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Influence of Superstructure Stiffness on Piled Raft Foundations in Layered Soil

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Abstract

Previous research often relied on simplified models that assumed a rigid connection between the superstructure and raft foundation. These models disregarded the influence of superstructure stiffness on soil-foundation interaction, leading to inaccurate predictions of raft bending moments, pile loads, and settlement. This paper investigated the impact of superstructure stiffness for three different structural systems (framing, coring, and shear wall systems) on the behavior of piled raft foundation as well as the presence impact of a 2-meter sand replacement beneath the raft under various loads. A 3D nonlinear finite element analysis using PLAXIS 3D and ETABS was conducted in soft to medium clay overlying a dense sand layer. Incorporating the superstructure stiffness reduced the maximum raft bending moments by (6.6% to 9.1%), (39.0% to 47.9%), and (18.2% to 22.3%) as well as the maximum raft shear forces by (39.2% to 46.9%), (25.6% to 49.2%), and (34.7% to 44.9%) for framing, coring and shear wall systems, respectively, under gravity, wind, and seismic loads beneath the raft's center. The presence of a 2m replacement layer beneath the raft had a negligible effect on the system's behavior(Less than 1.6%). In conclusion, the variation of superstructure stiffness affected the raft's internal forces; therefore, it can be economically advantageous to consider this while designing a piled raft foundation.

Keywords: *Piled raft foundation, Bending moments, Shear forces, Soil-structure interaction, Superstructure stiffness.*

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1. Introduction

Numerous studies have delved into the intricate interplay between superstructures, foundations, and soil. Meyerhof (1953) highlighted the significance of this interaction. Subsequent research focused on understanding how soil-structure interaction influenced the behavior of structures. This interaction had a profound impact on the structural response to various loads, including seismic, wind, and gravity. Factors such as soil properties, foundation type, and superstructure stiffness play crucial roles in determining the overall behavior of the system. Understanding these relationships is essential for designing safe and efficient structures that can withstand various loading conditions and minimize the risk of failure. Furthermore, neglecting the effects of soil-structure interaction can lead to

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inaccurate predictions of structural behavior and potentially devastating consequences.

Al-Shaya & Zeedan (2012) developed a 3D modeling approach to design raft foundations, considering the superstructure, raft, and soil. The relationship between raft thickness and other variables, such as soil type, was studied. Sunny and Mathai (2017) used ANSYS v17.0 to investigate the soil-structure interaction effect on piled-raft foundations in non-homogenous soil. The flexible base model exhibited a larger total building settlement compared to the fixed base model. Additionally, the soil-based flexible base model produced an average equivalent stress higher than the fixed base model. In contrast to the conventional approach of assuming a fixed base for the raft foundation system, Roopa et al. (2015) studied the response of high-rise structures constructed on a raft foundation system in clayey soil and demonstrated that there is a significant increase in the base shear for a flexible base due to the induced flexibility to the base by the soil's softness. Ibrahim et al., (2009) used ASTNII to perform a numerical study of piled raft foundations that were vertically loaded for square and rectangular buildings supported on a non-homogeneous Port-Said soil medium. The analysis considered the influence of the superstructure, pile diameter, and length. In summary, raft moments for rectangular and square geometries were found to be 11% and 25% higher, respectively, in cases without a superstructure compared to cases with a superstructure. Akbari et al. (2021) studied the effects of soil stiffness on the performance of a 10-story steel structure building on a piled raft foundation under seismic loading numerically by implementing a 3D finite element modeling via ABAQUS software. The percentage of the lateral load carried by the pile decreased with increasing soil stiffness (by 50% in loose sand, 40% in medium sand, and 30% in dense sand).

Most studies have not fully explored how different structural system types affect piled raft foundations, especially when considering superstructure stiffness. Consequently, this paper examines the impact of superstructure stiffness for three different structural systems (framing system, coring system, and shear wall system) as well as the presence of a 2 m sand replacement beneath the raft on the response of piled raft foundation under the influence of gravity, wind, and seismic loads.

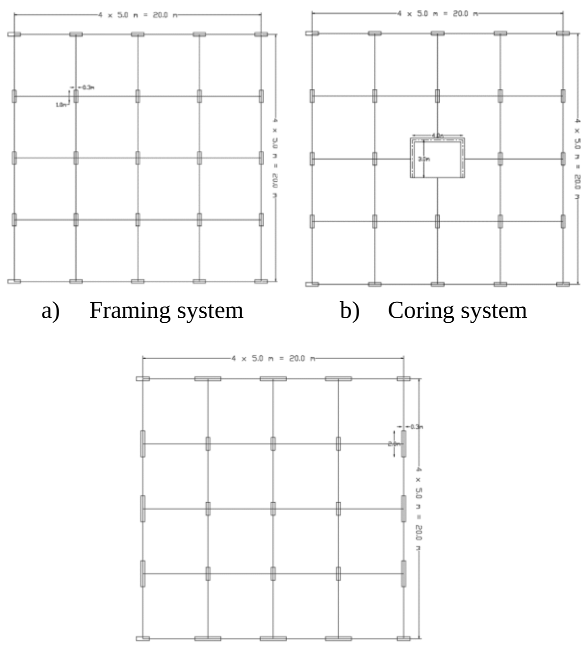
2. Parametric study

For the entire structure-foundation interaction analysis, a 20-story square reinforced concrete building with a piled raft foundation located on a two-layered soil system was utilized. An iterative process between a structural model (ETABS V20) and a geotechnical model (PLAXIS 3D V20) was used throughout the analysis.

To ensure compatibility of displacements between the geotechnical model and the structural model, vertical spring stiffnesses were determined through an iterative approach that effectively captured foundation performance due to the superstructure's applied loads. PLAXIS 3D program was used to simulate the interaction between the piles subjected to axial and lateral loadings and the surrounding soil for the piled raft system.

2.1 Structure and Foundation Characteristics

The square building, which had four bays in both the X and Y directions, was investigated for three different structural systems: shear walls, coring, and framing, to demonstrate the way the superstructure stiffness affected the response of the piled raft foundation, as seen in Fig.1.The ground and typical floors are 3.0 meters high. A solid concrete slab with a thickness of 140 mm, subject to a uniform load of 10 kN/m^2, worked as the structural system for each level. All structural elements dimensions, including walls, beams, columns, and core walls, are mentioned in Table 1. A square concrete raft with fixed pile heads was assumed to be at ground level. The raft's thickness was considered as 1 meter, and its plan dimensions were 22 m × 22 m with an overhang of 1 meter extended from both sides of the raft. The anticipated total vertical load on square rafts was 98.5 MN, 106.3 MN, and 108.4 MN for the column, core, and shear wall systems, respectively. As shown in Fig. 2, 81 (9×9) circular concrete vertical piles, with a diameter of 0.60 m and 15 m in length, were arranged for the three structural systems at 2.5 m intervals beneath the raft (S/D=4.16D). The end tips of the piles were embedded in the deep sand bottom layer and the slenderness ratio (L/D) of the piles was 25. The concrete's modulus of elasticity was assumed to be 2.41×10^{7}kN/m^2 while its density and Poisson's ratio were taken as 0.2 and 25 kN/m^3, respectively.



a) Framing system b) Coring system

c) Shear wall system

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

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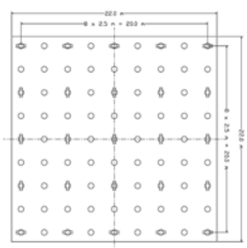
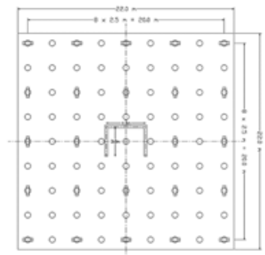
Table 1. Component dimensions for the superstructure

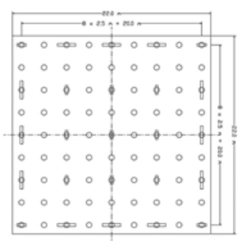
Element	Dimensions (m)
Column	1.0 × 0.3
Shear wall	2.0 × 0.3
Core	4.0 × 3.0× 0.3
Beam	0.60 × 0.25



a) Framing system



b) Coring system



c) Shear wall system

Fig. 2. Layout of a piled raft foundation for framing, coring, and shear wall systems

In accordance with ECP-201 (2012), this study employed the Simplified Modal Response Spectrum method for linear analysis of the structural response to earthquakes. Both service and ultimate combinations had been considered to obtain the settlement, raft bending moments, and shear forces as per ECP-203 (2018) for gravity, wind, and seismic loads. Horizontal wind loads were determined based on the vertical projection of the building's surface area, following the guidelines specified in ECP-201 (2012).

2.2 Constitutive soil Model and Parameters for Simulating the soil layers

The various soil layers are simulated using 3D finite element analyses (PLAXIS 3D) and elastic-perfectly plastic models based on soil failure criteria, namely Mohr-Coulomb (MC). To minimize boundary effects, a large-scale 3D prismatic cube with dimensions of 100 meters (length), 100 meters (breadth), and 40 meters (height) was used as the soil domain. This ensured that the loaded area was sufficiently far from the boundaries to avoid influencing the results. Fig. 3 illustrates the dimensions of the 3D PLAXIS model employed in the analysis.

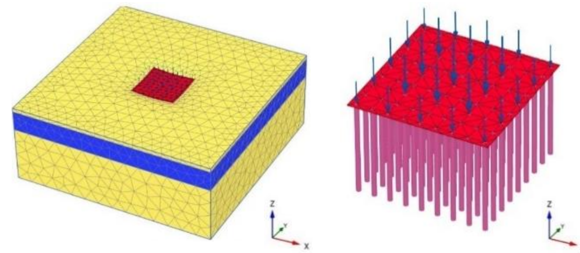


Fig. 3. 3D finite element modeling of a piled raft foundation in layered soil with a 2-meter sand replacement layer using PLAXIS 3D

The current study investigated two soil profiles;1) a two-layered profile with a soft to medium clay layer extended from the ground surface to a depth of 12 meters overlying a dense sand layer, and 2) a similar profile with a 2-meter sand replacement layer on top of the clay layer. In this analysis, the water table was assumed to be at a depth of 50 meters, eliminating the need to consider water effects. Table 2 provides the material parameters used to simulate the different soil layers and foundation systems.

According to Terzaghi et al. (1996), the unit weights and water content of the sand medium were selected. Following the guidelines established by Terzaghi and Peck (1948), Gibbs and Holtz (1957), Meyerhof (1956), and the ECP-202 (2001), a SPT value of 50 was deemed appropriate for the dense sand layers, indicating a relative density of 70%. This value aligns with the consensus among these experts in soil mechanics. Additionally, the shear strength parameters, elastic modulus, and Poisson's ratio for these sand layers were obtained from the work of Bowles (1982), Terzaghi et al. (1996), ASSHTO (1996), and ECP-202 (2001). The clay medium's characteristics were identified to be a soft to medium clay layer with an undrained modulus of elasticity of 4000 kPa and an undrained shear strength of 25 kPa; the drained parameters were determined to be $E'=0.85E_{un}$, based on Terzaghi et al., 1996, Bowels 1988, and ECP 202,2001.

Table 2. Soil Parameters for PLAXIS 3D

Parameters	Soft to Medium Clay	Dense Sand /Replacement Soil
Material Model	Mohr-Coulomb	
Drainage type	Undrained B	Drained
SPT	8	50
γ_{sat} (kN/m^3)	17.40	22.30
Φ (Degree)	-	38
ψ	0	8
v'	0.4	0.3
c_u (kN/m^2)	25	-
E_{50} (kN/m^2)	4000	50000

2.3 Finite Element Modelling Methodology

A comprehensive analysis of the piled raft foundation was conducted using PLAXIS 3D V20 and ETABS V20, two specialized software programs that simulate the intricate interaction between piles and the

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surrounding soil under various loading conditions. Vertical springs' stiffnesses were determined through an iterative approach to ensure consistent displacements between the geotechnical and structural models under gravity loads. The geotechnical model (PLAXIS 3D) used the finite element method to represent the piled raft foundation in layered soil. The piles were modeled as embedded beams with linear elastic properties. The interaction between the pile shafts and the soil was captured using elastoplastic line-to-volume and point-to-volume interfaces. This embedded pile model, which utilizes beam elements with nonlinear skin and tip interfaces, eliminates the need for mesh refinement around the piles, preventing mesh distortion. The raft was represented as a plate element and meshed using 6-noded triangular plate elements with linear elastic properties. The embedded beam element was modeled as a 3-noded line element that could interact with the 10-noded tetrahedral elements representing the soil field.

The total number of elements in the discretized mesh for the soil field was 10270 for the framing system, 10579 for the core system, and 10956 for the shear wall system and the mesh was automatically generated by the PLAXIS 3D program.

The interactive analysis reveals the interconnectedness of the structural and geotechnical models. The process involved calculating nodal reaction forces at the superstructure-foundation interface (raft) using ETABS, assuming a fixed boundary condition. Subsequently, an initial PLAXIS 3D run was conducted to determine pile head and raft settlements under gravity loads applied by the structural model with a fixed base. Based on the PLAXIS 3D results, individual pile head and raft stiffnesses were calculated, considering the distribution of settlement beneath the simulated raft and piles. These stiffness values were then incorporated into ETABS to recalculate the nodal reaction forces at the foundation system's interface. Revised gravity loads calculated by the structural software were incorporated into a second PLAXIS 3D iteration. This iterative process continued until the vertical displacements of the piles and raft, as determined by PLAXIS 3D and the structural software, converged to within a 6% tolerance, as shown in Table 3.

Additionally, the lateral pile stiffness was kept constant for cohesionless as well as cohesive layers according to Brooms (1964a) and Broms (1964b), respectively, while raft lateral stiffness was considered as 25% of the vertical stiffness at each iteration step. Upon convergence, a comprehensive comparison was conducted to assess the raft bending moments and raft shear forces along its center. This iterative process ensured a more accurate representation of the soil-structure interaction.

Table 3. Comparing foundation settlements between geotechnical and structural Models under gravity loads

Soil Profile	Structural system	Geotechnical analysis		Structural analysis		Diff. %
		Δ_{Raft} (mm)	Δ_{Piles} (mm)	Δ_{Raft} (mm)	Δ_{Piles} (mm)	
Soil Profile 1	Frame	6.4	6.4	6.4	6.1	4.91
	Core	7.3	7.3	7.2	7.0	4.82
	Shear wall	7.0	7.0	6.9	6.7	5.21
Soil Profile 2	Frame	6.4	6.4	6.3	6.0	5.68
	Core	7.3	7.2	7.2	6.9	4.91
	Shear wall	7.0	7.0	6.8	6.6	6.08

3. Results and Discussion

Utilizing PLAXIS 3D in conjunction with ETABS structure software, a series of numerical analyses on the behavior of piled raft foundations under gravity, wind, and seismic loads in two-layered soils. Three different superstructure stiffnesses (frame system, core system, and shear wall system) were investigated. The analysis employed the subsequent criteria;

I. Case I: Applying concentrated loads to the piled raft foundation model without considering the superstructure stiffness and utilizing a fixed boundary condition
II. Case II: Considering superstructure stiffness by performing iterations between the PLAXIS 3D model and the ETABS model until the convergence factor for the foundation system's settlement is less than 6%
III. Case III- Implementing the superstructure stiffness while considering 2m dense sand replacement below the raft

The findings demonstrated the interaction between the three different structural systems' soil, foundation, and superstructure on raft moments. These results are summarized in Table 4. The raft moments were reduced by 9.1%, 6.6%, and 8.6% for the framing system, 47.9%, 39.0%, and 44.3% for the coring system, and 22.3%, 18.2%, and 21.6% for shear wall system under gravity, wind, and earthquake loading, respectively, when the superstructure stiffness was incorporated. Additionally, using a 2m replacement below the raft while considering the superstructure stiffness decreased the raft bending moments by less than 1% due to improved contact pressure and settlement distribution compared to the case without the replacement layer.

In Fig. 4, Fig. 6, and Fig. 7, raft bending moments for column, core, and shear wall systems were depicted along its center axis (x-x), respectively, while considering/not considering the superstructure stiffness as well as the effect of using 2m of soil replacement beneath the raft with the incorporation of superstructure stiffness.

Table 4. Maximum raft bending moments considering/not considering superstructure stiffness

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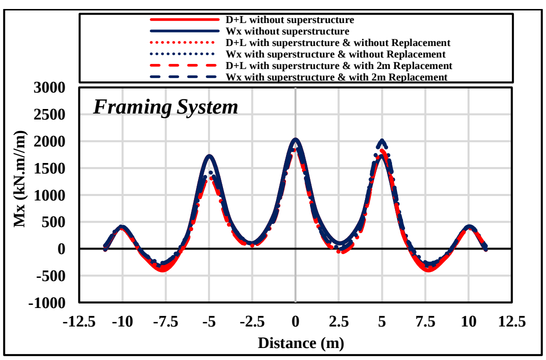
Loading Type	Structural system	Maximum Moments (kN.m/m)		
		Gravity loads	Wind Loads	Earthquake loads
CASE I	Frame	2029.4	2029.4	1892.8
	Core	1287.7	1287.7	1411.9
	Shear wall	2007.6	2007.6	1989.7
CASE II	Frame	1844.8	1895.4	1730.7
	Core	671.4	786.0	786.1
	Shear wall	1560.8	1642.1	1560.5
CASE III	Frame	1843.4	1887.4	1715.4
	Core	666.1	779.4	783.6
	Shear wall	1554.1	1634.1	1550.7

Fig. 7, Fig. 8, and Fig. 9 illustrate the maximum raft shear forces calculated along the raft's center axis (x-x) for framing, coring, and shear wall systems. The analysis revealed a pronounced decrease in the maximum raft shear forces by 41.3%, 39.2%, and 46.9% for the frame system, 36.2%, 25.6%, and 49.2% for the coring system, and 37.8%, 34.7% and 44.9% for the shear wall systems under gravity, wind, and earthquake loading, respectively when the superstructure stiffness was incorporated. Furthermore, using 2m sand replacement below the raft while considering the superstructure stiffness decreased the raft shear forces by less than 1.6%, as shown in Table 5.

This finding aligns with the observations reported by El Kamesh (2009), Ko et al. (2017), and Ibrahim et al. (2009).



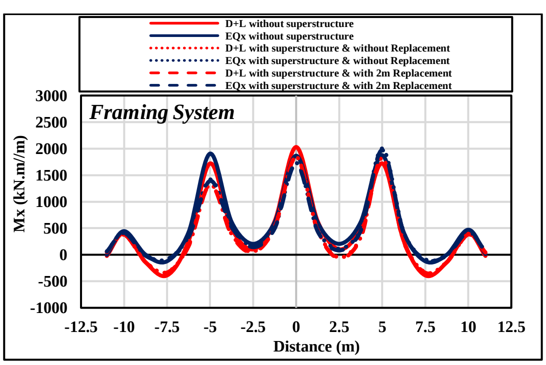
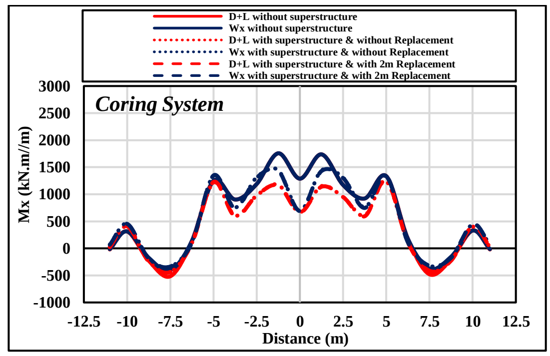


Fig. 4: Raft moments for framing system considering/not considering superstructure stiffness

Table 5. Maximum raft shear forces considering/not considering superstructure stiffness

Loading Type	Structural system	Shear Forces (know/m)		
		Gravity loads	Wind Loads	Earthquake loads
CASE I	Frame	2054.0	2054.0	2187.3
	Core	659.9	659.9	1682.3
	Shear wall	2637.1	2637.1	2963.8
CASE II	Frame	1206.3	1248.1	1162.2
	Core	420.9	491.2	855.4
	Shear wall	1639.9	1721.0	1632.5
CASE III	Frame	1219.8	1258.4	1166.9
	Core	414.1	484.3	853.2
	Shear wall	1656.6	1737.3	1646.7



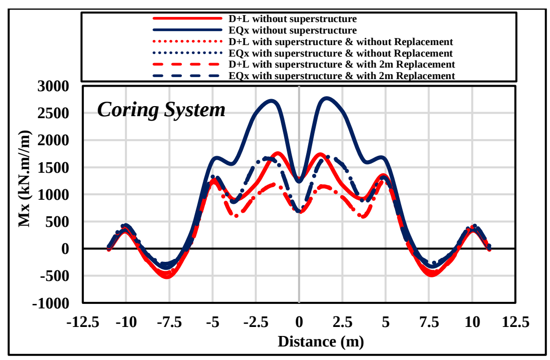
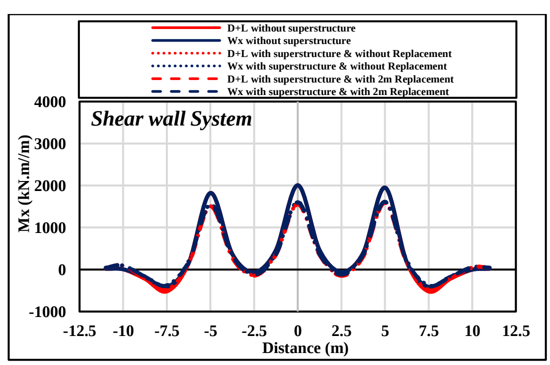


Fig. 5: Raft moments for coring system considering/not considering superstructure stiffness



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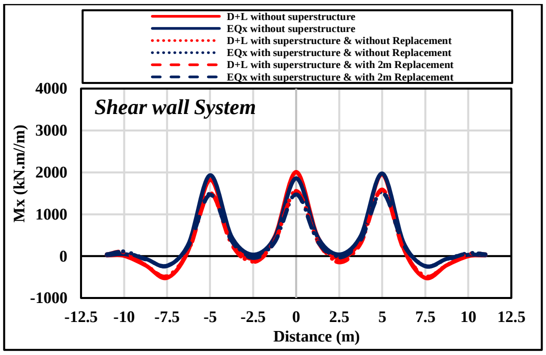
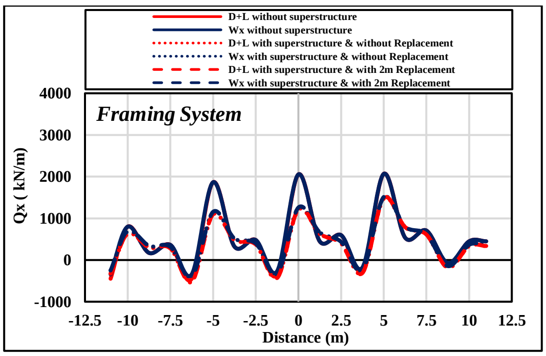


Fig. 6: Raft moments for shear wall system considering/not considering superstructure stiffness



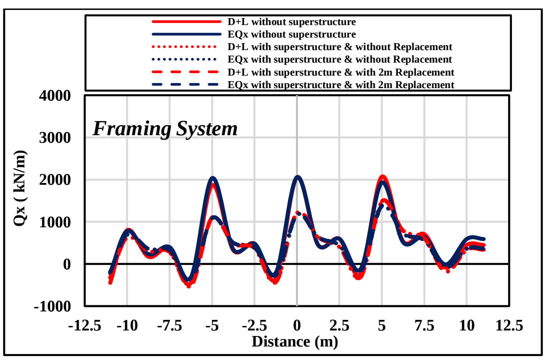
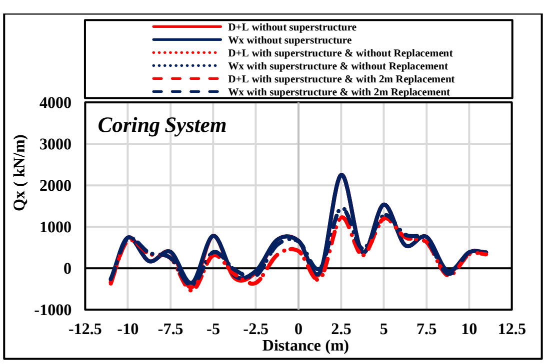


Fig. 7: Raft shear forces for framing system considering/not considering superstructure stiffness



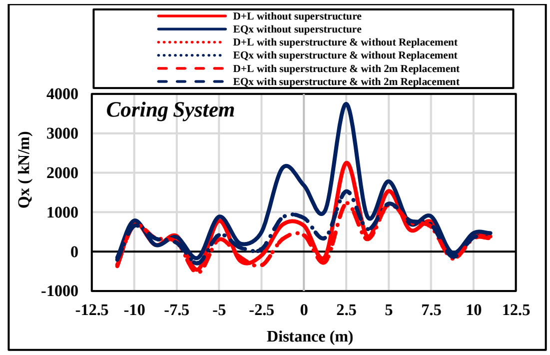
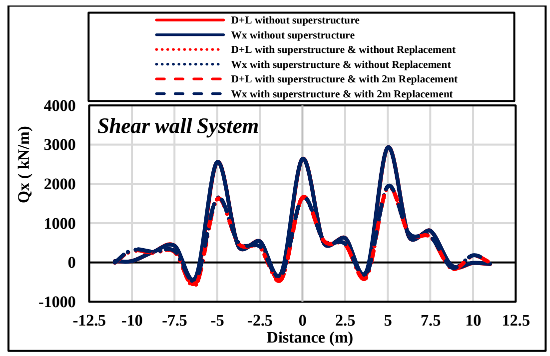


Fig. 8: Raft shear forces for coring system considering/not considering superstructure stiffness



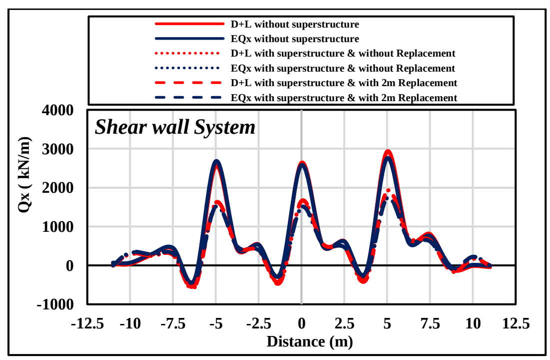


Fig. 9: Raft shear forces for shear wall system considering/not considering superstructure stiffness

4. Conclusion

Incorporating superstructure stiffness with various structural systems in clay soil results in a reduction in the raft's internal stresses, with the maximum reduction occurring at the center and gradually diminishing towards the raft's outer perimeter (bending moments and shear forces). This reduction is due to the increased rigidity introduced to the piles by the superstructure allowing for greater absorption of forces from the raft to the piles and the base become more flexible. This research is concerned with regular shapes of 20-story structures rested on uniformly distributed piled raft system in layered soil.

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The maximum raft bending moments beneath the center of the raft were significantly reduced, ranging from (6.6% to 9.1%) for framing systems, (39.0% to 47.9%), for coring systems, and (18.2% to 22.3%) for shear wall systems under gravity, wind, and earthquake loads. Furthermore, the maximum raft shear forces were also significantly reduced, ranging from (39.2% to 46.9%) for framing systems, (25.6% to 49.2%) for coring systems, and (34.7% to 44.9%) for shear wall system while incorporating the superstructure stiffness. These reductions occurred, considering gravity, wind, and earthquake loads.

Additionally, the behavior of the piled raft foundation is not significantly affected by considering 2m sand replacement above the clay layer while incorporating superstructure stiffness (reduction in the raft internal forces by less than 1.6%).

The variation of superstructure stiffness affects the raft's internal forces; therefore, it can be economically advantageous to consider this while designing the piled raft foundation. Consequently, the conventional fixed boundary requires validation prior to its application in engineering practice to ensure accurate predictions of well behavior and the design of superstructure-piled raft foundations.

Recommendations for future studies

This paper employed the simplified modal response spectrum method to analyze a 20-story square building subjected to earthquake loads. Three different structural systems were examined. Future research should explore a wider range of structural systems, including hybrid configurations and diverse and unconventional arrangements of cores and shear walls. To delve deeper into seismic response, alternative techniques like the nonlinear Time History method are recommended in addition to varying aspect ratios, building height, pile configurations, and material compositions.

In addition, to enhance performance in weak soil, consider implementing other ground improvement techniques, such as grouting or geosynthetic reinforcement. Additionally, groundwater effects should be included in future studies of long-term soil behavior, including soil creep, consolidation, cyclic loading effects, and variations in groundwater depth, which can significantly influence both soil behavior and foundation performance. Experimental validation might be conducted in future research to verify numerical results and provide practical engineering recommendations. Further, to simulate real-world conditions, the flexibility of piled raft foundations under various pile head boundary conditions also can be investigated.

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