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Effect of Pile Raft Area Ratio on Load Capacity of Piled Raft Foundation

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***Abstract**: The design of piled raft is based on the soil-structure interaction between the constituting elements , however, the piled raft subsoil interaction problem is highly complicated as it depends on large number of parameters like pile-raft geometry, pile spacing, subsoil type etc.*

The behavior of piled raft and various aspects of behavior relating to the load settlement and the load sharing response have been studied by various researchers. However it appears that the phenomenon of the interaction between the constituent elements has not been studied in detail.

It was noted by some researchers that the main parameter that influences the response of piled raft system is its stiffness. But the stiffness of a piled raft system depends on the elements in the system. The elements of the system are the soil, piles, superstructure and the raft. The stiffness of a piled raft system is governed by individual stiffness of the elements, thus, the parameters that should be studied must be identified accordingly. Moreover, it was observed that the ratio of piles to raft area has important influence on load sharing of piled raft component, therefore, the intended task of this paper is to study the relation between piles-raft area ratio to the load-sharing between the piles and the raft, as most of the researchers failed to understand the relationship between them and then found out the specific relation.

The total number of cases solved is (15) using the finite element method in this study and develop a numerical model to predict the load-settlement relationship and load sharing between the piles and the raft of the piled-raft foundations. The result of the analysis using the Plaxis to follow up load sharing of piled raft component through varying the spacing and number of piles for the piled raft of piles length of (30m) and raft width (20 m) at soil of (Cu = 60 kPa) . Again similar analysis is repeated on the same previous case, but now using piles length of (40 m) and (60 m) to study the relation between piles-raft area ratio to the load-sharing between the piles and the raft as the piles length is increased.

It was observed that the ratio of total piles area to raft area has important influence on load sharing of piled raft component. The piles load sharing varies from (15%) at piles-raft ratio of about (1 %) corresponding to pile spacing of (7D) to (42%) at piles/raft ratio equals to (7%) corresponding to a closely pile spacing of (3D) which means that the piles are taking more loading share and there is a tendency to behave as a mere piled system as the spacing between piles is reduced. Moreover , it can be deduced that a wider spacing of piles (5D) to (7D) will be the optimum spacing for the performance of the piled raft system with regards to the load distribution among the components of the piled raft system, but the system total load is lower when compared to that of closely spacing piles (3D), so that , a low ratio of piles tip load sharing and this share is further reduced with increasing piles length which supports the fact that the piles in the weak clayey soils behave as a floating pile which leads to neglect end bearing capacity in calculating the total pile load capacity.

1. Introduction

Piled-foundation is a composite foundation consisting of two elements; piles and raft, the applied loads are transferred to the subsoil both through the raft and the piles. The presence of the raft and its contribution in sharing the load is ignored in conventional design of piled foundations, such a foundation that allows the load to be shared between the raft and piles is called "piled raft foundation", which makes it an alternative to conventional piled foundation.

In the past, piled-raft foundation system have been considered in supporting structures in certain types of soil like sandy soils, nowadays; it is used in many types of soils. Moreover, piled-raft foundations have been used as foundations to support several types of structures such as bridges, buildings and industrial plants. The piled raft foundation has been used to support structures not only on favorable ground conditions as shown by Poulos [1] but also on unfavorable ground conditions with ground

improvement techniques as reported by Yamashita et al. [2].
The design of piled raft is based on the soil-structure interaction between the constituting elements , however, the piled raft subsoil interaction problem is highly complicated as it depends on large number of parameters like pile-raft geometry, pile spacing, subsoil type etc.
The behavior of piled raft and various aspects of behavior relating to the load settlement and the load sharing response have been studied by various researchers like Reul [3], Poulos [4]. However it appears that the phenomenon of the interaction between the constituent elements has not been studied in detail. As pointed out by Lee and Chung [5] the complex interaction can become favorable like increase in the group capacity or unfavorable like causing additional settlement.
It was noted by some researchers that the main parameter that influences the response of piled raft system is its stiffness. But the stiffness of a piled raft system depends on the elements in the system. The elements of the system are the soil, piles, superstructure and the raft. The stiffness of a piled raft system is governed by individual stiffness of the elements, thus, the parameters that should be studied must be identified accordingly. Moreover, it was observed that the ratio of piles to raft area (piles-raft area ratio) has important influence on load sharing of piled raft component. Increasing piles area yields increasing pile shaft peripheral area that increases the piles load capacity, therefore, the intended task of this paper is to study the relation between piles-raft area ratio to the load-sharing between the piles and the raft, as most of the researchers failed to understand the relationship between them and then found out the specific relation..

2. Methodology

2.1 General.

The finite element method is considered the most powerful tool among the other methods of analysis. The finite element method takes into account the effect of the interaction factors such as pile-to-pile, pile-to-raft, raft-to-raft and pile-to-soil interactions in the analysis process, therefore, the finite element method was selected in this study to develop a numerical model to predict the load-settlement relationship and load sharing between the piles and the raft of the piled-raft foundations.

Plaxis is geotechnical software based on the finite element method and it is intended especially for analyzing geotechnical problems. It can be considered as a special-purpose program. Plaxis can be used as a tool for practical analysis for most areas of geotechnical engineering. Piled-raft foundation is a three dimensional problem, which requires three dimensional modeling, so the piles group effect cannot be studied with axisymmetric (2D) models and consequently it requires performing calculations with Plaxis (3D) foundation . For that the Plaxis - 3D program version (1.6) was selected for developing the three-dimensional finite element model in this study.

2.2 Numerical Modeling

2.2.1 Geometry

A geometry model is a composition of bore holes and horizontal work planes. The work planes are used to define geometry lines and structures contour lines along the elevation level and the bore hole is used to define the soil properties, ground surface level and water table elevation

2.2.2 Material properties

The soil is modeled as a single layer of clay with strain hardening soil behavior. The main advantage of this model is its ability to consider the stress path and its effect on the soil stiffness and its behavior.

For modeling the piles, a linear elastic material model is considered where the pile is modeled as a volume pile of the massive circular type, so that the interfaces are modeled along the pile. The purpose of interface element is to simulate the relative friction between the piles and soil. Raft is represented as floor element with a linear elastic model. The properties of the floor (raft) and piles considered in the parametric study are shown in Table (1). The input soil properties considered in this numerical parametric study are presented in Table (2).

Table (1) Input properties of raft and piles used in numerical parametric study of piled raft.

Description	**Symbol**	**Piles & Raft**
Type	-	Concrete
F.E. Model	-	Linear Elastic
Unit Weight (kN/m^3)	γ	24
Modulus of Elasticity (GPa)	E	20
Poisson's Ratio	ν	0.2

Table (2) Input parameters of the soil properties used in numerical parametric study of piled raft.

Description	**Symbol**	**Unit**	**Clay Cu = 60 kPa**
F.E. Model	HS	-	Hardening
Type of model Behavior	-	-	Drained
Unit Weight	γ	kN/m^3	16
Secant Stiffness in Standard Drained Triaxial	E^{ref}_{50}	kPa	7 500
Tangent Stiffness for Primary Oedometer Loading	E^{ref}_{oed}	kPa	20 480

Unloading/Reloading Stiffness (Default = 3 E^{ref}_{50})	E^{ref}_{ur}	kPa	22 500
Cohesion	C	kPa	60
Friction angle	**Ø**	degree	10
Poisson's Ratio	**ν**	-	0.35
Interface Reduction factor	R_{inter}	-	0.7
Angle of dilatancy	ψ	-	0
Exponential Power	m	-	1

2.2.3 Mesh Generation

After the model has been completely built and all borehole information has been entered, an automatic local refinement will be performed by the program, it is recommended to generate a 2D finite element mesh before generating a full 3D mesh. PLAXIS (3D) program allows for a fully automatic mesh generation procedure, in which the geometry is divided into volume elements and compatible structure elements, if applicable.

2.2.4 Calculation Stages

After the mesh has been generated, the finite element model is completed, the calculation can be performed, before the calculation is started, the calculation stages have to be defined , the procedure of the calculation stages of the program is divided into three phases, and are:

1. Generate initial stresses and water pressures: the initial effective stresses are generated following the (Ko) procedure, where (Ko = 1 – sin φ); (Ko) represents the coefficient of the lateral earth pressure at rest which defines the relationship between horizontal and vertical stresses in the soil.
2. Piles and raft installation: the material of the floor cluster is replaced by raft material and the material of the piles clusters are replaced by the pile material and, if present, the interface elements between soil and pile are activated.
3. Loading: At this stage, the displacement is set to zero and the loading process begins. Firstly, a unit point load is activated on the top of the piled raft. Subsequently this load is increased until the automatic load-increment routine in the PLAXIS is unable to increase the load further.

After the model is created using the above steps and the calculation stages has been completed, the results can be evaluated from the program, then finding the load settlement curve of the footing. The load-settlement curves for each case are plotted for the node point located at the center of the top side of raft. The Plaxis (3D) software gives different outputs according to the requirements of the user, so that among the major outputs, deformations, stresses, strains, forces, etc. can be included. In relation to this study, load-displacement is the main concern, and for the next parametric study example the load sharing of piled raft component are also considered.

The calculated load capacity of piles was deducted from the load applied on the piled raft at the stopped stage (run) to get the load share by the raft of piled raft.

2.3 Numerical Results Verification

The verification has been previously performed by Waheed (2016) in which the numerical results according to Plaxis (3D) program are compared with the experimental data, It was concluded that the analysis using Plaxis gives reasonable results in comparison to the experimental outputs and hence, it can be used for studies of piled raft system in clayey soil of other parametric study, and then it is possible to estimate the ratio of load sharing between the piled raft components at the final stages of the loading.

3. Results and Discussions

The total number of cases solved is (15), each case symbol is indicating the case number followed by the parameters considered and their values. For clarification, for a case notation (PR(4×4)-B20L30D100S5) it indicates that, this case represents a raft supported by a (4×4) pile group, the first letter after the test number represents the parameter name which is the raft width (B) in this example, (20m) represents the value of this parameter, the second letter (L) represents pile length which is (30m), while the third letter (D) is the pile diameter in centimeters and is (100cm) here. The fourth letter (S) represents the pile spacing in terms of pile diameter and here is (5) times pile diameter.

The shape of raft is specified as square, so that for the study conducted here a uniformly distributed load is applied during loading stages and uniform distribution of piles is considered.

It is also assumed that the foundation soil is composed of a uniform homogeneous layer of clay down to a depth of about two times the pile length, while the ground water level is encountered very deep from the soil surface.

In order to illustrate the procedure considered in the analysis of the parametric study of a full size piled raft foundation, the case of (PR(4×4)-B20L30D100S5) is selected as typical piled raft case as an example of the analysis by the Plaxis software. The deformed mesh after loading stages has been completed for typical full scale piled raft case is shown in Figure (1) and the distribution of vertical displacement is seen in Figure (2). The numerical load settlement curve using the program for the typical full scale piled raft case is shown in Figure (3).

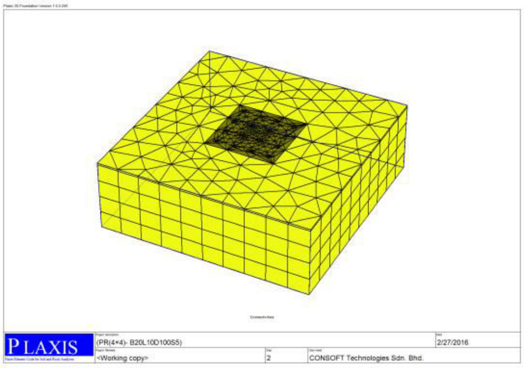


Figure (1) The deformed mesh of the typical full scale piled raft case (PR(4×4)- B20L30D100S5).

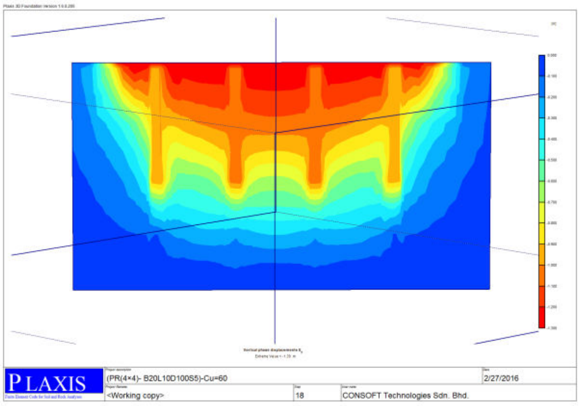


Figure (2) The distribution of vertical displacement of the typical full scale piled raft case (PR(4×4)- B20L30D100S5).

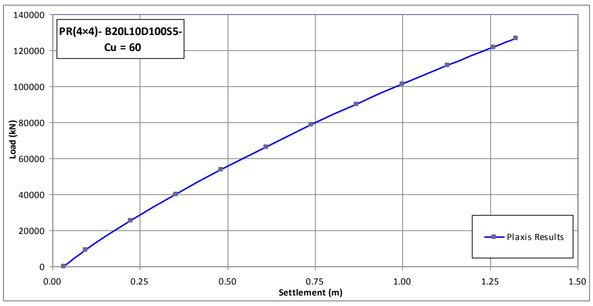
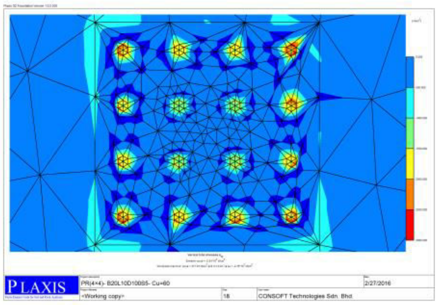


Figure (3) The numerical load settlement curve of the typical full scale piled raft case (PR(4×4)- B20L30D100S5).

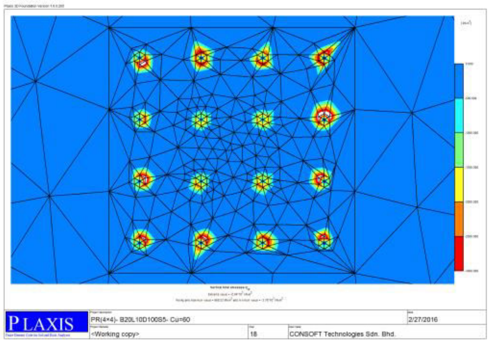
In order to predict the response of the piled raft component during different settlement level, the value of settlement is recorded and a cross section has been selected from the output of the program at pile head and tip levels in order to read the vertical stresses at these planes. In order to get an accurate value of piles capacity it was found that the junction at floor-pile is a high stress variation area because the changing of the area (at the junction) leads to lower value of piles capacity, therefore, it was decided to select a section (1m) below the floor to get accurate values.

The Plaxis software output of vertical total stress in contour plot for the sections at pile head and tip levels is shown in Figure (4). The stress is read at each pile and the average value of the reading for all piles is taken and then it was multiplied by the cross sectional area of the piles in order to calculate the load capacity of piles tip and piles.

The method to calculate piles tip capacity is the same as for total piles capacity but it was made at a cross section at the pile tip and considered only the contribution of the vertical stresses from loading phase by subtracting the stress of the two previous phases for pile and raft activation from the value of vertical stresses of loading phase.



A - The vertical stresses at pile head level.



B - The vertical stresses at pile tip level.

Figure (4) The Plaxis software output in contour plot for stresses at pile head and tip levels for the typical full scale piled raft case (PR (4×4)- B20L30D100S5).

In order to study the relation between piles-raft area ratio to the load-sharing between the piles and the raft, in addition most of the researchers failed to understand the relationship between them and then found out the specific relation .The result of the analysis using the Plaxis to follow up load sharing of piled raft component through varying the spacing and number of piles for the pile length of (30m) at soil of (Cu = 60 kPa) is presented in Table (3). The effect of varying piles-raft area ratio on the load sharing of piled raft component is shown in Figure (5).

Table (3) The results of load sharing of piled raft component at various pile number and spacing (piles length =30m & Cu=60kPa).

Case Name	Settlement considered (mm)	Total Load Applied (MN)	Load Sharing (%)			Settlement Ratio (S/Br)	Piles Raft Area Ratio (Ap/Ar)
			Piles tip	Piles	Raft		
PR(6×6)-B20L30D40S7	279	145.6	5	16	84	0.0139	1.13
PR(4×4)-B20L30D60S7	364	145.6	6	12	88	0.0182	1.13
PR(6×6)-B20L30D60S5	267	165.2	10	28	72	0.0133	2.54
PR(4×4)-B20L30D100S5	446	200	9	31	69	0.0223	3.14
PR(10×10)-B20L30D40S5	180	160.4	8	16	84	0.0090	3.14
PR(10×10)-B20L30D60S3	365	322	22	44	56	0.0182	7.06
PR(6×6)-B20L30D100S3	455	310.4	17	41	59	0.0227	7.06

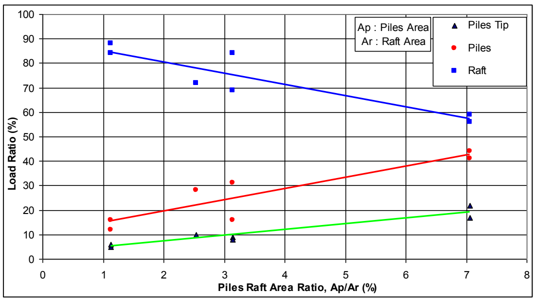


Figure (5) The variation of load sharing of piled raft component with piles raft area ratio for the pile length of (30m) and soil of (Cu = 60 kPa).

It can be seen that the load sharing of piles varies from (15%) at piles ratio about (1 %) to (42%) at piles ratio equals (7%), where this higher value of piles load sharing corresponds to the closely spacing piles (3D) which means that the piles are taking more load share and there is a tendency to have the raft on pile behaves as a fully piled system.

From the output of the above analysis, one can deduce that piles spacing of (5D) to (7D) are the optimum spacing for the performance of the system as a piled raft system, but the system sustains less overall load compared to that of closely spaced piles (3D). Increasing the spacing between piles decreases the total number of piles and results in the reduction of the total cost of the piled raft foundation which may be more economical. In order to study the relation between (piles-raft) area ratio and the load-sharing between the piles and the raft at various pile lengths, the previous analysis using Plaxis is repeated at the same previous case of (Cu=60 kPa), but with increasing the length of piles to (40m). The result of piled raft for the pile length of (40m) at soil of (Cu = 60 kPa) is shown in Table (4), and the effect of variation piles raft area ratio to the load sharing of piled raft component for the pile length of (40m) is seen in Figure (6).

Table (4) The results of load sharing of piled raft component at various pile number and spacing (pile length =40m & Cu=60kPa).

Case Name	Settlement considered (mm)	Total Load Applied (MN)	Load Sharing (%)			Settle. Ratio (S/Br)	Piles Raft Area Ratio (Ap/Ar)
			Piles tip	Piles	Raft		
PR(4×4)-B20L40D60S7	406	160.8	3	11	89	0.0203	1.13
PR(6×6)-B20L40D60S5	406	160.8	8	33	67	0.0203	2.54
PR(4×4)-B20L40D100S5	345	135.2	7	23	77	0.01725	3.14
PR(6×6)-B20L40D100S3	384	228	16	37	63	0.0192	7.06

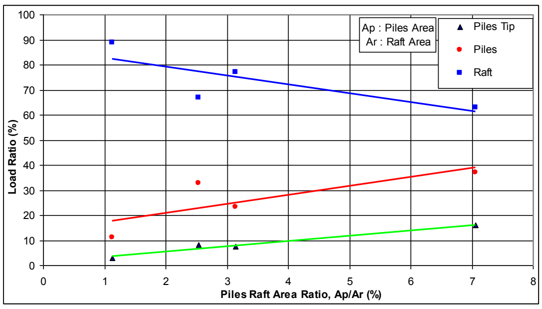


Figure (6) The variation of load sharing of piled raft component with piles raft area ratio for the pile length of (40m) and soil of (Cu = 60 kPa).

It can be observed after comparison the results of Figure (5) and Figure (6) that the system in case of piles length (40m) takes higher load compared to the length equals (30m), but increasing the length of piles from (30 m) to (40 m) does not affect the load sharing between piles and raft, which may be attributed to the small value of length increased with respect to the original length.

Again similar analysis using Plaxis is repeated on the same previous case of (Cu=60 kPa), but now using piles length of (60m) to study the relation between piles-raft area ratio to the load-sharing between the piles and the raft as the piles length is increased, and the results are illustrated Table (5). The effect of variation piles-raft area ratio with the load sharing of piled raft component for the pile length of (60m) can be seen in Figure (7).

Table (5) The results of load sharing of piled raft component at various pile number and spacing (pile length =60m & Cu=60kPa).

Case Name	Settlement Considered (mm)	Total Load Applied (MN)	Load Sharing (%)			Settlement Ratio (S/Br)	**Piles Raft Area Ratio (Ap/Ar)**
			Piles tip	Piles	Raft		
PR(4×4)-B20L60D60S7	465	176	3	10	90	0.023	1.13
PR(6×6)-B20L60D60S5	304	190.8	8	32	68	0.015	2.54
PR(4×4)-B20L60D100S5	476	168.8	6	22	78	0.024	3.14
PR(6×6)-B20L60D100S3	443	359.2	10	35	65	0.022	7.06

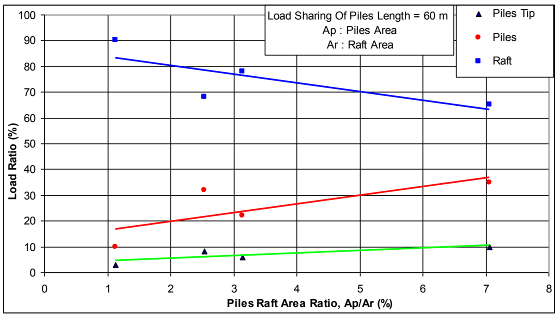


Figure (7) The variation of load sharing of piled raft component with piles raft area ratio for the pile length of (60m) and soil of (Cu = 60 kPa).

It can be observed, in general, that the increase in the length of piles from (30 m) to (60 m) does not affect the load sharing between piles and raft ,but there was an increase of the total capacity of the system compared to that of small piles length. A low ratio of piles tip load sharing is found, which if found to be reduced with increasing piles length ,this supports the fact that the piles in the weak clayey soils behave as floating piles and suggests to neglect the pile end bearing in calculating the total piles load capacity as indicated by some references.

4. Conclusions

Based on the results throughout this study, it can be concluded that:

1. The ratio of total piles area to raft area has important influence on load sharing of piled raft component. The piles load sharing varies from (15%) at piles-raft ratio of about (1 %) corresponding to pile spacing of (7D) to (42%) at piles/raft ratio equals to (7%) corresponding to a closely pile spacing of (3D) which means that the piles are taking more loading share and there is a tendency to behave as a mere piled system as the spacing between piles is reduced.
2. It can be deduced that a wider spacing of piles (5D) to (7D) will be the optimum spacing for the performance of the piled raft system with regards to the load distribution among the components of the piled raft system, but the system total load is lower when compared to that of closely spacing piles (3D).
3. The increase in the length of piles from (30 m) to (60 m) does not affect the load sharing between piles and raft ,but there was an increase of the total capacity of the system compared to that of small piles length.
4. A low ratio of piles tip load sharing is noticed and this share is further reduced with increasing piles length which supports the fact that the piles in the weak clayey soils behave as a floating pile which leads to neglect end bearing capacity in calculating the total pile load capacity .

5. References

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