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# Evaluation of Bearing Capacity of Vertically Loaded Strip Piled-Raft Embedded in Soft Clay

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***Abstract*—**Settlement and bearing capacity of a piled raft are the two important issues for the foundations of structures built on coastal areas from the geotechnical engineering point of view. Strip piled raft as a load carrying system can reduce the possible extensive consolidation settlements and improve bearing capacity of structures in soft ground. The aim of this research was to evaluate the efficiency of strip piled raft embedded in soft clay. The efficiency of bearing capacity of strip piled raft foundation has been evaluated numerically in two cases; in the first case, the cap is placed directly on the ground surface and in the second, the cap is placed above the ground. Regarding to the fact that the geotechnical parameters of the soft clay are considered at low level, low bearing capacity is expected. The length, diameter and axe-to-axe distance of piles were the parameters which varied in this study to find out how they affected the bearing capacity. Results indicate that increasing the length and the diameter of the piles increase the bearing capacity.

***Keywords*—**Soft clay, Strip piled raft, Bearing capacity, Settlement.

## I. Introduction

STRIP piled raft foundation is combination of both raft and piles and is known as a pile-enhanced raft or piled raft. An increasing number of the structures are constructed on soft ground causes the application of piled raft on soft ground increased. Piled raft foundations provide an economical foundation option for circumstances where the performance of the raft alone does not satisfy the design requirements [1]. Many studies on design piled-raft have been carried by researchers all over the world [2]-[8]. The design of piled-raft system basically involves examining of bearing capacity of supporting sub-soil and the permissible allowable total and differential settlements. Due to low bearing capacity and excessive settlement in coastal areas, use of piled raft is essential [9], [10]. Unfortunately, a few analytical methods have been developed for analysis of a piled raft on soft clay [11]. Evaluation of bearing capacity for strip piled raft is considered in two cases: (A) there is connection between raft and soil, thus soil contributed in load transfer, and (B) there is no connection between cap and soil and cap is located in determined level from soil, in this case because of gap, all of applied load carried by piles, therefore this paper summarizes using strip piled raft in two cases: (A) without gap (B) with one meter gap. In the case A (without gap) the behavior of a piled raft is affected by interaction between the soil and pile, and in the case B (with gap) the interaction between the soil, piles and raft is considered. Some methods of analyzing piled rafts have been developed and three of them have been reported by Poluos [1]. Three classes of analysis method have been declared:

- simplified calculation methods
- approximate computer-based method
- more rigorous computer.

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## II. Design Concepts

Randolph [12] has defined clearly three different design philosophies with respect to piled rafts:

The "conventional approach", in which the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft, primarily to ultimate load capacity.

"Creep piling" in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70-80% of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the preconsolidation pressure of the soil.

Fig. 1 conceptually illustrates the load-settlement behavior of piled rafts designed according to the first two strategies. Curve 0 shows the behavior of the raft alone, which in this case it settles excessively at the design load. Curve 1 represents the conventional design philosophy, for which the behavior of the pile-raft system is governed by the pile group behavior, and which may be largely linear at the design load [1]. In this case, the piles take the great majority of the load.

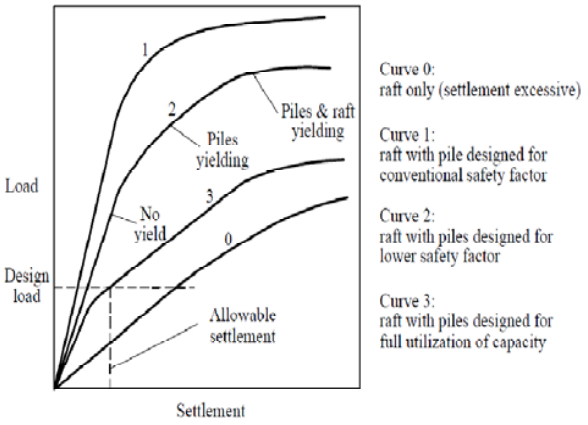



Fig. 1 Load settlement curves for piled rafts [1]

Curve 2 represents the case of creep piling where the piles operate at a lower factor of safety, but there are fewer piles, thus the raft carries more load than for Curve 1. Curve 3 illustrates the strategy of using the piles as settlement reducers, and utilizing the full capacity of the piles at the design load. Consequently, the load-settlement may be nonlinear at the design load, but the overall foundation system has an adequate margin of safety, and the settlement criterion is satisfied. Therefore, the design depicted by Curve 3 is acceptable and is likely to be considerably more economical than the designs depicted by Curves 1 and 2 [13].

## III. Finite Element Modeling

The finite element software ABAQUS [14] was used for describing the behavior of the piled raft. Fig. 2 shows 3D finite element mesh used in this analysis. It was supposed that pile rigidly was connected to the cap. As it was known strip piled raft should be continued in long distance, but here due to symmetry only a part of whole model was considered.

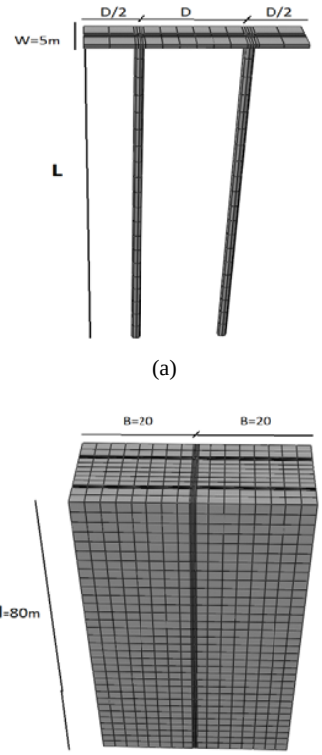
Relatively fine mesh is occupied near the pile-soil and raft-soil interfaces while a coarser mesh was used for further distance from the pile and raft. The 3D model of sub-soil should be extended in lateral directions with respect to the strip raft axis; therefore the boundary conditions defined in the lateral sides do not interfere in the calculation of the stresses at the piles vicinity. The soft clay sub-soil modeled using a Mohr-Coulomb model. To have simple analysis process, the parameters of material were constant. The raft and pile were modeled with an isotropic elastic Hookes model. The ultimate friction developed by piles in piled raft can be significantly greater than that for a single pile or pile in conventional pile group. This is because of the increased normal stresses generated between the soil and pile shaft by the loading on raft [15].

For pile-soil contact, the interface elements between pile and soil gives an effect on the behavior of a vertically loaded piled raft and the modeling of the pile-soil interfaces is an important concern. Therefore one of the main issues is identifying interaction between soil and pile. When a compressive normal pressure (p) applied on the cap, piles can only transfer shear forces along their lateral surfaces. When contact take places, according to modified Coulomb's friction theory, the relationship between shear force and normal pressure is shown in (1).

$$\tau = \mu * p \quad (1)$$

$\mu$ is a friction coefficient and p is normal pressure that varied in each level of soil.

As reported by Jeong et al [16] the interface friction coefficient ($\mu$) for clay varies from 0.2 to 0.4. Therefore, in this study interface friction coefficient ($\mu$) of 0.25 for soft clay was adopted.




(a)

(b)

Fig. 2 Finite element meshed: (a) piled raft, as shown axially distance and length of the piles are varied, (b) piled raft was embedded in the soil and dimension of soil was illustrated

The piles within the piled raft foundation develop more than twice the shaft resistance of a single isolated pile or a pile within a normal pile group, with the center piles showing the largest values. Thus, the usual design procedures for a piled raft, which assume that the ultimate pile capacity is the same as that for an isolated pile will tend to be conservative, and the ultimate capacity of the piled raft foundation system will be greater than that assumed in design [15]. Table I shows the material properties used for 3D finite element analysis. The material properties of the soil were adapted from some reference values as reported by Jeong et al. [16]. For soft clay in this study, attention was focused on the drained response of a pile-raft, so drained shear strength was used. Therefore consolidation effects were neglected.

TABLE I
Material Properties Used For 3D Finite Element

| Quantity | Soil | Pile | Raft |
|---|---|---|---|
| Young's modulus,(MPa) | 20 | 20000 | 20000 |
| Poisson's ratio:$\upsilon$ | 0.3 | 0.2 | 0.2 |
| Density=$\gamma$, (KN/m$^3$) | 18 | 25 | 25 |
| Undrained shear strength, (kPa) | 40 | - | - |

Using 3D finite element analyses has increased in recent decade. Sanctis L. D. et al. [17] has proposed a simple design criterion to evaluate the ultimate vertical load of a piled raft as

a function of its component capacities, which can be simply evaluated by the conventional bearing capacity theories. A broad parametric study is carried out using 3D FEM analysis to define the failure load coefficients accounting for the interaction between the raft and the pile group at failure. Also a guideline has been given to assess the factor of safety of vertically loaded piled raft.

Novak L. J. et al. [18] carried out analysis of pile-raft foundations with 3D finite-element method .They found following reasons for use of the 3D Finite Element Method (FEM): (1) the problem is so complex that simplified methods cannot model the problem correctly; and (2) codes for the FEM are available, powerful, and capable of being run on the personal computer.

Lee J. H.et al. [19] has conducted series of 3D elasto-plastic finite element analyses to investigate the bearing behavior of a square piled raft subjected to vertical loading. In this study, the main characteristic of these analyses was to permit soil slip at the pile–soil interface. Pile positions, pile number, pile length and loading distributions on the raft were varied, and the effects of pile–soil slip, pile geometries and loading types were examined. Furthermore, the proportion of load sharing of the raft and piles at the ultimate state and the relationship between the settlement and overall factor of safety was evaluated. The results show that the use of a limited number of

Piles, strategically located, might improve both bearing capacity and the settlement performance of the raft. Furthermore, the proportion of load sharing of the raft and piles at the ultimate state and the relationship between the settlement and overall factor of safety was evaluated. The results show that the use of a limited number of piles, strategically located, might improve both bearing capacity and the settlement performance of the raft.

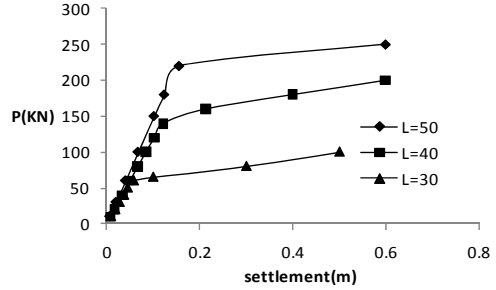
Reul O. et al. [20] carried out comparisons of in-situ measurements and numerical analyses for three piled raft foundations on over-consolidated clay between overall settlement, differential settlement and load carried by piles by back analysis. Three main performance indicators of the piled raft were proposed: the proportion of load carried by the piles, and the maximum settlement and maximum differential settlement, both as a proportion of the corresponding quantity for an unpiled raft foundation. The last indicator suggests that improved layout of the pile support can lead to a reduction both in the maximum differential settlement and in the overall quantity of piles. Numbers of numerical analyses on piled rafts were performed for different pile lengths and different horizontal distances for piles.

In this research three types of distance was assumed for the axe-to-axe distance and for each axially distance three types of length was supposed for piles. Three types of value for axe-to-axe distance are 5m, 15m and 20m. Also three types of length for piles are respectively 30m, 40m, and 50m. The thickness of cap and diameter of piles kept constant. The thickness of cap and the diameter of piles considered 0.5m and 1m, respectively.

## IV. Result

Figs. 3 and 4 show the effect of different pile length on the bearing capacity and load-settlement behavior in two cases: (A) with one meter gap and (B) without gap. As expected, both bearing capacity and settlement at failure load increased with increasing pile length. Also the settlement increased with increasing the load magnitude and settlement decreased by increasing the length of piles. In the case of without gap, results declared a great increase in the amount of bearing capacity rather than with gap. It is reasonable, because in the case of without gap, both cap and soil contribute in load transfer mechanism, while in the case of with gap the entire applied load carried by piles.

In both cases, if the applied load was constant, by increasing the length of piles the settlement decreased. As shown in the Figs. 3 and 4, in the case of with gap the length of pile is more effective than the case of without gap. It means in the case of with gap by increasing the length of pile( for example from 30m to 40m) the ratio of increasing ultimate load is more than the case of without gap, thus it is clear that increasing the length of pile, in the case of with gap, is more effective design strategy for improving foundation performance.

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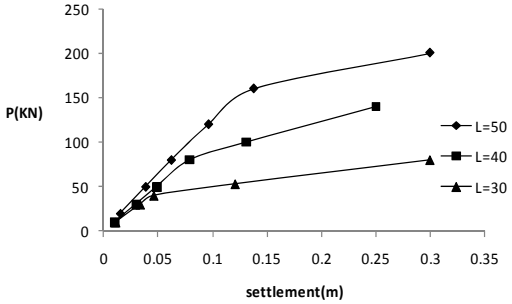


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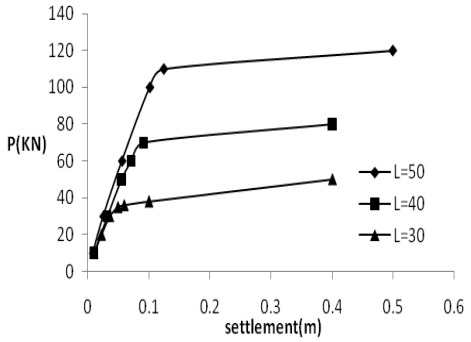
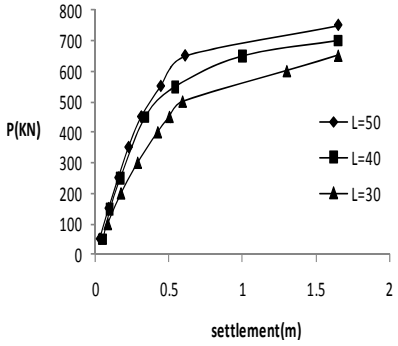


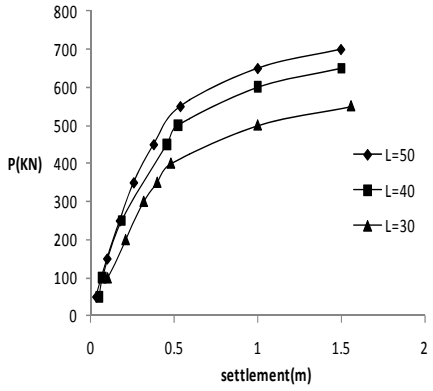

(c)

Fig. 3 Load settlement in the case of with gap: (a) axially distance (D) =10, (b) axially distance (D) =15, (c) axially distance (D) =20

For close pile spacing of piled raft, the settlement of the pile was slightly more than wide pile spacing. On the other hands by decreasing the axe-to-axe distance the settlement in the point of ultimate load increased, because by decreasing the axially distance, the probability of interference of stress bubble increased and it caused settlement increased. Results show by increasing the axially distance, the stress that carried by piles are also increasing.




(a)

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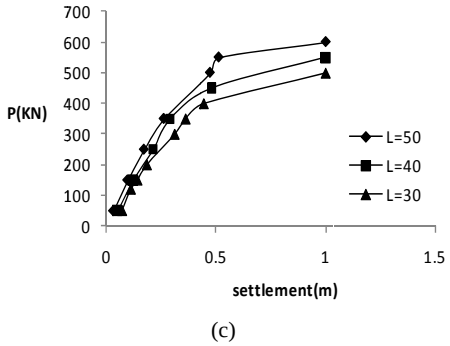


(c)

Fig. 4 Load settlement in the case of without gap; (a) axially distance (D) =10, (b) axially distance (D) =15, (c) axially distance (D) =20

## V. Conclusion

Piled raft foundations have the potential to provide economical foundation systems under the appropriate geotechnical conditions. The design criteria should be based on both ultimate load capacity and settlement criteria. A series of finite element analyses in two cases (with gap and without gap) were conducted to investigate the bearing behavior of piled raft subjected to vertical loading. In this study, the main characteristics of these analyses were the effect of axe-to-axe distance and pile length on bearing capacity. It is essential to take account of the various interactions which exist within a piled raft foundation: soil-pile, pile-raft, and soil-raft. These interactions are usually ignored in most conventional structural analyses, which may seriously underestimate the settlement and differential settlement, and also the amount of load carried by the raft. Both bearing capacity and settlement at ultimate load increased with increasing pile length in the case of with gap the length of pile is more effective than the case of without gap for increasing bearing capacity and wide pile spacing of piled raft caused settlement of the pile was shorter than close pile spacing.

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