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Evaluation of Piled Raft Foundations Behavior with Different Dimensions of Piles

R. Ziaie-Moayed, M. Kamalzare and M. Safavian
Department of Civil Engineering, Imam Khomeini International University, Ghazvin, Iran

Abstract: In the present study, the behavior of piled raft foundation with different pile diameters is investigated under vertical loading. Piled-raft foundations for high-rise buildings have been proved to be an appropriate alternative instead of conventional pile or mat foundations. Piled raft foundation system is able to support the applied loading with an appropriate factor of safety and reduce the settlement of foundation. In some cases the piles are arranged uniformly and in other cases they are planned strategically to achieve uniform settlement. Piled raft foundation's behavior has been investigated by many researches and the influence of some factor like pile lengths, pile distance, pile arrangement and cap thicknesses have been studied under vertical or horizontal static and dynamic loading. In this study, the raft, piles and supporting soil are modeled by a 3D finite element program. Using pile raft with different pile diameters in all types of soils, with unequal applied loads, has better operation than piled raft system with similar piles. But its behavior is not the same in all soils. Results show that the piled raft foundation with different pile diameters may be a good solution to reduce total and differential settlements if the bottom layer is a dense soil. If the bottom layer be a soft soil, using piled raft foundation with different pile diameters can't be a good way to control maximum and differential settlement of raft system and structure. In this case, using other ways such as piled raft system with different lengths piles may be a good attitude to control the maximum and differential settlements.

Key words: Piled raft foundation, different pile diameter, vertical settlement, 3D modeling, finite element method, deep foundation

INTRODUCTION

In a piled raft foundation, the total load of the superstructure is partly carried out by piles through skin friction and the remaining load is taken by raft through contact with the soil. In conventional piled foundation it is assumed that the raft does not carry any load even if the raft is in contact with the ground. Also, in conventional piled foundation, as the contribution of raft is ignored, long piles should be used which extend up to the deep hard strata. On the other hand, if only raft has to carry the total load of the superstructure, very thick raft is needed which increases the cost of the foundation. Such raft foundation undergoes excessive settlement. In such a condition, piled raft foundation can be considered as the best solution in which shorter piles and raft with lesser thickness can be provided. Since 1970 many researchers has studied about different properties of piled raft foundation and its influence on reducing the maximum and differential settlements.

Hooper (1973) studied the behavior of piled raft foundation supporting a tower block in London. The field measurements which took along several years were accompanied with the results of a finite element analysis. In the analysis it was assumed that the load is distributed uniformly on the raft. Based on the field measurements the estimated proportions of load taken by piles and the raft at the end of construction were 60 and 40%, respectively. It was found that the long-term effect of consolidation increases the part of load which carried by piles and decreases raft contact pressure. Potts and Martins (1982) considered mobilization of shear stress along a rough pile shaft in normally consolidated clay in terms of effective stresses acting in the clay. Their predictions of the stress changes that occur in the soil adjacent to the pile shaft were in a good agreement with some experimental results. Frank (1991) discussed design of 4 buildings supported on piled raft in Germany. The analysis shows that compared to a raft foundation, piled raft system reduces the settlement about 50%. They have reported actual measurements of pile head forces, contact pressure between raft and soil and the settlements of piled raft foundation for some of these buildings.

Liu and Novak (1991) presented pile-soil static interaction by the combination of finite and infinite elements. The pile and the near field soil medium were modeled by finite elements, whereas the far field soil medium was modeled by mapped infinite elements. Axially

Corresponding Author: Mehrad Kamalzare, No. 49, Tohid 3 Alley, Golestan Street, Motahari Avenue, Azadegan Square, Postal Code 3143933846, Karaj, Tehran, Iran Tel: 0098 912 6610 852 Fax: 0098 261 2245145

loaded single pile and single pile with cap subjected to monotonic loading were investigated. Yamashita *et al.* (1994) reported the behavior of a five story building on piled raft foundation of size 24×23 m with 20 piles of length 16 m and diameter 0.75 m. The results of field observations during construction and analytical study of the same building have been compared. Gandhi and Maharaj (1996) investigated the load sharing between pile and raft based on three-dimensional linear finite element method. The effects of spacing, soil modulus and length of pile on load sharing between pile and raft have been discussed. Poulos (2001) studied about horizontal and inclined loading apply to pile raft foundation. Maharaj (2003) presented the results based on three dimensional nonlinear finite element analysis of piled raft foundation. It was found that the ultimate load capacity of flexible raft improves with increasing the soil modulus and length of pile. However, although increasing the soil modulus reduced the overall settlement, it increased differential settlement.

Dynamic characteristic of piled raft foundation is also important and several papers exist, which deals with the dynamic characteristics of a structure supported by a piled raft foundation. Nakaia *et al.* (2004) did studies about dynamic characteristics of piled raft foundations. Katzenbach and Turek (2004) exhibited their research about effect of raft in piled raft foundation. They used a centrifuge model test and its simulation analysis was discussed, followed by a parameter survey based on the finite element analysis. In the centrifuge models test, structures supported by a piled raft foundation and by a pile foundation were considered. A parameter survey was performed from the viewpoint of foundation types and types of connection between the raft and the piles. It was found from this study that, although the effect of the pile head connection on the behavior of a superstructure is fairly small, when it compared to the type of foundation, it does affect the load bearing characteristics of piles even when piles are not connected to the raft foundation. One of the best ways to control the maximum and differential settlement of piled raft foundations is to use piles with different lengths in this system. Tan *et al.* (2005) researched about effect of using piled raft system with different length of piles in very soft clay for a 5 story building. A monitoring scheme on the structures was successfully implemented.

Based on study review, it is found that few studies are carried out on pile raft system with piles of different dimensions. The present research aims to analyze the piled raft foundation with piles of different dimensions by 3D finite element method. The soil has been modeled as Drucker-Prager elasto-plastic material. Based on finite element analysis load-settlement curves have been produced for different condition.

CONSIDERATION OF FINITE ELEMENT MODEL

Simplified 3D finite element analyses are used to model the pile raft system in this study. Plan of simplified 3D model is shown in Fig. 1 and the selected piled raft section is shown in Fig. 2. The raft, pile and soil in the selected piled raft section have been defined by solid 45 (brick 8 node) elements. The element types, used for this model, are available in Table 1. As it can be seen, element Brick-8node-Solid45 has been used for pile, raft and soil, element Contact-3D-surface to surface-Conta174 has been used for contact and element Target 170 has been used for target in the model. By using these elements all characteristics of the model can defined in ANSYS software. An interface zone is introduced around piles to purpose approximately the slip between the soil and pile. Considered soil depth in the analysis is about 40 m and

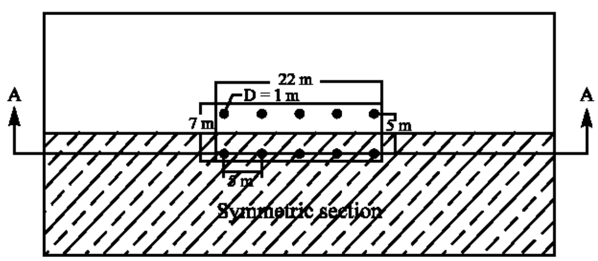

Fig. 1: Simplified plan of 3D model of raft and connected piles

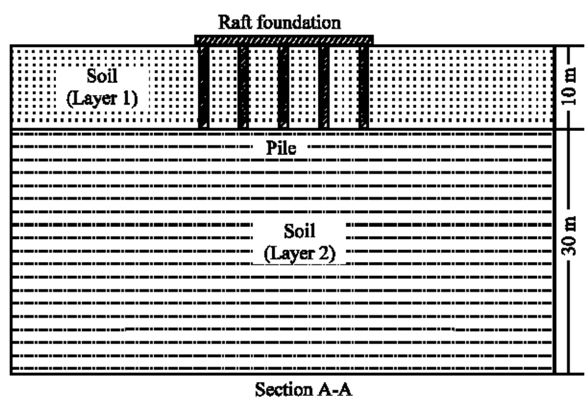

Fig. 2: Section of simplified 3D model of raft and connected piles

Table 1: Element types of materials used in modeling

Model	Element type
Pile	Brick-8node-Solid45
Raft	Brick-8node-Solid45
Soil	Brick-8node-Solid45
Contact	Contact-3D-surface to surface-Conta174
Target	Target 170

Source: Author's computation

Table 2: Material properties

Material	Model	Internal friction angle (φ°)	Dilatancy (Ψ)	Module of elasticity (E) (Mpa)	Poisson ratio (υ)	Cohesion (C) (kN m^{-2})
Pile	Elastic	-	-	30000	0.2	_
Raft	Elastic	-	-	30000	0.2	_
Very dense grave	Drucker prager	50	25	200	0.3	20
Dense gravel	Drucker prager	40	20	100	0.3	20
Medium sandy clay	Drucker prager	35	15	70	0.3	30
Medium clay	Drucker prager	20	5	30	0.3	60
Soft clay	Drucker prager	15	0	10	0.2	40

Source: Author's computation

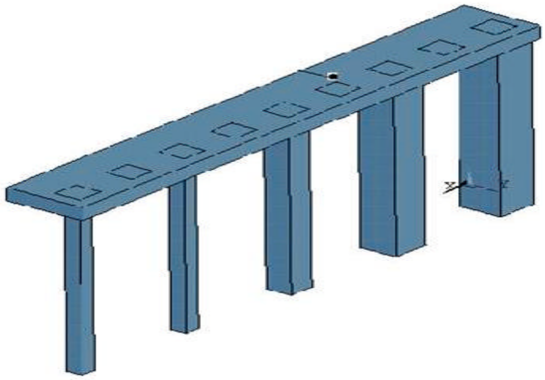

Fig. 3: 3D view of piled raft system with different pile diameters

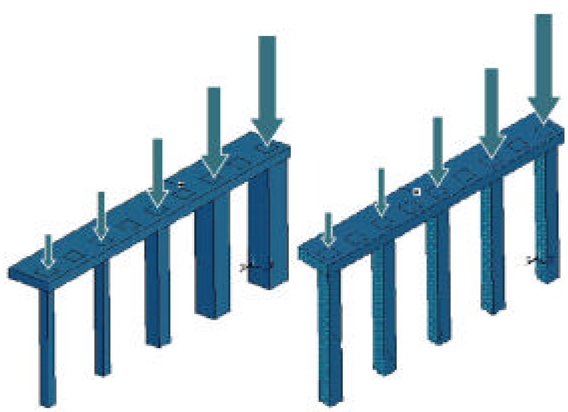

Fig. 4: 3D view of different piled raft models and loading on them

raft dimensions are 68×30 m. Concrete raft has 1.0 m thickness. In preliminarily model (piles with equal diameter) the cast in place concrete piles with dimensions of (1×1×10 m) have been considered. Then, in complimentary model, the square piles with 10 m lengths and different dimensions (0.6, 0.6, 1, 1.4, 1.6 m) are constructed (Fig. 3). As shown in Fig. 4, different point loads has been applied as concentrated loads on the respective nodes on the foundation.

Five different soils are used in two layers to achieve clear concepts of operation in all conditions. The selected

Table 3: Model properties

No. of model	Top layer	Bottom layer
1	Soft clay	Very dense gravel
2	Soft clay	Dense gravel
3	Soft clay	Medium sandy clay
4	Soft clay	Medium clay
5	Soft clay	Soft clay
6	Medium sandy clay	Very dense gravel
7	Medium sandy clay	Dense gravel
8	Medium sandy clay	Medium sandy clay

Source: Author's computation

soil has been idealized by Drucker-Prager elasto-plastic continuum. The concrete cast in place piles and concrete raft are modeled with elastic criteria. The properties of the material such as used model, internal friction angle, Dilatancy, module of elasticity, Poisson's ratio and cohesion of the pile, raft and soils are shown in Table 2. These parameters are in the range of moderate and prevalent values. The interface properties zone is selected similar to the soil properties. Combinations of these 5 soil types create 8 models with 2 layers. The models are used for 2 systems with equal and unequal diameter piles. Definition of soil layers for different models is shown in Table 3. Eight models have been analyzed which their top and bottom layer of soil differ for each model. Authors have chosen this layer in order to make comparison between different conditions.

In all proposed piled-raft systems, 2 cases are compared:

- Pile raft with the same pile diameters (System 1)
- Pile raft with piles of different diameters (System 2)

RESULTS AND DISCUSSION

The results of three dimensional analysis of pile raft system with equal and unequal pile diameter, placed in different soils have presented and a comparison has been done between different models. The vertical settlement contours for one of the analyzed models is shown in Fig. 5. Different colors shows different amount of settlement and by taking distance from the pile raft system, the amount of settlements become lower. Figure 5 has been extracted from finite element analysis.

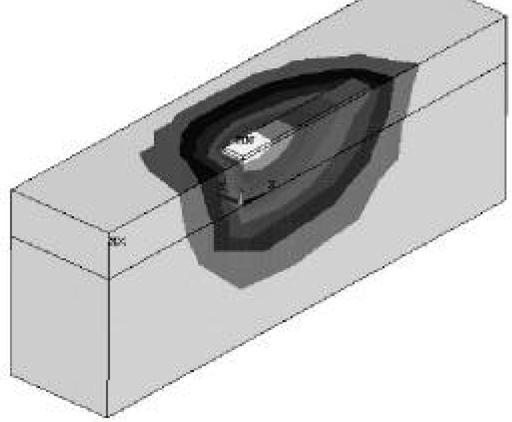

Fig. 5: Contours of vertical settlement for piled-raft system with piles of different diameter

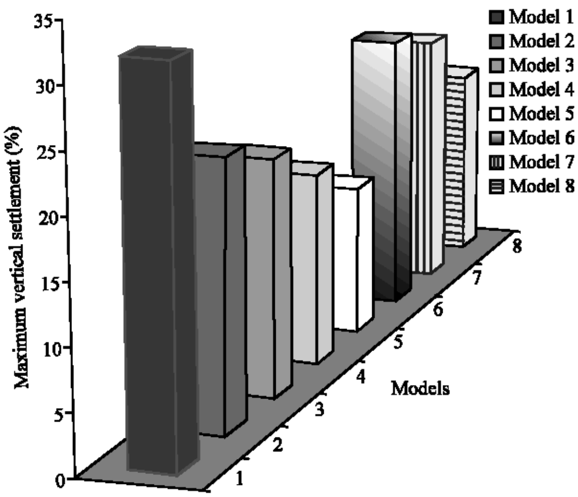

Fig. 6: Decrease amount in total vertical settlement when using pile raft system with different pile diameters

Table 4: Effect of using piles with different diameters on total and differential settlements

No. of models	Value of reduce in maximum settlement (cm)	Percent of reduce in maximum settlement	Value of reduce in differential settlement (cm)	Percent of reduce in differential settlement
1	2.3	31.9	2.7	96.4
2	1.5	22.4	1.8	94.7
3	1.3	20.0	1.4	85.7
4	1.1	16.4	0.6	66.7
5	0.8	12.9	0.3	75.0
6	1.5	23.8	2.0	83.3
7	1.4	21.9	1.6	76.2
8	1.0	16.7	1.2	70.6

Source: Author's Computation

The general pattern of vertical settlement of foundation may be evaluated from Fig. 5. The results of finite element analysis in selected models, including the effect of using different pile diameters on total and differential settlements are shown in Table 4. It can be seen that using piles with different diameters lead to lower settlements than using same diameter for all piles. It is because of creating more strength in places that the structure is under higher loads and lower strength in places that the structure sustains lower loads. On the other hand, the friction of piles in different parts of foundation is various and causes the structure to undergo lower differential settlement. Piles with larger diameters in places that sustain higher loads cause to decrease the distance between piles and it leads to increasing the axial stiffness of piles and subsequently increasing the load capacity of foundation.

The settlements of pile raft system with equal and unequal pile diameters have been obtained from analyses for each model and the amount of decreasing in total and differential settlements have been compared (Fig. 6). As it can be seen, maximum vertical settlement of each model (in percent) which has extracted from finite element analysis has been presented. Analysis of model 1 which soft clay and dense gravel have been placed in top and bottom layer respectively, shows that the maximum settlement reduces about 32% or 2.3 cm comparing with equal diameter piles (13% or 0.8 cm). It can be said that whatever the soil which the pile tip is placed on, be denser, more loads will be sustain by pile tip than by fraction and it causes more loading capacity of foundation and lower settlements too. Therefore, model 1, 6 and 2 which have denser soils in bottom layer (the layer which pile tip is placed on it), have the higher bearing capacity and model 5, 4 and 8 which have looser soils in bottom layer, have lower bearing capacity in comparison with other models. This is clearly shown in Fig. 6. However, if the lower soil be in saturate condition, it is not economical to use this system.

Differential settlements of pile raft foundation with equal and unequal pile diameters for each model are compared in Fig. 7. The amount of decrease in differential settlements varies between 0.3 to 2.7 cm (66 and 96%). It is clearly understood that by using system 2 (pile raft system with unequal pile diameters), in best conditions, in model 1 (top layer is soft clay and bottom layer is very dense gravel) differential settlement decreases 96.4% or 2.7 cm. This is shown in Fig. 8 along the length of raft foundation and it can be seen that by taking distance from edge of raft foundation, settlement decreases, which could be because of reduction in amount of stress in soil. These results confirm the obtained results of Potts and Martins (1982) which were in a good agreement with some experimental results. Similar investigation on pile raft foundation with equal pile diameter has been done by Maharaj (2003).

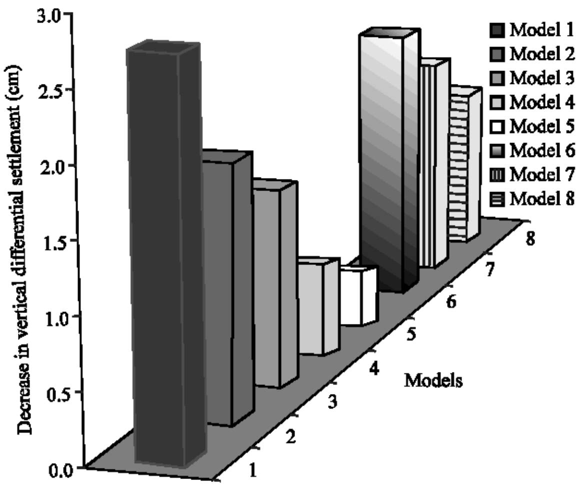

Fig. 7: Decrease amount in differential settlement when using pile raft system with different pile diameters

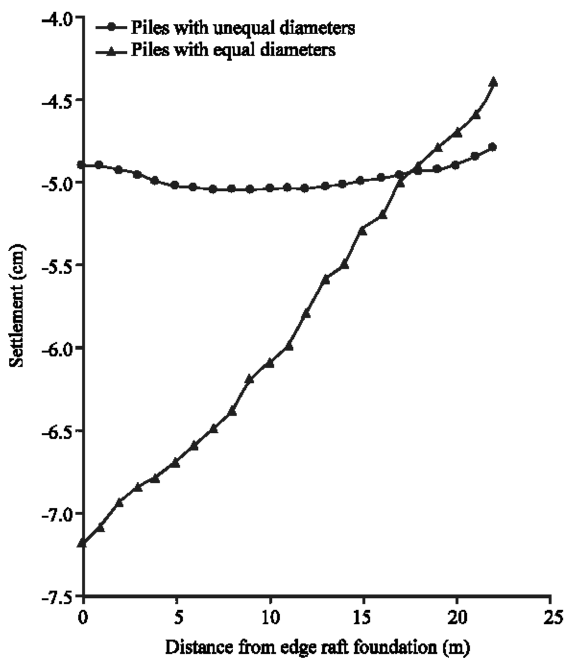

Fig. 8: Settlement along raft foundation length for model 1

However, if the bottom layer be a soft soil, using piled raft system with different pile diameters cannot be a good way to control the maximum and differential settlement of raft system and structure. In this case, using other ways such as piled raft system with piles of different lengths may be a good attitude to control maximum and differential settlements. Tan *et al.* (2005) researched about effect of using piled raft system with different length of piles in very soft clay.

From previous discussion, it can be concluded that pile raft systems with different pile diameters show better performance in comparison of systems with equal diameters. It is because of the more proper design of pile raft system; in places where higher loads are applied to the system, thicker piles are placed which can control the settlement and increase the bearing capacity of the system. On the other hand, in places under higher loads, larger diameters of piles cause a decreasing in the space between piles and consequently increase the bearing capacity of pile raft system.

CONCLUSIONS

Due to obtained results the following conclusions may be drawn:

- Using pile raft with different pile diameters in all types of soils, with unequal applied loads, has better operation than piled raft system with similar piles. But its behavior is not the same in all soil conditions. For example if the top layer is soft clay and the bottom layer is very dense gravel the operation of this system is better than the others
- Using piles with different diameters lead to lower total settlements than using same diameter for all piles. It is because of creating more strength in places that the structure is under higher loads and lower strength in places that the structure sustains lower loads
- In the best condition by using pile raft with different pile diameters, the maximum and differential settlement decrease 2.3 cm or 31.9% and 2.7 cm or 96.4%, respectively; this is an appropriate way to control the settlements of foundations
- Using piled raft system with different pile diameters can be a good suggestion to control the maximum and differential settlements of raft system and structure if the bottom layer is a dense soil. Besides it has economic advantages
- If the bottom layer be a soft soil, using piled raft system with different pile diameters can't be a good way to control the maximum and differential settlement of raft system and structure. In this case, using other ways such as piled raft system with piles of different lengths may be a good attitude to control maximum and differential settlements

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NOTATIONS

φ° = Internal friction angle
Ψ° = Dilatancy
E = Module of elasticity (MPa)
υ = Poisson ratio
C = Cohesion (kN m^{-2})

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