JES, Vol. 52, No. 6, Nov 2024 DOI: 10.21608/JESAUN.2024.301578.1350 Part A: Civil Engineering

Journal of
Engineering Sciences
Faculty of Engineering
Assiut University
JES
مجلة
العلوم الهندسية
كلية الهندسة
جامعة أسيوط
journal homepage: http://jesaun.journals.ekb.eg

Superstructure stiffness effect on the behavior of piled raft under wind and earthquake loadings

Received 4 July 2024; Revised 19 October 2024; Accepted 23 October 2024

Seham Fathy[1]
Ibrahim H. ElKersh[2]
Walid H. ElKamash[3]
Erfan Abd ElLatif [4]

Keywords
Piled Raft Foundations, load sharing, Settlement, Soil structure interaction, Superstructure stiffness

Abstract: Earlier studies relied on simplified methods, assuming uniform or concentrated loads directly transferred from the superstructure to the raft through a fixed boundary condition neglecting the influence of the superstructure's stiffness on the soil-foundation interaction. Consequently, these simplifications result in inaccurate predictions of raft bending moments, pile loads, and overestimation of the reaction forces with insignificant settlement underestimation. In this paper, 3D finite element analyses were conducted for a 20-story building with three different structural systems to study the influence of the superstructure stiffness on the performance of piled raft under wind and earthquake loads. An iterative procedure was undertaken between PLAXIS 3D and ETABS to achieve displacements compatibility between the geotechnical and structural models. A layered soil profile was studied, consisted of soft to medium clay overlying a dense sand layer. The impact of using a 2m replacement sand layer below the raft also was evaluated on the soil-foundation response. Including the stiffness of the superstructure increased the load shared by the piles by (5.5% to 6.4%), (6.0% to 7.0%), and (1.7% to 7.6%), and reduced the raft differential settlement by (25.3% to 37.2%), (24.4% to 37.4%), and (29.7%) under gravity, wind, and earthquake loadings, respectively. Moreover, employing a 2-meter replacement layer beneath the raft had a negligible impact on the behaviour of the piled raft foundation. Thus, the interaction of soil, foundation, and superstructure significantly influenced the structural response.

1- Introduction

In recent years, piled raft footings have been the preeminent choice for supporting high-rise structures from a geotechnical engineering perspective. A synergistic system, integrating a

---

[1] Teaching assistant, Dept. of Civil. Eng., Suez Canal University, Suez, Egypt. Seham_fathy@eng.suez.edu.eg
[2] Professor, Dept. of Civil. Eng., Suez Canal University, Suez, Egypt. himak2@hotmail.com
[3] Professor, Dept. of Civil. Eng., Suez Canal University, Suez, Egypt. waleed_el_kamash@hotmail.com
[4] Assist., professor, Dept. of Civil. Eng., Suez Canal University, Suez, Egypt. erfanlh@yahoo.com

https://doi.org/10.21608/jesaun.2024.301578.1350

raft, piles, and subsoil in which both piles and raft share the superstructure load to achieve optimal bearing capacity and settlement control. If the raft's contribution to the overall foundation capacity is considered, it is possible to drastically decrease the piles’ numbers therefore, the economical solution can be achieved. Part of the superstructure load is directly transferred to the subsoil through the raft, while the rest is transferred via the soil-pile interaction. The remaining load is transferred through the complex mechanism of soil-pile interaction. This study is considered a soil-structure interaction problem, considering the stiffness of both the structure and the supporting soil to achieve the optimal structural analysis solution.

Poulos (2001), confirmed that the performance of piled raft foundations is affected by several factors, including the piles’ numbers, the type of loading, the thickness of the raft, and the level of applied load. Akinmusuru (1980), demonstrated that the bearing capacity of piled raft foundations surpasses the combined bearing capacities of the raft and the pile group. Additionally, it was observed that increasing pile length had no impact on load distribution. Cooke (1986) provided field measurements of the load for piled rafts on stiff clays during working conditions. Results showed that the distribution of the load between the piles in piled raft foundations on clay soils was governed by the structural loading and the stiffness of the foundation system. Lin and Feng (2006) reported that a thick-piled raft has a larger bending moment than a thin-piled raft, and the bending moment increases while increasing raft dimensions. El Sawwaf et al. (2022), found that increasing the length and number of piles reduced settlement and differential settlement as raft-soil relative stiffness increased. Additionally, the pile load sharing decreased with increasing the sand cushion thickness and relative density. According to David's et al. (2008), the piles shared 50 to 80 % of the total applied load, while the raft handled the rest. On the other hand, Leung et al. (2010) concluded that in a piled raft foundation system, the raft carries ranging between 25 to 51% of the total applied loads. Furthermore, Alnuaim et al. (2017), discovered through centrifuge model testing, that in rigid rafts piles carried a larger load than flexible rafts since there was less interaction between the raft and subsoil. Fattah et al. (2013), found that augmenting the raft thickness from 0.75 to 1.5 m at the same load level reduced the differential settlement by over 90% while the piles carried between 24% and 79% of the total applied vertical load, relying on the pile configuration. As demonstrated by Fattah et al. (2024), in a piled-raft foundation situated on loose sand soil, the combined contribution of the edge and center piles was substantially more significant than that of the individual piles beneath the raft.

The significance of the interaction between the soil, foundation, and superstructure was emphasized by Meyerhof (1953). Since then, numerous instigations have been carried out to find out how soil-structure interaction affected the behavior of framed structures. Shaya and Zeedan (2012), proposed a new method for designing raft foundations using 3D modelling including the soil, raft, and superstructure considering soil-structure interaction. They created charts to depict the correlation between the raft's thickness and other factors, including soil type. Russo et al. (2013), discovered that combining the superstructure stiffness with the piled raft foundation for the Burj Khalifa Tower in deep deposits of calcareous rocks improved the stiffness by around 10% of the total bending stiffness. Sunny and Mathai (2017) conducted finite element analyses using ANSYS v17.0 in stratified soil. The overall building settlement in the flexible basis model was higher than in the fixed base model. Roopa et al. (2015), studied the response of a tall building on a raft footing in clayey soil and found a significant increase in the base shear for a flexible base in comparison with the conventional approach of assuming a fixed base for a raft foundation system. Ibrahim et al. (2009), conducted a numerical analysis of piled rafts that were vertically loaded for square and rectangular buildings supported on non-homogeneous Port-Said soil medium considering the effect of the superstructure, pile diameter and length using ASTNII. Raft moments for cases without superstructure were higher than alternative cases with superstructure by 11% for rectangular shapes and 25% for square shapes.

Although there is a wealth of research on piled rafts, parametric studies focusing on piled rafts in soft clay-particularly considering superstructure stiffness under wind and earthquake loads-are limited. Therefore, the effect of superstructure stiffness for three different structural systems (framing system- coring system - shear wall system), and the existence of a 2m replacement sand under the raft have been investigated in the current study on the response of piled raft under gravity, wind, and earthquake loads.

2- Parametric study

A 20-story square reinforced concrete building with a piled raft foundation located on the ground surface above a two-layered soil system has been selected for a comprehensive analysis of the structure-foundation interaction. A piled raft analysis has been undertaken using an iterative procedure between a geotechnical model (PLAXIS 3D) and a structural model (ETABS). The required output from the geotechnical model is a set of pile springs and raft springs that adequately capture the foundation performance due to the applied loads from the superstructure. The analysis aims to get compatibility between the geotechnical and structural models by providing pile springs and raft springs so that forces and displacement at the interface of the models are the same in both models. The analysis of piled raft was performed using the proprietary software PLAXIS 3D, which simulates the soil-structure interaction between the piles subjected to axial and lateral loading with the surrounding soil. Vertical spring stiffnesses were determined by an iterative process to achieve compatibility of displacements between the geotechnical model and the structural model.

The square building features 4 bays in both the X and Y directions and it was studied for three different structural systems; framing system, scoring system, and shear wall system to illustrate the superstructure stiffness effect on piled raft system as shown in Fig. 1. The ground floor and typical floors each have a height of 3.0 m. The structural system for all floors consists of a solid concrete slab with a thickness of 140 mm, which is subjected to a total uniform load of 10 kN/m². The dimensions of all structural components, including columns, beams, walls, and core walls, are providedin Table 1. A square concrete raft of dimensions 22 m × 22 m concrete raft, an overhang of 1(m), and fixed pile head conditions is considered to be at the ground surface and has a thickness of 1.0 (m). The anticipated total vertical load on square rafts is approximately98.5 MN, 106.3 MN, 108.4 MN for the column system, core system, and shear wall system, respectively. A total of 81 (9×9) circular concrete vertical piles of 0.60 m diameter and 15 m long are located below the raft at 2.5m spacing for the three structural systems as shown in Fig. 2. The slenderness ratio (L/D) of the piles is set at 25, with the tips of the piles resting in the bottom soil layer (dense sand). The concrete modulus of elasticity is assumed to be 2.41 × 10^7 kN/m², while the Poisson's ratio and concrete density are assumed to be 0.2 and 25 kN/m³, respectively, in the structural models.

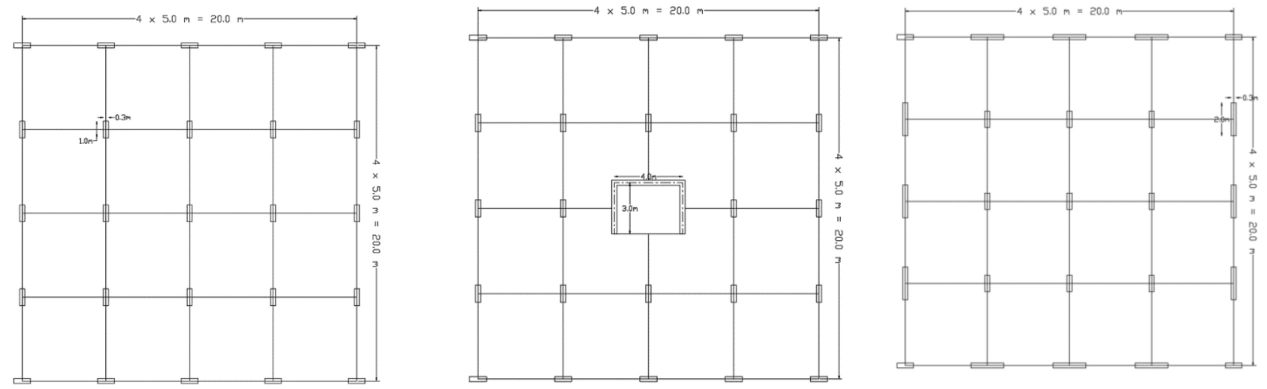


Fig. 1 : Superstructure typical floor layouts for 20 story building with the column, core system and shear wall system

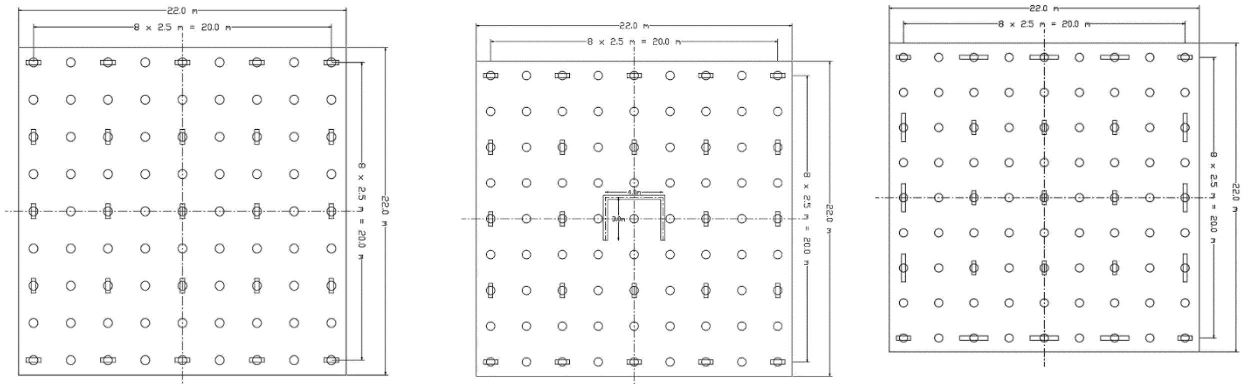


Fig. 2: Piled raft foundation layout for column, core and shear wall systems

Table 1: Dimensions of superstructure components

Shape	Dimensions (m)
Column	1.0 × 0.3
Shear wall	2.0 × 0.3
Core	4.0 × 3.0× 0.3
Beam	0.60 × 0.25

3- Constitutive soil Model and Parameters for Simulating the soil layers.

Soil, a complex and multifaceted material, demonstrates diverse behaviour during primary loading, unloading, and reloading. Its response is nonlinear even at stress levels significantly below failure, with stiffness fluctuating based on the applied stress. For simulating the different soil layers using 3D finite element analyses (PLAXIS 3D), elastic-perfectly plastic models based on soil failure criteria, specifically the Mohr-Coulomb (MC) model, are utilized. The soil domain is modelled as a 3D prismatic cube with dimensions of 100 m in length, 100 m in breadth, and 40 m in heightwhich relates to a large distance from the loaded area to eliminate the boundary effect on the results. Fig. 3 shows the dimensions of the used 3D PLAXIS-Model in the analysis.

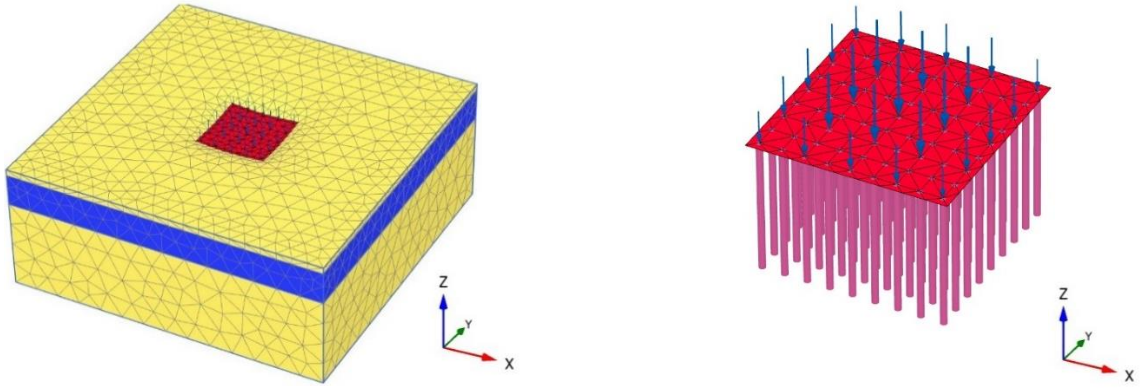


Fig. 3 : 3D finite elements foundation soil models using PLAXIS 3D for a piled raft in layered soil with 2m replacement sand layer

Two soil profiles are considered in the current study; the first one consists of two-layered soils, the upper is soft to medium clay layer, and the lower layer is considered to be dense sand (stiff soil) while the second soil profile studies the effect of the existence of 2m sand replacement on the top of the upper layer (soft soil). The water depth is considered to be at a depth of 50 m below the ground surface which means that the water effect is not considered in this study. The assigned material parameters for the simulation of different soil layers and foundation systems are given in Table 2 and Table 3. Following Terzaghi et al., (1996), Unit weights and water content of the sand medium were chosen, and as per the findings of Terzaghi and Peck (1948), Gibbs and Holtz (1957), Meyerhof (1956), and ECP-202 (2001), the SPT value is considered to be (50) and the relative density is equivalent to (70%) for dense sand layers. Also, shear strength parameters, Elastic modulus and Poisson ratio for sand layers are refereed from Bowels (1982), Terzaghi et al. (1996), ASSHTO (1996) and ECP-202 (2001).

The properties of the clay medium were taken to be soft to medium clay layer with an undrained shear strength of 25 kPa and undrained modulus of elasticity of 4000 kPa, with the drained parameters being $E'=0.85E_{un}$, according to Terzaghi et al.,(1996), Bowels (1988) and ECP-201,(2001).

Table 2: Soil profile 1

Layer No.	**Lithology**	**SPT**	**Depth (m)**		**γ_{sat} (kN/m^3)**	**ϕ (Degree)**	**c_u (kN/m^2)**	**E_{50} (kN/m^2)**
			From	**To**				
L1	Soft to Medium Clay	8	0	12	17.40	-	25	4000
L2	Dense Sand	50	12	40	22.30	38	-	50000

Table 3: Soil profile 2

Layer No.	**Lithology**	**SPT**	**Depth (m)**		**γ_{sat} (kN/m^3)**	**ϕ (Degree)**	**c_u (kN/m^2)**	**E_{50} (kN/m^2)**
			From	**To**				
L1	Replacement Sand	50	0	2	22.30	38	-	50000
L2	Soft to Medium Clay	8	2	12	17.40	-	25	4000
L3	Dense Sand	50	12	40	22.30	38	-	50000

4- Finite Element Modelling and Iteration Methodology

The piled raft modelling was performed using PLAXIS 3D & ETABS programs, which simulate the soil-structure interaction between the piles subjected to both axial and lateral loads with the surrounding soil. To ensure that the displacements between the structural model ETABS and the geotechnical model PLAXIS 3D were compatible, vertical spring stiffnesses were determined using an iterative approach. The finite element method based on a geotechnical model (PLAXIS 3D) is used for modelling the piled-raft in a layered soil. Soil parameters and piled raft material used in the analysis are given in Table 4 and

Table **5**. The piled raft is considered to be on the ground surface. Embedded beams are used to model the piles with linear elastic properties employing Elasto-Plastic line-to-volume and point-to-volume interfaces. This approach represents the pile as a series of beam elements with non-linear properties at the skin (surface) and tip of the pile... The raft is modelled as a plate element and meshed using 6-noded triangular plate elements with linear elastic properties. The embedded beam element is represented by a 3-noded line element that is capable of intersecting a 10-noded tetrahedral element, which models the soil field. (Reference Manual, PLAXIS). The total number of elements in the discretized automated mesh for square building structures including soil field are 10270, 10579 and 10956 for framing system, core system, and shear wall system, respectively. The roughness coefficient (interface reduction factor) (R_{inter}) is used to model the interface interaction between both the raft and piles with the surrounding soil. The present study assumes R_{inter} = 0.67 in sand soil (Brinkgreve et al., 2008) and R_{inter} = 0.5 in clay soil (Reference Manual, PLAXIS).

The proposed interactive analysis highlights the dependencies between the geotechnical and structural models, as well as the impact of data exchange throughout the design process on the calculation outcomes. The analysis process involved calculating the nodal reaction forces at the superstructure-raft interface under fixed boundary conditionsusing ETABS software. After then, an initial PLAXIS 3D run was undertaken to compute pile head settlements and raft settlement as per the gravity applied load by the structural model with fixation base. Individual pile head and raft stiffnesses (subgrade reactions) were calculated based on the observed distribution of settlement beneath the simulated raft and piles.calculated by PLAXIS 3D analysis which were then fed to the ETABS program and recalculated the nodal reaction forces at the interface of the foundation system.

Revised gravity-applied loads were obtained from the structural software and then used to run a second PLAXIS 3D iteration. The process was repeated until the convergence of vertical displacement at piles and rafts between PLAXIS 3D and the structural software fell within a tolerance limit (less than 6% according to O'Brien et al. (2012)). Once the iterations were completed, a comparative analysis was conducted to assess the raft bending moment, settlement of the superstructure along the raft's centre, and the load-sharing mechanism among the foundation components. To obtain the soil settlement and load distribution among the foundation components, the serviceability cases of loading (SLS) combinations are considered as per the ECP-203 (2018).

Table 4: Soil characteristics input for PLAXIS 3D analysis

Parameters	**Name**	**Soil Layer**	
		Soft to Medium Clay	**Dense Sand/ Replacement Soil**
Material Model	Model	Mohr-Coulomb	Mohr-Coulomb
Drainage type	Type	Undrained B	Drained
Unsaturated unit weight kN/m^3	γ_{unsat}	12.00	20.00
Saturated unit weight, kN/m^3	γ_{sat}	17.40	22.30
Young’s Modulus, kPa	E'	3400	50000
Poisson ratio	v'	0.4	0.3
Cohesion, kPa	c'_{ref}	25	0
Friction angle, degree	φ'	0	38
Dilatancy angle, degree	ψ	0	8
Interface Strength	-	Manual	Manual
Interface reduction factor	R_{inter}	0.5	0.67
K_o determination	-	$(1-\sin\phi)\ OCR^{\sin\phi}$	$1-\sin\phi$
Lateral earth pressure	$K_{o,x}$, $K_{o,y}$	0.85	0.3843

Table 5: Material properties for piled raft system in PLAXIS 3D

Parameters	**Name**	**Raft**	**Piles**
Material Model	Model	Elastic	Elastic
Unit weight kN/m^3	γ_c	25	25
Young’s Modulus, kPa	E	2.41×10^7	2.41×10^7
Poisson ratio	v	0.2	0.2
Thickness/ Diameter, m	d	1.0	0.6
Beam type	-	-	Predefined
Predefined Beam type	-	-	Massive Circular beam

4-1 Seismic loads

According to ECP-201 (2012), there are three primary methods for analyzing the structural response to earthquakes: Simplified modal response spectrum, Multi-modal response spectrum and Time History Analysis. This paper employs the simplified modal response spectrum method for a linear analysis of the structure's dynamic behavior for the horizontal elastic response spectrum type 1. The ETABS program initiates its analysis by determining the design elastic response spectrum at a specific vibration period, T, for a linear single-degree-of-freedom system with 5% viscous damping, denoted as $S_d(T)$The design peak ground acceleration (a_g) is assumed to be 0.25g in order to achieve the high-risk seismicity behavior. The importance factor of the structure is considered as unity. The time periods T_B, T_C and T_D as well as the soil factor S, which defines the elastic response spectrum, are set to 0.1, 0.25, 1.2 seconds, and 1.5, respectively.

4-2 Wind loads

Wind loads are applied to the vertical projected area of the building according to ECP-201 (2012). The air density and wind speed are considered equal to 1.25 kg/m^3, and 33 m/s, respectively. The topography and the structural factors are considered equal to unity according to ECP-201, 2012.

5- Soil-Structure Interaction Considerations

A set of numerical analysis shall be conducted to assess the impact of the stiffness of three different types of superstructures (frame system- Core system – shear wall system) on piled rafts under gravity, wind, and seismic loads. 3D finite element analyses (PLAXIS 3D) in addition to ETABS structure software have been used considering two-layered soil profiles with/without 2m sand replacement layer below the raft to simulate the combined soil structure interaction problem types as follows.

1. Type A - Neglecting the superstructure stiffness using a fixed boundary condition then applying loads (concentrated) to the piled raft foundation using the SAFE structural model without the superstructure.
2. Type B- Considering the superstructure stiffness through iterations between PLAXIS 3D model and the ETABS model until the convergence factor is less than 6% for the foundation settlement, at this point the superstructure loads are applied directly to the piled raft foundation system using the structural ETABS model.
3. Type C- Considering the superstructure stiffness while existing 2m sand replacement below the raft.

The above three types A, B & C are considered for each superstructure system type subjected to gravity, wind, and earthquake loads.

6- Results

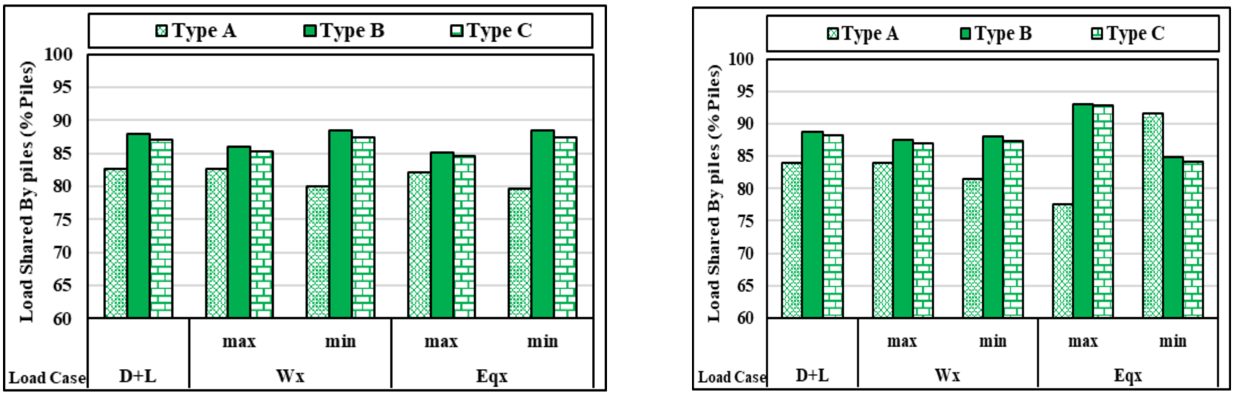
Table 6 summarizes the interaction between the building foundation and structure on the piled-raft footing component. This interaction is characterized by the percentage of the total imposed load from the superstructure that is carried by the piles for various structural systems. The results demonstrate a clear relationship between the structure and the foundation soil the analysis of piled-raft foundation-soil models considering superstructure stiffness will indicate foundation soil to be more rigid than the model without the superstructure. The percentage of the load taken by piles is more in Piled Raft models considering superstructure than in models without it by 6.4%, 7% 7.6% for the framing system, 5.9%, 6%, 5% for the coring system, and 5.5%, 6.3% and 1.7% for shear wall systems under gravity, wind and earthquake loading, respectively.

Error! Reference source not found. and **Error! Reference source not found.** illustrate the influence of superstructure stiffness on piled raft foundation as well as the presence effect of 2m soil replacement below the piled raft under gravity, wind, and earthquake loads through some parameters such as; maximum vertical settlement along the raft's center axis x-x as well as the differential settlement occurs between raft center and edge points. Also, the load-sharing ratio of the piles was investigated.

Table 6: Percentage of Load shared by piles (% piles), considering types A, B, and C for square building of different structural systems

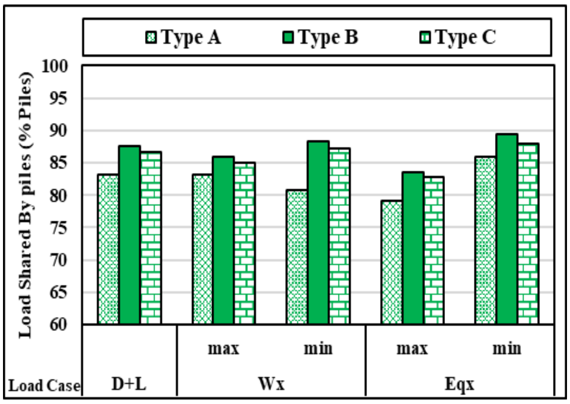
Soil-Structure Interaction Type	**Structural Model**	**Max. Percentage of Load shared by piles (% piles)**		
		Gravity loads	**Wind Loads**	**Earthquake loads**
Type A	Column	82.6%	82.6 %	82.2%
	Core	83.9%	83.9%	91.6%
	Shear wall	83.1%	83.1%	87.8%
Type B	Column	87.9%	88.4%	88.5%
	Core	88.8%	88.9%	96.2%
	Shear wall	87.7%	88.3%	89.3%
Type C	Column	87.1%	87.4%	87.4%
	Core	88.2%	88.3%	96 %
	Shear wall	86.6%	87.1%	88%

Table 7 shows the maximum raft settlements calculated below the raft centre as well as raft differential settlement between the centre and edge points of the raft for a square building with different structural systems. The findings indicate that various structural systems can lead to different levels of maximum and differential settlement in the foundation. The analysis revealed a pronounced increase in the maximum soil settlements when the superstructure stiffness was incorporated for framing and shear wall systems. This finding aligns with the observations reported by Sunny and Mathai, (2017). However, for coring system, the raft settlement beneath the center of the raft decreased by (0.7) % due to the rigidity of the coring system. Differential settlements in raft foundations are smaller when using a piled-raft model while considering the superstructure stiffness. Additionally. Incorporating a 2-meter soil replacement below the raft further decreases differential settlements while considering the superstructure. The predicted raft differential settlement is highest using the coring system and it is least in the shear wall system.



a. Framing System

b. Coring System



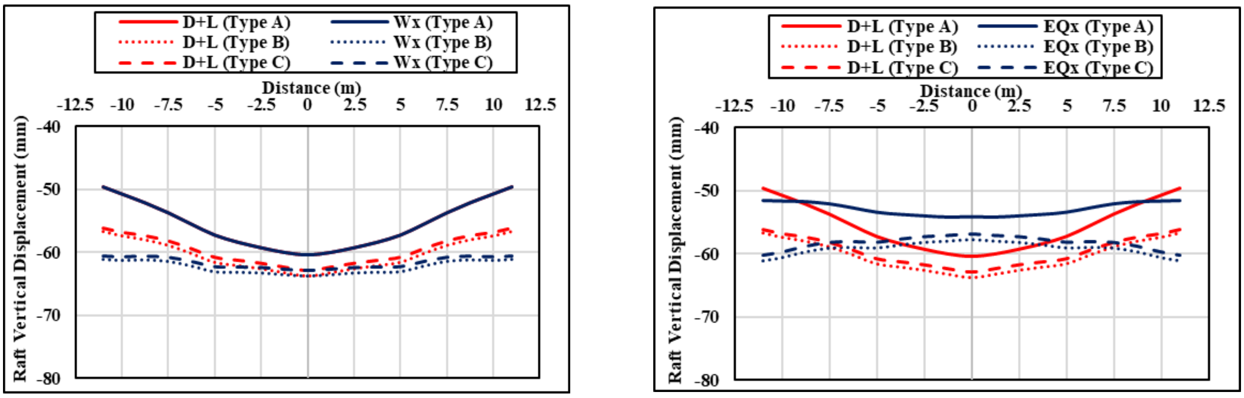
c. Shear wall system

Fig. 4: Percentage of load shared by piles, considering types A, B, and C of square building for a- framing b- coring & c-shear wall systems

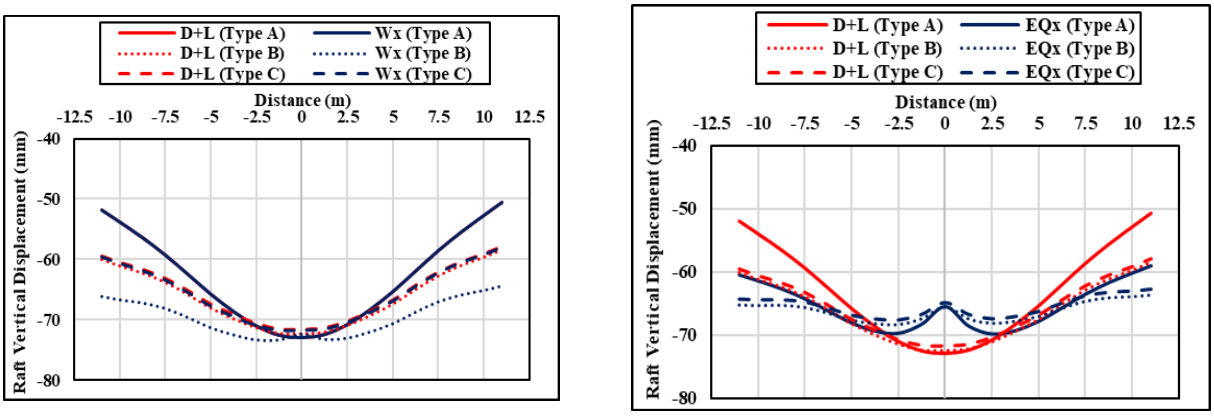
Table 7: Maximum raft settlement and differential settlement considering types A, B, and C of square structure building for different structural systems.

Soil-Structure Interaction Type	**Structural system**	**Maximum & Differential Soil Settlement (mm)**					
		Gravity loads		**Wind Loads**		**Earthquake loads**	
		Max. settlement	**Differential settlement**	**Max. settlement**	**Differential settlement**	**Max. settlement**	**Differential settlement**
Type A	**Column**	60.4	10.8	60.4	10.8	54.1	15.0
	Core	72.9	22.3	72.9	22.3	65.5	30
	Shear wall	65.0	6.2	65.0	6.2	58.5	12.3
Type B	**Column**	63.7	7.1	63.7	7.1	57.6	15.1
	Core	72.4	14.0	72.4	13.9	65.5	21.0

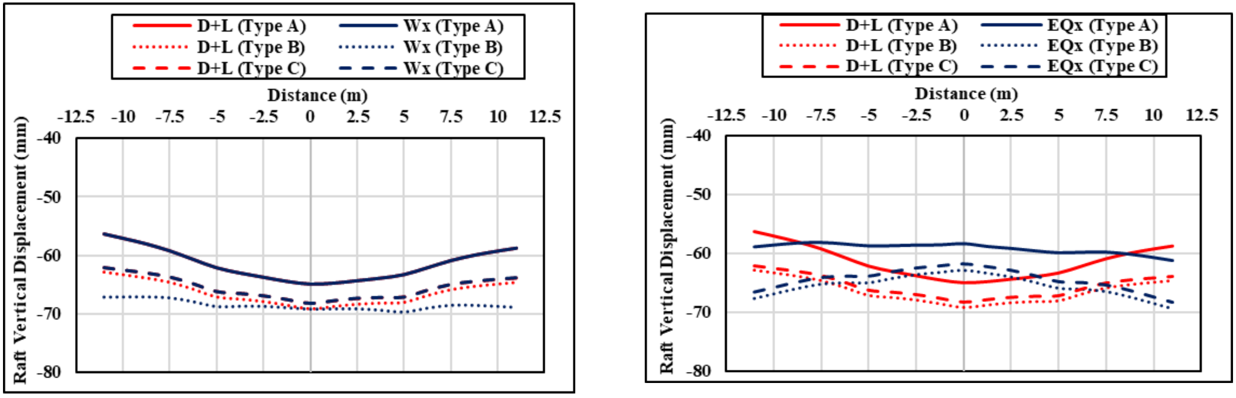
Soil-Structure Interaction Type	Structural system	Maximum & Differential Soil Settlement (mm)					
		Gravity loads		Wind Loads		Earthquake loads	
		Max. settlement	Differential settlement	Max. settlement	Differential settlement	Max. settlement	Differential settlement
	Shear wall	69.2	4.6	69.3	4.7	62.9	13.8
Type C	Column	62.8	6.8	62.8	6.8	56.9	14.5
	Core	71.6	13.8	71.7	13.7	64.8	20.5
	Shear wall	68.2	4.3	68.3	4.4	62.0	13.1



a- Framing system



b- Coring system



c- Shear wall system

Fig. 5: Maximum Raft vertical displacement at the central axis x-x, considering types A, B, and C for square building of a- framing b- coring & c- shear wall systems

7- Conclusion

Considering the superstructure stiffness of square shape on clay soil results in higher raft settlements, higher pile loads, and a reduction in the raft's differential settlement for a piled raft system, resulting in a reduction in the raft's internal stresses (bending moments) regardless the superstructure system type. Incorporating the superstructure stiffness increased the load carried by the piles by (5.5% to 6.4%), (6.0% to 7.0%), and (1.7% to 7.6%) under gravity, wind, and earthquake loads, respectively. In terms of the proportion of load shared by piles, the shear wall system performed the best when compared to other building structural systems.

Moreover, soil settlement increased by (5.4 to 6.5) %, (5.4 to 6.6) %, (6.5 to 7.6) %, while the raft differential settlement reduced by (25.3% to 37.2%), (24.4% to 37.4%), and (29.7%) under gravity, wind, and earthquake loadings, respectively.

Substituting the top 2 meters of soft to medium clay soil with dense sand has a negligible impact on the performance of a piled raft foundation.

For safety, if the superstructure's stiffness is not considered during structural analysis, load-sharing between the raft and piles should be neglected, and the entire load should be assumed to be carried by the piles alone.

The current study is limited to a square regular 20-story building, resting on a piled raft foundation in layered soil under dry soil conditions, consists of soft to medium clay layer followed by a dense sand layer. Future research could explore other irregular-building shapes as well as different soil conditions, such as loose sand followed by dense sand layers. Additionally, the influence of the groundwater table should be further investigated.

References

[1] Akinmusuru, J. O. (1980). Interaction of Piles and Cap In Piled Footings. Journal of the Geotechnical Engineering Division,ASCE, 106(11), 1263–1268. https://doi.org/10.1061/AJGEB6.0001062.

[2] Alnuaim AM, El Naggar H, El Naggar MH. (2017). Evaluation of piled raft performance using a verifed 3D nonlinear numerical model. Geotech Geol Eng 35:1831–1845. https:// doi.org/10. 1007/s10706- 017- 0212-1.

[3] Cooke, R. W. (1986). Piled raft foundations on stiff clays - a contribution to design philosophy. Géotechnique, 36(2), 169–203. https://doi.org/10.1680/geot.1986.36.2.169.

[4] Davids A., Wongso J., Popovic D., McFarlane A. (2008). A post-card from Dubai design and construction of some of the tallest buildings in the world. In: Proceedings of the CTBUH 8th World Congress 3–5. https://doi.org/ 10. 3850/ 97896 28014 194_ 0075.

[5] ECP-201. (2012). Egyptian Code for Loads Calculations in Structures and Building Works. National Housing and Building Research Center HBRC,Giza.

[6] ECP-202. (2001). Egyptian Code of Practice for Soil Mechanics and Design and Construction of Foundations (Sixth ed.,). National Housing and Building Research Center

HBRC,Giza.

[7] ECP-203. (2018). Egyptian Code for Design and Construction of Reinforced Concrete Buildings. National Housing and Building Research Center HBRC,Giza.

[8] El Sawwaf M., Shahien M., Nasr A., Magdy A . . . (2022).The behavior of piled rafts in soft clay: numerical investigation. J Mech Behav Mater 31(1):426–434

[9] Fattah, M., Al-Mosawe, M., & Al Zayadi, A. (2013). Time dependent behavior of piled raft foundation in clayey soil. Geomechanics and Engineering, 5(1), 17–36. https://doi.org/10.12989/gae.2013.5.1.017.

[10] Fattah, M., Waheed, M., & Hadi, D. (2024). Effect of Pile Configuration on the Behavior of Piled-Raft Foundations in Sandy Soil. Journal of Testing and Evaluation, 52(1). https://doi.org/10.1520/JTE20230164.

[11] Ibrahim, F., El Gendy, M., Salib, R., & El Kamash, W. (2009). Nonlinear analysis of piled raft with 3D-space structure. Port-Said Engineering Research Journal, 13(2), 1–21.

[12] Leung Y.F., Soga K., Lehane B., Klar A. (2010) .Role of linear elasticity in pile group analysis and load test interpreta-tion. J Geotech Geoenviron Eng 136:1686–1694. https://doi. Org/ 10. 1061/ (ASCE) GT. 1943- 5606. 00003 92.

[13] Lin, D., & Feng, Z. (2006). A numerical study of piled raft foundations. Journal of the Chinese Institute of Engineers, 29(6), 1091–1097. https://doi.org/10.1080/02533839.2006.9671208.

[14] Meyerhof, G. G. (1953). Some recent foundation research and its application to design. The Institution of Structural Engineers, 31(6), 151–167Al-Shayea, N. and Zeedan, H. (2012) A New Approach for Estimating Thickness of Mat Foundations under Certain Con- ditions. The Arabian Journal for Science and Engineering, 37, 277-290. http://dx.doi.org/10.1007/s13369-012-0178-5.

[15] O'Brien, A.S. & Burland, John & Chapman, T... (2012). Rafts and piled rafts. ICE manual of geotechnical engineering. 2. 853-886.

[16] Poulos, H. G. (2001). Piled raft foundations: Design and applications. Geotechnique, 51(2), 95–113. https://doi.org/10.1680/geot.2001.51.2.95

[17] Roopa, M., Naikar, H. G., & Prakash, D. S. (2015). Soil Structure Interaction Analysis on a RC Building with Raft foundation under Clayey Soil Condition. International Journal of Engineering Research & Technology ,IJERT, V4(12)), 319–323. https://doi.org/10.17577/IJERTV4IS120402.

[18] Russo, G. & Abagnara, Vincenzo & Poulos, Harry & Small, John. (2013). Re-assessment of foundation settlements for the Burj Khalifa, Dubai. Acta Geotechnica. 8. 10.1007/s11440-012-0193-4.

[19] Sunny, N., & Mathai, A. (2017). Soil Structure Interaction Analysis of Multi Storey Building. International Journal for Science Technology and Engineering, 3, 67-70.

[20] Thoidingjam, D.; Devi, K. R. (2017). Behavior of Pile Raft Foundation in Organic Clay. Indian Journal of Science and Technology, 10(31), 14. doi:10.17485/ijst/2017/v10i31/113867