# Piled-Raft Foundation Behaviour on Consolidating Soft Soil

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## Abstract

In areas where soft soil of low strength and high deformability extends over considerable depth from ground surface, deep foundation like piles are adopted by the designers for construction of high rise buildings, resulting high cost of construction. However, in such cases, a relatively cheaper foundation system like raft if adopted can counteract the possibility of shear failure due to huge super structural loads on the sub soil but the resulting settlement would be too large to be permitted. Thus, to have an economic foundation system, a raft is provided over the base of the proposed building and some piles are installed at specified location below the raft to increase the load carrying capacity of the combined system with reduced resulting settlement. But in a consolidating soft soil, the interaction between soil, raft and pile becomes time dependent. In this paper, a simple design methodology for pile raft system is proposed. An attempt has been made to incorporate the effect of time dependent consolidation settlement, calculated from the evaluated consolidation characteristics of the subsoil from soil exploration. Results of the pile load test data conducted at the site were considered for determination of pile capacity. It is shown that for a chosen piled-raft system in soft clayey subsoil, consideration of consolidation effect of the sub soil gives more rational evaluation of the interaction problem of a piled raft foundation.

**Keywords:** Piled-raft, consolidation, time dependent, soft clay, load test.

# 1. Introduction

In soft clayey subsoil, performance of a foundation is very much affected by time dependent soil deformation. Time dependent behaviour of soil results from properties of consolidation which has certain non linear characteristics. In soft ground, piled raft foundation are widely used and employed in construction of high rise buildings for their low overall and differential settlement with higher bearing capacity. The design of piled raft is based on the soil – structure interaction between the constituting elements and this is achieved through different method proposed by Poulos (2001), Katzenbach et al. (2000), Randolph (1994), Franke (1991). However, the piled raft subsoil interaction problem is highly complicated as it depends on large number of parameters like pile-raft geometry, pile spacing, sub soil characteristics etc. Especially, load deformation of soft soil may become non linear under high stress level. In case of submerged condition soft ground displays low strength, sensitive thixotrophy and high compressibility. Hence, in realistic design of piled raft foundation system time dependent behaviour of soil deformation and consolidation characteristic of the founding ground should be given due importance.

In this paper, an attempt has been made to formulate a design method for calculation of load carrying capacity of piled raft system in a soft consolidating underlying soil stratum. Pile elements are used to control or restrict the average settlement to a permitted value and at any point of time, the raft shares a portion of load so that the piles carry the remaining super structural load. The effect of ongoing consolidation settlement is considered in design. The time effects of interaction of piled raft and soil is numerically modelled. As a result, the time dependent behaviour of interaction of the piled raft and the soil is investigated in this paper by incorporating the effect of consolidation of the sub soil. Proposed method includes the field performance of pile from routine pile load test conducted at the construction site in Eastern part of Kolkata city in a very unique soft clay deposit extending from 2 m to 16 m (more or less) below ground level.

# 2. Literature Survey of Analytical studies on Piled-Raft

In the analytical field, pioneering work was started by Butterfield & Banerjee (1971) and thereafter important developed models are Strip-Spring model by Poulos (1991), Plate-Spring model of Clancy and Randolph (1992), Boundary element method by Sinha (1997), FEM application in raft and Boundary element for pile by Hain and Lee (1978), Franke et al. (1994), FEM analysis involving plain strain & axisymmetric problem by Hooper (1974); Prokoso & Kulhawy (2001), 3D FEA by Zhang et al. (1991). All these methods do have specific objectives in studying the overall & differential settlements, raft bending and parametric effects. Time effects in soil structure analysis was first considered by Wood et al. (1975) on the basis of 1D Terzaghi's model of consolidation by virtue of finite difference method. Then the time dependent response of the piled-raft-soil interaction system under vertical loading was analysed by Cheng et al. (2004) using 2D FEM based on Biot's theory of consolidation. The linear creep model was incorporated by Viladkar et al. (1993) into FEM in interaction analysis and it is found that bending moment, contact pressure and differential settlement vary with time. A simplified rheologic element model was used by Xia (1994) to evaluate the distribution of raft contact pressure on visco-elasto plastic soil. A three dimensional FEM is proposed by An et al. (2001) to predict the creep settlement of foundation on elasto visco plastic soil. The interaction analysis considering time effects induced by both viscosity and consolidation was conducted by Wang et al. (2001) in which a closed form fundamental solution of stresses of saturated visco elastic soil underlying raft under vertical loading is derived. However, a critical study of Poulos (2001) showed that results from such models shows large scatter from each other.

The literature survey on piled raft foundation design discussed above shows that, most of the previously formulated design cases overlook time-dependency of soil deformation and may give rise to inaccuracy in evaluation of interaction behaviour and unreliability in design of structures. Till date no approach has been made to formulate a relatively simple and accurate method for designing a piled raft foundation in consolidating foundation bed. Actual site conditions are to some extent simulated as isotropic. Settlement oriented design methodologies are also limited.

# 3. Proposed Design Methodology

For the present work, to understand the raft soil, raft pile and pile soil interaction of composite pile raft foundations some practical assumptions have been made for the stress strain behaviour of the pile, the subsoil and raft. The interaction of the pile and soil responses is restricted in linearly elastic region. Such assumptions have resulted in satisfactory outcome in the piled raft researches based numerical model of Roy and Chattopadhyay (2011) and on finite element models of Mossallamy et al.(2009), Jeong et al. (2003).

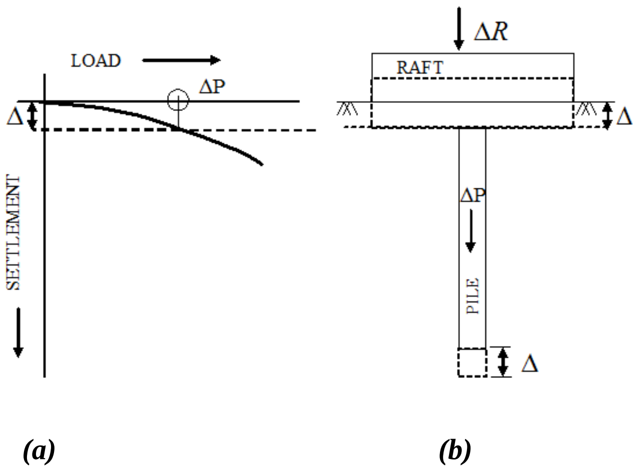
The proposed method is formulated basically to determine the time required, iteratively, by the piled raft composite foundation where load sharing and consequent load transfer between the pile and raft reaches an optimum balanced state for a super structural load on it in a soft consolidating sub soil. Study was also done to evaluate the separate individual load carrying capacities of raft and pile. As piles take huge load on a very small amount of settlement, corresponding load sharing and settlement of the raft is also studied. The time settlement relationship for the raft is also obtained taking into consideration consolidation properties of the existing soil profile. This is done to recognize time effects in interaction of piled raft and sub soil as it has got a practical significance as Chun-yi Cui et al. (2005) through his EVP soil model has shown that reactions and deformation of pile raft foundation varies with time in consolidating soft ground condition. Capacity of pile is determined through load test. The total settlement and load settlement characteristic of pile is determined through load settlement curves obtained from the routine load test.

## 3.1 Capacity of piled raft foundation

For a raft, proposed design approach starts with evaluation determination of its bearing capacity from both the shear failure criteria and permissible settlement limits for existing subsoil profile. The safe load for the raft is finalized following the most critical condition of the above two criteria. Now from the routine pile load tests the load that could be safely taken by the pile is evaluated through load settlement curves. Thus for a chosen settlement of ‘Δ’, if raft carries a load, ΔR and pile carries a load, ΔP, then the capacity of piled raft foundation, ΔPR can be expressed as

$$\Delta PR = \Delta R + \Delta P \qquad (1)$$

Here settlement ‘Δ’ takes care of both immediate and consolidation settlement of the subsoil profile. Figure 1 illustrates the schematic presentation of pile load test result and piled raft load sharing.




***Example Figure 1: Schematic diagram (a) Load settlement curve of routine pile load test; (b) Load taken by raft and pile at chosen settlement, Δ, from pile load test curve.***

## 3.2 Calculation of ΔP

The value of settlement ‘Δ’ of the combined pile-raft system, can be taken and adopted as per project requirement or subsoil condition and corresponding load on pile i.e. ΔP can be obtained directly from the load settlement curves of the conducted routine load test on pile. The value of ‘Δ’ can be varied to obtain required load sharing mechanism between the piles and the raft within linear zone of the load settlement curve of the pile.

## 3.3 Calculation of 'ΔR'

As mentioned previously, 'Δ' in the proposed approach is the total settlement i.e. sum of both initial and consolidation settlement for the raft. The value of 'ΔR' for raft is calculated considering both consolidation settlement and immediate settlement of the existing subsoil profile. At a consolidation settlement of Δc, let the load taken by the raft be ΔRc. At that load of ΔRc, corresponding immediate settlement, ΔI is calculated. ΔRc can be derived from the consolidation equation.

$$\Delta c = \frac{C_c}{1+e_o} H \log_{10} \frac{p_o + \Delta Rc}{p_o} \qquad (2)$$

From the above equation, $\Delta R_c$ can be written as

$$\Delta Rc = [10^{\frac{\Delta c}{CeH}}]p_o - p_o \qquad (3)$$

Where,

$p_o$ is the initial overburden pressure.

$$Ce = \frac{Cc}{1+e_o} \qquad (4)$$

H = height of compressible strata.

$C_c$ = compression index and

$e_o$ = initial void ratio of the consolidating layer.

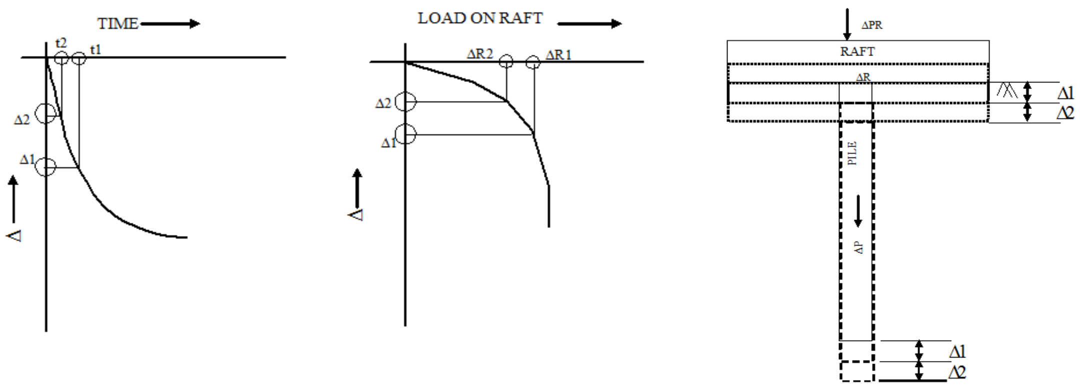
Finally, 'Δ' is to be re checked as

$$\Delta c + \Delta I \cong \Delta \qquad (5)$$

So that the total settlement of the raft and pile becomes almost identical and hence 'ΔR' can be written as

$$\Delta R = \Delta Rc \qquad (6)$$

Following the above equations, a program is developed to study the load transfer mechanism between the piles and raft. Now, iteratively $\Delta$ is selected and corresponding load on piles and raft is calculated. Figure 2 illustrates the schematic representation of time settlement curve of raft, load settlement of the raft and gradual consolidation settlement process of the piled raft foundation respectively. In addition, the time settlement of raft is incorporated to obtain the optimum time required to reach the balanced state of the piled raft foundation where load transfer and total settlement of piled raft becomes almost negligible and full load carrying capacity of the piled raft foundation is mobilised.




*(a)* *(b)* *(c)*

***Example Figure 2: Schematic diagram (a) Time settlement curve of raft; (b) Load settlement of raft at chosen settlements; (c) gradual consolidation settlement of pile raft composite.***

## 4 Results and Discussions

To elucidate the described principle of design of pile raft foundation on consolidating soft soil, an example problem of 15m by 15m square raft with 4 piles of length 30 m and diameter 1000 mm at a spacing more than 3 times its diameter is symmetrically arranged. A site in the eastern part of Kolkata city is selected for the present study. In the primary design stage, a large raft size was avoided keeping in view the soft subsoil condition and better understanding of the proposed methodology. The subsoil profile condition of the site and detail of pile load test is shown in Table 1 and Fig. 4 respectively.

## 4.1 Site Condition

A site in the eastern part of the Kolkata city, where a commercial cum residential buildings are proposed, is selected for critically analyzing the present design technique. Kolkata falls under typical deltaic region. The existing subsoil properties and other details are indicated in Table 1.

*Example Table 1: Soil profile with design soil parameters*

| Stratum thickness (m) | Description of soil | N | NMC (%) | $\gamma$(kN/m$^3$) | Shear parameters | | $\frac{C_c}{1+e_o}$ | $m_v$ in m$^2$/kN x $10^{-4}$ Range (kPa) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | C (kPa) | $\phi$ ($^o$) | | 25-50 | 50-100 | 100-200 |
| I (0 to 2) | Light grey, fly ash fill | - | - | - | - | - | - | - | - | - |
| II (2 to 8) | Silty clay with grey patches | 4 | 36 | 17 | 22 | 1 | 0.12 | 4.2 | 4 | 3.0 |

*Example Table 1 continued*

| Stratum thickness (m) | Description of soil | N | NMC (%) | $\gamma$(kN/m$^3$) | Shear parameters | | $\frac{C_c}{1+e_o}$ | $m_v$ in m$^2$/kN x $10^{-4}$ Range (kPa) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | C (kPa) | $\phi$ ($^o$) | | 25-50 | 50-100 | 100-200 |
| III (8 to 16) | Silty clay with decomposed vegetation | 3 | 42 | 16 | 20 | 1 | 0.13 | 5.3 | 5.5 | 4.4 |
| IV (16 to 22) | Bluish medium silty clay | 18 | 28 | 17 | 45 | 1 | 0.08 | 3.5 | 3.3 | 3.00 |
| V (22 to 30) | Medium dense silty sand with mica | 38 | 33 | 19 | 57 | 28 | - | - | - | - |
| VI (30 to 33) Bore stopped | Yellowish dense sand | 58 | 35 | 18 | - | 35 | - | - | - | - |

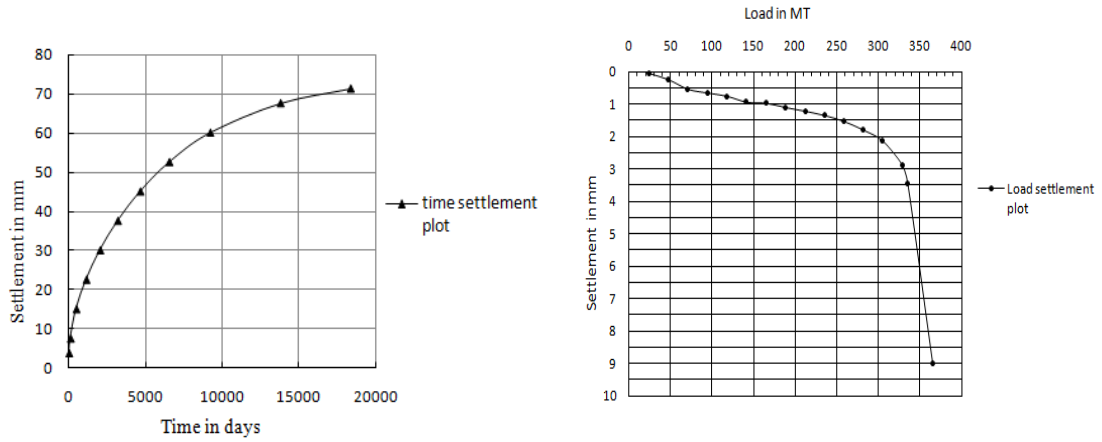
Water table was found to be at 0.8 m below existing ground level during soil exploration and is assumed to be below 2.0 m during dry weather condition.

## 4.2 Allowable load on Raft

Ultimate bearing capacity of the chosen raft was first calculated from the existing soil profile for the shear failure case. The corresponding safe bearing capacity was found to be 7.45 t/m$^2$. The value is quite satisfactory for the proposed site condition. But the total settlement at this capacity was found to be 225 mm which is beyond the permissible settlement for raft. Allowing the consolidation settlement of 100 mm, allowable capacity for the chosen raft becomes 4.0 t/m$^2$ i.e. 40 kPa for the present site condition, whereby the raft would be able to withstand quite a high load without suffering excessive settlement.

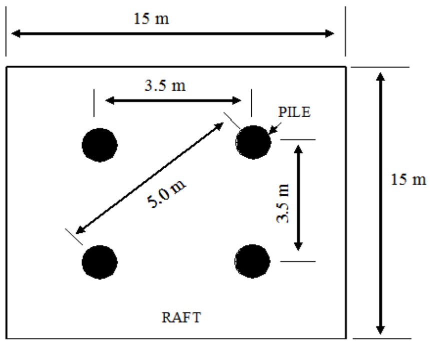
## 4.3 Calculation of ΔPR

ΔPR calculation as per the proposed method can be described as follows. Any super structural load more than 40 kPa is not permissible for the said raft as consolidation settlement would be beyond safe value. As mentioned previously, adopting the said raft to be supported by 4 piles arranged symmetrically shown in fig. 4(a) is considered and a pressure of 50kPa i.e. 1125 ton is applied on the piled raft foundation system. The capacity of pile from fig. 3(b) is 70 t corresponding to a settlement of 0.5 mm. Thus total load taken by 4 number of pile is 280 ton. At this point of settlement of 0.5 mm taken as Δ1, the load taken by raft comes to about 845 ton i.e. it is subjected to a pressure of 37.55 kPa. At a small settlement of 0.5 mm pile can take quite a large load. Considering this as the onset of the load sharing process between the raft and the pile and taking it as 1$^{st}$ iteration, following eqn. 3 to 6, a program is executed and results are tabulated in Table No. 2. For calculation of the ultimate time required by the pile raft foundation to reach a balanced state of load sharing, time settlement relationship for the adopted raft at a pressure range of 0.25 kPa to 0.5 kPa is plotted from the consolidation characteristic of the existing sub soil obtained from soil exploration and is given in fig. 3(a). The individual load carried by raft and piles for gradual consolidation settlement 'Δ' are also given in Table No.2. From fig 5 (a) and (b) stress time relation and stress settlement relationship respectively for the piled raft foundation could be observed. The curves reveals that approximately after a time span of 7.5 years of full load mobilisation, load transfer between piles and raft for the adopted piled raft reaches a balanced state. After this time period further consolidation settlement diminishes and attains a final value. If only piles are provided to carry a load of 1125 ton, from figure 3(b), required number of piles would have been 10 and if only raft is provided for bearing such a load, it would have suffered a settlement beyond a permissible value. Thus, pile raft foundation is proved to be more economic compared to individual pile or raft foundation and in addition overall settlement is controlled.




(a) (b)

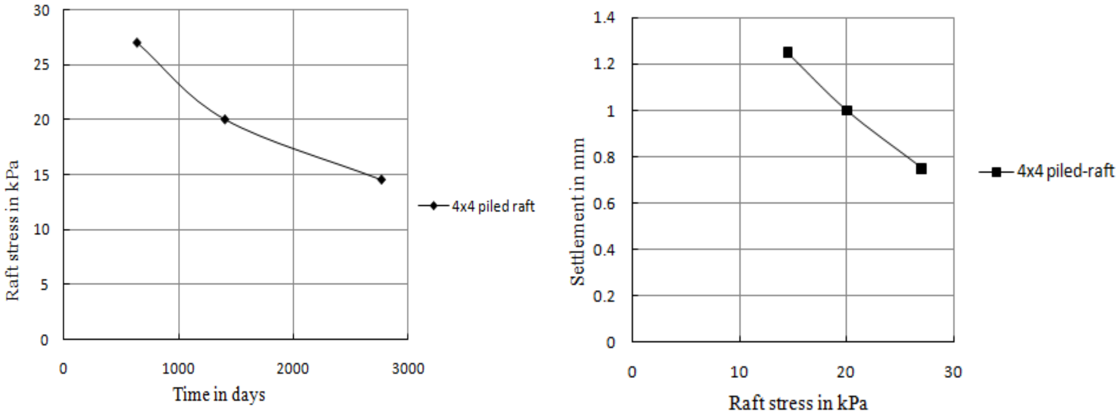
***Example Figure 3: (a) Time settlement curve of 15x15 sqm raft; (b) Load settlement curve of 1000 mm diameter pile having length 30 m and cut off at 2.0m below G.l.***




***Example Figure 4: Adopted piled-raft geometry.***

*Example Table 2: ΔP and ΔR values for gradual consolidation settlements*

| Iteration No. | Increment in consolidation settlement (mm) | Total settlement (mm) | ΔP (ton) | ΔR (ton) | Stress on raft (kPa) | Setting time in year | ΔPR (ton) |
|---|---|---|---|---|---|---|---|
| 1 | 0.5 | 0.5 | 70 | 845 | 37.55 | - | 1125 |
| 2 | 0.25 | 0.75 | 120 | 645 | 27 | 1.75 | |
| 3 | 0.25 | 1.0 | 170 | 450 | 20 | 2.1 | |
| 4 | 0.25 | 1.25 | 200 | 325 | 14.5 | 3.74 | |




(a) (b)

***Example Figure 5: (a) Stress-time curve of pile supported raft; (b) Stress versus settlement for adopted piled-raft foundation.***

## 5 Conclusions

Following conclusions can be drawn from the proposed simplified approach for the piled raft foundation on soft consolidating subsoil condition.

- In order to economize the design of a piled raft system, raft must be allowed to share some part of super structural load.

- In case of under lying soft sub soil profile to minimize the differential and overall settlement in piled raft foundation due consideration must be given consolidation characteristics of the founding stratum.

- The present method by virtue of its procedures, includes the all the soil-structure interaction effects of pile, raft and composite piled raft foundation system as the method is solely based on the determination of all the engineering characteristic of a site physically and capacity of pile is directly calculated from the routine load tests.

- In this proposed method the pile dimensions, raft dimensions, different suitable methods of pile group arrangement could be incorporated in tentative designs to make a most cost effective and efficient foundation system for a prototype foundation system.

- The proposed method can help the designer in the first design stage to check the rationality of a piled raft foundation and to investigate both the serviceability requirements as well as the ultimate limit state of the foundation required for a specific project and site condition.

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