Parametric Numerical Study of Pile Raft Foundation System

Irfan Jamil[1], Haleem Ullah Khan[1], Shahzeb[1], Hamza Alam Khan[1] and Wali Ullah[1]

[1]*University of Engineering and Technology Peshawar, Pakistan*

***Abstract*: Pile raft foundation has become the most suitable type of foundation for high rise buildings because of the characteristics that it can reduce both total and differential settlement, the combined action of pile and raft can increase the bearing capacity and considerably affect the size of foundation. Piled raft foundation is a new concept in which the total load coming from the superstructure is partly shared by the raft through contact with soil and the remaining load is shared by piles through skin friction and base resistance. In this research study a parametric study was performed numerically by changing the magnitude of different parameters such as raft thickness, raft dimension, stiffness of soil layer, poison's ratio, changing the number of piles and spacing to diameter ratio (s/d) of pile and its effect was observed on bending moment in raft, settlement of overall pile raft system. The percent load sharing between the piled raft components (piles and raft) has also been observed. This study will help the readers to take into account the effect of varying the magnitude of different parameters on its overall demand, contribution of piles and raft to a total load of structures and the effect of soil properties on this contribution.**

***Keywords*: Piled raft, Bending Moments, PLAXIS 3D, Settlement, Soil, Foundation**

I. INTRODUCTION

The foundation of a structure is that component of structure which is in direct contact with the ground, and transmits the load of the super structure to the ground. The term "foundation" illustrates the structural element that connects the structure to the ground. A raft foundation is used in most medium-sized buildings when the load on the structure is high enough. In some cases, if a shallow foundation is not adequate, foundation engineers usually design a completely pile system in which all the structural load is transferred to the subsoil by piles. Recently, due to more preponderant precision in geotechnical engineering, the correct and compassionate utilization of construction materials should be taken into account when designing the foundation. In traditional methods of the pile foundation system, huge settlements were located under the pile cap, which led to the separation of the raft and soil. The piles were considered as the only element which takes load. No attention was given to raft although raft takes considerable part of the load.

Recent greater development in piled raft has showed the interaction effect between various elements of combine piled raft system and soil must be taken into account because it greatly effects the settlement behavior of the piled raft system. The raft has both positive and negative effect on the settlement. Positive aspect is the raft confines the soils and increase the lateral stress between piles and underlying soil which leads to increase the bearing capacity of piles compare to free standing piles. Negative effect aspect is it produce interaction between raft and piles, and raft and soil [1]. Thus, due to design modifications, the raft becomes a component of the foundation. In recent years, there has been an increasing recognition that the utilization of piles can greatly reduce rafts total and differential settlement that leads to a considerable economy without compromising the safety and performance of the substratum [2]. Such a foundation makes utilization of both the raft and the piles and is referred to as a piled raft substructure (PRF).

A piled raft foundation is a composite foundation system in which piles and rafts distribute applied structural loads. In this system, both substratum elements have their own advantages. Piles may be utilized as settlement and stress reducers and raft may be use to abbreviate differential settlement. [3] Thickness and rigidity of raft can avail to distribute load uniformly to all piles. Within the conventional pile foundation system, it may be possible to reduce the number of piles, considering the contribution of the raft to the total capacity of the substratum. In such cases the pile provides majority of foundation stiffness at serviceability loads while the raft provides supplemental load capacity at ultimate loading. In situation where the raft might alone be used but does not satisfy the design requisites (total and differential settlements requisites) it may be possible to enhance the capacity of raft by the utilization of a constrained number of piles, strategically located so that it may improve the ultimate load capacity, total and differential settlement requirements. [1]

II. LITERATURE REVIEW

Pile raft take attention back in the mid-20th century, however many numerical analyses done by different researchers consider it as a pile group, work from Skempton (1953) [4] and Meyerhof (1959) [5] was numerical in nature and it was performed for settlement of pile groups. Loads transfer mechanism and other important aspects of the pile group were done by Fraser and Wardle (1975) [6], Poulos and Davis (1980) [7], Randolph (2003) [8]. The contributions from Coduto (1996), Poulos (1993) and Van Impe (1991) are also studied in relation to the equivalent raft methods of analysis [9]. The rapid developments in the numerical analysis of pile behavior and piled raft foundations saw numerous. The more rigorous methods of piled raft analysis began with the contributions of Kuwabara (1989) and extended by Poulos (1993) with further contributions from Ta and Small (1996), Zhang and

Small (2000), and Mendoca and Paiva (2003) [10]. Notably, Prakoso and Kulhawy (2001) [11] used the PLAXIS software in the 2D analysis of piled raft foundations.

Analysis of Combined piled foundation system is challenging because it involves complex interaction factors. Ignoring these interaction factors will lead to unsafe design [12]. Different methods have been developed to find the load sharing ratio between piles and raft and settlement of the piled raft system. These methods include Randolph method (1993), Burland's approach (1995) and Poulos-Davis-Randolph method (1994). To find bending moments in raft of a Piled raft system, a very simplified method was developed by Jamil. I (2019) based on Winkler springs which can incorporates interaction factors in SAP 2000 [13].

III. VARIOUS PARAMETERS TO BE STUDIED IN PILE RAFT FOUNDATION

1) Raft thickness
2) Dimension of raft
3) No of piles
4) Pile spacing
5) Stiffness of soil
6) Pile and raft capacity
7) Poisson ratio

IV. METHODOLOGY AND MATERIALS

For the present research study, the soil below the structure consists of clay layer up to 30m while the super structure load is applied as ideal point load. A finite element analysis was performed using PLAXIS 3D software and total six models were prepared for an ideal load condition. Properties of soil, raft and the embedded piles has been shown in table 1.

The staged construction phases are as follow:

1) The Initial phase
2) The Piles installation phase
3) The Raft construction phase
4) The Loading

Table 1: Properties of soil, raft and pile

Parameter	Soil	Raft	Embedded pile
Material	Soft-medium clay	Concrete	Concrete
Finite element model	Elasto-plastic	Linear isotropic	Linear isotropic
Modulus of elasticity (MPa)	1040	$3x10^7$	$3x10^7$
Poisson's ratio (υ)	0.3	0.2	0.2
Cohesion (KN/m^2) (c)	30	---	---
Angle of internal friction (ϕ)	10^o	---	---
Unit weight (KN/m^3)	γ_{sat} =19, γ_{unsat} =20	0	0

Six Case studies are performed in this study:
Case Study 1: The effect of raft thickness on bending moment and overall settlement of foundation.
Case Study 2: The effect of number of piles on bending moment and overall settlement of foundation.
Case Study 3: The effect of poisson ratio on overall settlement and percentage load taken by pile raft foundation.
Case Study 4: The effect of Stiffness of soil on overall settlement and bending moment.
Case Study 5: The effect of raft size on bending moment, settlement and percentage load taken by piles.
Case Study 6: The effect of spacing to diameter ratio (s/d) on bending moment and overall settlement of foundation.

V. RESULT AND DISCUSION

Case Study-1

The raft thickness is changed to keep the raft soil stiffness ratio constant. Raft used in the parametric study is square in plan and with different raft thickness as shown in Table 2 below. PLAXIS 3D FEM software was used to find effect of raft thickness on bending moment and maximum settlement.

Thus, by changing the thickness of raft while keeping stiffness of soil layer, raft dimension and no of piles constant, greater variation in bending moments and settlement was observed in pile raft foundation system. The resulting plot is shown in Fig. 1 for the maximum positive bending moment and Fig. 2 for settlement of overall pile raft foundation system.

It can be seen from the graphs that, as raft thickness increases, there is a substantial increase in the maximum positive bending moment. The rate of increase in bending moment becomes less at larger thicknesses. Increasing raft thickness is beneficial to avoid punching failure but it should be noted that increasing raft thickness would result in a higher bending moment. The effect of raft thickness is also shown on the overall settlement of the piled raft foundation for two different values of soil young's modulus which is shown below in Fig. 2. It can be noted from the plot developed that increasing raft thickness will decrease settlement at a very lower rate. From the literature, it is clear that increasing raft thickness will decrease differential settlement at a very lower rate but cannot reduce overall settlement substantially as verified from Fig. 2.

Table 2: Raft thickness variation

Raft (LXB) (m)	Pile spacing (s/d)	Pile length and diameter (m)	Soil young's modulus (MPa)	Thickness of raft (m)
30x30	3,9	25,1	10,40	0.3, 0.7, 1.1, 1.5, 1.9, 2.3, 2.7, 3

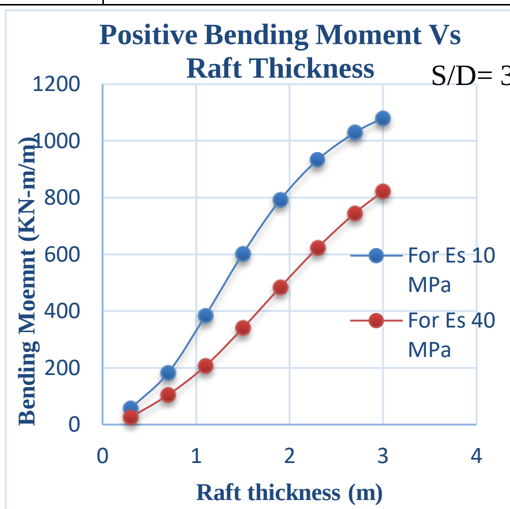


Fig. 1: Positive bending moment Vs Raft thickness

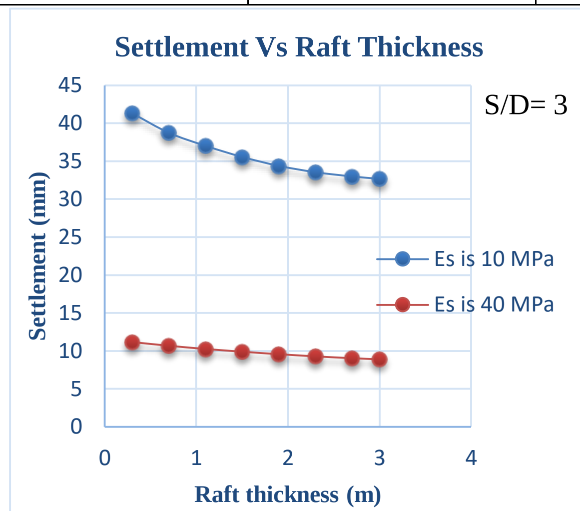


Fig. 2: Settlement Vs Raft thickness

Case Study-2

Piles used in foundation can be used to carry load of superstructure, works as a settlement and stress reducer. Thus, the number of Piles was varied with an equal increment to determine its effect on maximum bending moment, the raft dimension selected as 30x30 m, thickness of raft is 1.1 m, length of pile is 25 m, diameter of pile is 1 m and soil young's modulus is10 MPa. The number of piles was varied between 9 and 100 piles. The results with respect to bending moment and settlement are shown in Fig. 3 and Fig. 4 respectively. It can be seen from the Fig. 3. that maximum positive bending moment is reducing with increase in no of piles but with a smaller rate. The trend is not continuous as seem from plot. When the number of piles were 50, then the maximum bending moment observed was just above 500 KN-m/m, but it then saw a gradual increase and stood at 400 KN-m/m when the number of piles becomes 100 as shown in Fig. 3.The effect of no of piles on settlement is shown in Fig. 4 from which it can be noted that as no piles are increasing, there is a decrease in settlement. The important thing that can be noted as that increasing piles after some limit, there is less or no decrease in overall settlement. This is verified by Poulos (2001b) where he entitled this phenomenon as "Law of diminishing returns" which means that after some limit, additional no of piles has less or no effect on Settlement.

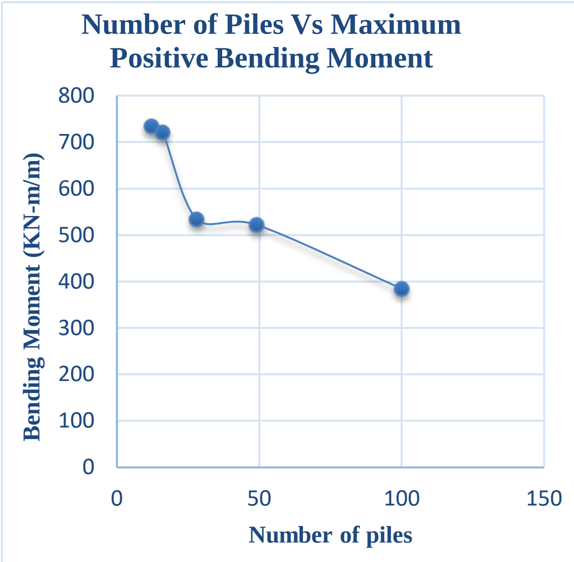


Fig. 3: Bending Moment Vs Number of piles

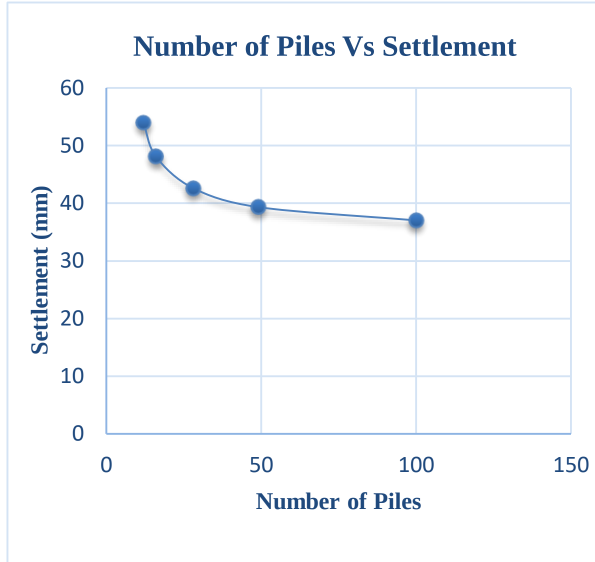


Fig. 4: No of piles vs Settlement

Case Study-3

Poisson ratio of a soil layer was increased from 0.2 to 0.45 with the increment of 0.25 and its effect on settlement and percentage load distribution in pile raft system is numerically calculated and is shown in plots below. It is clear from the Fig. 5 that with an increase in poisson ratio the load carrying capacity of raft increases because the strain in the transverse direction is more as compare to that of longitudinal direction so that's the reason that area of the raft in transverse direction increases due to which its load-carrying capacity increases.

It is clear from Fig. 6 that with the increase in poisson ratio the load-carrying capacity of pile decrease, because with the increase in strain in transverse direction there is a decrease in friction between soil and pile, thus most of the structural load will be resisted through base resistance due to which its load-carrying capacity decreases. It can be seen from the graph that as the poisson ratio of Soil layer changes there is a substantial decrease in the overall settlement of the pile raft system. From Fig. 7, it is clear that with an increase in poisson ratio the decrease in the settlement is mostly in a linear manner.

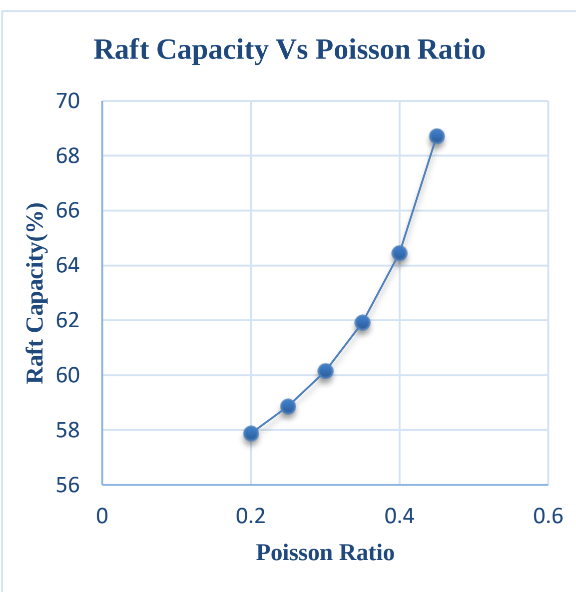


Fig. 5.

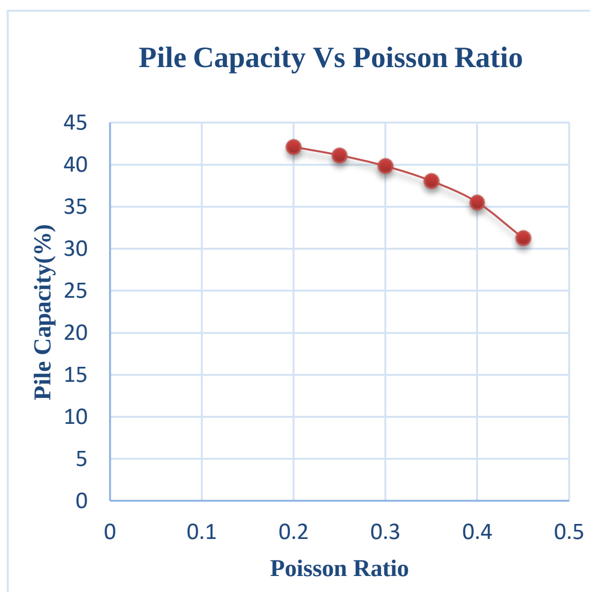


Fig. 6

Case Study-4

The stiffness of the structure influences the distribution of the load transferred to the pile raft foundation, settlement and bending moments. Therefore, the analysis was performed for two values of Es which are 10 MPa and 40 MPa and its effect on various parameters was obtained as shown in above Fig. 1 and Fig. 2. It can be deliberate from the above results that as soil young's modulus increases, there is a decrease in maximum positive bending moment. The maximum bending moment for raft thickness of 3 m is 1081 KN-m/m, for 10 MPa and for 40 MPa, maximum moment is calculated as 822.5 KN-m/m. The effect of soil young's modulus on overall settlement can also be noted from the above Fig 2. Elastic modulus of soil can reduce overall settlement substantially. The percent difference in both cases is between 60-75 %. This study shows the importance of soil young's modulus.

Case Study-5

The load carrying capacity of pile raft foundation is found to increase with increase in size of the raft. Further study was performed on changing the size of the raft with equal increment and the effect of this change on bending moment, load shearing between raft and piles was determined numerically. The total settlement of pile raft foundation was also determined numerically. Table 3 shows raft dimension for the proposed study.

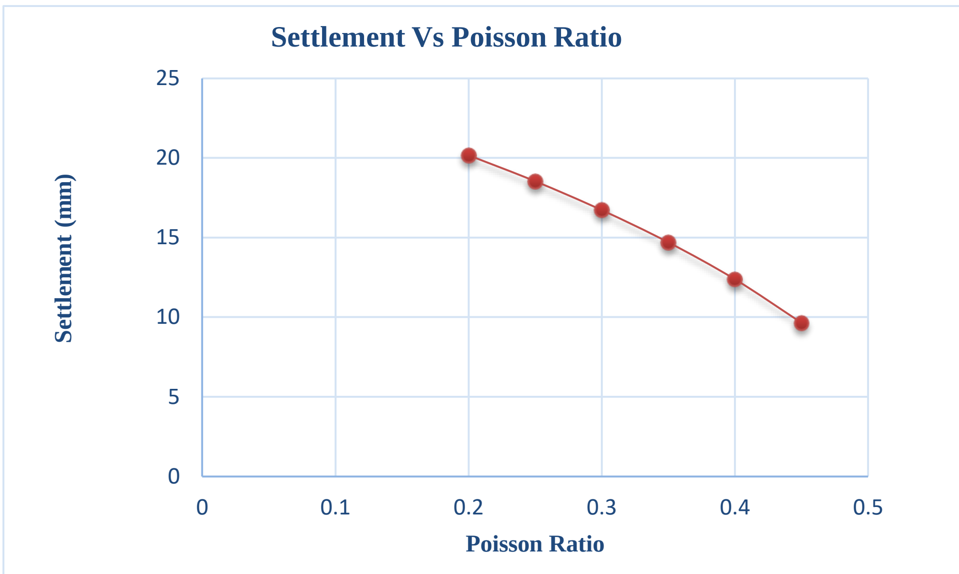
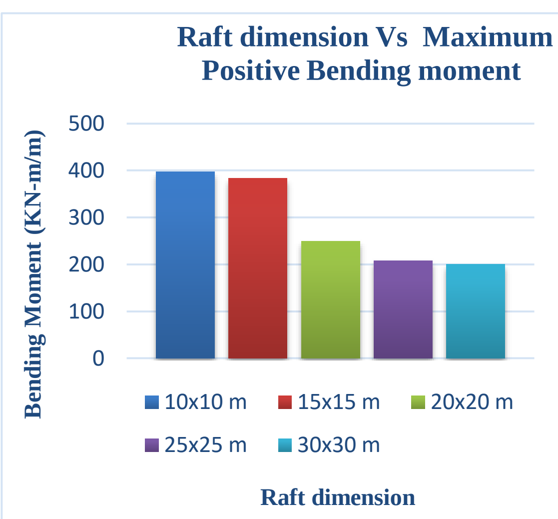


Table 3: Variation of raft dimension

The following results were obtained from PLAXIS 3D models as shown in Fig. 8, Fig. 9 and Fig. 10 below. As raft dimension increases settlement decreases with a moderate rate and its variation with raft dimension is shown below in Fig.10.



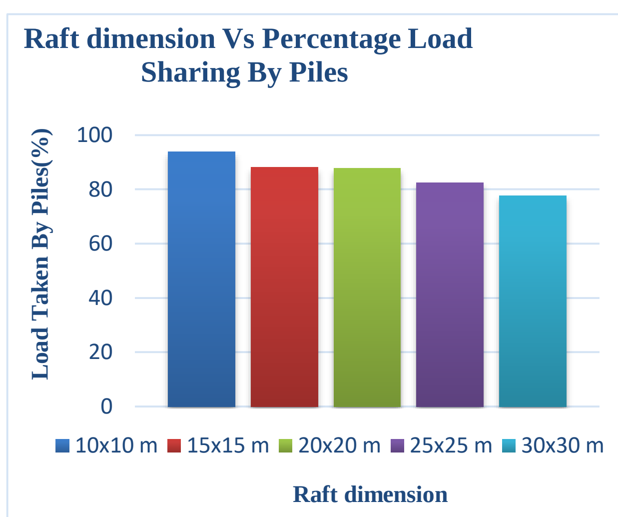
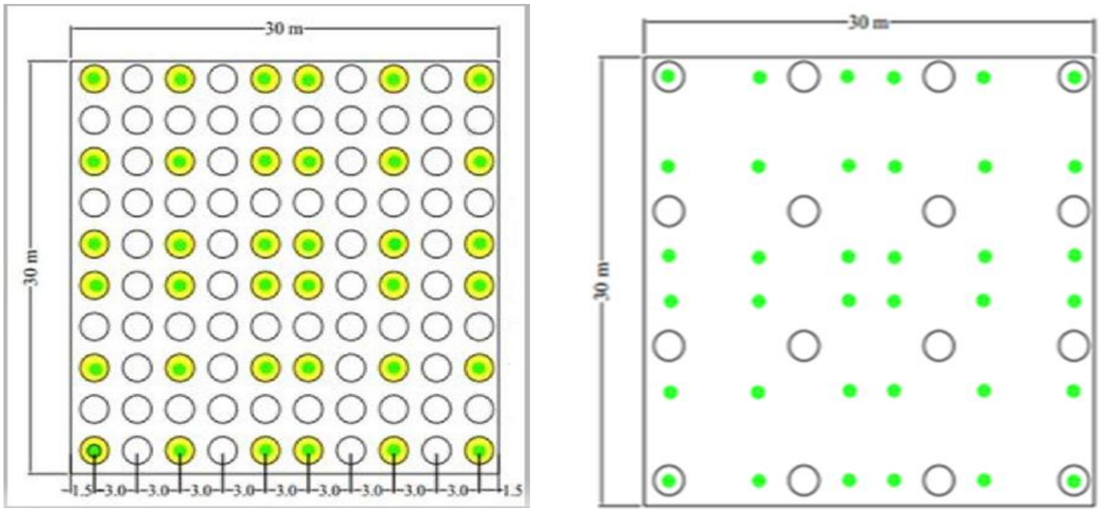


Fig. 7: Settlement vs Poisson ratio



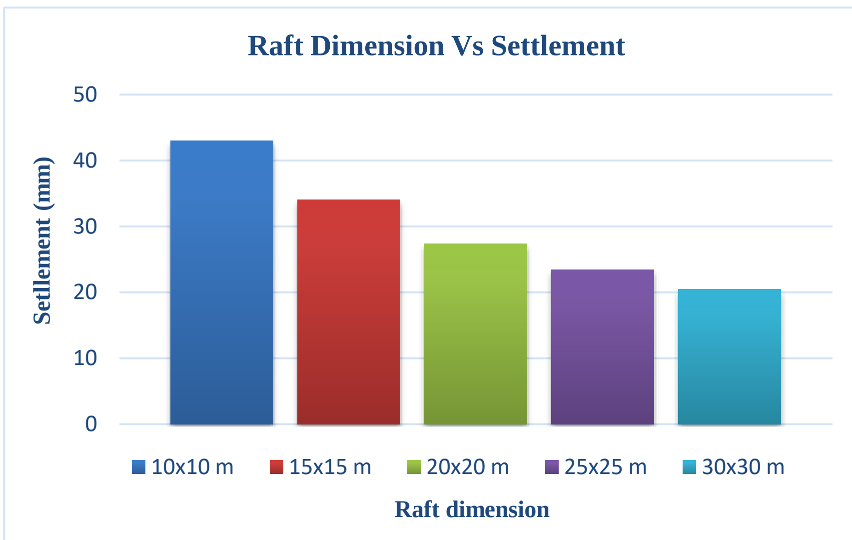


Fig. 10: Raft dimension vs Settlement

It can be visually perceived from the Fig. 8 that as raft dimension increases, there is a decrease in bending moment. Maximum moment noted for the raft of dimension 10x10 m was 406 KN-m/m while for the raft which has dimension 30x30 m, the maximum moment noted was 200 KN-m/m. Figure 9 shows that when the size of the raft increases the load taking capacity of raft also increases. At the same time the load transferring to piles decreases. For the raft which has dimension of 10x10 m, the load taken by piles is 94%, while for raft of dimension 30x30 m raft, the percent load taken by piles decreases to 77%.

Case Study-6

The spacing to diameter ratio is important because it decides the design of pile raft foundation, its efficiency and capacity. Therefore, with the same variation of the raft thickness, but s/d equal to 3 and 9, very important results have been obtained using the PLAXIS 3D software. The different layout of piles placement is shown below in Fig. 11 and Fig. 12.

The hatched circles in above Fig. 11 represent piles while, hollow circle shows load of 1MN for s/d=3. While in Fig. 12, the hollow circle shows piles and hatched green circle shows of 1MN for s/d=9. For s/d equal to 3, the maximum bending moment for raft thickness of 3 m is 1081 KN-m/m as shown in Fig.1 while, for s/d equal to 9 maximum moments is 1414 KN-m/m as shown in Fig. 13 for same value of Es equals to 10 MPA. As s/d increases, there is a substantial increase in settlement of pile raft foundation with the same trend in varying thickness of the raft for both s/d values. The plot shows that for same raft thickness raft settlement is about 42 mm for s/d=3 as shown in Fig. 2 and around 74 mm for s/d=9 as shown in Fig. 14.

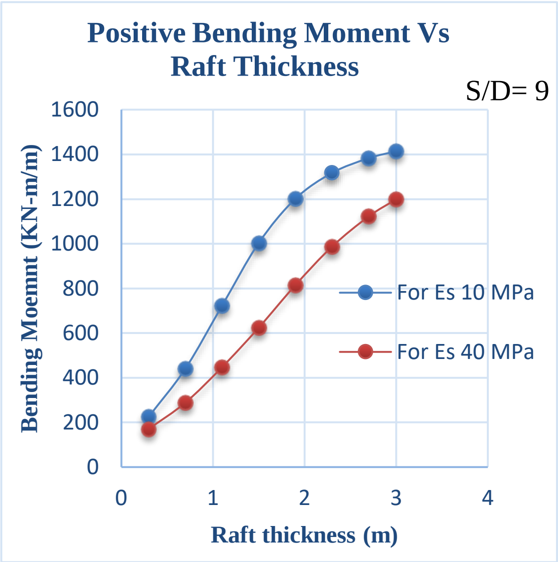


Fig. 11

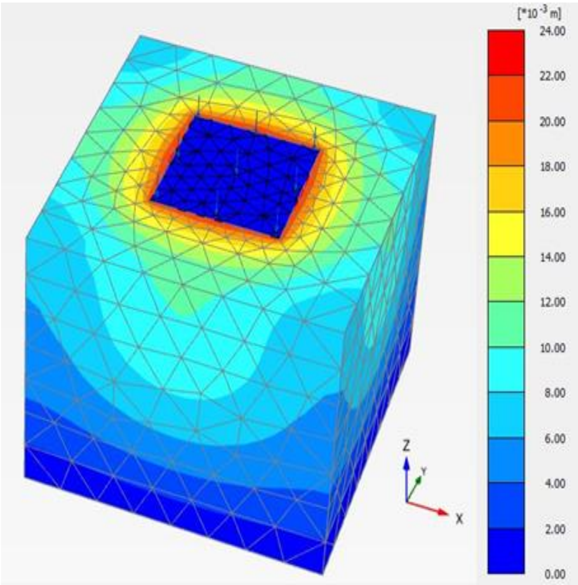


Fig. 14: Settlement vs S/D=9

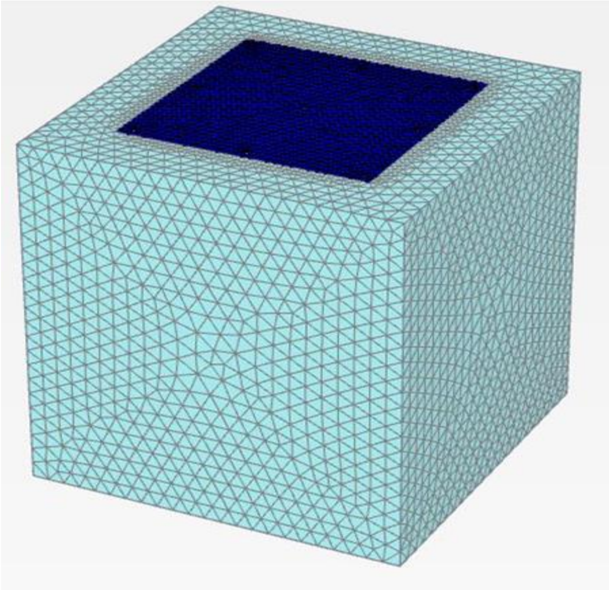


Fig. 15: Mesh model of PLAXIS 3D

PLAXIS 3D Software provides us the option of finest possible meshing size due to which we can get more accurate results. Mesh model is shown in Fig. 15. Furthermore, settlement contours were observed for all case studies of pile raft foundation using PLAXIS 3D software. Settlement contours for one of the model can be shown in Fig. 16. More ever, these contour help us to know the variation of settlement along the depth of soil layer.

Similarly, bending moment variation can also be observed for all case studies of pile raft foundation. Bending moment variation for one of the model can be shown in Fig. 17.

VI. CONCLUSION

The following result can be extracted from the performed study:

I. When raft thickness increases the maximum positive bending moment also increases.
II. As proved by the study that when elastic modulus of soil increases the bending moment and total settlement of piled raft system decreases. So Elastic modulus of soil play an important role and should be selected carefully.
III. As the spacing to diameter ratio of piles increases, the maximum positive bending moment also increases.
IV. Poulos (2001b) law of diminishing returns is also verified. According to this law an optimum number of piles can decrease the settlement, beyond this number piles has no or very little effect on settlement. So piles showed be strategically installed.
V. Increase in no of piles can also decrease maximum bending in raft.
VI. Increasing raft dimensions can cause decrease in bending moment as well as in overall settlement for same load.
VII. Increasing raft dimension cause increase in percentage of load taken by raft.

REFERENCES

[1]. Poulos, H.G., J. C. Small, and H. Chow. "Piled raft foundations for tall buildings." *Geotechnical Engineering Journal of the SEAGS & AGSSEA* 42.2 (2011): 78-84.
[2]. Xie, Yunfei, and Shichun Chi. "Optimization Method for Irregular Piled Raft Foundation on Layered Soil Media." Advances in Civil Engineering 2019 (2019).
[3]. Burland, J. B. "Piles as settlement reducers." In The 8th Italian Conference on Soil Mechanics. 1995.
[4]. [4]. Skempton, A. W. "Soil mechanics in relation to geology." Proceedings of the Yorkshire Geological Society 29, no. 1 (1953): 33-62.
[5]. Meyerhof, G. G. "Compaction of sands and bearing capacity of piles." Transactions of the American Society of Civil Engineers 126, no. 1 (1959): 1292-1322.
[6]. Fraser, R. A., and L. J. Wardle. "Analysis of stiffened raft foundations on expansive soil." (1975).
[7]. Poulos, Harry George, and Edward Hughesdon Davis. Pile foundation analysis and design. No. Monograph. 1980.
[8]. Randolph, Mark F. "Science and empiricism in pile foundation design." Géotechnique 53, no. 10 (2003): 847-875.
[9]. Miskin, Venkatesh M., Shivakumar B. Patil, and Raveendra Hegde. "Analysis & Design of pile raft foundation." The International Journal of Science and Technoledge 2, no. 11 (2014): 52.
[10]. Oh, Erwin, Quan-Minh Bui, Chanaton Surarak, Richard Adamec, and Bala Balasubramaniam. "Parametric study on piled raft foundation in sand using numerical modelling." Futur Mech Struct Mater 261 (2008).
[11]. Prakoso, Widjojo A., and Fred H. Kulhawy. "Contribution to piled raft foundation design." Journal of Geotechnical and Geoenvironmental Engineering 127, no. 1 (2001): 17-24.
[12]. J. Irfan, "Effects of Soil Pile Raft interaction on the design of Piled Raft Foundation," M.S. thesis, Dept. Civil. Eng., UET Peshawar. Pakistan, 2017.
[13]. Jamil, Irfan, and Irshad Ahmad. "Bending moments in raft of a piled raft system using Winkler analysis." Geomechanics and Engineering 18, no. 1 (2019): 41-48.