Ain Shams Engineering Journal (2015) 6, 421–428

Ain Shams University

Ain Shams Engineering Journal

www.elsevier.com/locate/asej
www.sciencedirect.com

CIVIL ENGINEERING

Numerical analysis of unconnected piled raft with cushion

Alaa Ata *, **Essam Badrawi**, **Marwa Nabil**

Structural Eng. Department, Faculty of Engineering, Zagazig University, Egypt

Received 23 May 2014; revised 4 October 2014; accepted 8 November 2014
Available online 29 December 2014

KEYWORDS

Piles;
Raft;
Unconnected piled raft;
Cushion

Abstract The analysis of piled raft foundations has improved over the last few decades to account for the combined contribution of raft and piles to provide a more efficient system. Unconnected piled raft foundation (UCPRF) is an economical and efficient system where the piles are separated from the raft by a structural fill cushion. The cushion acts to redistribute the load between raft and piles. In this study, ABAQUS finite element analysis software was used to investigate the load sharing capacity of the system. The effects of cushion, piles number, diameter, and length as well as raft thickness in reducing settlement were investigated. The study showed that UCPRF provides an economical alternative for a connected piled raft foundation subject to vertical axial loads. In the unconnected system, plain concrete piles are adequate, without the need of reinforcement, where their basic function is to strengthen the top and reduce the maximum settlements.

1. Introduction

Raft foundations are generally used to support buildings and structures, with or without basements, in dry or high water table conditions. When the shallow subsoil conditions are unfavorable (unsafe bearing capacity or excessive settlements) then load bearing piles are used to transfer the entire load to more competent soil layers. In many cases, the maximum and differential settlements are the controlling factors for the selection of piled raft foundations. The piled raft foundation consists of three load-bearing elements; namely piles, raft and subsoil. According to their relative stiffness, the raft distributes the total load transferred from the structure to the top soil and the connected piles. In conventional design of piled foundations, it was usually postulated that the overall load is supported by the piles. In piled raft foundation systems, the contribution of the raft is taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system. The concept of using piles to reduce raft settlement was first proposed by Burland et al. [1] who placed one pile under each column of a building. As reported by Solanki et al. [2] several reports were published on the use of piles as settlement reducers. Zhuang and Lee [3] used a finite element method to study the load sharing between the piles and the raft. They observed that load sharing between the piles in piled raft system was affected by pile stiffness, raft rigidity and pile length to width ratio. They also observed that as pile length

* Corresponding author. Mobile: +20 100 5413838.
E-mail addresses: accessata@yahoo.com (A. Ata), e_f_b_attia@yahoo.com (E. Badrawi), marwa_nabil_amin@yahoo.com (M. Nabil).
Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2014.11.002
2090-4479 © 2014 Faculty of Engineering, Ain Shams University. Production and hosting by Elsevier B.V.

increases the pile rigidity decreases and the load distribution become more uniform. Ta and Small [4] developed a method, which was based on finite layer method, for the analysis of piled raft foundation in layered soil. They found that load sharing between the piles in piled raft system was influence by thickness and stiffness of soil layer. Ta and Small [5] observed that load shared by piles increases as the bearing strata becomes stiffer. Russo [6] developed a numerical method for piled raft system, which considers non-linearity of the unilateral contact at the raft–soil interface and the nonlinear load–settlement relationship. They stated that non-linear analysis should be considered for the piled raft system because piles act as settlement reducers and their ultimate load capacity may be reached. Poulos [7] developed a simplified analysis method as a tool for preliminary design of piled raft foundation system. Poulos [7] reported that when a raft foundation alone does not satisfy the design requirements, using a limited number of piles might improve the performance of such foundations in terms of ultimate load capacity, total and differential settlements. Reu and Randolph [8] used a finite element method to model piled raft foundation in over consolidated clay. Reu and Randolph [8] observed that pile–raft interaction leads to an increase in the skin friction with an increase of the load or increase of the settlement.

Nakai et al. [9] performed centrifuge model tests followed by a parameter survey based on the finite element analysis for structures supported by piled foundations and piled raft foundations. Nakai et al. [9] showed that the effect of the pile head connection condition on the response characteristics of a superstructure is fairly small when compared to the type of the foundation. They also showed that the load bearing characteristics of piles were not affected, even when piles are not connected to the raft foundation. Nakai et al. [9] concluded that even for the case where piles are not connected to the raft, they have significant contribution to the dynamic soil–structure interaction.

El-Mossallamy et al. [10] reported that the settlement and the load sharing between the raft and piles are the main factors that control the design of piled-raft foundations. Comodromos et al. [11] observed that in case of pile cap loaded by a non-uniform vertical load, the load is mainly carried by the piles in the vicinity of the loaded area if the cap thickness is less than the pile diameter. They found that if the cap thickness is greater than the pile diameter, the type and the location of the applied load have no effect on the distribution of the load to the piles. In traditional pile–raft systems, piles are connected to the raft and extend down into competent soil at depth. While these piles are effective in reducing raft settlement, they may lead to significant shear forces and bending moments that will affect the structural design of the raft. In order to overcome problems of high stresses in the piles and raft, Cao et al. [12] and Wong et al. [13] suggested that the piles be disconnected from the raft and to treat these piles as reinforcement to the subsoil rather than as structural members. Moreover, the gap between the raft and the unconnected piles can be filled with a cushion of structural fill material. Liang et al. [14] stated that the cushion, which is composed of a sand-gravel mixture compacted in layers between the raft and top of piles, plays an important role in mobilizing the bearing capacity of the subsoil and modifying the load transfer mechanism of piles. Since then it has been described by many authors, including Lee et al. [15], Eslami and Malekshah [16] and Sharma et al. [17].

2. Methodology and developed model

A three-dimensional finite element commercial software (ABAQUS) is used in the analysis. Site investigation data are collected from Lake Mariout area, west of Alexandria city in Egypt, where large industrial and residential development have been recently planned and constructed. In general, the subsoil at the site consists of a top layer of medium dense sand and having an average thickness of 4 m. The top sand is followed by soft to very soft silty clay, extending down to a depth of 10 m. The soft clay is followed by a layer of stiff-to-very stiff clay extending down to a depth of 15 m. The fourth layer is dense sand and extends down to a depth of 35 m. Groundwater table exists at ground surface. The soil parameters are summarized in Table 1. In the analysis, raft and piles are modeled as elastic materials. The nonlinear behavior of soil is modeled with elastic ideally plastic constitutive model. The soft clay layer is modeled as an elastoplastic material with a non-associated flow rule and using the modified cam clay plasticity model. The other soil layers are modeled by elastic ideal plastic constitutive model following Mohr–Coulomb yield criterion. Soil mass is described by an eight-node brick, tri-linear displacement and tri-linear pore pressure element (C3D8P). Raft, pile and cushion are modeled as elastic materials by an eight-node linear brick element with reduced integration and hourglass control (C3D8R). A vertical pressure of 215 kPa is imposed on the raft, as a distributed load. The cushion, which is composed of coarse grained soil compacted in layers, is shown schematically in Fig. 1. Fig. 2 shows the finite element mesh for the unconnected system, which is comprised of the raft, the soil and the piles.

3. Parametric study

The main purpose of the parametric study is to investigate the performance of the unconnected piled raft of various geometries and dimensions. The parameters studied included, cushion thickness and properties, number of piles, pile's diameter and length and raft thickness. Details of the unconnected piled rafts that analyzed in this study are described below and are summarized in Table 2.

3.1. Verification of developed model

To validate the results of the developed model (ABAQUS 3-D model), an example of a piled raft presented by Poulos [18] is demonstrated. Poulos [18] presented this example of a raft supported on 9 piles, one under each column to evaluate the efficiencies of different analyses methods for predicting the behavior of piled-raft foundations. The rectangular raft is 10 m × 6 m and has a thickness of 0.5 m. The piles are 0.5 m in diameter and 10 m in length. The raft and soil are modeled with elastic properties. In addition, a 0.25-m-thick cushion of the same properties of soil is used to study the effect of unconnected system on the maximum settlement, corner pile settlement and percent of load taken by piles. Poulos [18] predicted the settlement and percent of load taken by piles of this piled-raft example using 6 analyses methods; (1) simplified PDR, (2) Geotechnical analysis of raft with piles (GARP5 software), (3) Geotechnical analysis of strip on piles (GASP

Table 1 Soil parameters used in modeling.

Material Model	Raft Elastic	Cushion Elastic	Pile Elastic	Med sand Mohr-col.	Soft clay Modified cam-clay plasticity	Stiff clay Mohr-col.	Dense sand Mohr-col.
λ-factor	–	–	–	–	0.174	–	–
κ-factor	–	–	–	–	0.028	–	–
Voids ratio	–	–	–	0.6	1.0	0.7	0.5
Poisson ratio	0.20	0.25	0.20	0.30	0.45	0.35	0.25
γ_{sat}, (kN/m^3)	25	20	25	18.0	16.0	18.0	18.0
E, (kN/m^2)	3.4×10^7	40,000	2.1×10^7	40,000	1250	20,000	70,000
K, (m/s)	–	–	–	0.0001	1×10^{-8}	1×10^{-7}	.0001
K_o	–	–	–	–	1.0	1.0	–
M	–	–	–	–	1.0	1.0	–
C_u, kPa	–	–	–	–	12.5	120	–
ϕ, °	–	–	–	35	–	5.0	38
Elevation (m)	–	–	–	0–4	4–10	10–15	15–35

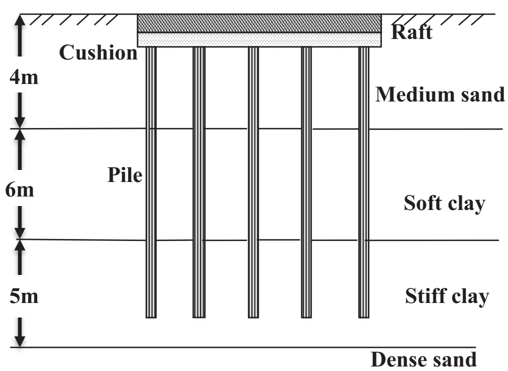


Figure 1 Schematic of unconnected piled raft and cushion.

software), (4) Simplified Burland, (5) 2-D Numerical (FLAC 2D software) and (6) 3-D Numerical (FLAC 3D software). Comparison between the results of model developed in the current study and the 6 models of the piled raft case presented by Poulos [18] is summarized Table 3. Maximum settlement, corner pile settlement and percent of load taken by piles predictions using the ABAQUS 3-D model were in good agreement with the predictions of other method. It can be also seen that the settlement of unconnected system is somewhat greater than that of the connected system, however, the percentage of load taken by piles for unconnected system decreased by 50% than that of the connected system.

4. Results and discussion

The maximum settlement of unconnected pile raft foundation, differential settlement of the raft foundation, axial load through the pile length and pile load ratio (α_{PR}) is the most important results that have been concentrating in this research. The load share between the pile and the raft is a parameter that is used to design of the piled raft foundation. The pile load ratio (α_{PR}) is defined as follows;

$$\alpha_{PR} = \frac{\sum P_{pile}}{P_{total}}, \qquad (1)$$

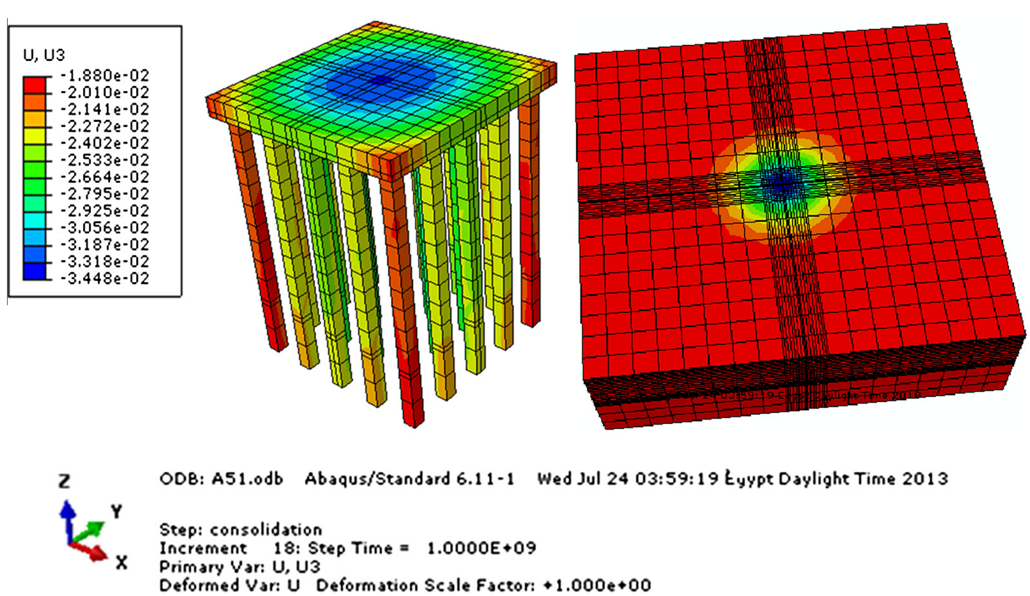


Figure 2 Finite elements mesh of unconnected piled raft foundation and the settlement shading of piles and raft.

Table 2 Summary of unconnected piled rafts in parametric study.

Parametric study	Raft dimensions		Cushion parameter		Pile group geometry			
	Length × width (m)	Thickness (m)	Thickness (m)	Modulus *E* (MPa)	Spacing (m)	Number n	Diameter (m)	Length *L* (m)
Cushion thickness	10 × 10	0.6	0.25, 0.5, 0.75, 1.0, 1.25, 1.5	40	3.5 d	5 × 5	0.6	12
Cushion properties	10 × 10	0.6	0.25	Varies from 20 to 3.4 × 107	3.5 d	5 × 5	0.6	12
Number of piles	10 × 10	0.6	0.25	40	14 d	2 × 2	0.6	12
					7 d	3 × 3		
					5 d	4 × 4		
					3.5 d	5 × 5		
					3 d	6 × 6		
					2.5 d	7 × 7		
					1.5 d	11 × 11		
Pile diameter	10 × 10	0.6	0.25	40	2.1 m	5 × 5	0.3, 0.4, 0.6, 0.8, 1.0, 1.4	12
Raft thickness	10 × 10	0.5–1.75 m	0.25	40	3.5 d	5 × 5	0.6	12

Table 3 Comparison of results from the developed ABAQUS 3-D model and the piled raft case published by Poulos [18].

Approach	Central settlement (mm)	Corner pile settlement (mm)	Percentage of load taken by piles
Simplified PDR (Poulos-Davis–Randolph)	36.8	–	77
Raft on Piles (GARP5)	34.2	26.0	65.1
Strip on Piles (GASP)	33.8	22.0	65.1
Simplified Burland	33.8	29.7	65.1
2-Dimensional numerical (FLAC 2-D)	65.9	60.5	79.5
3-Dimensional numerical (FLAC 3-D)	39.9	35.8	58.2
Connected system (ABAQUS 3-D used in this study)	31	23.5	73
Unconnected system (ABAQUS 3-D used in this study)	43	27.5	35

where ΣP_{pile} is the sum of loads at pile head and P_{total} is the total applied loads. This parameter defines the load distribution between piles and raft.

4.1. Effect of cushion

The gap between the raft and the piles is filled by a cushion of compacted structural fill material.

The cushion is used beneath the raft to redistribute the vertical stresses between the piles and the surrounding soil. In order to compare between the two cases of connected and unconnected systems, a simple square raft is used. The thickness and the elastic modulus of the cushion are varied, according to the data presented in Table 2. Analyses are performed for the following three cases:

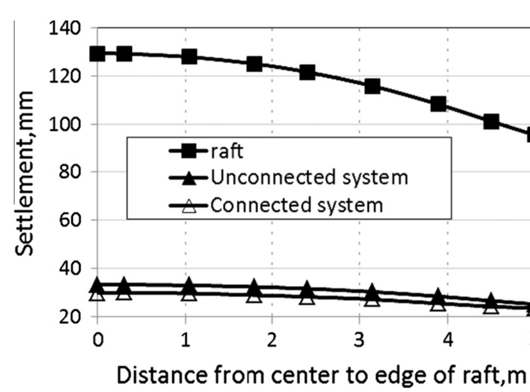


Figure 3 Maximum settlement of the raft, UCPRF and CPRF.

4.1.1. General effect of cushion

Analysis is performed for a 0.6 m thick square raft having an area of 100 m^2, supported on 25 unconnected piles spaced at 3.5 d, each pile is 0.6 m in diameter and 12 m in length. The cushion thickness is 0.25 m and has a modulus of 40 MPa. Fig. 3 shows a comparison of the settlements of the raft, connected piled raft, and unconnected piled raft systems. From the figure, it can be seen that, compared to the case of raft without piles, the maximum settlement of the connected piled raft has decreased by 77%, while the maximum settlement of the unconnected piled raft has decreased by 74%. Fig. 4 shows axial pile load versus pile length for connected and unconnected systems. From the figure, it can be seen that, the axial load along the pile length in the unconnected system is smaller than that in the connected system. The maximum axial load in the connected system occurs at the pile head, and then decreases along the length of the pile. However, in the uncon-

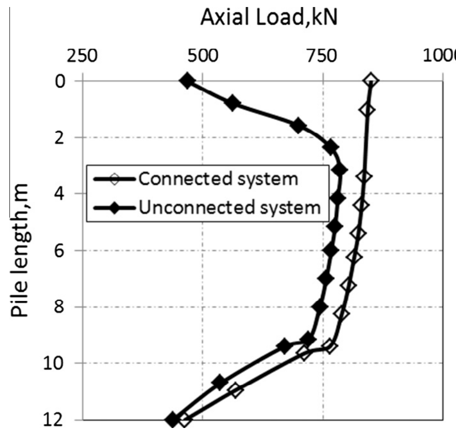


Figure 4 Axial load versus pile length of UCPRF and CPRF at center pile.

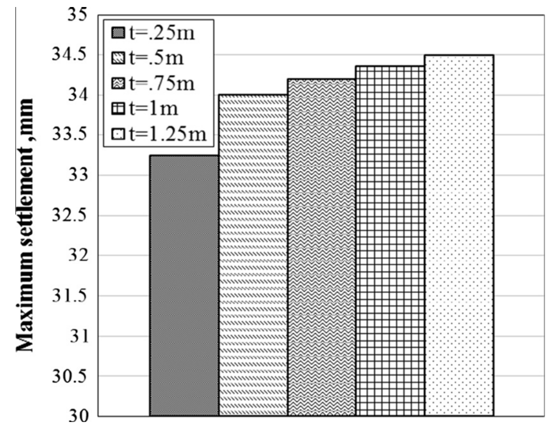


Figure 5 Maximum settlement versus the cushion thickness.

nected system, the location of maximum axial load is shifted downwards to a certain length below the pile head (approximately three meters in the studied model). The decrease of the axial load in the top three meters of the pile head is due to the load shared by the cushion. The vertical load shared by the cushion is then gradually transferred again to the lower parts of the pile via skin resistance. The transfer of the vertical load from the cushion to the pile is similar to the well-known downdrag phenomenon. Beyond the top three meters of the pile, the axial load in the pile starts to decrease following the same pattern as in the connected system. This load transfer behavior is similar to that described by Sharma et al. [17] for the unconnected piled raft system.

4.1.2. Effect of cushion thickness

Analysis is performed for a 0.6 m thick square raft having an area of 100 m^2 and supported on 25 unconnected piles. The cushion thickness is varied from 0.25 to 1.25 m. Fig. 5 shows the variation in the maximum settlement versus the cushion thickness. Fig. 6 shows the axial load versus pile length for various values of cushion thickness. The results of the numerical analysis show that the maximum settlement of the raft decreases slightly with the increase of the cushion thickness, and the axial load decreases slightly along the pile length. It is also noted that the axial load at the pile head decreases as the thickness of cushion increases. It may be concluded that, the load sharing between the cushion and the piles is affected by the thickness of the cushion.

4.1.3. Effect of cushion elastic modulus

Analysis is performed for a 0.6 m thick square raft having an area of 100 m^2 and supported on 25 unconnected piles. The Young's modulus of the cushion was varied from 20 MPa (representing soil material) to 34,000 MPa (representing concrete material). Fig. 7 shows the variation in the settlement versus the cushion elastic modulus. As seen in the figure, the overall settlement decreases slightly with the increase in the soil modulus from 20 MPa (loose soil) to 200 MPa (dense soil). As the cushion modulus increases from 200 MPa (dense soil) to 34,000 MPa (reinforced concrete) the overall settlement decreases significantly from 31 mm to 26 mm, corresponding to a reduction of 16%. Fig. 8 shows the axial load versus pile length for various values of cushion elastic modulus. It can be

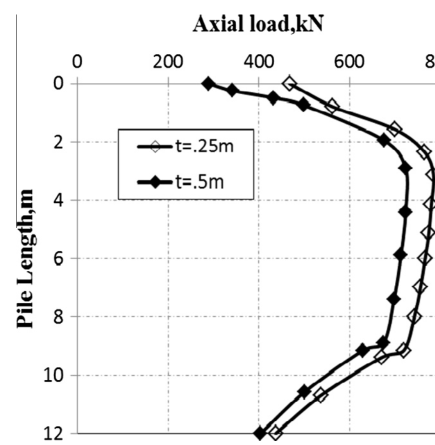


Figure 6 Axial load versus pile length for different cases of cushion thickness at center pile.

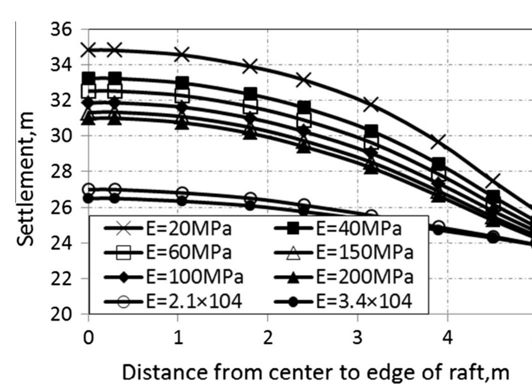


Figure 7 Settlement versus the cushion elastic modulus.

seen that, the axial load in the pile increases as the cushion modulus increase. In the two cases of elastic moduli of 21,000 and 34,000 MPa, the maximum axial load occurs at the pile head (connected system), but in the other cases, where the elastic moduli represents soil condition, the location of the maximum axial load is shifted to lengths lower than the pile head (unconnected system). Fig. 9 shows pile loading ratio versus cushion elastic modulus, the pile loading ratio increases with the stiffness of cushion. From this study, the results show

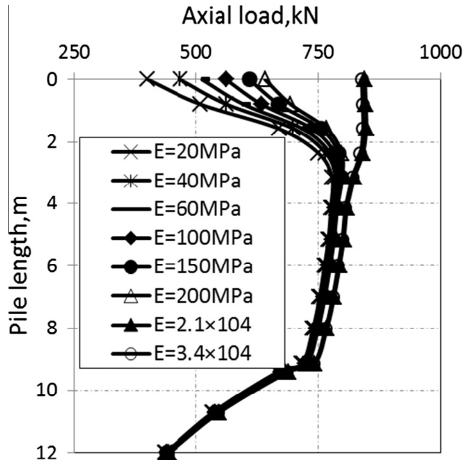


Figure 8 Axial load versus pile length for different cases of cushion elastic modulus at center pile.

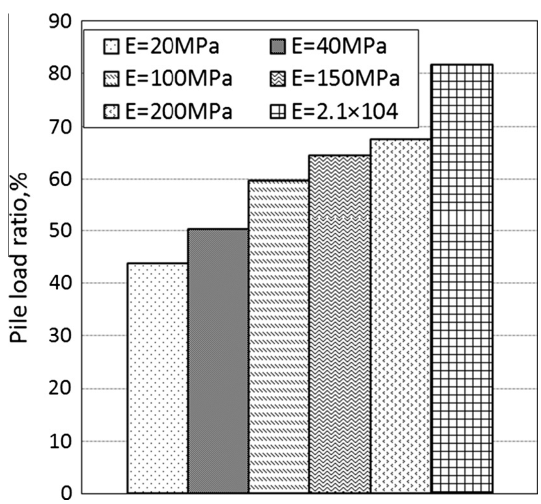


Figure 9 Pile loading ratio versus cushion elastic modulus.

clearly the transition from the unconnected to the connected system.

4.2. Effect of number of piles

Analysis is performed for a 0.6 m thick square raft having an area of 100 m^2 and supported on different number of piles varying from 4 to 121 pile arranged in square patters. The pile spacing was varied from 1.5 to 14 times the pile diameter. Fig. 10 shows the settlement versus number of piles for the unconnected system. From this figure, it can be observed that, the settlement of the system decreases with the increasing of the number of piles. The rate of reduction of the maximum and differential settlement increases as the number of piles increases up to 25 piles, after which the reduction is negligible. It can be also seen that when the piles are concentrated near the center either by reducing the spacing between the piles or increasing the number of piles, the overall settlement is decreased. Fig. 11 shows the ratio of the load shared by the piles versus the number of piles, for the case of the unconnected system. The results indicate the pile loading ratio increases as the number of piles increase. The most efficient

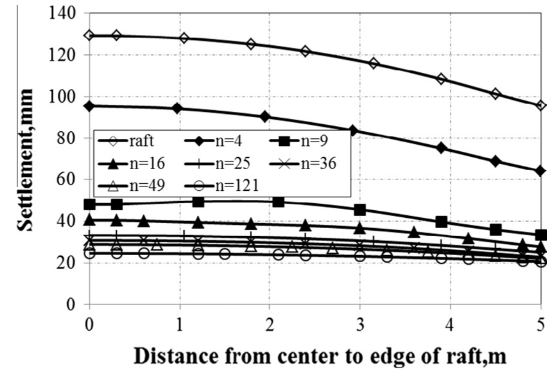


Figure 10 Settlement versus number of pile.

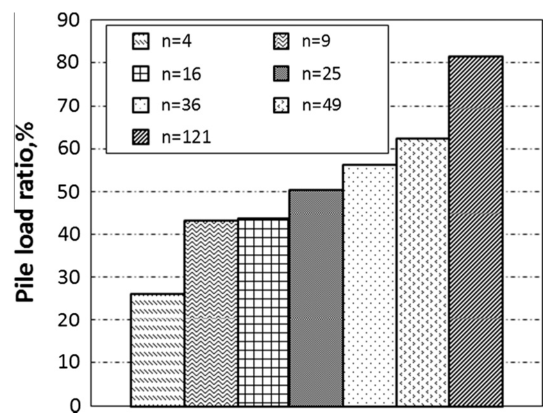


Figure 11 Pile loading ratio versus number of piles.

configuration is for a total 25 piles arranged in a 5 × 5 pattern, where the pile load ratio is 50%.

4.3. Effect of pile diameter

Analysis is again performed for a 0.6 m thick square raft having an area of 100 m^2 and supported on 25 unconnected piles, with pile diameters varying from 0.3 to 1.4 m. Fig. 12 shows the effect of the change in unconnected pile diameter on the settlement of the unconnected system. From the figure, it may be observed that, the overall settlement values decrease with the increase of pile diameter. The reduction rate of the differential settlement increases with the increase of pile diameter. This is due to the increase of the pile stiffness with increasing pile diameter.

4.4. Effect of raft thickness

Analysis is performed for a square raft having an area of 100 m^2 and supported on 25 unconnected piles, where the raft thickness was varied from 0.5 m to 1.75 m. The raft–soil relative stiffness (K_{rs}) is a major factor influencing the differential settlement of the unconnected foundation system. Horikoshi and Randolph [19] estimated the raft–soil relative stiffness (K_{rs}) of rectangular rafts using the equation,

$$K_{rs} = 5.57\frac{E_r}{E_s}\left(\frac{1-\upsilon_s^2}{1-\upsilon_r^2}\right)\left(\frac{B}{L}\right)^{0.5}\left(\frac{t_r}{L}\right)^3, \quad (2)$$

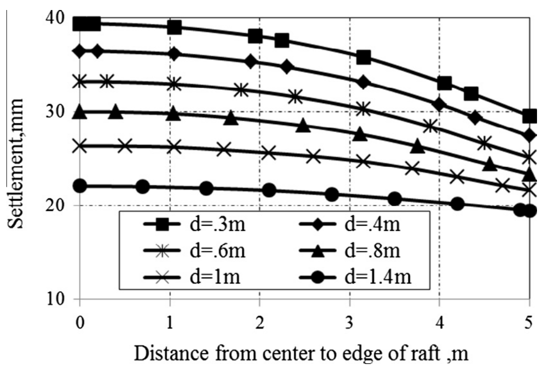


Figure 12 Overall settlement versus pile diameter.

where E_r and E_s are Young's moduli of the raft and the soil, respectively, υ_r and υ_s are Poisson's ratio of the raft and the soil respectively, t_r is the thickness of the raft, B and L are the width and the length of the rectangular raft, respectively. According to Horikoshi and Randolph [19], the raft is fully flexible when K_{rs} is smaller than 1.0, and the raft is fully rigid when K_{rs} is greater than 10. Fig. 13 shows the effect of raft thickness on the overall settlement of the unconnected system. From this Figure, it can be seen that the overall settlement decreases slightly with the increase of the thickness of the raft up to a thickness of 1.25 m, beyond this thickness, the overall settlement of the foundation decreases with the increase of the raft thickness. Fig. 14 shows the effect of raft–soil stiffness ratio (K_{rs}) on the maximum settlement of unconnected system.

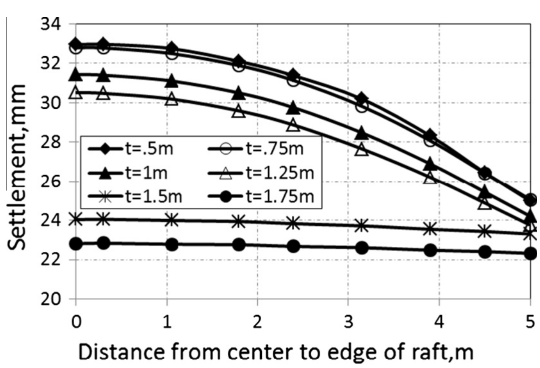


Figure 13 Settlement versus raft thickness.

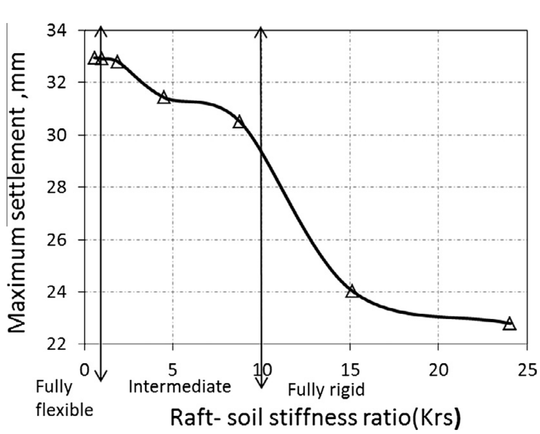


Figure 14 Maximum settlement versus raft–soil relative stiffness.

The results show that the maximum settlement of the foundation system decreases with the increase of the raft–soil stiffness ratio (K_{rs}). The differential settlement is significantly reduced with the increase of the raft thickness up to 1.5 m. It may be concluded that increasing the raft thickness (stiffness) is effective, primarily, in reducing the differential settlement. Increasing the raft thickness may be also beneficial in resisting the punching and shear from superstructure loadings.

5. Conclusions

Unconnected piled raft foundations have the potential to provide an engineered economical alternative for a connected piled raft foundation system subject to vertical axial loads. In the unconnected system, plain concrete piles are adequate, without the need of reinforcement, where their basic function is to strengthen the top soil and increase the load sharing capacity. The cushion placed between the raft and the piles acts to redistribute the vertical loads and plays an important role in increasing the bearing capacity of the subsoil and modifying the load transfer mechanism of the piles. The following are the specific conclusions of the conducted parametric study:

(1) Compared to the case of raft without piles, the maximum settlement of the connected piled raft has decreased by 77%, while the maximum settlement of the unconnected piled raft has decreased by 74%.
(2) The maximum axial load in the connected piled raft system occurs at the pile head, and then decreases along the length of the pile. However, in the unconnected system, the location of maximum axial load is shifted downwards to a certain length below the pile head (approximately three meters in the studied model). The transfer of the vertical load from the cushion to the pile is similar to the well-known downdrag phenomenon. Beyond the top three meters of the pile, the axial load in the pile starts to decrease following the same pattern as in the connected system.
(3) The load sharing between the cushion and the piles is affected by the thickness of the cushion. The axial load at the pile head decreases as the thickness of cushion increases.
(4) The axial load in the pile increases as the cushion modulus increase. When the elastic modulus value represents soil condition, the location of the maximum axial load is shifted to lengths lower than the pile head, and as the elastic modulus is increased to reach that of the concrete, the maximum axial load moves upwards closer to the pile top until reaching the value of the connected piled raft.
(5) For the same unconnected piles spacing, increasing the pile diameter results in a decrease in the overall settlement. This is due to the increase of pile stiffness with increasing pile diameter.

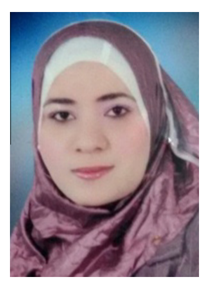
References

[1] Burland J, Brooms B, De Mello, Behaviour of foundations and structures. In: Proceedings of the 9th international conference on soil mechanics and foundation engineering, vol. 2. Tokio, Japan; 1977. p. 495–546.

[2] Solanki CH, Vasanvala SA, Patil JD. A Study on piled raft foundation: state of art. Int J Eng Res Technol (IJERT) 2013;2(8):1464–70.
[3] Zhuang GM, Lee IK. An elastic analysis of load distribution for raft–pile systems. Finite Element Anal Des 1994;18:259–72.
[4] Ta LD, Small JC. Analysis of piled raft systems in layered soils. Int J Numer Anal Methods Geomech 1996;20:57–72.
[5] Ta LD, Small JC. An approximation for analysis of raft and piled raft foundations. Comput Geotech 1997;20(2):105–23.
[6] Russo G. Numerical analysis of piled rafts. Int J Numer Anal Meth Geomech 1998;22(6):477–93.
[7] Poulos HG. Pile raft foundations design and applications. Geotechnique 2001;51(2):95–113.
[8] Reu O, Randolph M. Design strategies for piled rafts subjected to non-uniform vertical loading. J Geotech Geoenviron Eng 2004;130(1):1–13.
[9] Nakai Sh, Kato H, Ishida R, Mano H, Nagata M. Load bearing mechanism of piled raft foundation during earthquake. In: Proc. third UJNR workshop on soil–structure interaction, March 29–30. Menlo Park, California (USA); 2004.
[10] El-Mossallamy Y, Lutz B, Duerrwang R. Special aspects related to the behavior of piled raft foundation. In: 17 the international conference on soil mechanics & geotechnical engineering ICS-MGE. Alexandria, Egypt; 2009. p. 1366–9.
[11] Comodromos EM, Papadopoullou MC, Rentzeperis IK. Pile foundation analysis and design using experimental data and 3-D numerical analysis. Comput Geotech 2009;36:819–36.
[12] Cao XD, Wong IH, Chang MF. Behavior of model rafts resting on pile-reinforced sand. J Geotech Geoenviron Eng 2004;130(2):129–38.
[13] Wong IH, Chang MF, Cao XD. Raft foundations with disconnected settlement reducing piles. In: Design application of raft foundations and ground slabs. London: Thomas Telford; 2000. p. 469–86 [Chapter 17].
[14] Liang FY, Chen LZ, Shi XG. Numerical analysis of composite piled raft with cushion subjected to vertical load. Comput Geotech 2003;30:443–53.
[15] Lee HJ, Seo YK, Kim TH. Numerical analysis of piled-raft foundation considering sand cushion effects. In: Proceedings of the 16th international offshore and polar engineering conference. San Francisco, California (USA); 2006. p. 608–13.
[16] Eslami A, Malekshah S. Analysis of non-connected piled raft foundations (NCPRF) with cushion by finite element method. Comp Meth Civil Eng 2011;2(2):153–68.
[17] Sharma VJ, Vasanvala SA, Solanki CH. Effect of cushion on composite piled-raft foundation. J Eng Res Stud 2011;2(4):132–5.
[18] Poulos HG. Methods of analysis of piled raft foundations. A report prepared on behalf of technical committee TC18 on piled raft foundations. International Society of Soil Mechanics and Geotechnical Engineering; 2001.
[19] Horikoshi K, Randolph MF. On the definition of raft–soil stiffness ratio. Geotechnique 1997;47(5):1055–61.

Alaa Ata is a professor of Geotechnical Engineering at the Department of Structural Engineering, and General Manager of the Credit Hour Programs at the Faculty of Eng., Zagazig University, Egypt. His research interests include: soil improvement, deep foundations, recycling of industrial wastes and properties of calcareous sands.

Essam Badrawi is an assistant professor of Geotechnical Engineering at the Department of Structural Engineering, Faculty of Zagazig, Zagazig University. His research interests include applications of expanded polystyrene in geotechnical engineering, folded plate foundations and recycling of industrial wastes.



Marwa Nabil is an assistant lecturer at the Department of Structural Engineering, Faculty of Zagazig, Zagazig University. She is a Ph.D. Candidate currently working on her dissertation entitled “Behavior of unconnected piled raft systems with cushion under static and earthquake loadings”.