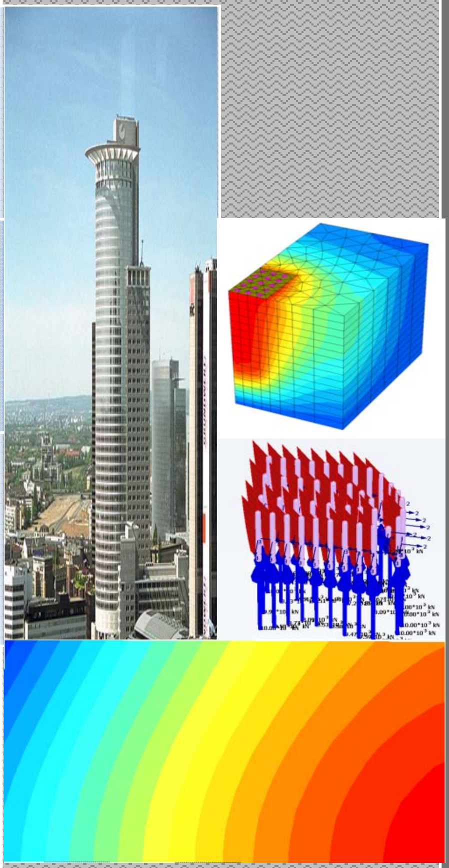
2009

Analysis and Parametric Study of Piled Raft Foundation Using Finite Element Based Software



A Thesis Submitted to School of Graduate Studies in Partial Fulfillment of the Requirement for Degree of Master of Science in Geotechnics

Simeneh Abate
Addis Ababa University

Addis Ababa University
School of Graduate Studies
Department of Civil Engineering

ANALYSIS AND PARAMETRIC STUDY OF PILED RAFT FOUNDATION USING FINITE ELEMENT BASED SOFTWARE

By

Simeneh Abate

B.Sc. in Civil Engineering
Addis Ababa University, 2005

A Thesis Submitted to School of Graduate Studies in
Partial Fulfillment of the Requirement for Degree of
Master of Science
in
Geotechnics

Advisor
Professor Alemayehu Teferra

May, 2009
Addis Ababa, Ethiopia

Addis Ababa University
School of Graduate Studies
Department of Civil Engineering

ANALYSIS AND PARAMETRIC STUDY OF PILED RAFT FOUNDATION USING FINITE ELEMENT BASED SOFTWARE

By

Simeneh Abate

A Thesis Submitted to School of Graduate Studies in
Partial Fulfillment of the Requirement for Degree of
Maser of Science
in
Geotechnics

Approved by Board of Examiners:

Prof. Alemayehu Teferra		
Advisor	*Signature*	*Date*
Internal Examiner	*Signature*	*Date*
Chair Person	*Signature*	*Date*

Acknowledgements

I am grateful to my advisor Professor Alemayehu Teferra, Department of Civil Engineering, Addis Ababa University for his close supervision and constructive suggestions during my research work.

I would also like to extend my acknowledgement to my colleagues for their support. I forward my special thanks to Metsihafe Mekibeb who gave me valuable comments on the analysis part of the thesis. Building Design Enterprise has made the PLAXIS 3D software available and provided me working place. The Organization’s Foundation and Material Testing Division staff was very cooperative and welcoming.

The help I received from my colleagues in Ethiopian Roads Authority is to be acknowledged. Finally I would like to express my deepest gratitude to my family for the fulfillment of all my interests.

Table of Contents

List of Figures

List of Tables

Abstract

The design of group piles depends on either the group or single pile capacity of piles. In conventional design method of such foundations, the stiffness of the pile cap is barely taken into account. Such design becomes too conservative if the pile cap is in contact with the ground. Because the pile cap contributes in transferring load to the ground and distributing load over the piles. The design method that considers the contribution of the pile cap and interaction between the different elements of group piles is called piled raft foundation. The concept of piled raft foundation leads to economical design.

In this paper, analysis and parametric study of piled raft foundation has been conducted. The study is performed using powerful finite element based software, PLAXIS. A number of parameters were selected from the elements of the piled raft system. According to their effect on the response of piled raft system, some are taken to be constant while others are varied. Among the varied parameters, raft thickness, pile length, pile spacing and pile number were considered. Other possibilities were also investigated in search of an optimum placement of piles.

The analysis results from the PLAXIS software have shown a close prediction to that of in-situ measurements and other numerical methods. From the parametric study, concentrating piles around the center for uniformly loaded rectangular piled raft foundation reduce the differential settlement.

1. Introduction

1.1. Back Ground

A geotechnical engineer faced with design of foundations considers shallow foundation for supporting a given simple structure. As the weight of the structure increases and the bearing capacity of the foundation soil compromise the stability or serviceability of the structure, one needs to resort to other foundation types.

Piles are good solution in site conditions where low bearing capacity and significant settlements are expected. In designing piles as foundation support for structures, it is a common trend to include a pile cap for joining of the pile heads. The pile cap is designed for structural section capacity only. But the pile cap has additional influence on the foundation system besides joining of pile heads and simple load transferring. Recent developments have shown that the stiffness of the pile cap influences the load transferring mechanism of the foundation system. The roll of the pile cap becomes significant if the cap is in direct contact with the foundation soil.

A piled raft is a foundation which acts as a composite construction consisting of three load bearing elements: piles, raft and subsoil. According to its stiffness, the raft distributes the total load of the structure as contact pressure and over the piles in the ground. The piled raft concept needs evaluation of a number of factors in order to come up with analysis/design models that simulate the actual site conditions.

The use of piled raft concept has lead to reduction of total as well as differential settlements. In many cases using raft foundation only induces excessive settlements which are not acceptable due to serviceability requirements. Placing of piles in systematic manner under the raft reduces such settlements to acceptable values. In addition to settlements, the bearing capacity of the whole system of foundation also improves.

The conventional design methods used for pile groups lead to a higher number of piles under the raft. With the concept of piled raft, this number can be reduced. This has proven piled rafts to be economical solution in foundation design for soil conditions where such design is applicable.

1.2. Objectives of the Research

Piled raft concept is not new from construction point of view. Any construction that involves inclusion of pile cap either for joining pile heads or forming pile groups some how act like a piled raft foundation. In Ethiopia, a number of high rise buildings are being constructed with foundation set up similar to piled raft foundation.

The economical and serviceability aspect of piled raft is attracting a number of geotechnical engineers. Researches are conducting on ultimate combination of piles and raft parameters that can lead to acceptable design requirements plus cost savings. These researches have provided a significant understanding of the parameters that affect piled raft performance. Application of this knowledge to our country will improve the performance of structures that are going to be built in the future.

Thus, the main objective this thesis will be on evaluating the parameters that affect piled raft performance from serviceability perspective. An indirect economical advantage of this kind of foundation can also be evaluated. Finite element software, PLAXIS, will be used as an analysis tool.

1.3. Organization of the Thesis

The thesis consists of five chapters. The first chapter is introduction to the concept of piled raft foundation. Literature review will be presented in the second chapter of the thesis. In the literature review a number of assessments will be done for future use. The theoretical formulations behind the proposed FEM based software will be discussed in chapter three.

Chapter four outlines the different parameters and results of the analysis done. Chapter five closes the whole theme of the thesis by making conclusions. In Appendices relevant drawings, tables, calculations and theoretical formulation of PLAXIS are presented.

2. Literature Review

2.1. Introduction

Piled raft foundation is assumed to have four kinds of interactions. These interactions are pile-pile, pile-raft, pile-soil and raft-soil (Fig 1). A model for full analysis and design of piled raft foundations has to predict these interactions accurately. The model has to be able to simulate the increasing settlement of a single pile under increasing loads, while taking into account the Pile-Soil-Interaction (Fig 1). Therefore, it is necessary to calculate the ultimate skin friction of the pile as a function of depth, in-situ stresses and the strength of soil-layers. The material laws used in the calculation must be explained in detail. It is recommended that a back analysis of a static pile test is carried out, to verify the numerical and material models.

With increasing raft settlement, the vertical and the horizontal stress states change (Interaction 3). Due to of a higher stress-state of the soil, the ultimate shear strength of the soil and thus the bearing capacity of the pile increase (Pile-Raft-Interaction). When the pile spacing is small, the Pile-Pile-Interaction additionally has to be taken into account. The requirements of the interactions 1 – 4 can only be satisfied by a three dimensional model of the total structure.

Different researchers have conducted analysis, design and performance of piled raft foundation. The researches done range from simple analysis methods by taking a number of assumptions to sophisticated analysis tools like finite element, boundary elements and case studies with site measurements.

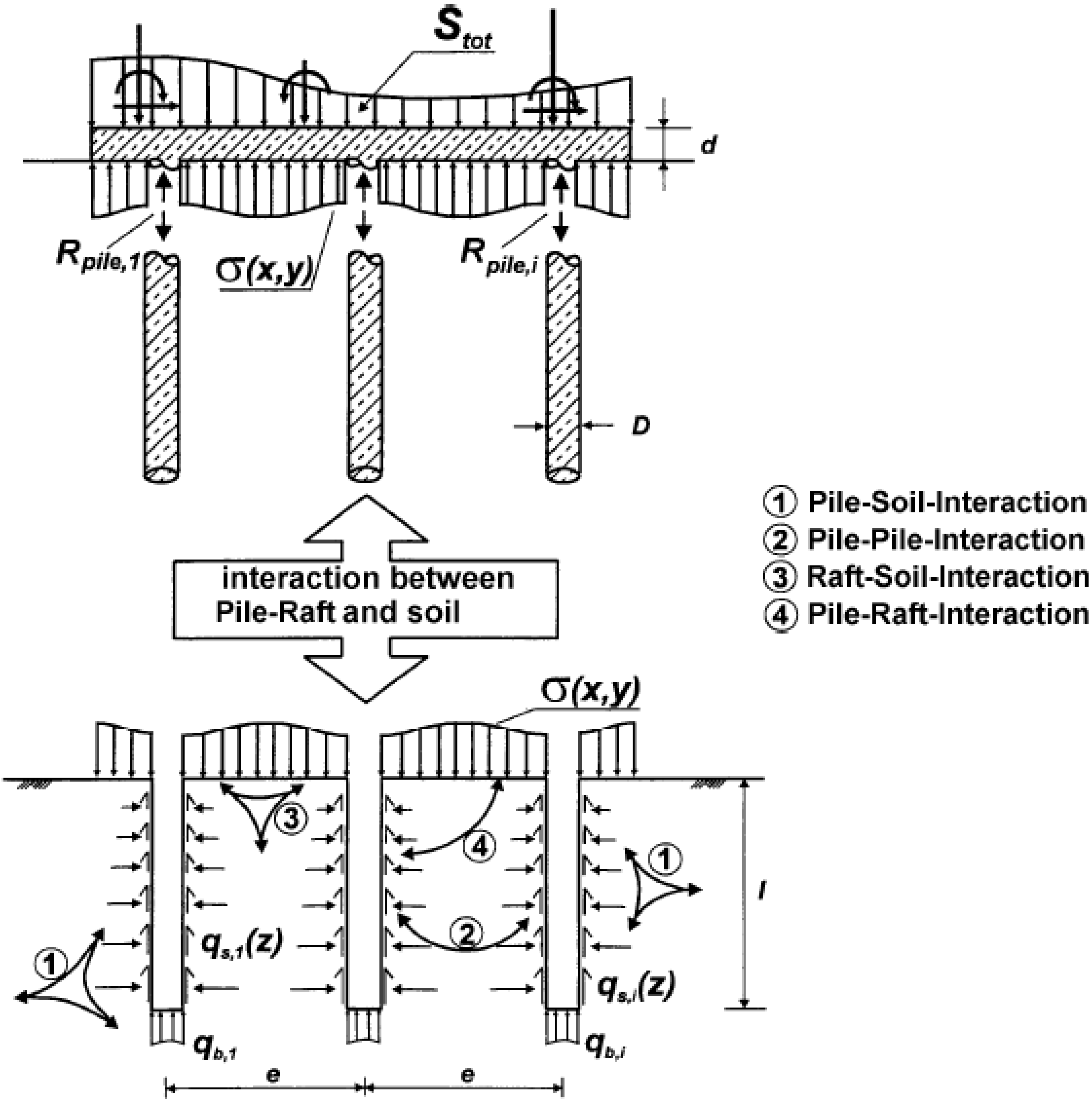


Figure 2.1 Interactions between pile, raft and soil in a piled raft foundation.

In this section, a number of these researches will be reviewed in accordance with the analysis and design methodology, parameters considered and conclusions reached. This review will be used as a future references in selection and developments of parameters as well as in making conclusions.

This chapter is organized into three sections. The first section reviews the different methodologies followed by different researchers for analysis and design of piled raft foundations. The assumptions and scenarios employed are also covered. Parametric studies will be listed in the second section with the parameters considered, results obtained and conclusions made. The last section will state the measurements and case studies conducted on actual structures.

2.2. Analysis/Design Methods

On July 2001, A Report Prepared on Behalf of Technical Committee TC18 on Piled Foundations by International Society of Soil Mechanics and Geotechnical Engineering illustrated methods of analysis of piled raft foundations. The well known author perhaps the most quoted author, H.G. Poulos, on a number of research papers has tried to list and explain methods of analysis for piled raft foundation. (Mekbib, 2004) and (Chow H. S., 2007) have also given enough outlines in their paper. The methods mentioned/explained by (Poulos, 2001) are presented in a number of other papers as well.

From the point of view of overall performance of piled raft foundation, it is desirable that a method be capable of predicting the entire load-settlement behavior of the system. As illustrated in (Fig 2.1), there are essentially three portions to the load settlement curve:

1. A more or less linear portion, representing the situation where both the piles and raft are behaving in an essentially linear manner.
2. A less stiff portion, in which the piles may have reached their full capacity, but the raft continues to carry increasing load.
3. A final portion, representing overall failure of the foundation system.

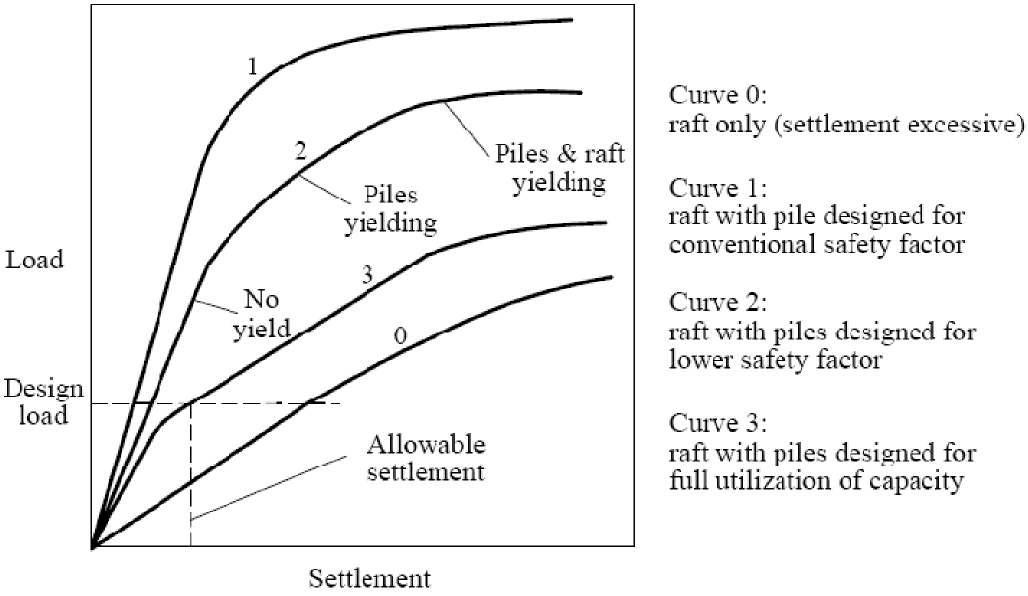


Figure 2.2 Load settlement curves for piled rafts according to various design philosophies

(Randolph, 1994) has defined clearly three different design philosophies with respect to piled rafts.

(i) The “conventional approach” in which the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft primarily to ultimate load capacity. In (Fig 2.2), Curve 1 represents this design philosophy in which the piles take the majority of load.

(ii) “Creep piling” in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70 – 80 % of the ultimate load capacity. Sufficient piles are included to reduce the net contact pressure between the raft and the soil to below the preconsolidation pressure of the soil. Curve 2 represents the case of creep piling where the piles operate at a lower factor of safety, but because there are fewer piles, the raft carries more load than (i).

(iii) Differential settlement control, in which the piles are located under the raft where high settlement is expected. This will make the settling area of the raft more stiff which ultimately reduce the differential settlement.

A number of methods can be cited in terms of their ability to predict load-settlement behavior of a piled raft foundation. But three broad classes of analysis methods are identified according to the assumptions, complexity and numerical methods employed.

a. Simplified calculation methods
b. Approximate computer-based methods
c. More rigorous computer-based methods

2.2.1 Simplified Calculation Methods

In the methods under this category, a number of simplifications in relation to the modeling of the soil profile and the loading conditions on the raft are involved. A brief discussion is made hereunder.

2.2.1.1 Poulos and Davis (1980)

This method is a convenient method for hand calculations which may be used as preliminary design tool. Elastic solutions are considered for stiffness and ultimate capacity calculations. The resulting load-settlement relationship is tri-linear as shown in (Fig 2.2). This method does not take into account the flexibility of the raft.

2.2.1.2 Randolph (1983, 1994)

(Randolph, 1983; 1994) has developed very approximate equations for the stiffness of piled raft system and load-sharing between the piles and the raft. This method is restricted to linear behavior of the piled raft system which indicates the foundation is designed essentially as a pile group with allowance for the load carried by the raft.

A modified method can be developed by combining (Poulos & Davis, 1980) and this method. The method which is named as Poulos – Davis – Randolph (PDR) Method tries to compute the load proportion share of the piles and the raft using the stiffness of the elements. The PDR method can be used to produce the tri-linear curve shown in (Fig 2.2).

2.2.1.3 Burland’s Approach

(Burland, 1995) has developed simplified process of design for piled raft foundations. One estimates the long term load – settlement relationship for the raft only and the design load P_0 gives a total settlement S_0. Similarly, an acceptable settlement value (S_d) which includes factor safety gives the load (P_1) from load settlement relationship.

The excess load (i.e. P_0 - P_1) is assumed to be carried by settlement – reducing piles. The design of the foundation will be performed accordingly by including the relevant factor of safety for the shaft and point resistance.

The bending moments in the raft can then be obtained by analyzing the piled raft as a raft subjected to the reduced loads. Unlike the bending moments, Burland did not explicitly set the method for estimating the settlement of piled raft. But one can adopt the approximate approach of (Randolph, 1994)

2.2.1.4 Other Methods

Other methods under this category are those of van (Impe & Clerq, 1995) and Equivalent Raft and Equivalent Pier Methods. The Equivalent Raft and Equivalent Pier methods are discussed in detail by (Randolph & Wroth, 1979).

2.2.2 Approximate Computer-Based Analysis

2.2.2.1 Strip on Springs Approach

(Poulos, 1991) modeled piled raft foundation as a strip supported on springs in which the strip represents the raft in one direction and the springs represent the piles. Approximate allowance is made for all four components of interaction. The effects of the parts of the raft outside the strip section being analyzed are taken into account by computing the free-field soil movements due to these parts and interaction with strip section.

The method is versatile and has been shown to give reasonable agreement with more complete analysis. But some limitations are observed. It can not consider torsional moments with in the raft, and thus it may not give consistent settlements at a point if strips in two directions through that point are analyzed.

2.2.2.2 Methods Employing a Plate on Springs Approach

In this type of analysis, the raft is represented by an elastic plate and the piles by springs. Some early approaches in this category e.g. (Hongladaromp, Chen, & Lee, 1973), neglected some of the interactions and hence gave stiffnesses which were too large, as revealed by studies made by (Brown & Wiesner, 1975) who compared such methods with more complete methods. (Poulos,

1994) employed a finite difference method for the plate and allowed for the various interactions via approximate elastic solutions. Allowance was also made for the effects of piles reaching their ultimate capacity, the development of bearing capacity failure below the raft, and the presence of free-field vertical soil movements acting on the foundation system.

(Clancy & Randolph, 1993) have adopted a more refined approach in which each pile is modeled as a series of rod finite elements while the raft is analyzed via two-dimensional thin plate finite elements. The four components of interaction are taken into account via elastic analyses. The method is restricted to analyzing the elastic response of the foundation. This method referred as hybrid method was employed on the thesis work by (Mekbib, 2004).

2.2.3 More Rigorous Numerical Methods of Analysis

2.2.3.1 Boundary element methods

In this type of approach, discretization is only required on the boundary of the system under consideration. This technique requires the transformation of the governing partal differential equation into an integeral equation. As only the boundaries have to be discretized, the number of sets of equations to be solved is generally smaller than the finite element or finite difference methods. Solutions such as stresses and displacements can be obtained directly by solving the system of equations. Since only the boundaries are discretized, interpolation errors are confined to the boundaries.

2.2.3.2 Simplified Finite Element Analysis

Simplified finite element analyses usually involve the presentation of the pile group or piled raft as either a plane strain problem, e.g. (Desai, 1974), or as an axi-symmetric problem, (Hooper, 1973).

The main problem in such a simplified approach is that only rather regular loading patterns may be analyzed, also it is not possible to obtain torsional moments in the raft.

2.2.3.3 Three – Dimensional Finite Element Analysis

In terms of ability to model a real problem, three-dimensional finite element analysis are usually considered to be the “ultimate weapon”, at least as far as the analysis is concerned (the problem of assigning appropriate parameters still remains, of course).

(Ottaviani, 1975) appears to have been the first to apply such an analysis to pile foundations. (Zhuang, Lee, & Zhao, 1991) and (Lee, 1993) have used a linear three-dimensional analysis to derive parametric solutions for the settlement and load distribution with in piled rafts. Among the parameters varied were the relative raft stiffness, the relative pile length, and the number of piles.

(Chow H. S., 2007) quotes Wang (1995) work as the most complete analysis which appears to have been undertaken to date. This analysis has involved nonlinear analysis of vertically loaded piled rafts via a nonlinear three dimensional analysis.

2.2.3.4 Methods combining Boundary Element and Finite Element Analysis

(Hain & Lee, 1978) published a seminar paper on piled raft analysis in which they represented the raft as a series of thin - plate finite elements, while the characteristics of the piles were computed from boundary element analysis

2.2.3.5 Combined Finite Layer and Finite Element Method

(Ta & Small, Analysis of Piled Raft Systems in Layered Soils, 1996) presented an approach based on the finite layer technique developed by (Small & Booker, 1986) to compute the behavior of piled rafts subjected to vertical loads in layered soils. The soil was divided into a series of horizontal layers; the raft was treated as a thin elastic plate and the piles were divided into rod elements corresponding to the soil layers. The soil was analysed by the finite layer method and the raft and piles were analyzed by the finite element method. (Ta, 1996) proposed two approximation methods (Type I and II) which may be used to compute interactions between the piles or piles and raft more efficiently. Displacement at any point on the soil surface can be approximated by a closed form polynomial equation. A type I approximation is limited to piled rafts with square raft elements of equal size and identical piles. A circular uniform load can then be used to represent the square block of contact pressure under the raft element. For the Type II approximation, the elements of the raft can be of different sizes, however, the interaction method was used to determine the interaction does not account for the group effect.

2.2.3.6 Variational Approach

This approach makes use of the principle of minimum potential energy to simulate the response of the foundation system. Discretisations are only required at the interface between the raft and soil. (Shen, Chow, & Yong, A Variational Approach for Vertically Loaded Pile Groups in an Elastic Half-space, 1999) developed a variational approach for analysis of pile groups with rigid pile cap not in contact with the ground. An extension of the method was developed by the same authors for the analysis of the cap in contact with the group (Shen, Chow, & Yong, 2000). Interaction between the cap, piles and soil was simulated by the use of Mindlin's solution and finite series were used to represent the deformation and shear stresses along the piles. The soil was modeled as an isotropic elastic half space and the piles were assumed to be linearly elastic. The analysis involved the isolation of the pile group-soil system from the pile-cap foundation and the interface between the pile cap and soil was discretized into a number of elements. The pile group-pile cap system was analyzed by the minimum potential energy principle.

2.3. Parametric Studies

It has been shown that a piled raft foundation has four kinds of interactions among its elements. A need, therefore, arises to predict a design method that optimizes these interactions. An optimized design of a piled raft can be defined as a design with minimum costs for the installation of the foundation and satisfactory bearing behavior for a given raft geometry and raft loading. A number of researchers have conducted parametric studies to hit this target.

(Reul & Randolph, 2004) have studied 259 different piled raft configurations using three – dimensional elastoplastic finite element analyses. In this study, the pile positions, the pile number, the pile length, and the raft-soil stiffness ratio as well as the load distribution on the raft has been varied.

In the parametric study, square unpiled rafts and piled rafts with an edge length of B = 38m have been considered. Three basic pile configurations were investigated. Pile configuration 1 has the piles uniformly distributed under the whole raft area. In Pile Configuration 2, the piles are placed only in the central area of the raft (beneath the core loading as detailed below). Pile Configuration 3 has piles under the central area of the raft as well as under the edges of the raft. The number of piles was varied between n = 9 and n = 169 and the pile length was varied between L_p = 10 m and L_p = 50 m. The pile diameter was held constant at d_p = 1.0 m. Pile spacing was varied between s = 3 m and s = 6 m. The raft soil stiffness ratio was varied between K_{rs} ~ 0.008 (approximately fully flexible) and K_{rs} ~ 54 (approximately rigid), where K_{rs} is defined by (Horikoshi & Randolph, 1998). As shown in (Fig 2.3), four different load configurations have been studied.

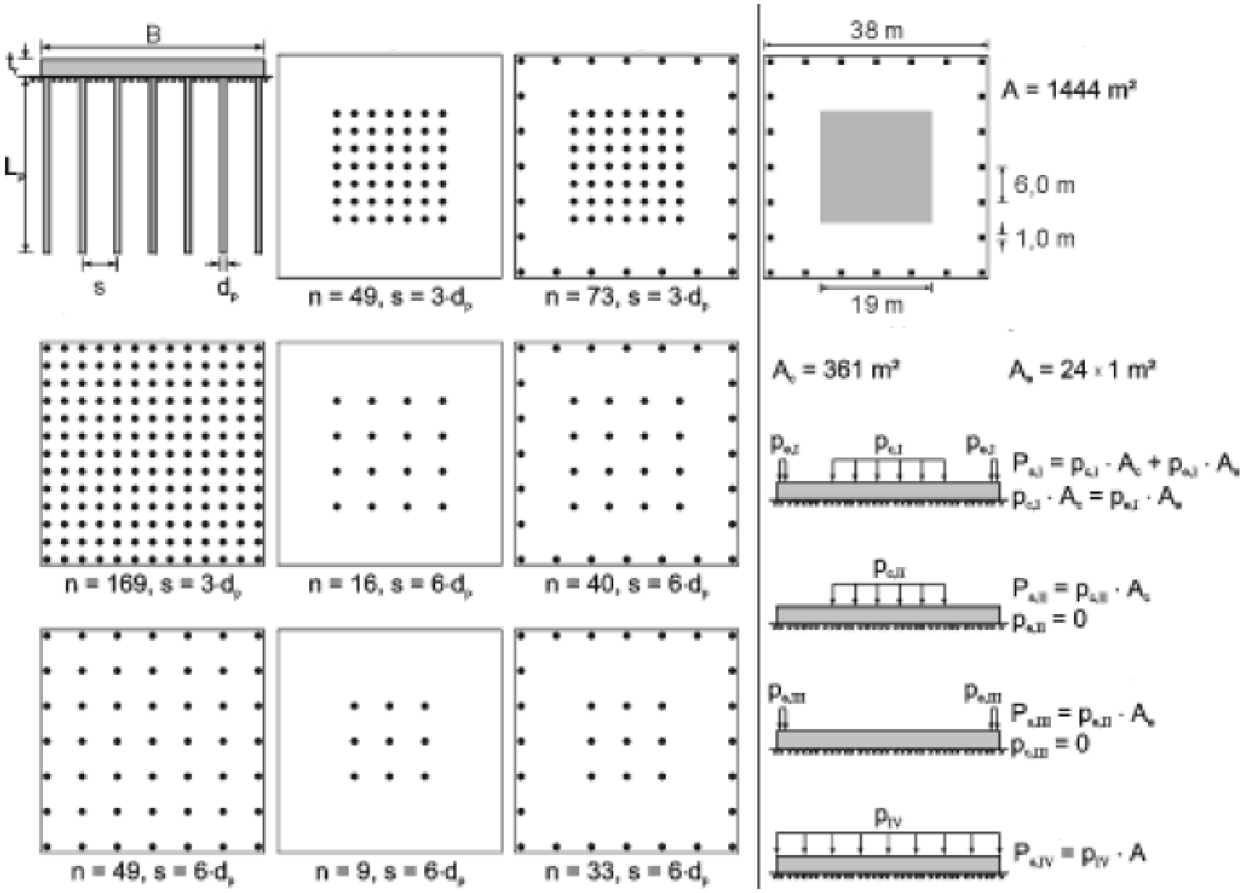


Figure 2.3 Some of the different arrangements of piles used in the parametric study (left) and the four load types (right). (Reul & Randolph, 2004)

The authors concluded from their analysis that the optimized design of a foundation depends on the subsoil conditions, the load configuration, and the load level. The main observations made are the following.

- For the same total length, smaller number of piles seems to perform better in reduction of average settlement than those with higher number of piles.
- The average settlement is the only parameter that is reduced compared to the unpiled raft, due to installation of piles, for all configurations studied.
- The overall stiffness of a piled raft decreases with increasing load level.
- The raft – soil stiffness and the load configuration affect the differential settlement much more than the average settlement.
- For a raft under uniform loading or core edge loading, the differential settlements can be most efficiently reduced by installation of piles only under the central area of the raft.
- For a raft subjected to uniform loading the installation of piles seems not to reduce the bending moments compared to the unpiled raft.

(Cunha, Poulos, & Small, 2001) investigated the design of piled rafts, outlining the influence of the major external variables that affect their design under concentrated column loads. According to the authors, the most important parameters that influence the design of piled raft foundation are those related to the pile characteristics (number, length, and disposition), raft characteristics (thickness), and the foundation's overall cost among others. These variables are incorporated into the parametric study performed with the basic data (soil conditions, load pattern, etc.) from an existing instrumented case history Yamashita et al. (1994) in which the final raft deformations and pile loads were known.

The Geotechnical Analysis of Raft with Piles program (GARP6) by Poulos and Small (1998) was adopted to evaluate the behavior of the reference rectangular piled raft subjected to vertical loading. This program is based on a simplified form of boundary element program in which the raft is represented as a linear elastic plate and the soil can be modeled either as an elastic plate and the soil can be modeled either as an elastic – layered continuum or as a Winkler spring medium. The piles are represented by elastic-plastic springs that can interact with each other and the raft.

The study considered 26 distinct parametric design alternatives and compared the analysis results against the reference design solution of the previous item (which represents Yamashita et al.'s case history). The adopted parameters and their variations are pile length (8 m and 16 m), raft thickness (0.3 m, 0.6 m and 1.2 m), number of piles (20, 10, 6 and 0) and finally pile/raft configuration. A comprehensive cost analysis was additionally carried out with the design data (geometry of the raft/piles, soil characteristics, etc.) in order to evaluate the relative costs of all alternate designs, with respect to the reference cost.

The observations made include

- Both differential settlement and maximum settlement tend to decrease as the raft thickness increase.
- For each raft thickness, by reducing the number of piles, there is slight tendency for both the maximum and average contact pressures to increase.
- The maximum pile load, for a specific raft thickness, is mainly dependent on both the number and length of the piles in the raft.
- It is noted that the load carried by the piles continuously decreases with an increase in raft thickness. This means that by increasing the raft thickness more load is absorbed by the raft.

For a given set up of piled raft foundation, the effects of pile group area, pile compressibility, poisson's ratio of soil and the stiffness of the piled raft system were studied by K. Horikoshi and M. F. Randolph. The analysis method used is that of (Clancy & Randolph, 1993) HyPR based on the hybrid approach of (Chow Y. , 1986).

A parametric study of piled raft behavior was performed to establish a framework for optimum design in terms of differential settlement. The following design practice is suggested by the authors of this study.

- Piles should be distributed over the central 16 to 25% of the raft area
- The pile group stiffness should be approximately equal to the stiffness of the raft alone ($K_{pr} \approx 1$)
- Total pile capacity should be designed for between 40 and 70% of the design load, depending on the pile group area ratio and poisson's ratio for the soil.

(Sommer, Wittmann, & Ripper, 1985) have conducted a parametric study with an ultimate goal of reducing settlement. The analysis of the foundation is done using finite elements. The deformation behavior of the soil was simulated by nonlinear elastic constitutive law, DUNCAN/CHANG (1972).

In a total number of 5 computations, both a foundation with monolithic raft, and a piled raft foundation with 15, 20, and 30 m long piles as well as the influence of super structure rigidity (20 m long piles), were investigated. The foundation was carried with 2 separate rafts, each with a total of 42 bored piles of Diameter D = 90 cm. The pile spacing varies from 3.5D to 3.0D.

The greatest settlements of about 26 cm were calculated for the raft foundation. For the piled raft foundation, the settlements become smaller with increasing pile length, the settlement decreases to approximately 12 cm (30 m – long piles). For pile lengths greater than 20 m no significant decrease in the settlements was observed. On this study, the influences of superstructure and pile raft load share are investigated.

The influence of pile – raft and pile – pile interaction on the behavior of piled raft is undertaken by (Katzenbach, Arslan, & Moormann, 2000). The load-bearing behavior of piled rafts in

Frankfurt Clay is examined by varying the geometry of the foundation. Two piled rafts which differ only in the number of piles were considered.

(Maharaj, 2004) presented the three dimensional nonlinear finite element analysis of piled raft foundation which is under the application of uniformly distributed load (UDL). The material nonlinearity of the soil medium has been idealized by Drucker-Prager Yield Criterion, Drucker and Prager (1952). The effect of raft and pile stiffness on load settlement behavior of piled raft foundation for uniformly distribute load (UDL) has been studied. A number of plots of load settlement curves have been produced as an output of the study.

The figures below reveal the UDL (uniformly distributed load) versus settlement curves for raft and piled raft foundation. By keeping the raft stiffness constant and increasing the stiffness of pile, the load carrying capacity of piled raft foundation increases as shown in (Fig 2.4). An excellent reduction in settlement is observed for a flexible raft with an increase in pile stiffness. Even for stiff raft, increase in pile stiffness is effective in increasing the load carrying capacity and reducing the settlement of piled raft foundation as shown in (Fig 2.5). From (Fig 2.4 and 2.5), the one with stiffer raft carries more load and reduces more overall settlement than the piled raft foundation with flexible raft for a given stiffness of piles. Piled raft foundation with flexible raft (K_r = 0.067) and stiff pile (K_p = 8000) and piled raft foundation with stiff raft (K_r = 0.67) and stiff pile (K_r = 80000) both undergo the same settlement and are having the same load carrying capacity as seen in (Fig 2.5). This is only possible if the over all stiffness of piled raft foundations become the same in both cases. An increase in raft stiffness is more effective in increasing the load carrying capacity and reducing the settlement of piled raft foundation than increasing the pile stiffness as demonstrated in (Fig 2.7).

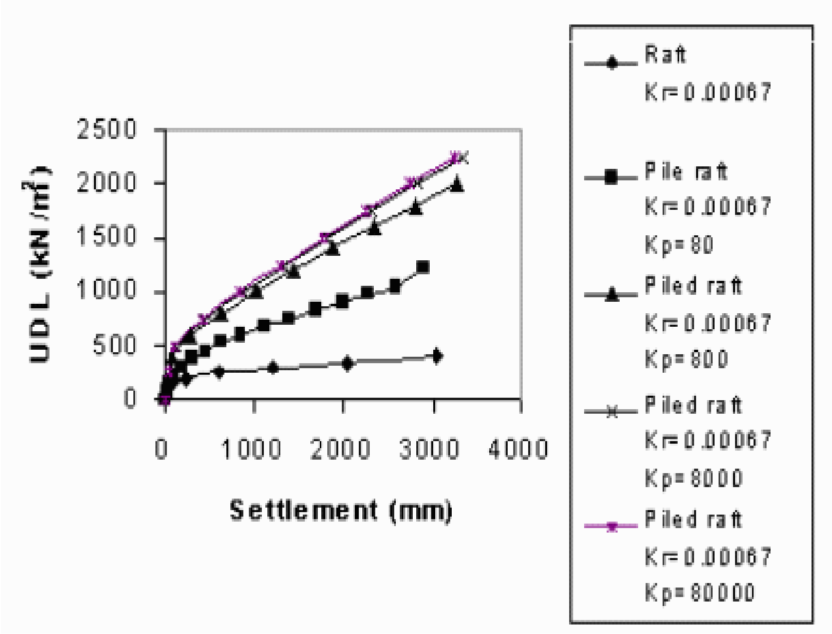


Figure 2.4 The effect of pile stiffness on load-settlement curves of piled raft foundation (flexible raft). (Maharaj, 2004)

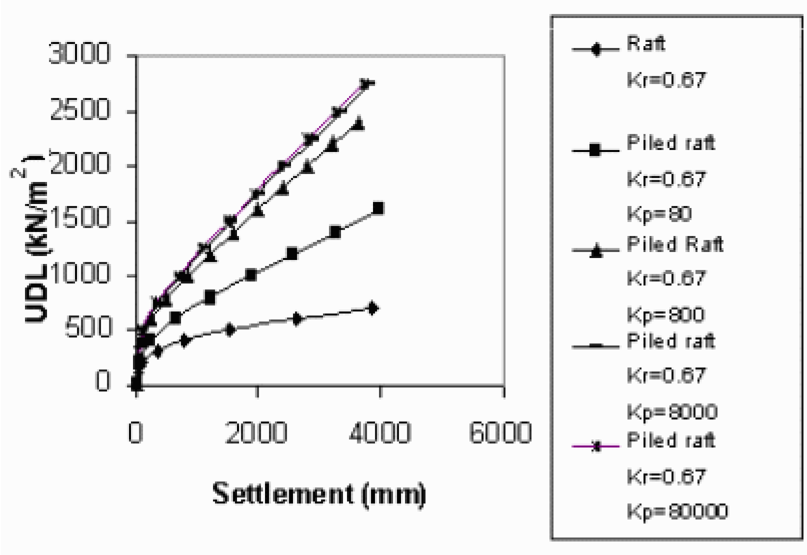


Figure 2.5 The effect of stiff pile on load-settlement curves of piled raft foundation (stiff raft). (Maharaj, 2004)

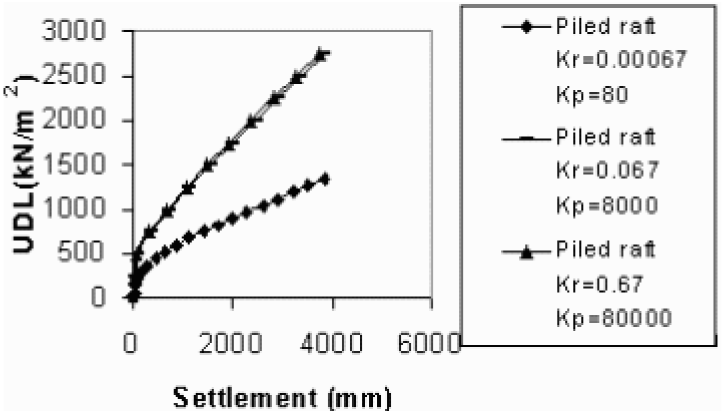


Figure 2.6 The effect of pile stiffness on load-settlement curves of piled raft foundation (flexible and stiff raft). (Maharaj, 2004)

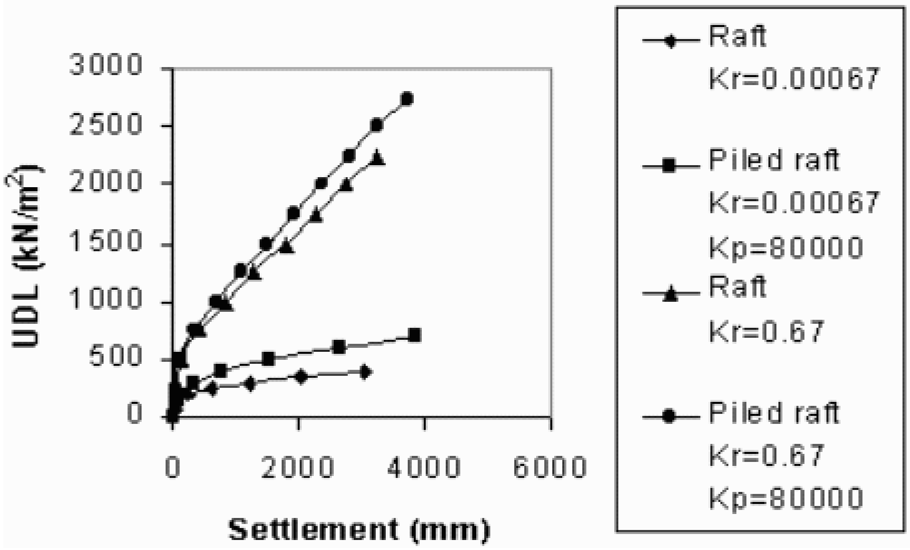


Figure 2.7 The effect of varying raft and pile stiffness on load-settlement curves of piled raft foundation. (Maharaj, 2004)

Recently, a parametric study was conducted by (Rabiei, 2009) on piled raft foundations using a computer program ELPLA. He varied the spacing, number and length of piles for his study. A uniformly distributed load was applied on the raft. The outputs of the study were presented in terms of raft bending moments and settlements. From this study, the following observations were made.

- Increasing the pile length uniformly decreases positive moment in the raft, total and differential settlements while the negative moment in the raft and pile forces increase.
- For constant center pile length with increasing outer pile length, maximum positive moment in the raft, differential settlement and percent of load on piles increases and central settlement decrease.
- For constant outer pile length with increasing center pile length, maximum positive moment in the raft, differential settlement and central settlement decreases and percent of load on piles increase.
- Except for thin rafts, the maximum settlement is not greatly affected by raft thickness, whereas the differential settlement decreases significantly with increasing raft thickness.

2.4. Measurements

There are a number of case studies under taken by different institutes. A detail of these studies is not presented here because the main aim of this paper is to conduct a parametric study. But measured results from three case histories on piled rafts in Frankfurt, Germany as presented by (Reul & Randolph, 2003) are given here.

In situ measurements for three buildings in Germany, Westend 1, Messeturm and Torhaus, have been given on this paper. The measurements are done by using instrumented piles, contact pressure cells, pore pressure cells, multi – point bore hole extensometers and inclinometers. Figure (Fig 2.8) shows Westend 1 raft measuring instruments installation places.

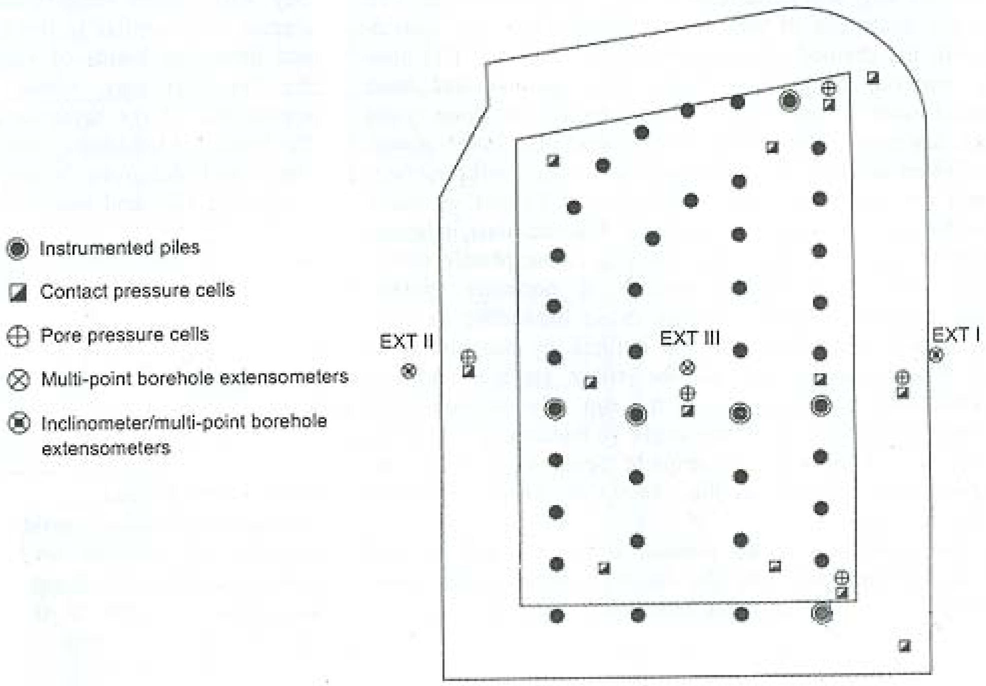


Figure 2.8 Ground plan of Westend 1 raft with measuring instruments installation position. (Reul & Randolph, 2004)

The measured settlement for Westend 1amounts to 120 mm in 2.5 years after completion of the shell of the building, Lutz et al. (1996). A minimum and maximum pile loads of 9.2 MN and 14.9 MN respectively were recorded which are taken from Franke & Lutz (1994). The last documented measurement (December 1998) on Messeturn gives a value of 144 mm for centeral settlement. Finally, the 130m high building, Torhaus, had an average settlement of 124mm on 1988, Sommer (1991).

3. Verification Examples from Literature

On this part of the thesis, it will be seen whether the result of PLAXIS software are consistent or not. To accomplish this task, 2 examples are picked from literature that have detail input and output data.

(Reul & Randolph, 2003) have given analysis and measurement results for three buildings in Germany. These buildings have piled raft foundation along with many other in Frankfurt am Main, Germany. The paper studied Westend 1, the Messeturm and Torhaus using three-dimensional elasto-plastic finite-element analyses. This paper employs Westend 1 and Torhaus results to validate the output of PLAXIS software.

***Structural Model*:** Finite element is used to model the soil and foundation. The soil and the piles are represented by first-order solid finite-elements of hexahedron (brick) and triangular prism (wedge) shape. The raft is modeled using first order shell elements of square and rectangular shape. The drained (long-term) shear parameters of soil were used. The non-linear material behavior of the soil (grains) has been modeled with a cap model that consists of three yield surface segment.

The contact zone between soil and raft, and soil and the large diameter bored piles, was modeled with thin solid continuum elements instead of special interface elements. A perfectly rough structure-soil contact was assumed. The raft and piles are considered to behave linear-elastically.

***Subsoil conditions*:** Frankfurt clay at the top under lain by the Frankfurt limestone characterize the site. Both of the above materials are modeled using an elasto-plastic cap model. The distribution of the young’s modulus of the Frankfurt clay with depth is assumed as nonlinear.

In modeling using PLAXIS, only the Frankfurt clay is used in addition, a linear variation of young's modulus is used.

3.1. WESTEND 1

A raft 47m x 62m is used with thickness of 3-4.65m. Forty bored plies with a length of 30m and diameter of 1.3m supports the raft with an arrangement shown below. The step-by-step analysis of the construction process employed is outlined below on tabular from.

Table 3.1 Westend 1; Step-by-step analysis of the construction process in the finite element analysis

Step	Applied load, P_{eff} (MN)	Mean vertical effective stress at foundation level (KPa)
1. In situ stress state	-	192
2. Excavation to a depth of 7mbelow ground level	-	66
3. Installation of the piles	-	66
4. Excavation to a depth of 14.5 m below ground level	-	0
5. Application of weight of raft minus uplift due to pore pressures as uniform load on subsoil	61.9	21.9
6. Installation of raft	61.9	21.9
7. Loading of raft	956.9	338

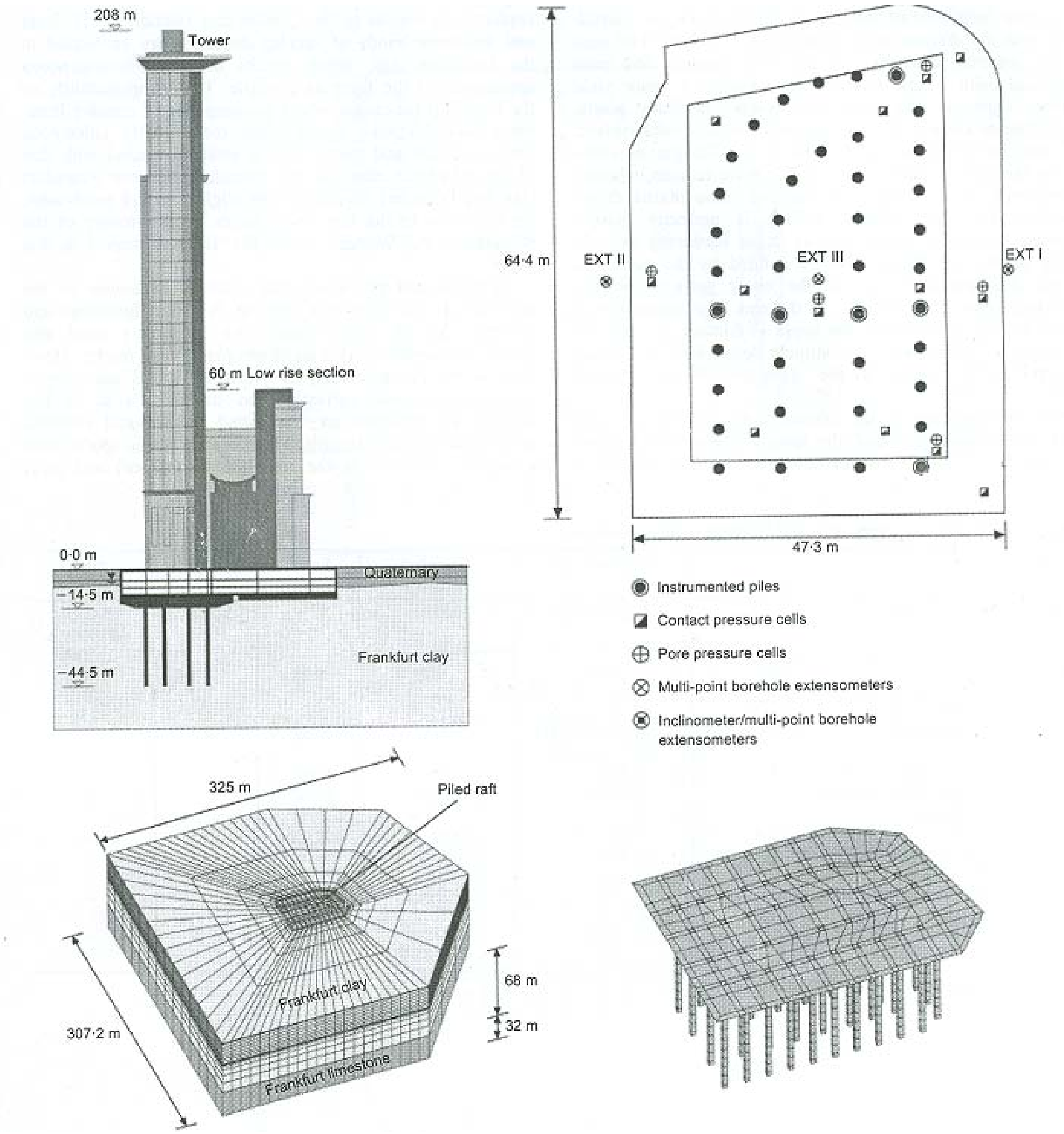


Figure 3.1 Westend 1 building with its raft layout and finite element models. (Reul & Randolph, 2003)

A similar modeling has been done using PLAXIS as a verification example. A rectangular raft is used instead of the shown above. A similar construction stages have been used to simulate all the ideas in the above table. The three dimensional model used is shown in the (Fig 3.2).

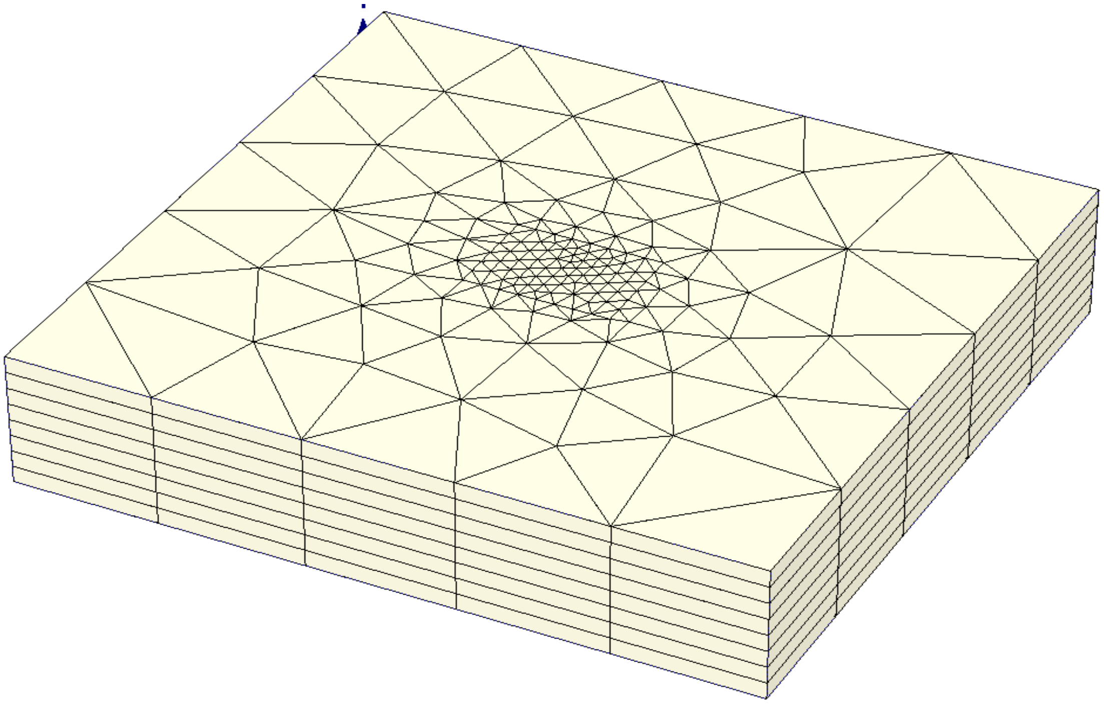


Figure 3.2 Three dimensional model of Westend 1 in PLAXIS 3D Foundation Software.

The PLAXIS software gives different outputs according to the requirements of the user. Among the major outputs, deformations, stresses, strains, forces, etc. can be included. In relation to this work, deformations are the main concern. But for this and the next verification example pile forces are also considered. The PLAXIS software output in contour plot is shown on (Fig 3.3) for deformation of Westend raft. A graphical and tabular out put of pile forces is shown on (Fig 3.4) and Table A4-1.

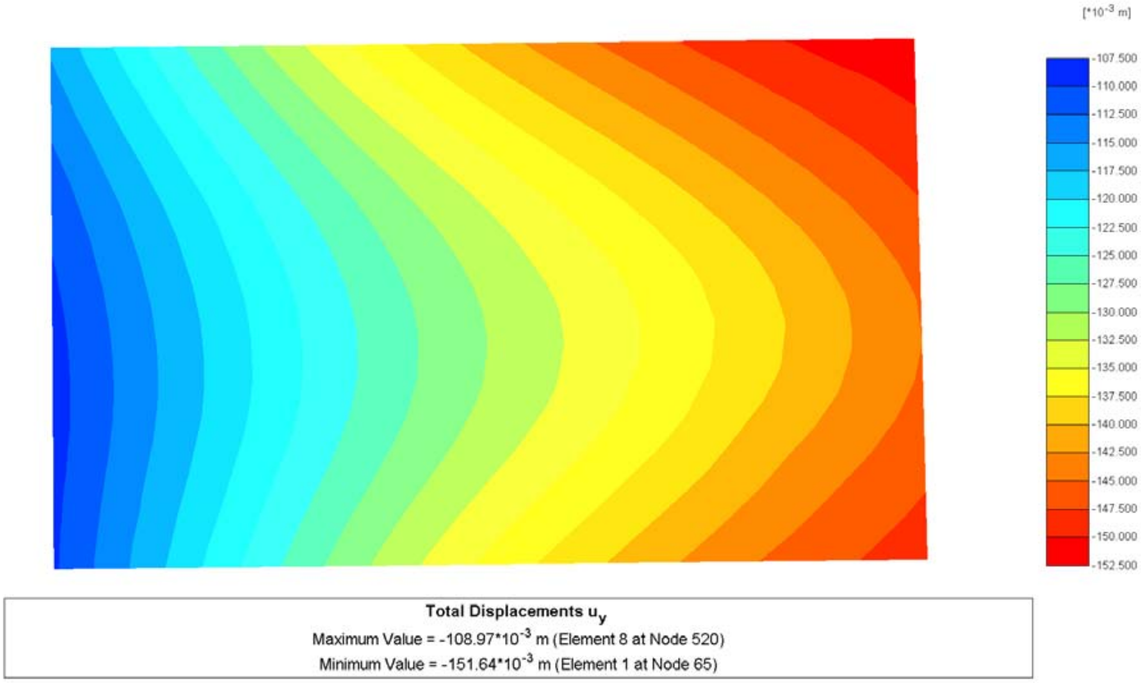


Figure 3.3 Raft deformation contour for Westend 1 in PLAXIS 3D Foundation Software.

The piled raft coefficient (α_{pr}) can be defined as the ratio of the load taken by the piles to the total load applied. The load sharing between the piles and the raft can be described using this coefficient. The coefficient can be given as

$$\alpha_{pr} = P_{piles}/P_{tot}$$

Where P_{piles} is total load taken by the piles

P_{tot} is the total load applied on the piled raft foundation

From Table A4-1, the total force carried by the piles is 655.37 MN while the total applied load is 956.9 MN. Thus the ratio results in 68.5%.

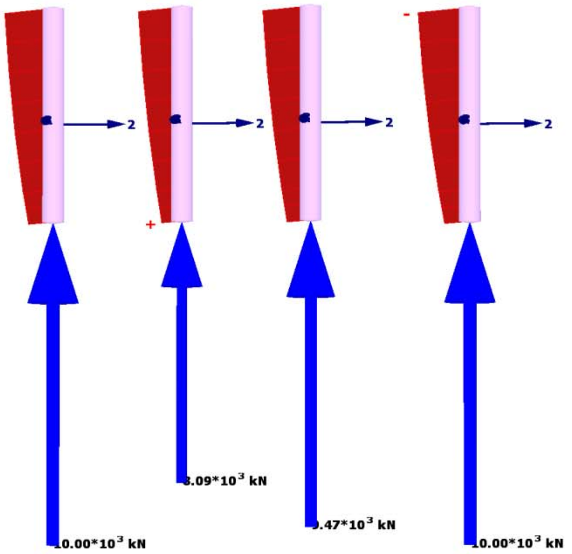


Figure 3.4 Some of the pile forces for Westend 1 in PLAXIS 3D Foundation Software.

A bar chart comparison is made for centre settlement, the maximum pile load and plied raft coefficient from the different methods listed below. The PLAXIS result is included here also for comparison purpose as shown in (Fig 3.5).

1) Simplified hand calculation method, (Poulos & Davis, 1980)
2) Strip on springs, (Poulos, 1991)
3) Plate on springs, (Poulos, 1994)
4) Combined finite element and boundary element method, (Ta & Small, 1996)
5) Combined finite element and boundary element method, Sinha (1996)
6) Combined finite element and boundary element method, Franke *et al* (1996)
7) Flexibility matrix method, (Randolph, 1983)
8) Load transfer approach for individual piles combined with elastic interaction between piles and raft, (Clancy & Randolph, 1993)

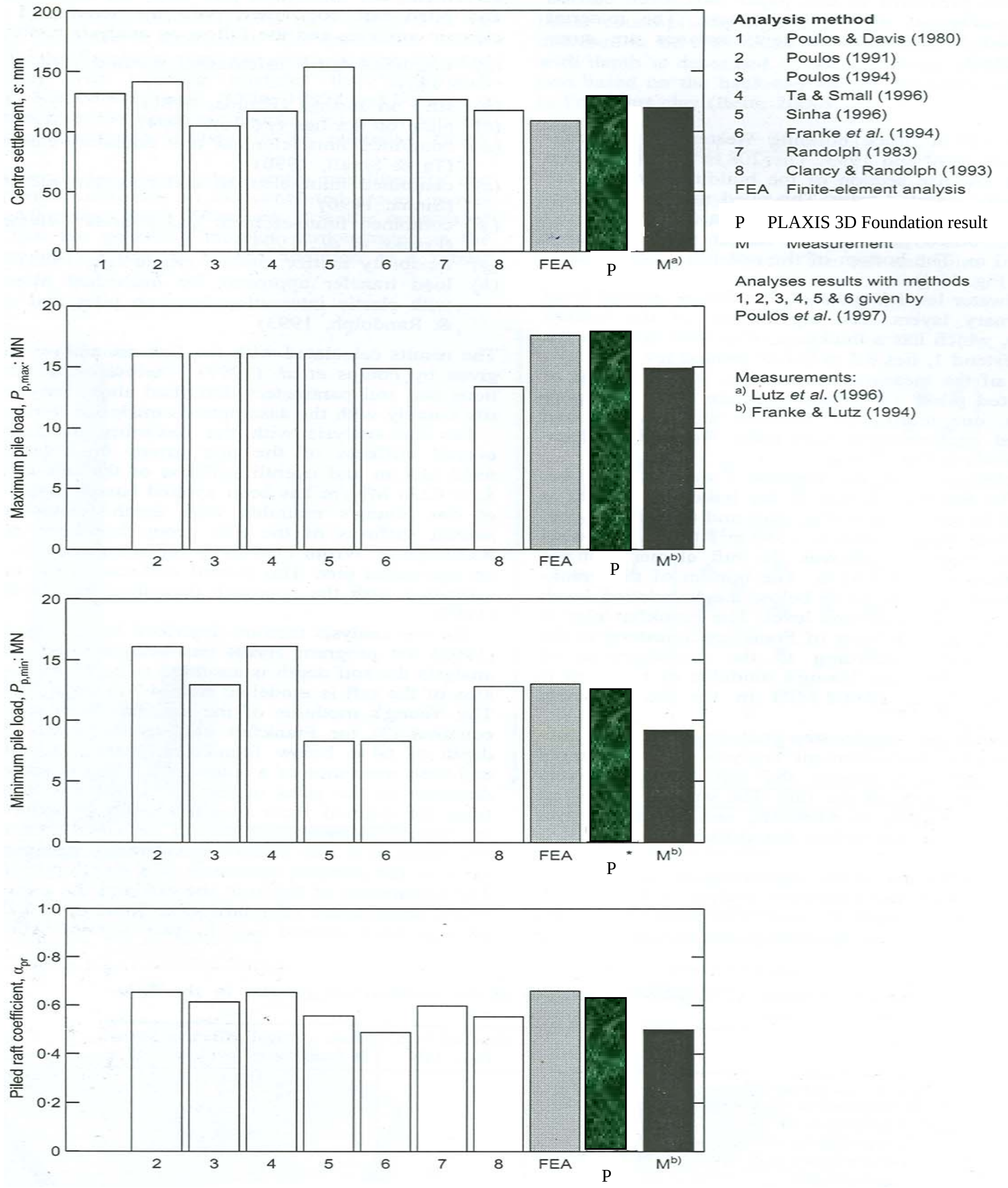


Figure 3.5 Westend 1: Comparison of different methods and measurements. (Reul & Randolph, 2003)

The measured center settlement amounts to 120 mm, a maximum pile load of 14.9 MN and a minimum load of 9.2 MN. The PLAXIS output shows a center settlement of 130 mm, a maximum pile load of 17.5 MN and a minimum pile load of 14.48 MN. A piled raft coefficient (ratio of load taken by the piles to total load applied) is found to be 68.5%. The results from PLAXIS agree well with both the measured as well as the numerical methods.

3.2. TORHAUS DER MESSE

Another verification example selected from the same paper, Reul O. and Randolph M. F. (2003), is a 130 m high Torhaus building. A total number of 84 bored piles with a length of 20m and diameter of 0.9 m are located under two 17.5 m x 24.5 m large rafts. The bottom of the 2.5 m thick raft lies just 3 m below the ground level. The subsoil comprises quaternary sand and gravel up to 2.5 m below the bottom of the rafts, followed by the Frankfurt clay.

PLAXIS modeling of the problem in a similar fashion as presented in the above paper. Uniform Frankfurt clay and step by step analysis of construction is used. Both the model used by Reul and Randolph and PLAXIS are given in the figures (Fig 3.6) and (Fig 3.7) respectively.

Table 3.2 Steps for Construction Stages in Torhaus Finite Element Analysis

Step	Applied load, P_{eff}: MN	Mean vertical effective stress at foundation level (KPa)
1. In situ stress state	-	45.0
2. Excavation to depth of 3 m	-	0
3. Installation of piles	-	0
4. Application of weight of raft as uniform load on subsoil	26.8	62.5
5. Installation of raft	26.8	62.5
6. Loading of raft	200	466.5

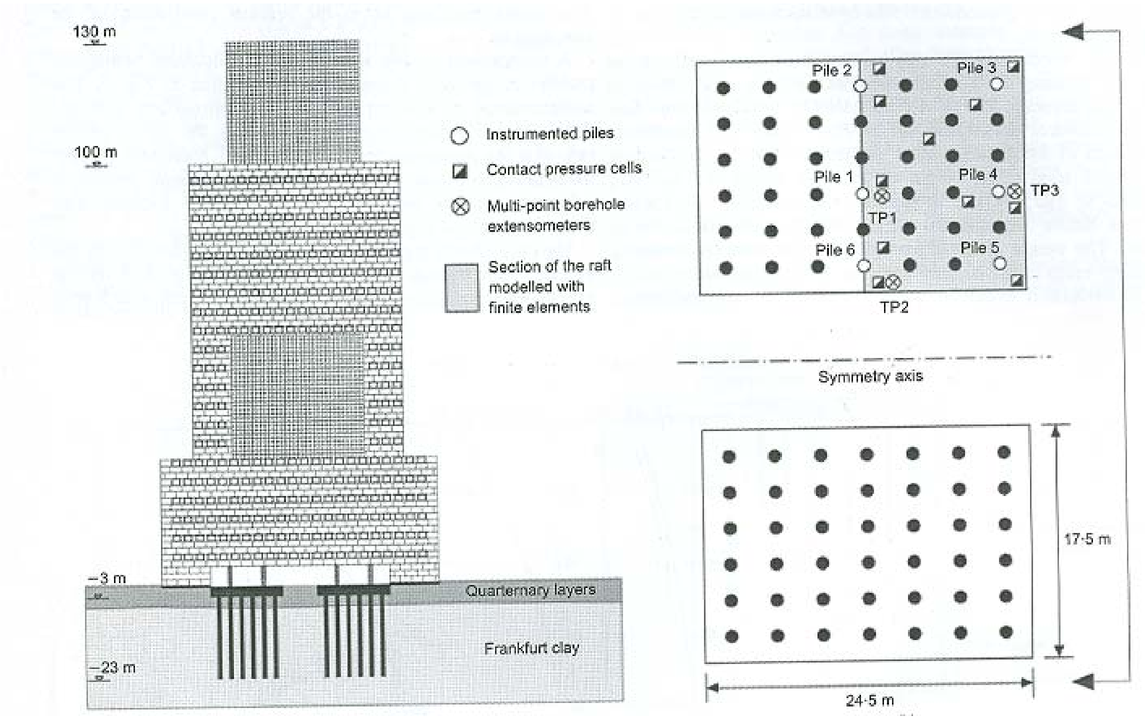


Figure 3.6 Torhaus: Profile view and ground plan of the raft. (Reul & Randolph, 2003)

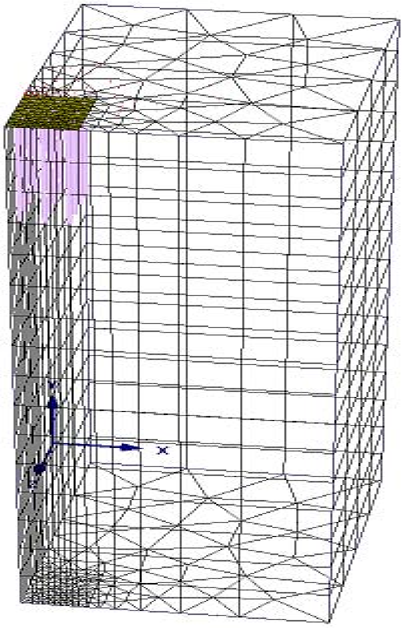


Figure 3.7 3D Finite Element Model of Torhaus using PLAXIS

The result for Torhaus raft settlement is plotted on (Fig 3.8) as a contour from PLAXIS.

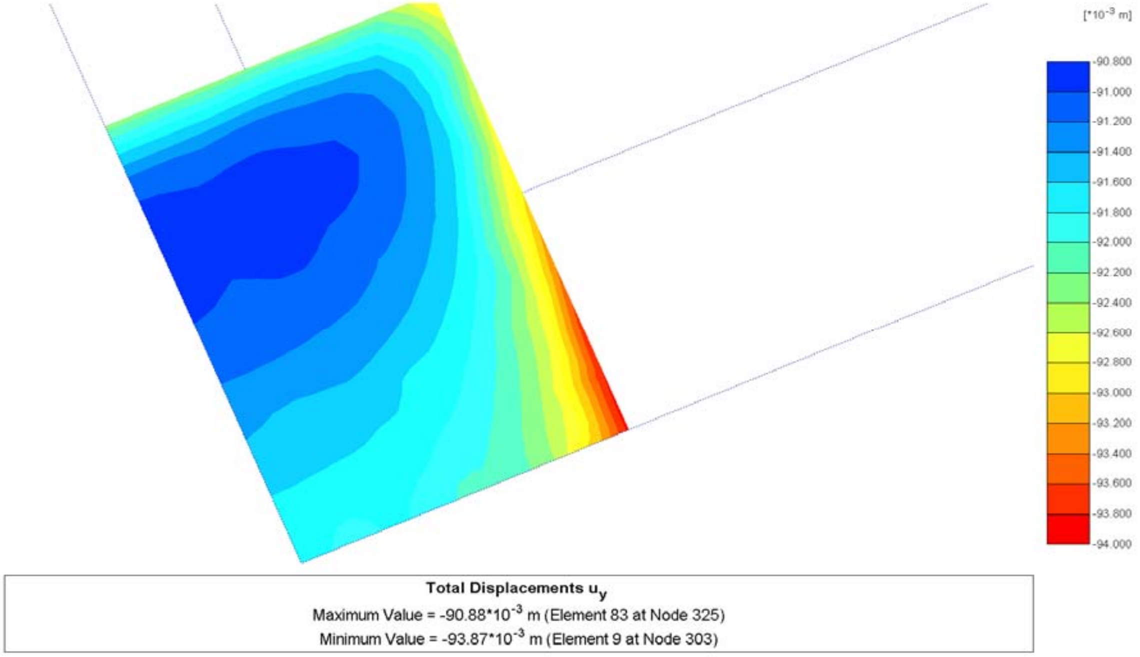


Figure 3.8 Torhaus raft deformation from PLAXIS software

From the last documented settlement measurement in 1988an average center settlement for the two rafts of 124 mm can be estimated, Sommer (1991). In the finite element analysis of (Reul & Randolph, 2003), a central settlement of 96 mm was calculated while the PLAXIS output gives a central settlement of about 92 mm. The graphical presentation of the raft deformation is given on (Fig 3.8).

3.3. OTHER

Finally, a work by Yasser El-Mossallamy Modelling titled “The behaviour of piled raft applying Plaxis 3D Foundation Version 2” as published on PLAXIS bulletin which was issued 23rd of March 2008 has demonstrated the capabilities of the software. He did a modeling of piled raft foundation and analyzed it using PLAXIS software. Settlement of about 4 cm is calculated at the raft center. This value agrees well with the measured value.

4. Analysis and Parametric Study

4.3. Parameter Identification

In the previous chapter of this thesis, three verification examples were analyzed using PLAXIS 3D Foundation software and the results were compared with measured values and other numerical methods. From the comparison made, the results from PLAXIS give reliable values. Thus, the parametric study in this section will be based on the results from this software.

There are a number of parameters to be considered if one is interested in conducting a full parametric study by considering all variables. But as reported on a number of literature, some of the variables have little or no effect in the piled raft system. In this paper, variables that have practical importance and reported to have significant influence in the piled raft system are considered.

The main parameter that influences the response of piled raft system is its stiffness. But the stiffness of a piled raft system depends on the elements in the system. The elements of the system are the soil, piles, superstructure (columns) and the raft. The stiffness of a piled raft system is governed by individual stiffness of the elements. Thus, parameters are identified accordingly.

The thickness, shape and dimension of the raft can be considered as variables in the parametric study. Shape and dimension are not most of the time design parameters. They are related to architectural or superstructure aspect of the structure which the piled raft is going to support. Thus, for this study, only the thickness of the raft shall be taken as one of the variables in the parametric study. The shape is specified as rectangular while an aspect ratio of 1.5 (B/L) is taken for the raft dimensions. A 45m by 30m rectangular raft is assumed. The Young’s modulus and the Poisson’s ratio are also kept constant.

The soil also contributes to the stiffness of piled raft system through Young’s modulus and Poisson’s ratio. The strength parameters of the soil can also be considered. This paper has assumed a uniformly laid soft/medium clay up to a depth of 70m in which the ground water is found at the foundation level. All parameters of the soil will be kept constant through out the analysis.

The arrangement, number, spacing, diameter and length can be called upon as the physical factors that contribute to the stiffness of the pile group. Arrangement and diameter are reported to have small or no roll in uniformly loaded piled raft system as per the works of (Reul & Randolph, 2004). However, pile number, spacing and length are the major variables in conducting parametric study of piled raft foundations. Young’s modulus and Poisson’s ratio for the piles will be kept constant.

In addition, loading of raft and arrangement of piles can be considered as another variable. For the study conducted in this paper, a uniform loading and uniform distribution of piles is mainly considered. But to supply the reader with justification some random arrangements are considered. Pictorial and tabular form of pile arrangements, variation of length of piles and thickness of raft are presented in Appendix 1.

The above discussion is backed up with relevant parameters that are going to be needed in the analysis using PLAXIS software.

Table 4.1 Relevant Soil, Raft and Pile parameters for Finite Element Analysis

Description	Soil	Raft	Pile
Type	Medium/Soft Clay	Concrete Grade C30 (EBCS-2)	Concrete Grade C30 (EBCS-2)
FE Model	Elasto-Plastic (Mohr-Coulomb)	Linear Isotropic	Linear Isotropic
Unit Weight	γ_{sat} = 18 KN/m^3 γ_{unsat} = 17 KN/m^3	γ = 24 KN/m^3	γ = 24 KN/m^3
Modulus of Elasticity	E_s = 8.0 MPa	E = 3.2 x 10^7 KN/m^2	E = 3.2 x 10^7 KN/m^2
Poisson's Ratio (ν_s)	0.3	0.2	0.2
Friction angle (ø')	20^o	-	-
Cohesion (c')	10 KN/m^2	-	-
Dilatancy angle (ψ)	0^o	-	-

PLAXIS 3D Foundation Software v 2.0 requires additional parameters to be filled as ultimate value for skin friction and base resistance. The calculation is illustrated in Appendix 2.

In the three-dimensional finite element model, only the quarter of the raft will be modeled (i.e. 22.5 m x 15.0 m) due to symmetry. The boundaries of finite element model will be 70 m x 45 m. A uniformly distributed load of 150KN/m^2 will be used. The phases in staged construction are

Initial Phase
Phase 1: Installation of the Piles
Phase 2: Installation of the Rafts
Phase 3: Loading the Pile Raft system

(Fig 4.1) below gives representative 3D model in PLAXIS

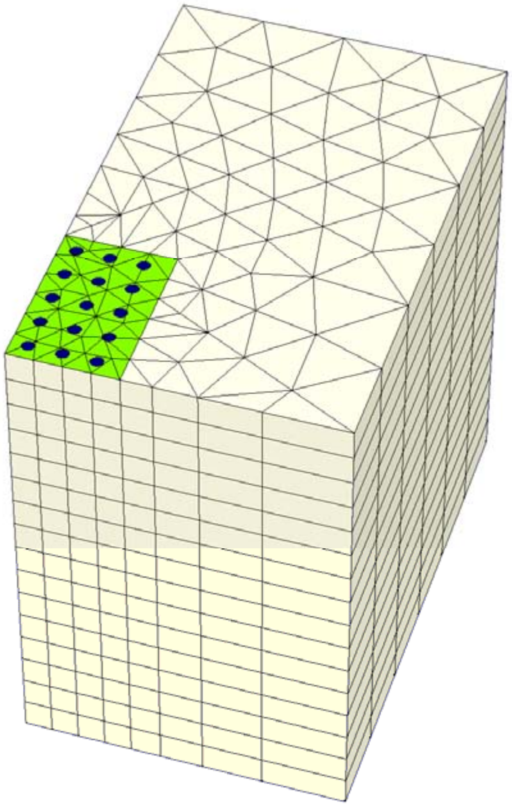


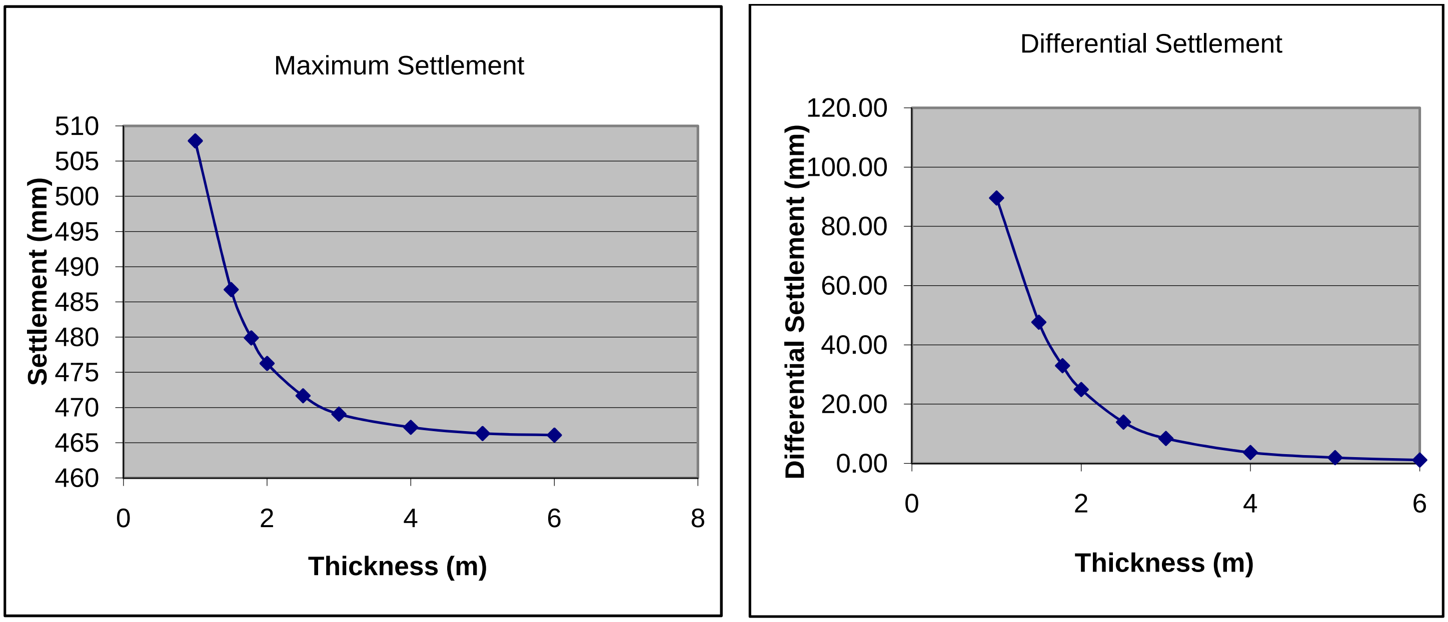
Figure 4.1 Typical 3D finite element model in PLAXIS for a piled raft foundation.

4.2. Analysis Results and Discussion

The parametric study conducted included a number of alternative arrangements of piles. Accordingly, the comparison criteria for ultimate design have been set to be the differential settlement and the total settlement. The maximum moments have been also been considered.

4.2.1 *Raft: Variation of Thickness*

Plots of centeral settlement and differential settlement are presented in (Fig 4.2).



a) Center Settlement b) Differential Settlement

Figure 4.2 Plots of central and differential settlement against thickness of raft.

The above figures show a well known trend that as the raft stiffness increases both the total and differential settlement decreases. One major point that should be stated from the figures is after a thickness of 2.5m there is little or no advantage in increasing the raft thickness interms of reduction in total and differential settlment. The same point is illustrated in the figures that follow for bending moments. The general set up of the local axes for the analyzed raft is given in (Fig 4.3). Local axis 1 runs along the length of the raft (+ve x-axis) while local axis 2 runs along the width of the raft (-ve z-axis). Local axis 3 runs out of the plane of the raft (+ve y-axis). From (Fig 4.4), one observes that after a thickness of 2.5 m, the bending moments in the raft do not increase substantially.

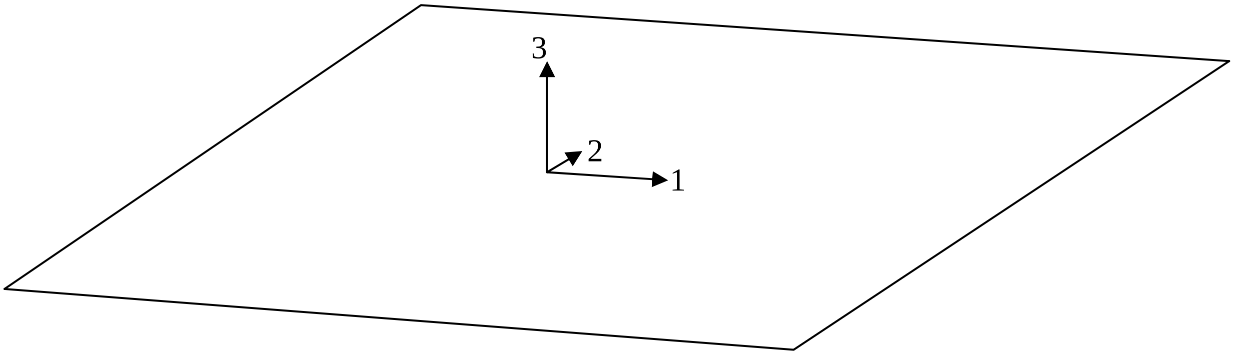
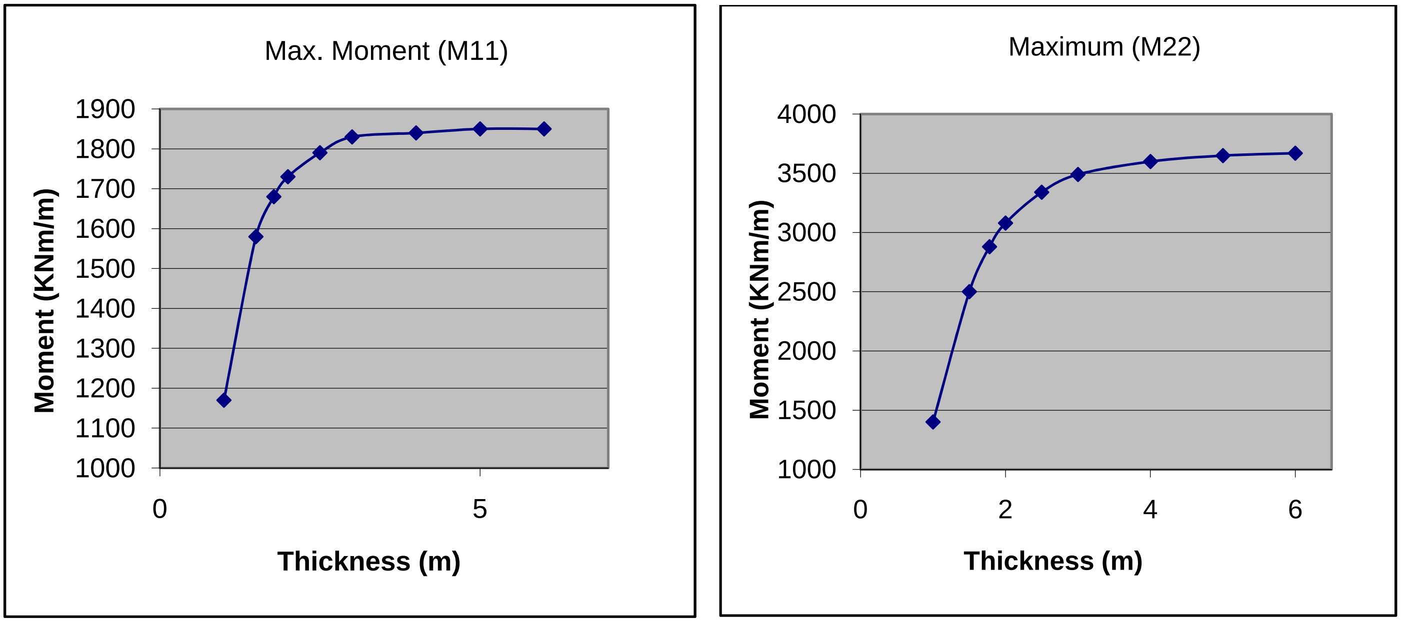
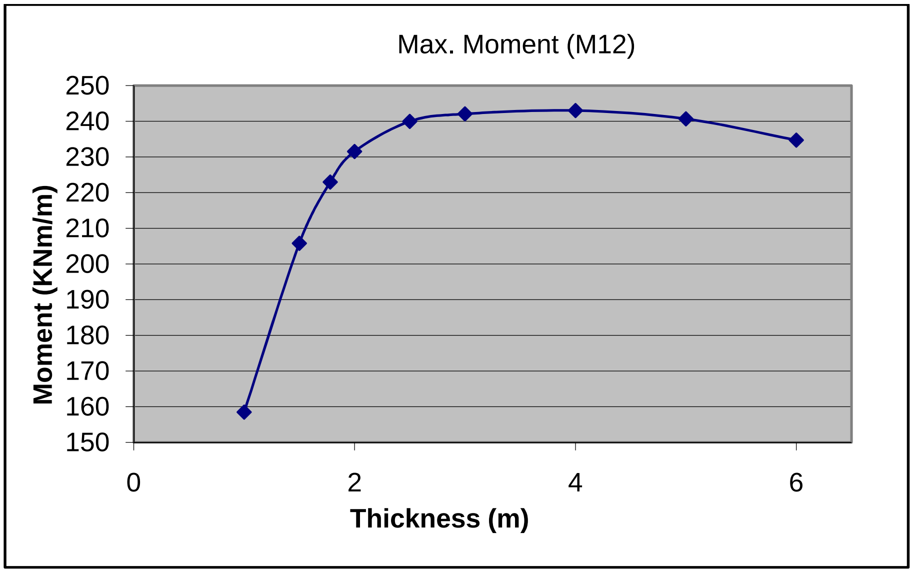


Figure 4.3 Local axes setup for raft forces determination.



a) Maximum moment in local axis 1

b) Maximum moment in local axis 2



c) Maximum in local axis 1-2

Figure 4.4 A plot of Maximum moments in different local axis against thickness of raft.

From the output of the above analysis, one can deduce that a reduction in differential settlement can be observed however with an increase of the bending moment. As the raft stiffness increase, both central and differential settlement decrease significantly. This will incur more load to be taken by the raft which ultimately yields higher bending moments. The rate of decrease in settlement and increase in moment seem to disappear at some specific raft thickness (around 2.5 m). From this point on, an increase in thickness of raft will not bring any significant change on both the settlement and moment of the raft. Thus, in order to decrease the total or differential settlement of a raft, one has to consider the associated increase in moment. The tabular form of this discussion followed by statistical analysis is presented in Table 4.2.

Table 4.2 Raft responses due to increase in thickness

Raft thickness (m)	*Diff. Settlement (mm)*	*Percentage of Differential Settlement*	*Percentage of Decrease of Differential Settlement*	*Percentage of Increase of M11*	*Percentage of Increase of M22*	*Percentage of Increase of M12*
1	89.60	17.64				
1.5	47.65	9.79	44.51	35.04	78.57	29.85
1.78	32.97	6.87	61.06	43.59	105.71	40.68
2	24.94	5.24	70.32	47.86	120.00	46.09
2.5	13.91	2.95	83.28	52.99	138.57	51.40
3	8.42	1.80	89.82	56.41	149.29	52.74
4	3.69	0.79	95.52	57.26	157.14	53.34
5	1.93	0.41	97.65	58.12	160.71	51.86
6	1.14	0.24	98.61	58.12	162.14	48.11

From Table 4.2, one can observe that a decrease in differential settlement by 83% will result in an increase of M11by 53%, M22 by 140% and M12 by 52%. This is of course achieved by increasing the raft thickness from 1.0 m to 2.5 m. A reduction of differential settlement of almost 100% can be achieved at 6.0 m for a little increase in moment in the raft.

4.2.2 Piled Raft: Variation of Spacing and Number

As seen in the problem formulation part of this thesis, a number of options were proposed for the parametric study. One of these was variation of spacing and number of piles as presented in (Fig A1.1) of Appendix 1. The output from the analysis is presented in Figures (Fig 4.5) to (Fig 4.8).

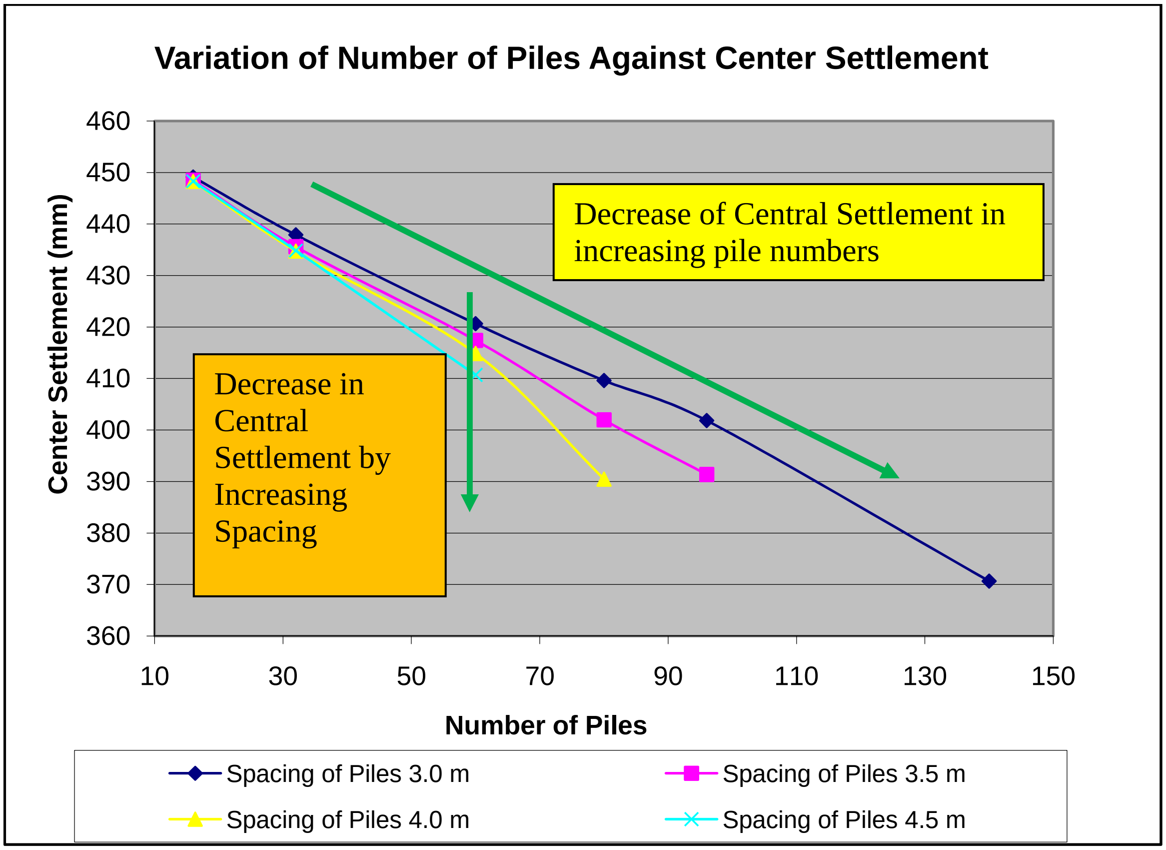


Figure 4.5 Central settlement of a piled raft foundation plotted against number of piles.

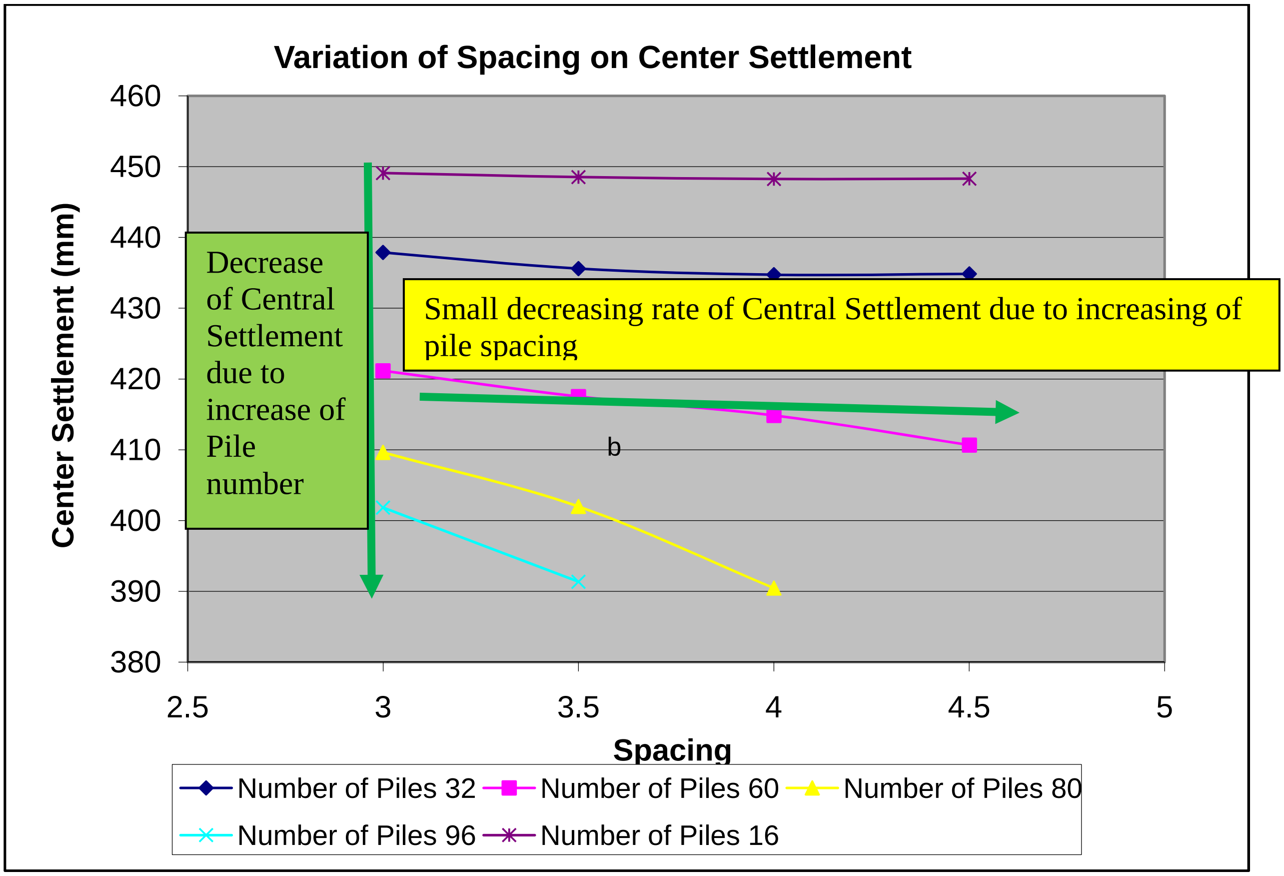


Figure 4.6 Central settlement of a piled raft foundation plotted against spacing of piles.

Figures (Fig 4.5) and (Fig 4.6) demonstrate that a significant decrease in central settlement can be observed in increasing the pile number while gradual decrease is seen in increasing the spacing of piles. One can reduce the central settlement by 50 mm, for example, by increasing the pile number from 16 to 96. The major reason for a decrease in central settlement in increasing spacing may be due to stress overlap in closely spaced piles. For closely spaced piles, the stresses over lap area will be large leading to higher settlement. Where as for the case of wider spaced piles, the stress overlap between adjacent piles will be lower and the settlement will also will be lower.

Similar plots as above are made for differential settlement and presented in figure (Fig 4.7) – (Fig 4.8). The figures illustrate that there is an optimum pile number which corresponds to minimum differential settlement for a given loading, spacing of piles and thickness of rafts. In figure (Fig 4.7) for example, the 3.0, 3.5 and 4.0 m spaced will have minimum differential settlement at 80 number piles. Moving vertically upwards for a given number of piles in (Fig 4.7), an increase in differential settlement occurs as the spacing gets wider for a given number of piles.

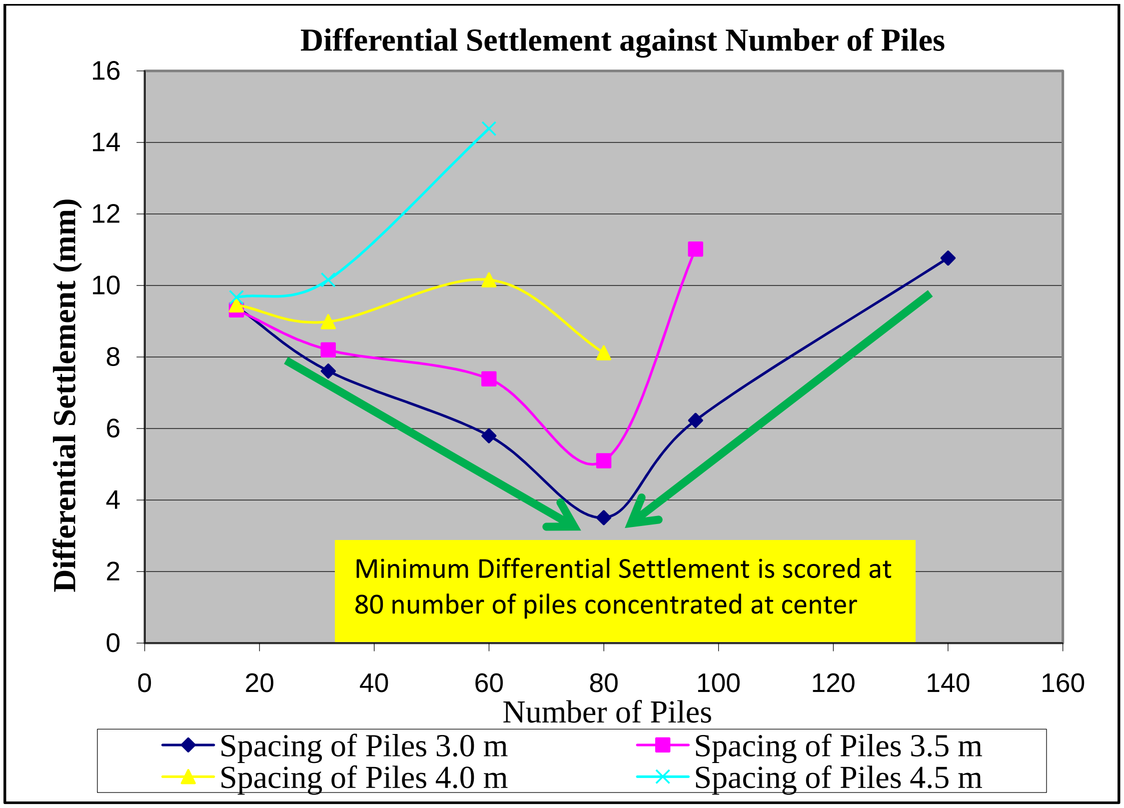


Figure 4.7 A plot of differential settlement against number of piles by keeping spacing constant.

The result for 4.5m spaced piles might look odd. However, differential settlement is quite related to the stiffness of the central area of piled raft system for uniformly loading. Thus, the stiffness ratio between the center and edge of the system is low for 60 piles compared to 16 piles which ultimately gave higher differential settlement.

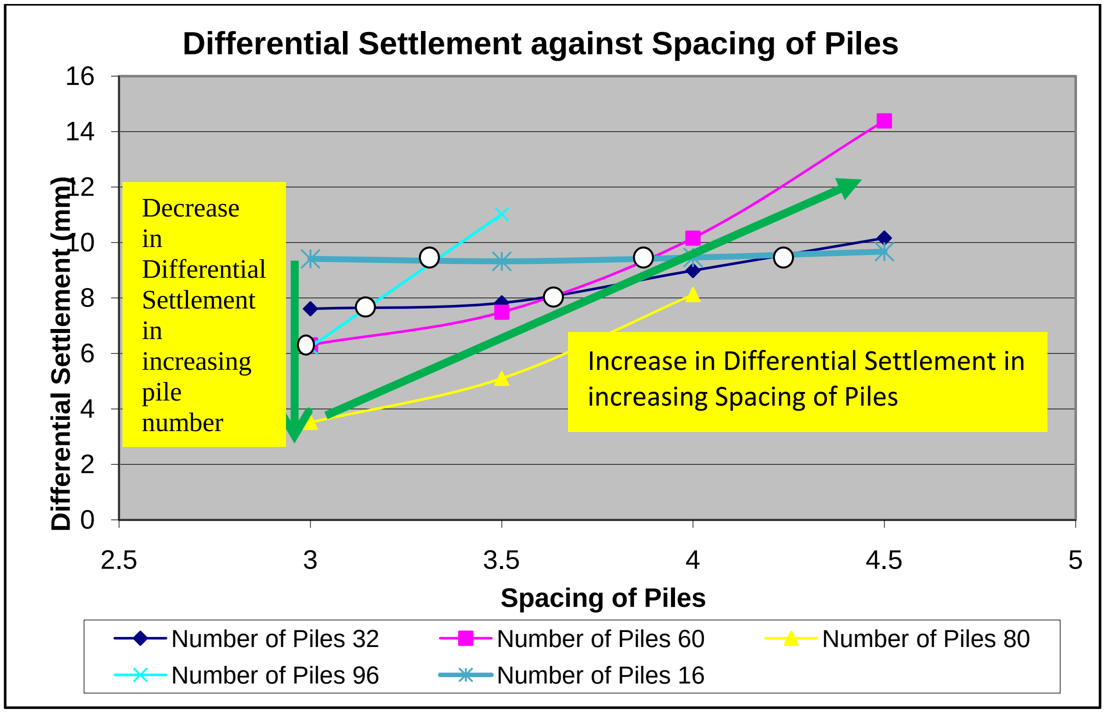


Figure 4.8 A plot of differential settlement against spacing for constant pile numbers.

In piled raft foundation design concept, one tries to decrease the differential settlement by keeping the central settlement to the accepted values of the prevailing codes. With the conventional method of design, a designer has to put higher number of piles under the raft in order to meet the differential settlement requirements. Simply putting piles under the raft leads to in decrease of both total and differential settlement. But allowing a higher total settlement which is in the range of the prevailing codes, one can obtain a lower number of piles. The white dots in (Fig 4.8) show the intersection of graphs for different number of piles illustrating the above fact.

The piled raft coefficient (α_{pr}) was defined previously as the ratio of the load taken by the piles to the total load applied. The effect of varying the spacing and number of piles on piled raft

coefficient can be studied accordingly. For the above cases, the tabular form of piled raft coefficient (α_{pr}) calculation is presented in Table A4-2 of Appendix 4.
From the tables, a low record of piled raft coefficient is found. A piled raft coefficient of 2% is found for 16 piles with spacing of 3m while a maximum value of 17% is calculated for 140 piles with spacing of 3m. The author believes these values and their rates of change are very low. This probably is because of the assumptions taken in the soil parameters. The strength and stiffness values taken for the soft clay of the parametric study are very low.

Despite the above the above results, one can see clearly that an increase in number or spacing of piles will make the piles carry more of the total load. This illustrates the shift of the load from the raft to the piles.

4.2.3 Piled Raft Foundation: Variation of Length

In this part of the analysis, the paper concentrates on two spacing of piles; the widest (4.5m) and the closest (3.0m) spacing. The pile numbers considered are also limited to 60 and 80 piles only. The length has been increased from 10m to 50m. The result of the analysis is presented in (Fig 4.9) and (Fig 4.10).

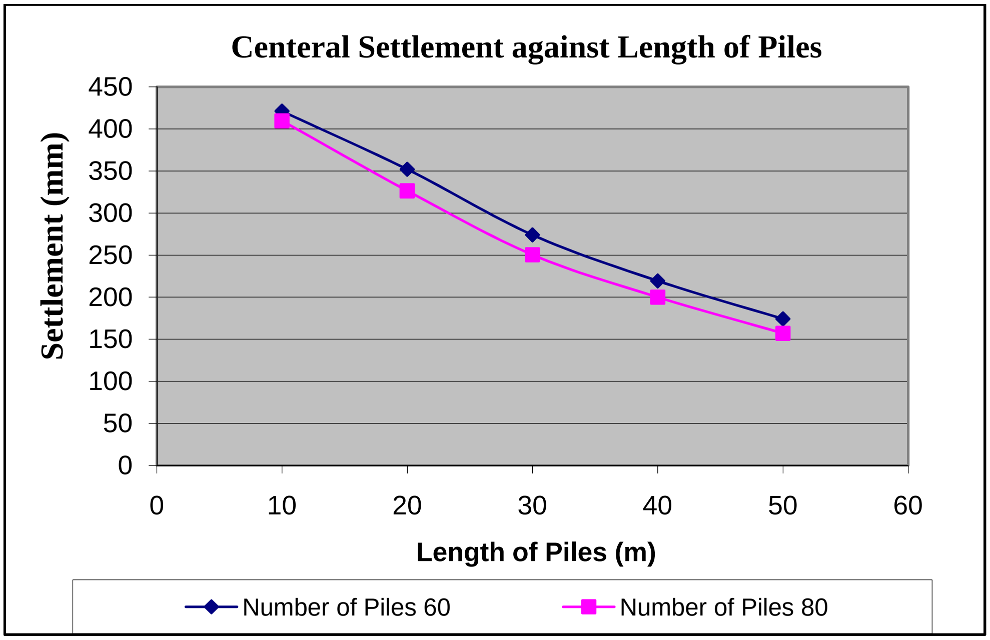


Figure 4.9 Variation of the central settlement with pile length (Pile spacing 3.0 m)

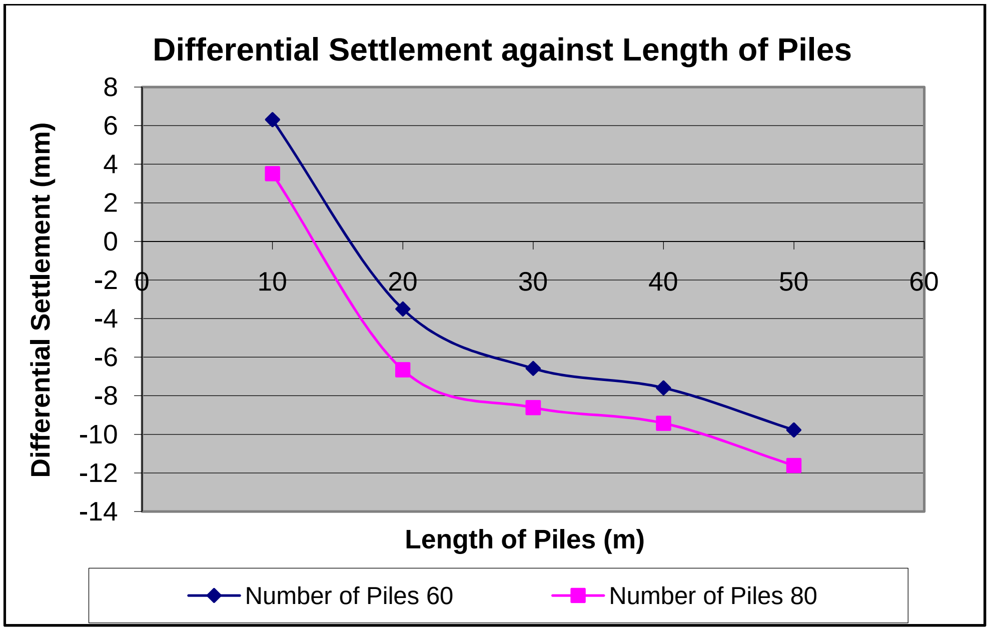


Figure 4.10 Variation of differential settlement with pile length (Pile spacing 3.0 m)

The increase in length of piles brings significant change in both the central settlement as well as the differential settlement. A similar decreasing pattern is observed for both spacing (3.0 m and 4.5 m) regarding central settlement as shown in figures (Fig 4.9) and (Fig 4.11). From figures (Fig 4.10) and (Fig 4.12), increase in length above 20 m yields differential settlement that is either with negative or constant value. For 32 piles with pile spacing of 4.5m, one can see that an increase length of pile did not reduce the differential settlement as shown in figure (Fig 4.12). The contribution of pile length to the stiffness of piled raft foundation is limited to some value.

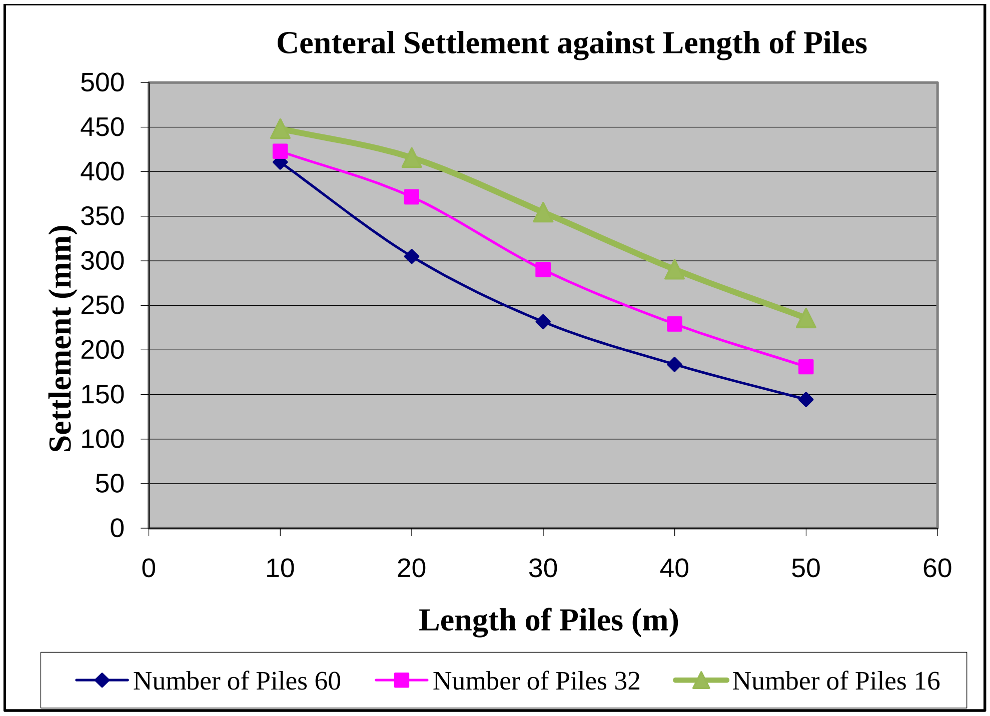


Figure 4.11 Variation of central settlement with length (Pile spacing 4.5 m)

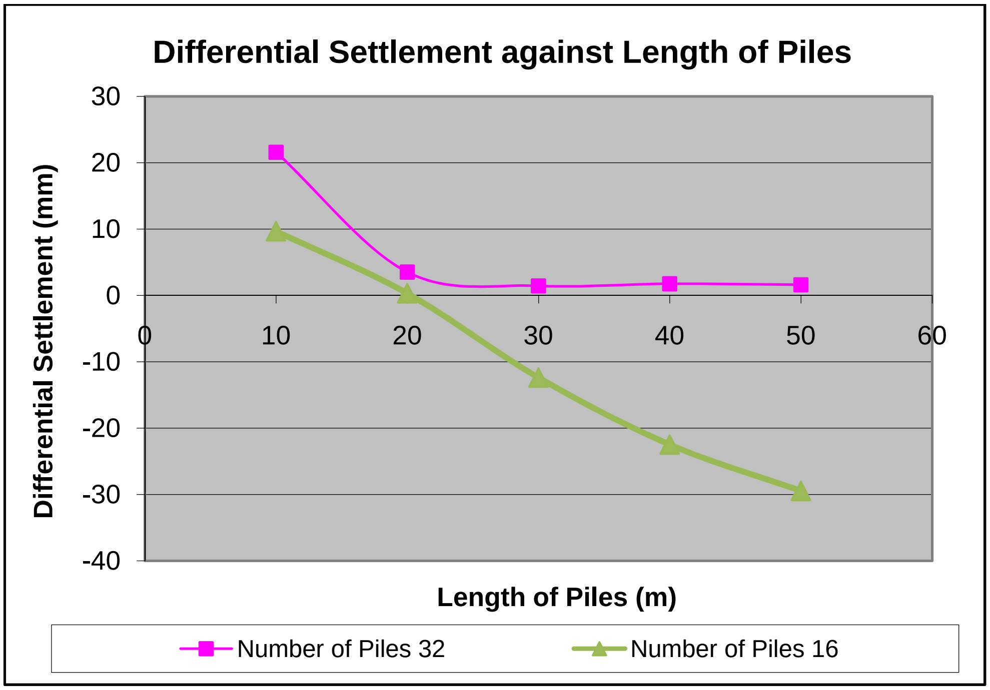


Figure 4.12 Variation of differential settlement with length (Pile spacing 4.5 m)

However in the case of differential settlement, negative values of differential settlement are observed in 3.0 m spaced 60 and 80 piles (Figure 4.10) and 4.5m spaced 16 piles (Figure 4.12). This is evident because of the stiffness of the raft and piles. As the pile length increases, the raft area where piles are located becomes stiffer. If the piles are spaced closely and have significant length, the unsupported raft that is around the edge act like a cantilever. Thus, the edge of the raft settles more than the central part.

The load share between the raft and the piles in increasing the length of the piles was also studied. Tables A4-3 to A4-6 give results from PLAXIS 3D Foundation software for pile loads. A maximum piled raft coefficient value of 67.75% was obtained for piled raft with 80 piles which are spaced 3.0m. All the results show increase in piled raft coefficient by using longer piles.

4.2.4 Piled Raft Foundation: Combinations

In this part of the analysis, the settlements of uniform and random arrangements of piles are investigated. Random arrangements of piles are considered for studying the change in behavior of piled raft foundation. Uniform and random arrangements of piles are defined as indicated pictorially in Appendix Al (Fig A1.1 and A1.2).

Figures (Fig 4.13) and (Fig 4.14) show the results from the above combinations. For uniformly distributed piles, previous sections of analysis results are taken. These are the line graphs with nomenclature of spacing of piles 3.0, 3.5, 4.0 and 4.5. On the other hand, the results for randomly distributed piles are shown as dots on the same graphs. The nomenclature for this kind of combination is combination 1-60, 1-32 and so on.

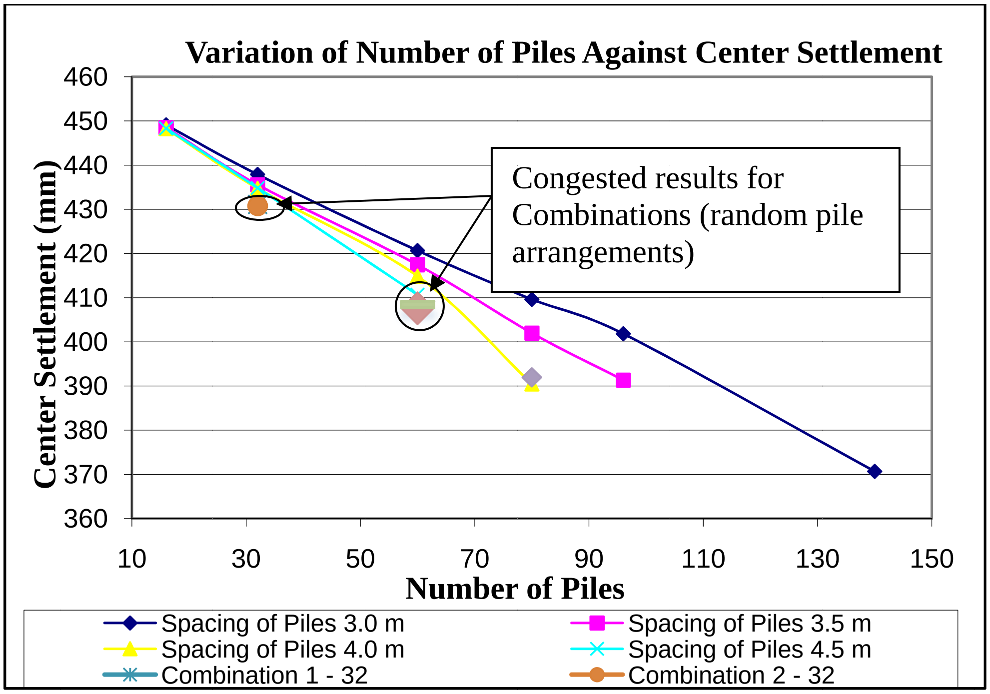


Figure 4.13 Centeral settlement for random pile arrangments (combinations) along with uniform ones (The naming is according to Appendix 1)

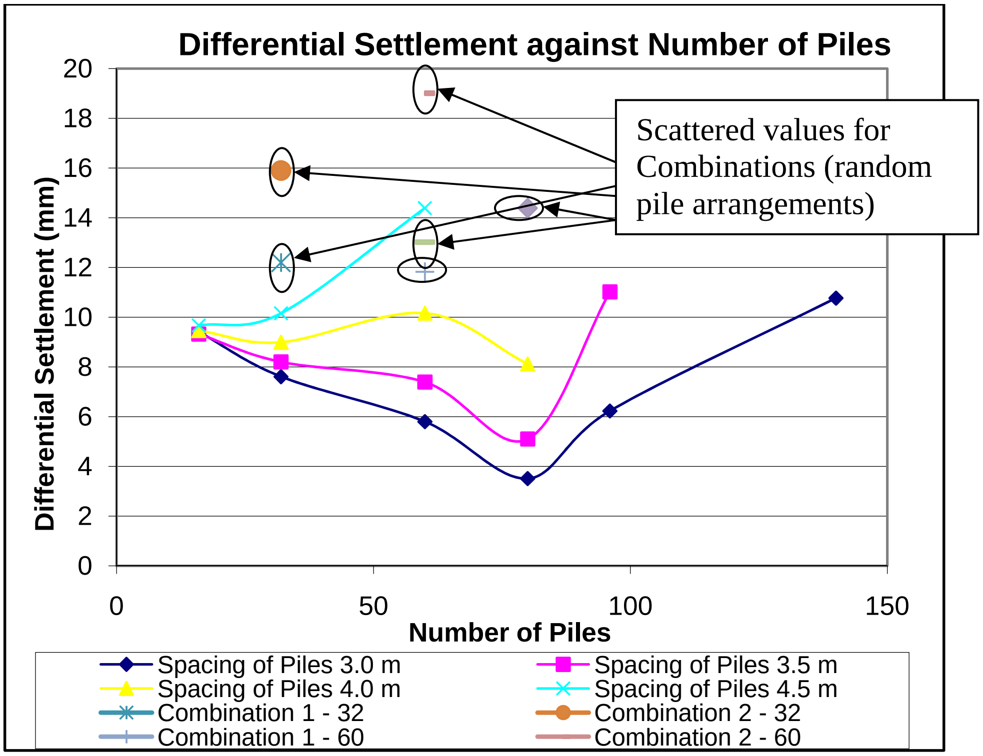


Figure 4.14 Differential settlement for random pile arrangments (combinations) along with uniform pile arrangments (The naming is according to Appendix 1)

The dots for randomly distributed piles stagger at one place for central settlement a little bit lower than uniformly distributed piles (Fig 4.13). But in case of differential settlement, the results went above the uniformly distributed piles. From the above results, the randomly distributed piles were not as effective as the uniform ones.

4.3. Comparing Results with Literature

In section 2.3 of this thesis, a number of parametric studies from other authors were presented. The assumptions made, results obtained and conclusions reached are briefly discussed. This section tries to compare the work done on this thesis with some of the Literatures and discusses on the differences and similarities.

The raft stiffness increase resulted in reduction both total and differential settlements. The maximum moment is observed to grow with raft thickness increase. (Rabiei, 2009) studied and found out similar curves to that of (Fig 4.2). Similar comments were made by (Reul & Randolph, 2004) where they clearly stated that increasing the thickness of the raft improves the performance of the raft with respect to settlement.

The effect of pile number was studied in all the quoted studies. Increasing the number of piles results in reduction of the total settlement and differential settlement. The piles also take more load that comes to the piled raft system. Similar observations were made in the given literatures. In case of differential settlement, this thesis work found out the specific number of piles that gives the minimum differential settlement value for given loading and thickness of raft as presented on (Fig 4.7). Most of the literatures failed to talk about specific values like this. The variation in spacing also determines the stiffness of the piled raft system. But as predicted on this work and other literatures, closely placing piles around the central area of the raft reduces the differential settlement significantly.

The pile length effect is studied on different literatures like (Reul & Randolph, 2004), (Sommer, Wittmann, & Ripper, 1985) and (Rabiei, 2009). The results show that an increase in length of piles significantly reduces the total and differential settlements. In addition the load transfer from the raft to the piles increases. As presented on (Cunha, Poulos, & Small, 2001), the systematic arrangement of piles improves the performance of piled raft foundation for column type of loading. In this study, it was clearly seen from (Fig 4.13) and (Fig 4.14) that systematic/random arrangement of piles do not improve the performance of the piled raft foundation.

Finally, the use of piled raft concept has been proofed to provide design options over the selection of number, spacing and length of piles and thickness of the raft. Thus, one can evaluate economical aspect of this foundation. Though this study did not include economic analyses, one can take a lead from the work of (Cunha, Poulos, & Small, 2001). An economical analysis was undertaken by these authors took different parameters that could affect the cost of a piled raft foundation. The outcome of the work from these authors showed that reducing the number of piles or thickness of the raft has effect in the total cost of the piled raft system. The authors recommend that detail investigations to be made in order to come up with conclusive results with respect to the economics of this foundation design concept.

5. Conclusions

The paper has demonstrated the major concept of piled raft foundation that piles can be utilized to reduce differential settlements with an eventual increase of total settlement which is acceptable in prevailing codes. The following conclusions are made:

1. The verification problems analysed using a finite element based software gave close results to the insitu measured values. This proofs the potential behind finite element method in modeling real three dimensional foundation problems.

2. Both the stiffnesses of the raft and pile group has a major role in determining the total and differential settlement of the piled raft system.

3. Increasing the thickness of raft has made a signficant reduction both in total and differential settlement up to a thickness of 2.5m.

4. Centeral settlement decrease with an increase in pile length while the decrease in differential settlement stops at a length of 20m.

5. For a uniformly loaded piled raft system, concentrating the piles at the center gives small differential settlement which would increase the centeral settlement.

6. In line with the current and previous studies, random/strategic placing of piles (for example, around the edge and at the center) is not a good option in terms of differential settlement reduction for a uniformly loaded raft.

6. Bibliography

1. Brown, P., & Wiesner, T. (1975). The Behaviour of Uniformly Loaded Piled Strip Footings. *Soils and Foundations, 15(4)* , 13-21.
2. Burland, J. (1995). *Piles as Settlement Reducers.* Pavia, Italy: Keynote Address, 18th Italian Congress on Soil Mechanics.
3. Chow, H. S. (2007). *Analysis of Piled-Raft Foundations with Piles of Different Lengths and Diameters.* Sydney: The University of Sydney.
4. Chow, Y. (1986). Analysis of Vertically Loaded Pile Groups. *Int. Jl. For Numerical and Analytical Methods in Geomechanics, Vol. 10* , 59-72.
5. Clancy, P., & Randolph, M. (1993). Analysis and Design of Piled raft Foundations. *Int. J. NAM Geomechs.*
6. Cunha, R. P., Poulos, H. G., & Small, J. C. (2001). Investigation of Design Alternatives for a Piled Raft Case History. *Journal of Geotechnical and Enviromental Engineering* , 635-641.
7. Desai, C. (1974). Numerical Design Analysis for Piles in Sands. *J. Geot. Eng. Div., ASCE, 100(GT6)* , 613-635.
8. Hain, S., & Lee, I. (1978). The Analysis of Flexible Raft-Pile Systems. *Geotechnique, 28 (1)* , 65-83.
9. Hongladaromp, T., Chen, N., & Lee, S. (1973). Load Distributions in Rectangular Footings on Piles. *Geotech. Eng., 4(2)* , 77-90.
10. Hooper, J. (1973). Observations on the Behaviour of a Piled-Raft Foundation on London Clay. *Proc. Inst. Civ. Engrs., 55(2)* , 855-877.
11. Horikoshi, K., & Randolph, M. (1998). A Contribution to the Optimum Design of Piled Rafts. *Geotechnique, Vol. 48, No. 2* , 301-317.
12. Impe, W. V., & Clerq, L. (1995). A Piled Raft Interaction Model. *Geotechnica, No.73* , 1-23.
13. Katzenbach, R., Arslan, U., & Moormann, C. (2000). Piled Raft Foundation Projects in Germany. In Hemsley, *Design Application of Raft Foundation* (pp. 323-391). Thomas Telford.
14. Lee, I. (1993). Analysis and Performance of Raft and Raft-Pile Systems. *Keynote Lect., 3rd Int. Conf. Case Hist. in Geot. Eng., St. Louis (also Res. Rep. R133, ADFA, Univ. NSW, Australia)* .
15. Maharaj, D. K. (2004). *The Electronic Journal of Geotechnical Engineering*. Retrieved 2007, from WORLD WIDE WEB OF GEOTECHNICAL ENGINEERS: http://www.ejge.com/2004/Ppr0349/Ppr0349.htm
16. Mekbib, M. (2004). *Performance of Piled Raft Foundations for Addis Ababa Soils.* Addis Ababa: Addis Ababa University.
17. Ottaviani, M. (1975). Three-dimensional Finite Element Analysis of Vertically Loaded Pile Groups. *Geotechnique, Vol. 25, No. 2* , 159-174.
18. Poulos, H. (1994). An Approximate Numerical Analysis of Pile-Raft Interaction. *Int. J. NAM Geomechs., 18* , 73-92.

19. Poulos, H. (1991). Analysis of Piled Strip Foundations. *Comp. Methods & Advances in Geomechs., ed. Beer et al, Balkema, Rotterdam, 1* , 183-191.
20. Poulos, H. (2001). *Methods of Analysis of Piled Raft Foundations.* International Society of Soil Mechanics and Geotechnical Engineering.
21. Poulos, H., & Davis, E. (1980). *Pile Foundation Analysis and Design.* New York: Wiley.
22. Rabiei, M. (2009). *The Electronic Journal of Geotechnical Engineering*. Retrieved 2009, from WORLD WIDE WEB OF GEOTECHNICAL ENGINEERS: http://www.ejge.com/2009/Ppr0906/Ppr0906s.pdf
23. Randolph, M. (1994). *Design Methods for Pile Groups and Piled Rafts.* New Delhi: S.O.A. Report, 13 ICSMFE.
24. Randolph, M. (1983). *Design of Piled Foundations.* Cambridge Univ. Eng. Dept., Res. Rep. Soils TR143.
25. Randolph, M., & Wroth, C. (1979). An Analysis of Vertical Deformation of Pile Groups. *Geotechnique, Vol. 29, No. 4* , 423-439.
26. Reul, O., & Randolph, M. (2004). Design Strategies for Piled Rafts Subjected to Nonuniform Vertical Loading. *Jl. of Geotechnical and GeoEnvironmental Engineering, Vol. 130, No. 1* , 1-10.
27. Reul, O., & Randolph, M. (2003). Piled Rafts in Overconsolidated Clay: Comparison of In situ Measurements and Numerical Analyses. *Geotechnique, Vol. 53, No. 3* , 301-315.
28. Shen, W., Chow, Y., & Yong, K. (2000). A Variational Approach for the Analysis of Pile Group-Pile Cap Interaction. *Geotechnique, Vol. 50, No. 4* , 349-357.
29. Shen, W., Chow, Y., & Yong, K. (1999). A Variational Approach for Vertically Loaded Pile Groups in an Elastic Half-space. *Geotechnique, Vol. 49, No. 2* , 199-213.
30. Small, J., & Booker, J. (1986). Finite layer analysis of layered elastic materials using a flexibility approach. *Part 2-circular and rectangular loadings. International Journal for Numerical Methods in Engineering 23* , 959-978.
31. Sommer, H., Wittmann, P., & Ripper, P. (1985). Piled Raft Foundation of a Tall Building in Frankfurt Clay. *Proc. 11 ICSMFE, San Francisco, 4* , 2253-2257.
32. Ta, L. (1996). *A Finite Layer Method for Analysis of Pile Groups, Rafts and Piled Raft Foundations in Layered Soils.* Australia: University of Sydney.
33. Ta, L., & Small, J. (1996). Analysis of Piled Raft Systems in Layered Soils. *Int. J. NAM Geomechs., 2* , 57-72.
34. Zhuang, G., Lee, I., & Zhao, X. (1991). Interactive Analysis of Behaviour of Raft-Pile Foundations. *Proc. Geo-Coast '91, Yokohama, 2* , 759-764.

7. Appendices

Appendix 1

The different combinations for the parametric study are as shown below.

Raft Thickness Variation

Thickness (m)	1.0	1.5	1.78	2.0	2.5	3.0	4.0	5.0	6.0

Spacing and Number of Piles Variation

Spacing of Piles (m)	Number of Piles					
3.0	140	96	80	60	32	16
3.5	96	-	80	60	32	16
4.0	80	-	-	60	32	16
4.5	60	-	-	-	32	16

The above tabular form is presented in pictorial for in figure A 1.1

Pile Length Variation

Length (m)	10.0	20.0	30.0	40.0	50.0

Other random combinations are also made for pile number of 32, 60 and 80.

3d-pile spacing
140 piles

4d-pile spacing
80 piles

3d-pile spacing
96 piles

3d-pile spacing
80 piles

3.5d-pile spacing
96 piles

4.5d-pile spacing
60 piles

3d-pile spacing
60 piles

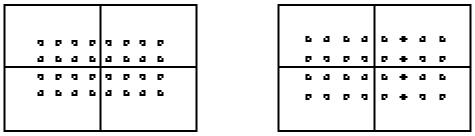
3.5d-pile spacing
80 piles

3d-pile spacing
32 piles

3.5d-pile spacing
32 piles

3.5d-pile spacing
60 piles

4d-pile spacing
60 piles



4d-pile spacing
32 piles

4.5d-pile spacing
32 piles

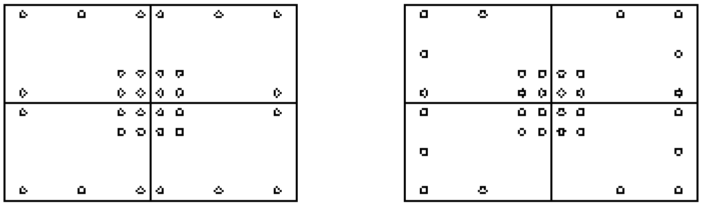
3d-pile spacing
16 piles

3.5d-pile spacing
16 piles

4d-pile spacing
16 piles

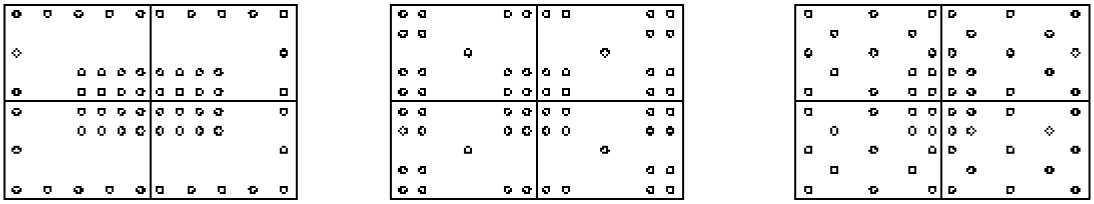
4.5d-pile spacing
16 piles

Figure A1- 1 Plan view of pile arrangements with uniform spacing (diameter = 1.0 m)



Combination - 1
32 piles

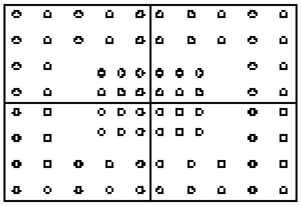
Combination - 2
32 piles



Combination - 1
60 piles

Combination - 2
60 piles

Combination - 3
60 piles



Combination - 1
80 piles

Figure A1- 2 Random arrangment of piles for the combinations (diameter = 1.0 m)

Appendix 2

In PLAXIS software the maximum or ultimate values of skin friction with its distribution pattern and base resistance are required as an input. Thus, here calculation is done according to Bowles (1997). The value calculated here are simple approximations because all piles with the same length will have the same value in the parametric study.

The skin friction distribution is assumed to be linear. Thus, the maximum skin friction values at the top and bottom are needed.

The skin friction according to Tomlinson (1971) is given by

$$Q_f = (\alpha c + K\sigma_z \tan\delta)(\pi d)$$

Where: $\alpha = 1.0$

$K = 0.5$ (simple approximation)

$\sigma_z = \gamma z +$ uniformly distributed load$= 150 KN/m^2$

$Q_f = (1.0*10 + 0.66*150*\tan20^o)(3.14*1.0) = 117\ KN/\ m^2$

Therefore, Maximum Skin Friction at the bottom ($T_{top,max}$) is considered to be 110 KN/m.

Maximum Skin Friction at the bottom ($T_{bot,max}$)

$Qf = (\alpha c + K\sigma_z \tan\delta)(\pi d)$

Where: $\alpha = 1.0$

$K = 0.5$

$\delta = ø' = 20o$

σ_z is calculated from over burden pressure and from the distributed load which vary with depth of piles.

$$\sigma_z = \gamma z + P/2\pi*i$$

where i is a factor which is found in any foundation text book

P is the load applied

Table A2- 1 Calculation for maximum skin friction at bottom of piles

Depth (m)	10	20	30	40	50
γz (KN/m^2)	80	160	240	320	400
i	0.56	0.31	0.18	0.11	0.08
$P/2\pi*i$ (KN/m^2)	84.37	45.97	26.90	17.09	11.64
σ_z (KN/m^2)	164.37	205.97	266.90	337.09	411.64
Tbot,max (KN/m)	125	149	184	224	266

Base Resistance (Fmax) is calculated from Bowles (1997)

$$Fmax = A_p*(cN'_c d_c s_c + \eta q N'_q d_q s_q + 1/2\gamma' B_p N_\gamma s_\gamma)$$

Janbu (1976)

N_γ term is often neglected when the pile width is not large

$N'_q = (\tan ø' + \sqrt{}(1 + \tan 2ø'))\ 2e\ (2\psi p \tan ø') = 4.37$

$N'_c = (N'_q - 1) \cot ø' = 9.26$

$A_p = 0.25\ \pi$

$d_c = 1 + 0.4 \tan^{-1} (L/B) = 1 + 0.4 \tan^{-1} L$

$d_q = 1 + 2 \tan ø' (1 – \sin ø')^2 \tan^{-1} (L/B)$

$\eta = s_c = s_q = 1.0$

Table A2- 2 Calculation for maximum base resistance at bottom of piles

Depth (m)	10	20	30	40	50
d_c	1.07	1.13	1.19	1.24	1.29
d_q	1.05	1.11	1.15	1.19	1.23
σz (KN/m2)	164.37	205.97	266.90	337.09	411.64
Fmax (KN)	672	864	1141	1469	1825

Appendix 3

In this part of the thesis, a theoretical background is given as presented on PLAXIS 3D FOUNDATION Scientific Manual Version 2. The author has tried reducing the presentation and content of the theory presented there to meet the purpose of the thesis. Thus, basic ideas related to piled raft foundation are explained here. A reader interested in the detail formulation and modeling of PLAXIS software is referred to the full scientific and material manuals that are found enclosed with the software.

1. Deformation Theory

The basic equations for the static deformation of a soil body are formulated within the frame work of continuum mechanics. The static equilibrium of a continuum can be formulated as:

$$\underline{\underline{L}}^{T}\,\underline{\sigma} + \underline{b} = \underline{0} \qquad \ldots \qquad (A3.1.1)$$

This equation relates the spatial derivatives of the six stress components, assembled in vector $\underline{\sigma}$, to the three components of the body forces, assembled in vector $\underline{b}$. $\underline{\underline{L}}^{T}$ is the transpose of a differential operator, defined as:

$$\underline{\underline{L}}^{T} = \begin{vmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{vmatrix}$$

In addition to the equilibrium equation, the kinematic relation can be formulated as:

$$\underline{\varepsilon} = \underline{\underline{L}}\,\underline{u} \qquad \ldots \qquad (A3.1.2)$$

This equation expresses the six strain components, assembled in vector $\underline{\varepsilon}$, as the spatial derivatives of the three displacement components, assembled in vector $\underline{u}$, using the previously defined differential operator $\underline{\underline{L}}$. The link between equation (A3.1.1) and (A3.1.2) is formed by a constitutive relation representing the material behavior. The general relation is repeated here for completeness:

$$\underline{\dot{\sigma}} = \underline{\underline{M}}\,\underline{\dot{\varepsilon}} \qquad \ldots \qquad (A3.1.3)$$

The combination of equations (A3.1.1), (A3.1.2) and (A3.1.3) would lead to a second order partial differential equation in the displacement $\underline{u}$.

According to the finite element method, a continuum is divided into a number of (volume) elements. Each element consists of a number of nodes. Each node has a number of degrees of freedom that correspond to discrete values of the unknowns in the boundary value problem to be solved. In the present case of deformation theory the degrees of freedom correspond to the displacement components. Within an element the displacement field $\underline{u}$ is obtained from the discrete nodal values in a vector $\underline{v}$ using interpolation functions assembled in matrix $\underline{\underline{N}}$:

$$\underline{u} = \underline{\underline{N}}\,\underline{v} \qquad \ldots \qquad (A3.1.4)$$

The interpolation functions in matrix $\underline{\underline{N}}$ are often denoted as shape functions. Substitution of equation (A3.1.4) in equation (A3.1.2) gives:

$$\underline{\varepsilon} = \underline{\underline{L}}\,\underline{\underline{N}}\,\underline{v} = \underline{\underline{B}}\,\underline{v} \qquad \ldots \qquad (A3.1.5)$$

In this relation $\underline{\underline{B}}$ is the strain interpolation matrix, which contains the spatial derivatives of the interpolation functions.

2. Finite Element Formulation

For the problem stated in this thesis, the basic geotechnical components for the finite element formulation are the raft, the distributed load on the raft, the soil, the piles and the boundary conditions. The interpolation functions of the finite elements and the type of numerical integration over elements used in the PLAXIS 3D FOUNDATION program are described hereunder.

Areas and surfaces in this program are either formed by 6-node triangular elements or by 8-node quadrilateral elements. The basis for floor elements and distributed loads on in the 3D finite element model are 6-node triangles. For triangular elements there are two local coordinates (ξ and η). In addition an auxiliary coordinate $\zeta = 1 - \xi - \eta$ is used. 6 – node triangular elements provide second order interpolation of displacements. The shape functions N_i have the property that the function value is equal to unity at node *i* and zero at the other nodes. The shape functions can be written as (see the local node numbering as shown in figure below):

$N1 = \zeta\,(2\zeta - 1)$ $\qquad N4 = 4\,\zeta\,\xi$

$N2 = \xi\,(2\xi - 1)$ $\qquad N5 = 4\,\xi\,\eta$

$N3 = \eta\,(2\eta - 1)$ $\qquad N6 = 4\,\eta\,\zeta$

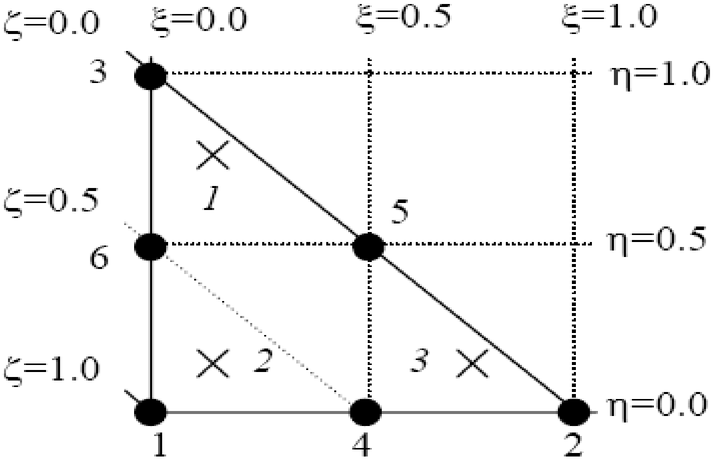


Figure A3- 1 Local numbering and positioning of nodes (●) and integration points (X) of a 6 node triangular element

One can formulate the numerical integration over areas as:

$$\iint F(\xi,\eta)d\xi\, d\eta \;\approx\; \sum_{i=1}^{k} F(\xi_i,\eta_i)w_i \;\ldots \qquad \text{(A3.2.1)}$$

The PLAXIS 3D FOUNDATION program uses Guassian integration with in the area elements.

Floor elements are different from the 6-node triangles in a sense that they have six degrees freedom per node instead of three, i.e. three translational d.o.f.s (u_x, u_y *and* u_z) and three rotational d.o.f.s ($ø_x$, $ø_y$, and $ø_z$). These elements are directly integrated over their cross section and numerically integrated using 3 point Guassian integration. The position of the integration points is indicated in figure below.

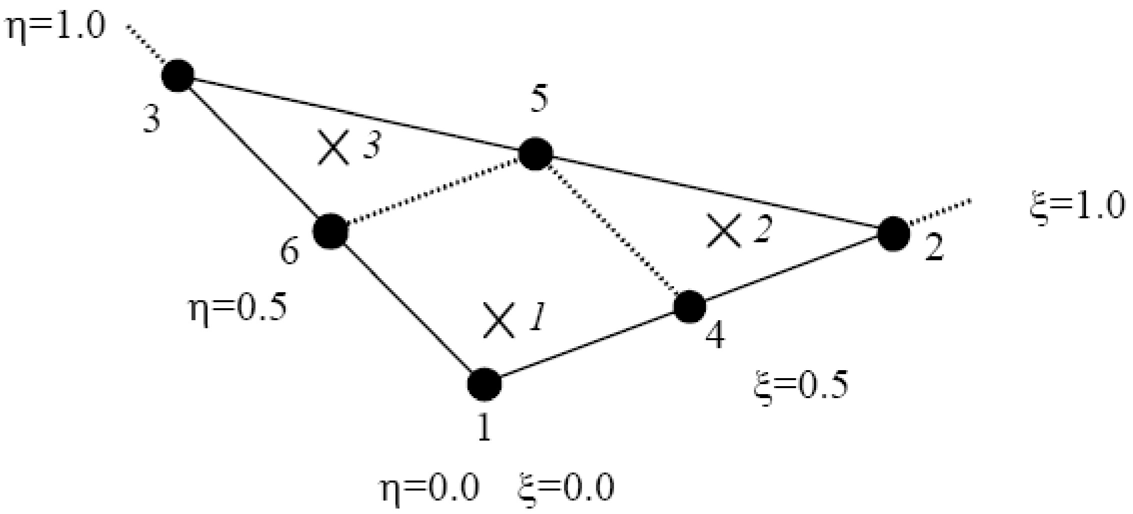


Figure A3- 2 Local numbering and positioning of nodes (●) and integration points (X) of a 6 node plate triangle

The soil volume is modeled by means of 15-node wedge elements. For wedge elements there are three local coordinates (ξ, η and ζ). The shape functions N_i have the property that the function value is equal to unity at node *i* and zero at other nodes.

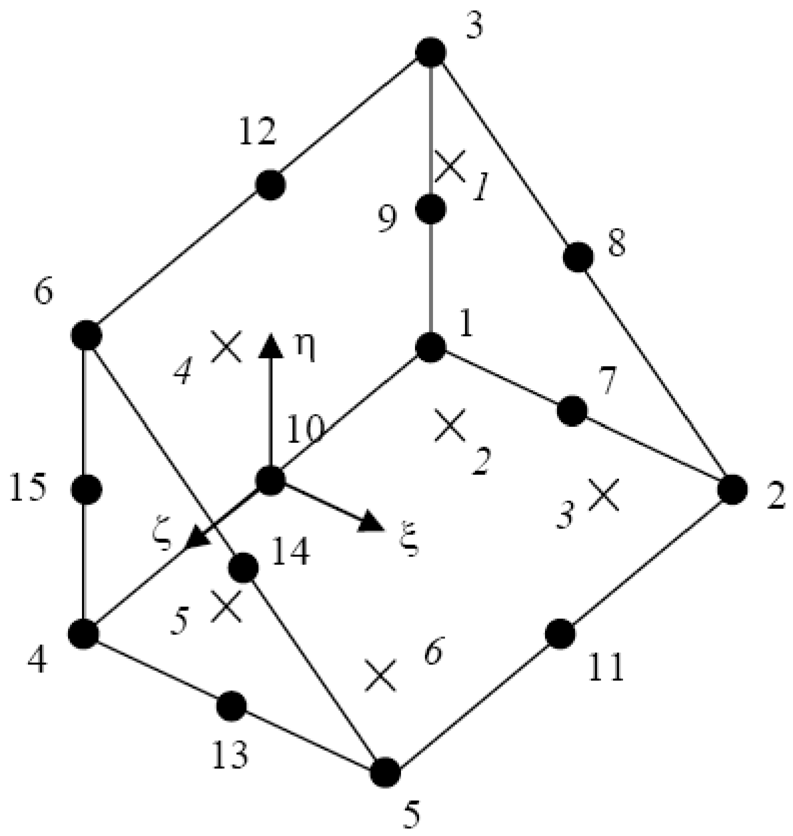


Figure A3- 3 Local numbering and positioning of nodes (●) and integration points (X) of a 15 node wedge element

The numerical integration for 15-node wedge elements can be formulated as:

$$\iiint F(\xi, \eta, \zeta) d\xi \, d\eta \, d\zeta \approx \sum_{i=1}^{k} F(\xi_i, \eta_i, \zeta_i) w_i \ldots \qquad \text{(A3.2.2)}$$

The Gaussian integration for 15-node wedge element is based on 6 sample points. The integration is a mixture between the 3-point integration of a 6-node triangular element and the 4-point integration of an 8-node quadrilateral.

The piles are modeled using special elements in PLAXIS called embedded piles. Embedded piles consist of beam elements to model the pile itself and embedded interface elements to model the interaction between the soil and the pile at the pile skin as well as the pile foot. Illustration of embedded pile with the embedded beam element denoted by the solid line is presented in the figure below. The blank grey circles denote the virtual nodes of the soil. The details of finite element discretisation and the skin and foot interactions are formulated in the Scientific Manual.

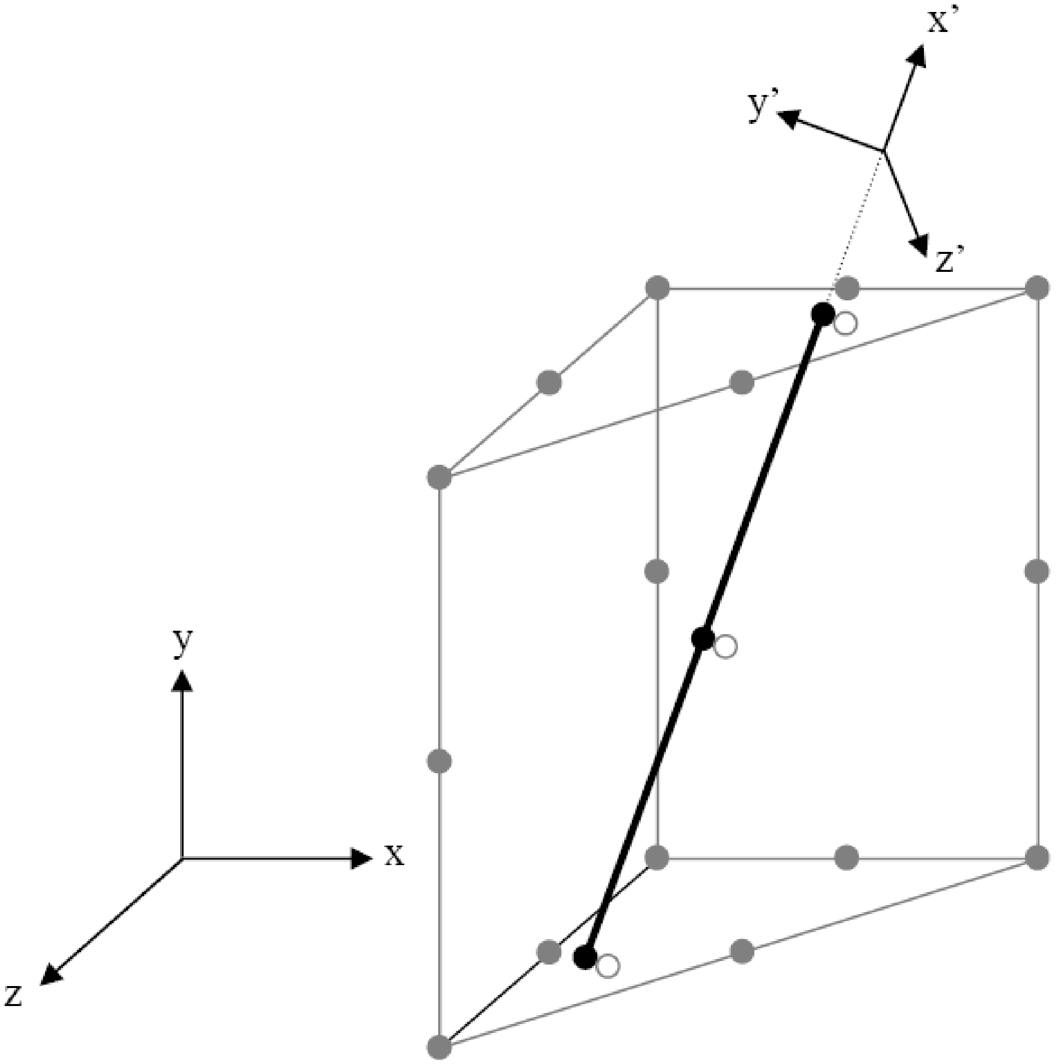


Figure A3- 4 Illustration of the embedded beam element denoted by the solid line. The blank grey circles denote the virtual nodes of the soil element.

3. Material Model

PLAXIS 3D FOUNDATION program has a number of material models that can be used in analysis of Geotechnical problems. They range from the simple models like linear elastic model to complex ones. The more complex model is selected more material data is required. The analysis conducted for the parametric study and verification examples consider the linear elastic and mohr-coloumb models. Thus, a brief description of these material models is given below. The reader is again advised to refer to PLAXIS 3D FOUNDATION Materials Manual Version 2 for details of the models.

The soil in the problems of this paper is modeled as elasto-plastic material. The basic principle of elasto-plasticity is that strains and strain rates are decomposed into an elastic part and plastic part:

$$\underline{\varepsilon} = \underline{\underline{\varepsilon}}^{e} + \underline{\underline{\varepsilon}}^{p} \qquad \underline{\dot{\varepsilon}} = \underline{\underline{\dot{\varepsilon}^{e}}} + \underline{\underline{\dot{\varepsilon}^{p}}} \qquad \ldots \qquad \text{(A3.3.1)}$$

Hooke's law is used to relate the stress rates to the elastic strain rates. According to the classical theory of plasticity, plastic strain rates are proportional to the derivative of the yield function with respect to the stresses. This means that the plastic strain rates can be represented as vectors perpendicular to the yield surface. This classical form of the theory is refereed to as associated plasticity. However, for Mohr-Coulomb type yield functions, the theory of associated plasticity overestimates dilatancy

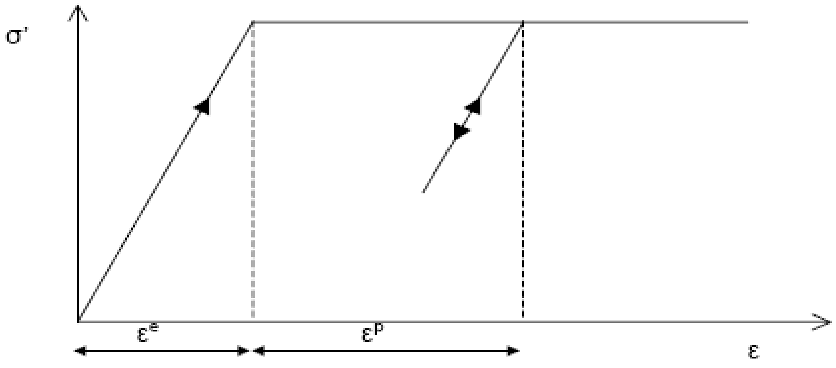


Figure A3- 5 Basic idea of an elastic perfectly plastic model

The Mohr-Coulomb yield condition is an extension of Coulomb's friction law to general states of stress. In fact, this condition ensures that Coulomb's friction law is obeyed in any plane within a material element. The full Mohr-Coulomb yield condition consists of six yield functions when formulated in terms of principal stresses and six plastic potential functions.

The two plastic model parameters appearing in the yield functions are the well known friction angle ø and the cohesion c. The condition f_i=0 for all yield functions together (where f_i is used to denote each individual yield function) represent a hexagonal cone principal stress space as shown in the Figure A3.6.

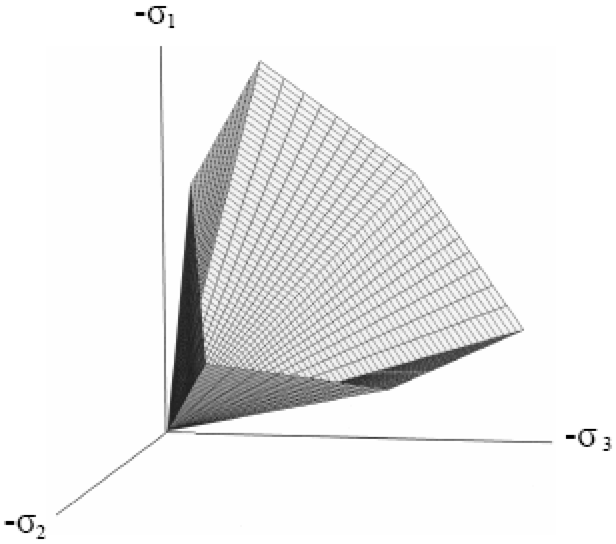


Figure A3- 6 The Mohr-Coulomb yield surface in principal stress space (*c* = 0)

The plastic potential functions contain a third plasticity parameter, the dilatancy angle ψ. This parameter is required to model positive plastic volumetric strain increments (dilatancy) as actually observed for dense soils. For stress states within the yield surface, the behavior is elastic and obeys Hooke's law isotropic linear elasticity, as discussed above. Hence, besides the plasticity parameters c, ø, and ψ input is required on the elastic Young's modulus E and Poisson's ratio *v*.

Appendix 4

The tables below give tabular outputs of PLAXIS 3D Foundation for pile forces of a verification example and parametric studies. These tables will be used to determine pile-raft load sharing of the problems analyzed.

Table A4- 1 PLAXIS output for pile forces in Westend Building.

Upper and Bottom	Pile Location			T_Skin [kN/m]	F_foot [kN]	T_Skin [kN/m]	Pile Force [kN]
	X [m]	Y [m]	Z [m]				
1	-27	0	-13	0.00	10000.00	7500.00	17500.00
3	-27	-30	-13	500.00			
1	-22	0	-13	0.00	10000.00	7500.00	17500.00
3	-22	-30	-13	500.00			
1	-16	0	-13	0.00	9496.95	7500.00	16996.95
3	-16	-30	-13	500.00			
1	-11	0	-13	0.00	8928.84	7500.00	16428.84
3	-11	-30	-13	500.00			
1	-6	0	-13	0.00	9273.63	7500.00	16773.63
3	-6	-30	-13	500.00			
1	0	0	-13	0.00	9000.55	7500.00	16500.55
3	0	-30	-13	500.00			
1	5	0	-13	0.00	9715.00	7500.00	17215.00
3	5	-30	-13	500.00			
1	10	0	-13	0.00	10000.00	7500.00	17500.00
3	10	-30	-13	500.00			
1	15	0	-11	0.00	10000.00	7500.00	17500.00
3	15	-30	-11	500.00			
1	19	0	-7	0.00	9439.00	7500.00	16939.00
3	19	-30	-7	500.00			
1	22	0	-4	0.00	10000.00	7500.00	17500.00
3	22	-30	-4	500.00			
1	24	0	-1	0.00	10000.00	7500.00	17500.00
3	24	-30	-1	500.00			
1	25	0	4	0.00	10000.00	7500.00	17500.00

Upper and Bottom	Pile Location			T_Skin [kN/m]	F_foot [kN]	T_Skin [kN/m]	Pile Force [kN]
	X [m]	Y [m]	Z [m]				
3	25	-30	4	500.00			
1	24	0	8	0.00	10000.00	7500.00	17500.00
3	24	-30	8	500.00			
1	21	0	8	0.00	10000.00	7500.00	17500.00
3	21	-30	8	500.00			
1	16	0	13	0.00	10000.00	7500.00	17500.00
3	16	-30	13	500.00			
1	10	0	13	0.00	9590.04	7500.00	17090.04
3	10	-30	13	500.00			
1	5	0	13	0.00	9472.37	7500.00	16972.37
3	5	-30	13	500.00			
1	0	0	13	0.00	8575.40	7500.00	16075.40
3	0	-30	13	500.00			
1	-6	0	13	0.00	8527.05	7500.00	16027.05
3	-6	-30	13	500.00			
1	-11	0	13	0.00	8087.63	7500.00	15587.63
3	-11	-30	13	500.00			
1	-16	0	13	0.00	8772.64	7500.00	16272.64
3	-16	-30	13	500.00			
1	-22	0	13	0.00	9502.59	7500.00	17002.59
3	-22	-30	13	500.00			
1	-27	0	13	0.00	10000.00	7500.00	17500.00
3	-27	-30	13	500.00			
1	-27	0	6	0.00	9972.66	7500.00	17472.66
3	-27	-30	6	500.00			
1	-20	0	6	0.00	8129.69	7500.00	15629.69
3	-20	-30	6	500.00			
1	-14	0	6	0.00	7508.00	7500.00	15008.00
3	-14	-30	6	500.00			
1	-8	0	6	0.00	7507.65	7500.00	15007.65
3	-8	-30	6	500.00			
1	-2	0	6	0.00	6978.87	7500.00	14478.87
3	-2	-30	6	500.00			

Upper and Bottom	Pile Location			T_Skin [kN/m]	F_foot [kN]	T_Skin [kN/m]	Pile Force [kN]
	X [m]	Y [m]	Z [m]				
1	5	0	6	0.00	7262.70	7500.00	14762.70
3	5	-30	6	500.00			
1	9	0	6	0.00	6985.79	7500.00	14485.79
3	9	-30	6	500.00			
1	15	0	6	0.00	8091.21	7500.00	15591.21
3	15	-30	6	500.00			
1	13	0	1	0.00	7666.57	7500.00	15166.57
3	13	-30	1	500.00			
1	9	0	-2	0.00	7654.46	7500.00	15154.46
3	9	-30	-2	500.00			
1	4	0	-5	0.00	7365.61	7500.00	14865.61
3	4	-30	-5	500.00			
1	-2	0	-5	0.00	7784.86	7500.00	15284.86
3	-2	-30	-5	500.00			
1	-8	0	-5	0.00	7987.32	7500.00	15487.32
3	-8	-30	-5	500.00			
1	-14	0	-5	0.00	7678.31	7500.00	15178.31
3	-14	-30	-5	500.00			
1	-20	0	-5	0.00	8411.83	7500.00	15911.83
3	-20	-30	-5	500.00			
1	-27	0	-5	0.00	10000.00	7500.00	17500.00
3	-27	-30	-5	500.00			

Note: In this table, pile identification is not done. A result with the same value x and z correspones to a single pile while the number 1 and 3 represent the upper and lower tip of this pile.

Table A4- 2 Load sharing between piles and raft from PLAXIS output by varying spacing and number for the pile length of 10m.

Pile Arrangement	Load Carried by Piles (KPa)	Load Carried by Raft (KPa)	% Carried by the Piles
16 (4) 3.0d	4.90	197.60	2.42
16 (4) 3.5d	5.10	197.40	2.52
16 (4) 4.0d	5.18	197.32	2.56
16 (4) 4.5d	5.19	197.31	2.56
32 (8) 3.0d	9.19	193.31	4.54
32 (8) 3.5d	9.84	192.66	4.86
32 (8) 4.0d	10.18	192.32	5.03
32 (8) 4.5d	10.36	192.14	5.12
60 (15) 3.0d	16.47	186.03	8.13
60 (15) 3.5d	17.82	184.68	8.80
60 (15) 4.0d	18.67	183.83	9.22
60 (15) 4.5d	19.19	183.31	9.47
80 (20) 3.5d	23.24	179.26	11.47
80 (20) 4.0d	24.19	178.31	11.95
96 (24) 3.0d	25.57	176.93	12.63
96 (24) 3.5d	27.55	174.95	13.60
140 (35) 3.0d	35.80	166.70	17.68

Table A4- 3 Load sharing between piles and raft from PLAXIS output by varying length for 80 piles with 3m spacing.

Pile Length (m)	Load Carried by Piles (KPa)	Load Carried by Raft (KPa)	% Carried by the Piles
10	21.47	181.03	10.60
20	38.78	163.72	19.15
30	61.38	141.12	30.31
40	94.35	108.15	46.59
50	137.20	65.30	67.75

Table A4- 4 Load sharing between piles and raft from PLAXIS output by varying length for 16 piles with 4.5m spacing.

Pile Length (m)	Load Carried by Piles (KPa)	Load Carried by Raft (KPa)	% Carried by the Piles
10	5.19	197.31	2.56
20	9.42	193.08	4.65
30	15.57	186.93	7.69
40	22.39	180.11	11.06
50	30.28	172.22	14.95

Table A4- 5 Load sharing between piles and raft from PLAXIS output by varying length for 32 piles with 4.5m spacing.

Pile Length (m)	Load Carried by Piles (KPa)	Load Carried by Raft (KPa)	% Carried by the Piles
10	10.36	192.14	5.12
20	18.63	183.87	9.20
30	28.68	173.82	14.16
40	40.67	161.83	20.09
50	57.12	145.38	28.21

Table A4- 6 Load sharing between piles and raft from PLAXIS output by varying length for 60 piles with 4.5m spacing.

Pile Length (m)	Load Carried by Piles (KPa)	Load Carried by Raft (KPa)	% Carried by the Piles
10	19.19	183.31	9.47
20	36.81	165.69	18.18
30	47.92	154.58	23.66
40	71.61	130.89	35.36
50	103.63	98.87	51.18