562, 2018.

[19] M. Sharafkhah, and I. Shooshpasha, "Physical modeling of behaviors of cast-in-place concrete piled raft compared to free-standing pile group in sand", *Journal of Rock Mechanics and Geotechnical Engineering*, Vol.10, Issue: 4, pp.703-716, 2018, doi: doi.org/10.1016/j.jrmge.2017.12.007

[20] T. Nguyen, P. Le, and V. Tran, "November. The Influence of Raft Thickness on the Behaviour of Piled Raft Foundation", *International Conference on Green Technology and Sustainable Development (GTSD)* pp. 483-488. IEEE, 2020, doi: 10.1109/GTSD50082.2020.9303145

[21] A. Ferchat, S. Benmebarek, and M.N. Houhou, "3D numerical analysis of piled raft interaction in drained soft clay conditions", *Arabian Journal of Geosciences,* Vol. 14, pp.1-12, 2021., doi: 10.1007/s12517-021-06783-3

[22] Q.M. Shafiqu, and R.H. Sa'ur, "Behavior of piled-raft foundation under earthquake loading in various types of soil", *International Journal of Civil Engineering and Technology*, Vol. 9, Issue: 11, pp.2770-2781, 2018.

[23] W. Abd Elsamee, 'Effect of Raft Rigidity on Load Sharing of Piled Raft Foundations', Design Engineering (Toronto), vol. 2021, pp. 2354–2371, Nov. 2021.

[24] F. W. Melese and H. F. Gebregziabher, "Behavior of Structurally Non-connected Settlement Reducing Piles under Raft Foundation", Vo.11, Issue:12, 2021.

[25] P. Bhartiya, D. Basu, and T. Chakraborty, "Nonlinear settlement of piled rafts in sandy soil", *International Journal of Geomechanics*, Vol. 21, Issue: 11, p.04021214, 2021, doi: 10.1061/(ASCE)GM.1943-5622.0002192

[26] A. Saeedi Azizkandi and R. Taherkhani, "Experimental study on connected and non-connected piled raft foundations subjected to eccentric loading," International Journal of Civil Engineering, vol. 18, no. 7, pp. 743–761, Jan. 2020. doi:10.1007/s40999-019-00493-4

[27] N.K. Meena, and S. Nimbalkar, "Effect of water drawdown and dynamic loads on piled raft: two-dimensional finite element approach", *Infrastructures*, Vol. 4, Issue: 4, p.75, 2019, doi: doi.org/10.3390/infrastructures4040075

[28] P. Halder, and B. Manna, "Seismic analysis of piled raft foundation—pseudostatic approach", In *Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions*, pp. 2771-2778, CRC Press, 2019.

فهم السلوك الداينميكي لمنظومة اساس الركائز-الحصيري من خلال الدراسات السابقة

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الملخص

ان الزيادة في عدد السكان والتطور العمراني الذي يشهده العالم في السنوات الاخيرة أدى الى الحاجة في استخدام اراضي غير صالحة للبناء بسبب وجود ترب غير ملائمة للبناء عليها منشات شاهقة. من هنا ظهر اهمية تطوير انواع من الاسس لها قابلية تحمل الاحمال العالية الساكنة والداينميكية. تم استخدام نظام اسس يعتمد على مبدأ التداخل بين التربة – الركائز – والاساس الحصيري والذي يساعد في زيادة قابلية التحمل وتقليل الهبوط. هنالك انواع عديدة من الترب الضعيفة والتي تعتبر ترب اشكالية من وجهة نظر الهندسة الجيوتقنية. واستنادا على ذلك اجريت دراسات عديدة عملية ونظرية على تصرف منظومة الاسس الركائز – الحصيري لفهم ميكانيكية مشاركة الاحمال بين مكونات منظومة الاسس تلك للوصول الى تصميم امن يحقق معايير التصميم من ناحية قابلية التحمل والهبوط.

الكلمات الدالة:

تربة ضعيفة، ركائز، أساس الركائز-الحصيري ، مشاركة الحمل، حمل الهزة الأرضية.