

List of Symbols

PRF = Piled raft foundations

UPR = Unpiled raft foundation or only raft foundation

SP = Single pile

PG = Pile group

EPC = Miniature earth pressure cells

CIR = Circular raft

SQ = Square raft

RECT = Rectangular raft

TRAP = Trapezoidal raft

I_d = Relative density of sand bed in percentage

Q_{ur} = Ultimate load of unpiled raft foundation in kN

q_{ult} = Ultimate bearing capacity of unpiled raft foundation in kN/m²

k_{ri} = Initial tangent stiffness of unpiled raft in kN/m

k_{sr} = Secant stiffness of Unpiled raft in kN/m

B_r = width/diameter of unpiled raft foundation in m

S_c = Shape factor

s = Settlement of foundation in mm

s/B_r = Ratio of settlement to width of raft termed as relative settlement

L = Embedded length of pile in mm for model study and in m for prototype study

d = External diameter of pile in mm for model study and in m for prototype study

d_i = Internal Diameter of pile in mm for model study and in m for prototype study

L/d = Ratio of embedded length of pile to the external diameter of pile

$Q_{u,sp}$ = Ultimate load of a single pile in kN

$Q_{u,pg}$ = Ultimate load of pile group in kN

S = Spacing of piles

η = Efficiency of pile group

H = H shape of piles

HSQ = Pile with hollow square cross section

HC = Pile with hollow circular cross section

k_{p1} = Initial tangent stiffness of single pile in kN/m

$(k_{pg})_i$ = Initial tangent stiffness of pile group in kN/m

$Q_{safe,sp}$ = Safe load on a single pile in kN

s_s = Settlement of a single pile in mm at load $Q_{safe,sp}$

R_s = Settlement ratio

s_g = Settlement of the pile group in mm at the same average load Q in kN per pile, i.e. at the total pile group load of $nQ_{safe,sp}$

IYL = Initial Yield Load in kN

FYL = Final Yield Load in kN

$LSPG$ = Load shared by pile group in piled raft foundation in kN

LSR = Load shared by raft in piled raft foundation in kN

% $LSPG$ = percentage of load shared by pile group in piled raft foundation

% LSR = percentage of load shared by raft in piled raft foundation

α_p = Piled raft coefficient

SRR = Settlement reduction ratio of PRF in percentage

LIR = Load improvement ratio of PRF

C_1 = Efficiency factor of raft in PRF at $IYL = (LSR)_{s_i} / (P_r)_{s_i}$

C_2 = Efficiency factor of pile group in PRF at $IYL = (LSPG)_{s_i} / (P_{pg})_{s_i}$

s_i = Settlement of PRF at IYL in mm

$(P_r)_{s_i}$ = Load taken by UPR at s_i in kN

$(P_{pg})_{s_i}$ = Load taken by only pile group at s_i in kN

$(LSR)_{s_i}$ = Load shared by raft in PRF at IYL in kN

$(LSPG)_{s_i}$ = Load shared by pile group in PRF at IYL in kN

C_3 = Efficiency factor of raft in PRF at $FYL = (LSR)_{f_{yl}} / Q_{ur}$

C_4 = Efficiency factor of pile group in PRF at $FYL = (LSPG)_{f_{yl}} / Q_{u, pg}$

$(LSR)_{f_{yl}}$ = Load shared by raft in PRF at FYL in kN

$(LSPG)_{f_{yl}}$ = Load shared by pile group in PRF at IYL in kN

β = Efficiency of Piled raft foundation

$(k_{pr})_p$ = Primary stiffness of piled raft foundation in kN/m

$(k_{pr})_s$ = Secondary stiffness of piled raft foundation in kN/m

CF = Configuration of pile in piled raft foundation

δ_0 = Soil-pile friction angle between plain mild steel surface and natural Badarpur sand

δ_1 = Soil-pile friction angle between mild steel surface fixed with sand particles passing 212 μm sieve retained on 75 μm and natural Badarpur sand

δ_2 = Soil-pile friction angle between mild steel surface fixed with sand particles passing 425 μm sieve and retained on 212 μm and natural Badarpur sand

δ_3 = Soil-pile friction angle between mild steel surface fixed with sand particles passing 600 μm sieve and retained on 425 μm and natural Badarpur sand

LVDT = Linear variable displacement transducer

E_s = Modulus of elasticity of sand in kPa

1 INTRODUCTION

1.1 General

The Combined Pile Raft Foundation (CPRF) is a geotechnical composite construction that combines the bearing effect of both foundation elements raft and piles by taking into considerations of the interactions between the foundation elements and the underlying subsoil. (CPRF Guideline). The most effective application of piled rafts is when the raft has adequate load capacity, but the settlement and/or differential settlements of the raft alone exceed the allowable values. Piled raft foundations (PRF) are found suitable for strong soil like dense sand and stiff clay and unfavorable for soft soils near the ground. The major advantage of using combined system is reduction in maximum and differential settlements with considerable improvement in serviceability criteria, increase in overall stability of foundation, reduction in number of piles compared to conventional pile foundation and reduction in bending stresses for the raft. The piled raft foundation system is mainly used for high-rise structures in which the analysis of forces carried by raft, piles and soil are very complex in nature. This complex soil-structure interaction mechanism involves the interaction among foundation elements and their surrounding soil and can be classified into following categories: pile - pile interaction, pile – raft (cap) interaction, raft (cap) – soil interaction, pile - soil interaction, and pile base - pile shaft interaction. In piled raft design, a crucial aspect is determining the proportion of load carried by the raft and the piles, as both components contribute to the overall load-carrying behaviour. Estimating the load-carrying capacity of a piled raft is intricate due to uncertainties surrounding load-sharing behaviour and interaction effects, which can vary with settlements.

The effect of number of piles on behaviour of piled raft foundation has been studied by many researchers like Cooke (1986), Mosa et al. (2011), El-Garhy et al. (2013), Juneja et al. (2013), Patil et al. (2014), and Jamil et al. (2023). They concluded that the load sharing by piles in piled raft foundation increased with increase in number of piles up to optimum numbers. El-Garhy et al. (2013), Juneja et al. (2013), and Patil et al. (2014) found that the effect of raft thickness on load sharing by raft in piled raft foundation is insignificant. El-Garhy et al. (2013) and Juneja et al. (2013) studied the effect of pile length on the behaviour of piled raft foundation. El-Garhy et al. (2013) found that pile length have insignificant influence on piled

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raft load sharing while Juneja et al. (2013) found that the load shared by the piles increased with the length of the pile. Akinmusuru (1980) conducted experiments on unpiled raft, pile groups and piled raft and showed that the bearing capacity of the piled raft foundations exceeds the sum of the bearing capacity of the raft and pile group. Phung (1993) and Lee and Chung (2005) carried out field test in loose to dense sand and found that raft-pile interaction is the governing factor for pile raft behaviour, which causes an increase in skin friction of piles due to contact pressure of raft on soil. Fioravante et al. (2008) and Balakumar Venkatraman (2009) found that the raft's contribution begins as the piles approach their maximum capacity i.e. at lower settlements piles share more load whereas raft shares higher load with increase in settlement. Vakili (2015) studied the load sharing mechanism of a piled raft foundation in sandy soil through small scale tests and three dimensional numerical analyses and concluded that the load sharing of a non-displacement piled raft foundation in homogeneous sand is a function of two variables, S/d_p (spacing to pile diameter ratio) and w/d_r (settlement to raft width ratio), but independent of soil relative density, number of piles, and pile slenderness ratio. Park and Lee (2015) investigated the load responses and interaction effects of piled rafts embedded in sands by performing experiments and found that the interaction factors between pile groups, piles and rafts, and rafts and piles displayed state-dependent and nonlinear variations with settlement. Elwakil et al. (2016) have done experimental and numerical study (PLAXIS 2D) of piled raft system proposed to construct the piled raft at $S/B = 0.7\%$ for the optimal performance. Nemanja Bralović et al. (2022) conducted experimental analysis on small-scale 1g physical models of piled raft foundation structures with a group of 2×2 piles in loose sand and found that the current conventional approach to design of piled raft foundations, at a high safety load factor in piles that assume to take the whole external applied load, is very conservative. Instead, it is more economical to apply a low bearing capacity factor for piles as settlement reducers and maximize use of raft bearing capacity to carry part of the external load.

Clancy and Randolph (1993), and Polous (2001) derived the equations for estimating piled raft stiffness, load shared by piles and raft in piled raft based on the stiffness of pile group and unpiled raft foundation. Burland (1995) developed a simplified design approach for piles designed to act as settlement reducers and to achieve their full geotechnical capacity at the design load in piled raft foundation. Omeman et al. (2012) created a simple model for

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predicting raft-pile settlement and load sharing for piled-raft foundations based on stiffness of pile groups and unpiled raft. Lee et al. (2014) investigated the load carrying capacity of piled rafts focusing on the non-linear load sharing behaviour of piled rafts and proposed a normalised load-sharing model, taking into account settlement-dependent load-sharing behaviour and load capacity ratio. Ashutosh Kumara and Choudhury (2018) proposed a new prediction method to estimate both the ultimate limit state (ULS) and serviceability limit state (SLS) bearing capacity of CPRF by evaluating the pile-raft and raft-pile interaction factors. Bhartiya et al. (2020) performed systematic linear-elastic finite-element analyses on a series of unpiled rafts (rafts without piles), pile groups, and piled rafts with different geometries and pile configurations to determine the stiffness of these rafts, pile groups, and piled rafts.

In a piled-raft foundation system, the piles provide most of the stiffness for controlling settlements at serviceability loads and the raft element provides additional capacity at ultimate loading. A geotechnical assessment for designing such a foundation system therefore needs to consider not only the capacity of the pile and raft elements, but their combined capacity and interaction under serviceability loading. The optimal utilization of piled rafts is achieved when the raft can deliver sufficient load capacity, but the settlement and/or differential settlements of the raft alone surpass allowable values.

The following design issues usually need to be addressed in the static design of foundations for high-rise buildings (Poulos, 2009). 1. Ultimate capacity of the foundation under loads. 2. Overall settlements. 3. Differential settlements, both within the high-rise footprint and between high-rise and low-rise areas. 4. Structural design of the foundation system, including the load-sharing among the various components of the system (for example, the piles and the supporting raft) and the distribution of loads within the piles. For this, and most other components of design, it is essential to have close co-operation and interaction between geotechnical and structural designers. In this research, attention will be concentrated on the first two design issues.

1.2 Demand and Aim of the Research

Currently, Indian cities are expanding horizontally and vertically due to migration of people from rural to urban areas. Educational institutes, health centers, industries and commercial

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activities all attract people from surrounding habitations into the cities. This puts immense pressure on the demand for housing and other facilities. This leads to expansion in all aspects of the city; the bad part is that there is increased congestion, pollution, competition as well as deforestation as the city tries to expand horizontally first. The lack of horizontal space however, leading to a potential breaking point has led builders to the brilliant solution of building vertically. ([The Importance of High Rise Buildings in India | Artech Realtors](#)). One of the solutions for support of high-rise structures is to provide piled-raft foundation.

Many researches had been done on piled-raft foundation but due to complex soil-structure interaction the behaviour of piled raft foundation yet not fully understood. Most of the experimental research work had been done on parametric study related to PRF. From the literature review, it was found that the effect of relative density of sand, contact pressure distribution below raft and load sharing mechanism between piles and raft in PRF is not fully understood. A complete analysis of load-settlement behaviour of PRF, load-sharing between piles and raft at different load/ settlement levels, development of analytical expression for load carrying capacity of piled raft is yet to be needed.

To understand this complex behaviour of piled raft foundation, the experimental work has been carried out on model unpiled raft, single pile, pile groups and piled raft foundation with different parameters of model foundation and foundation soil. The parameters considered in this study for model foundations are shape of raft, slenderness effect of pile, arrangements of piles, effect of raft-soil, pile-soil interaction on the behaviour of piled raft. The contact pressures of raft with soil were measured using miniature earth pressure cells (EPC). The experimental results compared with numerical results and the effect of pile configurations on the behaviour of prototype piled raft foundations was analyzed using PLAXIS 3D.

1.3 Limitations

- The tests are carried out in sand for vertical axial loads.
- The models are prepared with mild steel.
- The piles are modeled as hollow circular piles.
- Load-settlement characteristics and load sharing mechanism are studied for connected piled raft foundation system.
- The results are validated in PLAXIS 3D, version 2023.1.0 by Bentley Systems.

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- The numerical analyses are carried out considering Mohr- Coulomb model for soil and piles are considered as an embedded beam element.
- The experimental study is restricted to axial force in pile only.
- The 1g model tests are carried out.
- The contact pressure between raft and soil are measured by EPC placed at symmetrical locations beneath raft with surface of EPC and bottom surface of raft flushed.

1.4 Planning of the Research Work

During the initial phase of the project, a thorough literature study was conducted to establish the guidelines for laboratory tests. The research work conducted in the past was used as a reference to prepare the geometrical dimensions of the model rafts and piles. The model raft and piles were fabricated from mild steel and the dimensions of the piles and model raft were chosen to ensure that no stress concentration occurs at the boundary of the tank.

During the second phase of the experiment, extensive laboratory tests were conducted on single pile, pile group, unpiled rafts and piled rafts. In total, 5 model rafts, 6 single model piles, 9 model pile groups, and 22 model piled rafts were tested in a sandy soil with three relative densities under centrally loaded conditions. A total of 111 tests were conducted. The tests took into account various factors such as the shape of the raft, pile length, spacing, arrangements of piles, soil-pile frictions, shape of piles, and relative density of the sand bed. Based on the results of the laboratory tests, a summary of the findings was produced.

During the third phase of the study, laboratory tests were validated by simulating three-dimensional piled raft models using the commercial program PLAXIS 3D. Additionally, a comprehensive parametric study was conducted on a hypothetical square piled raft over sand using PLAXIS 3D software.

1.5 Layout of the Thesis

Chapter 1: Introduction

This chapter presents basic concept of piled raft foundation along with scope, aim and objective of the proposed research.

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Chapter 2: Literature review

This chapter provides a comprehensive review of previous studies on piled raft foundations. These studies were categorized to groups such as experimental developments, numerical/analytical developments, and case studies.

Chapter 3: Scope, Objectives and Scheme of investigation

Need for research in piled Raft Foundation, scope, objectives, scheme of investigation, and materials for the investigations are discussed in chapter 3.

Chapter 4: Experimental and numerical study

In this chapter the test soil, the geometry of the models, testing procedures, modeling of piled raft in PLAXIS 3D, validation of numerical model of piled-raft are described in details.

Chapter 5: Result, Analysis and Discussion

The main results obtained from the laboratory tests considering different influencing factors are discussed in this chapter. The results of the finite element numerical simulations are presented and compared with the experimental test results. A proposed preliminary design methodology aimed at estimating the number of piles, their lengths, spacing, probable settlement of the piled raft, and the factor of safety is discussed with an illustrative example.

Chapter 6: Summary of findings

This chapter summarizes the conclusions of this study along with suggestions for future research work.

At the end references were given used in this work.

2 CRITICAL STUDY ON PILED RAFT FOUNDATION

2.1 General

The critical study on piled raft foundation can be done using experimental method, numerical method or from the review of case studies on piled raft foundation. In this chapter, the experimental development made by various researchers is described in details in section 2.2. The developments on piled raft foundation topic through numerical studies are discussed in section 2.3 of this chapter. Various studies (observations) made by some researchers has been covered in section 2.4.

2.2 Experimental Developments

Numerous experimental findings that evaluate the performance of pile groups under various loading and soil conditions are reported in the literature (e.g., Al-Mahdi 2004, Lee and Chung 2005, Al-Mahdi 2006). Additionally, a number of small-scale tests have been carried out to examine the behaviour of piled raft foundations, and the results are summarized as follows.

Through a series of experiments on shallow footing, pile group, and piled raft under the same soil conditions, **Akinmusuru (1980)** showed that the bearing capacity of the piled raft foundations exceeds the sum of the bearing capacity of the raft and pile group. Further examples showed that the raft's bearing capacity in the piled raft foundation is comparable to that of a shallow footing. The following empirical relationship was suggested for determining the piled raft carrying capacity based on these observations:

$$Q_{PR} = \alpha' Q_{PG} + Q_R \quad (2-1)$$

where, Q_{PG} is the pile group's ultimate capacity, Q_R is the raft's ultimate capacity, and α' is the pile sharing factor that considers the influence of pile-soil-raft interaction on pile group ultimate capacity. It was demonstrated that Q_{PR} is always greater than the sum of Q_{PG} and Q_R and decreases as pile length increases. He also showed how pile length and raft shape affect piled raft load sharing. Experiment results on a single piled raft unit (Figure 2-1) demonstrated that increasing the raft width significantly increases the raft share; however pile length has little effect on load sharing.

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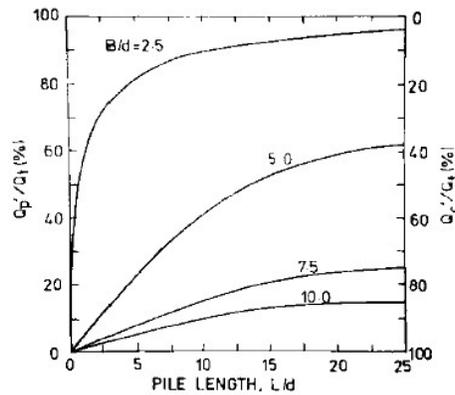


Figure 2-1: Load sharing between single pile and cap (after Akinmusuru,1980)

Wiesner and Brown (1980) conducted an experimental study on models of raft foundations in an over consolidated clay to investigate the validity of methods based on elastic continuum theory for predicting the behaviour of the piled-raft foundation subjected to vertical loading. In this study, measurements of settlements, strains and bending moments in the raft were made and were observed that predictions of theory which was based on the assumption that soil is a linearly elastic continuum can provide acceptable predictions for the behaviour of piled-raft foundations.

Liu et al. (1985), conducted field studies on piled raft foundations in sand and reported that block failure does not occur for groups of bored piles in sand. For determining piled raft carrying capacity, the following empirical equation was proposed:

$$Q_{PR} = n(\beta_s \delta_s Q_{SS} + \beta_b \delta_b Q_{sb}) + Q_R \quad (2-2)$$

where, Q_{PR} = the ultimate capacity of piled raft foundation; n = number of piles in the group; Q_{SS} = shaft capacity of single pile; Q_{sb} = base capacity of single pile

Q_R = raft ultimate capacity; δ and β = coefficients represent pile-soil-pile and pile-soil-raft interaction respectively with subscript “s” stands for shaft capacity and subscript “b” stands for base capacity of pile.

Cooke (1986) provided the findings of piled-raft foundation model tests. He compared piled-raft foundation behaviour to that of the un-piled raft and free-standing piled group. Cooke

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(1986) observed that the load distribution between piles in piled raft foundations was affected by pile number and spacing. He found that the settlement at the center of the raft foundation was greater than at the raft's edges.

Phung (1993) carried out field test in loose to dense sand and found that raft-pile interaction is the governing factor for pile raft behaviour, which causes an increase in skin friction of piles due to contact pressure of raft on soil.

Horikoshi and Randolph (1996) studied the settlement of piled-raft foundations on clay soil by conducting centrifuge experiments on piled-raft foundation models. They discovered that even a tiny group of piles might greatly lessen the raft's differential settlement. This study showed that a modest cap on a single pile might considerably boost the system's bearing capacity. Horikoshi et al. (2003) carried out centrifuge tests on piled-raft foundation models on sand soil that were exposed to vertical and horizontal loading. They investigated the effect of pile head connection rigidity on the behaviour of piled-raft foundations. This study found that as the cap comes into contact with soil, the confining stress surrounding the pile increases, increasing the pile's capacity. According to Horikoshi et al. (2003), the ultimate horizontal capacity of a piled-raft is greater than that of an un-piled raft.

Conte et al. (2003) conducted an experimental investigation using centrifuge tests to investigate the effect of raft and pile geometry modification on the rigidity of piled-raft foundations. They discovered that increasing the aspect ratio parameter, R_M as provided by equation (2-3), increases the rigidity of piled-raft foundations.

$$R_M = \frac{A_R}{A_g} \sqrt{\frac{n * s}{L}} \quad (2-3)$$

where, A_R = raft area; A_g = pile group area; n = number of piles; s = pile spacing; L = pile length

Cao et al. (2004) conducted experimental testing in plane-strain conditions to validate the usefulness of disconnected piles in decreasing raft settlement. In this study, the model raft was built on sand with a relative density of 70%, and numerous factors such as raft rigidity,

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pile length, pile arrangement, and pile number were changed. The testing results showed that unconnected piles beneath the raft are effective at preventing settlement and can carry up to 30% of the applied load on the raft at high pressures (Figure 2-2).

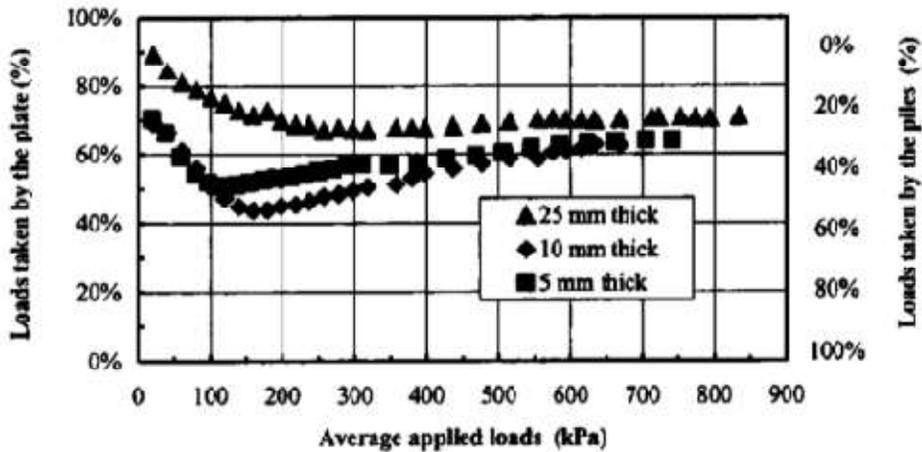


Figure 2-2: Fraction of loads taken by plates and piles for 500mm long piles (after Cao et al., 2004)

Lee and Chung (2005) conducted small scale model experiments on a single isolated pile, a single-loaded pile in a pile group, an un-piled footing, a freestanding pile group, and a piled raft. All of the pile groups in this study was made up of nine (3×3) piles driven into a compact sand deposit (Figure 2-3). The testing results indicated that contact between the raft and the underlying soil increases the skin friction of the piles as a function of pile spacing and pile position (Figure 2-4). The raft share in piled raft foundations was also shown to be comparable to un-piled raft behaviour.

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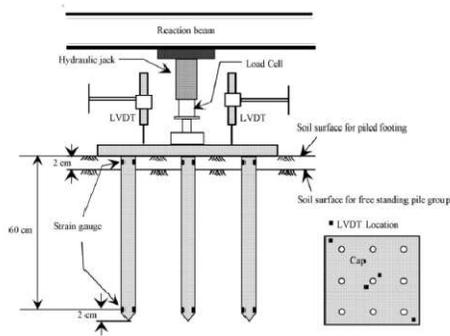


Figure 2-3: Schematic of test setup (after Lee and Chung, 2005)

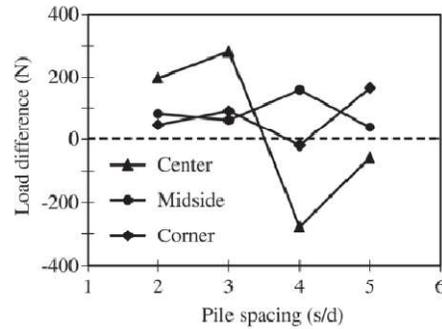


Figure 2-4: Difference in shaft friction between piles in free standing pile group and piled footing at the settlement of 3 mm or post-yield condition (after Lee and Chung, 2005)

Fioravante et al. (2008) published the findings of comprehensive centrifuge tests modeling a rigid circular piled-raft on sand soil to aid in the research of piles as settlement reducers and to quantify load sharing between the raft and piles. They discovered that when the number of piles increases, raft settlement reduces. The results demonstrated that displacement piles are more successful than non-displacement piles in reducing raft settlement. Fioravante et al. (2008) discovered that the raft's contribution begins as the piles approach their maximum capacity. They also noticed that piled-raft stiffness increased with the increase in the number of piles supporting the raft.

Balakumar Venkatraman (2009) conducted 1 g model tests on small-scale models to understand the load sharing and settlement reduction behaviour of circular piled raft resting on sand. The parameter analyzed were diameter, length and number of piles. The load-settlement response curves obtained analyzed and characterized. The characteristic response exhibited three phase behaviour irrespective of pile parameters and density of sand. The stiffness of piled raft system in the third phase is almost equal to raft-soil stiffness, which indicates that, piles perform essentially reducer rather than load sharing members. Finite

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element analysis for soil compares well with the experimental findings. At lower settlements piles share more load whereas raft shares higher load with increase in settlement.

Phung Duc Long (2010) endeavored to deepen the understanding of the load-transfer mechanism and load-settlement behaviour of a piled raft foundation in non-cohesive soil. The study also focused on the interaction between the piles, the cap, and the soil, with particular attention to the settlement-reducing effect of the piles. Three distinct series of large-scale model experiments (designated T1, T2, and T3) were carried out (Figure 2-5). Each test series included four separate tests on a shallow footing/cap (denoted as C), a single pile (S), a free-standing pile group (G), and a piled raft foundation (F) under identical soil conditions and geometry, as shown in Figure 2-5. The entire pile-cap-soil interaction of a piled footing in sand comprises interaction between the piles, known as pile-soil-pile interaction, as well as interaction between the piles and the pile cap (footing), known as pile-soil-cap interaction. The pile-soil-pile interaction is demonstrated by comparing the results of tests on free-standing pile groups with those on single piles, whereas the pile-soil-cap interaction is demonstrated by comparing the results of tests on piled footings with those on free-standing pile groups and on un-piled footings (cap alone).

Table 2-1 Summary of the large-scale field model tests, adopted from Phung Duc Long (2010)

Test Series	Pile Group and Cap (Footing)	Sand I_D , %	Separate tests in one test series	Pile length l_p (m)
T1	square group of five piles pile spacing $S=4b$ cap: 46cmx46cmx30cm	$I_D = 38\%$	T1C, shallow footing T1S, single pile T1G, pile group T1F, piled footing	- 2.0 2.1 2.3
T2	square group of five piles pile spacing $S=6b$ cap: 63cmx63cmx35cm	$I_D = 67\%$	T2C, shallow footing T2S, single pile T2G, pile group T2F, piled footing	- 2.0 2.1 2.3
T3	square group of five piles pile spacing $S=8b$ cap: 80cmx80cmx60cm	$I_D = 62\%$	T3C, shallow footing T3S, single pile T3G, pile group T3F, piled footing	- 2.0 2.1 2.3

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According to the test results, the carrying capacity of a piled raft (piled cap) foundation in non-cohesive soil P_{ft} can be calculated as follows:

$$P_{ft} = n(\eta_{1s}\eta_{4s}P_{ss} + \eta_{1b}\eta_{4b}P_{sb}) + \eta_6P_c \quad (2-4)$$

where, n = the number of piles in the group; P_{ss} and P_{sb} = the shaft and base capacities of a single reference pile, respectively; P_c = the cap capacity. Table 2-2 represents additional symbols, with the indices "s" and "b" representing the (pile) shaft and base, respectively.

Table 2-2 Definitions of load efficiency factors, adopted from Phung Duc Long (2010)

Symbols	Definition	comparison between
η_1	P_{gr}/nP_s	free-standing pile group and single pile
η_4	P_{ff}/P_{gr}	piled footing and free-standing pile group
η_6	P_{fc}/P_c	piled footing and shallow footing

By comparing the load per pile in a free-standing pile group with that of a single pile at a certain settlement, such as $s = 10$ mm, the efficiencies η_{1s} and η_{1b} , which show the influence of the pile-soil-pile interaction on the pile shaft and base capacities, may be determined. For moderately dense to dense sand, they considered the efficiency η_{1b} is unity, while for loose sand, it was considered more than unity.

Tests on piled footings done according to the second test protocol could clearly detect the efficiencies η_{4s} and η_{4b} , which reveal the influence of the pile cap interaction on the pile shaft and base capacities. They consider η_{4b} as unity for piles that are long enough ($L_p > 2.5B_c$, where L_p is the pile length and B_c is the cap width). The efficiency η_6 represents the impact of the pile-cap-soil contact on cap capacity, and it ranged from 1.0 for loose sand to 0.9 for medium dense to dense sand.

From the test result, they suggested that a practical procedure of design of piled footing in sand can be carried out with the steps below:

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- 1) To estimate the load taken by the cap (or unpiled raft) without causing excessive settlement. This load is equal to that can be taken in the cap in the piled raft footing P_{cap} ;
- 2) To estimate the load taken by the piles $P_{piles} = P_{total} - P_{cap}$, where P_{total} is the total applied load;
- 3) To determine the number of piles: As the piles are very close to failure state, the number of piles can be calculated as: $n = P_{piles} / P_s$, in which P_s is ultimate capacity of a single pile.

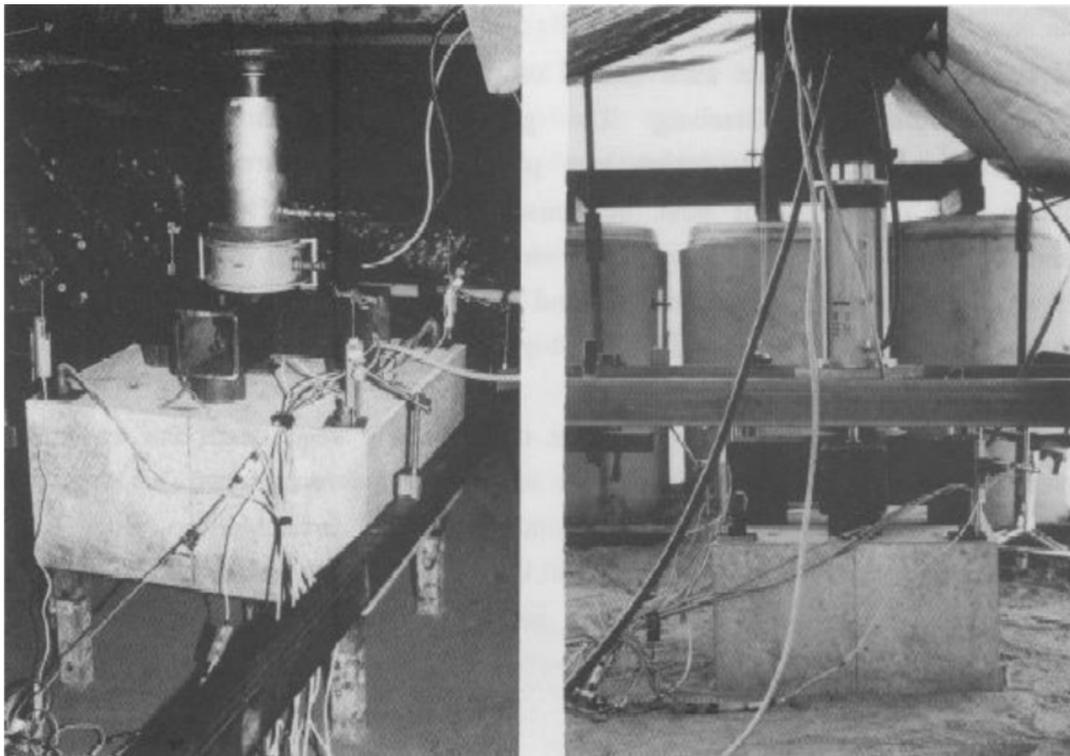
In Step 1, the load-settlement relationship for the raft/footing without piles is evaluated using any available method for shallow footings. The Load carried by the cap can be selected at a predetermined (allowable) settlement level. The piles will carry the remaining load in Step 2. If the pile-soil-pile interaction doesn't know, factor η_1 and the pile-cap interaction factor η_4 , can be taken as unity in Step 3. Furthermore, the number of piles can be estimated by dividing the load carried by pile group by the failure or creep load of a single pile. This is prudent because the pile shaft resistance increases significantly under cap-soil contact pressure.

The pile-soil-raft interaction governs piled raft behaviour through pile shaft capacity expansion; they found that the recorded pile share in a piled raft footing was much greater than the carried load by a free standing pile group in identical soil condition; pile position had no significant impact on the amount of the carried load by the pile in a piled raft system (Figure 2-6); prior to the piles failure, the majority of applied load was absorbed by the pile and was carried by the pile. In a piled raft footing, the raft's load-settlement behaviour was similar to that of a corresponding shallow foundation.

El Sawwaf (2010) examined connected and disconnected displacement piled raft footings under axial load and overturning moment (Figure 2-7). This study evaluated the effects of pile length, pile number, relative density of sand, and load eccentricity on the load-settlement behaviour of piled raft. The experiments were carried out at three distinct relative densities: 35%, 55%, and 80%. The following are the study's conclusions: the effectiveness of the piled raft system is affected by the load eccentricity ratio, pile layout, and relative density. Increasing the number of piles could only reduce settlement until a particular value was

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reached; the biggest improvement in raft behaviour was noticed when the sand was dense and the piles were attached to the raft (Figure 2-8). The study findings demonstrated that the use of short piles positioned near the edge of the raft effectively reduces both raft settlement and tilt while simultaneously increasing the strain borne by the raft. According to El Sawwaf (2010), the efficacy of short piles for increasing the performance of piled-raft foundations is dependent on pile configuration and load eccentricity ratio.



(a)

(b)

Figure 2-5: Field large-model tests set up: (a) Test on a free-standing pile group; (b) Test on a piled footing with the cap in contact with soil (after Phuong , 2010)

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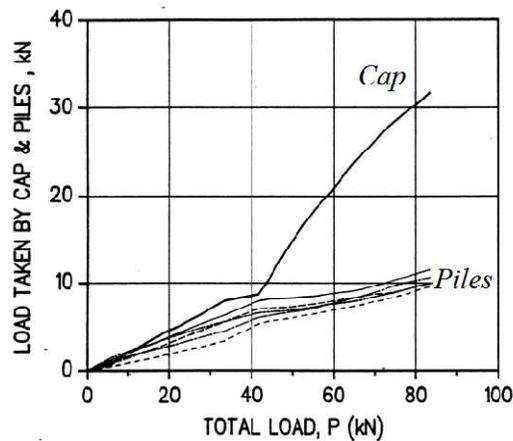


Figure 2-6 : Load share between cap and individual piles when the sand density and pile length are 38% and 2.3m respectively (after Phuong , 2010)

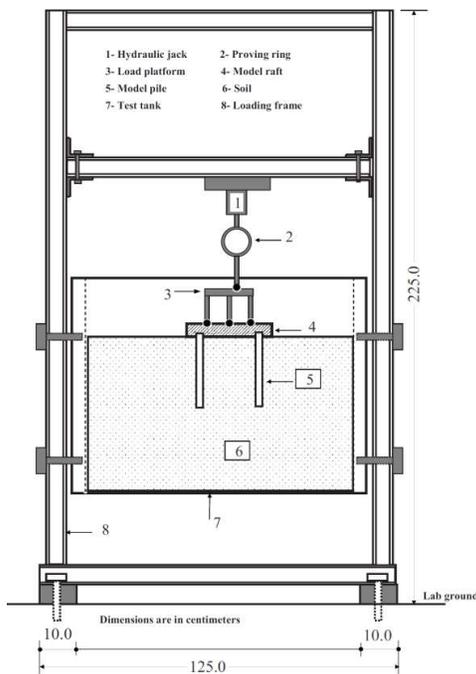


Figure 2-7: Schematic view of the experimental apparatus (after El Sawwaf , 2010)

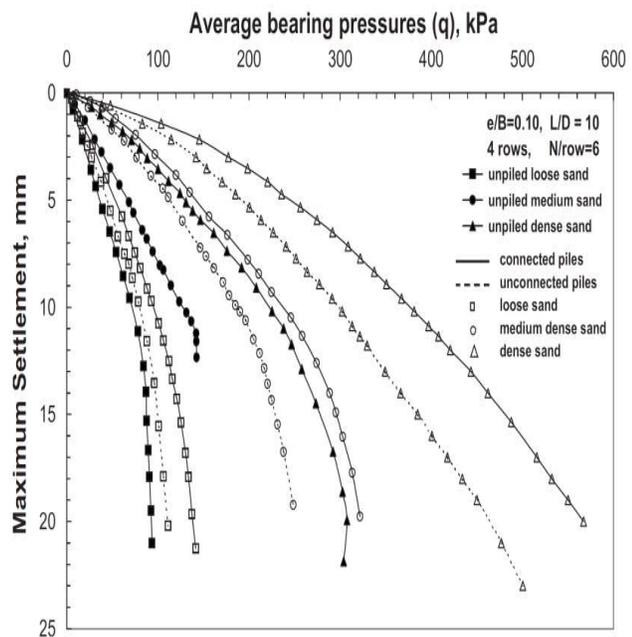


Figure 2-8 : Variation of average bearing pressures versus maximum settlement for different relative densities of sand (after El Sawwaf , 2010)

Fioravante and Gritti (2010) performed a centrifuge test on piled raft foundation in sandy soil and found that piles transfer the load from raft to wider and deeper volume of soil hence

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proved piles act as settlement reducer and also observed that sharing of load between pile and raft is related to stiffness of pile- soil system.

Matsumoto et al. (2010) used an experimental examination on piled-raft foundation models subjected to vertical and horizontal loads to evaluate the influence of pile head connection to the raft on the performance of piled raft foundations. They discovered that the pile head connection condition has no effect on the vertical loading behaviour of piled-raft foundations; however the horizontal load proportion borne by the raft decreases as the pile head connection becomes less stiff.

Beren Yilmaz (2010) carried out experimental research to observe the settlement behaviour of piled raft foundation system on clay. They used an aluminum model raft measuring $50 \times 50 \times 10$ mm and brass model piles measuring 2 mm in diameter for preparing model piled raft foundation. They performed the experiments on same foundation soil by changing number of piles (16 to 49). It was concluded that placing piles under the raft greatly lowers settlement of foundation as compared to unpiled raft. However, the experiments also produced another significant finding that decrease in the settlement of piled raft foundation gets smaller when the pile count rises even higher. In other words, the settlement was not significantly impacted by an increase in the number of piles. In this research, an analytical settlement analysis proposed by Clancy and Randolph (1993) had been used.

Based on experimental studies and the analytical calculations, they concluded the following points:

The design of combination systems such as piled raft foundations and settlement reduction piles should be based on a predetermined maximum permissible settlement.

- The ideal number of piles for each design situation should be found by a trial and error approach depending on the tolerable settlement.
- The allocation of loads between the pile and the raft must undergo meticulous examination, and the outcomes should be integrated into settlement analyses. In scenarios where settlement-reducing piles are employed, it is possible for the factor of safety against pile

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bearing capacity to approach or even reach unity. However, this does not necessarily indicate that the system has become unsafe.

As the number of piles increased, the reduction in settlement did not, and the settlement curve tends to behave as a straight line beyond a certain point. In other words, there is an optimal amount of piles that should be placed beneath the raft for each design. This results in cost savings and a quicker building time.

Giretti (2010) investigated the behaviour of rigid raft on settlement reducing piles subjected to axial loading using two series of centrifuge tests. The first set of experiments were carried out on a rigid circular raft supported by either displacement or non-displacement piles and laying on a bed of fully saturated loose sand ($D_r = 30\%$). The testing programme included raft and piled raft experiments with 1, 3, 7, and 13 piles (Figure 2-9). The model raft had an 88 mm diameter and a 15 mm thickness. The close ended and free headed model piles used in these testing had a diameter of 8 mm and a length of 160 mm. The centrifuge test findings demonstrated that piles reduce settlement and that the number of displacement piles required to minimize settlement to an acceptable level is less than that of non-displacement piles (Fioravante et al. 2008). Figure 2-10 depicts the changes in load sharing vs. settlement for several piled raft layouts. Load sharing fluctuates non-linearly with the settlement ratio (W/d_r), and pile share increases as the number of piles increases.

The second set of centrifuge experiments were conducted in two scenarios in which a rigid raft was either linked or separated from the driven piles in the dry sand deposit ($D_r = 60\%$). The testing program included raft, single pile, and piled raft tests with one, four, and nine displacement piles (Figure 2-11). The model raft had a 115 mm width and a 25 mm height. The model piles used were close ended and free headed, with diameters of 8 mm and lengths of 292 mm. According to the test results, connected piles work as settlement reducers by shifting the imposed load on their heads to deeper soil volume, whereas non-connected piles primarily serve as soil reinforcement. Furthermore, the pile-soil-raft interaction produces negative skin friction on the upper part of pile shafts, and the stiffness modulus of connected piled raft decreases by settlement until it reaches the raft stiffness at pile group failure point (Fioravante, 2011).

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Dr.Mosa J. Al-Mosawi et al. (2011) did experimental study to investigate the behaviour of piled raft system in sandy soil. They prepared a small scale “Prototype” model and tested in a sand box with load applied to the system through a compression machine. The settlement was measured at the centre of the raft, strain gages were used to measure the strains and calculate the total load carried by piles. They tested four configurations of piles (2×1, 3×1, 2×2 and 3×2) in the laboratory, in addition to rafts with different sizes. The effects of pile length, pile diameter, and raft thickness on the load carrying capacity of the piled raft system included in the load – settlement presentation. They found that the percentage of the applied load carried by piles to the total applied load of the groups (2×1, 3×1, 2×2 and 3×2) with raft thickness of 5 mm, pile diameter of 9 mm, and pile length of 200 mm was 28%, 38%, 56% and 79% respectively. The percentage of the load carried by piles was increased with the increase of number of piles.

Qaissy et al. (2013) performed experimental study on two different scale models with the same L/D_p (Embedment length to pile diameter ratio) and L/B_r (Embedded length to raft width ratio) to achieve the scale effect for the large scale model and plane strain condition for the small scale model. They found that the percentage of the load carried by raft to the total applied load of the experimental model in the case of four piles with raft was ranged between 60.6 - 64.8%.

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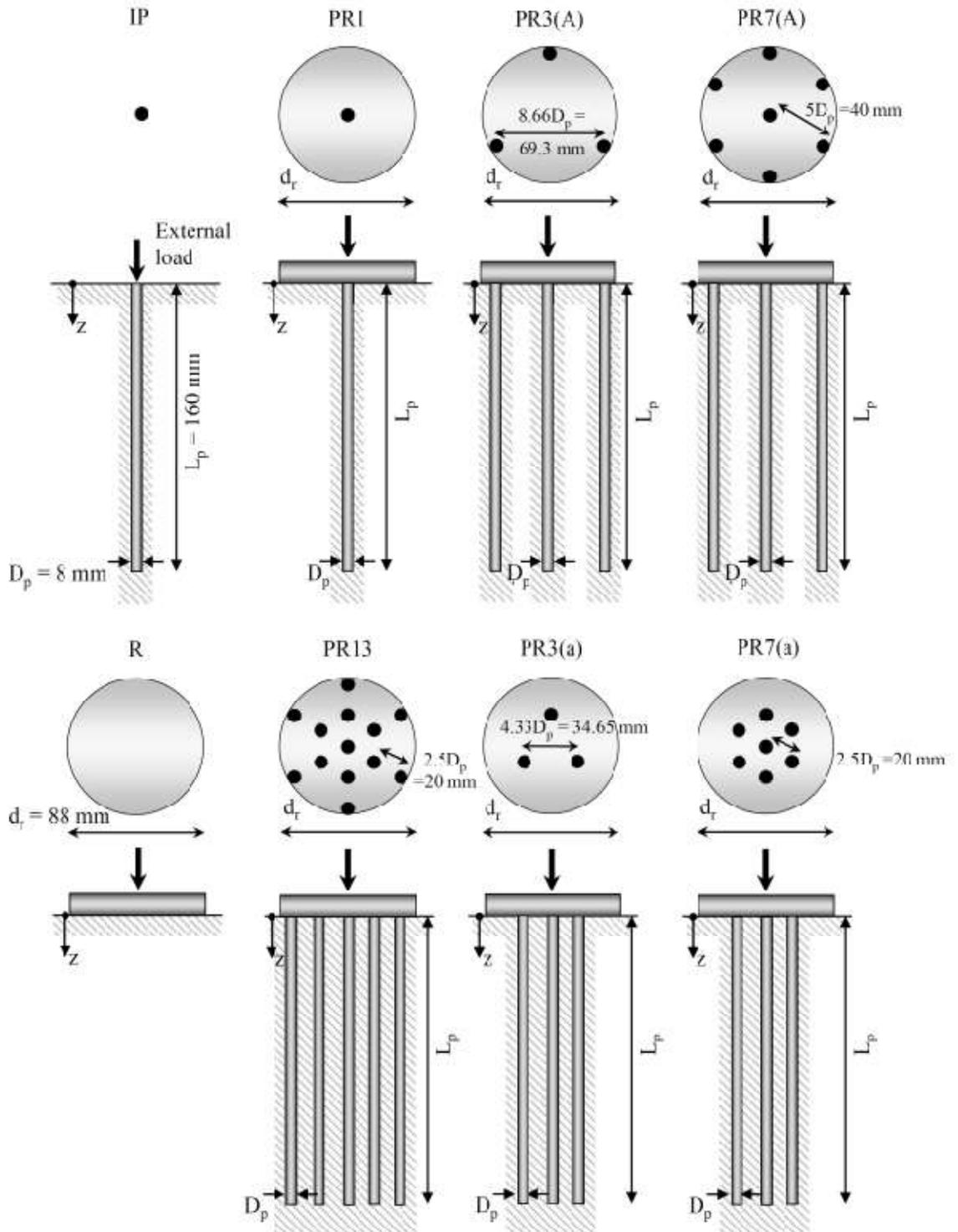


Figure 2-9 : Piled raft configurations in the centrifuge tests (after Giretti, 2010)

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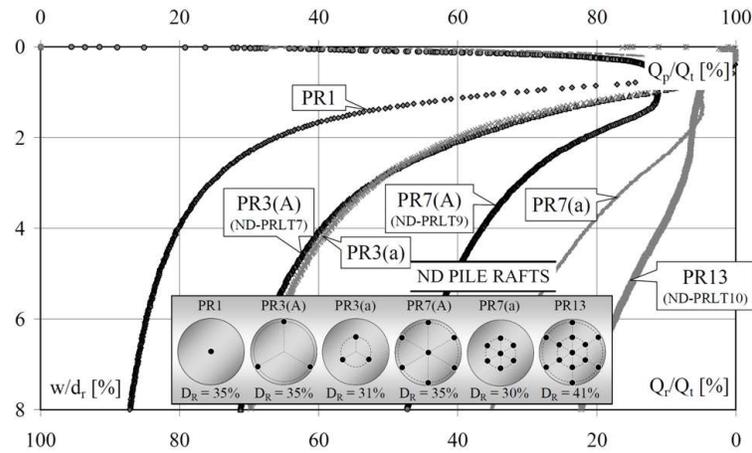


Figure 2-10 : Variation of load sharing versus raft relative settlement (settlement of piled raft over raft diameter) (after Giretti, 2010)

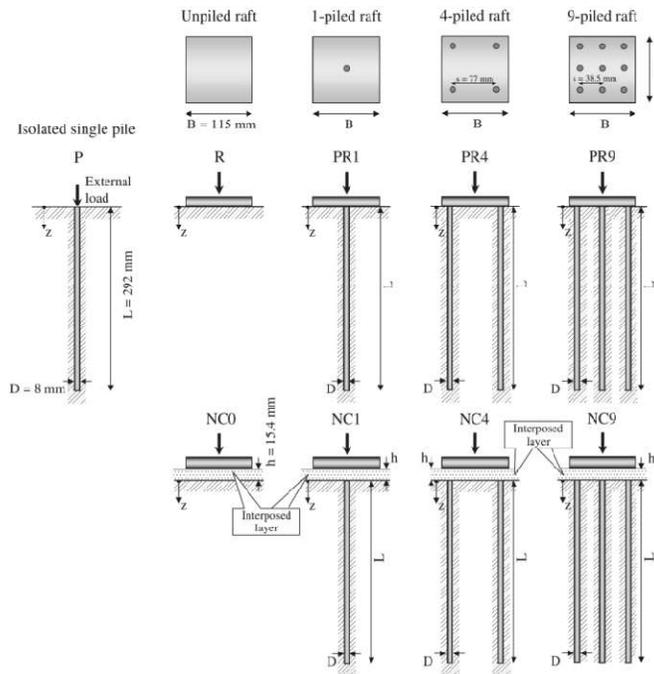


Figure 2-11 : Schematic view of model foundations in the series #2 of centrifuge tests (after Fioravante and Giretti, 2010)

El-Garhy et al. (2013) conducted small scale tests to investigate the behaviour of piled raft foundations in sand. The pile spacing was held constant in the test program ($S = 3.5 d_p$),

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while the pile length; number of piles, and raft thickness were varied. The test findings showed that: raft thickness and pile length had insignificant influence on piled raft load sharing (Figure 2-12 and Figure 2-13); increasing the number of piles results in a greater share of load borne by each individual pile when pile spacing and raft size were constant (Figure 2-13).

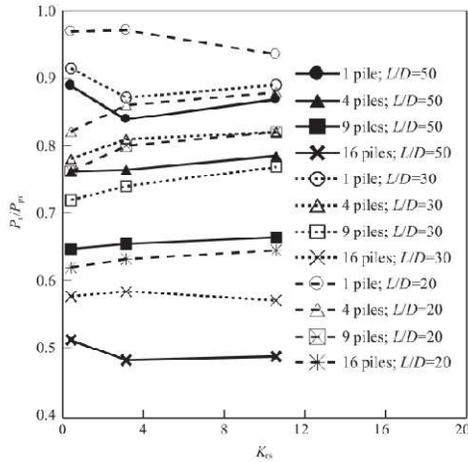


Figure 2-12 : Variation of raft share versus raft relative stiffness for piled raft with different number of piles and slenderness ratios (after El-Garhy et al., 2013)

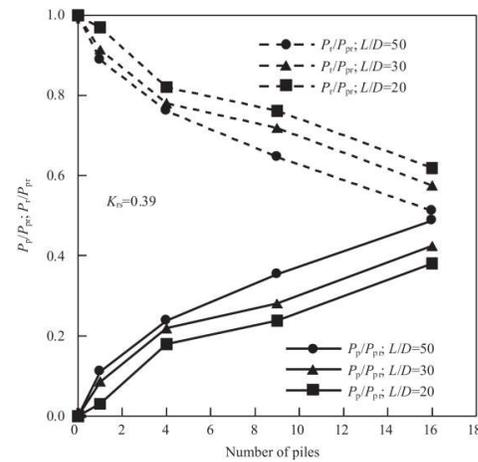


Figure 2-13 Load sharing of a piled raft with different number of piles and also various slenderness ratio (after El-Garhy et al., 2013)

Juneja et al. (2013) conducted 1g model tests to understand the effects of raft thickness, number and length of piles on the load shared by the piles. They computed load shared by the piles from the model tests as well as theoretically in terms of piled raft coefficients.

The piled raft coefficient, α_{PR} shows the load shared by the piles in piled raft is given as

$$\alpha_{PR} = \frac{\sum Q_{p,t}}{Q_{PR,ult}} \quad (2-5)$$

where, $Q_{p,t}$ = pile resistance

$Q_{PR,ult}$ = total resistance of the foundation

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Theoretically, the coefficients β_{PR} and ξ_{PR} were been also determined. The coefficients were been established in accordance with De Sanctis and Mandolini.

$$\beta_{PR} = \frac{\sum Q_{PR,ult}}{Q_{G,ult}} \quad (2-6)$$

where, $Q_{PR,ult}$ = ultimate load capacity of a piled raft, $Q_{G,ult}$ = ultimate load capacity of a pile group. β_{PR} shows the contribution of raft in the load bearing.

$$\xi_{PR} = \frac{Q_{PR,ult}}{Q_{UR,ult} + Q_{G,ult}} \quad (2-7)$$

where, $Q_{PR,ult}$ = ultimate load capacity of a piled raft, $Q_{G,ult}$ = ultimate load capacity of a pile group, $Q_{UR,ult}$ = ultimate load capacity of unpiled raft, ξ_{PR} shows the ultimate capacity of piled raft as a percentage of sum of ultimate capacities of raft and piles taken as separate components.

According to their observations, as the load increased, the overall load shared by the piles decreased. For a larger number of piles, the load shared by the piles increased with the length of the central pile and was roughly the same for different raft thicknesses. A large contribution of raft was obtained when fewer piles were used. Except for the single piled raft, where raft contributes significantly, the values of β_{PR} ranged from 1.9 to 2.9 in their testing. The findings agreed with those of Cook, who reported that β_{PR} varied from 1.25 to 2.5 depending on the length, spacing, number of piles, and breadth of the raft. It was also found that in general the value of β_{PR} i.e. the contribution of the raft decreases with the number of piles and length of piles. The values of ξ_{PR} for all the tests were found to be in the range of 0.99 to 1. i.e, the governing failure in both the pile group and piled raft was individual failure rather than block failure. This means that the ultimate capacity of the piled raft was found to be at least 99% of the ultimate capacities of the raft and piles taken separately. Such values are high and they suggested computing ξ_{PR} from experimental data.

Patil et al. (2014) performed experiments to study the behaviour of piled raft foundation system subjected to vertical load on dry sand. The experimental program included the model

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test on unpiled raft, raft supported by single pile, (2×2) and (3×3) pile groups with L/d ratio = 10 and spacing = $3d$. They concluded that the load bearing capacity of piled raft increased as the number of piles beneath the raft increased, Load improvement ratio increased at 10 mm and 20 mm settlement, as the number of pile increased. The raft thickness has insignificant effect on the settlement and the load sharing between piles and raft. The efficiency of piled raft foundation system in reducing settlement was minimal beyond a certain number of piles.

Radhika et al. (2015) did parametric study and numerical analysis of piled raft foundation on soft clay. Laboratory model tests were conducted on both unpiled and piled raft on soft clay. The model tests included the use of unpiled raft and piled raft of three configurations namely 1×1 , 2×2 and 3×3 with varying L/d Ratio of pile 23, 27 and 30. The results proved that ultimate load had increased and the settlement had reduced which was expressed by Load Improvement Ratio (*LIR*) and Settlement Ratio (*SR*). A parametric study indicated that an increase in pile length and the number of piles results in a reduction in settlement. Among the tested footing models, the maximum pile length was 180 mm. A piled raft with a 3×3 configuration demonstrated a 67% increase in ultimate load and an 83% reduction in settlement compared to the same configuration with a pile length of 140 mm. The observed settlement values from the experimental study were compared with numerical modeling using PLAXIS 2D, and the results showed good agreement.

Vakili (2015) studied the load sharing mechanism of a piled raft foundation in sandy soil through small scale tests and three dimensional numerical analyses. Experiments were conducted to examine the effects of density in homogeneous and stratified soil, particle size distribution of sand, pile installation method, and raft width on load sharing behaviour of piled raft foundation. In clean Silica sand, experiments were carried out on a shallow footing, a single pile, and a single piled raft unit. They observed in small scale tests that soil density altered the load sharing mechanism of a displacement piled raft, with the pile share increasing in denser soil. They found that, in non-displacement piled rafts the load sharing was independent of soil density and particle size distribution had insignificant effects on piled raft behaviour. One of the non-displacement piled raft experimental tests was used to calibrate the 3D numerical model, which was then expanded into 2×2 and 3×3 piled raft

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foundations. For a given settlement ratio, the load sharing outputs of the aforementioned models were compared.

From the experimental and numerical results and a literature review, they analyzed that the load sharing of a non-displacement piled raft foundation in homogeneous sand is a function of two variables, S/d_p (spacing to pile diameter ratio) and W/d_r (settlement to raft width ratio) ratios, but independent of soil relative density, number of piles, and pile slenderness ratio. They used experimental studies on non-displacement piled raft foundations in medium sand to build the load sharing empirical model. The empirical design chart developed for pile spacing ranges from $3.5 d_p$ to $6 d_p$ under operating load are shown in Figure 2-14.

Furthermore, **Yamashita et al. (2011) and Sinha (2013)** demonstrated that the relationship between load sharing and pile spacing reaches a saturation point at spacing = $6d_p$, so they suggested to use the proposed load sharing curve at $S/d_p = 6$ for any pile spacing greater than 6. They proposed empirical curves for load sharing as shown in Figure 2-14 to Figure 2-18.

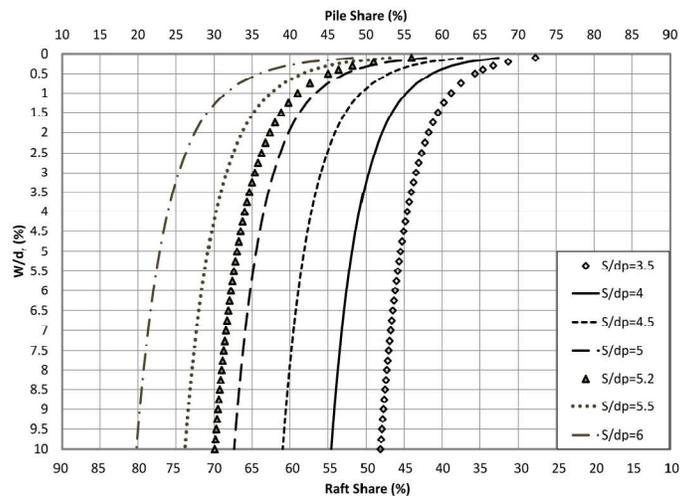


Figure 2-14 : The proposed empirical curves for estimating the load sharing of non-displacement piled raft in homogeneous sand as the function of W/d_r and S/d_p (after Vakili, 2015)

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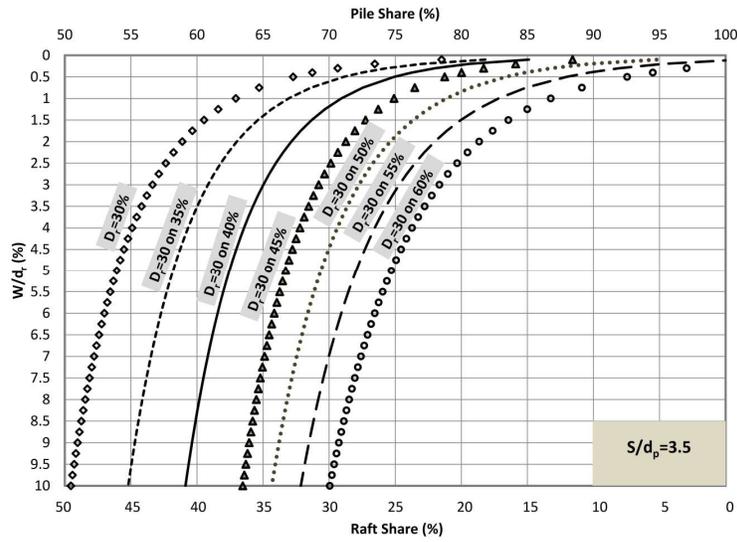


Figure 2-15 : Proposed empirical curves for estimating the load sharing of non-displacement piled raft in layered soil when the raft was founded on loose sand, and $S/d_p=3.5$ (after Vakili, 2015)

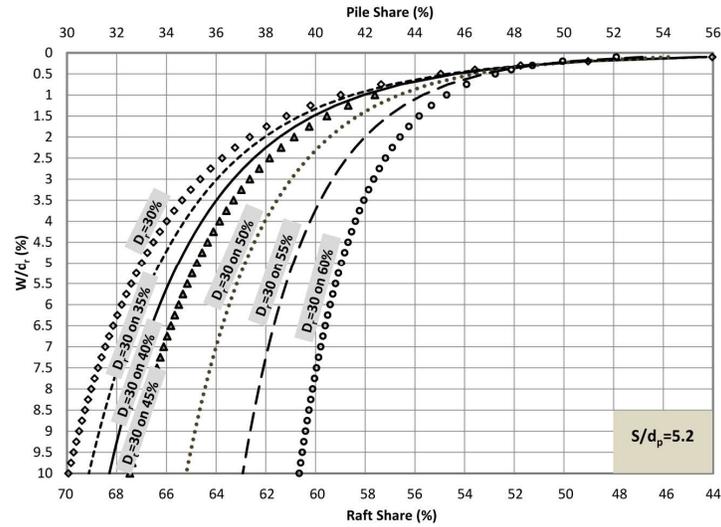


Figure 2-16 : Proposed empirical curves for estimating the load sharing of non-displacement piled raft in layered soil when the raft was founded on loose sand, and $S/d_p=5.2$ (after Vakili, 2015)

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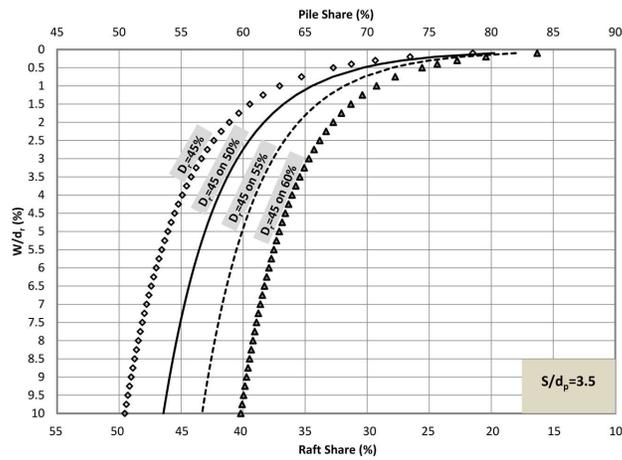


Figure 2-17 : Proposed empirical curves for estimating the load sharing of non-displacement piled raft in layered soil when the raft was founded on medium sand, and $S/d_p=3.5$ (after Vakili, 2015)

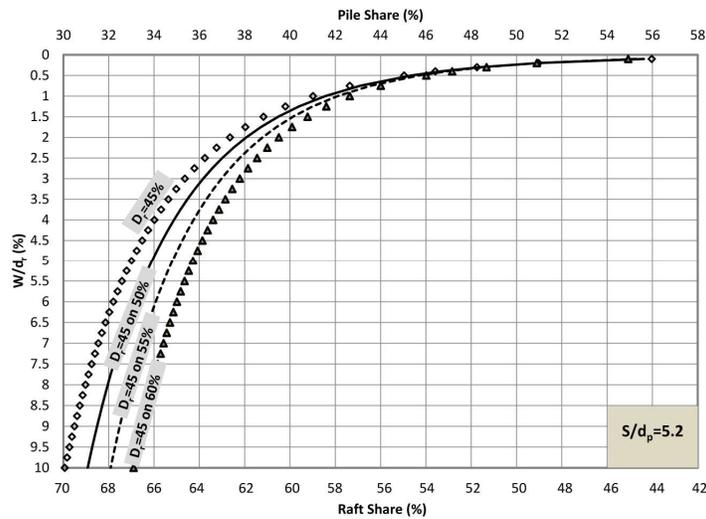


Figure 2-18 : Proposed curves for estimating the load sharing of non-displacement piled raft in layered soil when the raft was founded on medium sand, and $S/d_p=5.2$ (after Vakili, 2015)

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Park and Lee (2015) investigated the load responses and interaction effects of piled rafts embedded in sands. Several centrifuge load experiments were performed utilizing various model foundation types. In the tests, different types of piles, single piles, group piles, piled rafts, and unpiled rafts were used to examine the various interaction effects of piled rafts. They observed that for the early range of settlement, the load-settlement curves of piled rafts were comparable to those of group piles, and as settlement progressed, it became comparable to those of rafts. The interaction factors between pile groups, piles and rafts, and rafts and piles displayed state-dependent and nonlinear variations with settlement. Within the initial settlement range, the pile-to-raft and raft-to-pile interaction factors decreased, and with increasing settlement, it increased. The range of values for the raft-to-pile interaction factor was substantially smaller than the range for the pile-to-raft interaction factor. As opposed to single piles, piled rafts had different load responses and load transfer relationships, demonstrating that the effect of raft-to-pile interaction was more significant in the upper soil zone. They suggested that the mobilized factor of safety for rafts should always be greater than the safety factor for piles and piled rafts due to the lower mobilized load-carrying capability of rafts.

Elwakil et al. (2016) conducted an experimental and numerical study, employing PLAXIS 2D, to investigate the behaviour of a piled raft system. This research delves into the rationale behind using piles as settlement reducers for raft foundations, as well as the behaviour of piled rafts embedded in sand. Small-scale model tests were conducted, focusing on the effects of pile length and alignment on the ultimate load capacity attained.

The factor β is introduced and defined as

$$\beta = \frac{\text{piled raft load}}{\text{pile load} + \text{raft load}} = \frac{PR}{P + R} \quad (2-8)$$

Generally the ultimate capacity attained by piled raft models tested in this investigation had been expressed by the following equation:

$$Q_u = 0.036N + 0.7 \text{ for } 0.67 \leq L/B \leq 2.67 \quad (2-9)$$

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where, Q_u is the ultimate load carried by the piled raft in kN and N is the number of piles.

$$PR \geq P + R \text{ at } S/B = 0.7\% \quad (2-10)$$

where, PR =the piled raft load, P = the piles load, P , and R = raft load,

Following conclusions were highlighted in this study:

1. The load shared by the raft in piled raft foundation on sand was found around 39% of total load. The load shared by raft was increased as the length and number of the piles decreases.
2. The load carried by the piled raft is greater than the summation of the loads carried by the unpiled raft and the piles for each settlement ratio when S/B is less than or equal to 0.7%. It can be proposed to construct the piled raft at $S/B = 0.7\%$ for the optimal performance.
3. The maximum load achieved by the piled raft with 16 piles is 30% higher than the one with 4 piles.
4. Considering the size of settlements, the numerical model used in this study appears to operate in a very reasonable manner. This suggests that utilizing a plane strain model in PLAXIS 2D can save time compared to employing a more intricate three-dimensional model to obtain a preliminary result.
5. The finite element analysis improved comprehension of the piled raft soil system failure patterns. Additionally, it supported the findings of various researchers regarding the load transfer mechanism of an equivalent pier.

Jamil et al. (2023) carried out experimental and numerical studies on different small-scale models of piled raft foundations under vertical and lateral load. Small-scale models of the aluminum raft and galvanized iron (GI) hollow piles were tested under vertical and lateral loads in the experimental technique. For real-time load monitoring, vertical and lateral load cells were put on piles, while LVDTs were employed for displacement monitoring. PLAXIS 3D finite element software was employed in the numerical technique. A raft was classified as a plate element, and piles as embedded beams. Based on experimental and computational

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results, they discovered that vertical raft contact with soil had a direct link with lateral raft contribution. Because of the vertical load, a firm contact develops between the raft and the soil, resulting in a large lateral contribution. As a consequence, PLAXIS 3D was used to do a parametric analysis and it was discovered that vertical pressure was directly related to lateral raft resistance, whereas the other three parameters were inversely related. They found that as the number of piles increased from 1 to 13, the load shared by piles of piled raft foundation increased from 13% to 85% (Figure 2-19 and Figure 2-20).

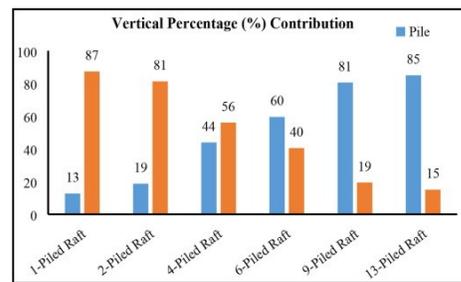
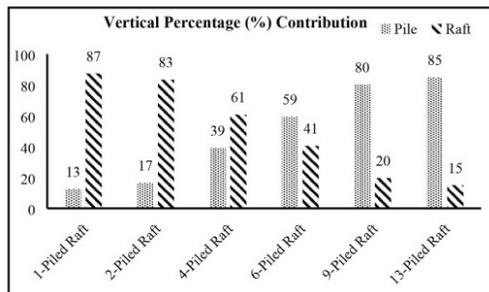


Figure 2-19 : Experimental results with $s/d = 6.67$ and $s/d = 3.33$ for 13 piled raft (after Jamil et. Al, 2023)

Figure 2-20 Numerical results with $s/d = 6.67$ and $s/d = 3.33$ for 13 piled raft (after Jamil et. Al, 2023)

2.3 Numerical/ Analytical Developments

For piled raft foundations, a number of analytical/numerical approaches have been put forth; some of these were compiled by Poulos and Davis (1980), Randolph (1983,1994), vanImpe and Clerq (1995), Burland (1995), Phung (2010), Lee et al. (2014), Alsanabani (2017), Garcia et al. (2019), and Bhartiya (2020). All analytical/numerical techniques could be divided into four groups:

- 1) Simplified analysis method: This makes a number of assumptions about how the soil profile should be modeled and how the raft should be loaded.
- 2) Approximate computer-based method: The approximate computer-based methods comprise the following broad approaches:
 - "Strip on springs" methods, where the piles are represented by appropriate stiffness springs and the raft is represented by a series of strip footings (e.g. Poulos, 1991);

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- Approaches based on the "plate on springs" principle, in which the piles are represented by springs and the raft by plates (e.g., Clancy and Randolph, 1993; Poulos, 1994; Viggiani, 1998; and Poulos and Georgiadis, 1998).

3) More rigorous computer-based method: The following are some of the most rigorous methods:

- Elastic theory is utilized to discretize the raft and the piles within the system using boundary element methods (e.g. Butterfield and Banerjee, 1971; Brown and Wiesner, 1975; Kuwabara, 1989; and Sinha, 1997).

- Techniques for the piles and the raft that combine boundary element and finite element analysis (Hain and Lee, 1978; Ta and Small, 1996; Franke et al., 1994; Russo and Viggiani, 1998)

- Simplified finite element analyses, which frequently entail modeling the foundation system as a plane strain problem (Desai, 1974) or an axi-symmetric problem (Hooper, 1974), as well as associated finite difference analyses utilizing the commercial software FLAC (e.g. Hewitt and Gue, 1994).

4) Accurate Numerical Method:

- Two-dimensional (2D) numerical analyses,
- Three-dimensional (3D) numerical analyses.

The simplified and numerical methods are discussed more below.

This makes a number of assumptions about how the soil profile should be modeled and how the raft should be loaded. Several simplified systems for analyzing piled raft foundations have been offered (e.g., Poulos and Davis 1980, Randolph 1994, Van Impe and Clercq 1995, and Borland 1995). Lee et al. (2014) provided a model for load-sharing determination that took into consideration the settlement-dependent variance in load-sharing behaviour more recently. Although this method is more advanced, the model's essential assumptions limit its

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applications. The Poulos-Davis-Randolph method, which is explained in the next section, is the most frequently accepted simplified method.

Simplified analysis method:

Poulos-Davis-Randolph (PDR) Method

The ultimate load capacity of a piled raft foundation can often be taken as the lesser of the following two values when analyzing vertical bearing capacity using simple approaches: (1) The total of the raft's ultimate capacities plus all of the piles, (2) The maximum capacity of a block containing the piles and the raft, plus the portion of the raft outside the piles' periphery.

There are different approaches for predicting stiffness, pile-raft interaction factors, settlement of a piled raft, and load sharing between the piles and raft component of a piled raft foundation.

Randolph (1983) presented a simplified approach for evaluating a piled raft foundation's load sharing. The approach was designed for a single piled raft unit with a floating pile coupled to a stiff circular cap and supported by an elastic semi-infinite mass. The stiffness of the piled raft evaluated using this method as follows:

The overall stiffness of piled raft system can be calculated as per **Clancy and Randolph (1993)** as below:

$$k_{pr} = \frac{(P_p + P_r)}{w_{pr}} = \frac{[k_p + k_r (1 - 2\alpha_{rp})]}{\left[1 - \left(\frac{k_r}{k_p}\right) \alpha_{rp}^2\right]} \quad (2-11)$$

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$$P_p = \frac{\left[1 - k_r \left(\frac{\alpha_{rp}}{k_p} \right) \right]}{\left(\frac{1}{k_p} \right) - k_r \left(\frac{\alpha_{rp}}{k_p} \right)} \frac{1}{2} w_{pr} \quad (2-12)$$

$$P_r = \frac{\left[\left(\frac{k_r}{k_p} \right) - k_r \left(\frac{\alpha_{rp}}{k_p} \right) \right]}{\left(\frac{1}{k_p} \right) - k_r \left(\frac{\alpha_{rp}}{k_p} \right)} \frac{1}{2} w_{pr} \quad (2-13)$$

where,

k_{pr} = overall stiffness of the piledraft system

P_p = Total load carried by pile group in combined foundation

P_r = total loadcarried by raft in combined foundation

k_p = overall stiffness of pile group in isolation

k_r = overall stiffness of raft in isolation

w_{pr} = overall piledraft settlement(for rigid raft $w_{pr} = w_p = w_r$)

α_{rp} = Interaction factor of pile group on raft

α_{pr} = interaction factor of raft on pile group

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k_p can be calculated using the relationship between number of piles and stiffness of single pile (initial tangent of load settlement curve of single pile) k_{p1} as mentioned by **Fleming et al. (1992)**

$$k_p = k_{p1} * (n)^{1-e} \quad (2-14)$$

where n represents the number of piles and the exponent ranges between 0.3 and 0.5 for friction piles.

The equation proposed by (Sales, 2000) can be used to express pile stiffness:

$$k_{p1} = \frac{P}{\delta} \quad (2-15)$$

where P is the load applied to the pile and δ is the displacement caused by the action of P on the pile's top.

In the absence of pile load test data, the pile is modeled as a series of linear elastic springs, while the resistances at the toe and shaft are modeled as nonlinear springs expressing soil deformation.

As per Randolph, stiffness factor for the system is defined by using equation (2-16)

$$\alpha_{rp} = 1 - \frac{\ln(n)}{\ln\left(\frac{2r_m}{d}\right)} \quad (2-16)$$

$$\alpha_{pr} = \alpha_{rp} \frac{k_r}{k_p} \quad (2-17)$$

where, n = ratio of the circular raft diameter to the pile diameter

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r_m = a measure of the radius of influence of the pile

$$r_m = 2.5[\rho L(1 - \nu_s)] \quad (2-18)$$

ρ = the degree of homogeneity of the soil

L = the pile length

ν_s = Poisson's ratio of the soil

For very slender piles, the pile length L is replaced by a limiting effective pile length L_e which may be calculated according to Fleming et al. (1992)

$$L_e = 1.5 d \sqrt{2(1 + \nu_s) \frac{E_p}{E_s}} \quad (2-19)$$

As per Clancy and Randolph (1993) the settlement of piled raft foundation can be calculated as below

$$\alpha_{rp} = \frac{k_p}{P_p} \left(w_{pr} - \frac{P_r}{k_r} \right) \quad (2-20)$$

$$\alpha_{pr} = \frac{k_r}{P_r} \left(w_{pr} - \frac{P_p}{k_p} \right) \quad (2-21)$$

Poulos (2001) discussed the design process for a piled raft, considering a three-stage process.

(a) A preliminary stage to determine whether utilizing a piled raft is feasible; and the necessary number of piles to meet design requirements.

(b) A second stage to determine the locations where piles are needed and their overall

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characteristics.

(c) A final comprehensive design step to determine the ideal number, placement, and configuration of the piles and to compute the loads and moments of the piles as well as the exact distributions of settlement, bending moment, and shear in the raft.

(a) Stage of preliminary design:

In the early stage, the performance of a raft foundation without piling must be evaluated. Conventional approaches can be used to estimate vertical and lateral bearing capacity, settlement, and differential settlement. If the raft alone supplies only a little part of the needed load capacity, the foundation will almost certainly need to be planned using the conventional methodology as a pile foundation. If, on the other hand, the raft alone has appropriate or nearly adequate load capacity but does not meet the settlement or differential settlement criteria, it may be feasible to consider the use of piles as settlement reducers or the 'creep piling' strategy.

The ultimate load capacity can often be taken as the lesser of two values when calculating vertical bearing capacity: (i) the total of the ultimate capacities of the raft plus all the piles; (ii) the ultimate capacity of a block including the piles and the raft, plus the section of the raft outside the piles' periphery.

A technique similar to that presented by Poulos and Davis (1980) can be used to estimate the load-settlement behaviour. However, a valuable addition to this method can be developed by employing Randolph's (1994) simple way of predicting the load sharing between the raft and the piles.

Randolph's definition of the pile problem is depicted in Figure 2-21. The stiffness of the piled raft foundation can be determined through his method as follows:

As per Poulos (2001) the stiffness of piled raft can be calculated as

$$k_{pr} = \frac{(P_p + P_r)}{w_{pr}} = \frac{[k_p + k_r (1 - \alpha_{cp})]}{[1 - k_r k_p \alpha_{cp}^2]} \quad (2-22)$$

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α_{cp} = The raft – pile interaction factor

$$\alpha_{cp} = 1 - \frac{\ln(r_c/r_0)}{\ln(r_m/r_0)} \quad (2-23)$$

where, r_c = Average radius of pile cap (corresponding to an area equal to the raft area divided by number of piles); r_0 = radius of pile;

$$r_m = 0.25 + \xi[2.5 * \rho L(1 - \nu_s) - 0.25]L \quad (2-24)$$

where,

$\xi = E_{sl}/E_{sb}$; $\rho = E_{sav}/E_{sl}$; ν_s = Poisson's ratio of soil; L = pile length; E_{sl} = soil Young's

modulus at level of pile tip; E_{sb} = soil Young's modulus of bearing stratum below pile tip; and E_{sav} = average soil Young's modulus along pile shaft. The raft stiffness k_r can be calculated using elastic theory, such as the solutions of Fraser and Wardle (1976) or Mayne and Poulos (1999). Elastic theory can also be used to estimate pile group stiffness, as detailed by Poulos & Davis (1980), Fleming et al. (1992), or Poulos (1989). In the latter situation, the single pile stiffness is calculated using elastic theory and then multiplied by a group stiffness efficiency factor determined roughly from elastic solutions.

As per **Poulos (2001)** the proportion of the total applied load carried by the raft is

$$X = \frac{P_r}{P_t} = \frac{[k_r(1 - \alpha_{cp})]}{k_p + k_r(1 - \alpha_{cp})} \quad (2-25)$$

where, P_r = load carried by the raft; P_t = total applied load.

The above equations can be used to develop a tri-linear load-settlement curve as shown in Figure 2-22. First, the stiffness of the piled raft can be computed from equation (2-22) for the number of piles being considered. This stiffness will remain operative until the pile capacity is fully mobilized. Making the simplifying assumption that the pile load mobilization

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occurred simultaneously, the total applied load, P_1 , at which the pile capacity is reached, is given by:

$$P_1 = \frac{P_{up}}{1 - X} \quad (2-26)$$

where, P_{up} = ultimate load capacity of the piles in the group; X = proportion of load carried by the raft (Equation (2-25)).

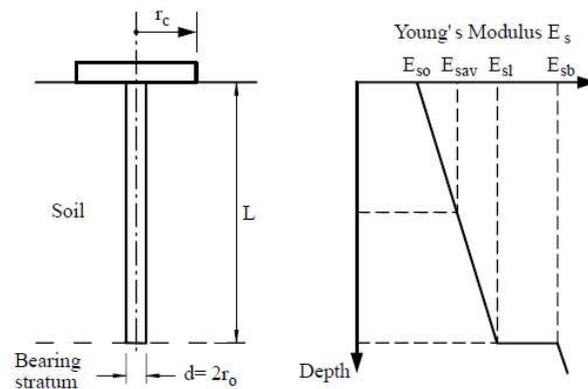


Figure 2-21: Simplified representation of a pile-raft unit (after Poulos, 2001)

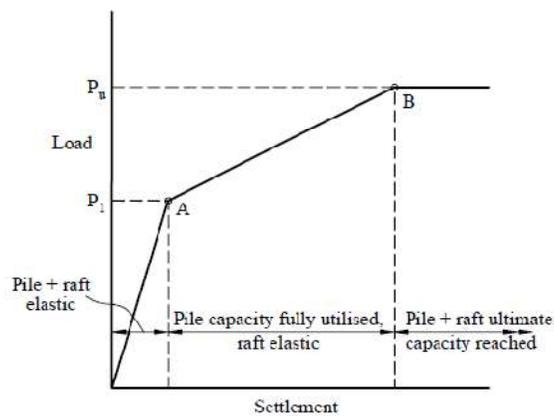


Figure 2-22 : Simplified load-settlement curve for preliminary analysis of piled raft foundation (after Poulos, 2001)

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Beyond that point (Point A in Figure 2-22), the stiffness of the foundation system is that of the raft alone (k_r), and this holds until the piled raft foundation system's ultimate load capacity is reached (Point B in Figure 2-22). The load-settlement relationship becomes horizontal at that point.

According to **Randolph (1994)**, and mentioned by **Garcia et al. (2019)** stiffness is the ratio between a particular load and the displacement it causes. Thus, up to point A of the Figure 2-22 graph, the settlement of a foundation can be given by:

$$w = \frac{P}{k_{pr}} \quad (2-27)$$

where: w is the settlement, k_{pr} is the stiffness of the piled raft foundation and P is the load applied on this foundation.

The stiffness factor for the system is defined by (Randolph, 1994):

$$k_{pr} = \frac{(P_p + P_r)}{w_{pr}} = \frac{[k_p + k_r (1 - 2\alpha_{rp})]}{\left[1 - \left(\frac{k_r}{k_p}\right) \alpha_{rp}^2\right]} \quad (2-28)$$

After point A, the settlement of this foundation can be written as follows:

$$w = \frac{P_1}{k_{pr}} + \frac{(P - P_1)}{k_r} \quad (2-29)$$

where, P is the load applied on this foundation, k_r is the stiffness of raft, P_1 is the load corresponding to point A (Figure 2-22)

The load settlement curves for a raft with varying pile numbers can be estimated using a computer spreadsheet or a mathematical program such as MATHCAD. The relationship between the number of piles and the average settlement of the foundation may thus be easily calculated. Figure 2-23 depicts the results of a typical set of calculations for both settlement and factor of safety in relation to vertical bearing capacity as a function of pile number. Such

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calculations provide a quick way to determine if creep piling or full pile capacity utilization design philosophies are likely to be practical.

(b) Second design stage: assessment of piling requirements

In the second design stage, assessing piling requirements becomes crucial. While preliminary phases often assume uniformly distributed loading over the raft surface, this oversimplification doesn't account for precise loading patterns, especially when column loadings are involved. To address this, a method is proposed for calculating the maximum column loadings that the raft can support in scenarios where no pile is situated beneath the column.

Figure 2-24 depicts a typical raft column. A pile beneath the column may be deemed necessary in at least four situations:

1. If the maximum moment in the raft below the column surpasses the allowable value for the raft.
2. If the maximum shear in the raft below the column exceeds the allowable value for the raft.
3. If the maximum contact pressure below the raft surpasses the allowable design value for the soil.
4. If the maximum local settlement below the column exceeds the allowable value.

The elastic solutions summarized by Selvadurai (1979) can be used to estimate the maximum moment, shear, contact pressure, and local settlement caused by column loading on the raft. These are for the ideal case of a single concentrated load on a semi-infinite elastic raft supported by a homogeneous elastic layer of great depth, but they do at least provide a rational basis for design.

1) Criteria for maximum moment:

The following approximations produce the maximum moments M_x and M_y below a column of radius c operating on a semi-infinite raft:

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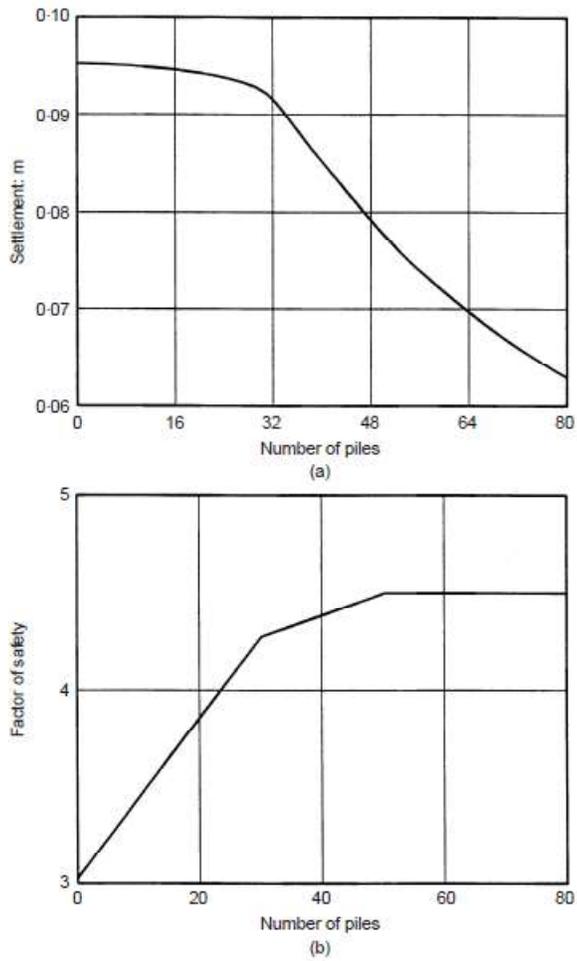


Figure 2-23 : Typical results from MATHCAD analysis: (a) settlement, (b) factor of safety plotted against number of piles (after Poulos, 2001)

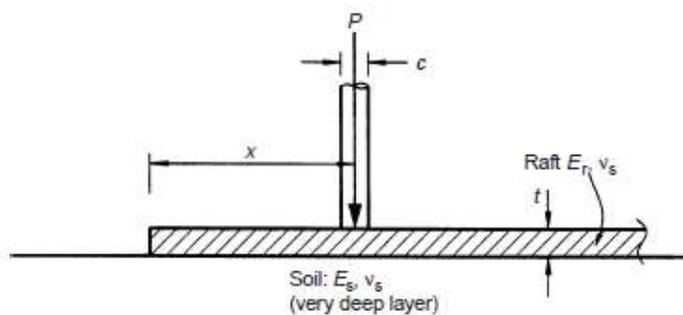


Figure 2-24: Definition of problem for an individual column load (after Poulos, 2001)

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$$M_x = A_x P \quad (2-30)$$

$$M_y = B_y P \quad (2-31)$$

where, $A_x = A - 0.0928 \ln(c/a)$; $B_y = B - 0.0928 \ln(c/a)$; $A, B =$ coefficients depending on x/a ; $x =$ distance of the column centre line from the raft edge; $a =$ characteristic length of raft $= t[E_r(1 - \nu_s^2)/6E_s(1 - \nu_r^2)]^{1/3}$; $t =$ raft thickness; $E_r =$ raft Young's modulus; $E_s =$ soil Young's modulus; $\nu_r =$ raft Poisson's ratio; and $\nu_s =$ soil Poisson's ratio. The coefficients A and B are plotted in Figure 2-25 as a function of the relative distance x/a

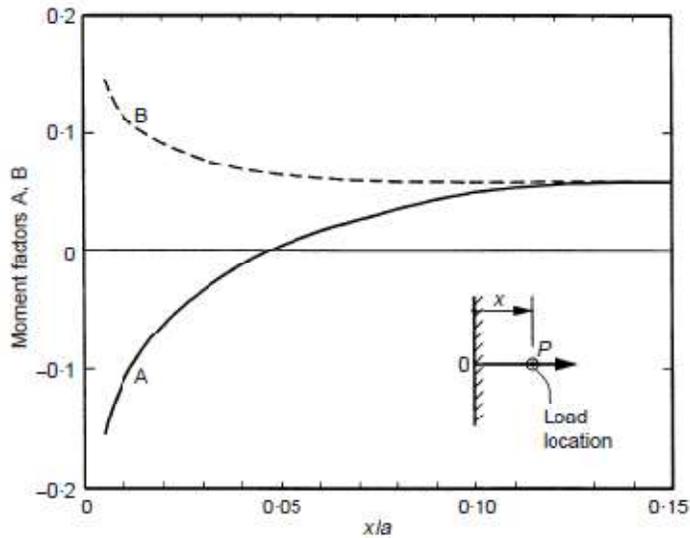


Figure 2-25 : Moment factors A, B for circular column (after Poulos, 2001)

The maximum column load P_{cl} that the raft can carry without exceeding the permissible moment is then given by

$$P_{cl} = \frac{M_d}{\text{larger of } A_x \text{ and } B_y} \quad (2-32)$$

Where, $M_d =$ Design moment capacity of raft

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2) Maximum shear criterion.

The maximum shear, V_{max} , beneath a column is given as

$$V_{max} = \frac{(P - q\pi c^2)c_q}{2\pi c} \quad (2-33)$$

Where, q = contact pressure below raft; c = column radius; and c_q = shear factor, plotted in Figure 2-26. As a result, if the raft's design shear capacity is V_d , the maximum column load, P_{c2} that can be applied to the raft is

$$P_{c2} = \frac{V_d 2\pi c}{c_q} + q_d \pi c^2 \quad (2-34)$$

Where, q_d = design allowable bearing pressure below raft.

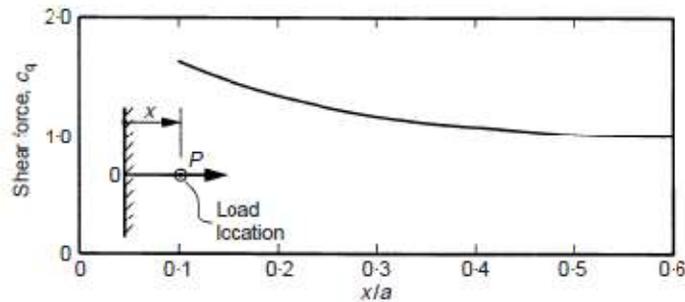


Figure 2-26 : Shear factor, c_q for circular column (after Poulos, 2001)

3) Maximum contact pressure criterion:

The maximum contact pressure at the raft's base q_{max} can be calculated as follows:

$$q_{max} = \frac{P \bar{q}}{a^2} \quad (2-35)$$

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Where, \bar{q} = factor is displayed in Figure 2-27 and a = characteristic length is defined in equation (2-30). P_{c3} , the maximum column load that can be applied without exceeding the allowed contact pressure, is then calculated.

$$P_{c3} = \frac{q_u a^2}{F_s \bar{q}} \quad (2-36)$$

Where, q_u is the ultimate bearing capacity of the soil beneath the raft and F_s is the factor of safety for contact pressure.

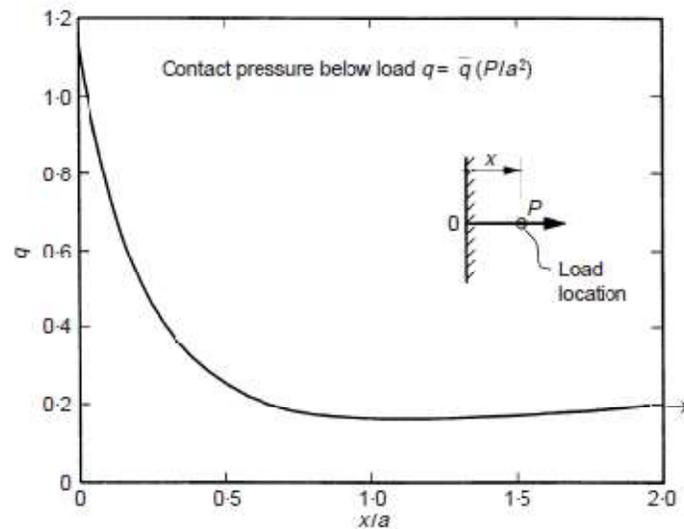


Figure 2-27 : Contact pressure factor, q (after Poulos, 2001)

4) Local settlement criterion

The settlement beneath a column (as a concentrated load) is given by

$$S = \frac{\omega(1 - \nu_s^2)P}{E_s a} \quad (2-37)$$

where, where ω = settlement factor is shown in Figure 2-28. This expression does not account for the impacts of adjacent columns on the settlement of the column under

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consideration, nor does it account for a local settlement superimposed on a more general settlement 'bowl.'

If the permitted local settlement is S_a , then the maximum column load P_{c4} that should not be exceeded is

$$P_{c4} = \frac{E_s S_a a}{\omega(1 - \nu_s^2)} \quad (2-38)$$

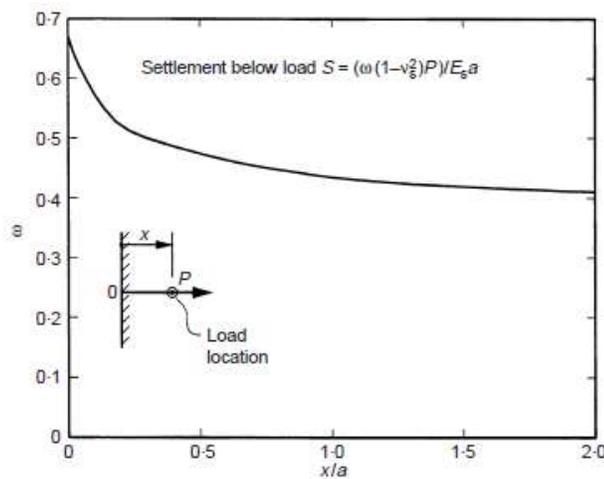


Figure 2-28 : Settlement factor, ω (soil assumed to be homogeneous and very deep) (after Poulos, 2001)

Assessment of pile requirements for a column location: If the actual design column load at a given point is P_c , a pile will be required if P_c exceeds the least of the four criteria listed above. That is, assuming

$$P_c > P_{crit} \quad (2-39)$$

where, P_{crit} is minimum of P_{c1} , P_{c2} , P_{c3} or P_{c4}

If the critical criterion is maximum moment, shear, or contact pressure (i.e. P_{crit} is P_{c1} , P_{c2} or P_{c3}), the pile should be constructed to meet the deficiency in load capacity. According to

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Burland (1995), only around 90% of the final pile load capacity should be considered mobilized beneath a piled raft system. On this basis, the ultimate pile load capacity, P_{ud} at the column site is calculated as follows:

$$P_{ud} = 1.11 F_p (P_c - P_{crit}) \quad (2-40)$$

where, F_p is the pile safety factor. While designing piles as settlement reducers, F_p can be assumed to be unity. If local settlement is the important criterion, the pile should be constructed to give adequate extra stiffness. The target stiffness, K_{cd} , of the foundation below the column is determined at a maximum local settlement of S_a .

$$K_{cd} = \frac{P_c}{S_a} \quad (2-41)$$

Using equation (2-22) as a first approximation, the required pile stiffness, k_p to attain this goal stiffness can be determined by solving the following quadratic equation:

$$k_p^2 + k_p [k_r (1 - 2\alpha_{cp}) - k_{cd}] + \alpha_{cp}^2 k_r k_{cd} = 0 \quad (2-42)$$

where, α_{cp} is the raftpile interaction factor and k_r is the raft stiffness around the column. The raft stiffness k_r can be determined as the stiffness of a circular foundation with a radius equal to the characteristic length, a (assuming that this does not result in a total raft area that exceeds the actual area of the raft).

(c) Detailed design stage:

Once the preliminary stage has determined that a piled raft foundation is feasible and an indication of the likely piling requirements has been obtained, a more detailed design is required to assess the detailed distribution of settlement and decide on the optimum locations and arrangement of the piles. The raft bending moments and shears, as well as the pile loads, should be obtained for the foundation's structural design.