A Study on Load Distribution Mechanism of Pile-Raft Foundation Systems

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***Abstract*:- Design concepts and load sharing mechanism of piled raft foundations have been studied in this thesis. In the conventional piled foundations, the load transferred only by the piles and the piles are used for the reducing of both total and differential settlements and the contribution of the raft is generally disregarded. In the first part of the thesis, design approaches in the literature have been discussed. In the second part of the thesis, parametric analyses have been conducted for typical foundation in over consolidated Bhaili clay and finite element analyses have been done for Aura prime building. Three dimensional analyses have been made by the widely used commercial software of Plaxis 3D and SAFE-2016, which solve the models by using the Finite Element Method. The foundation settlement and the load sharing between raft and pile have been investigated to identify the contribution of raft to the total capacity of piled raft foundations. The results showed that the raft can carry up to the 41.52% of the total applied load for an optimum number of piles for acceptable settlement levels.**

Keywords: Pile, raft, foundation, plaxis-3d, deep-foundation, soil-interaction, settlement, soil-pile interaction, safe-2016

INTRODUCTION

One of the most important aspects of a civil engineering project is the foundation system. Designing the foundation system carefully and properly, will surely lead to a safe, efficient and economic project overall. In other words, foundation system design is one of the most critical and important step when a civil engineering project is considered. Until quite recently, there were some separately used systems like shallow foundations such as rafts and deep foundations such as piles. However, lately the foundation engineers tend to combine these two separate systems. By combining these two systems, the foundation engineer will provide the necessary values for the design obtain the required safety and also come out with a more economical solution.

To carry the excessive loads that originate from the superstructures like elevated structures, spans, power plants or other common structures and to prevent excessive settlements, piled foundations have been created and broadly utilized in late decades. However, it is seen that the design of foundations considering just the pile or raft is not a feasible solution because of the load sharing mechanism of the pile-raft-soil. In this manner, the blend of two separate systems, to be specific "Piled Raft Foundations" has been created (Clancy and Randolph (1993)).

Piled Raft foundation system is verified to be economical foundation type comparing with the traditional piled foundations , where, just the piles are utilized for the diminishing both aggregate and differential settlements and the contribution of the raft is commonly ignored.

In this examination, conduct of the piled raft foundation systems under axial loads has been explored by comparing the traditional design approaches and investigating parametric analyses. In the literature, there are a lot of explores centering of these boundaries, like; the number of piles, length of piles, diameter of piles, pile spacing ratio, location of piles, stiffness of piles, distribution of load, level of load, raft thickness, raft dimensions and type of soil. In any case, through these boundaries, the number of piles, length of piles and level of load are emphasized in this examination. Effects of these parameters are discussed with the solutions of finite element models. To this end, parametric investigations are directed through the software Plaxis 3D and SAFE-2016 with the comparisons.

FINITE ELEMENT ANALYSIS OF PILED RAFT FOUNDATIONS

Geotechnical and Material Parameters for Input

Piled raft on two different software's were analyzed in this study. A typical 23-storey building in Bill village soil, in software PLAXIS-3D. The second one is in software SAFE-2016 with same building and soil parameters.

A typical 23-storey building in BHAILI

Soil Properties: The SPT data was taken from a report for a construction site on Bhaili, where the soil is commonly overconsolidated clay. Raw SPT-N values for four different boreholes are shown in Figure1.

Average of the SPT-N values has been taken to derive a single corrected SPT value, N60, which is shown in Figure2. It is assumed that the stiffness of the soil is linearly increasing; therefore the profile of the corrected N values is deeper than the

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profile of raw SPT-N values. For the input parameters of the Plaxis 3D, it is needed to convert the SPT-N values to soil stiffness parameter E'. The correlation of Stroud (1975) has been used for the N60 - E' relationship.

$$E' = N_{60} * 0.8$$

Where E' is in MPa

Corresponding E' values vs. depth has been shown in the Figure3. E' increases averagely 1.600 MPa per one meter depth, starting from the 10.24 MPa at ground level.

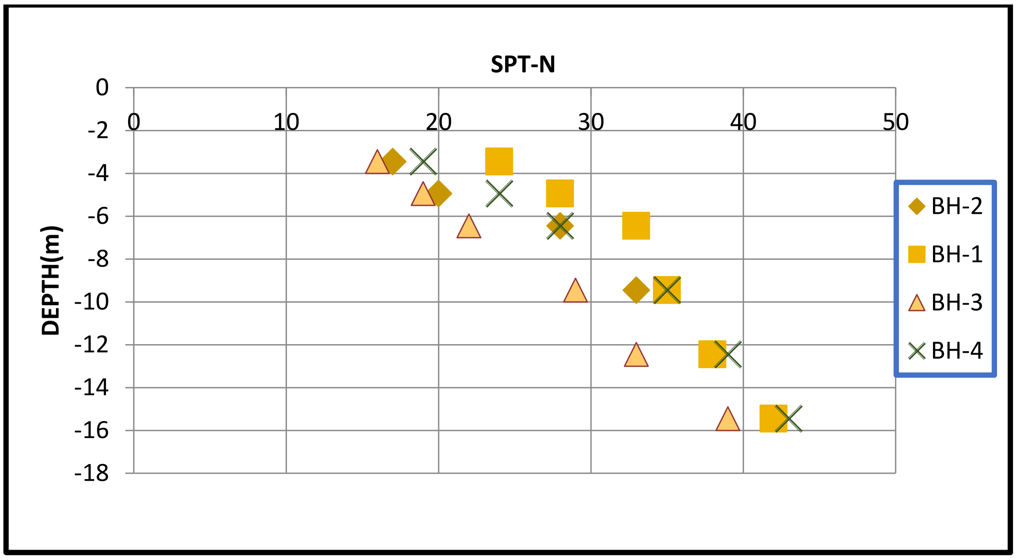

Figure 1 SPT-N values vs Depth(m)

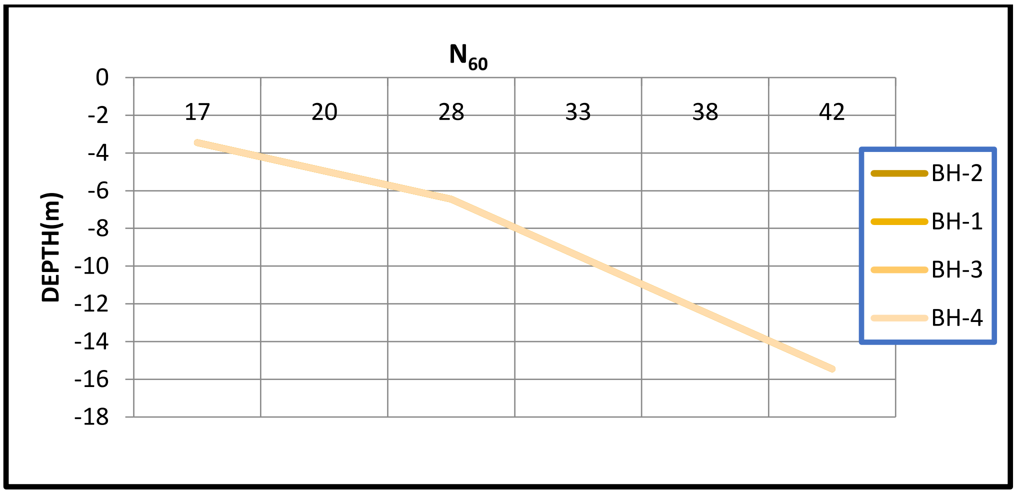

Figure 2 Corrected SPT-N values

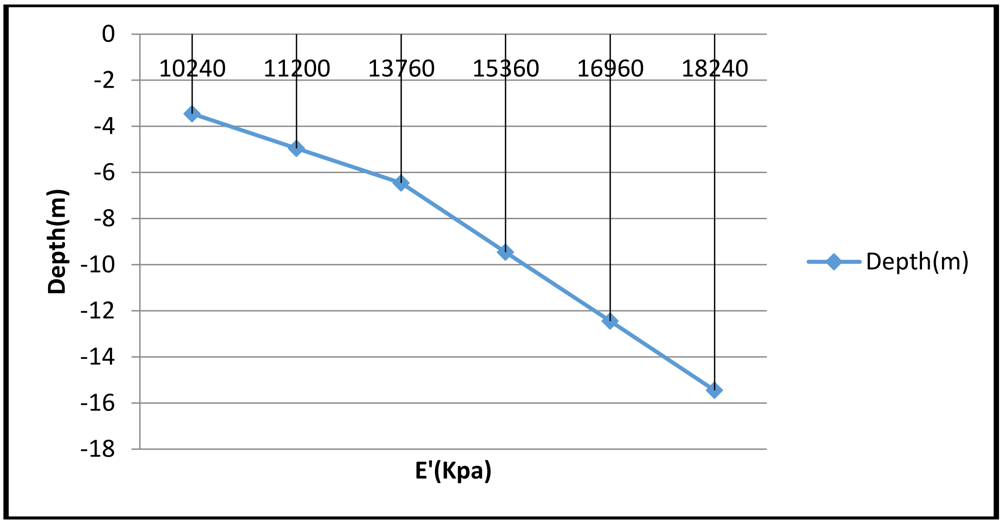

Figure 3 E' (kPa) vs. Depth (m)

Table 1 - Soil Properties for BHAILI CLAY

Parameter	Symbol	Overconsolidated Clay	Unit
Material Model	-	Mohr-Coulomb	-
Unsaturated weight	γ_{unsat}	18	kN/m^3
Saturated weight	γ_{sat}	18	kN/m^3
Stiffness	E'	10,240	kN/m^2
Stiffness Increment	$E_{increment}$	1600	kN/m^2/m
Cohesion	c'_{ref}	12	kN/m^2
Friction angle	φ'	25	-
Poisson ratio	ν'	0.25	-
Lateral pressure coefficient (K_{0x}=K_{0z})	K_0	0.8	-
Interface stiffness ratio	R_{inter}	1.0	-
Drainage Type	-	Drained	-

Structural Properties: The building is assumed as reinforced concrete building with 23- storey and 28x22m floor area. Piled raft foundation located at 5m below ground level. Raft thickness and the length of the piles are variable. Raft and pile properties used in the Plaxis 3D model are shown in Table 2 and Table 3. Piles are designed as embedded piles. Massive circular pile was selected among the predefined pile types for embedded piles. Skin resistance and the base resistance of embedded piles must be calculated and specified for the material input phase. The correlation of Stroud (1975), shown in Figure 28, has been used for the conversion of SPT-N values to shear strength of soil by taking the coefficient f1 as 4.6. In addition the unit skin friction multiplier is taken as 0.35 of Cu. With the multiplication of these coefficients by related area and circumference values of piles, maximum skin resistance at the top (T_{max}^{top}) and the bottom (T_{max}^{bottom}) of the pile and the base resistance were calculated for the piles with a diameter of 1m. Material and section properties, used in SAFE-2016 Analyses of raft and pile are shown in Table 4 and Table 5 for Building in BHAILI CLAY.

Table 2 Raft Properties for BHAILI CLAY

Parameter	Symbol	Raft	Unit
Material Model	-	Linear-Isotropic	-
Unit weight	γ	25	kN/m^3
Stiffness	E_{ref}	2.7386E+07	kN/m^2
Poisson ratio	ν	0.2	-
Thickness	t	1.6	m
Width - Breadth	W x B	30 x 24	m

Table 3 Embedded Pile Properties for BHAILI CLAY

Parameter	Symbol	Embedded Pile		Unit
Material Model	-	Linear Elastic		-
Unit weight	γ	30		kN/m³
Stiffness	E_{ref}	2.7386E+07		kN/m²
Diameter	d	0.75		m
Length	L	15	25	m
T^{top}_{max}	-	16.57	16.57	kN/m
T^{bottom}_{max}	-	55.79	81.94	kN/m
Base resistance	F_{max}	281.46	410	kN
No. of piles	-	110 & 210		-

Table 4 Material and section properties of Raft in BHAILI CLAY for SAFE-2016 Analyses

Parameter	Symbol	Raft	Unit
Property	-	Shell Thick	-
Unit weight	γ	25	kN/m³
Modulus of Elasticity	E	2.7386E+07	kN/m²
Poisson ratio	ν	0.2	-
Thickness	t	1.6	m
Width - Breadth	WxB	30 x 24	m

Table 5 Material and section properties of Pile in BHAILI CLAY for SAFE-2016 Analyses

Parameter	Symbol	Pile	Unit
Property	-	Frame - Pile	-
Unit weight	γ	25	kN/m³
Modulus of Elasticity	E	2.7386E+07	kN/m²
Poisson ratio	ν	0.2	-
Diameter	d	0.75	m
Length	L	15 & 25	m
No. of piles	-	110 & 210	-

Building-1: A typical 23-storey building in BHAILI

The building is a reinforced concrete building with 23-storey and 28x22m floor area. Piled raft foundation located at 5m below ground level (assuming two basements). Lengths of the piles are variable. Due to loading and the shape/geometry of the structure and also the soil beneath the foundation only a quarter of the foundation has been taken into account and the center of the model foundation has been placed in alignment with the z-axis the as shown in Figure 5. For the parametric analyses of the Building-1, sub-cases have been used, which are listed in the Table 6.

Table 6 Sub-cases of Building-1

Sub-Case	Number of piles	Pile length (m)	Distributed load (kPa)
Model-1	110	15	390
Model-2	110	25	390
Model-3	210	15	390
Model-4	210	25	390

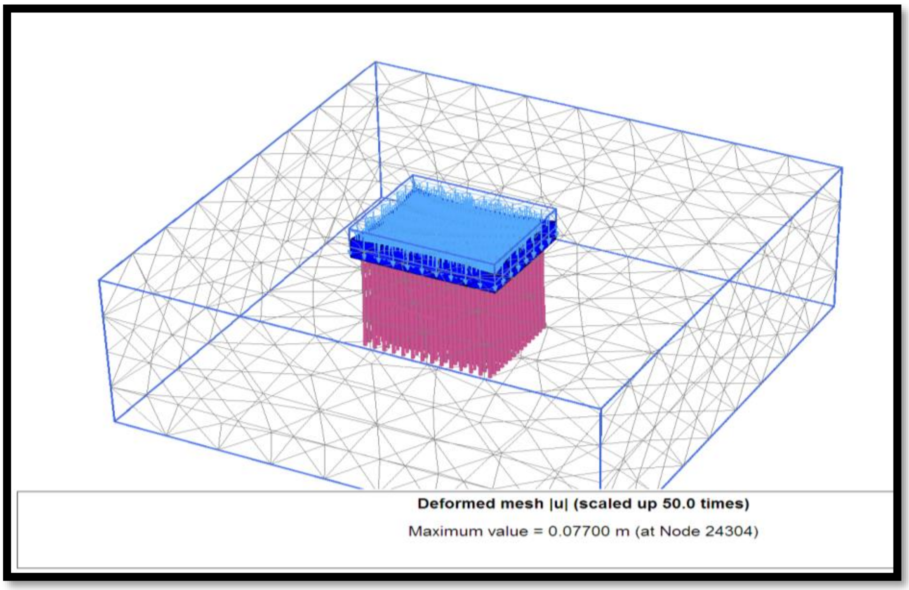

Figure 5 Deformed shape of Finite Element method of the piled raft foundation of Model-4

Raft and pile properties, including the geometrical properties, were previously tabulated in Table 5 and in Table 6. The raft thickness is taken as 1.6m. Ultimate capacity of 15m and 25m length piles are **3347kN** and **7374kN** respectively.

The maximum total (dead and live) load has been taken as **16.9kN/m²/floor**. Therefore, the maximum total design load of the structure becomes **202034KN** for the selected case with 23- storey building. Total **390 kN/m²** load applied to the foundation in the direction of gravity as distributed load.

SAFE-2016 Analyses
Simplified Method (Using the outputs of Manual Calculation):

SAFE-2016 software has been used for back analyses of the model. As mentioned before, the main supports are joint springs and area springs in SAFE-2016. The stiffness of soil is modeled by the joint and area springs. A sample of a 3D view of the Sap2000 model is shown in Figure 30. Raft settlements are taken as average by the suggested formula of Davis & Taylor (1962) as following;

$$S_{avg} = \frac{1}{3}(2S_{centre} + S_{corner})$$

To find the spring constant of raft and pile separately, a soil capacity is calculated by using soil parameters of site in BHAILI SOIL. Skin Resistance at bottom of pile is calculated by theoretical equation for 15m length and 25m length piles are 55.796KN/m and 81.94KN/m respectively. Similarly, End Bearing Résistance for 15m length and 25m length are calculated as 281.46KN and 410KN respectively. By considering the different allowable displacement of pile as 5mm, 10mm, 20mm, 50mm different spring constant are calculated shown in Table7

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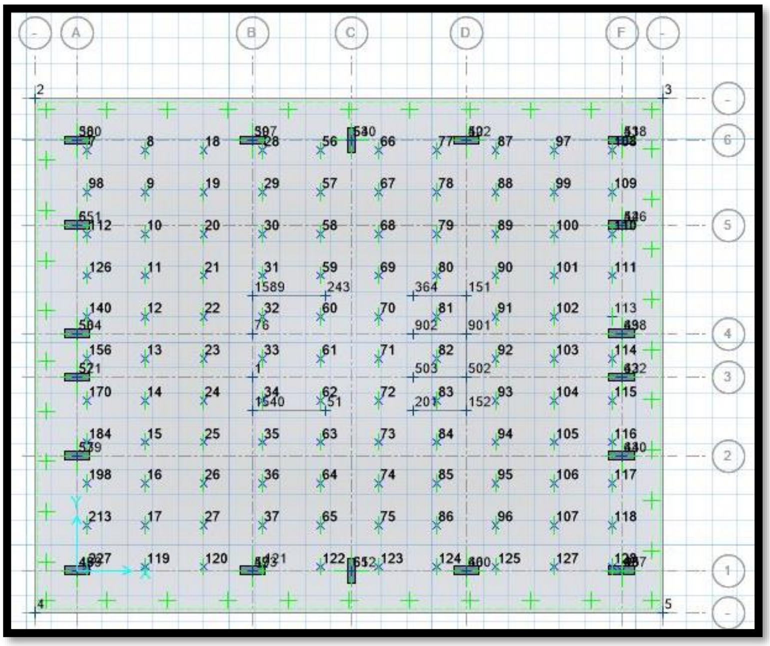

Figure 6: Plan View of SAFE-2016 model for Model-1

TABLE 7 FOR PILE SPRING CONSTANT

Allowable displacement (mm)	5(mm)	10(mm)	20(mm)	50(mm)
15m length pile	171546KN/m	85773 KN/m	42886KN/m	17154KN/m
25m length pile	413560KN/m	206780KN/m	103390kN/m	41356KN/m

Disregarding the outputs of Plaxis

Separate analyses have been conducted to observe the behavior of piled raft by disregarding the outputs of Plaxis. In these analyses, allowable loading capacities of piles have been divided to the variable allowable settlements (at the top of the pile) to the usage of spring stiffness of piles. Initially, maximum allowable settlement is taken as 0.01m. This results in to a spring constant of 85773 KN/m and 206780KN/m for 15m and 25m length piles, respectively. Also, to analyze the effect of raft contribution, raft springs have been used as; 0, 1000, 2000, 5000, 10000 kN/m/m2. This process has been repeated for the allowable settlements; 0.05m, 0.02m, 0.01m and 0.005m. All results are listed in Appendix V. Critical pile loads are listed in Table 8 and the locations of piles are shown in a quarter of the piled raft in Figure 7.

Figure 7 Piles taken as reference shown in a quarter of the piled raft.

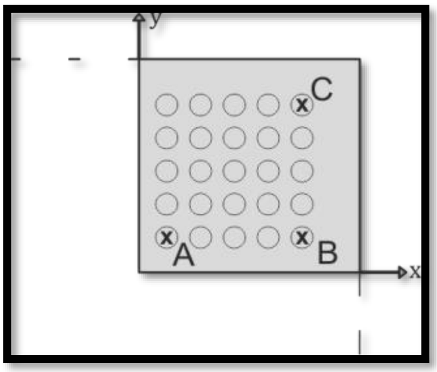

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Table 8 Comparison of pile loads (Model-1-15m pile length)

		Springs		Pile Loads (kN)		
		Pile (kN/m)	Raft (kN/m/m2)	A	B	C
SAFE 2016	k for 0.005m	171546	10,000	1458.165	2181.863	1782.005
	k for 0.010m	85773	10,000	1230.728	1585.339	1413.817
	k for 0.020m	42886	10,000	971.77	1091.729	1045.988
	k for 0.050m	17154	10,000	664.295	645.723	662.954

Pile load distributions

Case 1: A typical 23-storey building in BHAILI

Axial load distributions are plotted in Figure 8. All the piles are 15 m length. It is observed that the center piles have lower axial loads on both 110 piles and 210 piles situations. This is because of the pile group effects. However, for 210-pile case, it is observed that the axial load of the center pile is almost half of the outer piles. Center pile can approach to the load level of outer piles after the depth of 10m and moves parallel after this point. This may be the effect of small ratio of pile spacing and pile diameter, which causes the block movement of soil just beneath the center of raft. Therefore, considering the movement of the soil beneath the center of raft, shown in Figure 9 and Figure 10, the behavior of the center and corner piles is in reasonable.

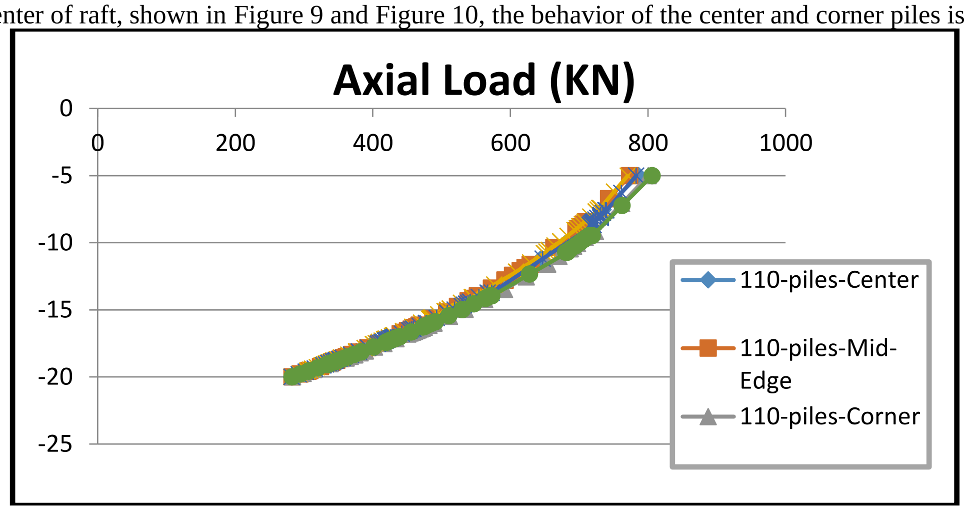

Figure 8 Comparison of axial load distributions along piles for different number of piles (Model-1 (110piles, 15m, 390kPa) vs. Model-3(210piles, 15m, 390kPa))

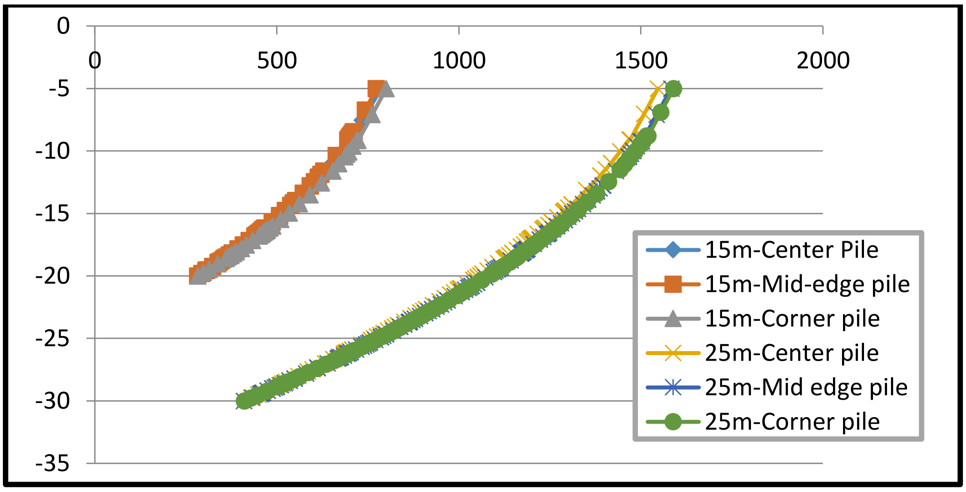

Figure 9 Comparison of axial load distributions along piles for different length of piles (Model-1 (110piles, 15m, 390kPa) vs. Model-2 (110piles, 25m, 390kPa))

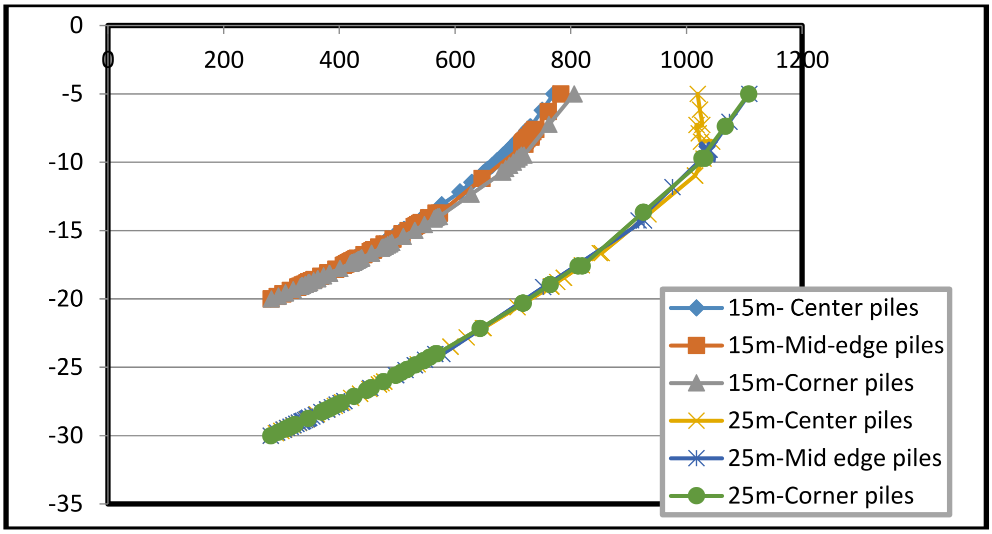

Figure 10 Comparison of axial load distributions along piles for different length of piles (Model-3 (210piles, 15m, 390kPa) vs. Model-4 (210piles, 25m, 390kPa))

Load Sharing of Raft

After all of the analyses have been carried out, the loads on each pile are added and subtracted from the total applied load to find the total load carried by the raft. The values are tabulated in Table 9. As stated in the previous subject, the usage of longer piles increases the shared load of piles. Other points can be listed as; total load carried by the raft increases in higher load levels and it also increases in higher number of piles for longer piles. However, the load on raft is decreased by the higher number of piles for shorter piles.

Table-9 Model cases for Building-1 with variable number of piles, pile length

Models	Number of piles	Pile Length(m)	Dist. Load(kPa)	Total Load(KN)	Pile Load(KN)	Raft Load(KN)	Load on Piles(%)	Load on raft(%)
1	110	15	390	280800	86285	194514	30.73%	69.27%
2	110	25	390	280800	172359	108440	61.38%	38.62%
3	210	15	390	280800	164040	116759	58.42%	41.58%
4	210	25	390	280800	23036	50563	81.99%	18.01%

Table-10 Comparison of load and settlement with different spring constant

	Spring constant		**Load (KN)**		
Max Allow. Sett	Pile (KN/m)	Raft (KN/m/m2)	Pile (KN)	Raft (KN)	Pile load/Total load
5mm	171546	0	231324	0	**100%**
	171546	5000	195776	35548	**84.6%**
	171546	10000	171005	60318	**73.92%**
10mm	85773	0	231324	0	**100%**
	85773	5000	171982	59341	**74.34%**
	85773	10000	139650	91673	**60.36%**
20mm	42886	0	231324	0	**100%**
	42886	5000	140426	90898	**60.70%**
	42886	10000	105837	231324	**45.75%**
50mm	17154	0	231324	0	**100%**
	17154	5000	96046	135277	**41.52%**
	17154	10000	68968	162356	**29.81%**

Table-18- Maximum and minimum Settlement of Rafts

	PLAXIS		**SAFE-2016** (Considering raft spring 2000KN/m2)	
	Max. Sett. (mm)	Min. Sett. (mm)	Max. Sett. (mm)	Min. Sett. (mm)
Model-1-(110 piles-15m)	-134	-105	-80	-65
Model-2-(110 piles-25m)	-73	-60	-51	-34
Model-3-(210 piles-15m)	-98	-80	-54	-42
Model-4-(210 piles-25m)	-72	-58	-31	-20

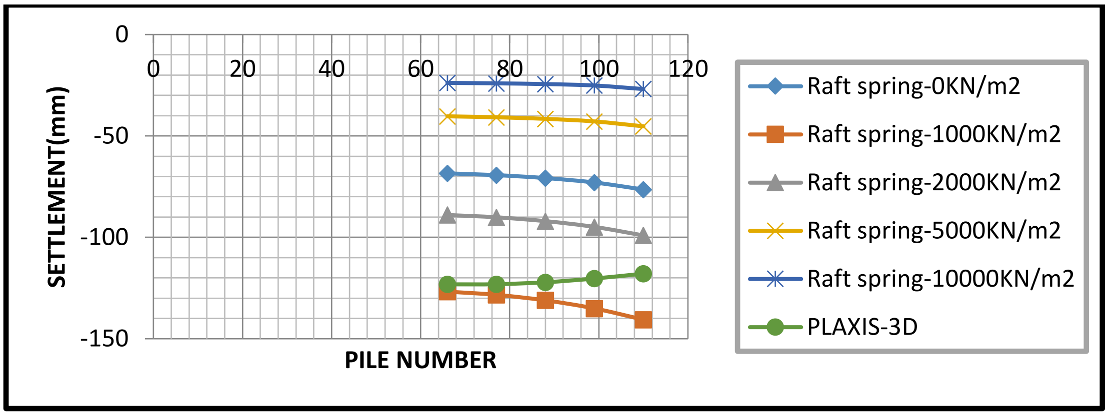

Figure 11 Settlements at the head of piles (i.e. Outer piles)

(Model 1-110 piles-15m)

SUMMARY AND CONCLUSION

Piled raft systems are verified to be an economical foundation type comparing the conventional piled foundations, where, only the piles are used for the reducing of both total and differential settlements and the contribution of the raft is generally disregarded. In this study, the foundation settlement and the load sharing between raft and pile have been investigated to identify the contribution of raft to the total capacity of piled raft foundations.

In the first part of this study, a detailed literature review for the design of piled raft foundations has been presented. Advantages and disadvantages of different approaches have been discussed to model the piled raft foundation systems. Also the factors affecting the behavior of piled raft foundations have been discussed. Discussed factors are; the number of piles, length of piles, diameter of piles, pile spacing ratio, location of piles, stiffness of piles, distribution of load, level of load, raft thickness, raft dimensions and type of soil.

In the second part, a case has been created for Bhaili Clay and parametric analyses have been conducted with the help of Plaxis 3D software. Variables for the parametric analyses are pile number, pile length. In addition, a case study, SAFE-2016 Analyses validate the method of the calculation. Results show that the calculation method is in line with the actual piled raft behavior.

CONCLUSIONS

A method presented to find the settlements in Safe-2016 by using the outputs of the Plaxis. Using the embedded pile feature of Plaxis, raft and pile load sharing is calculated and the corresponding load-settlement curves are plotted. Taking the constant of the slope of this curve as the total spring of elements, corresponding average spring constants are assigned to the piles and raft in Safe-2016.

The proposed method of analysis becomes more realistic with the additional soil springs connected to the raft. This may be helpful for structural/foundation engineers to calculate the deformations more accurate and the structural properties of raft more effective.

Average percentage of raft load share is **41.52%** for the allowable settlement of 65mm for the Plaxis Analysis. For the SAFE-2016 Analysis, at the final design load, raft can carry up to **29.81%** of applied load. The main reasons for the difference in these two cases are the Raft Spring, the foundation characteristic (number of piles and length of piles) and the soil stiffness.
HYP8: The principle of consuming income and not capital is not applied in construction project management.

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