BEHAVIOR AND DESIGN OF PILED RAFT FOUNDATIONS UNDER DYNAMIC AND STATIC LOADING

by
Şafak Söylemez
B.S., Civil Engineering, Dokuz Eylül University, 2012

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Civil Engineering
Boğaziçi University
2015

To my Mother

ACKNOWLEDGEMENTS

No work of this magnitude can be accomplished without the assistance of so many great individuals. First and foremost, I would like to express my deepest gratitude to my thesis advisor Prof. Erol Güler. I would like to thank him for his invaluable guidance, support and patience for my endless questions related to deep foundations and soil dynamics. His expertise in piled raft foundations and enthusiasm to soil dynamics improved my research and prepared me for its challenges. He is an outstanding professor, teacher, researcher and true embodiment of a mentor. I am privileged to have had the opportunity to work with and learn from him.

Thank you Harry Poulos, Ellen Rathje, Gürkan Özden, Özer Çinicioglu, Ayse Edinçliler, for your courses, interactions and inspirations during this study. Thank you for introducing me to the excitement of research. I also thank to Civil Engineering Department of the University of Texas at Austin. Thank you for teaching me new approaches to thought. My experience at Texas has been wonderful, and provided me with excellent memories for my educational and social life.

I would also like to specially thank my father and brother who reminded me often times that there is a life outside the university. Both of them have made me a better person, and for this, I am eternally grateful. My sincere thanks and deepest appreciation are extended to my friends and colleagues for their sincere and continuous support, understanding but more importantly their invaluable friendship since I met them.

Last but not least, my special and greatest gratitude goes to my mother, Aysel Söylemez. Thank you for your endless support, motivation, encouragement, love and patience throughout my life. This study would have been very difficult without you and I would like to dedicate this thesis to you.

ABSTRACT

BEHAVIOR AND DESIGN OF PILED RAFT FOUNDATIONS UNDER DYNAMIC AND STATIC LOADING

In the scope of this thesis, piled raft foundation systems wereanalyzed for both static and dynamic cases. The effect of end bearing and shaft friction piles and also the effect of pile lengths were evaluated for both piled and conventional raft foundations. Usually, neglecting the contribution of the raft, pile foundations are designed with an assumption that piles are resisted all loads. However, it is obvious that raft is a part of foundation system and if there is a contact between raft and soil, raft carries some proportion of structural loads. Regarding this contribution, it can be lead considerably economy. In this study, static and dynamic behavior and their design criteria of piled raft foundation is evaluated. Two different simplified approaches which are developed by Poulos and Randolph were used forall hand calculations. Microsoft Excel for numerical analyses and Plaxis 2D 2015 AE commercial software for FEM analyses were used. Both numerical analyses and finite elements analyses were conducted for all static models. In addition to static analyses, by using previous earthquake accelerations, three time history analyses were performed for both conventional and piled raft foundations and their results were compared. The material parameters used in the analysis are selected by personal experience and the analysis method and load levels were obtained from the reference studies. An undrained - drained material models were employed in the short and long term analysis of this study inmodeling the soil to analyze clay behavior for piled raft foundations that designed with both floating and end bearing piles. Within this thesis, the researchers basicly focused on the short term behavior. The behavior of the piled raft foundation systems, deflections and internal forces of the foundation members, elastic displacements of piles etc. were evaluated.

ÖZET

KAZIKLI RADYE TEMELLERIN DINAMIK VE STATIK YÜKLER ALTINDAKI DAVRANISI VE TASARIMI

Bu çalisma kapsaminda, kazikli radye temeller statik ve dinamik durum için analiz edilmistir. Geleneksel ve kazikli radye temel sistemi için sürtünme ve uç kazigi olan kaziklarin kullanilmasi durumuve kazik uzunlugunun etkisi irdelenmistir. Genellikle, kazikli temeller radyenin etkisi ihmal edilerek, bütün yüklerin kaziklar tarafindan tasindigi varsayimi ile projelendirilir. Bununla birlikte, radye de temel sisteminin bir parçasidir ve radye ve zemin arasinda temas var ise radyenin de yüklerin bir kisminin tasinmasina katkida bulundugu asikârdir. Bu katkiyi dikkate almak önemli miktarda ekonomi saglayabilmektedir. Bu çalismada, kazikli radye temellerin statik ve sismik davranisi ile tasarim kriterleri degerlendirilmistir. Poulos ve Randolph tarafindan önerilen iki farkli yaklasim el hesabi yapilirken kullanilmistir. Nümerik analizler için Microsoft Excel Programi, sonlu elemanlar yöntemi kullanilarak yapilan analizler için ise Plaxis 2D 2012 AE kullanilmistir. Statik durum için yapilan bütün analizler nümerik hesap yöntemleri ve sonlu elemanlar metodu kullanilarak gerçeklestirilmistir. Statik analizlere ek olarak, üç tane geçmis yillardaki deprem ivmesi kullanilarak zaman tanim alaninda hesap yapilmis ve sonuçlar karsilastirilmistir. Analizlerde kullanilan malzeme parametreleri tecrübeye dayanarak seçilmis, analiz metodu ve yük seviyesi referans çalismalardan elde edilmistir. Kil zemini temsil etmek için hem yüzen kaziklarla hemde uç kaziklari ile tasarlanan kazikli radye temellerde drenajsiz ve drenajli malzeme modelleri kullanilmistir.Kisa dönem analizlerine odaklanan bu tez kapsaminda, kazikli radye temellerin davranisi, temel sisteminin deplasmanlari ve iç kuvvetleri, kaziklarin elastik deplasmanlari vs. degerlendirilmistir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

A	Base area of the raft
a	Characteristic length of the raft
A_{bp}	Pile tip area
A_m	Coefficient to estimate maximum moment
A_p	Cross-sectional area of the pile
A_{sp}	Pile shaft area
B	Average pile diameter
B_m	Coefficient to estimate maximum moment
C	Bearing capacity factors
c	Radius of circular column
C_q	Shear Factor
CR	Conventional Raft
C_u	Undrained shear strength of the soil
d	Actual embedded depth of the
D_f	Depth of the raft
E	Young's modulus
E_p	Young's modulus of pile concrete
E_s	Young's modulus of soil
E_{sav}	Average soil Young's modulus along pile shaft
E_{sb}	Soil Young's modulus of bearing stratum below pile tip
E_{sl}	Soil Young's modulus at level of pile tip
F_c	Bearing capacity factors
F_D	Embedment correction factor for raft settlement
FEM	Finite elements method
Fs	Factor of safety
f_{sc}	Pile shaft friction in compression
G	Shear modulus
G_1	Soil modulus at the level of pile base
G_b	Soil shear modulus below the level of pile base

$G_{l/2}$	Soil shear modulus at the l/2 level
h_i	Thickness of the i'th soil layer
i	Number of the soil layer
I_p	Influence factor
K_{cd}	Target stiffness for an allowable settlement
k_p	Axial stiffness of the single pile
K_{pg}	Stiffness of the pile group
K_{pr}	Stiffness of piled raft
Kr	Stiffness of the raft alone
L	Length of the piles
L_r	Length of the raft
Md	Design moment capacity of the raft foundation
N	Number of piles
N_c	Bearing capacity factors
P	Concentrated load
P_{av}	Stress distribution
PR	Piled Raft
P_t	Total load
P_{up}	Ultimate load capacity of the piles in the group
q	Contact Pressure of the Raft
Q_{ac}	Allowable bearing capacity of the Single Pile
q_c	Pile end bearing capacity
q_d	Allowable bearing pressure below the raft
$Q_{G,ult}$	Ultimate bearing capacity of the pile group
$Q_{PR,ult}$	Ultimate bearing capacity of piled raft
q_u	Ultimate bearing capacity of soil below the raft foundation
Q_{uc}	Ultimate bearing capacity of the Single Pile
$Q_{ult,raft}$	Ultimate bearing capacity of the Raft Alone
R	Radius of the pile
r_0	Radius of pile
r_b	Radius of pile base

r_m	The distance that the shear stress becomes negligible(maximum radius)
s	Spacing of the piles
S_a	Allowable local settlement
$Sc.$	Seconds
Spr	Settlement of piled raft
Sr	Settlement of raft alone which carries total applied loading
t	Thickness
V_d	Design shear capacity of the raft
w	Settlement factor
wt	Pile head settlement
X	Proportion of the load carried by the raft
I_ϵ	Influence factor for vertical strain
η	Efficiency factor
υ	Poisson's ratio
α_{cp}	Raft - pile interaction factor
α_G	Coefficients for the pile group for Viggiani - Mandolini Method
α_{UR}	Coefficients for the raft for Viggiani - Mandolini Method
β_{PR}	Coefficient defined in Viggiani - Mandolini Method
β_z	Axial stiffness correction factor for embedded rafts
δ	Distance of the column center line from the raft edge
ζ_{PR}	Coefficient defined in Viggiani - Mandolini Method
λ_{cd}	Depth factor for Meyerhof method
λ_{cs}	Shape factor for Meyerhof method
λ_{qd}	Depth factor for Meyerhof method
λ_{qs}	Shape factor for Meyerhof method
$\lambda_{\gamma d}$	Depth factor for Meyerhof method
$\lambda_{\gamma s}$	Shape factor for Meyerhof method

LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional

1. INTRODUCTION

Introduction chapter of the thesis includes literature survey of the research, design issues, advantages of piled raft foundation system, previous studies about piled rafts andfavorable and unfavorable situations for piled rafts.

1.1. Background of the Research

In common practice, if a shallow or raft foundation is not adequate to carry design loads, for conventional methods, pile groups are designed by which all structural loads are resisted by only piles. However, it is obvious that raft is a part of foundation systems. If there is a contact between raft and soil, structural loads are resisted with both piles and rafts. Regarding this contribution, it can be lead considerable economy for pile construction.

In some cases, a foundation system could be adequate to carry structural loads but differential or total settlements could exceed allowable limits. In general, piles with raft foundation are used as a member that reduces settlements. (Broms, 1976; Burland *et al.*, 1977) Such a foundation systems are called piled raft foundations or pile enhanced rafts that provide cost effective solution than conventional piled foundations. For most piled raft foundation systems, piles are used to reduce settlements. The carried proportion of the superstructure load by the raft is generally secondary issue. Over the past decades, many study have been conducted to improve design accuracy and to simplify design of piled raft foundation systems.

Many examples of effective use of piled rafts have been published. (Sommer *et al.*, 1985; Price and Wardle, 1986; Franke 1991, Harry Poulos and JC Small 2011 etc) As noted by Franke (1991) the failure mode of a large pile groups are significantly different from a single pile. As opposite of single pile, the interaction effect causes different slip mechanism that begins from the base and continue to upwards. If there is a contact between raft and soil, slip do not occur at shallow depths.

A piled raft foundation system combines the capacity of both raft and pile members and design and analysis of such a foundation system requires take into consideration four different interactions.

(i) Pile-Soil Interaction
(ii) Pile-Pile Interaction
(iii) Raft-Soil Interaction
(iv) Pile Raft Interaction

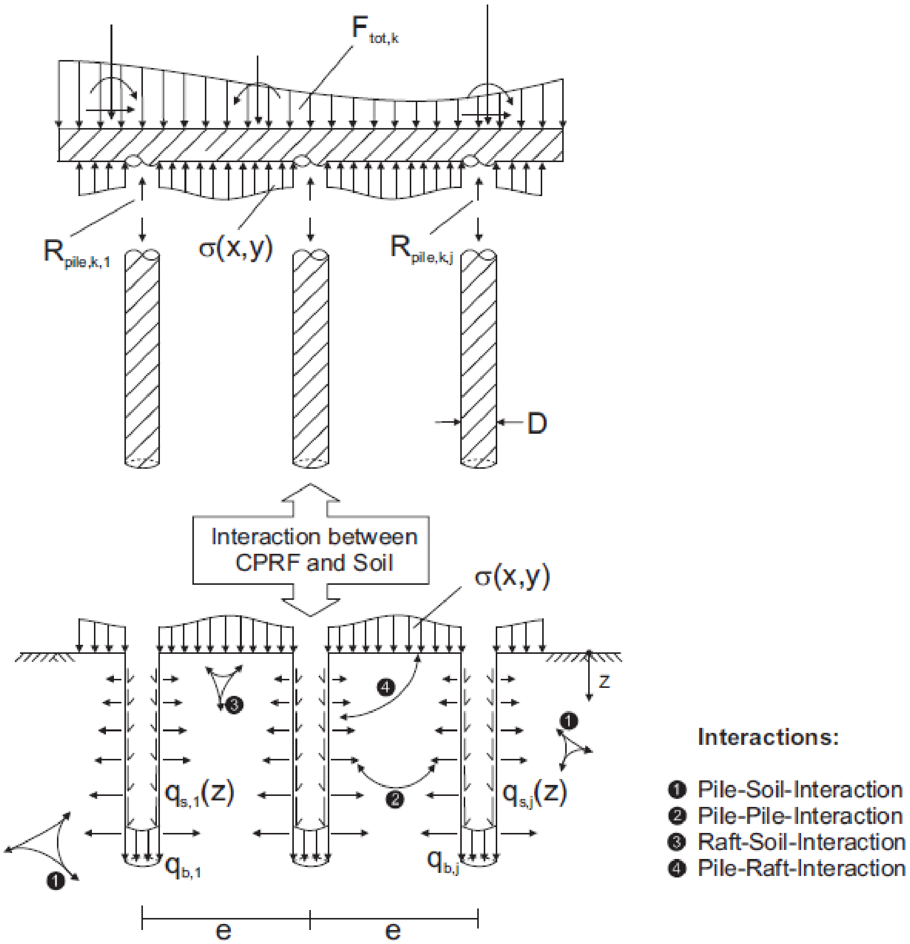

Figure 1.1. Interactions of Piled Raft Foundation.

1.2. Design Issues

Following issues usually need to consider in the design of piled raft foundation system.

(i) Ultimate capacity of the system under combination of lateral, vertical and moment loading conditions.
(ii) The impact of dynamic effect of earthquakes, wave loadings etc. on the foundation system capacity and movements.
(iii) Overall and differential settlements with the effects entirely.
(iv) Structural design of the system, including distribution of loads between raft-pile and pile-pile.
(v) Possible hazards of environmental effects.
(vi) Earthquake effects for the structural and foundation system and the possibility of liquefaction in the soil that surrounding or supporting the foundation.
(vii) Dynamic response of both foundation and structural system to blasting, wind forces etc.

Analyzing a piled raft foundation, designer must consider any other potential risk that is not included above. According to some approaches, designer can use a single factor of safety to decide the number of piles that can resist lateral and vertical loads coming from loading combinations.

1.3. Advantages of Piled Raft Foundation System

Piled rafts contribute to load carrying capacity and these types of foundations keep settlements at an acceptable level. Consequently, a piled raft foundation system reduces the number of piles. Additionally, rafts may provide abundance. In other words, if piles are located in a karstic soil, one or more pile integrity could be damaged and these types of damages could compensate by raft. Under such circumstances, raft allows redistribution of loads and it reduces the effect of pile weakness.

Another advantage of rafts is due to pressure that transmit from itself lateral pressure increases and load carrying capacity of piles located beneath raft is higher than open-end piles (Katzenbach *et al.*, 1998). Piled raft foundation system is a suitable solution especially for tall buildings because it provides both stiffness and additional bearing capacity (Poulos, 2011).

One of the major benefits of raft directly on the ground is block type of failure. Geotechnical design of such a foundation system requires not only evaluation of ultimate bearing capacity of pile and raft but also evaluation of their combined capacity with interaction effect.

1.4. Previous Studies for Piled Rafts

Recently, researchers suggest that for piled raft design, the priority should give to serviceability condition. The term, serviceability, means that calculated differential and total settlement values are acceptable.

This new approach is included in Eurocode as a “piles are settlement reducer elements for rafts”. In Eurocode Part 7 “the provisions of this Section, should not be applied directly to the design of piles that are intended as settlement reduces, such as in some piled raft foundations”. Even if designer is not referred any specific approach but the Eurocode indicates other design methods. International Society of Soil Mechanics and Engineering have been preparing a methodology to design piled raft foundations.

According to Mandolini’s opinion (1998) that intends to satisfy serviceability condition,

- Usually, increasing the number of piles is useful but there is an upper limit for number of piles and after this point, further increase is useless. Increasing number of piles does not always bring together an optimum solution and conventional design approach results beyond this point.
- To limit average settlements for small and medium rafts, it is a practicable way is to use piles that L, length, larger than B, raft widths. On the other hand, this approach slightly reduces average settlements for large rafts. ($B_r > 15$m)
- Relatively small number of piles with a suitable location gives optimum solution rather than uniformly distributed large number of piles or thicker rafts. Suitable location depends on distribution of loads.
- Bending moments and differential settlements are affected by raft thickness but

there is no effect of raft thickness on average settlements and percentages of load carried by raft and piles.

A number of analyses have been conducted by Poulos (2001) to assess the effect of the number of piles, the nature of loading, raft thickness, applied load level. Many important results obtained by Poulos from the analyses such as:

(i) The amount of maximum settlement reduces with pile number but there is a limit for reduction. Over a certain number of piles the amount of settlement almost constant. Likewise, ultimate bearing capacity of foundation system increases with pile number up to a limit.
(ii) Difference between the amount of settlement at the corner and edge does not affected from the number of piles on a regular basis. By concentrating the piles at the middle of raft foundation, smallest differential settlement can be obtained.
(iii) The amount of maximum settlement and ultimate bearing capacity of foundation is not controlled sensitively by raft thickness.
(iv) Increasing raft thickness causes higher bending moments and lower maximum settlement.

Additionally, the same opinion shared by both Mandolini and Poulos that the key successful prediction is more the ability to choose appropriate geotechnical parameters rather than the details of the analysis employed. The importance of selection of suitable geotechnical parameters for design cannot be denied.

1.5. Favorable and Unfavorable Situations for Piled Rafts

If a raft foundation has adequate bearing capacity but total or differential settlements exceed allowable limits, piled rafts can be used effectively. Soil profiles consisting relatively stiff and dense clayey soils and soil profiles there is no soft stratum within the depth of foundation are favorable for piled raft foundation system. Under these circumstances, raft provides a large portion of stiffness and load bearing capacity.

Conversely, soil profiles consisting soft clays and loose sands near the surface, soft compressible layers at shallow depths and soil stratum that has swelling potential are unfavorable conditions for this foundation system.

Many research have been conducted to understand the behavior of piled rafts and developed a number of methods. Poulos, Small, Ta, Shinha & Chen (1997) identified three broad classes of analysis method:

Taking everything into consideration, if soil layer underneath the raft is weak therefore raft cannot resist most of the structural loads; conventional approaches should be used to design such a foundation system. According to Katzenbach and Moorman (2001) if $E1/E2 \leq 1/10$ for layered soils and inorganic soils, fills and soft soils are not suitable to piled raft foundations.

2. CLASSIFICATION OF METHODS OF ANALYSIS

2.1. Simplified Calculation Methods

There are four simplified analysis methods to evaluate the efficiency of the piled rafts. Moreover, these methods are effectively used to analyze traditional piled foundations.

2.1.1. Poulos Method

Three staged design procedures are recommended by Poulos which can be conducted by hand calculations at preliminary stage and more detailed analyses with computer. According to the Poulos (1980-2001), there are three main stages to design piled rafts,

(i) Preliminary design stage for assessment of feasibility of piled rafts and required number of piles for structural and geotechnical requirements.
(ii) Second stage to assess pile locations and general characteristics of piles.
(iii) A detailed main stage optimization of location, number, quantity of piles and detailed analyses for settlements, bending moment distribution and pile loads and moments.

Usually, preliminary design and second stages could be conducted by hand calculation but detailed third stage requires a computer calculation to consider soil-raft, pile-soil, pile-pile, pile-raft interaction effects.

2.1.1.1. Preliminary Design Stage. At the preliminary design stage, firstly, vertical bearing capacity of the raft is calculated. If only the raft can resist a small portion of the structural loads, the foundation should be designed with conventional methods. However, if raft can carry most of the structural loads, piled raft foundation system could be suitable for this structure.

Evaluating the piled raft system, vertical load carrying capacity should be determined. After this evaluation a trial and error method should be used to optimize such a foundation system and the load that share between the raft and the piles.

Ultimate bearing capacity of a piled raft foundation should be selected as lesser between these two

- The sum of ultimate bearing capacities of the raft and piles
- The ultimate bearing capacity of a block and the raft, plus the section of the raft outside the periphery of the piles.

To estimate settlement behavior and the load sharing mechanism of the piled rafts a method is described by Poulos & Davis (1980). Additionally, the method developed by Randolph (1994) was adapted by Poulos to the design procedure.

The definition of the problem that handled by Poulos is illustrated below.

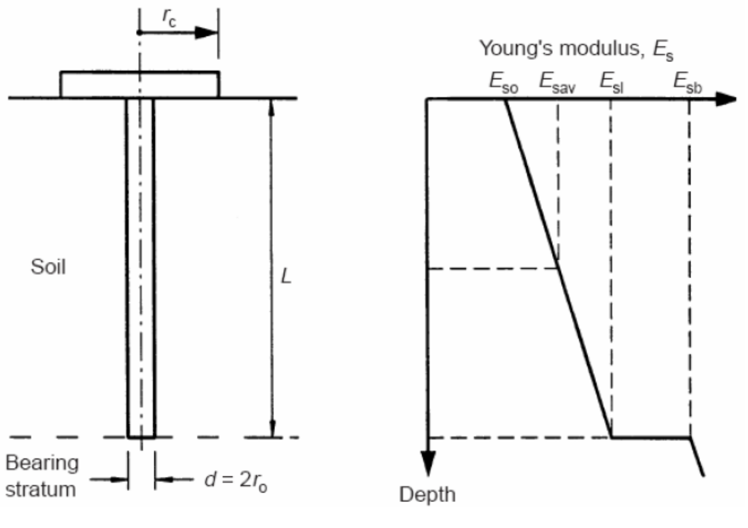

Figure 2.1. Poulos Piled Raft Foundation Definition.

Figure Definition of the problem, the stiffness of the foundation system (Randolph

(1994).

$$K\text{pr} = \frac{Kp + Kr * (1 - \alpha_{cp})}{1 - {\alpha_{cp}}^2 * Kr/Kp} \tag{2.1}$$

where is the K_{pr} stiffness of piled raft, is the K_p stiffness of the pile group, is the K_r stiffness of the raft alone, is the α_{cp} raft - pile interaction factor.

K$_p$ and K$_r$ can be estimated via elastic theory. To estimate K$_r$, solutions of Fraser & Wardle (1976) or Mayne & Poulos (1999) may be used. Similarly, solutions of Poulos & Davis (1980), Fleming *et al.*, (1992) or Poulos (1989) may be used to estimate the K$_p$. The carried proportion of the load by raft is

$$\frac{P_r}{P_t} = \frac{Kr * (1 - \alpha_{cp})}{Kp + Kr * (1 - \alpha_{cp})} \tag{2.2}$$

where is the P_r load carried by the raft, is the P_t total applied load, is the The raft - pile interaction factor, α_{cp}, can be estimated as follows.

$$\alpha_{\text{cp}} = 1 - \frac{\ln\left(\frac{r_c}{r_0}\right)}{\xi} \tag{2.3}$$

where is the r_c average radius of the pile cap (corresponding to an area equal to the raftarea divided by number of piles), is the r_o radius of pile.

$$\zeta = In(r_m/r_0) \tag{2.4}$$

$$r_m = 0.25 + \zeta[2.5p(1 - \upsilon) - 0.25] * L \tag{2.5}$$

$$\zeta = E_{sl}/E_{sb} \tag{2.6}$$

$$pX = E_{sav}/E_{sl} \tag{2.7}$$

where is the v Poisson's ratio of soil, is the L Length of the piles, is the E_{sl} soil Young's modulus at level of pile tip, is the E_{sb} soil Young's modulus of bearing stratum below pile tip, is the E_{sav} average soil Young's modulus along pile shaft.

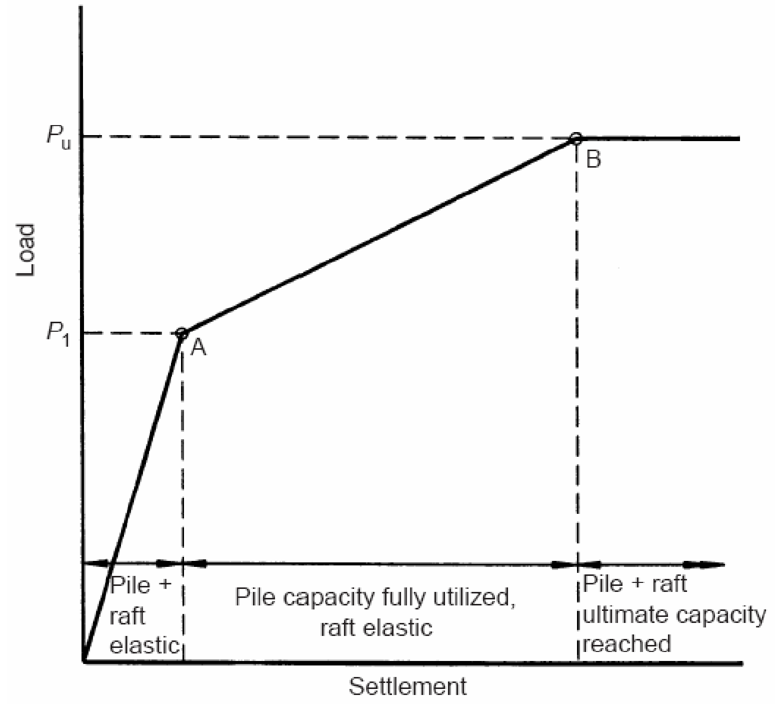

Figure 2.2. Simplified Load - Settlement Curve for Preliminary Analysis.

It can be seen that from the Figure, beyond point A the stiffness of the system is equal to raft alone and the capacity of the raft is used entirely.

The tri-linear load-settlement curve can be obtained by using the equations above. Firstly the stiffness of the piled raft foundation is calculated. To simplify the assumption that the pile capacity mobilization is occurs simultaneously, P1, the total applied load at which the pile can resist can be obtained by:

$$P = \frac{P_{up}}{1 - X} \tag{2.8}$$

where is the P_{up} ultimate load capacity of the piles in the group, is the X proportion of the load carried by the raft.

2.1.1.2. Second Stage of Design. Many methods on the literature consider a uniform load distribution on the raft. This is an acceptable assumption for preliminary design stage but it is not adequate for detailed design stage. For an economical solution, piles should be concentrated according to column loading.

The model study for this methodology is presented in Figure 2.3.

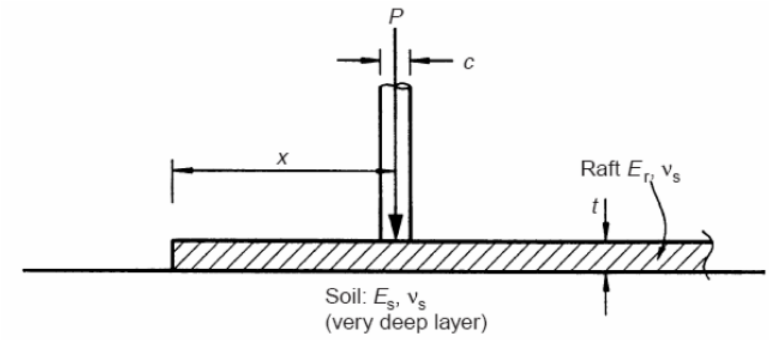

Figure 2.3. Definition of the Problem for an Individual Column Load.

where is the c radius of circular column, is the P concentrated load, is the t thickness, is the E_r young's modulus, is the υ Poisson's ratio, is the E_s young's modulus (for greater depth), is the υ_s Poisson's ratio(for greater depth).

There are four circumstances in which piles should be added below a column:

- The maximum moment below the column exceeds the allowable value for the raft foundation
- The maximum shear force below the column exceeds the allowable value for the raft foundation
- The maximum contact pressure below the raft exceeds the allowable bearing capacity of the soil
- If the amount of local settlement below the column exceeds the allowable value

2.1.1.3. Maximum Moment criteria. The maximum moments Mx and My below a column that can be seen at the model are:

$$M_x = A_x * P \tag{2.9}$$

$$M_y = A_y * P \tag{2.10}$$

$$Ax = A_m - 0.0928(c/a) \tag{2.11}$$

$$By = B_m - 0.0928(c/a) \tag{2.12}$$

where is the A_m, B_m coefficients depending on δ/a, is the δ distance of the column center line from the raft edge.

$$a = t * \left[E_r \left(1 - {\upsilon_s}^2\right) / 6E_s \left(1 - {\upsilon_s}^2\right)\right]^{1/3} \tag{2.13}$$

The coefficients A and B are plotted in figure below:

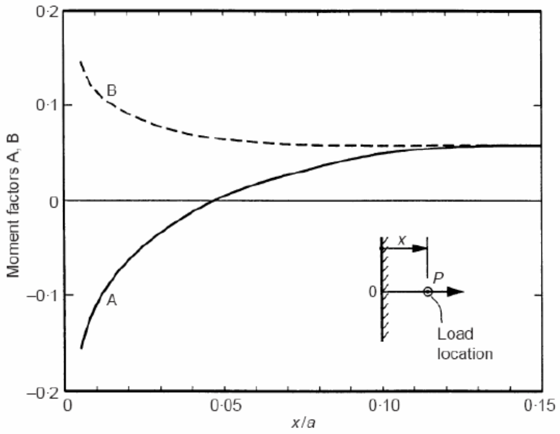

Figure 2.4. Moment Factors A, B for Circular Column.

The Maximum allowable Column Load, Pc1, can be obtained by using the formula given below where is the P_{c1} = Md / larger of Ax and By, is the Md: Design Moment Capacity of the Raft Foundation.

2.1.1.4. Maximum shear criteria. The maximum shear force below a column is:

$$Vmax = \frac{(P - q\pi c^2)\, c_q}{2\pi c} \tag{2.14}$$

where is the q Contact Pressure of the Raft, is the C_q Shear Factor (Given Figure Below).

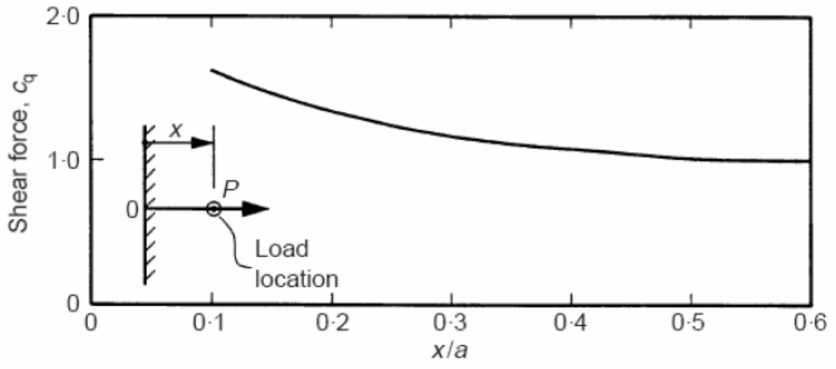

Figure 2.5. Shear Factor, C$_q$.

The maximum allowable columns shear force, Pc2, for raft foundation

$$P_{c2} = \frac{V_d 2\pi c}{C_q} + q_d \pi c^2 \tag{2.15}$$

where is the V_d Design shear capacity of the raft, is the q_d Allowable bearing pressure below the raft.

2.1.1.5. Maximum contact pressure criteria. The maximum contact pressure on the base of the raft is

$$q_{max} = \frac{\bar{q} * P}{a^2} \tag{2.16}$$

where is the q Load factor (from the Figure given below).

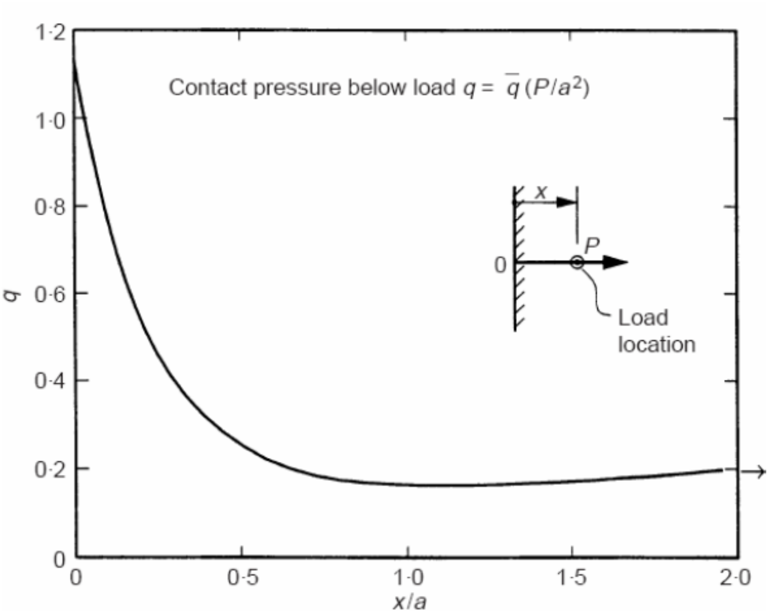

Figure 2.6. Contact Pressure Below Load q.

The maximum allowable shear force, P_{c3}, can be obtained with

$$P_{c3} = \frac{q_u * a^2}{Fs * \bar{q}} \tag{2.17}$$

where is the q_u Ultimate bearing capacity of soil below the raft foundation, is the F_s Factor of safety.

2.1.1.6. Local Settlement criteria. The amount of the settlement below such a column is

$$S = \frac{w\,(1 - {\upsilon_s}^2)\,P}{Es * a} \tag{2.18}$$

where is the w Settlement factor (given figure below).

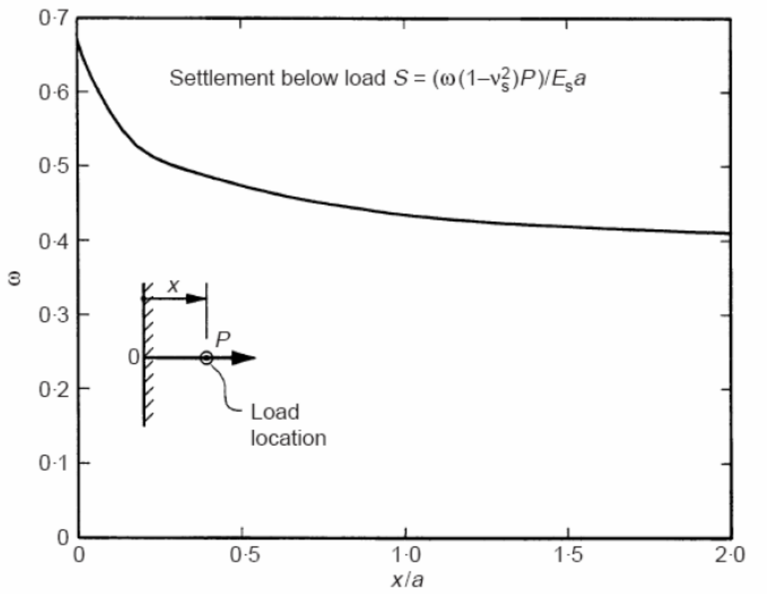

Figure 2.7. Settlement Factor, (Poulos, 2001).

The maximum allowable column load for local settlement, Pc4, can be obtained as

$$P_{c4} = \frac{S_a * E_s * a}{w\left(1 - {V_s}^2\right)} \tag{2.19}$$

where is the S_a Allowable local settlement.

2.1.1.7. Pile requirements for a column location. If P_{crit} value is lower than allowable column load P_c, which is minimum of P_{c1}, P_{c2}, P_{c3} and P_{c4} values, additional piles are required below a column location.

The piles are to be added to provide additional bearing capacity for maximum moment, shear or contact pressure criteria. The ultimate bearing capacity of the piles that use 90% of their capacity is given below.

$$P_{ud} = 1.11 * F_p * (P_c - P_{crit}) \tag{2.20}$$

where is the F_p Factor of Safety for Piles. The piles are to be added to provide additional stiffness for local settlement criteria,

$$K_{cd} = P_c/S_a \tag{2.21}$$

where is the K_{cd} Target Stiffness for an allowable settlement, S_a, is the K_p, can be obtained by solving equation below, as a first approximation.

$$K_p{}^2 + K_p \left[K_r \left(1 - 2\alpha_{cp}\right) - -K_{cd}\right] + \alpha_{cp}{}^2 K_r K_{cd} = 0 \tag{2.22}$$

where is the K_p the stiffness of the pile group, is the K_r stiffness of the raft around the column.

2.1.1.8. Third stage of the design. This stage of design of piled rafts requires the use of computer codes and optimizes the foundation system by changing length, diameter and/or location of the piles.

The raft bending moments, shears and the pile loads should also be obtained for structural design of foundation elements.

Three broad class analysis methods are suggested in Poulos' Approach.

- Simplified calculation methods
- Approximate computer based methods
- More rigorous computer based methods

- Guidelines for Economical Design (Poulos, 1994)

Horikoshi and Poulos have conducted detailed analyses and they suggested this guideline for an economical piled raft foundation system.

(i) 16-25% of piles should be concentrated at the middle of the foundation system.

(ii) The axial stiffness of the raft alone should be almost equal to the pile group stiffness(or equivalent pier)

(iii) Piles should carry 50-70% of their ultimate bearing capacity, depending on the ratio of the area of pile group and poisson's ratio of the soil. To avoid excessive differential settlement, mobilization of the piles should not be higher than

2.1.2. Randolph Approach

Randolph who has important contribution on this subject is an important researcher. M.F. Randolph (1994) suggested three different design methodologies for piled rafts.

(i) Conventional Approach
(ii) Creep Piling Approach
(iii) Differential Settlement Control

2.1.2.1. Conventional approach. This approach termed "conventional" because, it implies that foundation is designed essentially as a pile group with regular spacing, however, it is allowed that the load transmitted by pile cap to the ground. Within this approach, only60-75% of total structural loads is carried by piles.

2.1.2.2. Creep piling approach. There are two main principles behind this approach.

- All piles designed to carry working load that is 70-80% of its ultimate bearing capacity because it is accepted that creep is begin at this capacity value.
- Net contact pressure must be decreased to below the preconsolidation pressure of the clay by using sufficient number of piles. Selecting working load as a creep load, designer could prevent high loads at the edge of foundation.

A case history is published in the literature by Hansbo (1993) illustrated in figure below, which compares two buildings one on conventional piles and one on creep piles.

Both the length and number of the piles can be reduced without significant difference in the performance of the foundation.

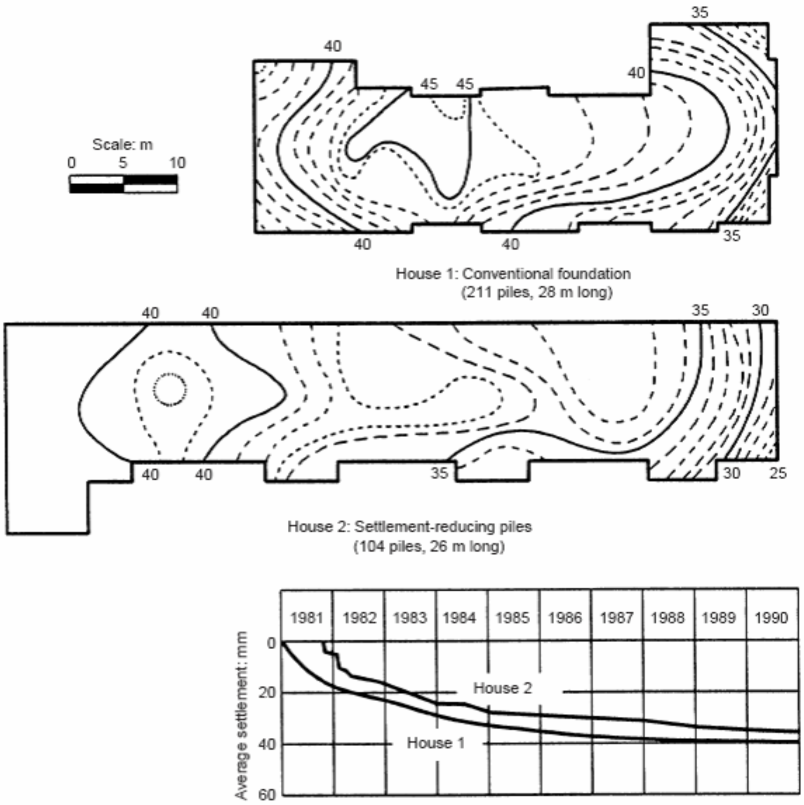

Figure 2.8. Settlement Performance of the Buildings (Conventional Versus Creep Piles Approaches).

Figure: Settlement Performance of the buildings (Conventional versus Creep Piles Approaches).

This approach has also been investigated for non-cohesive soil (Hansbo, 1993; Phung,1993, 1993) the increase of effective stress which occurs due to load transmitted from the pile caps causes higher load carrying capacity. Actually, the performance of the foundation may be analyzed by using conventional methods.

<u>2.1.2.3. Differential settlement control.</u> Previous two approaches mainly imply that piles beneath the rafts are distributed uniformly. By using this method, concentrated piles (nonuniformly distributed piles) are used to reduce settlements and bending mo-

ments.

First and second approach purpose an acceptable amount of total settlement, however third approach directly purposes to reduce the amount of differential settlements.

The logic behind this approach can be seen in the figure below. A raft foundation tends to settle excessively. By using concentrated piles at the center of raft foundation, probably loaded to close to their ultimate capacity, the amount of settlements can be reduced significantly.

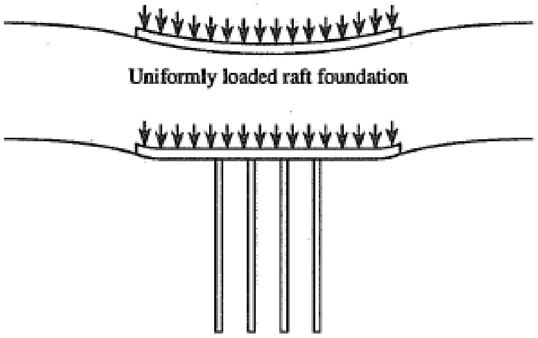

Figure 2.9. Deflected View of Raft (Raft Versus Piled Raft Foundation).

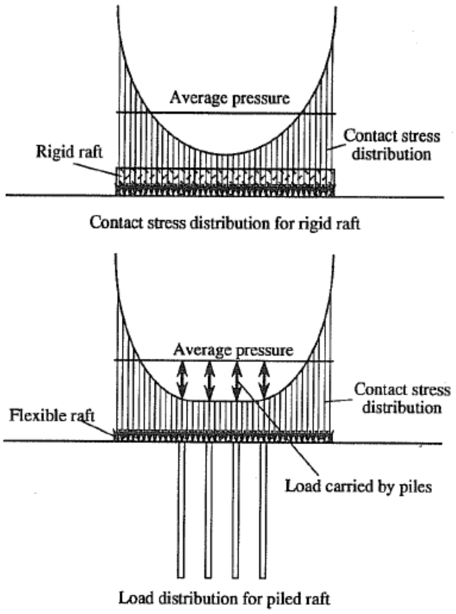

Figure 2.10. Stress Distribution for Piled Raft and Rigid Raft.

The main idea behind this method is to obtain a nearly perfectly rigid raft foundation system. For the purpose of obtaining such a system, the central piles should be designed to resist 50-70% of average applied pressure. Thereby, the load distribution underneath the rafts will be almost uniform like a rigid raft and differential settlements could be minimized by using this methodology.

The foundation scheme for MesseTurm can be seen in the figure below.

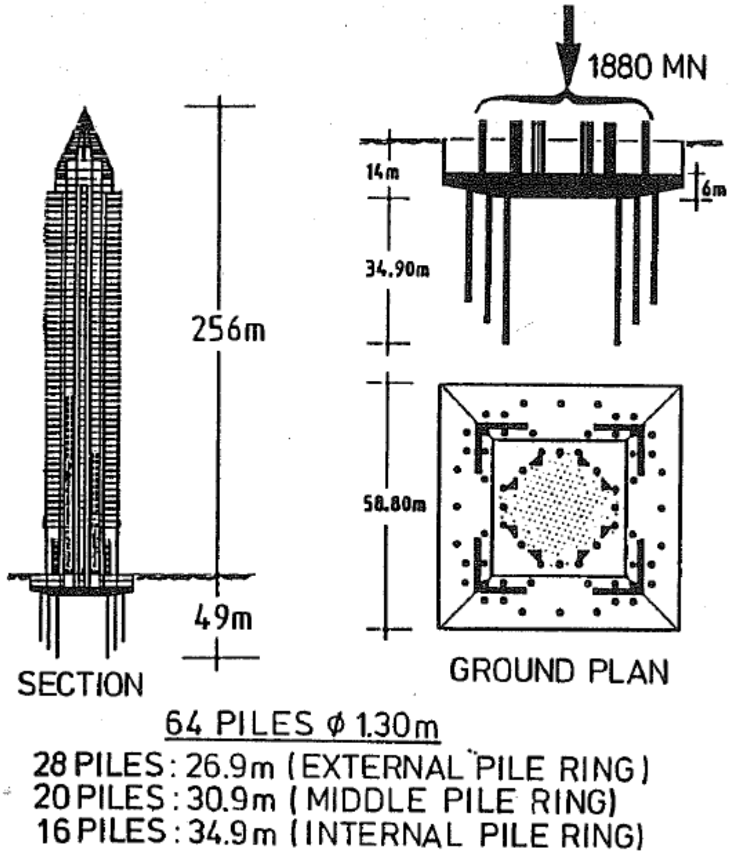

Figure 2.11. Foundation Scheme for Messe Turm Building.

While the central piles are longer than outer piles (which provide a greater support for centre) there are no piles at the center of the foundation. Settlement behavior of the building was assessed for 18 months period. Despite of thick raft foundation, different settlements occurred significantly. Moreover, measured contact pressure at the outer region and central region are less than 200 kPa and about 260 kPa respectively. (compared with average applied pressure of 540 kPa) (Sommer *et al.*, 1991).

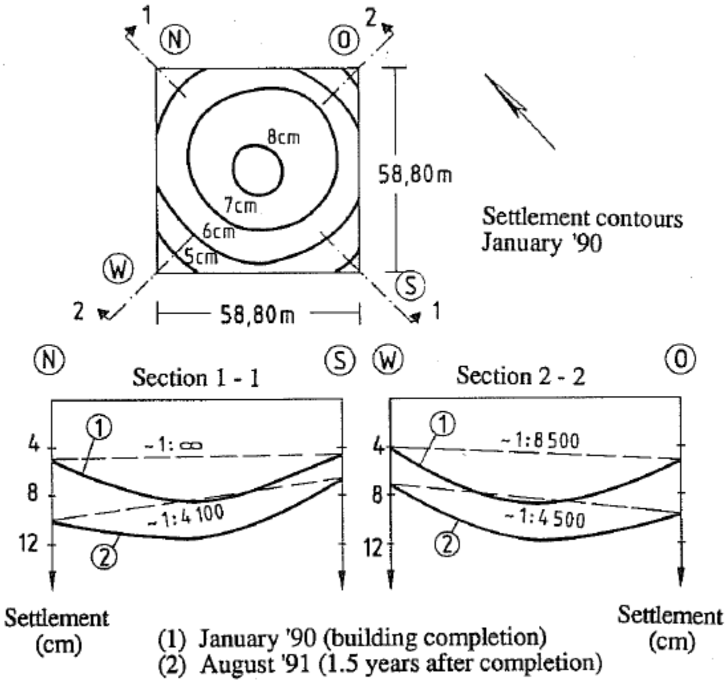

Figure 2.12. Measured Settlements of the MesseTurm (Sommer *et al.*, 1991).

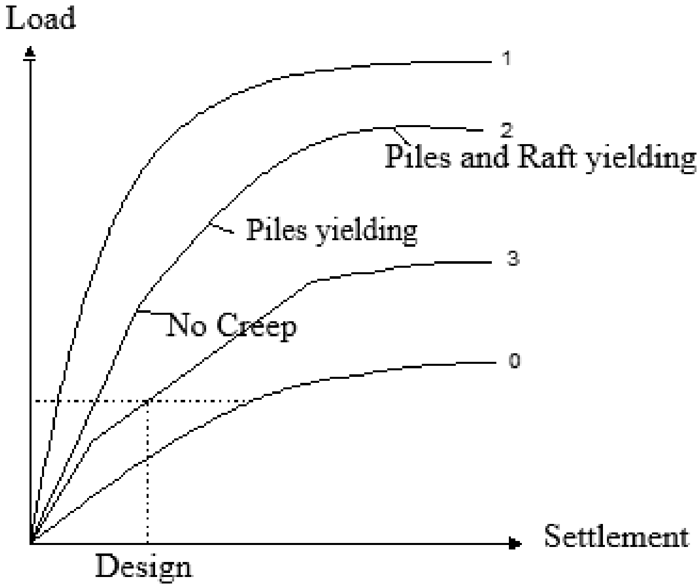

Figure 2.13. Different Design Approaches for Piled Raft Foundation.

For first curve, foundation behavior is mainly controlled by piles and most of the structural loads are carried by piles. Second curve represents a foundation that is designed by using creep piles approach. Reduced number of piles is used and raft section is loaded more. Third curve represented the foundation that piles are used to reduce the amount of settlements and bearing capacity of piles is used entirely. For design loads, settlement behavior could be nonuniform but, the amount of settlement is acceptable.

2.1.3. Viggiani - Mandolini Approach

The new Italian code recommended main findings of this research. Within the research, various configurations of piled raft foundation system were evaluated for the aspect of their bearing capacity on soft clays and as a result, some suggestions are proposed for piled raft foundation system. Methodology to analyze piled rafts:

$$Q_{UR,ult} = \left(CF_cN_cC_u\right)A \tag{2.23}$$

$$Q_{G,ult} = \eta n Q_{s,ult} \tag{2.24}$$

$$Q_{PR,ult} = \alpha_{UR}Q_{UR,ult} + \alpha_G Q_{G,ult} \tag{2.25}$$

$$\beta_{PR} = \frac{Q_{PR,ult}}{Q_{G,ult}} \tag{2.26}$$

$$\xi_{PR} = \frac{Q_{PR,ult}}{Q_{UR,ult} + Q_{G,ult}} \tag{2.27}$$

where is the $Q_{ur,ult}$ ultimate bearing capacity of unpiled raft, is the $Q_{G,ult}$ ultimate bearing capacity of the pile group, is the $Q_{s,ult}$ individual pile capacity, is the $Q_{PR,ult}$ ultimate bearing capacity of piled raft, is the C, F_c, N_c bearing capacity factors, is the C_u undrained shear strength of the soil, is the A base area of the raft, is the η efficiency factor, is the n number of piles, is the α_{UR}, α_G coefficients for raft and the pile group, is the ζ_{PR}, β_{PR} coefficients defined for the methods.

Some important parametric studies for piled rafts had been conducted by Mandolini. Within the parametric study, many configurations considered. The results of this study are given below.

Table 2.1. The Results of the Parametric Study (Mandolini, 2006).

Case	L/d	n	s/d	B_R/d	K_{UR}/ P_{ref}d ($x10^{-3}$)	K_G/ P_{ref}d ($x10^{-3}$)	K_{PR}/ P_{ref}d ($x10^{-3}$)	$Q_{UR,ult}$/ $P_{ref}d^2$	$Q_{G,ult}$/ $P_{ref}d^2$	$Q_{PR,ult}$/ $P_{ref}d^2$	β_{PR}	α_{UR}
1	40	49	4	28	9.2	43.8	44.3	1.235	4.090	4.909	1.2	0.41
2	40	9	4	28	9.2	15.7	19.9	1.235	751	1.282	2.43	0.95
3	40	9	8	28	9.2	22.2	24.8	1.235	751	1.891	2.52	1.00
4	20	49	4	28	9.9	27.7	28.3	1.235	1.364	2.12	1.55	0.41
5	20	9	4	28	9.9	7.8	13.5	1.235	251	1.446	5.77	1.00
6	20	9	8	28	9.9	12.1	15.7	1.235	251	1.465	5.85	1.00
7	40	25	4	20	5.9	28.4	28.9	630	2.087	2.644	1.27	0.42
8	40	9	4	20	5.9	15.7	17.7	630	751	1.284	1.71	0.78
9	40	9	8	20	5.9	22.2	23.1	630	751	1.348	1.79	0.97
10	20	25	4	20	5.9	16.1	16.8	630	696	1.088	1.56	0.48
11	20	9	4	20	5.9	7.8	10.4	630	251	761	3.04	0.87
12	20	9	8	20	5.9	12.1	13.3	630	251	809	3.23	0.98
13	20	9	4	12	2.7	7.8	8.1	227	251	408	1.63	0.66
14	40	9	4	12	2.7	15.7	16.0	227	751	976	1.3	0.61

The failure load coefficient, α_{UR}, varies between 0.4 and 1. The coefficient, α_{UR}, has anaverage value 0.75 and it tends to decrease for closely spaced piles. $A_G/A \rightarrow 1$.

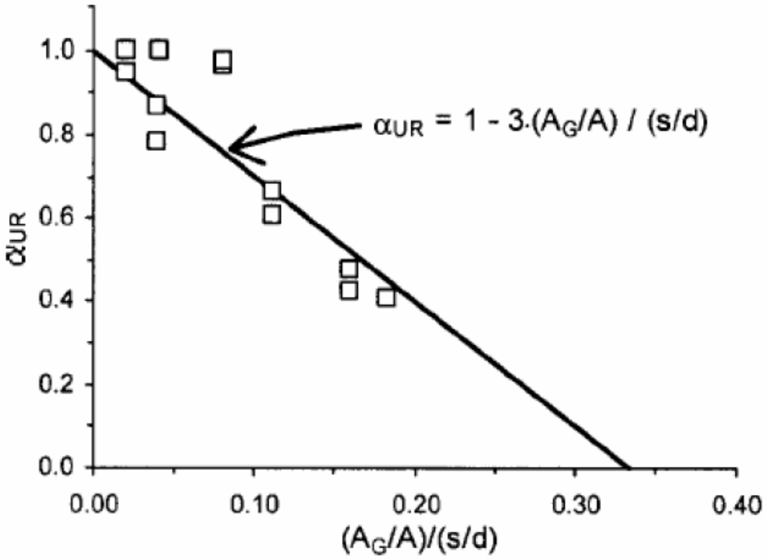

Figure 2.14. Variation of Failure Load Coefficient.

These analyses are very beneficial to optimize design of foundation system. For AG/A = 1, which represents the piles that are uniformly distributed below the raft, s/d= 6 (α_{UR}=0.5), which can be used for initial design. For instance, same percentage can be obtained for piles with s/d =3 which are concentrated at the central part of raft.

$$A_G = \left[\left(\sqrt{n} - 1\right)\right]^2 \tag{2.28}$$

where is the s distance between piles, is the d diameter of piles.

According to the research conducted by Cooke (1986), the amount of settlements of unpiled rafts is roughly three times of piled rafts. Because the effect of raft foundation, factor of safety for piled foundation is substantially higher. Applying block theory, Cooke found that the factor of safety for piled rafts vary between 6 and 14. Finally he concluded, the amount of settlement of unpiled raft and piled foundation designed with factor of safety FS=3 very close to each other.

Table 2.2. Safety Factors corresponding to a settlement of w = 0.35%B$_R$.

Case	L/d	n	s/d	B$_r$/d	FS$_{UR}$	FS$_G$	FS$_{PR}$	ζ_{PR}
1	40	49	4	28	1.95	6.46	7.76	0.92
2	40	9	4	28	1.95	1.19	2.89	0.92
3	40	9	8	28	1.95	1.19	2.99	0.92
4	20	49	4	28	1.95	2.15	3.35	0.82
5	20	9	4	28	1.95	0.4	2.28	0.97
6	20	9	8	28	1.95	0.4	2.32	0.99
7	40	25	4	20	2.11	6.98	8.84	0.97
8	40	9	4	20	2.11	2.51	4.29	0.93
9	40	9	8	20	2.11	2.51	4.51	0.98
10	20	25	4	20	2.11	2.33	3.64	0.82
11	20	9	4	20	2.11	0.84	2.54	0.86
12	20	9	8	20	2.11	0.84	2.7	0.92
13	20	9	4	12	2.26	2.49	4.06	0.86
14	40	9	4	12	2.26	7.47	9.71	1.00

According to the results above, ΔPR value is changed in a range between 0.82 - 1.00. The results show that, at least 82% of the total capacities of the unpiled raft and pile group is mobilized in case of a piled raft for a settlement of w = 0.35% B_R. (d=1 m for the analyses, it means w≈100 mm, 70mm and 40mm for BR/d= 28, 20 and 12 respectively) After a number of calculations,

$$\xi_{PR} = \frac{Q_{PR,ult}}{Q_{UR,ult} + Q_{G,ult}} = \frac{FS_{PR}}{FS_{UR} + FS_G} \tag{2.29}$$

ζ_{PR} values has a range between 0.82 to1.00 as expected. The sum of the factor of safety values with conventional methods for unpiled raft and pile group is slightly higher from safety factor of piled rafts.

For the purpose of the design of piled rafts as a conservative approach, $FS_{PR} = 0.8\,(FS_{UR} + FS_G)$ (the value, 0.8, can be used safely)

2.1.4. Burland Approach

If piles are used to reduce settlements and their geotechnical capacity is fully utilized Burland (1995) has developed a simplified approach of analysis. The raft stiffness in this method is calculated via commercial software, GARP. The ultimate load carrying capacity of the piles is reduced at column location to estimate bending moments. Additionally it is assumed that piles are fully mobilized. To evaluate settlement behavior of a piled raft foundation system under total applied loads, stiffness ratios are estimated from Randolph's approach. Burland's design concept is given in Figure 2.15.

- By using the design load P_0 gives a value for total settlement S_0, estimating long term total settlement of only raft.
- Considering a factor of safety value, determine an acceptable value for design settlement S_d.
- P_1 is a value that must be resisted by the raft corresponding to S_d.
- The excessive load P_0-P_1 must be carried by piles. The shaft resistance of the

piles is fully utilized and the calculation for shaft friction of the piles does not include a factor of safety. On the other hand, a mobilization factor, 0.9, can be used to estimate ultimate shaft capacity, P_{su}.

- Piled raft can be analyzed using a reduced column load as a reduced raft foundation by which if the piles localized below a column that resist higher level load than P_{su}. For such kind of columns, the reduced value of the load is given below.

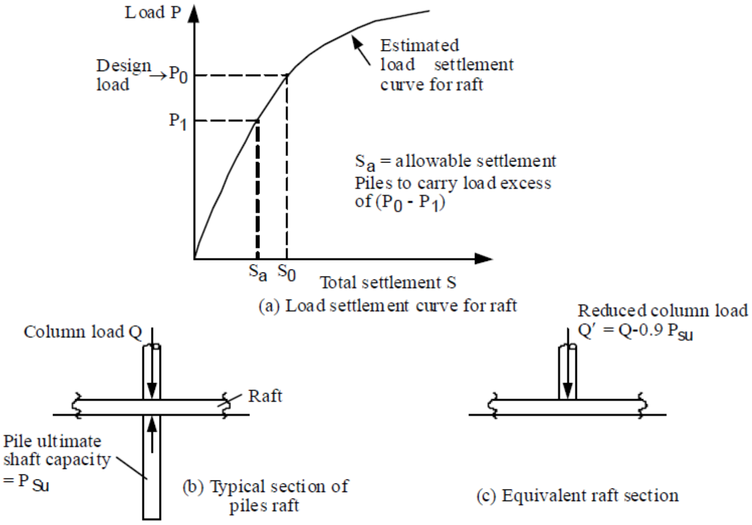

Figure 2.15. Burland's Design Concept.

$$Q_r = Q - -0.9P_{su} \tag{2.30}$$

- By analyzing the piled raft foundation system as a raft alone that carries reduced Q_r load, bending moments of raft foundation can be obtained.
- Estimating total and differential settlements of piled raft foundation system is not given in Burland's approach but the approach which is given by Randolph (1994) can be used.

$$Spr = Sr * Kr/Kpr \tag{2.31}$$

where is the S_{pr} Settlement of piled raft, is the S_r Settlement of raft alone which carries total applied loading, is the K_r Stiffness of raft, is the K_{pr} Stiffness of piled raft.

2.1.5. Estimation of Piles and Raft Stiffness

To conduct a simplified approach, most of methods in literature use initial axial stiffnesses of piles and raft. There are many equations in available to obtain this stiffness values. Poulos and Davis (1974) is developed an equation for loaded circular rafts located on elastic half.

According to Poulos and Davis (1974) single pile and raft stiffnesses can be calculated as shown below;

Because the curves are prepared for circular raft foundation, an equivalent circular area is used for calculations.

2.1.5.1. Axial stiffness of the raft (K_r) is.

$$Kr = \frac{V}{\rho_z} \tag{2.32}$$

where is the V Vertical Load.

$$\rho_z = \frac{P_{av} * a}{E} * I_p \tag{2.33}$$

where is the P_{av} Stress Distribution, is the E Young's modulus of soil, is the I_p Influence factor (obtained from curve below).

$$P_{av} = \frac{P}{\pi a^2} \tag{2.34}$$

where is the a Equivalent circular raft area.

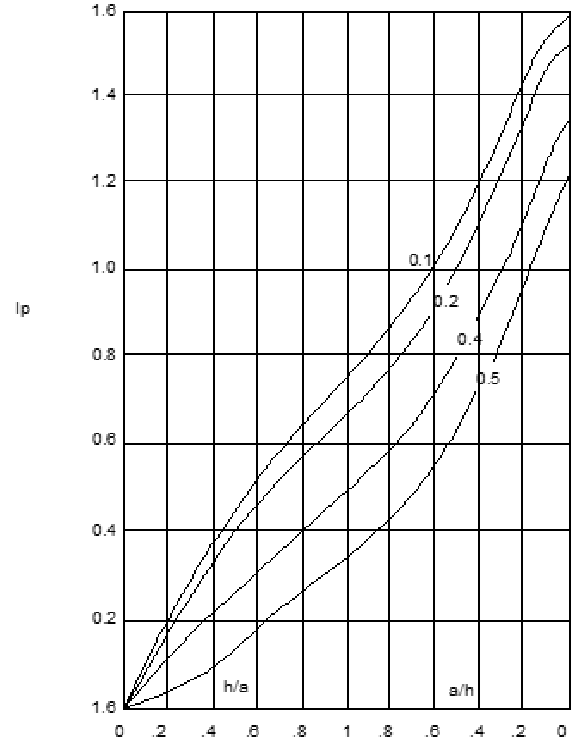

Figure 2.16. Influence factor (I_p) for vertical displacement for rigid circle (Poulos & Davis 1974).

2.1.5.2. Axial stifness of the piles (K_p) is.

$$K_p = \frac{2\pi}{\zeta} l G_1 \rho \frac{\tanh\left(\mu l\right)}{\mu l} \tag{2.35}$$

$$\zeta = ln\left(r_m/r_0\right)\ (measureofradiusofinfluenceofpile) \tag{2.36}$$

where is the r_m the distance that the shear stress becomes negligible(maximum radius), is the r_0 Radius of the Pile, is the G Shear Modulus, is the ρ the ratio of the shear modulus at the pile mid - depth to that at the base, 1 for constant G, is the μ Coefficient.

$$\mu l = \frac{1}{r_0}\sqrt{\frac{2}{\zeta\lambda}} \tag{2.37}$$

$$\lambda = \frac{E_p}{G} \tag{2.38}$$

$$G = \frac{E}{2\left(1+\upsilon\right)} \tag{2.39}$$

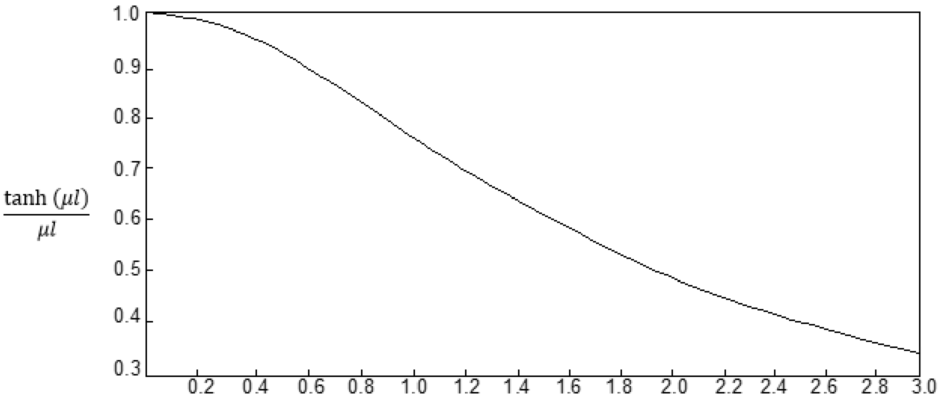

Figure 2.17. The variation of $\tanh(\mu l)/(\mu l)$ with μl (Randolph & Wroth, 1978).

There is another raft approach to estimate raft stiffness in FEMA 356(2000). This method can be used to calculate embedded raft foundation. The equation is given below;

$$\beta z{=}1+\frac{1}{21}\frac{D_f}{\mathrm{B}}\left(2+2.6\frac{\mathrm{B}}{L_r}\right).\left[1+0.32\left(\frac{d\left(B+L_r\right)}{BL_r}\right)^{2/3}\right] \tag{2.40}$$

$$K_r{=}\frac{G_B}{1-\upsilon}1.55\left(\frac{L_r}{\mathrm{B}}\right)^{0.75}+0.8.\beta z \tag{2.41}$$

$$K_{pa}{=}\ 0.5642\frac{E_pA_p}{R}\left(\frac{E_s}{E_p}\right)^{0.5} \tag{2.42}$$

where is the D_f Depth of the raft, is the B Average Pile Diameter, is the L_r Length of the raft, is the d Actual embedded depth of the, is the K_r Rigidity of the raft, is the β_z Axial stiffness correction factor for embedded rafts, is the K_{pa} Single pile axial stiffness, is the E_p Young's modulus of Pile Concrete, is the A_p Area of single pile, is the R Radius of the Pile, is the G Shear modulus of soil below the raft, is the ν Poisson's ratio E_s Young's modulus of soil around pile.

There are many methods available to calculate pile stiffness. Sanchez-Salinero (1982) gave available methods in literature from different studies. Some of these equations are given below:

$$k_p = 0.56(E_pA_p)/R(E_s/E_p)^0.50(Winkler) \tag{2.43}$$

$$k_p = 0.69(E_pA_p)/R(E_s/E_p)^0.61(Poulos) \tag{2.44}$$

$$k_p = 0.79(E_pA_p)/R(E_s/E_p)^0.60(Blaney) \tag{2.45}$$

where is the k_p Axial stiffness of the single pile, is the E_p Young's modulus of the pile, is the E_s Young's modulus of the soil, is the A_p Cross-sectional area of the pile, is the R Radius of the pile.

Another method to calculate pile stiffness is given above in Section 2.4.1 which is developed by Randolph.

Many methods to calculate single pile and raft stiffness value are given above. Additionally pile group stiffness is required to perform many approaches. Pile group stiffness is lower than addition of total number of single pile stiffness values. According to Poulos (2000), pile group stiffness is calculated as shown below:

$$K_{pg}{=}k_p * \sqrt{n} \tag{2.46}$$

where is the K_p Single pile axial stiffness, is the K_{pg} pile group stiffness, is the n number of pile in the group.

2.2. Approximate Computer Methods

2.2.1. Strip - Springs Method (Poulos, 1991)

Within this method, a section of the raft and the piles are represented by a strip and springs, respectively. All four components of interaction (pile-raft, raft-soil, pile-soil, and pile-pile) are considered. Additionally, considering free soil movements that interacts strip element, the effects of the rafts outside the strip section can take into account. Research shows that, the results obtained by this method are closer to complete analyses but the method does not consider the effect of torsional moment.

A software, GASP (Geotechnical Analysis of Strip with Piles) can be used for this analogy. The method shows a well agreement with more complicate analysis methods. By limiting contact pressures, GASP take into consideration soil nonlinearity and raft uplifting capacity approximately. Additionally, pile capacity is evaluated for a single pile (in a pile group), the beneficial effect of raft is not considered by the GASP. Due to this assumption is quite conservative for a soil that is convenient for piled raft foundation system, GASP analyses could be on the safe side.

To avoid unrealistic settlement predictions due to wrong assumptions about soil yielding, while performing a nonlinear analysis in which strips in two directions are analyzed, nonlinearity in the longer direction and sorter direction should be linear. Such a method for analysis simulates piled raft foundation behavior more realistic.

2.2.2. Plate-Springs Method (Poulos, 1994)

The method uses elastic plate for raft, springs for the piles to represent piled raft foundation system. Hongladaromp *et al.*, (1973) did not consider some interaction factors and they obtained very high stiffness values. Poulos (1994), used finite difference method for raft and springs for the piles. This analysis can be conducted by using a software, GARP(Geotechnical Analysis of Raft with Piles).This method considers interaction between foundation members and nonlinear behavior of the piles. By using this method, pile and raft loads, bending moments of raft foundation, total and differential settlements can be calculated.

Allowing to layer of soil profile, the software can calculate bearing capacity failure of the raft and free-field soil settlements. The assumptions involved are quite similar with GASP.

By using a hyperbolic load settlement curve for single piles, Russo (1998) and Russo and Viggiani (1997) proposed similar approach that consider nonlinear behavior of the piles and various interactions.

Poulos *et al.*, (2001) have investigated the effect of rigidity of the raft. In conclusion, it was seen that there is no significant difference between stiff raft and flexible raft in the computed deflections for the foundation.

Thin shell elements to represent raft will show a reasonable agreement with deflections, moments. Even if the raft is extremely thick, there are no important differences. However, if concentrated loads are higher, soil might be yield and this method of analysis might not reflect real behavior of soils.

2.3. More Rigorous Computer Methods

2.3.1. More Rigorous Computer Methods

Within this method, the piles and raft and all interfaces are modeled with discrete sections. Usually, Mindlin (1936) function is used to solve the movements in the soil. Moreover, the behavior of the foundation is solved by using finite difference or finite elements methods. (Randolph 1994) The elastic compression of the piles is considered but raft is assumed as a rigid member. Researches show that, under elastic conditions with normal pile spacing, only a small portion of the loads is carried by the raft. Modelling both free-standing piles and piled raft foundation, Kuwabara (1989) conducted a more detailed analysis. Then, Randolph extended Kuwabara's study to allow the free-soil movements, and limit contact pressure between raft and soil,

2.3.2. Finite Elements Method

Using finite elements, all parts of the foundation system can be analyzed effectively. The analyses consider non-linear behavior of the system and it is more suitable way to represent actual soil behavior. There are two types of analyses for finite element method.

- Plane-Strain (2-D) Analysis

Assuming infinitely long third dimension, plane strain analysis can be performed. Within these types of analyses, strain at third dimension is assumed to be 0. Especially, this method is used frequently to simulate actual behavior of enormously long systems. However, there is a significant drawback of this method that torsional moment cannot be obtained with this analysis because the strains for third dimension are assumed to be 0.

- Plane-Strain (3-D) Analysis

For the purpose of obtaining more realistic solution, in general, 3-D analysis is used as an "ultimate weapon". Firstly, Wang (1998) conducted a three dimensional analysis for piled raft foundation system. Although, 3-D analysis gives more suitable solution for geotechnical engineering, due to the inadequate capacity of the computers and economical aspects, the analysis method is not used frequently. However, in recent days, with more developed computers, this method have been using more frequently.

It is obvious that, even if it is the most suitable way to represent actual soil behavior, more realistic solution can only be obtained with appropriate geotechnical parameters.

There are complex interactions between piles; raft and soil for a piled raft foundation system and finite element model can be used effectively for evaluate this behavior. However, the plane strain finite element models include basic assumptions and Desai *et al.*, (1974) showed that these types of models can provide reasonable results. Additionally, to avoid excessive modeling and calculation time, this type of models can be used.

2.3.3. Combination of Boundary Element and Finite Element Methods

Hain & Lee in 1978 combined both boundary element and finite element methods to analyze complex system. Within this method, pile behavior is estimated by boundary element method, and raft behavior is represented by finite element methods.

2.4. Settlement Calculation Methods

2.4.1. Settlement Ratio Method

Considering interaction effects within a pile group, the method that is recommended by Butterfield and Douglas (in Fleming, W. *et al.*, 1992) is an effective way to analyze settlement behavior. K, means that the sum of stiffness of all piles. The stiffness of pile group K expressed as:

$$K_{pg} = \eta_{w*} n * k_p \tag{2.47}$$

where is the K_{pg} stiffness of pile group, is the n number of piles, is the k_p axial stiffness of the single pile

The factor η_w is the inverse of the settlement ratio, R$_s$, and it implies efficiency. If there is no no interaction between piles, η_w would equal to:

$$\eta_w = n^{-e} \tag{2.48}$$

The value, e, varies between 0.4 and 0.6 (Poulos (1993)). This value mainly depends on five factors:

(i) pile slenderness ratio, L/d (length of the pile /pile diameter)
(ii) pile stiffness ratio, λ=Ep/Gl (pile modulus/soil shear modulus)
(iii) pile spacing ratio, s/d (pile spacing/pile diameter)
(iv) homogeneity of soil, characterized by ρ,
(v) Poisson's ratio, υ.

With combination of these five factors, the value of e can be estimated with using curves below. (Fleming *et al.*, 1992). The upper curve allows a base of e to be chosen, with pile slenderness ratio (L/d) (assuming λ=1000, s/d=3, ρ=0.75, υ =0.3). The four curves in lower part of the figure then modify this basic value of pile stiffness ratio, s, υ and ρ.

The amount of base and shaft settlement will be similar to the pile head.
w_t for a single stiff pile.
P_t, can be expressed as:

$$P_t = P_b + P_s = w_t(\frac{P_b}{W_b} + \frac{P_s}{w_s}) \tag{2.49}$$

where is the P_t total load.
After a number of calculations equation becomes:

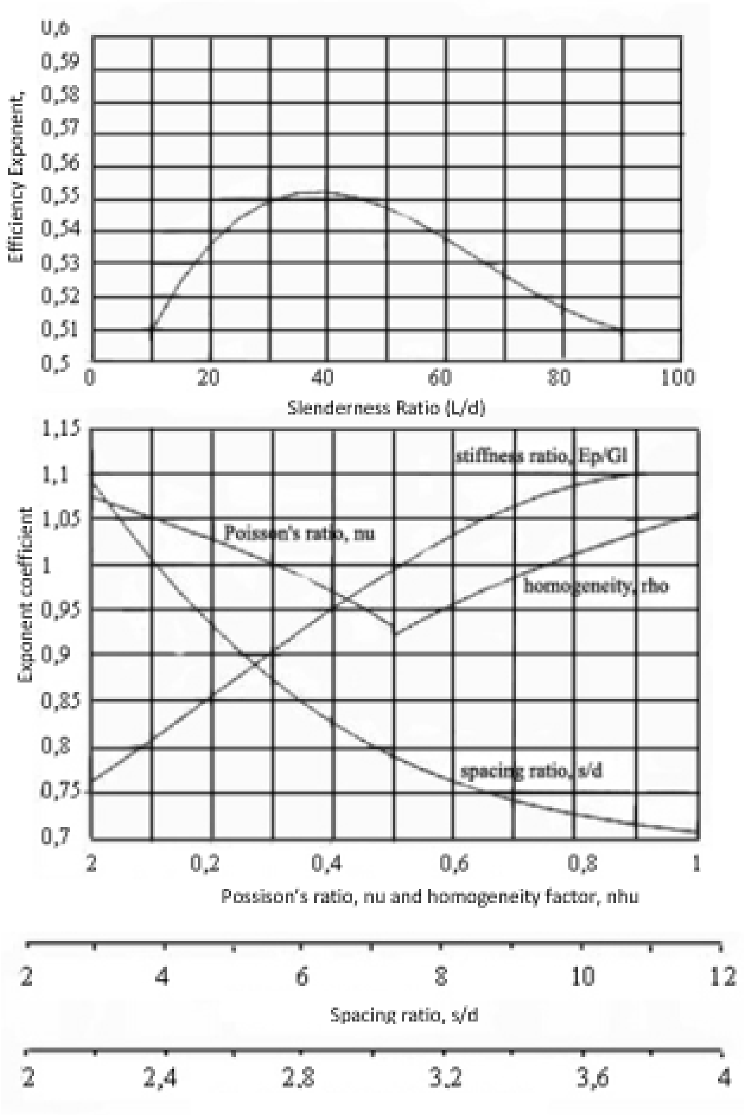

Figure 2.18. Charts for Calculation of Exponent e for Efficiency of Pile Groups. (Fleming, *et al.*, 1992).

$$\frac{P_t}{w_t * r_0 * G_1} = \frac{4 * r_b * G_b}{(1-\upsilon)\, *\mathrm{r}_0 * \mathrm{G}_1} + \frac{2\pi G_{1/2}}{G_1} * \frac{L}{r_0} \tag{2.50}$$

where is the G_1 soil modulus at the level of pile base, is the r_b radius of pile base, is the $G_{l/2}$ soil shear modulus at the l/2 level, is the G_b soil shear modulus below the level of pile base, is the r_0 radius of the pile, is the wt: pile head settlement.

The change of shear modulus with depth can be idealized as linear, according to G=G$_{0+mz}$ (where z is depth). (Figure Below) (Fleming, W.G. *et al.*, (1992)).

$$\rho = G_{l/2}/G_l \tag{2.51}$$

$$\xi = G_l/G_b\,(RandolphandWroth,\,(1978)) \tag{2.52}$$

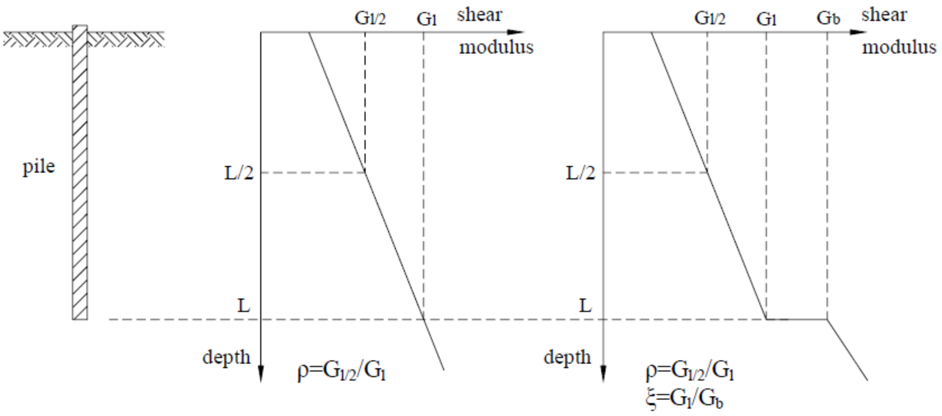

Figure 2.19. Assumption for Soil Shear Modulus with Depth.

Using the appropriate boundary conditions, Load settlement ratio expressed as:

$$kp = \frac{P_t}{G_1 r_0 w_t} = \frac{\frac{4\eta}{(1-\upsilon)\xi} + \frac{2\Pi\rho}{\zeta}\frac{\tanh(\mu\mathrm{L})}{\mu\mathrm{L}}\frac{\mathrm{L}}{r_0}}{1 + \frac{4\eta}{\Pi\lambda(1-\upsilon)\xi}\frac{\tanh(\mu\mathrm{L})}{\mu\mathrm{L}}\frac{\mathrm{L}}{r_0}} \tag{2.53}$$

where is the k_p single pile stiffness.

$$\eta = r_b/r_0\,(ratioofunderreamedforunderreamedpiles) \tag{2.54}$$

$$\xi = G_l/G_b(ratioofend-bearingforend-bearingpiles) \tag{2.55}$$

$$\lambda = E_p/G_l\,(pile-soilstiffnessratio) \tag{2.56}$$

$$\zeta = ln\left(r_m/r_0\right)\;(measureofradiusofinfluenceofpile) \tag{2.57}$$

$$\mu = \left(2/\left(\zeta\lambda\right)\right)^{0,5} L/r_0\,(measureofpilecompressibility) \tag{2.58}$$

where is the r_m maximum radius. Finally settlement of the pile group:

$$\delta group = \frac{P_{group}}{K} \tag{2.59}$$

2.4.2. Equivalent Raft Method

Both equivalent pier and equivalent raft methods are suitable to determine the amount of settlement of piled raft foundation system. (Randolph (1994) Making a choice between the two method, R that considers spacing of piles, the number of piles and the length of the piles can be used.

$$R = \sqrt{\frac{n * s}{L}} \tag{2.60}$$

where is the n the number of the piles, s spacing of the piles, is the L length of the piles.

In case of R>4 use of equivalent raft method is a convenient way to calculate the amount of settlement of a piled raft foundation system whereas for cases R<2 equivalent pier method is more suitable way.

According to equivalent raft method, piled raft foundation is represented with an assumed raft foundation that located 2/3L below the actual foundation level. (Tomlinson, 2001) To determine the length of the equivalent raft, it is assumed that the load is distributed with $\frac{1}{4}$ ratio. The total settlement of the system can be calculated as the settlement of the equivalent raft plus elastic compression of the piles above the equivalent raft foundation. According to Van Impel (1991) if the total area of the piles/

the area of the pile group>0.1, equivalent raft method can be conducted.

$$w_{avg} = w_{raft} + \Delta w \tag{2.61}$$

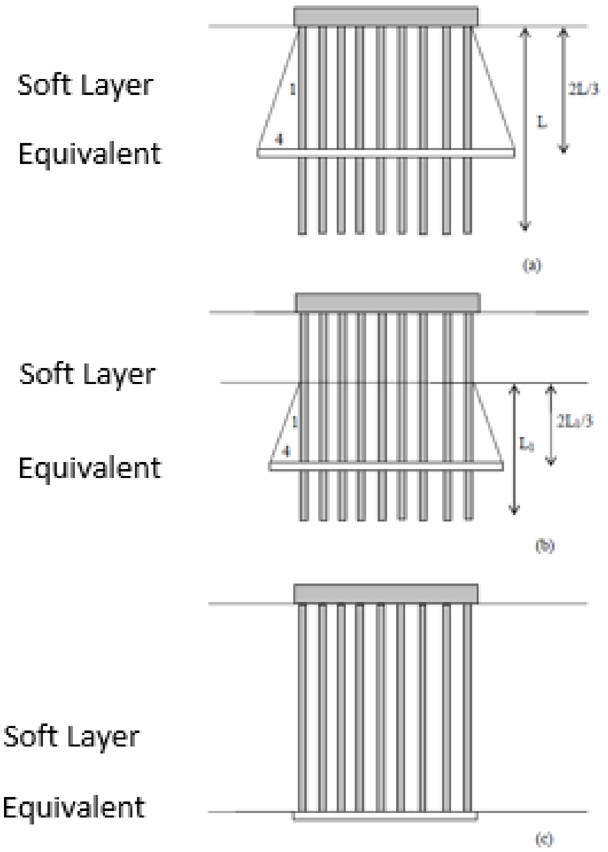

Figure 2.20. Equivalent Raft Method a) Primarily Friction Piles, b) Friction and End-Bearing Piles, c) Primarily End-Bearing Piles.

where is the w_{raft} total of the settlement of the raft, is the Δ_w elastic compression of the piles above the level of the equivalent raft, is the w_{raft} can be expressed as

$$w_{raft} = F_d * q * \sum_{i=1}^{n} \left(\frac{\mathrm{I}}{\mathrm{E_s}}\right)_{\mathrm{i}} * \mathrm{h_i} \tag{2.62}$$

where is the F_D embedment correction factor for raft settlement from Fox (1948), is the q applied pressure, is the I_ϵ influence factor for vertical strain, is the E_s Young's Modulus of soil, is the h_i thickness of the i'th soil layer, is the i number of the soil layer.

It is an important advantage that, by using equivalent raft method, variations of soil stiffness can be considered. If there is a soft layer that below the base of the piles, this advantage can be used effectively.

2.4.3. Equivalent Pier Method

Another alternative way is that the equivalent pier method by which pile group is represented with an equivalent pier. There are two types of approaches that can be used in this method.

(i) A pier with equivalent L$_e$ length and the pier have an equal area to pile group (A$_g$).
(ii) A pier with de diameter and the pier have an equal length to the pile group (L).

For multiple layer soils, use of equivalent diameter approach is a more suitable way.

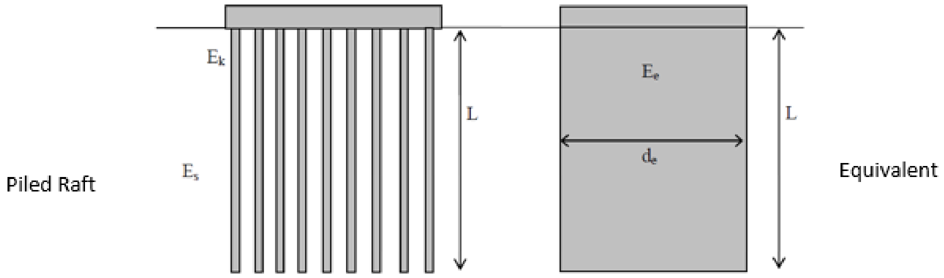

Figure 2.21. Equivalent Pier Method.

$$d_e = \sqrt{\frac{4 * A_g}{\pi}} = 1.13\sqrt{Ag} \tag{2.63}$$

where is the A_g area of the pile group.
Equivalent young's modulus of the pier is expressed as:

$$E_{eq} = E_s + (E_p - E_s) * \frac{A_p}{A_g} \tag{2.64}$$

where is the E_p Young's modulus of the miles, is the Es average Young's Modulus of the soil penetrated by the piles, is the A_p the sum of cross-sectional area of the piles in the group.

A comparison table of several analysis methods including simplified, approximate and the advanced procedures for piled raft foundation system is given below.

Table 2.3. Comparison Table of Simplified, Approximate and Aprocedures.

Method	Response Characteristics					Problem Modelling			
	Settle -ment	Diff. Settl.	Pile Loads	Raft BM	Tors. Shear	Nonlin. Soil	Non-lin. Pile	Non- unif Soil	Raft Flexib.
Poulos & Davis -1980	X					X			
Randolph -1983	X		X						
Van Impe & Clerq -1995	X	X							
Equivalent Raft (Poulos, 1994)	X	X							
Brown & Wiesner -1975	X	X	X	X					X
Clancy & Randolph -1993	X	X	X	X	X			X	X
Poulos -1994	X	X	X	X	X	X	X	X	X
Kuwabara -1989	X		X						
Sinha -1996	X	X	X	X	X	X	X		X
Franke *et al.*, (1994)	X	X	X	X	X		X		X
Hooper -1973	X	X	X	X		X		X	X
Lee *et al.*, -1993	X	X	X	X	X			X	X
Ta & Small -1996	X	X	X	X	X			X	X
Wang -1995	X	X	X	X	X	X	X	X	X
Katzenbach *et al.*, -1998	X	X	X	X	X	X	X	X	X

3. ANALYSES OF PILED RAFT FOUNDATION SYSTEMS

3.1. Introduction

As it is mentioned before, piled raft foundation systems are complex systems that have to analyze with appropriate computer software that consider all four interactions. After using previously introduced simplified approaches, a two dimensional finite elements program Plaxis 2D AE is used to analyze the model. By using this software, the behavior of piled raft foundation and conventional piled raft foundations are evaluated. After evaluating static behavior of the models, dynamic behavior is analyzed for three different earthquake accelerations. For these evaluations, Wells Earthquake (1990), El Salvador Earthquake (2001) and Parkfield Earthquake (1990) are used. The behavior of piled raft foundation systems with floating and end bearing piles, carried load proportion by the raft, elastic displacements of the piles and internal forces is evaluated for seven different cases.

By using finite elements method and simplified approaches from literature that developed by Randolph and Poulos, carried superstructure load proportion by the raft and elastic settlements are calculated.

3.2. Method of Analysis

A hand calculation and advanced analyses methods are used for this study. Both conventional and piled raft are analyzed and compared for all seven cases. Within this study, due to the ultimate capacity of the piles that penetrating into the rock is significantly higher than the floating piles, two hypothetical superstructure cases are used for analyses.One of which is a 15 storey building that resting on a very deep clay layer.15m, 20m, 25m and 30m floating piles are used for 15 storey building. The other case considered a 35 storey building. For 35 storey building, piles are penetrated 3m deep into to rock but other parts of piles and the raft are surrounded by clay soil that has the same properties with first case. 13m, 18m, 23m and 30m end bearing piles are used to estimate the effect of pile length for piled raft foundation system. For both static and dynamic cases, an undrained behavior is considered. Additionally, a drained material model is used to analyze long term behavior of the foundation systems. This study basicly focused on the short term behavior of the foundation because it is assumed that construction will be very fast.

The static behavior is analyzed by using simplified and advanced analysis methods. Details of calculations and analyses are given in the following sections. Following methods are used to analyze problems:

- Poulos' Simplified Approach
- Randolph's Simplified Approach
- 2D Finite Elements Advanced Method (Plaxis 2D AE)

In this study, two dynamic analyses are conducted. Two piled raft foundations with 23m pile length that 3m penetrates into the bed rock and 20m floating piles are analyzed with finite element method. The dynamic analyses were performed by Wells, El Salvador and Parkfield earthquake accelerations. For the same pile lengths as in the static analyses, the contribution of the raft and internal forces are evaluated. It is assumed that construction will be very quick, due to this reason; mostly short term behavior is considered. The behaviour of the piled raft foundation in long term also evaluated in terms of load sharing ratio between the raft and pile group. The ultimate capacity of the piled raft foundation system is calculated with short term parameters which is critical.

3.3. Model Parameters and Qualifications

A two dimensional finite elements software is used to analyze the behavior of both conventional piled raft foundation and piled raft foundation. Additionally, considering the increase of the weight of buildings, 12kN/m^2 and 15kN/m^2 for each story is used to represent dead and live loads for 15 and 35 storey buildings respectively.

In order to represent soil properties, undrained hardening soil model is used to analyze soil and a drained mohrcoulomb material model is used to simulate rock behavior. 100cm pile diameter is selected for pile diameter. The length of raft foundation is selected as 20mx40m.

For piled raft foundation system with floating piles, 78 piles are used with 3.2m pile spacing in x direction and 3m pile spacing in y direction.(6x13) Moreover, for end bearing piles, 36 piles are used with 3.2m and 5m piles spacing in x and y direction, respectively.(6x6).

In order to distinguish the long term and short term behavior of the foundation soil, two sets of analyses have ben conducted. Parameters used for long term and short term static analyses are given in Table 3.1 and Table 3.2.

Table 3.1. Model Parameters (Short Term).

Static Analyses							
Material	E_{50} (kN/m^2)	υ -	c (kN/m^2)	φ (degree)	g_{unsat} (kN/m^2)	g_{sat} (kN/m^2)	Material Con.
Clay	20000	0.495	40	1	19	20	Undrained
Rock	1000000	0.3	264	30	25	27	Drained

Table 3.2. Model Parameters (Long Term).

Static Analyses							
Material	E_{50} (kN/m^2)	υ -	c (kN/m^2)	φ (degree)	g_{unsat} (kN/m^2)	g_{sat} (kN/m^2)	Material Con.
Clay	20000	0.495	40	20	19	20	Undrained
Rock	1000000	0.3	264	30	25	27	Drained

Dynamic analyses are performed with a higher cohesion value than static analyses.

The parameters used in the dynamic analyses are given in Table 3.3.

Table 3.3. Model Parameters (Earthquake Case).

Dynamic Analyses							
Material	E_{50}	E_{oed}	E_{ur}	υ	c	Rayleigh Damping	
	(kN/m^2)	(kN/m^2)	(kN/m^2)	-	(kN/m^2)	α	β
Clay	20000	50000	60000	0.495	60	0.01	0.01
Rock	1000000	-	-	0,3	264	0.01	0.01
	φ (degree)	g_{unst} (kN/m^2)	g_{sat} (kN/m^2)	Material Type	Material Model		
Clay	1	19	20	Undrained	Hardening Soil		
Rock	30	25	27	Drained	Mohr Coulomb		

Three different earthquake records were used to simulate the behavior of the raft foundation under earthquake loading condition. The properties of the earthquakes are summarized below.

The records of these earthquakes are given in Figure 3.1; Figure 3.2 and Figure 3.3.

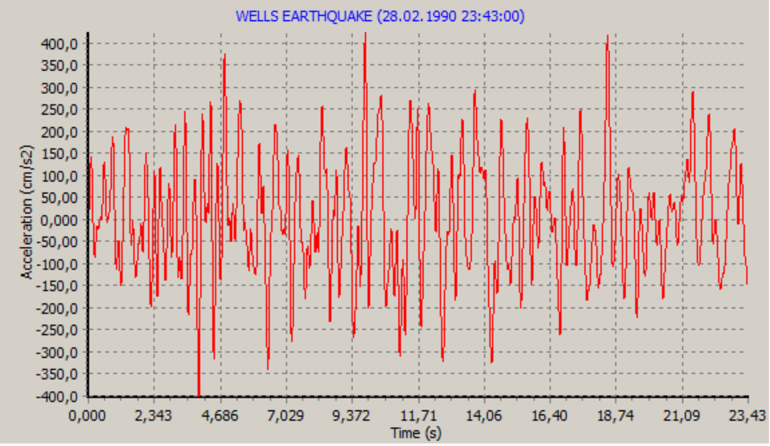

Figure 3.1. Wells Earthquake Acceleration Record.

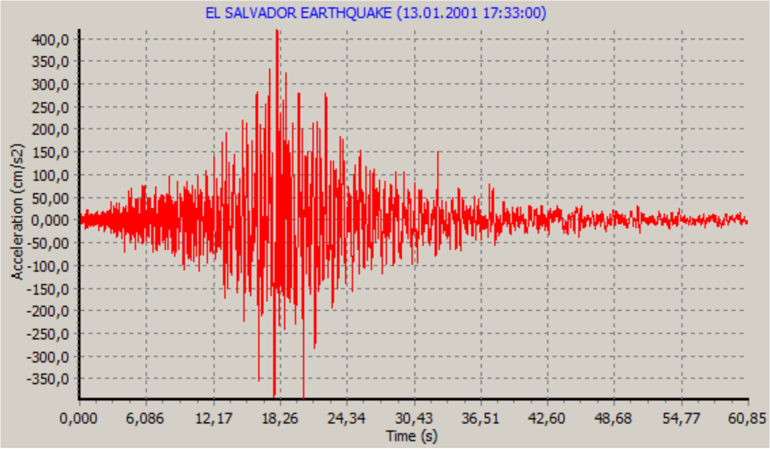

Figure 3.2. El Salvador Earthquake Acceleration Record.

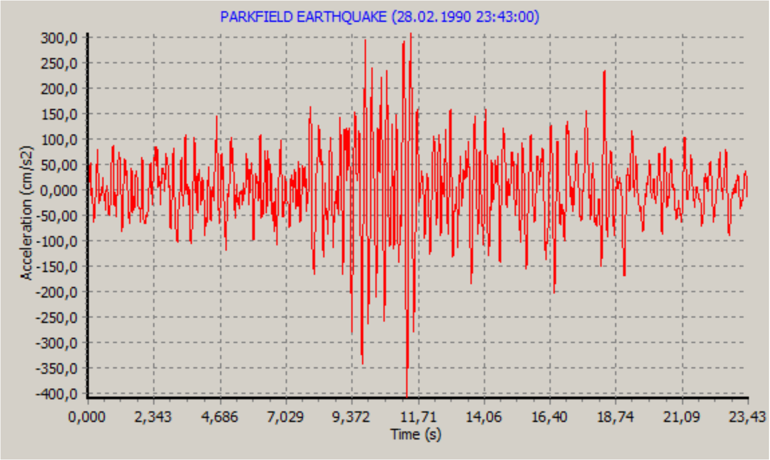

Figure 3.3. Parkfield Earthquake Acceleration Record.

These earthquakes are selected because their peak accelerations are close to 0.4g peak ground acceleration. By using these accelerations, more realistic results for the piled raft foundations which located in high seismicity are obtained.

Altogether eight models have been investigated. A representative model for a raft with floating pile is given in Figure 3.4. Four different pile lengths have been investigated where the depth of bedrock, or in other words the depth of the model was kept constant. The last case investigated is the case where the piles are socketed into the bedrock. This case is illustrated in Figure 3.5. For the end bearing piles three alternatives have been investigated with different raft to bedrock distances.

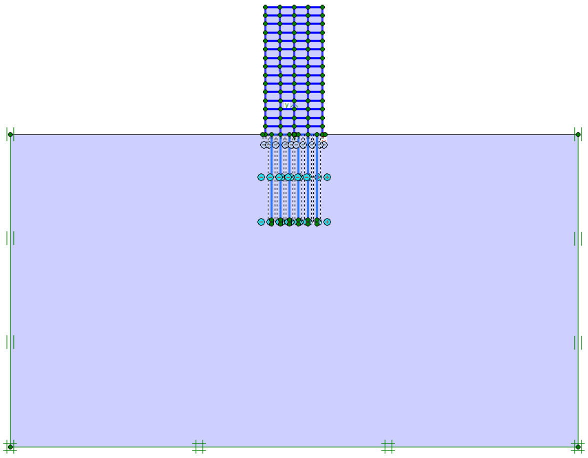

Figure 3.4. Piled Raft Foundation with Floating Piles FEM Model.

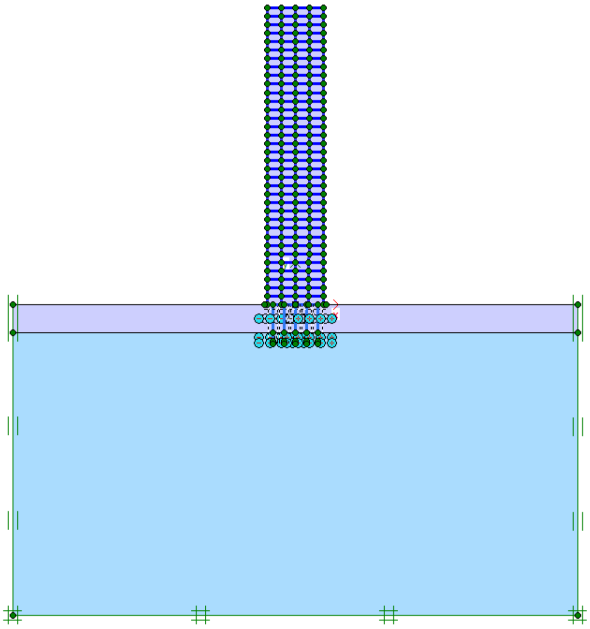

Figure 3.5. Piled Raft Foundation with End-Bearing Piles FEM Model.

3.4. Static Analyses Results

The dimensions of the foundation system are determined first by using short term term behavior which is expected to represent the worst case scenario. However analyses have been repeated also with the long parameters of the soil to understand the behavior of the pile-raft system in the long term.

3.4.1. Superstructure Weights

For on piled raft foundation system with floating piles; It is assumed that this building has a raft foundation with 1m thickness and dead and 12kN/m^2 is used for dead and live load coming from superstructure W1= 12*20*40*15 + 1*25*20*40 = 160000 kN(15 Storey Building) For on piled raft foundation system with end bearing piles; It is assumed that this building has a raft foundation with 2.5m thickness and dead and 15kN/m^2 is used for dead and live load coming from superstructure W_1= 15*20*40*35 + 2,5*25*20*40 = 470000 kN (35 Storey Building).

3.4.2. Raft Bearing Capacity

Within this study, the same dimensions for the raft are used for all cases.

$$\begin{aligned} q_{ur} &= c * N_c * \lambda_{cs} * \lambda_{cd} + D_f * \gamma * N_q * \lambda_{qs} * \lambda_{qd} \\ &+0,5 * \gamma * B * N_\gamma * \lambda_{\gamma s} * \lambda_{\gamma d} \,(Meyerhof) \end{aligned} \tag{3.1}$$

$$\lambda_{cs,}\lambda_{qs,}\lambda_{\gamma s} ShapeFactors \tag{3.2}$$

$$\lambda_{cd,}\lambda_{qd,}\lambda_{\gamma d} DepthFactors \tag{3.3}$$

$$\begin{aligned} N_q &= e^{\pi * tan\varphi} * \left[(1 + sin\varphi) \,/\, (1 - sin\varphi)\right] = \\ &e^{\pi * tan1} * \left[(1 + sin1) \,/\, (1 - sin1)\right] = 1.09 \end{aligned} \tag{3.4}$$

$$N_c = \ (Nq - 1) * cot\varphi = (1,09 - 1) * cot1 = 5,38 \tag{3.5}$$

$$N_\gamma = \ (Nq - 1) * tan\,(1,4 * \varphi) = 0,00 \tag{3.6}$$

$$\begin{aligned} \lambda_{cs} &= 1 + 0,2\,(B/L) * tan^2\,(45 + \varphi/2) = \\ &1 + 0,2\,(20/40) * tan^2\,(45 + 1/2) = 1,104 \end{aligned} \tag{3.7}$$

$$\begin{aligned} \lambda_{\gamma s} = \lambda_{qs} &= 1 + 0,1\,(B/L) * tan^2\,(45 + \varphi/2) \\ &= 1 + 0,1\,(20/40) * tan^2\,(45 + 1/2) = 1,052 \end{aligned} \tag{3.8}$$

$$\begin{aligned} \lambda_{cd} &= 1 + 0,2\,(D_f/B) * tan^2\,(45 + \varphi/2) \\ &= 1 + 0,2\,(1/20) * tan^2\,(45 + 1/2) = 1,010 \end{aligned} \tag{3.9}$$

$$\begin{aligned} \lambda_{qd} = \lambda_{\gamma d} &= 1 + 0,1\,(D_f/B) * tan^2\,(45 + \varphi/2) \\ &= 1 + 0,1\,(1/20) * tan^2\,(45 + 1/2) = 1,005 \end{aligned} \tag{3.10}$$

$$\begin{aligned} q_{ult,r} &= 40 * 5,38 * 1,104 * 1,01 + 1 * 20 * 1,09 * 1,052 * 1,005 \\ &+0,5 * 20 * 20 * 0,00 * 1,052 * 1,005 = 263kN/m^2 \end{aligned} \tag{3.11}$$

$$q_{a,r} = 263/3 = 87,6kN/m^2 \tag{3.12}$$

$$Q_{ult,r} = 263 * 20 * 40 = 210400kN \tag{3.13}$$

$$Q_{a,r} = 87,6 * 20 * 40 = 70080kN \tag{3.14}$$

Ultimate and allowable bearing capacity of the raft foundation is calculated with the method that developed by Meyerhof. According to the calculations, ultimate bearing capacity of the raft is $q_{ult,r,}$ 263 kN/m^2 and allowable bearing capacity of the raft is calculated as 87,6 kN/m^2 for a 3 FOS value.

3.4.2.1. For Case 1 (Pile Length: 15m, Floating).

$$Q_{uc} = A_{sp} * f_{sc} + A_{bp} * q_{cp} \tag{3.15}$$

Where is the A_{sp} pile shaft area, is the f_{sc} pile shaft friction in compression, is the A_{bp} Pile tip area, is the q_c Pile end bearing capacity.

$$f_{sc} : \alpha * c_u \tag{3.16}$$

$$q_{cp} : c_u * N_c \tag{3.17}$$

$$Q_{uc} = 0,9 * 40 * \pi * 1 * 15 + \pi * 1^2/4 * 40 * 9 = 1979kN \tag{3.18}$$

Ultimate capacity of a single pile in compression, Q_{uc}, is calculated as 1979kN. Ultimate capacity of the raft, $Q_{ult,r,}$ is calculated as 210400kN previously.Ultimate load carrying capacity of the piles and raft foundation is calculated as; 1979*78 + 210400 = 364762 kN Factor of safety of the foundation system for the case 1 is calculated below; FOS: 364762/160000 = 2.28

3.4.2.2. For Case 2 (Pile Length: 20m, Floating).

$$Q_{uc} = A_{sp} * f_{sc} + A_{bp} * q_{cp} \tag{3.19}$$

Where A_{sp} pile shaft area, is the f_{sc} pile shaft friction in compression, is the A_{bp} pile tip area, is the q_c pile end bearing capacity.

$$f_{sc} : \alpha * c_u \tag{3.20}$$

$$q_{cp} : c_u * N_c \tag{3.21}$$

$$Q_{uc} = 0,9 * 40 * \pi * 1 * 20 + \pi * 1^2/4 * 40 * 9 = 2545kN \tag{3.22}$$

Ultimate capacity of a single pile in compression, Q_{uc}, is calculated as 2545kN. Ultimate capacity of the raft, $Q_{ult,r,}$ is calculated as 210400kN previously. Ultimate load carrying capacity of the piles and raft foundation is calculated as; 2545*78 + 210400 = 408910kN Factor of safety of the foundation system for the case 2 is calculated below; FOS: 408910/160000 = 2.56

3.4.2.3. For Case 3 (Pile Length: 25m, Floating).

$$Q_{uc} = A_{sp} * f_{sc} + A_{bp} * q_{cp} \tag{3.23}$$

Where A_{sp} pile shaft area, is the f_{sc} pile shaft friction in compression, is the A_{bp} pile tip area, is the q_c pile end bearing capacity.

$$f_{sc} : \alpha * c_u \tag{3.24}$$

$$q_{cp} : c_u * N_c \tag{3.25}$$

$$Q_{uc} = 0,9 * 40 * \pi * 1 * 25 + \pi * 1^2/4 * 40 * 9 = 3110kN \tag{3.26}$$

Ultimate capacity of a single pile in compression, Q$_{uc}$, is calculated as 3110kN. Ultimate capacity of the raft, Q$_{ult,r}$, is calculated as 210400kN previously. Ultimate load carrying capacity of the piles and raft foundation is calculated as; 3110*78 + 210400 = 452980kN Factor of safety of the foundation system for the case 3 is calculated below; FOS: 452980/160000 = 2.83.

3.4.2.4. For Case 4 (Pile Length: 30m, Floating).

$$Q_{uc} = A_{sp} * f_{sc} + A_{bp} * q_{cp} \tag{3.27}$$

Where is the A_{sp} pile shaft area, is the f_{sc} pile shaft friction in compression, is the A_{bp} pile tip area, is the q_c pile end bearing capacity.

$$f_{sc} : \alpha * c_u \tag{3.28}$$

$$q_{cp} : c_u * N_c \tag{3.29}$$

$$Q_{uc} = 0,9 * 40 * \pi * 1 * 30 + \pi * 1^2/4 * 40 * 9 = 3675kN \tag{3.30}$$

Ultimate capacity of a single pile in compression, Q$_{uc}$, is calculated as 3675kN. Ultimate capacity of the raft, Q$_{ult,r}$, is calculated as 210400kN previously. Ultimate load carrying capacity of the piles and raft foundation is calculated as; 3675*78 + 210400 = 497050kN Factor of safety of the foundation system for the case 4 is calculated below; FOS: 452980/160000 = 3.1.

The overview of factor of safety values are shown in Table 3.4 for piled raft foundation systems that designed with 78 floating piles.

Table 3.4. Comparison Table of FOS of Piled Raft Foundation Systems with Floating Piles.

Floating Piles	
Pile Length(m)	FOS
15	2.28
20	2.56
25	2.83
30	3.10

3.4.2.5. For Case 5 (Pile Length: 13m, End-Bearing).

$$Q_{uc} = A_{sp} * f_{sc} + A_{bp} * q_{cp} \tag{3.31}$$

Where is the A_{sp} pile shaft area, f_{sc} pile shaft friction in compression, is the A_{bp} pile tip area, is the q_c Pile end bearing capacity

$$f_{sc} : 2 * N_{\varphi} * q_{uo} \tag{3.32}$$

$$N_{\varphi} = tan^2 \left(45 + \varphi/2\right) = tan^2 \left(45 + 30/2\right) = 3 \tag{3.33}$$

$$q_{cp} : c_u * N_c \tag{3.34}$$

$$Q_{uc} = 0,9 * 40 * \pi * 1 * 10 + \pi * 1^2/4 * 2 * 3 * 8000 = 38830kN \tag{3.35}$$

Ultimate capacity of a single pile in compression, Q_{uc}, is calculated as 38830kN. Ultimate capacity of the raft, $Q_{ult,r}$, is calculated as 210400kN previously. Ultimate load carrying capacity of the piles and raft foundation is calculated as; 38830*36 + 210400

= 1608280kN Factor of safety of the foundation system for the case 5 is calculated below; FOS: 1608280/470000 = 3,42

3.4.2.6. For Case 6 (Pile Length: 18m, End-Bearing).

$$Q_{uc} = A_{sp} * f_{sc} + A_{bp} * q_{cp} \tag{3.36}$$

Where is the A_{sp} pile shaft area, is the f_{sc} pile shaft friction in compression, is the A_{bp} pile tip area, is the q_c pile end bearing capacity.

$$f_{sc} : 2 * N_{\varphi} * q_{uo} \tag{3.37}$$

$$N_{\varphi} = tan^2\left(45 + \varphi/2\right) = tan^2\left(45 + 30/2\right) = 3 \tag{3.38}$$

$$q_{cp} : c_u * N_c \tag{3.39}$$

$$Q_{uc} = 0,9 * 40 * \pi * 1 * 15 + \pi * 1^2/4 * 2 * 3 * 8000 = 39395kN \tag{3.40}$$

Ultimate capacity of a single pile in compression, Q$_{uc}$, is calculated as 39395kN. Ultimate capacity of the raft, Q$_{ult,r}$, is calculated as 210400kN previously. Ultimate load carrying capacity of the piles and raft foundation is calculated as; 39395*36 + 210400 = 1628620kN. Factor of safety of the foundation system for the case 6 is calculated below; FOS: 1628620/470000 = 3.46.

3.4.2.7. For Case 7 (Pile Length: 23m, End-Bearing).

$$Q_{uc} = A_{sp} * f_{sc} + A_{bp} * q_{cp} \tag{3.41}$$

Where is the A_{sp} pile shaft area, is the f_{sc} pile shaft friction in compression, is the A_{bp} pile tip area, is the q_c Pile end bearing capacity.

$$f_{sc} : 2 * N_{\varphi} * q_{uo} \tag{3.42}$$

$$N_{\varphi} = tan^2\left(45 + \varphi/2\right) = tan^2\left(45 + 30/2\right) = 3 \tag{3.43}$$

$$q_{cp} : c_u * N_c \tag{3.44}$$

$$Q_{uc} = 0,9 * 40 * \pi * 1 * 20 + \pi * 1^2/4 * 2 * 3 * 8000 = 39961kN \tag{3.45}$$

Ultimate capacity of a single pile in compression, Q$_{uc}$, is calculated as 39961kN. Ultimate capacity of the raft, Q$_{ult,r}$, is calculated as 210400kN previously. Ultimate load carrying capacity of the piles and raft foundation is calculated as; 39961*36 + 210400 = 1648996kN. Factor of safety of the foundation system for the case 7 is calculated below; FOS: 1648996/470000 = 3.51. The overview of factor of safety values are shown in Table 3.5 for piled raft foundation systems that designed with 36 end bearing piles.

Table 3.5. Comparison Table of FOS of Piled Raft Foundation Systems with End Bearing Piles.

End Bearing Piles	
Pile Length(m)	FOS
13	3.42
18	3.46
23	3.51

3.4.3. Analyses of Piled Raft Foundations Section 1 - Piled Raft Foundations with Floating Piles

Table 3.6. Short Term Results of FEM Model for Case 1.

	Piled Raft Foundation [Case 1(15m)]			
On Clay		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	710	191.5	244.2
	2	435.3	133.3	254.5
	3	479.4	52.79	112.9
	4	475.3	57.69	118.6
	5	435.5	128.7	252.7
	6	708.2	193.1	244.7
		Total Pile Load(kN)		3243.7
		Raft Load(kN)		756.3
		Carried Proportion By Piles (%)		81.1
		Carried Proportion By the Raft(%)		18.9

Table 3.7. Long Term Results of FEM Model for Case 1.

	Piled Raft Foundation [Case 1(15m)]			
On Clay		Static(Long-Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	773.5	176.5	299.1
	2	395.5	70.8	271.4
	3	404.5	28.82	96.2
	4	403.5	28.72	95.92
	5	395.5	70.74	218.4
	6	772.7	176.2	299
		Total Pile Load(kN)		3145.8
		Raft Load(kN)		854.2
		Carried Proportion By Piles (%)		78.6
		Carried Proportion By the Raft(%)		21.4

Table 3.8. Short Term Results of FEM Model for Case 2.

	Piled Raft Foundation [Case 2(20m)]			
On Clay		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	781.9	171	261.4
	2	396.9	132.8	319.2
	3	442.5	58.35	144.5
	4	443	57.45	142.4
	5	401.1	133.3	317.8
	6	788.9	170.2	258.9
		Total Pile Load(kN)		3244.3
		Raft Load(kN)		755.7
		Carried Proportion By Piles (%)		81.1
		Carried Proportion By the Raft(%)		18.9

Table 3.9. Long Term Results of FEM Model for Case 2.

	Piled Raft Foundation [Case 2(20m)]			
On Clay		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	928	213.7	427.5
	2	335.5	107.7	318.1
	3	405.2	41.11	127.6
	4	404.9	40.9	127
	5	330.8	107.8	318.6
	6	930	213.3	428.1
		Total Pile Load(kN)		3332.4
		Raft Load(kN)		667.6
		Carried Proportion By Piles (%)		83.3
		Carried Proportion By the Raft(%)		16.7

Table 3.10. Short Term Results of FEM Model for Case 3.

	Piled Raft Foundation [Case 3(25m)]			
On Clay		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	839.5	156.3	250
	2	378	128	316.5
	3	437.2	54.2	140.5
	4	437.7	54.37	141.6
	5	378.4	128.4	317.4
	6	839.7	155.8	249.2
		Total Pile Load(kN)		3310.5
		Raft Load(kN)		689.5
		Carried Proportion By Piles (%)		82.8
		Carried Proportion By the Raft(%)		17.2

Table 3.11. Long term Results of FEM Model for Case 3.

	Piled Raft Foundation [Case 3(25m)]			
On Clay		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	913.5	132.4	253.4
	2	374.2	78.76	235.4
	3	450.9	31.28	99.15
	4	451.1	31.29	99.2
	5	374.1	78.76	235.5
	6	913.5	132.4	253.4
		Total Pile Load(kN)		3477.3
		Raft Load(kN)		522.7
		Carried Proportion By Piles (%)		86.9
		Carried Proportion By the Raft(%)		13.1

Table 3.12. Short Term Results of FEM Model for Case 4.

	Piled Raft Foundation [Case 4(30m)]			
On Clay		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	864.2	151.1	244.5
	2	373.4	129.5	316.3
	3	449.5	53.39	10.88
	4	447.2	53.43	138.7
	5	374.8	129.7	316.4
	6	865.1	151	243.7
		Total Pile Load(kN)		3374.2
		Raft Load(kN)		625.8
		Carried Proportion By Piles (%)		84.4
		Carried Proportion By the Raft(%)		15.6

Table 3.13. Long Term Results of FEM Model for Case 4.

	Piled Raft Foundation [Case 4(30m)]			
On Clay		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	1043	204.4	452.6
	2	333.4	106.9	351.7
	3	405.6	39.01	138.8
	4	405.2	38.97	138.7
	5	333.8	106.9	351.6
	6	1042	204.3	94.48
		Total Pile Load(kN)		3563
		Raft Load(kN)		437
		Carried Proportion By Piles (%)		89.1
		Carried Proportion By the Raft(%)		10.9.

3.4.3.1. Finite Elements Method. Table 3.6 to Table 3.13 gives the results of the FEM analyses. By using finite elements method, piled raft foundation systems are analyzed for the pile lengths 15m, 20m, 25m and 30m. According to the results of the short term analyses, carried load proportion of the raft is calculated as 18.9%, 18.9%, 17.2% ve 15.6%, respectively. In long term, the carried proportion of the raft is calculated as 21.4%, 16.7%, 13.1% and 10.9%, respectively. For longer pile lengths, normal forcesthat carried by the piles are increased. As it can be seen from the analyses results, because of increasing stiffness of the pile group, increasing pile length brings together increasing load proportion carried by the piles.

In long term, the carried load proportion of the raft is little bit lower than short term proportions. Due to the lower young's modulus and poisson's ratio used in the long term behavior, it is reasonable to obtain lower proportion of the rafts.

3.4.3.2. Simplified Approaches. To determine the load sharing ratio between the raft piles, two different approaches are used. To estimate single pile stiffness, an equation developed by Randolph (1994) that considers the pile length is used. A commercial software, Microsoft Excel, is used for analyses.

Table 3.14. Simplified Approaches Input Table for Case 1 (Short Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	20000	1	15	78

Young's modulus of the soil at level of pile tip (kN/m^2)	20000		Raft Information	
			Young's Modulus of the soil below the raft, Esr (kN/m^2)	20000
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)	20000		Poisson's Ratio, υ	0.45
			Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2)	20000		Length of the Long side of the raft, L(m)	40
Total load carried by Foundation System(kN)	160000		Depth of the Raft, Df (m)	1
			Effective Depth of the Raft, de(m)	1

Table 3.15. Simplified Approaches Calculation Table for Case 1 (Short Term).

CALCULATIONS				
Shear Modulus of the Soil, G1 (kN/m^2)	6896.55			
Shear Modulus of the Soil at pile base, G_b(kN/m^2)	6896.55			
Average shear Modulus along the pile, G_{avg}(kN/m^2)	6896.55			
Shear Modulus of the Soil below the raft, G (kN/m^2)	6896.55			
Area of a Single Pile, A (m^2)	0.785			
Pile Radius at tip, r0 (m)	0.5			
Pile Radius at base, rb (m)	0.5			
Vertical Pile Stiffness			Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	196706		Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	1737263		Stiffness of the Raft, Kr(kN/m^2)	907566
Foundation System				
Equivalent Raft Radius, rc(m)	10.26		Poulos' Approach	
ρ	1		Raft Pile Interaction Factor, α_{cp}	0.1878
ζ	1		Carried load proportion by raft, X	0.32
rm	20.625		Stiffness of Piled Raft, K_{pr}(kN/m)	2347175
ζ	3.7197		Randolph's Approach	
η	1.0000		Raft Pile Interaction Factor, α	0.1795
λ	4393.5		Carried load proportion by raft, O	0.15
μ_l	0.0039		Stiffness of Piled Raft, K_{pr}(kN/m)	1791800

Table 3.16. Simplified Approaches Results Table for Case 1 (Short Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	32	Proportion Carried By the Raft, %	15.2
Proportion Carried By Piles, %	68	Proportion Carried By Piles, %	84.8
Qraft(kN)	51190.1	Qraft(kN)	24349.4
Qpiles(kN)	108810	Qpiles(kN)	135650.6
Elastic Settlement of the Foundation System, Spr(cm)	6.8	Elastic Settlement of the Foundation System, Spr(cm)	8.9

Table 3.11, Table 3.12 and Table 3.13 shows the details of the calculations. Ac-

cording to the approaches that developed by Randolph and Poulos, in short term, carried proportion of the raft is estimated as 15.2% and 32.0, respectively for 15m floating piles. Elastic Settlement of the piled raft foundation system is calculated as 6.8 cm and 8.9 cm.

Table 3.17. Simplified Approaches Input Table for Case 1 (Long Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	17333	1	15	78
Young's modulus of the soil at level of pile tip (kN/m^2)		17333		Raft Information	
				Young's Modulus of the soil below the raft, Esr (kN/m^2)	17333
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		17333		Poisson's Ratio,υ	0.3
				Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2)		17333		Length of the Long side of the raft, L(m)	40
				Depth of the Raft, Df (m)	1
Total load carried by Foundation System(kN)		160000		Effective Depth of the Raft, de(m)	1

Table 3.18. Simplified Approaches Calculation Table for Case 1 (Long Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	6666.538		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	6666.538		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	6666.538		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6666.538		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	175564.6	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	1550544.8	Stiffness of the Raft, Kr(kN/m^2)	689305
Foundation System			
Equivalent Raft Radius, rc(m)	10.26	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	0.2373
ζ	1	Carried load proportion by raft, X	0.27
rm	26.2500	Stiffness of Piled Raft, K$_{pr}$(kN/m)	1961851
ζ	3.9608	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.1380
λ	4545.087	Carried load proportion by raft, O	0.12
μ_l	0.00383	Stiffness of Piled Raft, K$_{pr}$(kN/m)	1589081

Table 3.19. Simplified Approaches Results Table for Case 1 (Long Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	27.5	Proportion Carried By the Raft, %	12.1
Proportion Carried By Piles, %	72.5	Proportion Carried By Piles, %	87.9
Qraft(kN)	43979.1	Qraft(kN)	19400.6
Qpiles(kN)	116020.9	Qpiles(kN)	140599.4
Elastic Settlement of the Foundation System, Spr(cm)	8.2	Elastic Settlement of the Foundation System, Spr(cm)	10.1

According to the approaches that developed by Randolph and Poulos, in long term term, carried proportion of the raft is estimated as 27.5% and 12.1, respectively for 15m floating piles. These values are little bit lower than the short term case. The details of the calculation is given in the Table 3.17, Table 3.18 and Table 3.19.

Table 3.20. Simplified Approaches Input table for Case 2 (Short Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	20000	1	20	78
				Raft Information	
Young's modulus of the soil at level of pile tip (kN/m^2)		20000		Young's Modulus of the soil below the raft, Esr (kN/m^2)	20000
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		20000		Poisson's Ratio,υ	0.45
				Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2)		20000		Length of the Long side of the raft, L(m)	40
Total load carried by Foundation System(kN)		160000		Depth of the Raft, Df (m)	1
				Effective Depth of the Raft, de(m)	1

Table 3.21. Simplified Approaches Calculation Table for Case 2 (Short Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	6666.538		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	6896.552		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	6896.552		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6896.552		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	236354.6	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	2087427.5	Stiffness of the Raft, Kr(kN/m^2)	907566
Foundation System			
Equivalent Raft Radius, rc(m)	10.26	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	0.2461
ζ	1	Carried load proportion by raft, X	0.27
rm	27.50000	Stiffness of Piled Raft, K$_{pr}$(kN/m)	2617182
ζ	4.0073	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.1333
λ	44393.5	Carried load proportion by raft, O	0.12
μ_l	0.003373	Stiffness of Piled Raft, K$_{pr}$(kN/m)	2137726

Table 3.22. Simplified Approaches Results Table for Case 1 (Long Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	26.8	Proportion Carried By the Raft, %	11.8
Proportion Carried By Piles, %	73.2	Proportion Carried By Piles, %	88.2
Qraft(kN)	42959.4	Qraft(kN)	18823.2
Qpiles(kN)	117040.6	Qpiles(kN)	141176.8
Elastic Settlement of the Foundation System, Spr(cm)	6.1	Elastic Settlement of the Foundation System, Spr(cm)	7.5

According to the Poulos' and Randolph's approaches carried proportion by raft is calculated as 26,8% and 11.8% for piled raft foundation system that designed with 20m length floating piles. Elastic settlements values are 6.1m and 7.5cm. The inputs, intermediate levels and the results of the analyses is given in Table 3.20, Table 3.21 and Table 3.22.

Table 3.23. Simplified Approaches Input Table for Case 2 (Long Term).

<table>
<tr><th colspan="7">PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)</th></tr>
<tr><th>Concrete Class</th><th>Young's Modulus of the pile concrete (kN/m^2)</th><th>Young's Modulus of the Soil (kN/m^2)</th><th>Pile Diameter (m)</th><th>Pile Length (m)</th><th colspan="2">Number of Piles</th></tr>
<tr><td>C25</td><td>30300000</td><td>17333</td><td>1</td><td>20</td><td colspan="2">78</td></tr>
<tr><td colspan="2" rowspan="2">Young's modulus of the soil at level of pile tip (kN/m^2)</td><td rowspan="2">17333</td><td rowspan="7"></td><td colspan="3">Raft Information</td></tr>
<tr><td colspan="2">Young's Modulus of the soil below the raft, Esr (kN/m^2)</td><td>17333</td></tr>
<tr><td colspan="2" rowspan="2">Young's modulus of the bearing stratum at level of pile tip (kN/m^2)</td><td rowspan="2">17333</td><td colspan="2">Poisson's Ratio,υ</td><td>0.3</td></tr>
<tr><td colspan="2">Length of the short side of the raft, B (m)</td><td>20</td></tr>
<tr><td colspan="2" rowspan="2">Average Young's modulus along the pile shaft (kN/m^2)</td><td rowspan="2">17333</td><td colspan="2">Length of the Long side of the raft, L(m)</td><td>40</td></tr>
<tr><td colspan="2">Depth of the Raft, Df (m)</td><td>1</td></tr>
<tr><td colspan="2">Total load carried by Foundation System(kN)</td><td>160000</td><td colspan="2">Effective Depth of the Raft, de(m)</td><td>1</td></tr>
</table>

Table 3.24. Simplified Approaches Calculation Table for Case 2 (Long Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	6666.538		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	6666.538		
Average shear Modulus along the pile,G$_{avg}$(kN/m^2)	6666.538		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6666.538		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	212819.4	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	1879570.3	Stiffness of the Raft, Kr(kN/m^2)	689305
Foundation System			
Equivalent Raft Radius, rc(m)	10.26	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	0.2889
ζ	1	Carried load proportion by raft, X	0.23
rm	35.0000	Stiffness of Piled Raft, K$_{pr}$(kN/m)	2239120
ζ	4.2485	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.1038
λ	4545.087	Carried load proportion by raft, O	0.09
μ_l	0.003317	Stiffness of Piled Raft, K$_{pr}$(kN/m)	1915599

Table 3.25. Simplified Approaches Results Table for Case 2 (Long Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	22.6	Proportion Carried By the Raft, %	9.4
Proportion Carried By Piles, %	77.4	Proportion Carried By Piles, %	90.6
Qraft(kN)	36130.9	Qraft(kN)	15046.3
Qpiles(kN)	123869.1	Qpiles(kN)	144953.7
Elastic Settlement of the Foundation System, Spr(cm)	7.1	Elastic Settlement of the Foundation System, Spr(cm)	8.4

As it can be seen in Table 3.23, Table 3.24 and Table 3.25, in long term, the values of 22.6% and 9.4% is obtained for the carried proportion by the raft in piled raft foundation system. The elastic settlements of the foundation system are calculated as 7.1 cm and 8.4 cm with simplified approaches available in literature.

Table 3.26. Simplified Approaches Input Table for Case 3 (Short Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	20000	1	25	78
Young's modulus of the soil at level of pile tip (kN/m^2)		20000		Raft Information	
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		20000		Young's Modulus of the soil below the raft, Esr (kN/m^2)	20000
Average Young's modulus along the pile shaft (kN/m^2)		20000		Poisson's Ratio,υ	0.45
Total load carried by Foundation System(kN)		160000		Length of the short side of the raft, B (m)	20
				Length of the Long side of the raft, L(m)	40
				Depth of the Raft, Df (m)	1
				Effective Depth of the Raft, de(m)	1

Table 3.27. Simplified Approaches Calculation Table for Case 3 (Short Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	6896.552		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	6896.552		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	6896.552		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6896.552		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	273925.4	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	2419243.8	Stiffness of the Raft, Kr(kN/m^2)	907566
Foundation System			
Equivalent Raft Radius, rc(m)	10.26	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	0.2859
ζ	1	Carried load proportion by raft, X	0.23
rm	34.3750	Stiffness of Piled Raft, K$_{pr}$(kN/m)	2896707
ζ	4.2305	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.1072
λ	4393.5	Carried load proportion by raft, O	0.10
μ_l	0.003017	Stiffness of Piled Raft, K$_{pr}$(kN/m)	247016

Table 3.28. Simplified Approaches Results Table for Case 3 (Short Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	23.1	Proportion Carried By the Raft, %	9.7
Proportion Carried By Piles, %	76.9	Proportion Carried By Piles, %	90.3
Qraft(kN)	36930.6	Qraft(kN)	15491.6
Qpiles(kN)	123069.4	Qpiles(kN)	144508.4
Elastic Settlement of the Foundation System, Spr(cm)	5.5	Elastic Settlement of the Foundation System, Spr(cm)	6.5

For 25m pile length, according to the results of the analysis of two different approaches, carried load proportion of the raft is calculated as 23.1% and 9.7%. Elastic settlements of the piled raft foundation system are estimated as 5,5cm and 6.5cm. The details of the calculations is given in Table 3.26, Table 3.27 and Table 3.28.

Table 3.29. Simplified Aapproaches Input Table for Case 3 (Long Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	17333	1	25	78
Young's modulus of the soil at level of pile tip (kN/m^2)		17333		Raft Information	
				Young's Modulus of the soil below the raft, Esr (kN/m^2)	17333
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		17333		Poisson's Ratio,υ	0.3
				Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2) Total load carried		17333		Length of the Long side of the raft, L(m)	40
				Depth of the Raft, Df (m)	1
by Foundation System(kN)		160000		Effective Depth of the Raft, de(m)	1

Table 3.30. Simplified Approaches Calculation Table for Case 2 (Long Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	6666.538		
Shear Modulus of the Soil at pile base, G_b(kN/m^2)	6666.538		
Average shear Modulus along the pile, G_{avg}(kN/m^2)	6666.538		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6666.538		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	248254.1	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	2192520.6	Stiffness of the Raft, Kr(kN/m^2)	689305
Foundation System			
Equivalent Raft Radius, rc(m)	10.26	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	0.3244
ζ	1	Carried load proportion by raft, X	0.19
rm	43.7500	Stiffness of Piled Raft, K_{pr}(kN/m)	2517911
ζ	4.4716	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0840
λ	4545.087	Carried load proportion by raft, O	0.08
μ_l	0.002967	Stiffness of Piled Raft, K_{pr}(kN/m)	2227038

Table 3.31. Simplified Approaches Results Table for Case 3 (Long Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	19.1	Proportion Carried By the Raft, %	7.7
Proportion Carried By Piles, %	80.9	Proportion Carried By Piles, %	92.3
Qraft(kN)	30605.1	Qraft(kN)	12399.4
Qpiles(kN)	129394.9	Qpiles(kN)	147600.6
Elastic Settlement of the Foundation System, Spr(cm)	6.4	Elastic Settlement of the Foundation System, Spr(cm)	7.2

Table 3.29, Table 3.30 and Table 3.31 shows the details of the simplified analyses. Compare with short term, a lower value of the load proportion carried by the raft is obtained by using Randolph's and Poulos' approaches in long term. The superstructural load proportion carried by the raft is obtained as 19.1% and 7.7%.

Table 3.32. Simplified Approaches Input Table for Case 4 (Short Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	20000	1	30	78
Young's modulus of the soil at level of pile tip (kN/m^2)		20000		Raft Information	
				Young's Modulus of the soil below the raft, Esr (kN/m^2)	20000
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		20000		Poisson's Ratio,υ	0.45
				Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2)		20000		Length of the Long side of the raft, L(m)	40
Total load carried by Foundation System(kN)		160000		Depth of the Raft, Df (m)	1
				Effective Depth of the Raft, de(m)	1

Table 3.33. Simplified Approaches Calculation Table for Case 4 (Short Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	6896.552		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	6896.552		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	6896.552		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6896.552		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	309863.2	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	2736637.4	Stiffness of the Raft, Kr(kN/m^2)	907566
Foundation System			
Equivalent Raft Radius, rc(m)	10.26	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	0.3154
ζ	1	Carried load proportion by raft, X	0.20
rm	41.2500	Stiffness of Piled Raft, K$_{pr}$(kN/m)	3176517
ζ	4.4128	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0903
λ	4393.5	Carried load proportion by raft, O	0.08
μ_l	0.002754	Stiffness of Piled Raft, K$_{pr}$(kN/m)	2782721

Table 3.34. Simplified Approaches Results Table for Case 3 (Short Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	20.2	Proportion Carried By the Raft, %	8.3
Proportion Carried By Piles, %	79.8	Proportion Carried By Piles, %	91.7
Qraft(kN)	32263.8	Qraft(kN)	13248.6
Qpiles(kN)	127636.2	Qpiles(kN)	146751.4
Elastic Settlement of the Foundation System, Spr(cm)	5.0	Elastic Settlement of the Foundation System, Spr(cm)	5.7

As it can be seen in the Table 3.32, Table 3.33 and Table 3.34, the carried load proportion of the raft is estimated as 20.2% and 8.3% according to Poulos' and Randolph's approaches, respectively. Elastic settlement of the foundation system is calculated as 5.0 cm and 5.7 cm.

Table 3.35. Simplified Approaches Input Table for Case 4 (Long Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	17333	1	30	78
Young's modulus of the soil at level of pile tip (kN/m^2)		17333		Raft Information	
				Young's Modulus of the soil below the raft, Esr (kN/m^2)	17333
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		17333		Poisson's Ratio,υ	0.3
				Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2) Total load carried		17333		Length of the Long side of the raft, L(m)	40
				Depth of the Raft, Df (m)	1
by Foundation System(kN)		160000		Effective Depth of the Raft, de(m)	1

Table 3.36. Simplified Approaches Calculation Table for Case 4 (Long Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	6666.538		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	6666.538		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	6666.538		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6666.538		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	282270.1	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	2492941.7	Stiffness of the Raft, Kr(kN/m^2)	689305
Foundation System			
Equivalent Raft Radius, rc(m)	10.26	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	0.3509
ζ	1	Carried load proportion by raft, X	0.17
rm	52.5000	Stiffness of Piled Raft, K$_{pr}$(kN/m)	2793634
ζ	4.6540	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0710
λ	4545.087	Carried load proportion by raft, O	0.07
μ_l	0.002708	Stiffness of Piled Raft, K$_{pr}$(kN/m)	2526442

Table 3.37. Simplified Approaches Results Table for Case 4 (Long Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	16.6	Proportion Carried By the Raft, %	6.6
Proportion Carried By Piles, %	83.4	Proportion Carried By Piles, %	93.4
Qraft(kN)	26530.0	Qraft(kN)	10608.0
Qpiles(kN)	133470.0	Qpiles(kN)	149392.0
Elastic Settlement of the Foundation System, Spr(cm)	5.7	Elastic Settlement of the Foundation System, Spr(cm)	6.3

The input and intermediate parameters can be seen in Table 3.35 and Table 3.36, respectively. The result of the analyses of the simplified approaches for Case 4 is given in Table 3.37.

For piled raft foundation systems with floating piles, an overview of the carried proportion of the load by the raft is given in Table 3.38.

Table 3.38. Carried Proportion of the Load by the Raft for Floating Piles.

	Pile Length (m)	FEM %	Poulos %	Randolph %
Floating	15 (Short Term)	18.9	32	15.2
	15 (Long Term)	21.4	27.5	13.1
	20 (Short Term)	18.9	26.8	11.8
	20 (Long Term)	16.7	22.6	9.4
	25 (Short Term)	17.2	23.1	9.7
	25 (Long Term)	13.1	19.1	7.7
	30 (Short Term)	15.6	20.2	8.3
	30 (Long Term)	10.9	16.6	6.6

According to the results from Finite Element Method, Poulos' Method gives higher carried load proportion by the raft. Additionally, Randolph's Method gives conservative results for load sharing ratios between raft and piles. Additionally, the carried proportion of the load by the raft is slightly lower in long term.

This study basicly focused on short term behavior because it is assumed that construction will be very fast. Elastic displacements of the piles calculated by finite elements method are given tables below.

Table 3.39. Short Term Elastic Displacements of the piles for Case 1.

Elastic Displacements of the Piles (mm) (Short Term)				
On Clay Piles	Pile No	$Uy_{(tip)}$	$Uy_{(Top)}$	Elastic Displacement
Piled	1	104.705	104.904	0.199
Raft	2	106.835	106.977	0.142
Foundation	3	108.224	108.372	0.148
Case 1	4	108.267	108.414	0.147
(15m)	5	106.95	107.092	0.142
(Static)	6	104.891	105.089	0.198

Table 3.40. Short Term Elastic Displacements of the piles for Case 2.

Elastic Displacements of the Piles (mm) (Short Term)				
On Clay Piles	Pile No	$Uy_{(tip)}$	$Uy_{(Top)}$	Elastic Displacement
Piled	1	76.983	77.283	0.3
Raft	2	79.451	79.633	0.182
Foundation	3	81.01	81.199	0.189
Case 2	4	81.066	81.255	0.189
(20m)	5	79.629	79.808	0.179
(Static)	6	77.294	77.592	0.298

Table 3.41. Short Term Elastic Displacements of the piles for Case 3.

Elastic Displacements of the Piles (mm) (Short Term)				
On Clay Piles	Pile No	Uy$_{(tip)}$	Uy$_{(Top)}$	Elastic Displacement
Piled Raft Foundation Case 3 (25m) (Static)	1	59.922	60.327	0.405
	2	62.537	62.757	0.22
	3	64.13	64.361	0.231
	4	64.115	64.347	0.232
	5	62.497	62.718	0.221
	6	59.863	60.269	0.406

Table 3.42. Short Term Elastic Displacements of the piles for Case 4.

Elastic Displacements of the Piles (mm) (Short Term)				
On Clay Piles	Pile No	Uy$_{(tip)}$	Uy$_{(Top)}$	Elastic Displacement
Piled Raft Foundation Case 4 (30m) (Static-Short Term)	1	47.631	48.135	0.504
	2	50.384	50.641	0.257
	3	52.009	52.287	0.278
	4	52.023	52.299	0.276
	5	50.416	50.675	0.259
	6	47.693	48.197	0.504

According to the results of the analyses, which is shown in Table 3.39, Table 3.40 Table 3.41 and Table 3.42, settlements of the foundation system are decreased with longer piles but elastic displacements of the piles are increased. These results can be explained with the carried load proportion by the piles. As it is expected, with longer piles, settlement values of the foundation system decreases.

Maximum and minimum displacements and internal forces of the raft is given in the tables below;

Table 3.43. Short Term Deflections of the Raft Foundation for Floating Piles.

Maximum and Minimum Deflections of the Raft (Short Term)				
Case		Max.(m)	Min.(m)	Differential (m)
On Clay	Case 1 (15m)	0.1087	0.1047	0.004
	Case 2 (20m)	0.08158	0.07697	0.00461
	Case 3 (25m)	0.06472	0.05996	0.00476
	Case 4 (30m)	0.05266	0.0478	0.00486

Table 3.44. Short Term Internal Forces of the Raft Foundation for Floating Piles.

Internal Forces of the Raft (Short Term)				
Case		N(kN)	V(kN)	M(kNm)
On Clay	Case 1 (15m)	371.7	466.8	923.8
	Case 2 (20m)	354.7	517.7	999.9
	Case 3 (25m)	324.9	536.9	1047
	Case 4 (30m)	320.1	541.2	1059

Short term deflections and internal forces occurred on the raft can be seen in Table 3.43 and Table 3.44, respectively. For the same raft thickness, increasing load carrying proportion brings together higher differential settlement values. According to the research from literature, raft thickness has a significant effect on differential settlements.

With longer piles, as it is expected, total settlement values are increased. Shear forces and moment values are higher for longer pile lengths. With increasing pile length, carried load proportion by the raft is decreased. Due to this condition, shear forces of the piles increase.

According to the finite elements method, deflections on the raft is calculated as shown below,

Table 3.45. Short Term Settlements of Foundation System for Floating Piles.

	Settlements(m) (Short Term)			
On Clay	Case No	Node 1 (7m)	Node 2 (10m)	Node 3 (13m)
	Case 1(15m)	0.1054	0.1087	0.1079
	Case 2(20m)	0.07784	0.08158	0.08075
	Case 3(25m)	0.06092	0.06472	0.06376
	Case 4(30m)	0.04872	0.05266	0.05177

The short term settlements of the piled raft foundations with floating piles are given in the Table 3.45. According to the results of the analyses, for 15m pile length, foundation system settles 10.8mm in average, however, for 30m pile length, settlement values are calculated as 5.3mm. It can be seen from literature, increase of the pile length causes lower settlement values. For piled raft foundation systems with floating piles, an overview of the carried proportion of the load by the raft is given in Table 3.46.

Table 3.46. Overwiev of the Results for Floating Piles for Static Case.

	Pile Length (m)	FEM (%)	Poulos (%)	Randolph (%)
Floating	15 (Short Term)	18.9	32	15.2
	15 (Long Term)	21.4	27.5	13.1
	20 (Short Term)	18.9	26.8	11.8
	20 (Long Term)	16.7	22.6	9.4
	25 (Short Term)	17.2	23.1	9.7
	25 (Long Term)	13.1	19.1	7.7
	30 (Short Term)	15.6	20.2	8.3
	30 (Long Term)	10.9	16.6	6.6

3.4.4. Section 2 - Piled Raft Foundations with End Bearing Piles

3.4.4.1. Finite Elements Method. For piled raft foundation systems with end bearing piles, internal forces of the piles, load sharing ratio between the pile group and the raft is given below;

Table 3.47. Short Term Results of FEM Model for Case 5.

	Piled Raft Foundation [Case 5(10m+3m)]			
		Static(Short Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
On Rock	1	2208	199.1	252.6
	2	1580	82.33	123.1
	3	1427	19.46	27.53
	4	1432	27.63	34.1
	5	1589	75.87	117.8
	6	2207	200.8	252.2
		Total Pile Load(kN)		10443
		Raft Load(kN)		1307
		Carried Proportion By Piles (%)		88.9
		Carried Proportion By the Raft(%)		11.1

Table 3.48. Short Term Results of FEM Model for Case 5.

	Piled Raft Foundation [Case 5(10m+3m)]			
On Rock		Static(Long-Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	2481	61.7	62.26
	2	1580	23.06	47.15
	3	1457	12.54	22.8
	4	1459	18.7	22.74
	5	1581	22.95	46.86
	6	2479	57.55	59.07
		Total Pile Load(kN)		11037
		Raft Load(kN)		713
		Carried Proportion By Piles (%)		93.9
		Carried Proportion By the Raft(%)		6.1

Table 3.49. Short Term Results of FEM Model for Case 6.

	Piled Raft Foundation [Case 5(10m+3m)]			
On Rock		Static(Long-Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	2292	161.6	182
	2	1687	43.57	61.98
	3	1556	12.24	17.58
	4	1556	12.18	17.58
	5	1690	43.46	62.01
	6	2291	161.4	181.9
		Total Pile Load(kN)		11072
		Raft Load(kN)		678
		Carried Proportion By Piles (%)		94.2
		Carried Proportion By the Raft(%)		5.8

Table 3.50. Long Term Results of FEM Model for Case 6.

	Piled Raft Foundation [Case 5(10m+3m)]			
On Rock		Static(Long-Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	2455	53.8	52.18
	2	1623	20.37	41.48
	3	1473	16.32	20.82
	4	1473	8.63	20.71
	5	1623	20.35	41.41
	6	2455	54.71	50.07
		Total Pile Load(kN)		11102
		Raft Load(kN)		648
		Carried Proportion By Piles (%)		94.5
		Carried Proportion By the Raft(%)		5.5

Table 3.51. Long Term Results of FEM Model for Case 6.

	Piled Raft Foundation [Case 5(10m+3m)]			
On Rock		Static(Long-Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	2395	108	133.9
	2	1634	36.53	51.49
	3	1512	10.34	14.87
	4	1512	10.37	14.89
	5	1635	36.55	51.52
	6	23955	107.4	133.8
		Total Pile Load(kN)		11083
		Raft Load(kN)		667
		Carried Proportion By Piles (%)		94.3
		Carried Proportion By the Raft(%)		5.7

Table 3.52. Long Term Results of FEM Model for Case 7.

	Piled Raft Foundation [Case 5(10m+3m)]			
On Rock		Static(Long-Term) Case		
	Pile No	N (kN)	V (kN)	M (kNm)
	1	2479	51.35	54.05
	2	1644	27.24	42.48
	3	1473	9.362	21.6
	4	1473	13.6	21.64
	5	1644	20.9	42.53
	6	2480	55.2	54.78
		Total Pile Load(kN)		11193
		Raft Load(kN)		557
		Carried Proportion By Piles (%)		95.3
		Carried Proportion By the Raft(%)		4.7

The short term and long term analyses results of the FEM are given in Table 3.47 to Table 3.52. Finite elements analyses are performed for piled raft foundation systems with 13m, 18m and 23m piles lengths that penetrate 3m into the rock. According to the results of the calculations, carried load proportion by the raft is calculated as 11.1%, 5.8% and 5.7%, respectively. It can be seen that, in long term, the carried proportion of the load by the raft calculated as, 6.1%, 5.5% and 4.7%.

Due to increase of the length of piles, pile group stiffnesses are increases. Because pile stiffness and raft stiffness affected the load sharing ratio between the raft and piles, increasing pile lengths causes the decrease in carried load proportion by the raft. The effect of pile group stiffness can be seen in literature.

According to the results of the Finite Element Method Analyses, lower carried proportion of the load by the raft is obtained from the long term analyses.

<u>3.4.4.2. Simplified Approaches.</u> For such kind of piled raft foundation systems, because the young's moduli of the soil layers are significantly different from each other, 200.0000 kN/m^2 is used for average young's modulus of pile tip.

Table 3.53. Simplified Approaches Input Table for Case 5 (Short Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	20000	1	13	36
Young's modulus of the soil at level of pile tip (kN/m^2)	1000000		Raft Information		
			Young's Modulus of the soil below the raft, Esr (kN/m^2)	20000	
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)	1000000		Poisson's Ratio,υ	0.45	
			Length of the short side of the raft, B (m)	20	
Average Young's modulus along the pile shaft (kN/m^2)	20000		Length of the Long side of the raft, L(m)	40	
			Depth of the Raft, Df (m)	1	
Total load carried by Foundation System(kN)	470000		Effective Depth of the Raft, de(m)	1	

Table 3.54. Simplified Approaches Calculation Table for Case 5 (Short Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	68965.517		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	344827.59		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	68965.517		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6896.5517		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	2074086.3	Vertical Rigidity Factor, βz	1.062270338
Stifness of the Pile Group, Kp(kN/m)	12444518.0	Stiffness of the Raft, Kr(kN/m^2)	9077566.1843
Foundation System			
Equivalent Raft Radius, rc(m)	22.22	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	-0.5095
ζ	0.2	Carried load proportion by raft, X	0.10
rm	6.1750	Stiffness of Piled Raft, K$_{pr}$(kN/m)	14552249.56
ζ	2.5137	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0155
λ	439.35	Carried load proportion by raft, O	0.02
μ_l	0.0132319	Stiffness of Piled Raft, K$_{pr}$(kN/m)	12482597.99

Table 3.55. Simplified Approaches Results Table for Case 1 (Short Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	9.6	Proportion Carried By the Raft, %	1.5
Proportion Carried By Piles, %	90.4	Proportion Carried By Piles, %	98.5
Qraft(kN)	45098.7	Qraft(kN)	71.69.0
Qpiles(kN)	424901.3	Qpiles(kN)	462831.0
Elastic Settlement of the Foundation System, Spr(cm)	3.2	Elastic Settlement of the Foundation System, Spr(cm)	3.8

The carried proportion of the load by the raft is calculated as 9.6% and 1.5% with Poulos' and Randolph's approaches for a piled raft foundation system that designed with 13m piles that penetrated 3m into the rock. Elastic settlement of the foundation system is estimated as 3,2cm and 3,8cm. The input parameters can be seen in Table 3.53. Additionally, the results and the intermediate steps of the simplified analyses can be seen in Table 3.54 and Table 3.55.

Table 3.56. Simplified Approaches Input Table for Case 5 (Long Term).

<table>
<tr><th colspan="6">PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)</th></tr>
<tr><th>Concrete Class</th><th>Young's Modulus of the pile concrete (kN/m^2)</th><th>Young's Modulus of the Soil (kN/m^2)</th><th>Pile Diameter (m)</th><th>Pile Length (m)</th><th>Number of Piles</th></tr>
<tr><td>C25</td><td>30300000</td><td>17333</td><td>1</td><td>13</td><td>36</td></tr>
<tr><td colspan="2" rowspan="2">Young's modulus of the soil at level of pile tip (kN/m^2)</td><td rowspan="2">1000000</td><td rowspan="7"></td><td colspan="2">Raft Information</td></tr>
<tr><td>Young's Modulus of the soil below the raft, Esr (kN/m^2)</td><td>17333</td></tr>
<tr><td colspan="2" rowspan="2">Young's modulus of the bearing stratum at level of pile tip (kN/m^2)</td><td rowspan="2">1000000</td><td>Poisson's Ratio,υ</td><td>0.45</td></tr>
<tr><td>Length of the short side of the raft, B (m)</td><td>20</td></tr>
<tr><td colspan="2" rowspan="2">Average Young's modulus along the pile shaft (kN/m^2) Total load carried</td><td rowspan="2">20000</td><td>Length of the Long side of the raft, L(m)</td><td>40</td></tr>
<tr><td>Depth of the Raft, Df (m)</td><td>1</td></tr>
<tr><td colspan="2">by Foundation System(kN)</td><td>470000</td><td>Effective Depth of the Raft, de(m)</td><td>1</td></tr>
</table>

Table 3.57. Simplified Approaches Calculation Table for Case 5 (Long Term).

CALCULATIONS				
Shear Modulus of the Soil, G1 (kN/m^2)	76923.077			
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	384615.38			
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	76923.077			
Shear Modulus of the Soil below the raft, G (kN/m^2)	6666.5385			
Area of a Single Pile, A (m^2)	0.785			
Pile Radius at tip, r0 (m)	0.5			
Pile Radius at base, rb (m)	0.5			
Vertical Pile Stiffness			Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	2162463.2		Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	12974779.4		Stiffness of the Raft, Kr(kN/m^2)	689305
Foundation System				
Equivalent Raft Radius, rc(m)	22.22		Poulos' Approach	
ρ	1		Raft Pile Interaction Factor, α_{cp}	-0.4263
ζ	0.2		Carried load proportion by raft, X	0.07
rm	7.1500		Stiffness of Piled Raft, K$_{pr}$(kN/m)	1.4E+07
ζ	2.6603		Randolph's Approach	
η	1.0000		Raft Pile Interaction Factor, α	0.0111
λ	393.9		Carried load proportion by raft, O	0.01
μ_l	0.0139745		Stiffness of Piled Raft, K$_{pr}$(kN/m)	1.3E+07

Table 3.58. Simplified Approaches Results Table for Case 5 (Long Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	9.6	Proportion Carried By the Raft, %	1.5
Proportion Carried By Piles, %	90.4	Proportion Carried By Piles, %	98.5
Qraft(kN)	45098.7	Qraft(kN)	71.69.0
Qpiles(kN)	424901.3	Qpiles(kN)	462831.0
Elastic Settlement of the Foundation System, Spr(cm)	3.2	Elastic Settlement of the Foundation System, Spr(cm)	3.8

Table 3.56, Table 3.57 and Table 3.58 shows the steps and the results of the analyses. The carried proportion of the load by the raft is calculated as 6.9% and 1.1% by using simplified approaches. The elastic settlement values obtained with simply formulas is 1.1cm and 1.2cm.

Table 3.59. Simplified Approaches Input Table for Case 6 (Short Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	200000	1	18	36
Young's modulus of the soil at level of pile tip (kN/m^2)		1000000		Raft Information	
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		1000000		Young's Modulus of the soil below the raft, Esr (kN/m^2)	20000
Average Young's modulus along the pile shaft (kN/m^2)		20000		Poisson's Ratio,υ	0.45
Total load carried by Foundation System(kN)		470000		Length of the short side of the raft, B (m)	20
				Length of the Long side of the raft, L(m)	40
				Depth of the Raft, Df (m)	1
				Effective Depth of the Raft, de(m)	1

Table 3.60. Simplified Approaches Calculation Table for Case 6 (Short Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	68965.517-2		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	3444827.58-2		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	68965.517-2		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6896.5517-2		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	2053465.6	Vertical Rigidity Factor, βz	1.0622703
Stifness of the Pile Group, Kp(kN/m)	12320793.4	Stiffness of the Raft, Kr(kN/m^2)	907566.18
Foundation System			
Equivalent Raft Radius, rc(m)	22.22	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	-0.3364
ζ	0.2	Carried load proportion by raft, X	0.09
rm	8.5500	Stiffness of Piled Raft, K$_{pr}$(kN/m)	13955385
ζ	2.8391	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0157
λ	439.35	Carried load proportion by raft, O	0.02
μ_l	0.01124497	Stiffness of Piled Raft, K$_{pr}$(kN/m)	12358892

Table 3.61. Simplified Approaches Results Table for Case 6 (Short Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	8.8	Proportion Carried By the Raft, %	1.5
Proportion Carried By Piles, %	91.2	Proportion Carried By Piles, %	98.5
Qraft(kN)	41192.5	Qraft(kN)	7244.3
Qpiles(kN)	428807.5	Qpiles(kN)	4662755.7
Elastic Settlement of the Foundation System, Spr(cm)	3.4	Elastic Settlement of the Foundation System, Spr(cm)	3.8

As it can be seen in Table 3.59, Table 3.60 and Table 3.61, for a piled raft foundation system that designed with end bearing piles, carried load proportion by the raft is calculated as 8.8% and 1.5% with Poulos' and Randolph's method respectively. Elastic settlement of such kind of piled raft system is calculated as 3.4cm and 3.8cm.

Table 3.62. Simplified approaches input table for Case 6 (Long Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	17333	1	18	36

			Raft Information	
Young's modulus of the soil at level of pile tip (kN/m^2)	1000000		Young's Modulus of the soil below the raft, Esr (kN/m^2)	17333
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)	1000000		Poisson's Ratio,υ	0.45
			Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2)	20000		Length of the Long side of the raft, L(m)	40
Total load carried by Foundation System(kN)	160000		Depth of the Raft, Df (m)	1
			Effective Depth of the Raft, de(m)	1

Table 3.63. Simplified Approaches Calculation Table for Case 6 (Long Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	76923.077		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	384615.38		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	76923.077		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6666.5385		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	2191228.5	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	13147371.2	Stiffness of the Raft, Kr(kN/m^2)	689305
Foundation System			
Equivalent Raft Radius, rc(m)	22.22	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	-0.2708
ζ	0.2	Carried load proportion by raft, X	0.06
rm	9.9000	Stiffness of Piled Raft, K$_{pr}$(kN/m)	1.4E+07
ζ	2.9857	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0109
λ	393.9	Carried load proportion by raft, O	0.01
μ_l	0.011876	Stiffness of Piled Raft, K$_{pr}$(kN/m)	1.3E+07

Table 3.64. Simplified Approaches Results Table for Case 6 (Short Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	6.2	Proportion Carried By the Raft, %	1.1
Proportion Carried By Piles, %	93.8	Proportion Carried By Piles, %	98.9
Qraft(kN)	28973.2	Qraft(kN)	5088.4
Qpiles(kN)	441026.8	Qpiles(kN)	464911.6
Elastic Settlement of the Foundation System, Spr(cm)	3.3	Elastic Settlement of the Foundation System, Spr(cm)	3.6

The long term analyses results of Case 7 is given in the Table 3.62, Table 3.63 and Table 3.64. The carried load proportion by the raft is calculated as 6,2% and 1,1% with Poulos' and Randolph's approaches for a piled raft foundation system that designed with 18m piles that penetrated 3m into the rock. Elastic settlement of the foundation system is estimated as 3,3cm and 3,6cm.

Table 3.65. Simplified Approaches Input Table for Case 7 (Short Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	200000	1	23	36
				Raft Information	
Young's modulus of the soil at level of pile tip (kN/m^2)		1000000		Young's Modulus of the soil below the raft, Esr (kN/m^2)	20000
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		1000000		Poisson's Ratio,υ	0.45
				Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2)		20000		Length of the Long side of the raft, L(m)	40
				Depth of the Raft, Df (m)	1
Total load carried by Foundation System(kN)		470000		Effective Depth of the Raft, de(m)	1

Table 3.66. Simplified Approaches Calculation Table for Case 7 (Short Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	68965.5172		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	344827.586		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	68965.5172		
Shear Modulus of the Soil below the raft, G (kN/m^2)	68965.5172		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	2027751.9	Vertical Rigidity Factor, βz	1.0622703
Stifness of the Pile Group, Kp(kN/m)	12166511.3	Stiffness of the Raft, Kr(kN/m^2)	907566.18
Foundation System			
Equivalent Raft Radius, rc(m)	22.22	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	-0.2302
ζ	0.2	Carried load proportion by raft, X	0.08
rm	10.9250	Stiffness of Piled Raft, K$_{pr}$(kN/m)	13545507
ζ	3.0842	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0159
λ	439.35	Carried load proportion by raft, O	0.02
μ_l	0.00994789	Stiffness of Piled Raft, K$_{pr}$(kN/m)	12204634

Table 3.67. Simplified Approaches Results Table for Case 7 (Short Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	8.3	Proportion Carried By the Raft, %	1.6
Proportion Carried By Piles, %	91.7	Proportion Carried By Piles, %	98.4
Qraft(kN)	38894.1	Qraft(kN)	7340.5
Qpiles(kN)	431105.9	Qpiles(kN)	462659.5
Elastic Settlement of the Foundation System, Spr(cm)	3.5	Elastic Settlement of the Foundation System, Spr(cm)	3.9

The carried load proportion by the raft is calculated as 8.3% and 1.6% with two different approaches. According to Poulos and Randolph, elastic settlements of the piled raft foundation system is calculated as 3,5 cm and 3.9cm. Table 3.65, Table 3.66 and Table 3.67 shows the details of the analyses employed.

Table 3.68. Simplified Approaches Input Table for Case 7 (Long Term).

PILED RAFT FOUNDATION SYSTEM (Poulos' and Randolph's Approaches)					
Concrete Class	Young's Modulus of the pile concrete (kN/m^2)	Young's Modulus of the Soil (kN/m^2)	Pile Diameter (m)	Pile Length (m)	Number of Piles
C25	30300000	17333	1	23	36
Young's modulus of the soil at level of pile tip (kN/m^2)		1000000		Raft Information	
				Young's Modulus of the soil below the raft, Esr (kN/m^2)	17333
Young's modulus of the bearing stratum at level of pile tip (kN/m^2)		1000000		Poisson's Ratio,υ	0.3
				Length of the short side of the raft, B (m)	20
Average Young's modulus along the pile shaft (kN/m^2)		20000		Length of the Long side of the raft, L(m)	40
Total load carried by Foundation System(kN)		470000		Depth of the Raft, Df (m)	1
				Effective Depth of the Raft, de(m)	1

Table 3.69. Simplified Approaches Calculation Table for Case 7 (Long Term).

CALCULATIONS			
Shear Modulus of the Soil, G1 (kN/m^2)	76923.077		
Shear Modulus of the Soil at pile base, G$_b$(kN/m^2)	384615.38		
Average shear Modulus along the pile, G$_{avg}$(kN/m^2)	76923.077		
Shear Modulus of the Soil below the raft, G (kN/m^2)	6666.5385		
Area of a Single Pile, A (m^2)	0.785		
Pile Radius at tip, r0 (m)	0.5		
Pile Radius at base, rb (m)	0.5		
Vertical Pile Stiffness		Stiffness of Raft Foundation	
Single Pile Stiffness, Kzz(kN/m)	2201399.7	Vertical Rigidity Factor, βz	1.06227
Stifness of the Pile Group, Kp(kN/m)	13208398.4	Stiffness of the Raft, Kr(kN/m^2)	6893305
Foundation System			
Equivalent Raft Radius, rc(m)	22.22	Poulos' Approach	
ρ	1	Raft Pile Interaction Factor, α_{cp}	-0.1744
ζ	0.2	Carried load proportion by raft, X	0.06
rm	12.6500	Stiffness of Piled Raft, K$_{pr}$(kN/m)	1.4E+07
ζ	3.2308	Randolph's Approach	
η	1.0000	Raft Pile Interaction Factor, α	0.0109
λ	393.9	Carried load proportion by raft, O	0.01
μ_l	0.0105061	Stiffness of Piled Raft, K$_{pr}$(kN/m)	1.3E+07

Table 3.70. Simplified Approaches Results Table for Case 7 (Long Term).

RESULTS			
Poulos' Approach		Randolph's Approach	
Proportion Carried By the Raft, %	5.7	Proportion Carried By the Raft, %	1.1
Proportion Carried By Piles, %	94.3	Proportion Carried By Piles, %	98.9
Qraft(kN)	26911.1	Qraft(kN)	5064.1
Qpiles(kN)	443088.9	Qpiles(kN)	464935.9
Elastic Settlement of the Foundation System, Spr(cm)	3.3	Elastic Settlement of the Foundation System, Spr(cm)	3.6

In long term, the carried load proportion of the load by the raft is estimated as 5.7% and 1.1% with Poulos' and Randolph's approaches, respectively. Compare with short term, it is reasonable to obtain lower carried proportion for the long term analyses. The details of the analyses can be seen in the Table 3.68, Table 3.69 and Table 3.70.

For piled raft foundation systems with end bearing piles, an overview of the carried proportion of the load by the raft is given in the Table 3.71.

Table 3.71. Comparison Table of Carried Proportion by the Raft for End Bearing Piles.

	Pile Length (m)	FEM (%)	Poulos (%)	Randolph (%)
End Bearing	13 (Short Term)	11.1	9.6	1.5
	13 (Long Term)	6.1	6.9	1.1
	18 (Short Term)	5.8	8.8	1.5
	18 (Long Term)	5.5	6.2	1.1
	23 (Short Term)	5.7	8.3	1.6
	23 (Long Term)	4.7	5.7	1.1

The carried load proportion by the raft is decreased with longer end bearing piles. According to the results of the finite elements method, the raft carries higher proportion of the load than Randolph's simplified approaches. Moreover, elastic settlements of the piled raft foundations with end bearing piles are lower than piled raft foundation systems that designed with end bearing piles.

In the scope of this thesis, basicly short term behavior is considered due to rapid construction. Elastic displacements of the piles are given in Table 3.72, Table 3.73 and Table 3.74.

Table 3.72. Short Term Elastic Displacements of the piles for Case 5.

Elastic Displacements of the Piles (mm) (Short Term)				
On Rock Piles	Pile No	$Uy_{(tip)}$	$Uy(_{Top})$	Elastic Displacement
Piled	1	13.31	14.82	1.51
Raft	2	13.6	14.68	1.08
Foundation	3	13.74	14.71	0.97
Case 5	4	13.74	14.71	0.97
(10+3m)	5	13.61	14.69	1.08
(Static)	6	13.33	14.84	1.51

Table 3.73. Short Term Elastic Displacements of the piles for Case 6.

Elastic Displacements of the Piles (mm) (Short Term)				
On Rock Piles	Pile No	$Uy_{(tip)}$	$Uy_{(Top)}$	Elastic Displacement
Piled	1	13.12	14.65	1.53
Raft	2	13.22	14.47	1.25
Foundation	3	13.37	14.51	1.14
Case 6	4	13.37	14.5	1.13
(15+3m)	5	13.22	14.47	1.25
(Static)	6	13.12	14.66	1.54

Elastic displacements of the piles are increased with longer pile lengths.Additionally,

Table 3.74. Short Term Elastic Displacements of the piles for Case 7.

Elastic Displacements of the Piles (mm) (Short Term)				
On Rock Piles	Pile No	Uy$_{(tip)}$	Uy$_{(Top)}$	Elastic Displacement
Piled	1	10.1	12.96	2.86
Raft	2	11.14	13.05	1.91
Foundation	3	11.45	13.21	1.76
Case 7	4	11.46	13.21	1.75
(20+3m)	5	11.15	13.05	1.9
(Static)	6	10.21	12.96	2.75

displacement values at top of the piles are increased. Because of the rock layer at the end of pile tip, displacement values of the end bearing piles at the pile tip are higher than floating piles.

Maximum and minimum displacements and internal forces of the raft are given in the Table 3.75 and Table 3.76.

Table 3.75. Short Term Deflections of the Raft Foundation for End Bearing Piles.

Maximum and Minimum Deflections of the Raft (Short Term)				
Case		Max.(m)	Min.(m)	Differential (m)
On Rock	Case 5 (13m)	0.01556	0.01466	0.0009
	Case 6 (18m)	0.01528	0.01446	0.00082
	Case 7 (23m)	0.01356	0.0129	0.00066

Table 3.76. Short Term Internal Forces of the Raft Foundation for End Bearing Piles.

Internal Forces of the Raft (Short Term)				
Case		N(kN)	V(kN)	M(kNm)
On Rock	Case 5 (13m)	233.5	1425	2843
	Case 6 (18m)	45.96	1432	2847
	Case 7 (23m)	44.97	1436	2849

Increasing pile load causes little increase in shear forces and moment values on the raft. For piled raft foundations with end bearing piles, normal forces on the raft is significantly lower than piled raft foundations with floating piles.

According to the finite elements method, deflections on the raft is calculated as shown below in Table 3.77.

Table 3.77. Short Term Settlements of Foundation System for End Bearing Piles.

	Settlements(m)			
On Rock	Case No	Node 1 (7m)	Node 2 (10m)	Node 3 (13m)
	Case 5 (13m)	0.01469	0.01485	0.01468
	Case 6 (18m)	0.01447	0.01452	0.01447
	Case 7 (23m)	0.01314	0.01337	0.01314

As it can be seen in literature, piled raft foundation systems with longer piles give lower settlement values.

3.5. Dynamic Analyses Results

3.5.1. a) Piled Raft Foundations with Floating Piles

For three earthquake accelerations, the load sharing ratio and internal forces in the system are given below for a piled raft foundation system with floating piles. Since in the dynamic analysis the load distribution changes continuously, an approach has been adapted to investigate the stresses at certain times. To be as representative as possible, the outputs for the 1^{st}, 3^{rd}, 6^{th} etc seconds have been evaluated. To cover the most severe part of the earthquake time history this analysis has been continued up to 30 seconds. The results of the analyses are given in Table 3.74 through Table 3.74. For the dynamic analysis only Case 2 was taken into consideration and three different earthquake records have been used in the analyses. Table 3.78, Table 3.80 and Table 3.82 show the internal forces occurred on the piles and the raft during Wells Earthquake acceleration. Table 3.79, Table 3.81 and Table 3.83 show the results of the analyses in terms of carried proportion of the superstructural load by the raft and the pile group for different seconds.

Table 3.78. Wells Earthquake Internal Forces for Case 2.

Internal Forces - Wells Earthquake Case (20m Piles - Case 2)											
	Sc.	Raft	1st Pile			2nd Pile			3rd Pile		
		N	N	V	M	N	V	M	N	V	M
Wells Earthquake	1	809	761	189.6	312.4	327.6	177.1	383.3	390.9	54.21	134.7
	3	1093	761.3	212.8	352.6	286	241.8	475.3	352	67.97	150.4
	6	1336	599.1	98.57	557.4	319.7	109	598.3	360.7	126.3	488.6
	9	943.6	859.2	166.4	247.3	397.7	40.24	160	371.9	131.2	140.2
	12	1015	1022	363.8	380.9	390.9	121.4	343.6	312.2	248.2	168.5
	15	677.4	927.7	353.4	477	419.7	135.7	401.6	418.7	88.92	226.4
	18	669.4	826.7	298.8	486.2	435.2	155.7	410.9	433.2	33.88	141.4
	21	556.3	750.5	483.5	987	398	246.1	818.2	440.7	117.5	567.2
	24	784.5	967	408.4	596	381.2	215.2	564.5	386.6	90.94	351
	27	987.4	784.9	509.3	966.3	320.4	246.9	745.3	328.6	61.8	365.8
	30	849.3	853.3	463.1	1055	449.2	260.9	975.8	427.1	132.4	737.4
	Units are kN and m.										
	Sc.		4th Pile			5th Pile			6th Pile		
			N	V	M	N	V	M	N	V	M
	1		392.1	71.91	191.1	341.3	180.9	412.1	823.5	185.2	300.2
	3		357.8	84.92	240.2	308.9	242.8	543.5	754.6	173.6	392.5
	6		399.7	89.27	195.2	464.1	56.88	188.1	964.8	147.1	274.9
	9		365.9	143.1	445	377.4	101.1	507.8	834.2	264.7	587.1
	12		277.2	80.33	226.6	264.2	84.05	453.6	615.1	412	842.3
	15		442.4	63.85	182.4	454.2	155.8	423.1	872	396.5	596
	18		428.9	62.17	187	426.5	179.6	424.8	881.1	373	522.5
	21		464.1	29.48	238.6	492.7	101.7	247.3	990.5	168.9	375.1
	24		404.5	26.91	131.9	426.3	138.3	288.8	688.7	340	530.8
	27		314.6	79.4	250.2	334.2	232.4	414.6	887.4	389.6	554.5
	30		393.3	66.77	380.5	379.1	124.5	522.3	678.4	404.8	707.2

Table 3.79. Wells Earthquake Results of FEM Model for Case 2.

Load Sharing Ratio - Wells Earthquake Case (20m Piles - Case 2)				
Sec.	Raft	Pile Group	Raft %	Pile Group (%)
1sc.	809	3036.4	21	79
3sc.	1093	2820.6	27.9	72.1
6sc.	1336	3108.1	30.1	69.9
9sc.	943.6	3206.3	22.7	77.3
12sc.	1015	2881.6	26	74
15sc.	677.4	3534.7	16.1	83.9
18sc.	669.4	3642.4	15.5	84.5
21sc.	556.3	3108.7	15.2	84.8
24sc.	784.5	3271	19.3	80.7
27sc.	987.4	2884.7	25.5	74.5
30sc.	849.3	1729.6	32.9	67.1

Table 3.80. El Salvador Earthquakeinternal Forces for Case 2.

Internal Forces - El Salvador Earthquake Case (20m Piles - Case 2)											
	Sc.	Raft	1st Pile			2nd Pile			3rd Pile		
		N	N	V	M	N	V	M	N	V	M
El Salvador Earthquake	1	728.2	804.1	153.2	262.4	352.7	176.4	384.4	408.1	60.95	157
	3	867.8	775.4	92.25	200	344.8	221.3	430.9	403.9	64.42	161.2
	6	893.4	766.9	87	194.8	343.4	229.3	443.4	402.5	65.48	165.6
	9	891.6	768.5	90.73	186.4	348.2	227.2	435.9	404.2	65.96	160.7
	12	890.8	753.7	113.3	226.7	340.6	222	445.1	398.2	57.53	160.4
	15	1021	723.6	180.4	363.3	310.2	219.7	490.9	354.4	35.37	152.4
	18	1197	762.1	240.6	447.3	332.2	79	370.6	337.2	138.1	320.8
	21	1092	681.1	308.8	765	336	99.24	594.3	364.6	164	557.6
	24	783.4	834.9	174.8	216.4	443.6	46.54	157	432.3	133.5	148.7
	27	670.8	1005	82.88	211.8	486.1	70.39	115.6	453.7	85.53	101.5
	30	593.3	856.9	236.4	212.3	440	157.8	505	462.5	104.8	348.9
	Sc.		4th Pile			5th Pile			6th Pile		
			N	V	M	N	V	M	N	V	M
	1		408.1	61.53	158.4	353.6	175.2	382	823.5	149.8	253.4
	3		403.6	66.32	167.7	345.1	221.7	433.8	787.6	87.71	192.8
	6		402.3	67.15	167	344.1	230.1	441.8	785.5	79.73	179.6
	9		403.2	66.48	173.3	346.5	227.1	446.1	784.5	87.13	190
	12		400.7	67.01	167.7	354.3	228.5	439.4	796.7	94.57	178.3
	15		367.8	50.79	146.6	353.1	220.4	429.6	800.8	114.4	182.9
	18		341.2	140.9	171.8	347.3	66.93	224.4	804.5	216.5	258.5
	21		400.5	160.2	221	457.3	20.87	175.3	921.1	72.34	246.3
	24		417.8	177	359	430.3	58.82	284.7	837.8	267.9	424.4
	27		416.3	184.5	444.7	403.6	87.09	437.7	712.7	339.7	629.7
	30		444.9	109.5	103.5	472.3	41.94	103.6	892.6	223	203.8

Table 3.81. El Salvador Earthquake Results of FEM Model for Case 2.

Load Sharing Ratio - El Salvador Earthquake Case (20m Piles - Case 2)				
Sec.	Raft	Pile Group	Raft %	Pile Group (%)
1sc.	728.2	3150.1	18.8	81.2
3sc.	867.8	3060.4	22.1	77.9
6sc.	893.4	3044.7	22.7	77.3
9sc.	891.6	3055.1	22.6	77.4
12sc.	890.8	3044.2	22.6	77.4
15sc.	1021	2909.9	26	74
18sc.	1197	2924.5	29	71
21sc.	1092	3160.6	25.7	74.3
24sc.	783.4	3396.7	18.7	81.3
27sc.	670.8	3477.4	16.2	83.8
30sc.	593.3	3569.2	14.3	85.7

Table 3.82. Parkfield Earthquake Internal Forces for Case 2.

Internal Forces - Parkfield Earthquake Case (20m Piles - Case 2)											
Parkfield Earthquake	Sc.	Raft	1st Pile			2nd Pile			3rd Pile		
		N	N	V	M	N	V	M	N	V	M
	1	737	798.9	162.7	278.1	349.3	176.4	389.3	405.9	59.79	158.5
	3	950.6	790.1	128.5	190.6	344.9	227	421	392.5	71.03	152.6
	6	1009	796.7	98.85	130.3	368.4	161.4	257.3	374	30.12	71.67
	9	890.6	768.8	81.18	188.8	343.3	229.2	441.7	402.8	65.71	165.5
	12	1123	800.8	190.8	243.1	360.5	49.28	159.9	356	117.3	162.5
	15	1061	811.3	217.2	313.8	360	55.08	213.5	361.2	123.6	209.5
	18	1004	825.2	202.7	272.3	376.3	49.76	181	371.8	101.4	152.3
	21	1035	786.4	176.1	210.4	390.9	42.04	138.2	387.9	90.8	120
	24	935.8	814.3	263	366.6	391	60.87	245.3	389.2	111.9	215.6
	27	1239	770.8	302.3	527.3	303.3	111.5	420.8	304	87.11	223.1
	30	1234	827.9	386.3	758.9	341.7	208	701.2	329.1	129	471.6
	Sc.		4th Pile			5th Pile			6th Pile		
			N	V	M	N	V	M	N	V	M
	1		407.2	63.45	158.7	354.3	176.5	381.4	823.4	152.2	252.5
	3		381.6	65.58	193.3	312.3	228.3	488.9	729	149.9	324.2
	6		365.4	65.6	293.9	337.1	198.4	543.5	759.1	142.6	376.8
	9		402.9	66.29	165	344.2	229.7	439.4	784.8	73.46	174.9
	12		350.4	137.3	285.1	344	64.71	301.8	812.4	184.5	340
	15		360.6	123.8	229.5	361.8	58.01	229.9	852.6	215.7	323.8
	18		364.8	132.6	273.9	360.5	65.89	280.4	835.5	244	387.9
	21		383.9	143.6	302.2	387.8	65.02	295.6	857.2	179.2	305.1
	24		381.7	134.8	218.6	383.5	47.08	195.2	845.8	124.5	192.7
	27		293.2	186.7	314.5	292.6	144.3	434.5	782.5	381.1	616.6
	30		302.2	104.8	172.1	287.3	114.5	239.4	737.8	355.8	455.4

Table 3.83. Parkfield Earthquake Results of FEM Model for Case 2.

Load Sharing Ratio - Parkfield Earthquake Case (20m Piles - Case 2)				
Sec.	Raft	Pile Group	Raft %	Pile Group (%)
1sc.	737	3139	19	81
3sc.	950.6	2950.4	24.4	75.6
6sc.	1009	3000.7	25.2	74.8
9sc.	890.6	3046.8	22.6	77.4
12sc.	1123	3024.1	27.1	72.9
15sc.	1061	3107.5	25.5	74.5
18sc.	1004	3134.1	24.3	75.7
21sc.	1035	3194.1	24.5	75.5
24sc.	935.8	3205.5	22.6	77.4
27sc.	1239	2746.4	31.1	68.9
30sc.	1234	2826	30.4	69.6

According to the results of the analyses, the normal and shear forces and the momentsoccurred on the piles are significantly different for three different earthquake accelerations. Due to the characteristics of the earthquake accelerations used in the analyses, the change on the internal forces is reasonable.

According to the dynamic analyses results, sometimes, the contribution of the rafts is lower than static loading. Additionally, when end bearing piles are used, the contribution of the raft is quite lower than floating piles.

The overview of the results of the load sharing ratios for floating piles is given Figure 3.6.

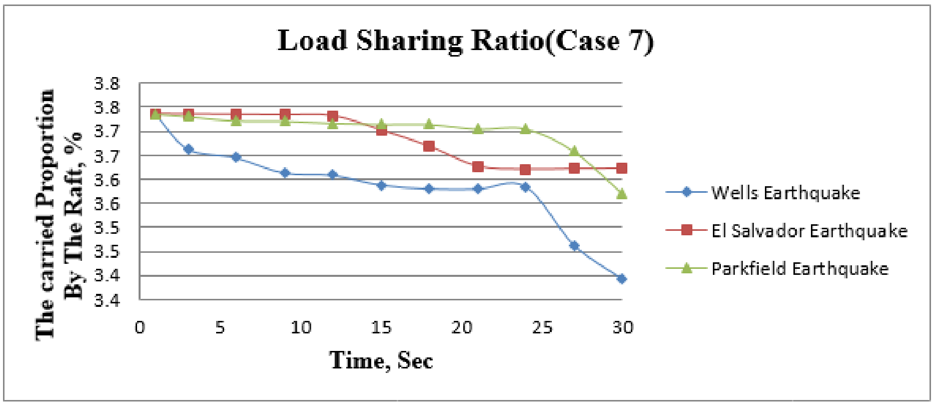

Figure 3.6. Comparison Graph of Carried Proportion by the Raft for Case 2.

The internal forces of the raft can be seen in Table 3.84 for such a foundation system.

Table 3.84. Envelope Internal Forces of the Raftfor Case 2.

<table>
<tr><th colspan="5">Internal Forces of the Raft</th></tr>
<tr><th colspan="2">Case 2 (20m)</th><th>N(kN)</th><th>V(kN)</th><th>M(kNm)</th></tr>
<tr><td rowspan="3">Floating</td><td>Wells Earthquake</td><td>671.2</td><td>777.8</td><td>1661</td></tr>
<tr><td>El Salvador Earthquake</td><td>561.4</td><td>689.6</td><td>1261</td></tr>
<tr><td>Parkfield Earthquake</td><td>437</td><td>660.1</td><td>1143</td></tr>
</table>

It can be seen that in Table 3.84, while the internal forces occuring in the raft is slightly different from each other, the moment values are significantly different.

All in all, the contribution of the raft is different for the three earthquake accelerations. In addition, it can be concluded that the contribution of the raft is quite important during an earthquake.

3.5.1.1. Piled raft foundations with end bearing piles. For three earthquake accelerations, the load sharing ratio and internal forces in the system are given below for a piled raft foundation system with end bearing piles that penetrates 3m to the bedrock. The internal forces occurred on the piles and the raft is given in Table 3.85, Table 3.87

and Table 3.88 for three different earthquake accelerations. Similarly, the results of the dynamic analyses for end bearing piles are given in Table 3.86, Table 3.88and Table 3.90.

Table 3.85. Wells Earthquake Internal Forces for Case 7.

Internal Forces - Wells Earthquake Case (23m Piles - Case 7)											
Wells Earthquake	Sc.	Raft	1st Pile			2nd Pile			3rd Pile		
		N	N	V	M	N	V	M	N	V	M
	1	437.5	2417	151.4	260.2	1665	33.88	28.46	1547	13.49	43.65
	3	429	2423	154.1	265.4	1668	35.66	76.27	1549	13.5	47.35
	6	426.8	2414	155.2	267.4	1667	37.02	78.61	1549	13.02	46.27
	9	423	2417	149.2	256.4	1669	31.64	68.09	1549	13.14	36.77
	12	422.5	2418	157.3	271.2	1668	38.47	81.55	1549	12.66	46.78
	15	420.1	2423	160.7	277.3	1669	41.19	86.74	1549	16.83	50.68
	18	419.2	2416	155.3	267.8	1668	36.92	78.64	1550	13.04	46.95
	21	419.1	2414	150.9	259.6	1668	33.1	71.16	1550	12.52	39.53
	24	419.8	2433	153.2	263.8	1672	34.25	73.61	1550	14.58	47.63
	27	405.7	2356	124.6	212.6	1660	13.61	30.63	1551	12.49	22.75
	30	397.6	2291	96.86	242.1	1649	11.15	71.89	1550	35.63	67.35
	Sc.		4th Pile			5th Pile			6th Pile		
			N	V	M	N	V	M	N	V	M
	1		1548	13.81	44.52	1667	34.02	71.42	2427	151.3	260.7
	3		1549	13.44	39.77	1668	32.64	68.58	2424	149.6	257.6
	6		1549	13.8	40.53	1670	31.43	66.57	2433	149	256.5
	9		1549	13.58	49.65	1669	36.84	77.18	2431	155	267.7
	12		1550	14.03	39.6	1671	30.02	63.79	2430	147	252.9
	15		1550	13.9	35.27	1671	27.47	59.02	2426	144	247.7
	18		1551	13.51	38.98	1672	31.75	67.12	2433	149.4	257.3
	21		1550	14.05	46.42	1672	35.58	74.57	2435	153.9	265.5
	24		1550	11.98	38.32	1668	34.48	72.23	2416	151.7	261.7
	27		1556	32.16	84.72	1695	57.84	117.7	2491	183.9	320.2
	30		1562	56.1	130.4	1725	82.48	165.9	2549	216.5	381.2

Table 3.86. Wells Earthquake Results of FEM Model for Case 7.

Load Sharing Ratio - Wells Earthquake Case (23m Piles - Case 7)				
Sec.	Raft	Pile Group	Raft %	Pile Group (%)
1sc.	437.5	11271	3.7	96.3
3sc.	429	11281	3.7	96.3
6sc.	426.8	11282	3.6	96.4
9sc.	423	11284	3.6	96.4
12sc.	422.5	11286	3.6	96.4
15sc.	420.1	11288	3.6	96.4
18 sc	419.2	11290	3.6	96.4
21sc.	419.1	11289	3.6	96.4
24sc.	419.8	11289	3.6	96.4
27sc.	405.7	11309	3.5	96.5
30sc.	397.6	11326	3.4	96.6

Table 3.88. El Salvador Earthquake Results of FEM Model for Case 7.

Load Sharing Ratio - El Salvador Earthquake Case (23m Piles - Case 7)				
Sec.	Raft	Pile Group	Raft %	Pile Group (%)
1sc.	437.5	11271	3.7	96.3
3sc.	437.4	11271	3.7	96.3
6sc.	437.3	11271	3.7	96.3
9sc.	437.2	11271	3.7	96.3
12sc.	437	11272	3.7	96.3
15sc.	433.5	11275	3.7	96.3
18 sc	429.6	11279	3.7	96.3
21sc.	424.8	11285	3.6	96.4
24sc.	424	11284	3.6	96.4
27sc.	424.1	11283	3.6	96.4
30sc.	424.2	11284	3.6	96.4

Table 3.87. El Salvador Earthquake Internal Forces for Case 7.

Internal Forces - El Salvador Earthquake Case (23m Piles - Case 7)										
El SalvadorEarthquake	Sc.	Raft	1st Pile			2nd Pile			3rd Pile	
		N	N	V	M	N	V	M	N	V	M
	1	437.5	2417	151.4	260.2	1665	33.88	72.51	1547	13.49	43.65
	3	437.4	2417	151.4	260.3	1665	33.89	72.54	1547	13.49	43.68
	6	437.3	2416	151.4	260.2	1665	33.85	72.44	1547	13.47	43.38
	9	437.2	2417	151.3	260.1	1665	33.8	72.39	1547	13.53	43.98
	12	437	2417	151.9	261.2	1665	34.31	73.33	1547	13.45	44
	15	433.5	2417	150.7	259	1666	33.16	71.12	1548	13.29	41.98
	18	429.6	2420	148.3	254.8	1668	30.9	67.03	1548	13.68	40.78
	21	424.8	2417	155.8	268.3	1667	37.36	79.29	1549	12.91	46.62
	24	424	2419	150.6	258.8	1668	32.73	70.32	1549	13.4	40.75
	27	424.1	2417	151	259.4	1668	33.15	70.99	1549	12.72	38.37
	30	424.2	2416	153.7	264.5	1667	35.54	75.79	1549	13.42	45.64
	Sc.		4th Pile			5th Pile			6th Pile		
			N	V	M	N	V	M	N	V	M
	1		1548	13.81	44.52	1667	34.02	71.42	2427	151.3	260.7
	3		1548	13.81	44.5	1667	34.02	71.4	2427	151.3	260.6
	6		1548	13.83	44.79	1667	34.05	71.5	2428	151.4	260.8
	9		1548	13.77	44.2	1667	34.11	71.57	2427	151.4	260.9
	12		1548	13.84	44.16	1667	33.62	70.65	2428	150.9	259.9
	15		1548	13.85	45.75	1668	34.94	73.26	2428	152.6	263.1
	18		1548	13.32	46.48	1668	37.34	77.65	2427	155.4	268
	21		1550	13.87	40.01	1671	31.06	65.87	2431	148.3	255.5
	24		1549	13.4	45.88	1670	35.71	74.85	2429	153.6	265.1
	27		1549	14.08	48.26	1670	35.29	74.18	2430	153.2	264.5
	30		1550	13.38	40.98	1671	32.9	69.4	2431	150.5	259.3

Table 3.89. Parkfield Earthquake Internal Forces for Case 7.

Internal Forces - Parkfield Earthquake Case (23m Piles - Case 7)											
Parkfield Earthquake	Sc.	Raft	1st Pile			2nd Pile			3rd Pile		
		N	N	V	M	N	V	M	N	V	M
	1	437.5	2417	151.4	260.2	1665	33.88	72.51	1547	13.49	43.65
	3	436.9	2417	151.9	261.1	1665	34.24	73.17	1547	13.5	44
	6	435.8	2416	151.2	259.8	1666	33.63	72.02	1547	13.49	43.28
	9	435.7	2417	150.7	259.1	1666	33.22	71.33	1547	13.59	43.91
	12	435.2	2417	151.4	259.9	1666	33.65	71.86	1547	13.13	39.69
	15	434.9	2417	152	261.1	1666	34.2	73.01	1547	13.44	42.89
	18	434.9	2416	151.8	260.8	1666	34.07	72.8	1547	13.13	42.24
	21	433.8	2416	152.2	261.7	1666	34.44	73.54	1548	13.35	43.24
	24	433.8	2417	149.5	256.7	1666	32.03	68.99	1548	13.4	40.72
	27	428.4	2396	141.4	242.4	1663	25.75	56.9	1548	12.16	29
	30	418.1	2383	130.9	223.5	1662	17.57	40.01	1549	10.47	16.11
	Sc.		4th Pile			5th Pile			6th Pile		
			N	V	M	N	V	M	N	V	M
	1		1548	13.81	44.52	1667	34.02	71.42	2427	151.3	260.7
	3		1548	13.77	44.14	1667	33.71	70.87	2428	151	260.1
	6		1548	13.74	44.74	1667	34.36	72.11	2428	151.8	261.6
	9		1548	13.66	44.1	1667	34.77	72.79	2427	152.3	262.3
	12		1548	14.11	48.28	1667	34.39	72.36	2428	151.8	261.7
	15		1548	13.79	45.07	1667	33.84	71.2	2428	151.2	260.6
	18		1548	14.1	45.73	1667	33.97	71.41	2429	151.4	260.9
	21		1548	13.83	44.56	1668	33.67	70.83	2429	151.1	260.3
	24		1548	13.79	47.09	1667	36.08	75.37	2427	153.8	265.3
	27		1550	14.68	57.7	1675	42.85	88.47	2450	163.4	282.5
	30		1553	26.69	72.72	1684	52.2	106.6	2463	175.4	304.7

Table 3.90. Parkfield Earthquake Results of FEM Model for Case 7.

Load Sharing Ratio - Parkfield Earthquake Case (23m Piles - Case 7)				
Sec.	Raft	Pile Group	Raft %	Pile Group (%)
1sc.	437.5	11271	3.7	96.3
3sc.	436.9	11272	3.7	96.3
6sc.	435.8	11272	3.7	96.3
9sc.	435.7	11272	3.7	96.3
12sc.	435.2	11273	3.7	96.3
15sc.	434.9	11273	3.7	96.3
18 sc	434.9	11273	3.7	96.3
21sc.	433.8	11275	3.7	96.3
24sc.	433.8	11273	3.7	96.3
27sc.	428.4	11282	3.7	96.3
30sc.	418.1	11294	3.6	96.4

According to the results, when end bearing piles are used, the contribution of the raft is quite lower than floating piles. Moreover, the change of the contribution of the raft foundation is not quite different during the earthquake.

The internal forces occuring in the piles are not substantially different for three earthquake accelerations.

The results of the load sharing ratios between the piles and the rafts in dynamic conditions for end bearing piles are given in Figure 3.7.

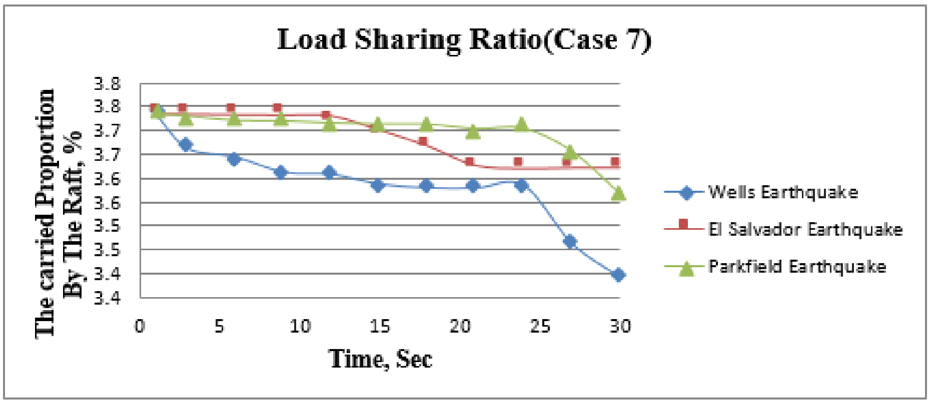

Figure 3.7. Comparison Table of Carried Proportion by the Raftfor Case 7.

According to the results, when end bearing piles are used, the contribution of the raft is quite lower than floating piles.

The shear and normal forces and moment values occuring in the raft with end bearing piles is given in Table 3.91.

Table 3.91. Envelope Internal Forces of the Raft for Case 7.

Internal Forces of the Raft				
	Case 7 (23m)	N(kN)	V(kN)	M(kNm)
End bearing	Wells Earthquake	248.8	2258	4305
	El Salvador Earthquake	170.9	1859	3524
	Parkfield Earthquake	118.7	1613	3107

The internal forces on the raft with end bearing piles are quite a bit lower than floating piles. Additionally, shear forces and moment values are significantly higher on the raft with end bearing piles.

This study examines one piled raft foundation with end bearing piles and one piled raft foundation with floating piles with 3 different earthquake accelerations. The results of the load sharing ratios between the piles and the rafts under dynamic conditions are given below.

The results of the analyses show that the contribution of the raft is greatly determined by the soil below the pile tip.In addition, the load sharing ratio between the piles and the raft is significantly affected by the characteristic of the earthquake accelerations. According to the dynamic analyses results, the contribution of the rafts is quite lower than static loading for piled raft foundations with end bearing piles. However, there is no substantial change for a piled raft foundation with floating piles in the dynamic and static loading condition. Additionally, when end bearing piles are used, the contribution of the raft is quite lower than floating piles.

4. CONCLUSION

Within the scope of this thesis, the concept of piled raft foundation, its design philosophies and application examples are comprehensively introduced. Calculation results, abilities of different methods available in literature examined for seven hypothetical cases. Thus, efficiency of the methods available in the literature is evaluated. This study focused on the dynamic and static behavior and design of piled raft foundations. Pile load transfer mechanisms, interactions between raft-soil-piles and pile lengths are taken into account in the analyses. Both advanced and simple formulas are used to evaluate the contribution of the raft foundation. This study also extends the knowledge related to the settlement performance of the piled raft foundation systems and the internal forces occurring on the piles and rafts.

In the scope of this thesis, basicly short term behavior is considered because it is assumed that shear in soil will be very fast due to the rapid construction. The contribution of the raft can be clearly seen from all analyses results. According to the results of the analyses, load sharing ratio between the raft and piles is greatly affected from soil below the pile tip.

General overview of load sharing ratio between the raft and pile group with different methods is given in Table 4.1.

Table 4.1. Overview of the Static Analyses Results.

	Pile Length (m)	FEM (%)	Poulos (%)	Randolph (%)
Floating	15 (Short Term)	18.9	32	15.2
	15 (Long Term)	21.4	27.5	13.1
	20 (Short Term)	18.9	26.8	11.8
	20 (Long Term)	16.7	22.6	9.4
	25 (Short Term)	17.2	23.1	9.7
	25 (Long Term)	13.1	19.1	7.7
	30 (Short Term)	15.6	20.2	8.3
	30 (Long Term)	10.9	16.6	6.6
End Bearing	13 (Short Term)	11.1	9.6	1.5
	13 (Long Term)	6.1	6.9	1.1
	18 (Short Term)	5.8	8.8	1.5
	18 (Long Term)	5.5	6.2	1.1
	23 (Short Term)	5.7	8.3	1.6
	23 (Long Term)	4.7	5.7	1.1

The stiffness of the soil underneath the raft is greatly affected the amount of the carried load by the raft. It can be seen from analyses results, total settlement values are decreased for longer pile lengths. Moreover, if soil below the pile tip is relatively higher, minor portion of the superstructure load is carried by the raft. The carried load proportion of the raft in piled raft foundation system with floating piles is higher than the raft in piled raft foundation with end bearing piles. The reason for this is lower settlement values for end bearing piles. The carried proportion by the raft increases with higher settlement values.

Additionally, because the longer piles carry higher proportion of the superstructure load, elastic displacements of the piles are higher. Additionally, longer pile length brings together the higher values for elastic displacements.

With longer pile length, carried load proportions by the piles are increased for both floating and end bearing piles. Considering the proportion of load carried by the raft depends on its stiffness relative to that of the piles, the results are convenient to literature.

The analysis results of the simplified approaches gives important information about for the initial stage of piled raft foundation design. Results of analyses of both simplified approaches and advanced methods have very close results. In comparison with finite element method, simplified approach developed by Randolph gives quite conservative results. Moreover, Poulos' simplified method gives higher carried load proportion for floating piles. Within this study, three casesevaluated for end bearing piles. Poulos' method gives lower load proportion for the raft for only one case. The others are higher from finite elements method. In addition to that point, in some cases, the carried proportion of the load by the raft is lower in long term behavior due to the decreased stiffness and poisson's ratio.

The results of the analyses show that the piled raft foundations with floating piles can be used effectively in earthquake regions or buildings exposed to lateral loadings. The contribution of the raft in a piled raft foundation with end bearing piles can be neglected due to the safety reasons. It is founded that the number of piles used in conventional approaches can be reduced safely in such buildings. Moreover, according to the results of the analyses, there are important differences between the other methods and Randolph (1994) methods.

Taking all the results into account, under dynamic loading, the load transfer mechanisms of the piles to the deeper strata and the characteristics of earthquake accelerations have an effect on the contribution of the raft foundations. Consequently, it is required that to consider both static and dynamic condition of the piled raft foundation during the design stage.

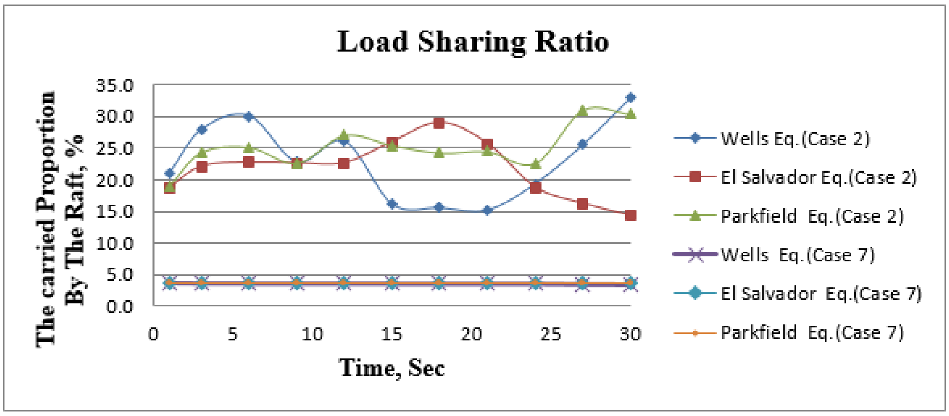

Figure 4.1. Load Sharing Ratio between the Raft and Pile Group for All Cases.

It can be seen that in Figure 4.1, the contribution of the raft is slightly affected by the earthquake characteristics for the piled raft foundations with end bearing piles. However, the piled raft foundations with floating piles are influenced by the characteristics of the earthquake accelerations.

Moreover, internal forces are not significantly different for three different earthquake accelerations for end bearing piles. However, due to the characteristics of the earthquake accelerations used in the analyses, the internal forces on the piles are significantly different from each other for piled raft foundations with floating piles.

Advanced analysis techniques give more accurate results than simplified approaches. However, one should be careful to obtain most realistic results and the analyses results obtained from the software should be checked by using simply formulas available in literature. Additionally, the importance of structural design is very important and designing a piled raft foundation system, designer should consider structural issues for piles and raft.

In conventional piled raft foundation concept, the contribution of the raft is neglected. Raft's contribution is reserved as an additional safety factor. In addition, in piled raft concept, calculations should be performed with a global factor of safety. Therefore, the importance of the parameters to simulate soil behavior cannot be denied. Poulos *et al.*, (2001) stated that “the key to successful prediction is more the ability to choose appropriate geotechnical parameters rather than the details of the analysis employed”.

The characteristics of an earthquake and the lateral loadings affecting on the building greatly influence the contribution of the rafts. One has to take into account pile-soil, raft-soil, pile-pile and pile-raft interactions.

REFERENCES

Bowles, J.E., 1996, "Foundation Analysis and Design (5), Singapore", *McGgrawHill International Editions.*

Burland, J.B., B.B. Broms and V.F.B. Mello, 1977, "Behavior of Foundations and Structures", *9th ICSMFE, State-of-the-Art Report*, Vol. 2, pp. 495-546.

Burland, J.B., 1995, "Piles as Settlement Reducers",*18th Italian Congre Soil Mechanic.*

Butterfield, R. and P.K. Banerjee, 1971, "The Problem of Pile Group Pile Cap Interaction", *Géotechnique*, Vol. 21, No. 2, pp. 135-142.

Butterfield, R. and R.A. Douglas, 1981, "Flexibility Coefficient for the Design of Piles and Pile Groups", *Contains Content that is Written Like an Advertisement Technical Note*, Vol. 1, No. 108, pp 140-141.

Cooke, R.W., 1986, "Piled Raft Foundations on Stiff Clays a Contribution to Design Philosophy", *Géotechnique*, Vol. 36, No. 2, pp. 169-203.

Cunha, R.P., H.G. Poulos, J.C. Small, 2001, "Investigation of Design Alternatives for a Piled Raft Case History", *Journal of Geotechnical and Geoenvironmental Engineering*, Vol.127, No. 8, 635-641.

Das, Braja M. 1997, "Advanced Soil Mechanics", *2nd edition*, Taylor & Francis, Washington D.C..

De Mello, V.F.M., 1969, "Foundations of Buildings on Clay", *State of the art Report*, Vol. 1, pp. 49-136.

Desai, C.S., 1979, *Elementary Finite Element Method*, "Elementary Finite Element Method", Prentice Hall, New York.

Desai, C.S., L.D. Johnson and C.M., Hargett, 1974, "Analysis of Pile Supported Gravity Lock", *American Society of Civil Engineering Journal of Geotechnical Engineering*, Vol. 100, No. 9, pp. 1009-10029.

Ersoy, U., 1995, "Betonarme Temel Ilkeler ve Tasima Gücü Hesabi", *Evrim Yayin Evi*, Ankara.

El - Mossallamy, Y., 2002, "Innovative Application of Piled Raft Foundation in Stiff and Soft Subsoil", *American Society of Civil Engineering Journal*, Vol. 1, pp. 426-439.

El - Mossallamy, Y., 2008, "Modelling the Behavior of Piled Raft Applying Plaxis 3D Version 2, *Plaxis Bulletin*, Vol. 23, pp. 10-13.

Fleming, W.G.K., A.J. Weltman, M.F. Randolph, W.K. Elson, 1992, "Piling Engineering", *Plaxis Bulletin*, Vol. 3, pp. 100-130.

Fox, L., 1948, "The Mean Elastic Settlement of a Uniformly Loaded Area at a Depth Below the Ground Surface", P*rocoduce 2nd International Conferenci Soil Mechnaics and Foundation Engineering*, Vol. 1, pp. 129-130.

Griffiths, D.V., P. Clancy and M.F. Randolph, 1991, "Piled Raft Foundations Analysis by Finite Elements", *7th International Conference on Computer Methods and Advances in Geomechanics*, Vol. 2, No. 1, pp. 1153-1157.

Hain, S.J., I.K. Lee, 1978, "The Analysis of Flexible Raft-Pile Systems", *Géotechnique* Vol. 28, No. 1, pp. 65-83.

Horikoshi, K., 1995, Optimum Design of Piled Raft Foundations", Ph.D. Thesis, University of Western Australia.

Horikoshi, K. and M.F. Randolph, 1996, "Centrifuge Modeling of Piled Raft Foundations on Clay", *Géotechnique*, Vol. 46, No. 4, pp. 741-752.

Horikoshi, K. and M.F. Randolph, 1998, “A Contribution to Optimum Design of Piled Rafts”, *Géotechnique*, Vol. 48, No.3, pp. 301-307.

Horikoshi, K., T. Matsumoto, Y. Hashizume and T. Watanabe, 2005, “Performance of Pile Draft Foundations Subjected to Dynamic Loading”, *International Journal of Physical Modelling in Geotechnis*, vol, 2, pp. 51-62.

Horikoshi, K., T. Matsumoto, Y. Hashizume, T. Watanabe, and H. Fukuyama, 2005, “Performance of Pile Draft Foundations Subjected to Statichorizontal Load”, *International Journal of Physical Modelling in Geotechnic*, Vol. 2, pp. 37-50.

Katzenbach, R., C. Moormann, 2001, “Recommendations for the Design and Construction of Piled Rafts”, *Soil Mechanics and Geotechnical Engineering*, Vol. 2, pp. 124-126.

Katzenbach, R., U. Arslan, C. Moormann, 2004, “Piled Raft Foundation Projects in Germany”, *Design Applications of Raft Foundations*, Vol. 4, pp. 323-392.

Katzenbach, R., A. Schmitt, J. Turek, 2005, “Assessing Settlement of High-Rise Structures by 3D Simulations”, *Computer-Aided Civil and Infrastructure Engineering*, Vol. 20, No. 3, pp. 221-229.

Kuwabara, F., 1989, “An Elastic Analysis for Piled Raft Foundations in a Homogenous Soil”, *Soils Foundation*, Vol. 28, No.1, pp. 82-92.

Mayne, P.W., H.G. Poulos, 1999, “Approximate Displacement Influence Factors for Elastic Shallow Foundations”, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 125, No. 6, pp. 453-460.

Poulos, H.G., 1991, “Analysis of Piled Strip Foundation”, *Computer Methods and Advances in Geomechanics*, Vol. 1, pp. 183-191.

Poulos, H.G., 2000, “Practical Design Procedures for Piled Raft Foundations”, *Design Applications of Raft Foundations*, Vol. 1, pp. 425-467.

Poulos, H.G. 2001, “Piled Raft Foundations Deign and Applications”, *Geotechnique*, Vol. 51, No. 2, pp. 95-113.

Poulos, H.G. and E.H. Davis, 1974, “Elastic Solutions for Soil and Rock Mechanics”, *John Wiley*, New York.

Poulos, H.G. and E.H. Davis, 1980, “Pile Foundation Analysis and Design”, *John Wiley*, New York.

Poulos, H.G. 1989, “Pile Behavior: Theory and Application”, *Géotechnique*, Vol. 39, No. 3, pp. 365-415.

Poulos, H.G., 1991, “Computer Methods and Advances in Geomechanics”, *Composition Methods and Advances in Geomech*, Roterdam.

Poulos, H.G., J.C. Small, L.D. Ta, J. Sinha, and L. Chen, 1997, “Comparison of Somemethods for Analysis of Piled Rafts”, *International Conference on Soil Mechanics and Foundation Engineering*, Vol 1, pp. 1119-1124.

Poulos, H.G., 2000, “Pile-raft Interaction-Alternative Methods of Analysis”, *Developments in Theoretical Geomechanics*, Vol. 1, pp. 445-463.

Poulos, H.G., 2000, “Practical Design Procedures for Piled Raft Foundations”, *Design Applications of Raft Foundations*, Vol. 5, pp. 425-467.

Poulos, H.G., 2001, “Piled Raft Foundations: Design and Applications”, *Géotechnique*, Vol. 51, No.2, pp. 95-113.

Poulos, H.G., 2001, “Methods of Analysis of Piled Raft Foundations”, *International Society for Soil Mechanics and Geotechnical Engineering*, Vol. 3, No. 4, pp. 67-69.

Prakoso, W.A. and F.H. Kulhawy, 2001, “Contribution to Piled Raft Optimum Design”, *American Society in Civil Engineering Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 1, pp. 17-24.

Randolph, M.F. and C.P. Wroth, 1978, “Analysis of Deformation of Vertically Loaded Piles”, *Journal of Geotechnical Engineering*, Vol. 104, No. 12, pp. 1465-1488.

Randolph, M.F., 1994, “Design Methods for Pile Groups and Piled Rafts”, *Soil Mechanics and Foundation Engineering*, Vol. 5, pp. 61-82.

Randolph, M.F., 2003, “Science and Empiricism in Pile Foundation Design”, *Géotechnique*, Vol. 53, No. 10, pp. 847-875.

Reul, O., 2001, “Numerical Study on the Bearing Behavior of Piled Rafts Subjected to Nonuniform Vertical Loading”, *Deptartment of Civil and Resource Engineering*, Australia.

Russo, G. and C. Viggiani, 1998, “Factors Controlling Soil-Structure Interaction of Piled”, *Soil-Structure Interaction in Civil Engineering*, Vol. 1, pp. 297-322.

Sanctis, L. and A. Mandolini, 2006, “Bearing Capacity of Piled Rafts on Soft Clay Soils”, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 132, No. 12, pp. 1600-1610.

Skempton, A.W. and D.H. MacDonald, 1956, “The Allowable Settlements of Buildings”, *Institution of Civil Engineers*, Vol. 3, No. 5, pp. 727-784.

Small, J.C. and J.R. Booker, 1986, “Finite Layer Analysis of Layered Elastic Materials Using a Flexibility Approach”, *International Journal forNumerical Methods in Engineering* Vol. 23, pp. 959-978.

Small, J.C. and H.H. Zhang, 2000, “Piled Raft Foundations Subjected to General Loadings”, *Developments in Theory. Geomechanics*, Vol. 1, pp. 431-444.

Ta, L.D., J.C. Small, 1996, “Analysis of Piled Raft Systems in Layered Soils”, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 2, pp. 52-72.

Terzaghi, K. and R.B. Peck, 1967, “Soil Mechanics in Engineering Practice”, *JohnWiley Sons*, New York.

Wong, I.H., M.F. Chang, X.D. Cao, 2000, “Raft Foundations with Disconnected Settlement-Reducing Piles”, D*esign Applications of Raft Foundations*, Vol. 5, pp. 425-467.