Performance Evaluation of Piled Raft Foundations in Layered Soil Under Different Piled-raft Configurations using Numerical Methods

Ararso Gudeta Shifera

A Thesis Submitted to the Department of Civil Engineering,
College of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil Engineering (Specialization in Geotechnical Engineering)

Office of Graduate Studies
Adama Science and Technology University

June 2025
Adama, Ethiopia

Performance Evaluation of Piled Raft Foundations in Layered Soil Under Different Piled-raft Configurations using Numerical Methods

Ararso Gudeta Shifera

Advisor: Argaw Asha (PhD)

A Thesis Submitted to the Department of Civil Engineering,

College of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Civil engineering (Specialization in Geotechnical Engineering)

Office of Graduate Studies

Adama Science and Technology University

June 2025
Adama, Ethiopia

DECLARATION

I hereby declare that this Master Thesis entitled "**Performance Evaluation of Piled Raft Foundations in Layered Soil Under Different Piled-raft Configurations using Numerical Methods"** is my original work. That is, it has not been submitted for an academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Ararso Gudeta Shifera	____________________	__________________
Name of student	Signature	Date

RECOMMENDATION OF ADVISOR

I, the advisor of this thesis, hereby certify that I have closely advised the student while developing this final thesis and read the draft thesis entitled “**Performance Evaluation of Piled Raft Foundations in Layered Soil Under Different Piled-raft Configurations using Numerical Methods”** prepared under my guidance by Ararso Gudeta.

Therefore, I recommend the submission of the thesis to the department for further review and evaluation.

Argaw Asha (PhD)	____________________	__________________
Advisor	Signature	Date

APPROVAL PAGE

I hereby certify that the recommendation and suggestion given by the thesis review committee are appropriately incorporated into the final thesis entitled “**Performance Evaluation of Piled Raft Foundations in Layered Soil Under Different Piled-raft Configurations using Numerical Methods”** by Ararso Gudeta.

Argaw Asha (PhD) ______________ ______________
Advisor Signature Date

APPROVAL OF BOARD OF REVIEWERS

We, the undersigned, members of the board of reviewers of the final thesis open defense by Ararso Gudeta have read and evaluated the thesis entitled “**Performance Evaluation of Piled Raft Foundations in Layered Soil Under Different Piled-raft Configurations using Numerical Methods”** and assessed the understanding of the candidate about the research. This is, therefore, to certify that the thesis is accepted and we recommend the implementation of the final thesis.

Chairperson	Signature	Date
Internal Examiner	Signature	Date
External Examiner	Signature	Date

Finally, approval and acceptance of the thesis are contingent upon the submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and College Graduate Committee (CGC).

Department Head	Signature	Date
College Dean	Signature	Date
Office of Postgraduate Studies	Dean Signature	Date

ACKNOWLEDGEMENT

Foremost, I would like to thank my Almighty God for giving me the courage, strength, and health to start and finish this research paper. I am also deeply grateful to my advisor, Dr. Argaw Asha, for providing me with scientific advice, experience sharing, and constructive criticism during my research work. I would also like to express my deep gratitude to the Ethiopian Geological Survey, Addis Geosystems PLC, Gondwana Engineering PLC, and Classic Consulting Engineering PLC for their support during data collection. Furthermore, I would like to thank Dembi Dollo University for sponsoring my postgraduate studies and funding this research. I would like to express my sincere gratitude to Dr. Kabtamu Getachew for his invaluable guidance and support throughout this research. Finally, I would like to give thanks to my beloved family and friends for their endless moral and economic support, as well as to all those who have contributed to the success of this study.

Table of Contents

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

R_{total},s	Settlement dependent on the total resistance of pile and raft	h	Group efficiency
$R_{raf\ t}$,s	Settlement-dependent resistance of raft	f_{avg}	Average unit frictional resistance
R_{pile},k,j	Settlement-dependent resistance of pile	Q_{pt}	The load carried at the pile tip
α_{pr}	piled raft coefficient	Q_s	The load carried by skin friction of the pile
C	Cohesion	Q_p	Load carrying capacity of the pile
D	Depth of pile	Q_{pr}	Load carrying capacity of unpiled raft
Ψ	Dilatancy angle	a_r, b_r	model parameters for the normalized hyperbolic
δ	Angular distortion	n	Number of piles
K_{rs}	Raft soil stiffness ratio	P_g	The perimeter of the cross-section block
σ_{ii}	Normal stress	X_g	Pile group effect factor
γ	Unit weight	L_p	Pile length
E	Modulus of elasticity	L_r	Raft length
ν	Poisson’s ratio	B_r	Raft width
σ_f	Failure Normal stress	$Q_{g(u)}$	The ultimate load-bearing capacity of each pile without the group effect
τ_f	Failure shear stress	B_g	Pile group width
Ø	Friction angle	A_g	Pile group area

ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
CPRF	Combined Pile Raft Foundation
FEM	Finite Element Method
CAD	Computer-Aided Design
PLC	Public Limited Company
ETABS	Extended Three-Dimensional Analysis of Building Systems
SAFE	Slab Analysis by the Finite Element Method
SPT	Standard Penetration Test
EBCS	Ethiopian Building Code Standards
PR	Piled Raft
UR	Unpiled Raft
GASP	Geotechnical Analysis of Strip with Piles

ABSTRACT

Large civil constructions that are frequently built on soft soil sites due to rapid urbanization can lead to settling, particularly in urban regions with few rock sites. Despite their significant weight, high-rise buildings must have minimum differential settlement in order to comply with strict safety rules. Through the creation of a composite foundation, in which the piles serve as settlement reducers and share the load from the superstructure with the raft, piled raft foundations have been successfully utilized for the past four to five decades all over the world to maximize the foundations of civil engineering structures. In these foundations, piles share the load of the superstructure with the raft and serve as settlement reducers. Numerical methods are often required because of the intricate soil-structure interaction in pile raft foundations and the lack of field data. In this study, the load-settlement behavior of piled raft from previous numerical works was analytically simulated to validate the 3D finite element model. When uniform vertical force is applied to layered soil, the effectiveness of a rectangular combination piled raft system with different piled raft configurations have been assessed. The analysis looks at the effects of several factors using Plaxis 3D, a strong finite element tool taking constant number of piles 16. The reaction of piled-raft foundations is also examined parametrically, taking into account the effects of raft thickness, pile length, pile spacing, and pile diameter. It was found that the differential settlement was decreased by 59.92% and 57.26% for uniform piled raft configurations and non-uniform piled raft configurations by raising the raft thickness from 0.7 to 1.7 meters, respectively. The maximum settlement did, however, rise by 0.19% and 0.69% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. The maximum settlement amount was decreased by 3.0% and 3.30% for uniform and non-uniform piled raft configurations, respectively by increasing pile spacing from 3D to 4D. Additionally, from the total settlement reduction obtained by increasing pile length from 9m to 12m, the maximum settlement was reduced by 7.85% and 17.42% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Hence, the findings from the current research can give deep insight into understanding of different piled raft configurations performances under uniformly distributed vertical load.

Keywords- *Piled - raft, Finite element, Plaxis 3D, Settlement, and Soil-structure interaction.*

CHAPTER 1

1. INTRODUCTION

1.1. Background

Large civil infrastructure including power plants, bridges, high-rise buildings, and industrial facilities are now more important than ever due to the previous decades' growing urbanization. But a lot of these buildings are being constructed on soft soil sites, which might cause ground sinking, especially in cities where there aren't many rock sites. Despite the enormous weight of the structure, the permitted differential settlement of the structure in high-rise structures is quite limited due to the stringent safety rules. For loads to be transferred from the superstructure to the substructure, adequate foundations are necessary.

Although buildings are built from the ground up, they may collapse or fail in a variety of various ways if the foundation fails. A shallow raft foundation might not satisfy design requirements when a heavy structure is constructed on weak soil, requiring load transmission to a deeper, more competent layer. To withstand the enormous loads brought on by superstructures and to stop excessive settlements, piling foundations were created. However, building foundations with just piles or rafts is not practical because of the load-sharing process between earth, rafts, and piles. Excessive differential settlement and significant construction expenses would result from this. As a result, "Piled Raft Foundations," which combine two different approaches, have been developed (Clancy & Randolph, 1993).

Using sustainability principles in engineering design has gained more attention in recent years. In this sense, it has been demonstrated that piling raft foundations provide a number of advantages over traditional foundations, such as using less material, requiring less time and money to build, and having a less negative environmental impact. Furthermore, using piled raft foundations can lessen the amount of excavation needed, which can lessen the negative effects on the environment and nearby populations. Because of this, piled raft foundations might be considered a sustainable substitute for traditional foundation systems (Deb & Pal, 2019).

To determine the total settlement, differential settlement, and ultimate load capacity for different loading scenarios, as well as the weight carried by each interacting component, especially the raft and the pile, various input parameters must be analyzed. Analytical methods can be used to determine the behavior of piled raft systems, but these methods are often insufficient due to the complex three-dimensional interaction between the soil, raft, and pile. Consequently, these issues are frequently resolved by numerical methods, especially with the advancement of sophisticated knowledge and high-performance computer instruments (H. G. Poulos, 2001a).

Numerical analysis techniques for piled raft foundation systems fall into three main categories: (1) computer-based approaches that are more rigorous, (2) computer-based approaches that are more approximate, and (3) simplified calculation techniques. The most practical of these techniques are 3D linear/nonlinear finite element or finite difference approaches (H. G. Poulos, 2001a). Recent work has been done on nonlinear 3D finite element and finite difference analysis. However, in these 3D finite element and finite difference assessments, representing the soil-structure interface remains a difficulty.

Choosing the right input parameters to provide useful output results is the primary challenge when using numerical methods on stacked raft foundation systems. The procedure of identifying appropriate values for these input parameters can be changed by conducting a back analysis on thoroughly documented case histories. Parametric evaluations examine how stacked raft foundation systems behave under axial loads by examining various factors. The factors pile number, pile length, pile diameter, pile spacing ratio, pile position, pile stiffness, load distribution, load level, raft thickness, raft dimensions, and soil type were the subject of numerous research in the literature (Yamashita et al., 2011).

The type of soil found at the site is another crucial consideration in the design of piled raft foundations. The properties of various soil types can affect how well the foundation performs. For example, to guarantee sufficient support for the structure on soft soils, it might be required to lengthen or increase the number of piles. The soil may also be prone to settling in regions with a high water content, and in order to avoid differential settlement, the raft thickness may need to be increased. A thorough understanding of the soil conditions is therefore critical in the design and construction of piled raft foundations (D. D. C. Nguyen et al., 2013).

It is crucial to remember that study into the relationship between the pile, raft, and soil is still underway in order to better understand the behavior of piled raft foundations. According to recent research, it might be necessary to take into account how many elements, including pile spacing, pile arrangement, and soil-structure interaction, affect how piled raft foundations behave. Additionally, more investigation is required to assess how these elements affect the piled raft foundations' long-term performance (Lee et al., 2015a).

However, this study emphasized the effects of the number of piles, length of piles, diameter of piles, pile spacing, and raft thickness for rectangular rafts. The solutions of finite element models were used to discuss the effects of these parameters. Parametric analyses of the piled raft were carried out using Plaxis 3D software. By varying the parameters, it is possible to understand how the behavior of piled raft foundation systems changed with different input values (Taghavi Ghalesari et al., 2015). The results of this study can be used to enhance design parameters and improve the performance of piled raft foundation systems.

1.2. Statement of the Problem

Using a raft foundation frequently only leads to excessive settlements that are unacceptable because of serviceability limit state requirements because of the building's large weight. However, these settlements can be reduced to manageable levels by methodically placing piles underneath the raft. Additionally, when fewer settlements occur, the foundation system's overall bearing capacity is increased (Ferchat et al., 2018). Traditional pile group design methods result in a greater number of piles under the raft. However, using the concept of the piled raft, this number can be reduced (Clancy & Randolph, 1993). High-rise buildings and other types of civil constructions are built on piled-raft foundations depending on the type of soil. The use of a piled raft foundation reduced total and differential settlements (H. G. Poulos, 2001a).

In our country, the majority of study has mainly compared the efficacy of pile raft foundations with separate pile and raft constructions. When choosing the best course of action based on various aspects, including settlement reduction and economic viability, this is advantageous. The selection of a pile raft foundation design, however, requires the assessment of numerous factors, such as load levels, raft thickness, pile length, pile diameter, pile spacing, pile orientation, and more. Real-world situations show that structures differ from this conventional design, necessitating a range of foundation shapes, usually approximating a rectangular form, even though the majority of research focuses on square raft models.

A square raft foundation provides a more balanced load distribution on the soil compared to a rectangular one. With equal length and breadth, it offers a more consistent pressure dispersal, potentially mitigating the chance of excessive settlement in specific areas. On the other hand, a rectangular raft foundation with unequal dimensions might lead to uneven pressure distribution, resulting in differential settlement or localized overstressing of the soil. This difference in load distribution helps a square raft foundation experience less differential settlement compared to a rectangular foundation (Bhartiya et al., 2022). As differential settlement may cause structural damage to the building, a square raft foundation can be a preferable option in certain situations.

Further research must explore the optimal combination of pile and raft parameters to achieve a balance between design prerequisites and cost-effectiveness. The study is expected to substantially enhance comprehension of the factors affecting piled raft performance. By applying this knowledge domestically, the performance of upcoming structures can be markedly improved. The findings of this research could serve as a valuable reference for designing effective combined piled raft systems. It is important to note that there are limitations in sourcing literature specifically related to our country.

1.3. Objective of the Study

1.3.1. General Objective

The general objective of this study is performance evaluation of piled raft foundations in layered soil under different piled-raft configurations.

1.3.2. Specific Objectives

- To assess piled raft settlement under uniform vertical load with different PRC;
- To carry out and compare settlement analysis of piled raft foundation with different pile spacing and raft thickness;
- To investigate load sharing ratio and maximum bending moments of piled raft on different parametric studies.

1.4. Significant of the Study

This study holds significant importance in geotechnical engineering and foundation design. Piled raft foundations, which combine the load bearing capacities of both piles and rafts, are increasingly being used in structures subjected to complex loading conditions particularly in areas with challenging soil profiles. By employing numerical methods to assess the performance of this foundations in layered soil, the research provides insight into how variations in pile arrangement, length, spacing and different piled raft configurations affect overall stability, load distribution, and settlement behavior. This understanding is crucial for optimizing foundation design, particularly in urban areas where space constraints and subsurface conditions can vary widely. Additionally, the findings can contribute to the development of guidelines and standards, ultimately advancing the field of geotechnical engineering and improving structural resilience.

Rafts are often considered as a structural "cap" that links the pile heads to the columns above them. However, their positive impact on load/settlement behavior is frequently ignored. As structural components, rafts are mainly in contact with the soil and can distribute the load from the superstructure to the underlying soil. By acknowledging this contribution, the overall length and diameter of the piles may be considerably reduced. In addition to this primary importance, the study also explores critical parameters of the foundation, such as pile diameter, number of piles, spacing, and raft thickness, which all influence the performance of piled raft foundations.

1.5. Scope of the Study

The parametric analysis of pile raft foundation as a displacement control on weak soils in Addis Ababa only took into account a uniformly distributed vertical load acting on the foundation system. No further fieldwork or laboratory testing was done for this study; instead, all pertinent data was obtained from the design office and various sources of literature. Because the research region is in earthquake zone 3, dynamic analysis such as the impacts of vibration and seismic stresses on piled raft foundations was not included in the study; instead, it concentrated only on static analysis.

1.6. Limitation of the Study

Due to incomplete information in the acquired data, this study used a variety of correlation equations and criteria that were taken from other sources of literature.

1.7. Organization of the Study

The research was primarily divided into five chapters. The study's background, problem description, goals, and scope are all introduced in the first chapter. The second chapter outlined the purpose of the study and was primarily a review of the literature. Reviews of the pile raft foundation concept, design philosophy, design considerations, analysis method, load carrying behavior, parametric studies, finite element modeling, soil distribution in Addis Ababa, and research gaps are covered in this section. The third chapter presents the study's methodology, including the parameters for the input subsoil, pile, and raft materials as well as the proposed constitutive behavior that governs them. A discussion of the study's numerical model is also included. The results were presented, analyzed, and interpreted in the fourth chapter. The conclusion and suggestions were covered in the fifth chapter.

CHAPTER 2

2. LITERATURE REVIEW

2.1. Introduction

Any foundation's main goal is to transfer the weight to the ground so that the structure can be used safely, dependably, and serviceably (Sinha, A., & Hanna, A. M. 2017). The first option for foundation design is a shallow foundation, which, provided the topsoil has sufficient bearing strength, can sustain the weight of a superstructure without suffering from significant total or differential settlements. Nonetheless, the need for high-rise structures and heavily loaded superstructures has grown rapidly in recent decades, especially in regions with substandard subsurface conditions. The need for foundations with high bearing capacities and low total and differential settling values has increased as a result.

The application of various foundation types can enhance the transfer of loads. One popular way to uniformly distribute a building's weight throughout its base is to use raft foundations. Spread footings could not be sufficient in situations when building loads are high or soil pressure is low; in these cases, a raft foundation might be more economical. Raft foundations can provide the necessary bearing capacity, but they might not be able to keep differential and total settlements within reasonable bounds. The use of deep foundations, such as pile foundations, is an additional choice for transferring heavy loads. These are employed when the loading is unequal and there are no stable bearing layers within attainable depths. The load is pushed deeper into the earth by the pile foundation, and in order to meet the load-bearing capability, the pile may need to be lengthy.

By utilizing a combined pile raft foundation (CPRF) system, which combines both types of foundations for more cost-effective and efficient results, the difficulties presented by either raft or pile foundations can be overcome (Johnson et al., 2019a). In 1957, Zeevaert made the first attempt to combine both shallow and deep foundations for the compressible volcanic clay in Mexico City. Recent projects have shown that a pile raft foundation can achieve the desired load-bearing capacity with minimal differential settlement and shorter pile lengths.

In order to develop a more efficient approach, the assessment of piled raft foundations has progressed over the last few decades to take into account the combined contribution of the raft and the piles. When the upper soil layers are too brittle or compressible to bear the weight of the superstructure, piles—structural elements composed of steel, concrete, or wood—are employed to transfer the load to the bedrock or stronger soil layer underneath (Das, B. M. (2011). On the other hand, raft foundations transfer the entire structural load and lessen differential settlements because they cover the entire building area. Typically, long and thin, piles move foundation loads from low-bearing soil layers to deeper rock and soil layers with high-bearing capacities. (Srilakshmi et al., 2013).

2.2. The Pile Raft Foundation Concept

For competent soils close to the surface, shallow foundations such as rafts are appropriate. Even with sufficient safety features to prevent bearing capacity failure, excessive settling can still happen. Reducing bearing stresses can help control raft settlements. Composite foundations known as "piled rafts" use piles to share weight and reduce settlement. Through the pile shaft and base, the weight is distributed to deeper soil after being moved from the raft to the shallow soil and pile heads. To examine how the foundation components interact, full-scale model testing in a variety of settings and configurations are required (Sinha, 2013).

A composite arrangement in which the raft and piles share the load is called a piled raft foundation. By taking the raft's contribution into account, the number of piles in a traditional piled foundation can be greatly decreased. The raft adds additional load capacity, but the piles provide the majority of the foundation's rigidity. When a raft foundation is unable to satisfy design specifications, such as settlement requirements, the addition of piles can improve the foundation's performance.

According to Poulos, 2016 the traditional design assumes that piles bear the entire load, but a new approach suggests using piles to reduce settlements while a load is shared between the raft and piles. This reduces the number of necessary piles and optimizes the design, but a small number of piles can cause bending moments and stresses in the pile heads. Using strategically placed piles with a raft foundation can improve load capacity and settlement performance. (El-Garhy et al., 2013). Overall, introducing piles to an unpiled raft foundation improves bearing capacity and reduces settlement.

Three alternatives are available for supporting a massive building on a substantial clay deposit. If the clay layer has very little shear strength, load-bearing piles can be utilized; if the clay layer has sufficient shear strength, a raft foundation can be employed. A piled raft can be utilized to limit discomfort to nearby structures and decrease settlements when the clay layer is of moderate strength. (Maharaj & Gandhi, 2004).

2.2.1. Interaction of Soil and Structure in the Context of CPRF Elements

The piles, raft, and subsoil are the three load-bearing elements that make up a piled raft foundation. The raft distributes the whole load transmitted from the structure to the topsoil and the associated piles according to their individual rigidities (Ata et al., n.d.). Only subsoil types that lack extremely stiff and strong layers' comparison to the layer immediately beneath the raft can employ the CPRF design idea. Otherwise, as is the situation when the pile base is in solid rock, the restricted movement of the pile base will draw strains and eventually result in traditional end-bearing piles (Katzenbach et al., 2007). The relationship between the stiffness under the raft and at the pile basis must be smaller than 1/10 (Hanisch et al., 2002).

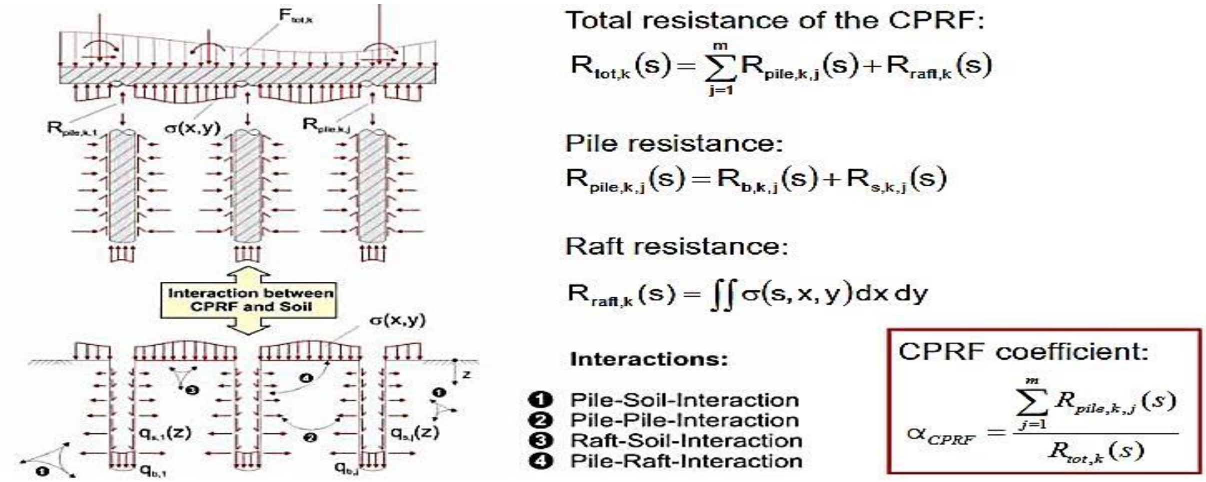


Figure 2.1: Common load-bearing components of piling raft foundations; soil-structure interaction (Katzenbach et al., 2007).

Examining CPRF systems entails considering how the various components interact with one another (Figure 2.1). The behavior of the soil around a pile under load is known as "pile-soil interaction," and it influences the pile's capacity as well as how the weight is distributed to adjacent piles or the raft. The interaction between adjacent heaps in a group that affects their ability to support loads and transfer loads to other piles is known as pile-pile interaction. Raft-soil interaction is the relationship between a piled raft foundation's raft and the soil that influences the settlement behavior of the foundation as well as the amount and distribution of loads transferred to the piles. In a piled raft foundation, pile-raft interaction refers to the interaction between the piles and the raft, which influences the settlement behavior of the foundation as well as the capacity of the pile and the distribution of loads inside the foundation. Crucial elements in pile-raft interaction are the raft's stiffness and the piles' relative stiffness. (D. Nguyen et al., 2013).

2.2.2. The Benefits of Pile Raft Foundation

By using piles to supply the majority of the stiffness at serviceability loads and the raft element to give additional capacity at ultimate loading, piling raft foundations are intended to reduce settling. The number of piles needed might be decreased in situations where the raft offers more capacity. In the event that certain piles are faulty, weak, or experience poor subsurface circumstances, the raft can also serve as a backup. The raft reduces the potential influence of pile "weakness" on the foundation's overall performance by facilitating a certain amount of load redistribution from the damaged piles to the unaffected ones (Katzenbach et al., 2007).

Piled rafts also have the advantage of improving the load capacity of a pile relative to those that stand freely because the pressure the raft applies to the soil can increase the lateral stress between the piles below it and the surrounding soil. A geotechnical evaluation must consider the combined capacity and interaction of the pile and raft components during serviceability loading in addition to their individual capacities when building this kind of foundation system. Piled rafts work best when the raft can support a significant amount of weight but its own settlement and/or differential settlements are higher than allowed (H. Poulos et al., n.d., 2011).

According to H. G. Poulos, (2001) for piled raft foundations, soil profiles with reasonably dense sand or relatively stiff clays are ideal. In both situations, the raft can provide a sizable portion of the required rigidity and load capacity, while the piles enhance the foundation's functionality rather than acting as its main source of support.

2.3. The Design Philosophy of Piled Rafts

One advantage of directly casting a pile cap on the ground is that it may result in block-type failure. Slippage between the soil and each pile at its base is caused by interaction effects within a collection of heaps. Relative slippage, however, is impossible at shallow levels if the pile cap strikes the soil surface directly. This results in the ultimate limit condition, which is defined by the total punching failure of the soil block around the piles (Franke et al., 2015).

(Randolph & Wroth, 1978) outlines three different approaches to piled raft design.

2.3.1. Conventional Approach

With some regard for the load transferred from the raft to the ground, the traditional method for designing a foundation entails evenly placing piles over the foundation area to create a pile group that bears the majority of the load. For small piled rafts that need pile support from a capacity perspective, this method is suitable (Kambala, 2010). The raft primarily contributes to the final load capacity, whereas the piles are meant to support the majority of the weight (H. G. Poulos, 2001b).

2.3.2. Creep Piling Approach

The Creep Piling Approach entails building piles to function at a working load—typically 70–80% of the ultimate load capacity—where substantial creep occurs. By adding enough piles to lower the net contact pressure between the raft and soil, the objective is to benefit from the effective stress compensation provided by the excavated soil. This method optimizes pile capacity to regulate the raft's load carrying capacity, and pile spacing is modified appropriately. (Algulin & Pedersen, 2014).

2.3.3. Differential Settlement Control Approach

To reduce absolute settling, piles are uniformly distributed beneath the raft in both the conventional and creep piling techniques. Nevertheless, a more focused strategy for minimizing differential settlements is arranging the piles strategically to minimize differential settlements without appreciably lowering the average settlement (H. G. Poulos, 2001b). The load settlement behavior of piled rafts constructed using the three design philosophies is depicted in Figure 2.2.

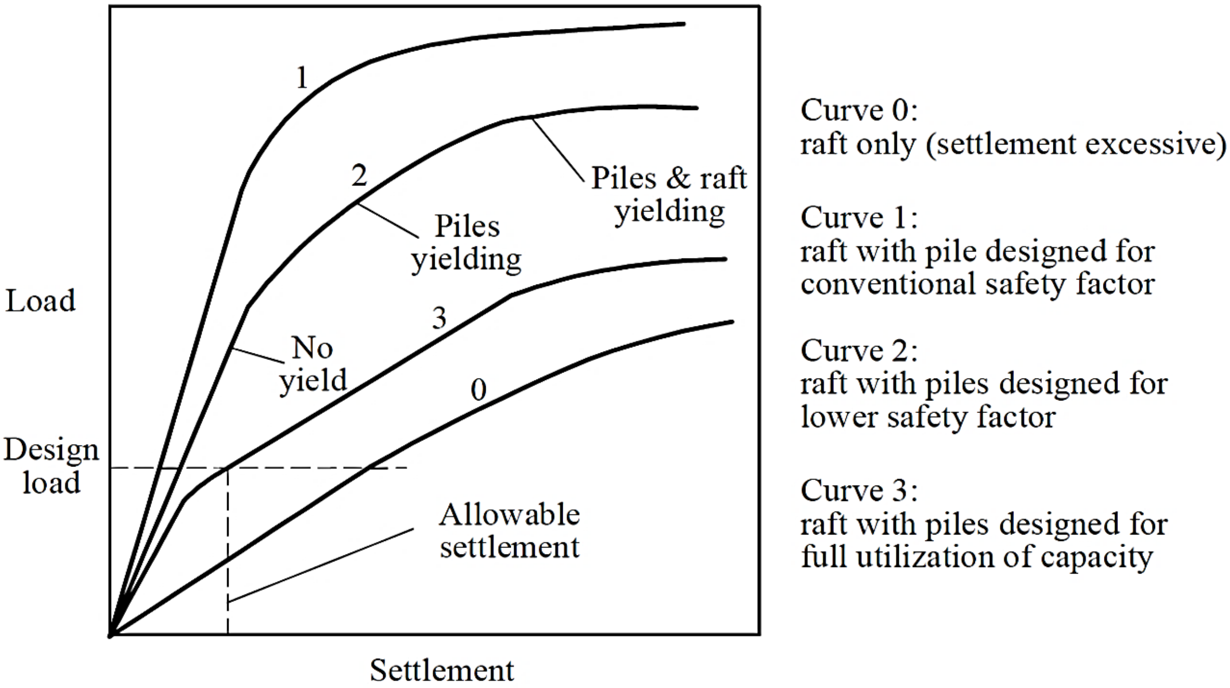


Figure 2.2: Comparing several design ideas for a piled raft's load-settlement behavior (H. G. Poulos, 2001b)

Curve 0 illustrates the behavior of a raft alone, which shows severe settlement at the design load. A typical heaped raft design is shown in Curve 1, where the pile group behavior controls the piled raft's behavior. Curve 2 illustrates the creep piling technique, in which fewer piles function at a lower factor of safety and hence load the raft more. The system of using piles as settlement reducers, where the piles' full capacity is used at the design load, is shown in Curve 3. For financial considerations, Curve 3's design is the one that is recommended.

2.4. An Analysis of the Design

To guarantee an optimal design, a number of crucial factors must be taken into account while designing a stacked raft foundation system. These elements, as emphasized by (H. G. Poulos, 2001b), include the ultimate load capacity for vertical, lateral, and moment loading, maximum settlement, and differential settlement. Additionally, the load sharing between the piles and the raft, as well as the moments and shears of the raft for structural design, and the pile loads and moments for the structural design of the piles must also be considered. By taking these factors into account, engineers can design a piled raft foundation system that can withstand external loads and perform as intended over its service life, ensuring the safety and stability of the structure it supports.

2.4.1. Both favorable and unfavorable circumstances for piled rafts

When the soil profiles comprise dense sands or somewhat stiff clays, and when the raft by itself cannot provide the required load capacity but can provide adequate stiffness, piled rafts perform well. In these instances, the piles improve the performance of the foundation, while the raft supplies a large amount of the necessary load capacity. However, soft clays or loose sands near the surface, soft compressible layers at shallow depths, soil profiles experiencing consolidation settlements, or swelling movements caused by external sources are all characteristics that are inappropriate for piled rafts. In such cases, the raft might not offer considerable load capacity or rigidity, and the ongoing compression of the layers beneath may diminish the raft's role in the foundation's enduring stiffness. Take safety steps for consolidating and swelling soils (H. G. Poulos, 2001b).

2.5. Analysis Method

There are various methods for analyzing piled raft foundations, as described by (H. G. Poulos, 2000). These techniques fall into three general categories: rigorous computer-based techniques, approximate computer-based techniques, and simplified calculation techniques. Hand calculations using theoretical answers for the elastic continuum of a raft and piles are used in simplified approaches. Several assumptions regarding soil behavior and loading conditions are made in this method. Approximate computer-based methods are also based on elastic theory, and H. G. Poulos, (2001b) identifies three main approaches for this category.

2.5.1. Simplified Analysis Methods

Simplified methods of analysis are often used in the design of piled raft foundations to estimate the foundation's total stiffness. Such as Davis and Poulos's approach, Randolph's approach, Burland’s approach, etc. One such method is the Poulos-Davis-Randolph (PDR) method, which involves computing the stiffness of the raft as an equivalent circular footing using elastic theory. The stiffness of the piles is computed using closed-form approximate solutions (Randolph & Wroth, 1978), while the group settlement ratio (which is used to compute pile group stiffness) is estimated using an approximated formula $R_S = n^{0.5}$, where n = the number of piles (Jayarajan, P., & Kouzer, K. M. (2015). This approach can provide a preliminary estimate of the piled raft's stiffness and load-carrying capacity, but it makes several assumptions and simplifications about the behavior of the soil and loading conditions.

2.5.2. Approximate Computer-Based Methods

In 1991, Poulos HG, developed an approximate numerical analysis method for piled raft foundations, wherein the raft is represented as a sequence of strip footings, and the piles are illustrated as springs with suitable stiffness. The method considered the interactions between the soil, raft, and piles Figure 2.3.

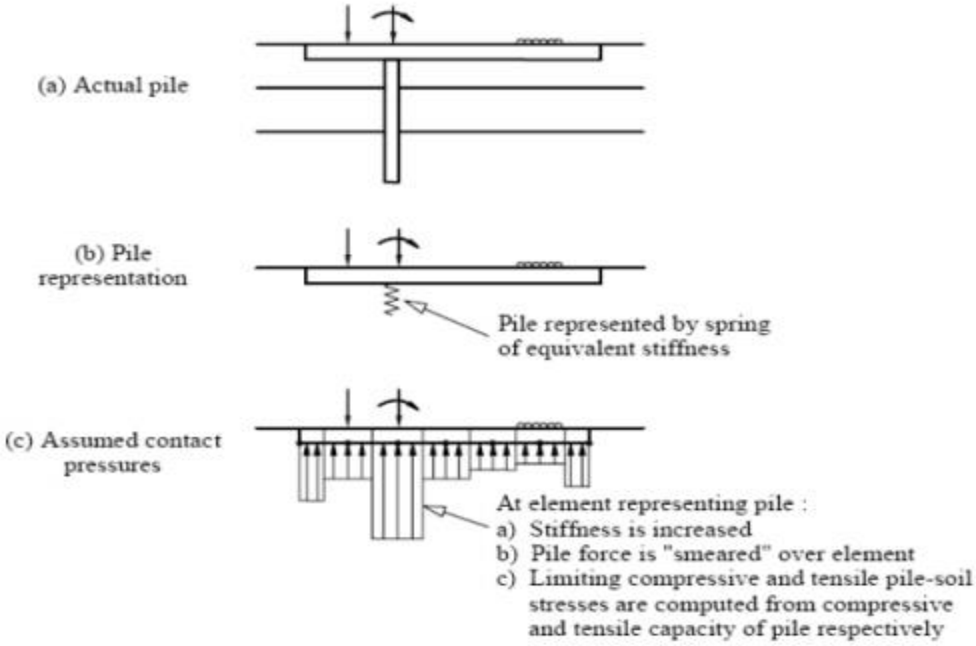


Figure 2.3: Representation of piled raft via GASP analysis (Poulos HG, 1991)

The approach was implemented with a computer program called Geotechnical Analysis of Strip with Piles (GASP) for practical purposes. Although the method provided reasonable results, it has limitations in accounting for torsional moments within the raft and may not provide consistent settlements when analyzing two strips in two directions through a specific point. Clancy & Randolph, (1993) formulated a hybrid approach that modeled the raft with two-dimensional thin plate finite elements and the piles with one-dimensional finite elements.

2.5.3. Rigorous Computer-Based Methods

Various computer-based methods, ranging from simplified 2D to more complex 3D methods, are available for foundation analysis. The rigorous computer-based methods provide better results compared to the simplified methods. The appropriate model and constitutive rules can yield results close to theoretical solutions. By utilizing advanced software, complex foundation issues can be resolved more efficiently through the application of finite element and boundary element techniques. Prakoso & Kulhawy, (2001) investigated the behavior of piled raft foundations using a 2D numerical method, but it was challenging to model concentrated loads and piles, and torsional moments could not be determined. H. G. Poulos, (2001a) noted that the 2D analysis overestimated settlement and pile loads due to plain strain assumptions, making 3D analysis more practical, especially for large-scale projects.

2.5.4. Boundary Element Method

The boundary element method is a technique that analyzes the interaction between soil and structure by considering the influence functions of the soil and foundation plate. With this method, only the boundaries of the foundation system need to be divided into elements, which reduces computation time and computer storage compared to the finite element method. Kuwabara, (1989) used this method to study the behavior of group piles in a homogeneous elastic soil, where the raft was modeled as rigid and piles as compressible. The raft was divided into rectangular elements, while the piles were divided into shaft and base elements. While the boundary element method can be utilized for non-linear elastic or plastic models (Franke et al., 2015)

2.5.5. Finite Element Method

The design and analysis of piled raft foundations require accurate modeling of both the structure and soil, taking into account their mechanical behaviors to address complex soil-structure interactions. Over the last 40 years, advances in computer engineering and software technology have led to an increase in the application of finite element analysis (FEM) for geotechnical structure design. With the advent of high-speed computers, the computational time required for FEM analysis has decreased, which has encouraged geotechnical engineers to use it for solving more complicated problems. According to Katzenbach et al., (2007), three-dimensional FEM analysis is gaining popularity in practical applications.

2.6. Load Carrying Behavior of Pile Raft

2.6.1. Load Carrying Behavior of a Single Pile

When designing a foundation, it is important to ensure that the structure's total load is safely transferred to the soil, with a sufficient safety factor to prevent bearing capacity failure.

Settlements should also be limited to ensure the safety and serviceability of the structure. Pile foundations may be necessary in some cases, such as when bridge piers are located on eroded riverbeds. In other cases, a comparative analysis of alternative solutions may be necessary to determine whether a pile foundation is the best choice, such as in the case of a pile foundation versus a shallow foundation on strengthened soil. Concrete piles can be divided into two categories: precast piles and cast-in-situ piles, depending on the method used during installation. Piles can be point or end-bearing, or friction piles, depending on their length and load transfer mechanism. Point-bearing piles are used when there is bedrock or rock-like material at a reasonable depth, and the ultimate capacity of the piles depends on the load-bearing capacity of the underlying rock material (Das, B. M. (2011). The ultimate load carried by the pile is given by:

$$R_{ck} = \frac{R_{cm}}{x} \quad \ldots\ldots\ldots\ldots\ldots\ldots \tag{2-1}$$

$$R_c = \frac{R_{ck}}{g_t} \ldots\ldots\ldots\ldots\ldots\ldots \tag{2-2}$$

$$R_c = \frac{R_{bk}}{g_b}\frac{R_{sk}}{g_s} \ldots\ldots\ldots\ldots\ldots\ldots \tag{2-3}$$

Where: -

R_{cm}=the measured value of ultimate bearing resistance
R_{ck} =characteristic value
R_c =design value
R_{bk} =characteristic base resistance
R_{sk} =characteristic shaft resistance
x =factors to apply on measured values
g_t =total factors of safety on the characteristic pile resistance
g_b =partial factors of safety on the base resistances
g_s =partial factors of safety on the shaft resistances

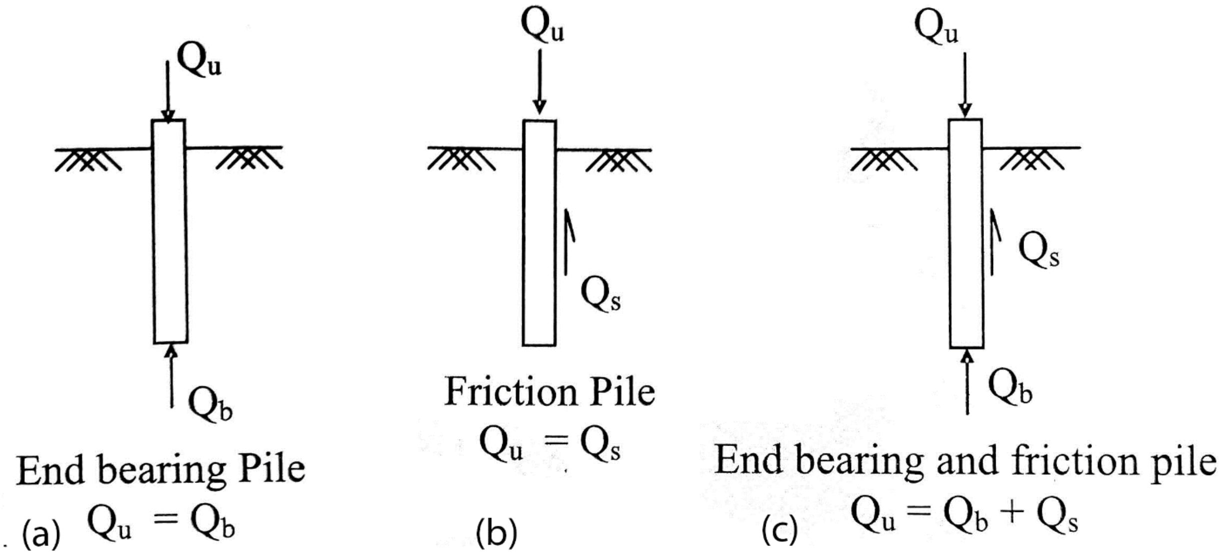


Figure 2.4: The mechanisms of the load transfer to the soil piles: (a) point or end-bearing piles, (b) friction piles, and (c) combined (Das, B. M. 2011).

In cases where there is no layer of rock or rock-like material at a reasonable depth, using point-bearing piles is not cost-effective. In these situations, piles are driven through softer soil to specified depths, and they are known as friction piles (Murthy). Friction piles derive most of their resistance from skin friction because there is no hard layer for them to bear on. Conversely, the utilized feature loads Q or F are increased by the factors g_F to determine the compression design load Q_c or F_c, which can be expressed as $Q_c = F_c = g_F F = g_F Q$.

2.6.2. Load Carrying Behavior of Group of Piles

Piles are commonly utilized in clusters to transfer the structural weight to the ground. A foundation, known as a pile cap, is built above the group of piles. It is assumed that the pressure distributed from the piles to the soil will intersect, as illustrated in the diagram. Figure 2.5, reducing the load-bearing capacity of the piles. The number of piles in the group = $n_1 * n_2$. Considering group pile length (L_g) and group pile width (B_g)

where: -

$L_g=(n_1-1)s + 2(D/2)$ ……………………………………………………………………….(2-4)

$B_g=(n_2-1)s + 2(D/2)$………………………………………………………………………..(2-5)

To ensure that the group of piles can support the weight, they should be positioned at a distance that guarantees the total bearing capacity of the group is at least equal to the sum of the individual piles' bearing capacity. Typically, the minimum distance between piles, known as "s," is 2.5 times the pile diameter, or "D." In practice, the spacing is usually about 3 to 3.5 times the pile diameter (Das, B. M. 2011). For friction piles, engineers often employ a simplified analysis to calculate the group efficiency, especially in sandy soil. Depending on the spacing between the piles within the group, the piles may function and fail in one of two ways.

As A Block*:* with dimensions Lg* Bg*L, in this case, the skin/frictional capacity is given by:

$$Q_{g(u)}= f_{avg}* P_g* L \quad\text{……(2-6)}$$

$$P_g=2s(n_1+n_2-2)+4D \quad\text{……(2-7)}$$

Where: -

P_g = the perimeter of the cross-section block

f_{avg} =average unit frictional resistance.

L = length of pile,

As Individual Piles: The calculation of the failure load $Q_{g(u)}$ for a group consisting of n piles, where each pile has a failure load of $Q_{(u)}$, is determined using this equation:

$$Q_{g\,(u)} =h*N*Q_{(u)} \quad\text{……(2-8)}$$

$$Q_{(u)}=f_{avg}* P_s* L \quad\text{……(2-9)}$$

$$h=\frac{Q_{g(u)}}{NQ_{(u)}}=\frac{2(n_1+n_2+2)s+4D}{f_{avg}*p_{pile}*L} \quad\text{……(2-10)}$$

$$Q_{g(u)}=\frac{2(n_1+n_2+2)s+4D}{f_{avg}*p_{pile}*L}(N*Q_{(u)}) \quad\text{……(2-11)}$$

Where: -

$Q_{g(u)}$ =the failure load of the group

$Q_{g(u)}$=the failure load of the single pile

N =the total number of piles in the group

h = group efficiency of the load-bearing capacity of a group pile

f_{avg} =average unit frictional resistance.

Sanzeni & Danesi, (2022) suggests adopting h= 1, except for those cases for which piles were bored without care. Concerning piles in cohesive soils, Viggiani, C. (2000) suggests assuming h= 0.6-0.7.

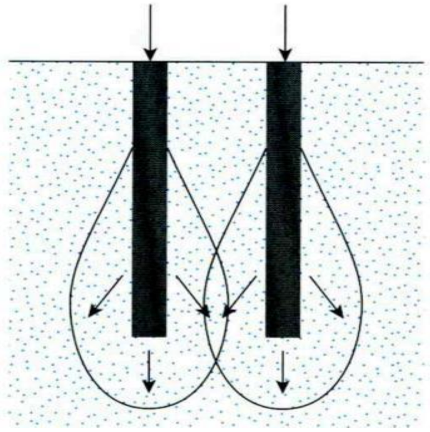


Figure 2.5: Stress overlaps between two piles

2.6.3. Load Carrying Capacity of Piled Rafts

Piled rafts have complex load responses and load-carrying behaviors that arise from the combined effects of various structural elements and interactions between the foundation and the surrounding soil. Figure 2.6 illustrates the typical configurations of group piles, unpiled rafts, and piled rafts. In the case of group piles, a pile cap is usually employed and positioned between the superstructure and piles. Even though the pile cap is typically placed in contact with the soil surface, its load-carrying capacity is often neglected (Lee et al., 2014).

The load-carrying capacity of piled rafts can be decomposed into those of rafts and piles, given as follows:

$$Q_{pr}=Q_p+Q_r \quad \text{.....} (2\text{-}12)$$

Where: -

Q_{pr} =the load-carrying capacity of piled raft

Q_r =the load-carrying capacity of the raft

Q_p =the load-carrying capacity of the pile

In terms of the load-carrying capacity of the group piles and unpiled raft, the above equation can be re-written as: -

$$Q_{pr}=h_r*Q_{ur} + h_p*Q_{pg} = h_r*Q_{ur} + h_p(x_g*N*Q_{sp}) \quad \text{.....} (2\text{-}13)$$

Where: -

Q_{ur} =the load-carrying capacity of the unpiled raft

Q_{gp} =the load-carrying capacity of group piles

Q_{sp} =the load-carrying capacity of single piles

Q_p =the load-carrying capacity of the pile

x_g =pile group effect factor

h_r =load capacity and efficiency factor for a raft

h_p =load capacity and efficiency factor for piles

$$h_r = Q_r / Q_{ur} \quad (2\text{-}14)$$

$$h_p = Q_p / Q_{gp} \quad (2\text{-}15)$$

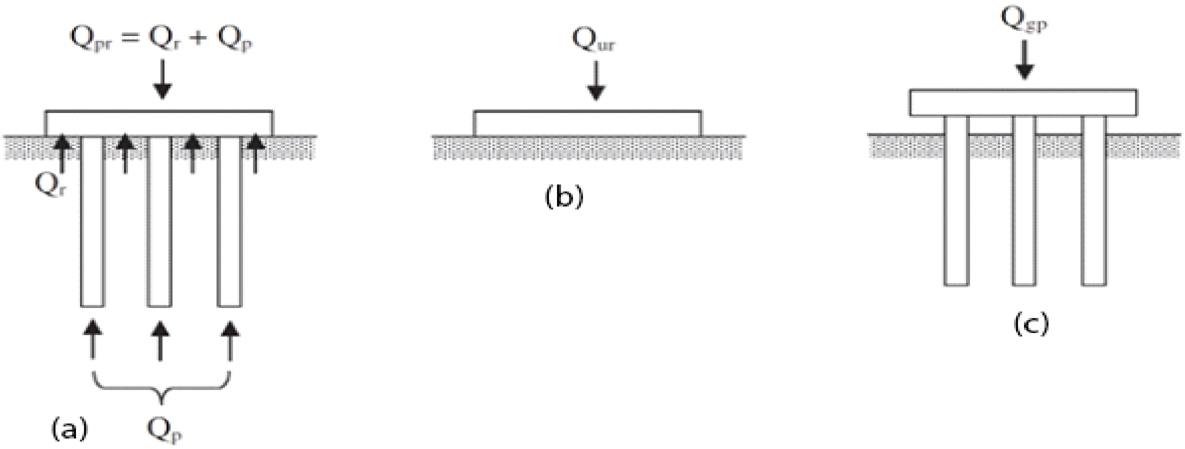


Figure 2.6: A typical configuration of (a) piled raft; (b) unpiled raft; and (c) group piles (Lee et al., 2014)

In traditional pile design, the factor x_g is used to determine the efficiency of the pile group and assess its load capacity. Equation (2.14 and 2.15) includes the load capacity efficiency factors h_r and h_p, which indicate the ratios of load capacities for piles and raft when used in a piled raft to those of unpiled raft and group piles. These factors are used to account for the interactions that can occur between the foundation components of piled rafts.

For clayey soils, the load capacity efficiency factor for the raft can be expressed in the following equation.

$$h_r = 1 - 3\left(\frac{A_g / A_r}{S_p / D_p}\right) \quad (2\text{-}16)$$

Where: -

A_g =the area defined by the perimeter line of piles

A_r = area of the raft

S_p = center-to-center pile spacing distance

D_p =pile diameter

Equation (2.16) reveals that the value of hr fluctuates between 0 and 1, which denotes the shift from the failure of the unpiled raft (hr = 1) to the failure of the piled raft due to block failure of piles (hr = 0). The equation is distinct from the load-carrying capacities of the unpiled raft and group piles because of the interactions that take place between the raft and piles when they are combined in a piled raft.

2.6.4. Load-Sharing Behavior of Piled Rafts

The load distribution behavior of a piled raft foundation is influenced by various factors, such as the settlement of the foundation system, the dimensions of the raft and piles, and the soil condition below the foundation (Cerato & Lutenegger, 2006). To determine the ultimate load capacity in foundation design, it is recommended that settlement equal to 10% of the pile diameter or raft width should be considered. As the settlement increases, the proportion of load carried by the raft becomes greater. To comprehend the load-sharing mechanism of a piled raft foundation more fully, a settlement-based load-sharing model proposed by (Lee et al., 2014) is briefly explained below.

Equation (2.17) expresses the load-sharing behavior of the piled raft system in terms of the load-sharing ratio, ap, which is the ratio of the load supported by the piles to the total load applied to the piled raft.

$$\alpha_p=\frac{Q_p}{Q_{pr}} = \frac{Q_p}{Q_r+Q_p} = 1-\frac{Q_r}{Q_{pr}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2\text{-}17)$$

In 1996 Horikoshi & Randolph carried out centrifuge tests and reported the values of α_p for flexible foundations with varying numbers of piles. The study showed that α_p decreases with an increase in the load level, but this load-sharing parameter decreases less as the number of piles increases. This indicates that as the settlement increases, the load supported by the piles decreases, causing the load supported by the raft to increase in a piled raft foundation system.

2.6.5. Normalized Load – Settlement Relationship

Foundations exhibit non-linear load-settlement responses due to the non-linear stress-strain behavior of soils. As explained by Lee et al., (2014), hyperbolic load-settlement relationships have been commonly utilized to represent the non-linear load responses of foundations.

The nonlinear load-settlement relationship can be defined as:

$$Q = \frac{s}{a+b+s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2\text{-}18)$$

Where: - Q = load s = settlement; and a and b are hyperbolic parameters.

In order to account for the differences in the geometric and mechanical properties of the raft and piles, a normalized load-settlement relationship was introduced in terms of relative settlement and load. The load and settlement were normalized using the foundation size and ultimate load capacity, respectively. When Equation (2.19) is normalized with the ultimate load capacity and raft width, the resulting normalized relationship for rafts is as follows:

$$\frac{Q_r}{Q_{r,u}} = \frac{\frac{s}{B_r}}{a_r+b_r\left(\frac{s}{B_r}\right)}\text{………………………………………………………}(2\text{-}19)$$

Where:

Q_r =load imposed on the raft

$Q_{r,\,u\,=}$ the ultimate load capacity of the raft

s = settlement

B_r =raft width

a_r,b_r = model parameters for the normalized hyperbolic load settlement relationship of the raft

Similarly, the normalized load-settlement relationship for piles can be described in Equation (2.20):

$$\frac{Q_p}{Q_{p,u}} = \frac{\frac{s}{D_p}}{a_p+b_p\left(\frac{s}{d_p}\right)}\text{………………………………………………………………….. }(2\text{-}20)$$

Where:

Q_P =load imposed on piles

$Q_{P,\,u}$ =the ultimate load capacity of piles

s =settlement

D_p =pile diameter

a_p, b_p =model parameters for the normalized hyperbolic load settlement relationship for piles.

Equations (2.19) and (2.20) have flexible applicability to different foundation and soil conditions because they are normalized formulations. Normalizing these equations includes the effects of local soil conditions and changes in foundation geometry and mechanics through the ultimate load capacity and foundation size. The original hyperbolic parameters (a and b in equation (2.18) vary for different foundation and soil conditions. However, the normalized model parameters (a_r, b_r, a_p, and b_p) can be considered unique since they were derived in normalized terms. After Lee et al. (2014) performed the derivation, the values of these normalized model parameters were found to be 0.02, 0.8, 0.01, and 0.9, respectively. The normalized hyperbolic load-settlement curves using Equations (2.19) and (2.20) for rafts and piles were plotted as shown in Figure 2.7. The values of $\frac{Q_r}{Q_{r,u}}$ and $\frac{Q_p}{Q_{p,u}}$ both vary from 0 to 1 for the range of normalized settlements of $\frac{s}{B_r}$and $\frac{s}{B_p}$from 0 to 0.1

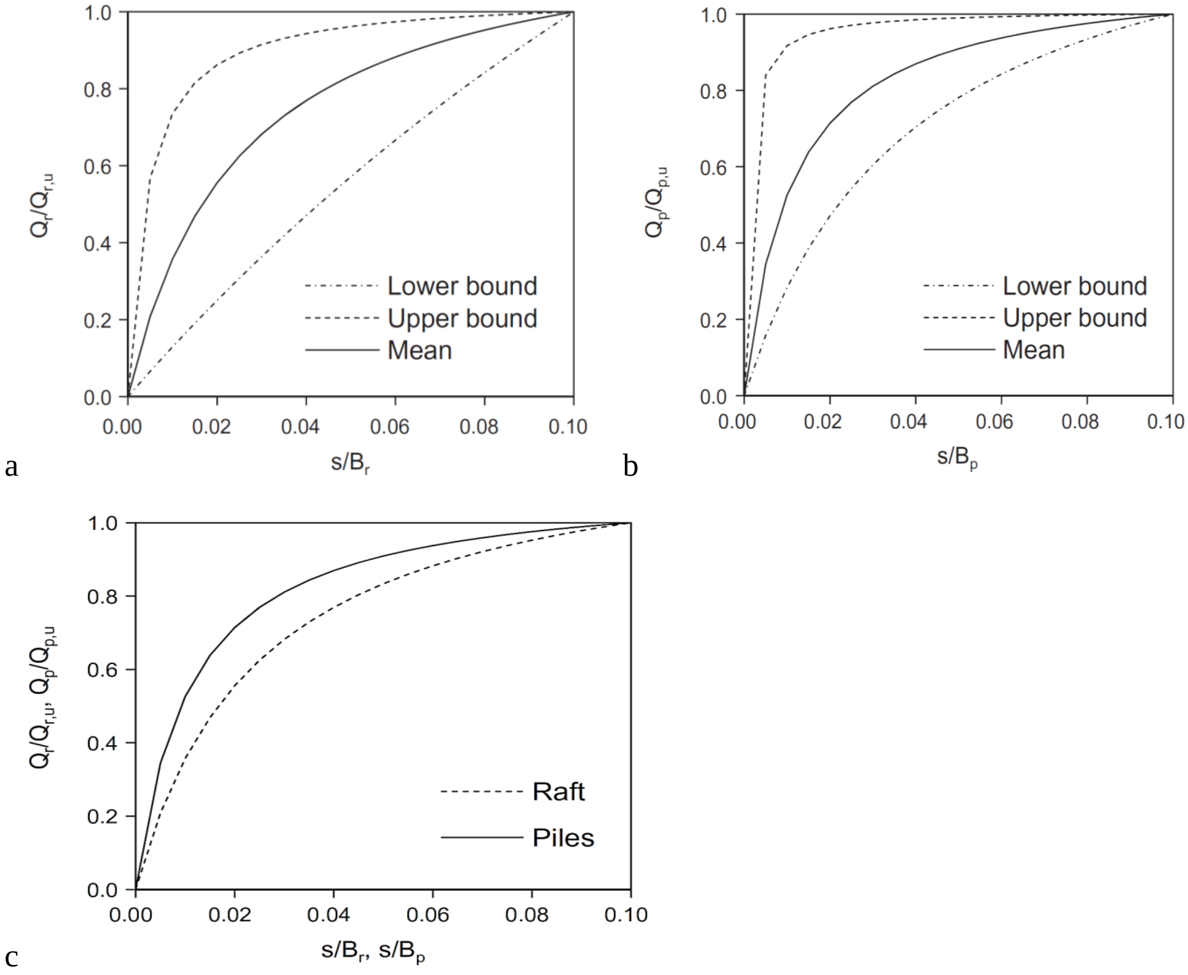


Figure 2.7: Normalized load–settlement curves of (a) raft; (b) piles; and (c) raft and piles (Lee et al., 2014)

2.7. Parametric Study

2.7.1. Factors Affecting CPRF

The analysis of this complex three-dimensional structure entails considering various parameters related to geometry, mechanics, and by-products. The geometric parameters encompass aspects such as the pile dimensions (such as length, diameter, spacing, and number), as well as raft dimensions (such as length, breadth, and thickness). On the other hand, the mechanical properties involve the characteristics of the soil (such as modulus of elasticity and Poisson's ratio), while the by-product parameters could involve various interaction factors, such as the interaction between piles, the raft, and the soil, as well as other derived parameters (Sinha, 2013).

2.7.2. Pile Raft Geometry

Raft Thickness

Rafts that are thin or flexible have a tendency to undergo greater deformation compared to those that are rigid or thick. As a result of this significant deformation, flexible rafts cause a greater amount of deformation in the subsoil, which ultimately leads to a higher load being transferred by the raft and inducing a higher reaction force. Alnuaim et al., (2013) explained that the stiffness of the raft can be determined by:

$$K_f = \left[\frac{E_f}{E_s}\right]\left[\frac{2t}{s}\right]^3 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2\text{-}21)$$

Where:

k_f =stiffness of the raft

Ef = raft young's modulus

Es =average elastic modulus of the soil

t =raft thickness

s =pile spacing

Alnuaim et al., (2013) classify rafts into three categories based on their flexibility: perfectly rigid (if $k_f > 10$), perfectly flexible (if $k_f < 0.01$), and intermediate flexibility (if the value of kf falls between 0.01 to 10, as determined using Equation (2.21). In a centrifuge test conducted as part of this study, the load carried by the raft was observed for two different pile spacing values and various raft thicknesses as a function of the total displacement of the piled raft. At a pile spacing to diameter ratio of 4, the load carried by the raft was significantly different, being approximately 65% and 55% for raft thicknesses of 0.3 m and 2 m, respectively, due to a high difference in kf, which was about 0.05 and 2.2 for the two thicknesses, respectively. On the other hand, the values of kf were quite close in the case of pile spacing to diameter ratio of 10, being approximately 0.004 and 0.07 for raft thicknesses of 0.3 m and 1.25 m, respectively, resulting in a narrow variation of approximately 75% in the load carried by the raft. This is because a thick raft at large spacing is more flexible, resulting in increased interaction between the raft and soil compared to a similar raft with a smaller pile spacing.

Pile Diameter

In their study, Mali & Singh, (2018) a square (45 m * 45 m) raft with K_{rs} of 0.09, a load of 200kpa, and piles of L_p/D_p equal to 30 and in order to understand the effect of D_p, simulations were conducted on a piled-raft with varying D_p from 0.5 to 2.0 m for a different ratio of pile group width to raft width (B_g/B_r) (0.2, 0.4, 0.6, and 0.8). It can be observed that the average settlement ratio ($R_{avg)}$ decreases as the D_p increases (Figure 2.8(a)). An increase in D_p (up to 1.0 m for B_g/B_r = 0.6 and 0.8) may be due to the enhanced stiffness of the piled raft. At a D_p of 1.0 m, the maximum stiffness for the piled-raft system may have been achieved. The impact of D_p on the differential settlement ratio (R_{diff}) is illustrated in Figure 2.8(b). When the B_g/B_r ratio shifts from 0.2 to 0.6, the R_{diff} decreases up to D_p = 1.0 m and stays constant afterward. As the B_g/B_r ratio moves from 0.6 to 0.8, R_{diff} significantly rises for each pile diameter.

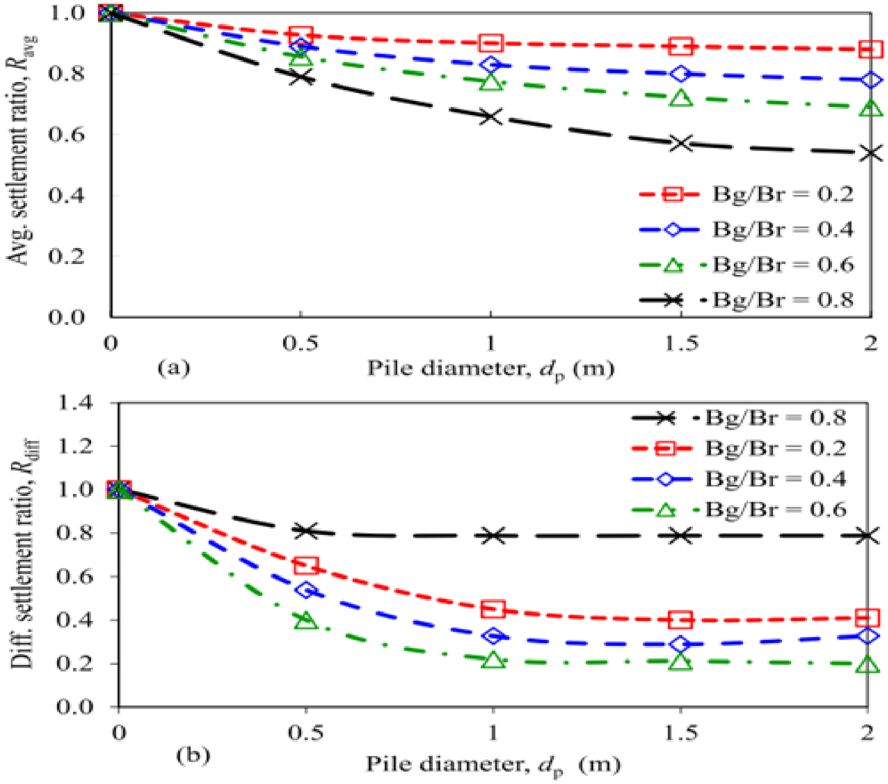


Figure 2.8: Effect of pile diameter on (a) average settlement ratio and (b) differential settlement ratio (Mali & Singh, 2018)

Influence of Pile Spacing

Alnuaim et al., (2013) stated that piled rafts with small pile spacing experience less deformation at the center compared to those with large pile spacing. Maharaj & Gandhi,

(2004) analyzed a 3x3 group of piles with varying pile spacing and observed that settlement increased as pile spacing increased, recommending a pile spacing of 2d-3d for future research. Maharaj & Gandhi, (2004) noted that pile spacing greatly affects maximum settlement, differential settlement, bending moment in the raft, and load shared by the piles. Lee et al., (2015b) demonstrated in Figure 2.9 that the load-carrying capacities of individual piles in a piled raft foundation increase with increased center-to-center pile spacing. Additionally, as pile spacing increases, the load-carrying capacity of the piled raft foundation decreases, indicating a higher proportion of load taken by the piles.

As the spacing between piles decreases, the stress fields around the piles start to overlap more, which leads to a reduction in the load-carrying capacity of the piles. In a study conducted by El & Nashaat, (2018) both experimental and theoretical analyses were used to investigate the effect of pile spacing on the ultimate capacity and load shearing of non-rested and directly rested piled raft foundations on the soil. The study varied the center-to-center spacing between piles from 2 to 7 pile diameters. The results showed that for a pile cap directly rested on soil, increasing the spacing between piles led to an increase in ultimate capacity. However, for a pile cap non-rested on soil, the ultimate capacity decreased after the pile spacing exceeded four times the pile diameter.

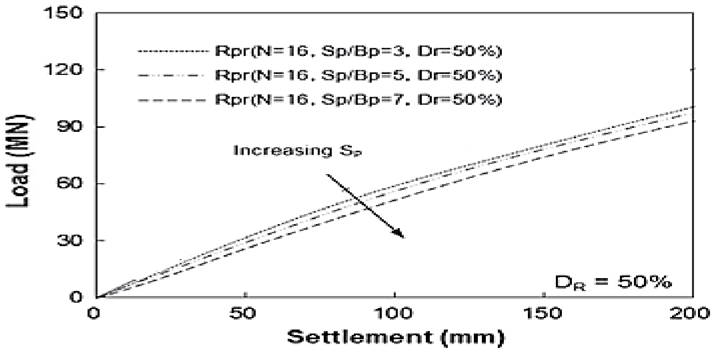


Figure 2.9: Decomposed load–settlement curves of the piled raft with different pile Spacing (Lee et al., 2015b)

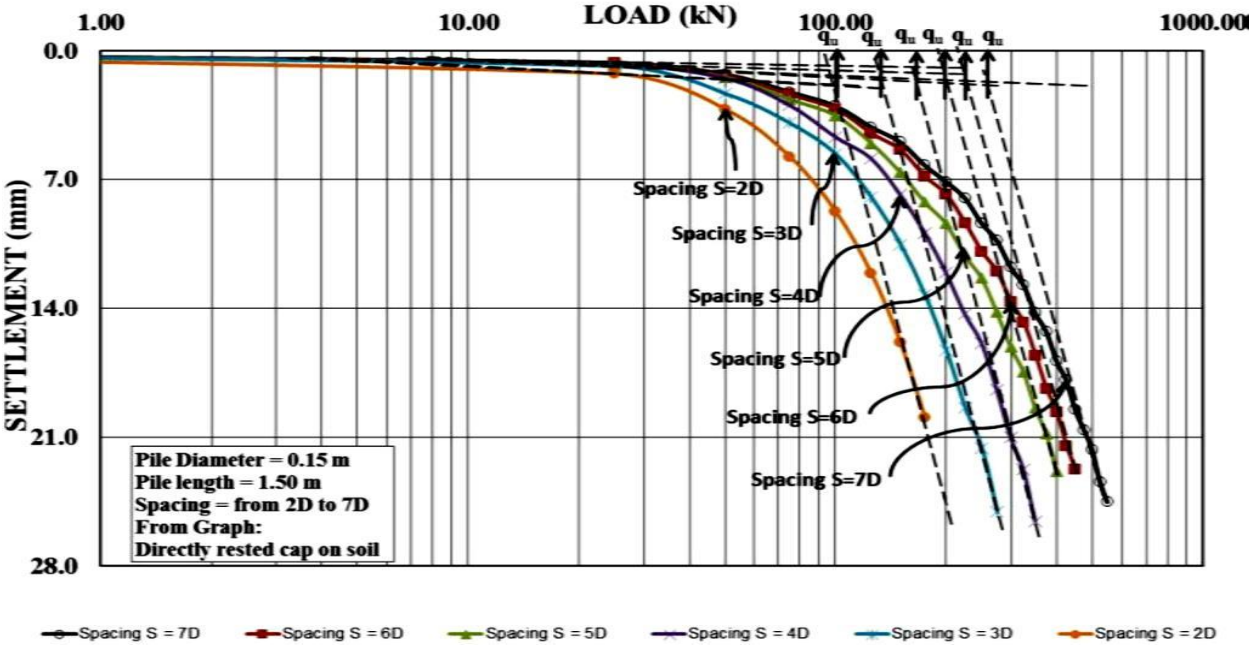


Figure 2.10: Settlement vs load for different pile spacing (Samee, 2018)

Furthermore, it was found that in the case of pile caps non-rested on soil, the frictional load transferred to the soil around the pile shaft increases as the spacing between piles increases. However, in the case of Pile-Cap directly rested on soil, the load transferred to the soil by friction increases as the spacing between piles increases up to four times the pile diameter, after which the load values decrease as the spacing between piles continues to increase. Figure 2.10 illustrates the settlement of the piled raft foundation for different pile spacings under varying imposed loads.

Influence of Pile Length

Kumar, (2018) found that the use of non-uniform pile length in a piled raft foundation with a proper arrangement can meet all settlement requirements, even under non-uniform loading conditions of high-rise buildings. This design approach can reduce the foundation cost while satisfying the design aspects.

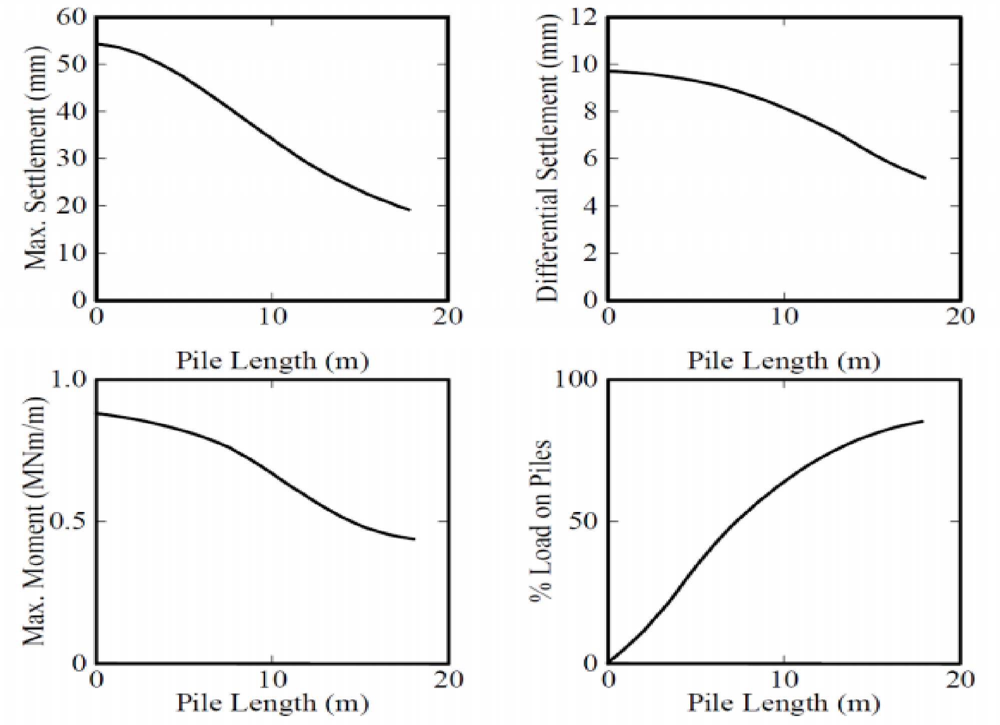


Figure 2.11: Effect of pile length on the foundation (Van Impe, W. F., & Lungu, I. (2001).

Van Impe, W. F., & Lungu, I. (2001) investigated the impact of varying pile lengths on the maximum and differential settlement of a 0.5m thick raft with nine piles using the GARP program. Figure 2.11 illustrates the influence of pile length on maximum settlement, the differential settlement between the center and outer piles, the maximum moment in the raft, and the proportion of load carried by the piles. The results indicated that increasing the pile length leads to decreasing settlement, differential settlement, and maximum moment but increases the proportion of load carried by the piles.

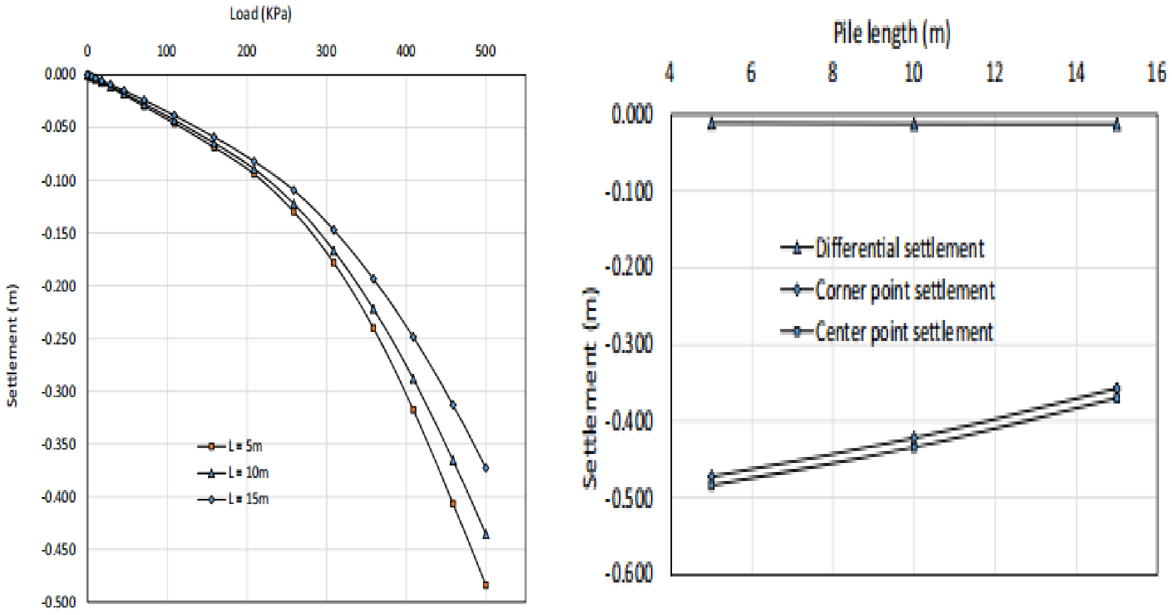


Figure 2.12: Load settlement curve for different pile lengths (Sinha, A., & Hanna, A. M. (2017).

Sinha & Hanna (2017) investigated how the length of piles affects the settlement of a piled raft foundation using piles of three different lengths (5m, 10m, and 15m). The analysis assumed a raft thickness of 2m, a spacing of 6D between piles, and a pile diameter of 1m for all pile lengths. The findings displayed in Figure 2.12 reveal that as the pile length increased, the capacity of the piled raft system also increased; meanwhile, the settlement observed at the central point of the raft reduced. However, the pile length did not have a substantial impact on the differential settlement within the raft. Consequently, engineers may need to balance the pile spacing and pile length to attain a cost-effective design.

Influence Number of Piles

In their study, Ata et al. (2015) performed an analysis on a 0.6 m thick square raft with a 100 m2 area, supported by varying numbers of piles (from 4 to 121) arranged in square patterns. The spacing between the piles ranged from 1.5 to 14 times their diameter under an axial load of 750KN. Figure 2.13 illustrates the relationship between settlement and the number of piles in the unconnected system. This figure reveals that as the number of piles increases, the settlement in the system decreases. The decrease in maximum and differential settlement occurs more rapidly as the number of piles goes up to 25, after which the reduction becomes minimal. Additionally, it is evident that concentrating the piles closer to the center, either by reducing the spacing between them or increasing their number, results in a lower overall settlement.

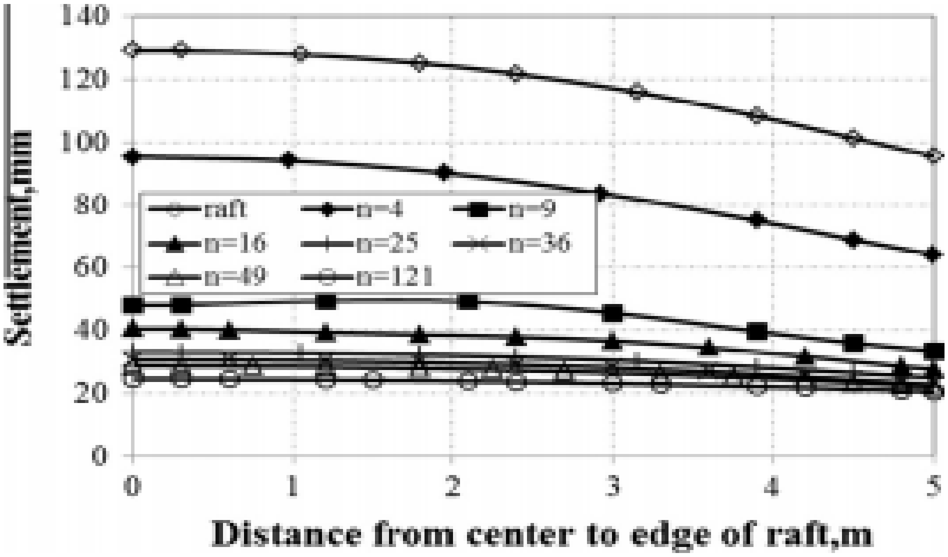


Figure 2.13: Normalized Settlement vs the number of piles (Ata et al., 2015)

In a study by Van Impe & Lungu (2001), it was found that the number of piles in a piled raft foundation has a significant impact on reducing the settlement of the raft. However, after adding about 15 piles, the additional reduction in settlement becomes very small. Therefore, it is possible to optimize foundation design and achieve the required settlement performance by carrying out analyses to determine the minimum number of piles needed.

Poulos (2001a) investigated the impact of the number of piles on the performance of piled raft foundations. Figure 2.14 presents the correlation between the central settlement and the number of piles obtained from simplified PDR analysis for a load of 12 MN, as well as the ultimate load capacity and the number of piles. The study found that increasing the number of piles decreases the maximum settlement, but after 20 or more piles, the reduction in settlement becomes negligible. Additionally, for a small number of piles, the maximum settlement under concentrated loading is greater than that under uniform loading, but this difference reduces for 10 or more piles.

Moreover, as the number of piles increases, the load carried by them also increases. However, the rate of increase in load-carrying capacity becomes very small beyond about 15 piles. Thus, increasing the number of piles may not always lead to the best foundation performance, and there is a limit beyond which additional benefit is minimal.

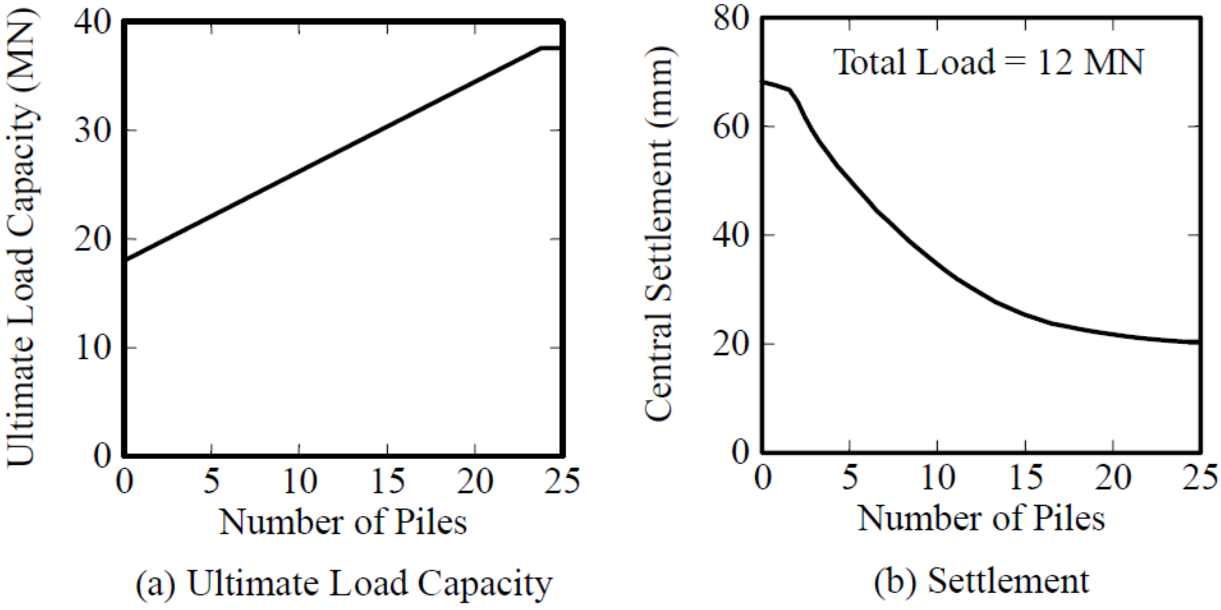


Figure 2.14: Effect of the number of piles on the ultimate load capacity and settlement (Poulos,2001a)

To sum up, the authors mentioned above indicate that piled raft foundations provide benefits such as decreased settlement and enhanced bearing capacity of the foundation, which can be evaluated by varying different parameters of the system. Finite element method analyses can be conducted to investigate the impact of these parameters on the maximum settlement of the piled raft foundation. To validate the findings, the outcomes of the finite element method could be compared to results from centrifuge tests conducted by other researchers. Based on the results, optimal parameters for the foundation can be determined.

2.8. Finite Element Modeling of Piled Raft Foundation

2.8.1. Introduction

Piled raft foundations are widely used to support structures on soft and compressible soil. These foundations consist of a reinforced concrete slab that spans over a group of piles, which transfer the loads from the structure to the soil. The behavior of piled raft foundations under different loading conditions can be complex and difficult to predict using traditional analytical methods. Finite element analysis (FEA) is a powerful tool that can be used to simulate the behavior of piled raft foundations and provide insight into their performance. Plaxis 3D is a widely used FEA software that can simulate the behavior of piled raft foundations and provide accurate predictions of their response (Al-Juaidi, A. H., Ahmed, M. F., & Al-Mahaidi, R. (2020).

2.8.2. The 3D FEM Numerical Modeling Process:

The 3D FEM numerical modeling process for piled raft foundations using Plaxis 3D typically involves several steps. First, the soil and structural components are modeled as continuum bodies. The soil is typically modeled using the Mohr-Coulomb, Hardening Soil, or Soft Soil constitutive models, etc., which describe the behavior of soil under different loading conditions. The structural components, such as the piles and raft, are modeled using beam or shell elements. Based on the dimensions of the raft and piles, piled rafts can be categorized into small piled rafts ($B_r < L_p$) and large piled rafts ($B_r > L_p$). In small piled rafts, piles are primarily added to achieve an adequate safety factor against bearing failure. In contrast, large piled rafts primarily use piles to reduce settlement (Mali & Singh, 2020; Russo, 1998; Viggiani, 2001). The model has then meshed to discretize the soil and structural components into smaller elements, which allows for a more accurate simulation of the behavior of the system. Finally, the loads and boundary conditions are applied to the model, and the analysis is run to simulate the behavior of the piled raft foundation (Johnson et al., 2019b; Nguyen et al., 2013; Sulaiman Al-Ne’aimi & Hussain, 2021).

The continuum's constitutive model is vital for numerical modeling. Plaxis 3D offers several models, such as Mohr-Coulomb for granular soils and Hardening Soil and Soft Soil for cohesive and soft soils, respectively. The model choice depends on soil properties and loading conditions.

Numerous studies have employed Plaxis 3D to analyze piled raft foundations under various load conditions. For instance, Vu & Matsumoto (2016) used the software to assess static and cyclic loading, finding accurate predictions for foundation behavior like settlement and lateral displacement. Mali & Singh (2018) also applied Plaxis 3D to study foundations on soft clay soil, confirming the software's accuracy in predicting settlement, bearing capacity, and load distribution.

Geometric modeling is essential in the finite element process of piled raft foundations. Accurately representing foundation geometry, including raft, piles, and soil profile, is necessary and can be achieved using software like PLAXIS 3D (Bhaduri & Choudhury, 2020). Inaccurate geometry may generate inaccurate results. Various tools in PLAXIS 3D allow for importing CAD files, terrain modeling, and meshing (Brinkgreve et al., 2016). Site investigation data, such as borehole logs and geotechnical testing results, can help improve model accuracy (Bourgeois et al., 2012).

Meshing, dividing the model into small finite elements, is crucial for the geometric modeling process. It should be dense enough to capture local behavior but not computationally expensive. Different meshing techniques are available, such as triangular, quadrilateral, and tetrahedral elements (Lee et al., 2010). Accurate geometric modeling and proper meshing techniques are essential for precise and efficient piled raft foundation simulations.

Boundary conditions are essential in numerical modeling. Plaxis 3D offers various options, such as fixed, fixed displacement, and free boundary conditions, depending on the analysis needed. Fixed conditions suit modeling a compressed pile, fixed displacement fits for a foundation under lateral loads, and free conditions work for the soil under undrained loading (Brinkgreve et al., 2015).

Choosing the right finite element type is crucial in the finite element modeling process. Plaxis 3D provides various element types, like linear and quadratic, to represent foundation and soil behavior. Element type depends on problem complexity, desired precision, and computing resources. Simple problems may use linear elements, while complex ones needing higher accuracy can use quadratic elements (Reul & Randolph, 2004).

The modeling of the contact zone between the piles and the raft is a critical aspect of finite element modeling of piled raft foundations. The contact zone must be modeled accurately to ensure that the interaction between the piles and the raft is correctly captured. This can be achieved using interface elements, which represent the behavior of the contact zone between the piles and the raft. Plaxis 3D offers a range of interface elements, including the zero-thickness interface element and the embedded beam element, that can be used to model the contact zone (Brinkgreve et al., 2016).

In finite element modeling, loads are applied to the foundation and soil either gradually or in discrete steps based on loading conditions. Careful selection of loading steps is crucial for accurately capturing foundation and soil behavior, which can be determined through preliminary analysis (Lee et al., 2010).

The mesh sensitivity analysis is a crucial step in the finite element modeling process. The mesh must be fine enough to accurately capture the behavior of the system, but a very fine mesh can result in a significant increase in computational time. The mesh sensitivity analysis involves conducting several simulations with different mesh densities to determine the optimal mesh density for the problem. This can be achieved using the convergence criteria in Plaxis 3D, which allows the user to determine when the analysis results have converged to a stable solution (Brinkgreve et al., 2016).

2.9. Soil Distribution in Addis Ababa

Addis Ababa, situated on the western margin of the Ethiopian Rift, is characterized by diverse volcanic rock formations. The Entoto mountain chains to the north feature rhyolite, trachyte, and minor obsidian-rich tuffs, known as EntotoSiliccis, as well as aphanitic basalt. Volcanic centers such as Wachacha and Furi primarily contain trachytic rock, while Yerer Hill and surrounding areas like KokebeTsebah and Kotebe are primarily composed of rhyolites. Basalt covers the north and northwest parts extending from the Entoto ridge to Filwoha, with appearances around Bole International Airport and the upper Akaki River valley. Trachytic basalts are found in areas like Bole Bulbula, Zenebework, and Ayertena, while ignimbrites and welded tuffs are located in Filwiha, Cazanchis, and Legehar. Residual soils, including red clays and black cotton soils, occupy large areas in KolfeKeranyo, Asko, Mekanisa, and Lebu, with colluvial and alluvial deposits present at the foot of hills and riverbanks (Dejen, 2017).

The climate of Addis Ababa is classified as subtropical highland with occasional rain, short rainy seasons, and average rainfall and temperatures varying from 8mm in November to 258mm in August, and average high and low temperatures of 24.8°C and 8°C in March and January respectively. The tectonic and volcanic activities of the region are connected to the formation of the rift valley and are bounded by faults and lineaments, making Addis Ababa susceptible to seismic hazards. The seismic hazard map of Ethiopia indicates a 100-year return period, or approximately a 50% chance of being exceeded in 50 years (Dejen, 2017).

2.10. Research Gaps

As table 2.1 illustrate, most of the existing studies on the parametric analysis of pile raft foundations have focused on square-shaped rafts, which do not reflect the actual shape of most structures. Moreover, there is a lack of research on the local soil conditions and their effects on the performance of pile raft foundations in Ethiopia. Therefore, there is a need to investigate the behavior of rectangular pile raft foundations, especially on weak soil types that are commonly found in Addis Ababa and other parts of Ethiopia. Hence, this research conducted a parametric study of rectangular pile raft foundations on weak soil types in Ethiopia. The study considered the soil-raft-pile interactions and the load distribution over the foundation system.

Table 2.1: Dimension of raft used by the previous researcher

Author	Dimension of raft	Raft thickness
(Bandyopadhyay et al., 2020)	18 m × 18 m	1, 1.5, 2
(Johnson et al., 2019)	20 m × 20 m	1
(Lin & Feng, 2006)	15 m × 15 m, 30 m ×30 m	1, 5
(Taghavi Ghalesari & Janalizadeh Choobbasti, 2018)	24 m × 24 m	0.5, 1, 1.5
(Rabiei, 2010)	30 m × 30 m	1
(Ghalesari et al., 2013)	18 m ×18 m	0.5, 1, 1.5
(Mali & Singh, 2018)	45 m × 45 m	1, 2, 3
(Rabiei, 2009)	20 m × 20m	0.7
(Al-Ne’aimi & Hussain, 2021)	10 m × 10 m	1.0, 1.5, 2.0
(Mali & Singh, 2019)	45 m × 45 m	2
(Mali & Singh, 2020)	45 m × 45 m	0.5, 1, 1.5, 2
(Vu et al., 2014)	8 m × 8 m	1
(Taghavi Ghalesari et al. 2015)	18 m × 18 m	0.5, 1, 1.5

CHAPTER 3

3. METHODOLOGY

3.1. General

This section describes the study area and the process undertaken to achieve the general and specific objectives of the study. To fulfill these aims, many stages were followed. First, a complete literature analysis was undertaken to get a deep understanding of pile raft foundations, including relevant factors, procedures, and the impacts of these parameters on the settlement of the structure. Representative information was then obtained from government organizations involved in these issues, geotechnical design offices, and businesses that specialize in geotechnical investigations. Taking into account the number of boreholes and the extent of the area covered, the research area where weak soil could be found was determined based on the collected data. Parameters used as input for numerical modeling of the foundation system using Plaxis 3D were identified. Subsequently, numerical modeling of pile raft foundations for different parameters was conducted. Results and discussions were made based on the output of the model. Finally, conclusions and recommendations were drawn. Figure 3.2 show the flow chart of this research in a better way.

3.2. Study Area and Design

The study was carried out in Addis Ababa, Ethiopia, where the problem of building on weak soils is prevalent. The study area is found in the eastern part of Addis Ababa in the local area known as Bole Arabsa V, Latitude. 8.97773° or 8° 58' 40" north; Longitude. 38.88772° or 38° 53' 16" east and can be accessed via Semit Roundabout. This study relates to the analysis of a piled raft foundation with weak soil found in Addis Ababa, Ethiopia.

To accomplish the goals outlined in the problem description, an experimental research design was chosen for this investigation. A simulation analysis was used to conduct the study, and written statements, tables, and graphs were used to convey the findings. The primary method used to conduct this study was a desk study. To guide the quantitative study, a variety of pertinent books, case studies, and literature on the research topic were examined. The literature review was crucial in understanding the various techniques and methods used in previous studies on pile raft foundation design effectively on weak soils. The study findings will be used to develop conclusions and recommendations for the local building sector on how to design pile raft foundations on weak soils.

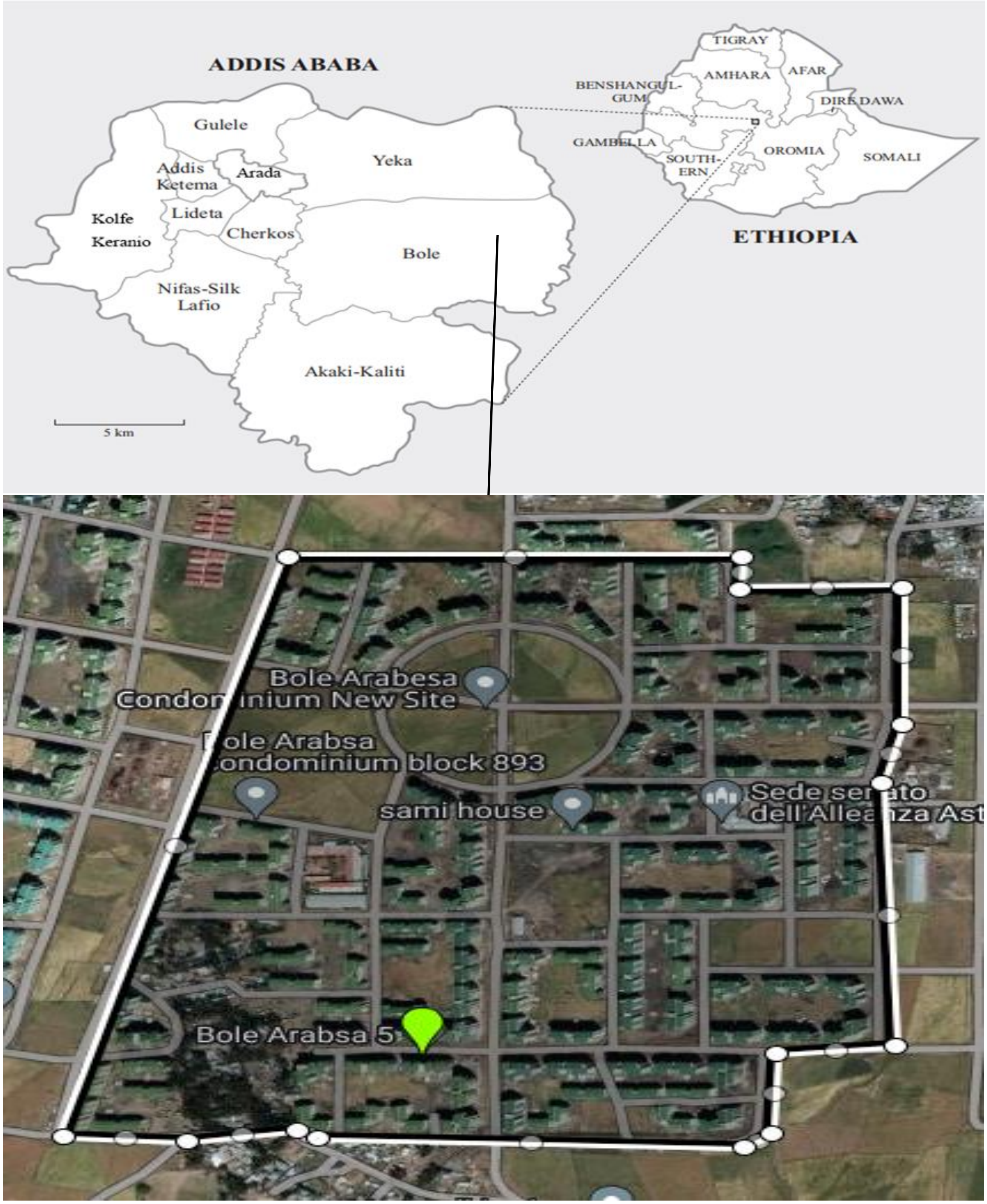
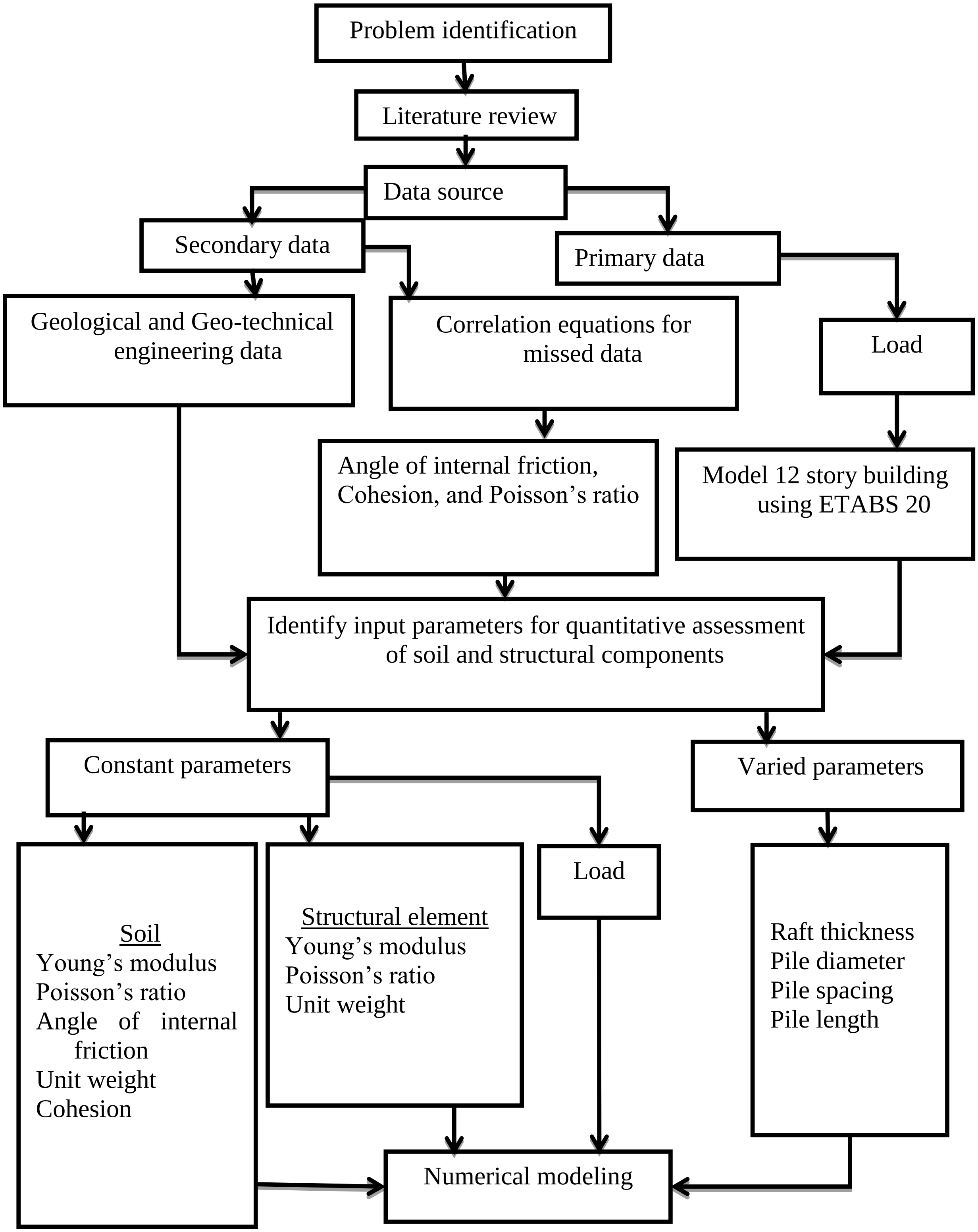


Figure 3.1: Detail of study area


Problem identification
Literature review
Data source
Secondary data
Primary data
Geological and Geo-technical engineering data
Correlation equations for missed data
Load
Angle of internal friction, Cohesion, and Poisson's ratio
Model 12 story building using ETABS 20
Identify input parameters for quantitative assessment of soil and structural components
Constant parameters
Varied parameters
Soil
Young's modulus
Poisson's ratio
Angle of internal friction
Unit weight
Cohesion
Structural element
Young's modulus
Poisson's ratio
Unit weight
Load
Raft thickness
Pile diameter
Pile spacing
Pile length
Numerical modeling

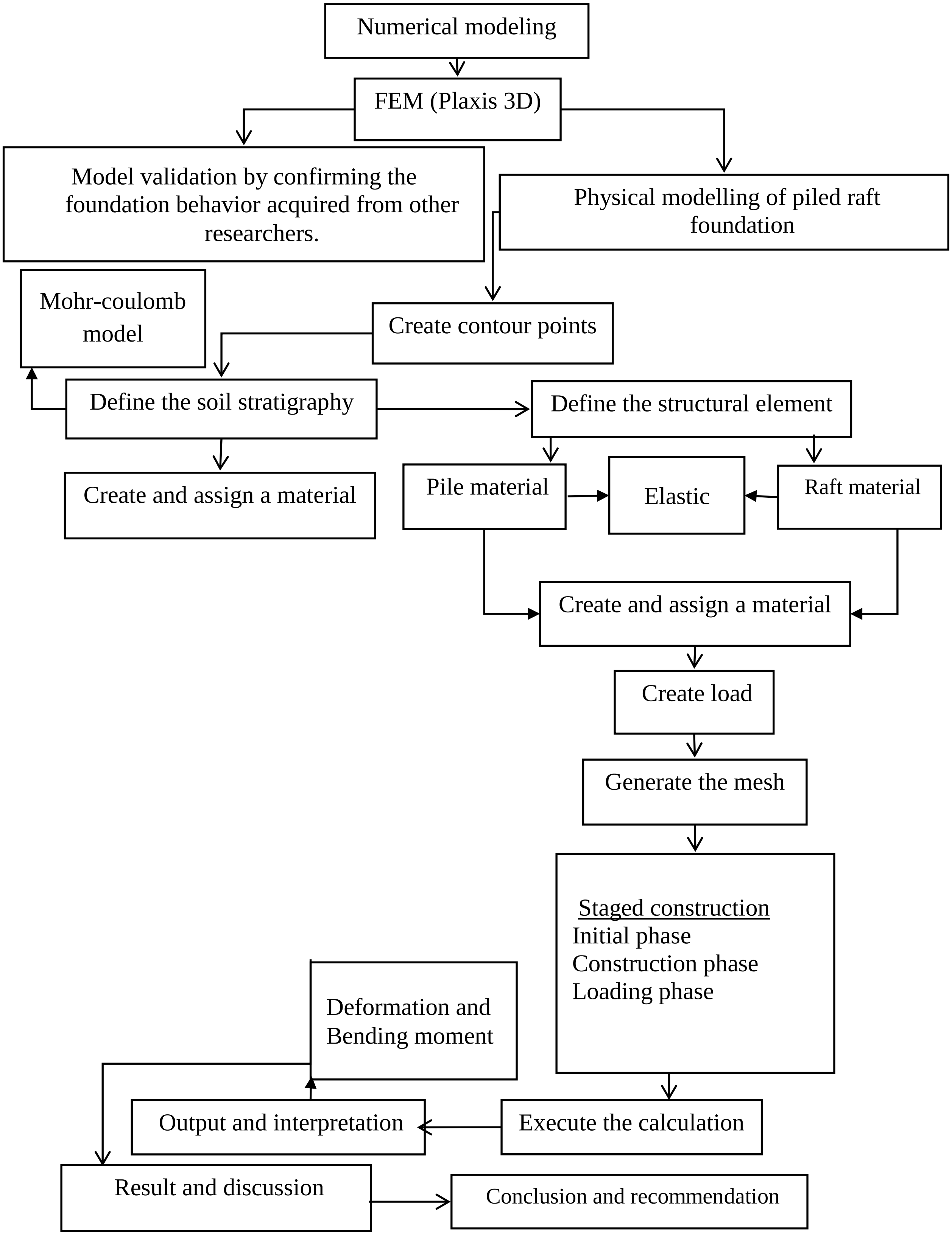


Figure 3.2: Design methodology (procedure)

3.3. Sampling Technique

Purposive sampling approaches, which are non-probabilistic methods, were used in this study's sample procedure. Samples that were easily available and capable of meeting the study's goals were chosen by the researchers. Purposive sampling was also employed to select items that reflected the research questions and study region. This selection strategy aimed to ensure that the selected samples were typical of the study's gap and objective, enabling the findings to be applied to comparable situations. By selecting participants according to these criteria, the study aimed to gain a comprehensive understanding of the research issue and offer relevant suggestions for the local building industry in Addis Ababa, Ethiopia.

3.4. Data Collection

In this research, the data collection method utilized both primary and secondary data sources. A load of a 12-story building, designed using ETABS 20 software, was used as primary data. Secondary data consisted of a comprehensive review and analysis of resources such as publications, literature, journals, books, and case studies focused on pile raft foundation analysis and design. Furthermore, a desk study of data from design offices was conducted to gather relevant information on the subject. Utilizing secondary data sources offers a cost-effective and time-efficient approach to obtaining information on the research topic while ensuring that the study's objectives are met.

3.5. Analysis Method

In this work, the potent finite element-based program PLAXIS 3D CONNECT Edition V20 was used to do a thorough analysis and parametric research of stacked raft foundations. The stacked raft system's components were chosen based on a number of criteria; some were maintained constant, while others were changed according to how they affected the system's response. The parameters that were varied included raft thickness, pile diameter, pile spacing, pile length, and pile number. The material properties of both soil and structural elements were kept constant throughout the study.

The aim of this research is to examine the impact of pile group layout on the settlement features of a piled raft. Various factors contribute to the pile group layout, such as the piles' diameter, their embedded depths, the numbers and configuration of piles, as well as spacing of piles. In a structure with a given architectural plan and subjected to specified loading, altering one or more of these factors results in corresponding changes in the total and differential settlements. These settlements often serve as the governing factors for the type of structure considered in this study. Data analysis was conducted using suitable statistical tools on the data collected from the Plaxis software, and the findings were displayed in tables and graphs.

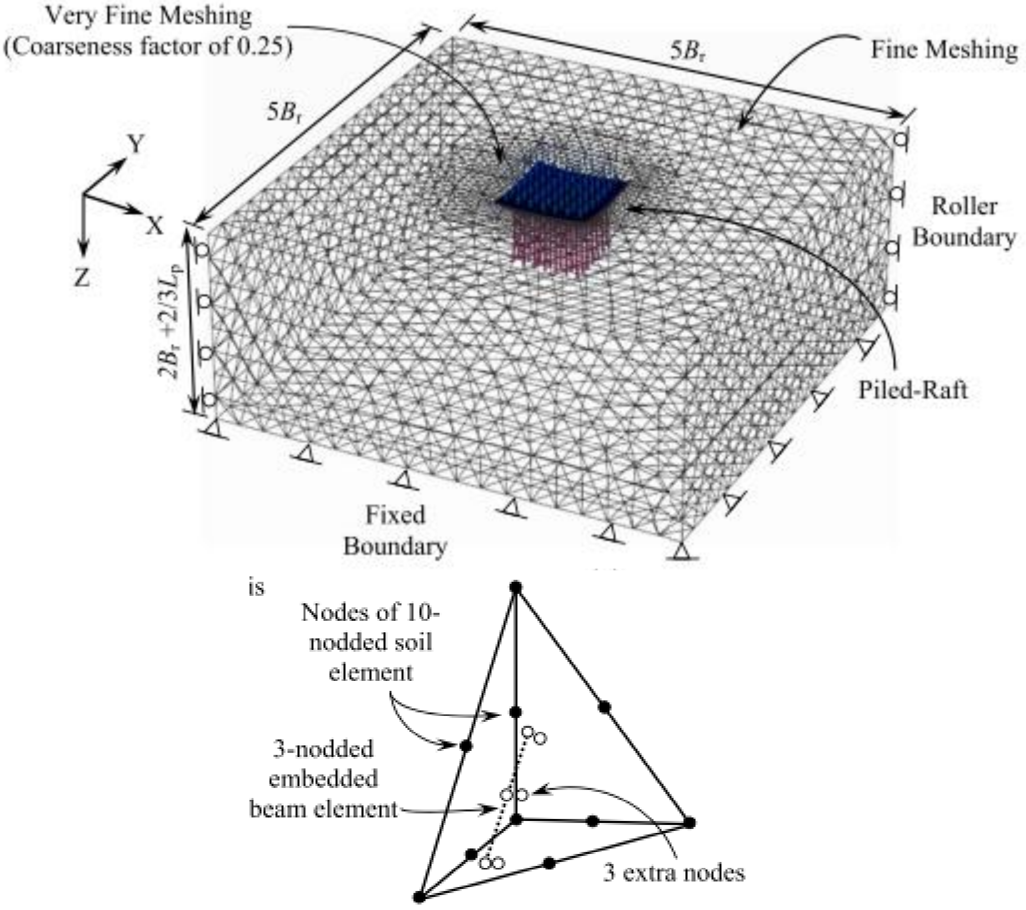
3.6. Development of Finite Element Numerical Model in PLAXIS 3D

3.6.1. Finite Element Mesh and Boundary Conditions

The model is composed of a soil continuum with undisturbed boundary conditions, a rectangular raft foundation geometry with a 1.5 length-to-width ratio (Lr/Br = 1.5), an interface component, and a uniformly distributed load (UDL) of 360 kPa. For this research case, the foundation has a width of 10 m (Br) and a length of 15 m (Lr). Figure 3.3 shows the typical finite element mesh used in the present study. According to the design office report, water was not encountered in all boreholes while drilling the subsurface. Consequently, the water table was not considered, and a drained analysis was employed for this study.

At the raft's edge, the model's lateral soil domain boundaries were set at a distance equal to twice the raft's width and were limited against horizontal movement (i.e., horizontal displacement) while allowing vertical movement (i.e., vertical displacement) of the soil. In a raft foundation, the pressure bulb was created with a size up to double the raft's width, whereas in a pile group, it was formed at two-thirds of the pile length. Consequently, the bottom soil boundary had a vertical distance equal to twice the raft's width plus two-thirds of the pile length, and it was limited in both horizontal and vertical movements.

The examination of a piled raft consisted of three phases, including the initial phase, the construction phase, and the loading phase. During the initial phase, which involves setting up the initial geometry configurations and the corresponding stress field, the soil domain was activated. In the construction phase, the piled-raft geometry was activated, while in the loading phase, the applied load was activated and executed. Preliminary analysis of the unpiled raft under the imposed load revealed that the chosen lateral boundaries of the soil domain were adequate, as the observed area of plastic strain developed in the soil was equal to the raft's width (Br) laterally from the raft's edge.



(b)

Figure 3.3 (a) Boundary and typical finite element mesh used in the parametric study, and (b) 10-node tetrahedral element with 3-node embedded beam element (Mali & Singh, 2018)

3.6.2. Constitutive Modeling

The Mohr-Coulomb model, widely used in the modeling of geotechnical works, has the advantage of needing few input parameters, and all these parameters can be obtained from the standard soil tests. The soil was represented using 10-node tetrahedral elements and the elastic-perfectly plastic Mohr-Coulomb model (Figure (3.3b)). The required parameters for this modeling included cohesion, internal friction angle, Young's modulus, and Poisson's ratio. According to the Mohr-Coulomb failure criteria, yielding or failure occurs in the soil mass when the mobilized shear stress on any plane reaches the soil's shear strength.

In order to make the analysis process more straightforward, constant material parameter values were utilized across the soil domain. The raft was designed using triangular plate elements. Upon meshing, these plates consist of 6-node triangular plate elements, each having six degrees of freedom (including three translational and three rotational).

The piles were modeled as embedded beam elements. These embedded beams are composed of beam components combined with unique interface elements that facilitate interaction with the surrounding soil. Essentially, the piles are considered bored piles. Once meshed, these beam elements transform into 3-node line elements with six degrees of freedom for each node, including three translational and three rotational movements.

The raft and piles maintain an elastic state due to their modulus of elasticity being higher than the soil's, leading to the raft and piles material being considered linearly elastic. A rigid connection connects the piles and raft. In this analysis, the interface element is represented by the interface reduction factor (R_{inter}), which signifies the interface element's strength as a percentage of the adjacent soil's shear strength. The pile-soil interface technique used is illustrated in Figure 3.4. Figure 3.4(a) and (b) respectively illustrate the "no slip" and "slip" conditions between the soil and pile elements.

The raft-soil interface was regarded as a smooth contact with a R_{inter} of 0.8. According to the Plaxis 3D manual, interface suggestions for the reduction factor for the interaction of sand and concrete range between 0.8-1, and the interaction of clay and concrete, ranges between 0.7-1. The soil-pile interaction was modeled using embedded interface elements of 3-node line elements with node pairs instead of single nodes. One node in each pair is part of the beam element, while the other is a point in the 10-node wedge element belonging to the soil element. The primary reason for introducing interface elements is to simulate displacement discontinuity between the structural elements (raft and piles) and the soil mass.

In the finite element formulation, the coordinates of each pair of nodes are identical, signifying that the interface element has zero thickness (h = 0) (Figure 3.4(a)). The Mohr-Coulomb failure criterion is followed by interface elements, and when the soil's shear stress (τ) is equal to its yield shear strength ($\sigma_h \tan\varphi + c_u$), slippage occurs at the interface (Figure 3.4(b)). Elastic shear behavior exists until the shear stress reaches a critical value (γ_{crit}), after which the shear displacement increases without an accompanying rise in shear stress (Figure 3.4(c)). The primary purpose of introducing interface elements is to simulate displacement discontinuity between structural elements (piles) and the soil mass.

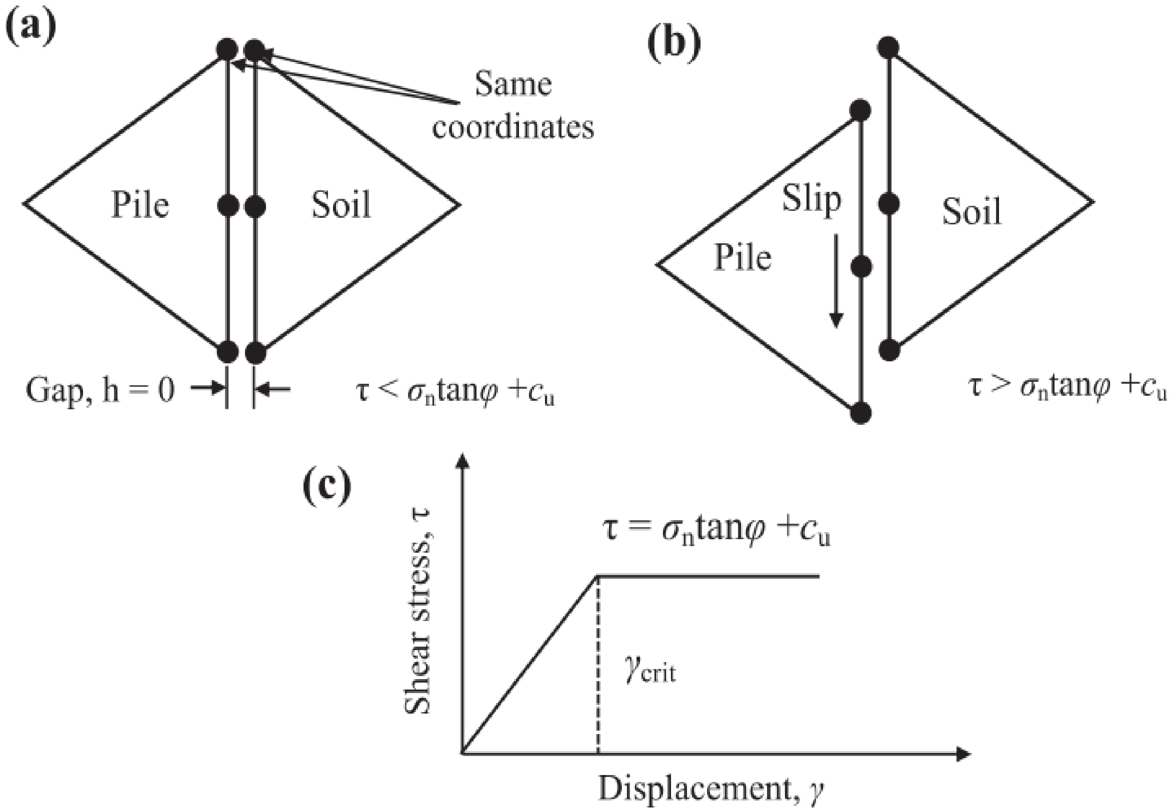


Figure 3.4: Pile-soil interface modeling technique (a) no slip, (b) slip, and (c) Coulomb frictional law (Jeong et al., 2004 ; Kézdi, Á., & Réthái, L. 1974).

3.6.3. Input Parameter for Numerical Analysis

The Soil Mass

The analysis examined the predominant characteristics of weak soil obtained from various design offices and used these values for the research. The soil was modeled as a Mohr-Coulomb Elastoplastic medium to represent material non-linearity. A two-layer subsoil model was established for Addis Ababa's Bole Arabsa V using 280 borehole data, with medium to very stiff high plastic silty clay and medium dense to very dense silty sand soil as the primary type. These boreholes extended 10m and 15m from the ground surface. In their report, subsurface water was not encountered in all boreholes during the course of drilling. As a result, the water table was not considered for this study.

Geotechnical parameters for the layers were sourced from the collected data, and missing information was estimated using empirical equations derived from the Standard Penetration Test (SPT) values of the boreholes. Empirical relationships based on the Standard Penetration Test (SPT) N value are commonly employed because of their simplicity and usefulness in estimating various parameters like cohesion, angle of friction, Poisson’s ratio, shear wave velocity, and bearing capacity. SPT is a widely used method for general soil characterization.

Young’s modulus, cohesion, angle of friction, and Poisson’s ratio of layers were not given in the soil investigation report. Therefore, Young’s modulus of layers has been determined using Table A.1 according to USCS (Kézdi, Á., & Rétháti, L. (1974); Obrzud, R., & Truty, A. 2012). Cohesion, angle of friction, and Poisson’s ratio were determined using a correlation equation developed by (R. Kumar et al., 2016).

Raft

The raft was regarded as a flat slab with consistent thickness positioned on the ground's surface. Upon modeling the raft, it was discovered that its occupied volume was significantly smaller compared to the soil mass. Consequently, smaller-sized elements were utilized for meshing the raft. A rectangular raft foundation geometry with a 1.5 length-to-width ratio (Lr/Br = 1.5) was assumed. For this research case, the foundation has a width of 10 m (Br) and a length of 15 m (Lr). The initial Raft thickness was determined using SAFE 20 software, which imported loads from the ETABS output to resist punching forces on the list. Raft thicknesses of 0.7 m, 1.2 m, and 1.7 m were utilized for the analysis. Relevant properties of the raft were gathered from prior journal publications and articles.

Piles

In this study, piles were modeled in a manner similar to the raft. Each building frame's raft was assumed to be supported by a group of piles with circular cross-sections. Small-diameter bored piles were defined as those with a diameter of 600mm or less, whereas large-diameter bored piles had diameters greater than 600mm, as per (Mulatu, 2019). The research began by using a 0.6m diameter for the piles, which was then increased to 0.8m and 1m. According to (Mulatu, 2019), for bored cast-in-situ piles, the spacing shall be at least 3 times the diameter of the pile but not less than 1.10m. Therefore, the study started by using 3D spacing on the raft's shorter side, which later grew to 4D and 5D. At the same time, a distance of 1.5 times the shorter side spacing was used for the spacing on the raft's longer side.

The pile length was an additional parameter used to examine the settlement of the structure. Since this research focuses on settlement, a large piled raft with $B_r > L_p$ was selected, chosen for an L_p of 15m, and reduced to 12 m and 9 m. Another factor taken into account in the analysis is the number of piles. Pile numbers 4, 9, and 16 were utilized, representing uniformly arranged piles in configurations of 2 x 2, 3 x 3, and 4 x 4, respectively.

Load

It is assumed that the total load exerted on the structural system is evenly distributed across the raft's entire surface area. This kind of load transmission is expected in a relatively flexible raft. When the load is applied, the flexible raft may experience differential settlements (Roshan et al., n.d.). Due to this, the stress distribution due to uniform load will be non-uniform. For this research, the load was obtained from ETABS output for a 12-story apartment used for residential purposes. This is relevant because the Ethiopian Building Code Standard offers guidelines and regulations for building construction and safety, but it does not specify a minimum number of stories for high-rise buildings. A building is generally considered a high-rise if its height exceeds 36 meters or 12 floors, while a skyscraper must reach a height of at least 150 meters (Farouk 2011, n.d; Mosie, n.d.2022). The ETABS output provides point load data, which has been converted to uniform areal load to align with the initial assumption of uniform vertical load. Thus, the assumption that loads are uniformly distributed may not give accurate behavior as per actual conditions, but it can be acceptable for all practical purposes.

3.6.4. Mesh Sensitivity Analysis

The finite element model's results are influenced by the number of elements. To examine this effect on the proposed piled raft foundation, five distinct finite element meshes were tested using a biased mesh system with varying element numbers and sizes, while keeping other parameters constant. Table 3.1 and Figure 3.5 show the generated elements and maximum central settlement.

Table 3.1: Effect of the number of elements on maximum settlement

Trial No.	Mesh coarseness	Number of elements	Maximum central settlement (m)
1	Very coarse	1685	0.1500
2	Coarse	3012	0.1525
3	Medium	7941	0.1600
4	Fine	19765	0.1499
5	Very fine	50426	0.1525

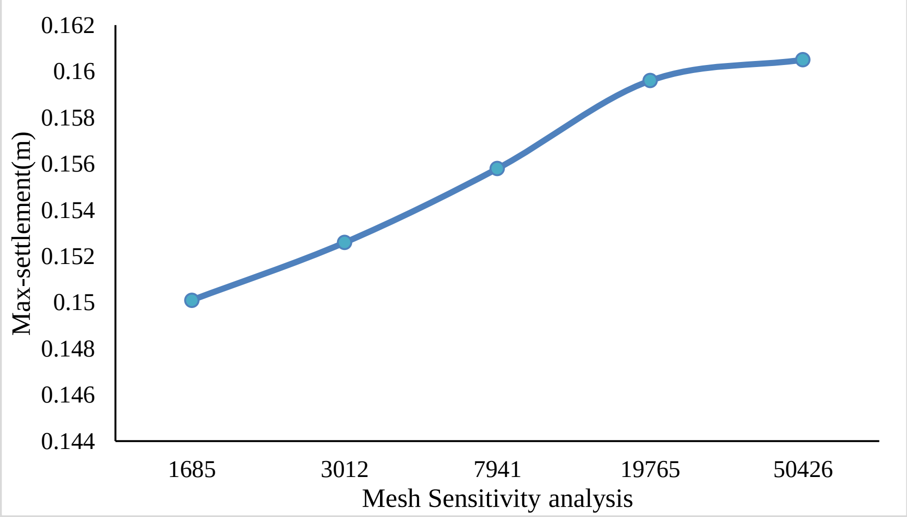


Figure 3.5: Effect of mesh coarseness on maximum central settlement

Figure 3.5 demonstrates that the maximum central settlement rises as the number of elements increases until reaching 19,765 elements. Beyond this point, the increase in the number of elements has a negligible impact on the maximum central settlement. Thus, the fourth trial model was chosen for further analysis. A global fine mesh was utilized for the entire soil domain, while a considerably finer mesh was chosen near the structural components. The extremely fine mesh was created with a 0.25 coarseness factor, which indicates that the element size in this very fine mesh is 0.25 times smaller than the element in the fine mesh.

3.7. Model Validation

In this research, the validity of the modeling approach was tested by comparing the numerical findings to existing literature, specific studies by (Ferchat et al., 2021; (Teji & Ashango, 2023). The case study centered on a piled raft system with a square raft measuring 24 x 24 m and a 2 m thickness. This raft, fully embedded in soft clay, rests on 16 circular piles that are 1.0 m in diameter and 15 m long. These piles are evenly placed beneath the raft, having a spacing (Sp) of six times their diameter (D). The foundation surface was subjected to a uniformly distributed vertical load to simulate loading. Table 3.1 provides an overview of the soil and foundation parameters used in the numerical model. Figure 3.5 shows a comparison between the load-settlement behavior of the piled raft from the current finite difference analysis and the finite element analyses of (Ferchat et al. (2021), Mali & Singh (2018), and Sinha & Hanna (2017)). The present numerical study's results are in good agreement with previous numerical research.

Table 3.2: Material parameters used in the analyses (Sinha & Hanna, 2017)

Parameter	Clay	Pile	Raft
Young’s modulus, E (MPa)	54	25,000	34,000
Poisson’s ration, ν	0.15	0.2	0.2
Unit weight, γ (kN/m^3)	19	25	25
Friction angle, φ’ (°)	20	-	-
Cohesion, c’ (kPa)	20	-	-

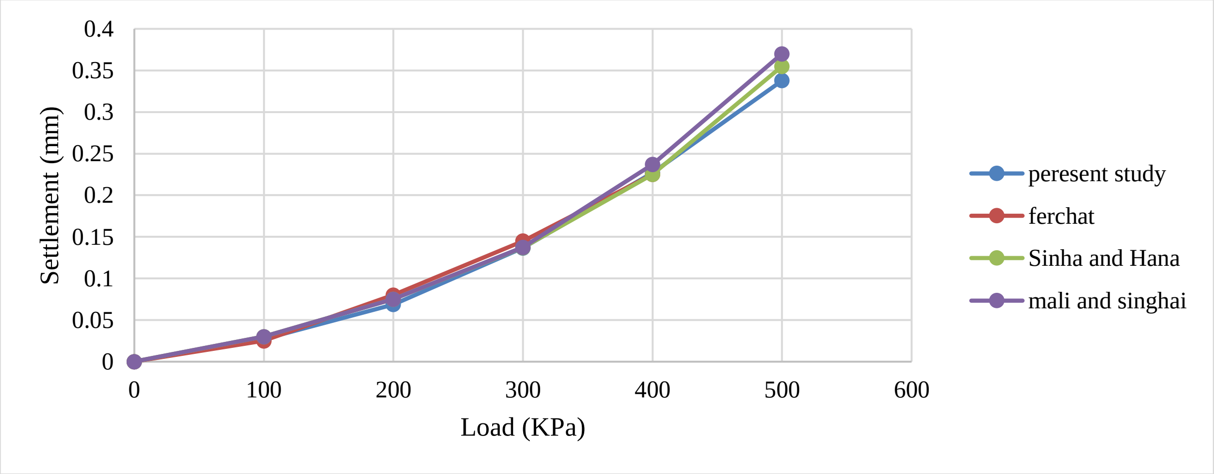


Figure 3.6: Comparison of the current study's results and previous numerical studies on load-settlement behavior of piled raft

CHAPTER 4

4. RESULTS AND DISCUSSION

4.1. General

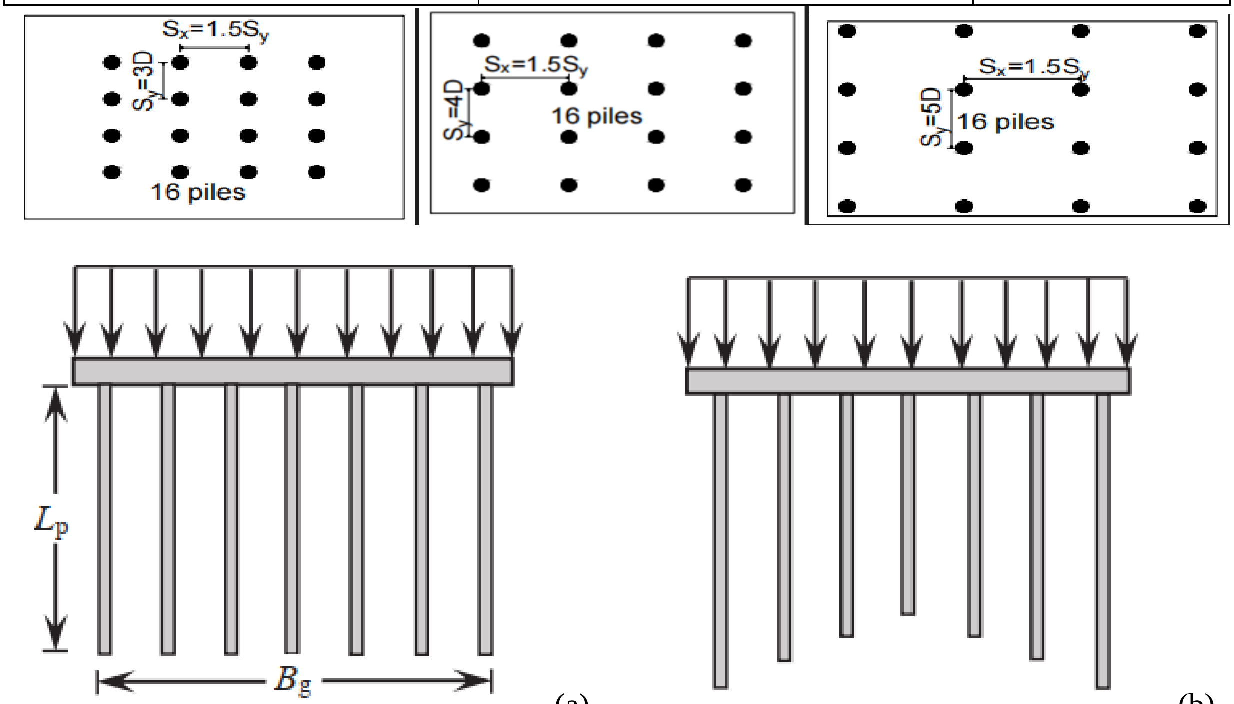
The performance of a piled raft (PR) foundation system under uniform vertical load under various piled raft configurations in a layered soil profile was investigated in detail using parametric analysis, taking into consideration the three-dimensional (3-D) interactions between the soil, piles, and raft. In a rectangular raft, the study took into account factors such raft thickness, pile length, pile diameter and pile spacing. Several foundation types, such as piled raft (PR) with different piled raft configurations including uniform piled raft configurations, non-uniform piled raft configurations and un-piled raft (UR), were considered in order to assess the interaction impacts of the piled raft for drained soil conditions. In order to minimize the storage and time required for numerical computations, smaller foundation dimensions were considered in this study, along with the general dimensions commonly used by most researchers and standards. Figure 4.1 shows an example of piled rafts considered in the present parametric study for different lengths of piles and pile spacing. Table 4.1 and Table 4.2 summarize the foundation and soil parameters, as well as the geometric configurations of the piled-raft model used in the parametric analysis, respectively.

Table 4.1: Material properties used in the parametric analysis

Parameters	Soil Property		Concrete Property	
	Soil 1	Soil 2	Pile	Raft
FE Model	Elasto-Plastic	Elasto-Plastic	Elastic	Elastic
Young's Modulus, E (MPa)	20	25	25000	25000
Poisson's Ratio, ν	0.275	0.35	0.25	0.25
Angle of internal friction, Ø' (°)	9.3	35.7	-	-
Unit weight, γ, kN/m3	17	18	25	25
Cohesion, c' (kPa)	75.6	48	-	-

Table 4.2: Geometric configurations of piled-raft model for parametric analysis

Parameters	Unit	Value
Raft width, B_r	m	10
Raft length, L_r	m	15
Raft thickness, t_r	m	0.7, 1.2, 1.7
Number of piles		16
Pile length, L_p	m	9, 12, 15
Pile spacing, Sy_p		3D, 4D, 5D
Pile diameter, D_p	m	0.6, 0.8, 1



(a) (b)

Figure 4.1: Some Examples of piled rafts with different PRC considered for parametric analysis; (a) uniform piled raft configurations and (b) non-uniform piled raft configurations

4.2. General Behavior of Un-Piled Raft

An un-piled raft is a type of foundation system that distributes building loads over a large area of soil without the use of deep piles. Instead of relying on deep foundations, un-piled rafts utilize a thick, reinforced concrete slab, which distributes the load of structure uniformly over the ground. This design is particularly better in soft or unstable soil conditions where traditional foundations might not be effective. By minimizing differential settlement and providing stability, un-piled rafts are commonly used in residential and commercial building where soil conditions may not support standard foundation types. Their construction generally involves consideration of soil-bearing capacity, hydrostatic pressure, and sufficient thickness to ensure structural integrity.

At the site, a rectangular raft measuring 10 by 15 meters is located on a stratified soil profile. The top layer of medium to extremely stiff high-plastic silty clay, which is 5 meters deep, is followed by a layer of medium-dense to very-dense silty sand that extends downhill. Raft thickness is an important factor to take into account when building a foundation system, particularly for un-piled raft foundations. The raft's stiffness or flexibility affects how a piled raft behaves. The flexibility and stiffness of the raft have been evaluated in the current study using Viggiani's (2001) raft-to-soil stiffness ratio. This ratio is presented in Equation (4.1).

$$\boldsymbol{K_{rs}} = \frac{\boldsymbol{4 * E_r * (1 - \nu_s{}^2)}}{\boldsymbol{3 * E_s * (1 - \nu_r{}^2)}} * \frac{\boldsymbol{t_r{}^3}}{\boldsymbol{B_r{}^3}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{(4-1)}$$

where Er is Young's modulus of the raft; vs is the Poisson's ratio of soil; Es is Young's modulus of soil, vr is the Poisson's ratio of the raft; Br is the width of the raft, and tr is the thickness of raft.

Therefore, it is evident from Equation 4.1 that the ratio of raft-to-soil stiffness increases with raft thickness. Furthermore, according to Viggiani (2001), a Krs value more than or equal to 1 indicates perfect stiffness, a Krs value between 0.001 and 1 indicates intermediate flexibility, and a Krs value of 0.001 indicates perfect flexibility. The Krs values for raft thicknesses of 0.7, 1.2, and 1.7 meters in this investigation are, respectively, 0.1311, 0.66, and 1.878. In comparison to the other thicknesses, the raft with a 0.7 m thickness is comparatively more flexible. A similar pattern was observed in the study by Mali & Singh (2018), although because of the broader raft width, the Krs values were lower than in the current investigation.

In this work, the behavior of a rectangular un-piled raft foundation with raft thicknesses of 0.7, 1.2, and 1.7 meters under a uniformly distributed vertical load of 360 KPa was investigated. Though an increase in raft thickness also led to a decrease in differential settlement because the increased raft rigidity allowed the load to be distributed more evenly on the soil, Figure 4.2 shows that the maximum settlement increased as the raft thickness increased because the increased self-weight added more load to the soil. The thickness of the raft needs to be carefully evaluated in order to guarantee a balance between maximum settlement and differential settlement as well as the overall stability of the foundation system. This is due to the fact that a thicker raft can more effectively support vertical loads and lessen the possibility of differential settlement, both of which are essential for the structure's stability and safety (Mali & Singh, 2020).

Table 4.3: Raft thickness vs raft settlement of different PRCs

Raft thickness (m)	Max-settlement (mm)	Diff-settlement (mm)
0.7	159.6	23
1.2	167.1	6.6
1.7	173.4	3.1

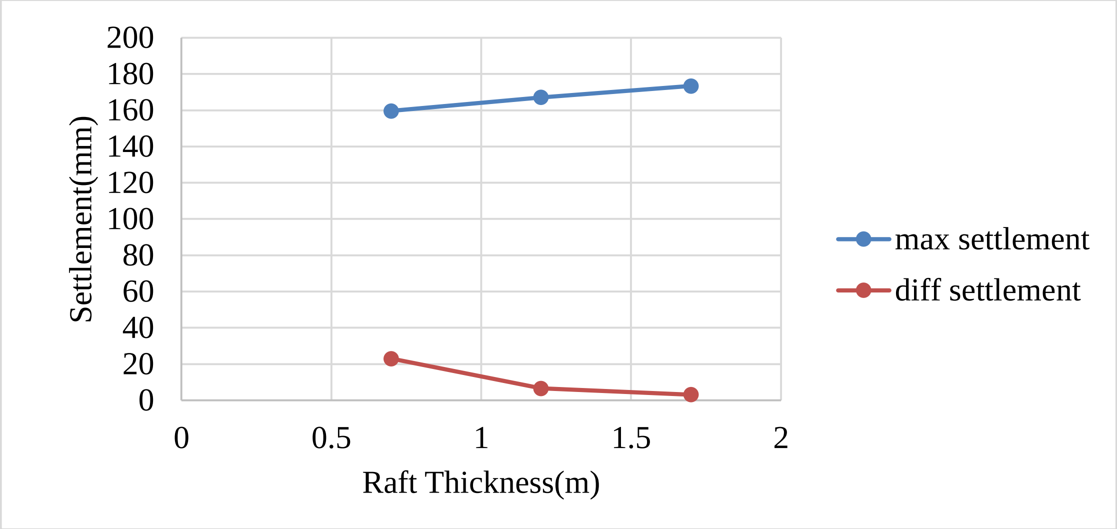


Figure 4.2: Raft thickness vs raft settlement of un-piled raft

The graph shows how raft thickness affects a raft foundation's maximum and differential settlement. Maximum settlement is increased from 159.6 mm to about 167.1 mm as the raft thickness grows from 0.7 m to 1.2 m, yielding a rise of almost 4.70 % in percentage. Comparably, differential settling also exhibits a significant decrease, decreasing by 71.30 % from about 23 mm at 0.7 m thickness to around 6.6 mm at 1.2 m thickness. According to this analysis, raft thickness can effectively decrease differential settlements, improving the un-piled raft foundation's overall performance and stability. While maximum settlement increases with increase of raft thickness, which is due to increase in self weight of raft.

4.3. Uniform and Non-Uniform Pile Lengths

In piled raft foundations, uniform piles are constructed to same length, offering simplicity and predictability making them easier and often more cost effective to design; however, they may not effectively address varying soil conditions potentially leading to differential settlement of overstressed areas. In this study the length of each piles considered is 9 m, where total pile length for uniform piled raft configurations is (9x16) equals to 144 m.

A non-uniform length piled-raft is a type of foundation design that uses both piles and raft slab to support structures, particularly in challenging soil conditions or on sites with variable loads. Unlike traditional uniform piled rafts, which uses piles of uniform length, a non-uniform configuration allows for varying pile lengths to address site specific conditions, such as soil bearing capacities, differential settlement, and varying load distributions. The PRCs were altered in such way that the total length of piles Lt in each PRC became 144 m.

Table 4.4: Pile lengths used for different piled-raft configurations (Alnuaim et al., 2013)

Type of pile	Pile length (m)	
	Uniform piled - raft configurations	Non-uniform piled - raft configurations
P_{1}- P_{12} (12 piles) - outer piles	9	$L_{(1-12)} = 1.1\ L_{(13-16)} = 9.3$
P_{13}-P_{16} (4 piles) - central piles		$L_{(13-16)} = L_{(1-12)} / 1.1 = 8.2$

In this study, for non-uniform piled raft configurations, piles are classified into two categories based on their lengths. Externally placed piles and centrally placed pile groups. Generally, external piles are longer than central piles, Table 4.4 shows external piles are 1.1 times of central pile group (Alnuaim et al., 2013).

The number of piles categorized under external pile group are 12 piles, while the number of piles categorized as central piles are just 4 piles. Therefore, total number of piles are 16 piles used for this study of different piled raft configurations. As far as the practical application of such PRC is concerned, in the foundation of Messe Turm Tower (Frankfurt), raft of non-uniform thickness and non-uniform pile length (length was more at center and decreasing towards the edges of raft) had been used successfully (Poulos 2001).

4.3.1. General Behavior of Piled Rafts

Understanding the load-settlement relationship, which is essential for predicting the behavior of any foundation system, was the aim of this study. In order to test the response of a rectangular un-piled raft with a thickness of 0.7 meters under various uniformly distributed load intensities, sixteen (16) piles with diameters of 0.8 meters, spacing of 3D meters, and lengths of 9 meters were positioned on the un-piled raft foundation for a piled raft configuration of both uniform piled raft configurations and non-uniform piled raft configurations.

Table 4.5: The settlement of the piled and un-piled raft foundations with respect to load

Load (kN/M^2)	Maximum settlement (mm)		
	Un-piled raft	Uniform Piled-raft	Non-Uniform Piled-raft
360	159.6	103.1	101.20
540	281.7	162.8	170.10
720	454.2	236	259.40
900	850.2	321.3	361.20

Specifically, the raft was subjected to loads of 360 kPa, 540 kPa, 720 kPa, and 900 kPa. The uniform piled raft had maximum settlements of 103.1 mm, 162.8 mm, 236 mm, and 321.3 mm. And that of the non-uniform piled raft had maximum settlements of 101.20 mm, 170.10 mm, 259.40 mm, and 361.20 mm, while the un-piled raft had maximum settlements of 159.6 mm, 281.7 mm, 454.2 mm, and 850.2 mm Table 4.5. When the load was increased by 50% from the initial 360 kPa to 540 kPa, the settlement increased by 78.38% (un-piled) and 57.9% (uniform piled), and that of the non-uniform piled raft is increased from 101.20mm to 170.10mm which is about 68.08 %. The settlement increased by 184.58% (un-piled) and 128.9 % (uniform piled) and 156.3% (non-uniform piled raft configurations) when the load was doubled to 720 kPa. Ultimately, when the load increased to 900 kPa, 2.5 times the original value of 360 kPa, the settlement increased 432.7% (un-piled), 211.64% (uniform piled) and 256.9% (non-uniform piled raft configurations).

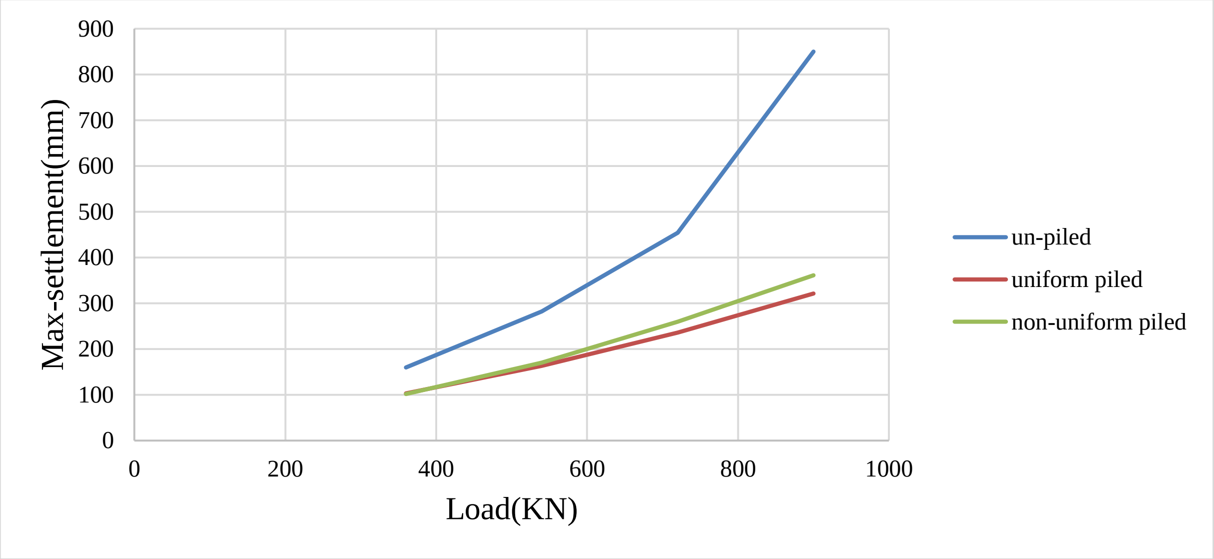


Figure 4.3: The settlement of the un-piled raft configurations, uniform and non-uniform piled raft configurations with respect to load

This observation demonstrates a pattern of increased settling with increasing applied loads, as demonstrated in Figure 4.3. Finally, the settlement increased 432.70% (un-piled), 211.64% (uniform piled) and 256.9% (non-uniform piled) when the load increased to 900 kPa, which was 2.5 times the initial value of 360 kPa. As seen in Figure 4.3, this observation shows a pattern of greater settling with higher applied loads for all types of piled raft configurations.

When a load is placed on the soil surface, the soil particles compress, resulting in this increased settlement of the raft. The soil particles are pushed closer together as the vertical pressure increases, reducing the overall volume of the soil beneath the raft and resulting in slow settlement. As a result, the soil undergoes more compression as the applied load on the raft rises, ultimately resulting in a faster rate of settling of piled raft foundations.

4.3.2. Effect of Pile Spacing

The objective of the investigation was to analyze how the spacing of piles affects the performance of piled rafts with different piled raft configurations i.e., uniform and non-uniform piled raft configurations. The models employed three different pile spacing along the shorter side of the rectangular raft, specifically 3D, 4D and 5D, while the longer side had a spacing of 1.5 times that of the shorter side. The piles were 9 meters long, with a diameter of 0.6 meters and a raft thickness of 0.7 meters, and were subjected to an applied loading of 360 KPa. The effect of pile spacing was examined for configurations comprising 16 piles. A comprehensive analysis of the maximum settlement, differential settlement, and maximum bending moment of piled rafts with varying pile spacing was conducted by modifying these parameters for different piled raft configurations, and comparing performance of them.

Effects of Pile Spacing on the Maximum Settlement of Different PRCs

It is evident that for any number of piles, the maximum settlement decreases as the pile spacing increases for both uniform and non-uniform PRCs up until it reaches 4D then it started decreasing, as demonstrated in Figure 4.4. It should be noted that as the pile spacing increases (with a constant number of piles), the width of the pile group (Bg) also increases and reaches optimum foundation performance beyond which the increase in pile spacing increases the maximum settlement, resulting in an expanded area covered by the piles (Ag).

When pile spacing increases the area covered by the piles(Ag) also increases, that means piles are evenly distributed under the raft area (Ar) so that this has great impact on the reduction of maximum settlement until 4D. However, when pile spacing is increased more than 4D, the increase in area of pile group (Bg) has increased the maximum settlement.

Table 4.6: Comparison of maximum settlements for different pile spacing

Pile spacing (Sy)	Maximum settlement (mm)	
	Uniform PRCs	Non-uniform PRCs
3D	110	99.35
4D	105.3	95.66
5D	106.7	102.20

Based on Table 4.6, the maximum settlement was reduced for 3D to 4D pile spacing by 3.91% and 3.71% for uniform and non – uniform piled raft configurations, respectively. On the other hand, when the pile spacing increases from 4D to 5D, the maximum settlement increases by 1.33% for uniform piled raft configurations and 6.84% for non-uniform piled raft configurations. Out of these, the non-uniform piled raft configuration has better settlement reduction rate compared to uniform piled raft configurations when the spacing of the pile increases until the spacing reaches 4D.

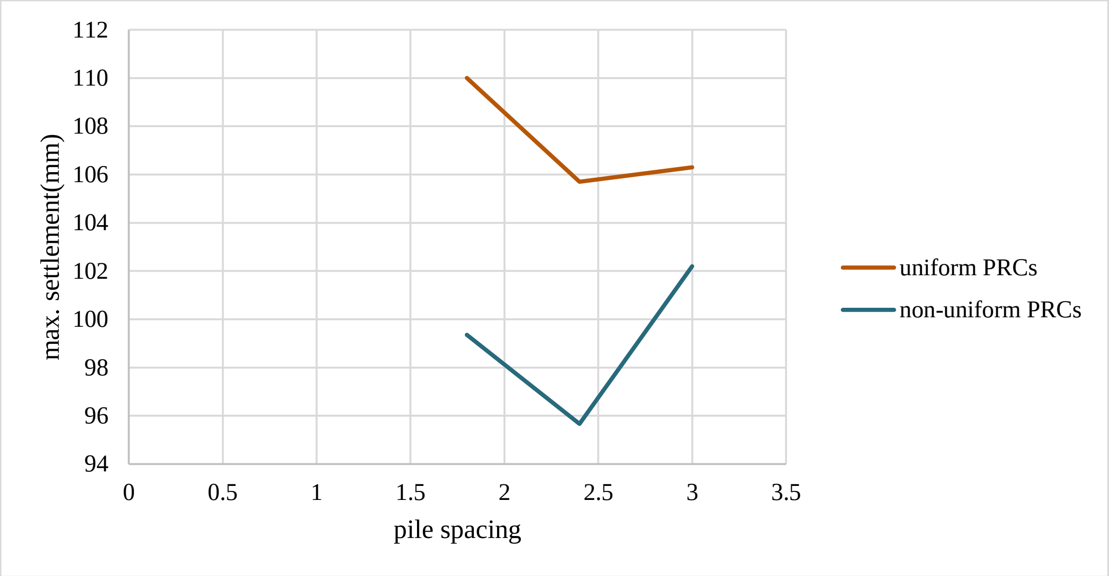


Figure 4.4: Effect of pile spacing on maximum settlement for different pile numbers

The relationship between maximum settlement and pile spacing for both uniform and non-uniform piled raft configurations is depicted in Figure 4.4. The maximum settlement for uniform piled raft configurations first falls with increasing pile spacing, reaching a minimum at about 4D before slightly increasing once more. This implies that the ideal spacing to reduce settlement exists. On the other hand, the maximum settlement of the non-uniform piled raft configurations decreases more noticeably as pile spacing increases, with a noticeable dip at about 4D before stabilizing. This trend indicates that non-uniform configurations may be more effective in reducing settlement compared to uniform configurations, particularly at certain spacing. Overall, both configurations highlight the importance of pile spacing in optimizing foundation performance, but non-uniform arrangements demonstrate a greater capacity for minimizing maximum settlement.

Pile Spacing Effect on Differential Settlement of Different PRCs

A distinct pattern in the differential settlement behavior as pile separation rises is evident from the experimental results shown in Figure 4.5. Remarkably, the trend runs counter to the maximum settlement trend. It is specifically evident that the differential settling rises with increasing pile spacing for both uniform and non-uniform piled raft layouts. This is explained by the fact that as pile spacing increases, the piles tend to move away from the center of the raft, increasing the pile group area (Ag). Wider spacing can lead to uneven load distribution across the raft, causing some areas to experience more stress than others. This uneven stress can lead to varying levels of settlement.

The soil between widely spaced piles may not effectively carry the load, leading to greater deformation in those areas. This can create a disparity in settlement between the piles and the surrounding soil. Closer pile spacing allows for better interaction between the piles and the raft, distributing loads more uniformly. Increased spacing reduces this interaction, which can lead to higher differential settlement.

Table 4.7: Comparison of differential settlements for different pile spacing of different PRC

Pile spacing (Sx)	Differential-settlement(mm)	
	Uniform pile length	Non-uniform pile length
3D	3.5	3.70
4D	14.84	16.35
5D	31.61	36.15

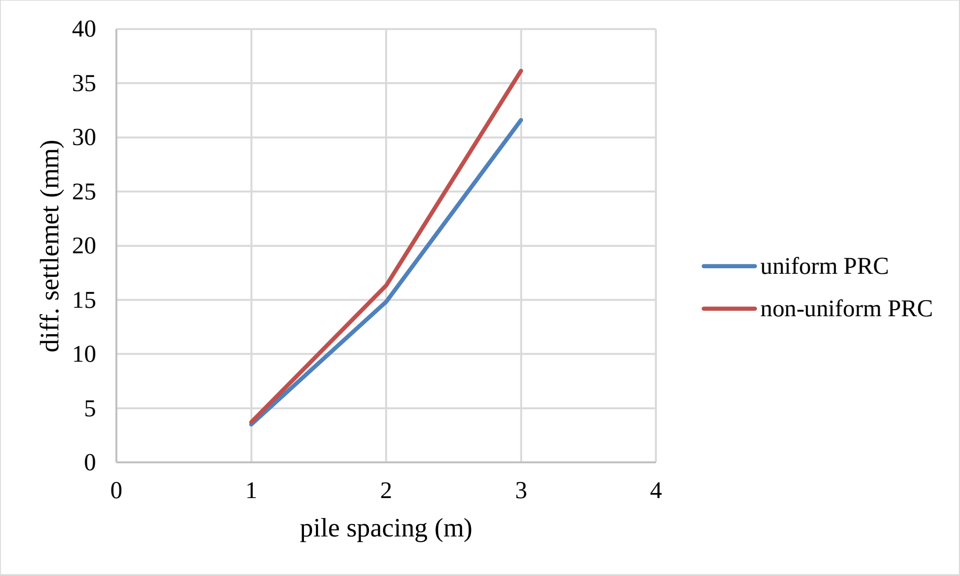


Figure 4.5: Effect of pile spacing on differential settlement for different pile numbers

In general, Figure 4.5 illustrates relationship between pile spacing and differential settlement for both uniform and non-uniform pile reinforcement configurations (PRCs). As the pile spacing increases from 1.8 meter to 3 meters, a clear upward trend in differential settlement is observed for both types of PRCs. The data indicates that differential settlement is greater in non-uniform PRCs compared to uniform PRCs at the same spacing intervals. At a pile spacing of 3 meters, the differential settlement reaches approximately 36mm for non-uniform PRCs, highlighting the impact of pile arrangement on settlement behavior. This suggests that careful consideration of pile spacing and configuration is crucial in minimizing differential settlement in foundation design.

Pile Spacing Effect on Load Sharing Ratio of Different PRCs

Figure 4.6 illustrates how pile spacing affects the load-sharing ratio for various piled raft configurations. For both uniform and non-uniform piled raft configurations, the load-sharing ratio rises as pile spacing increases. Since piles begin to function as distinct elements with larger pile spacing, this could be the reason for the mobilization of higher relative movement between piles and soil as well as maximal load capabilities. In order to maximize the load capacity of the raft and piles, piles should be positioned intelligently.

Table 4.8: Effect of pile spacing on load-sharing ratio for different PRCs

Pile spacing (m)	Load sharing ratio, $\alpha_{(pr)}$	
	Uniform PRC	Non-uniform PRC
3D	0.65	0.267
4D	0.82	0.51
5D	0.92	0.65

Based on Table 4.8, the load sharing ratio was increased for 3D to 4D pile spacing by 26.15% and 91.01% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Similarly, when the pile spacing increases from 4D to 5D, the load sharing ratio has been increased by 12.19% for uniform piled raft configurations and 27.45% for non-uniform piled raft configurations. Out of these, these non-uniform piled raft configuration has better load-sharing ratio increased rate compared to uniform piled-raft configurations when the spacing of the pile increases.

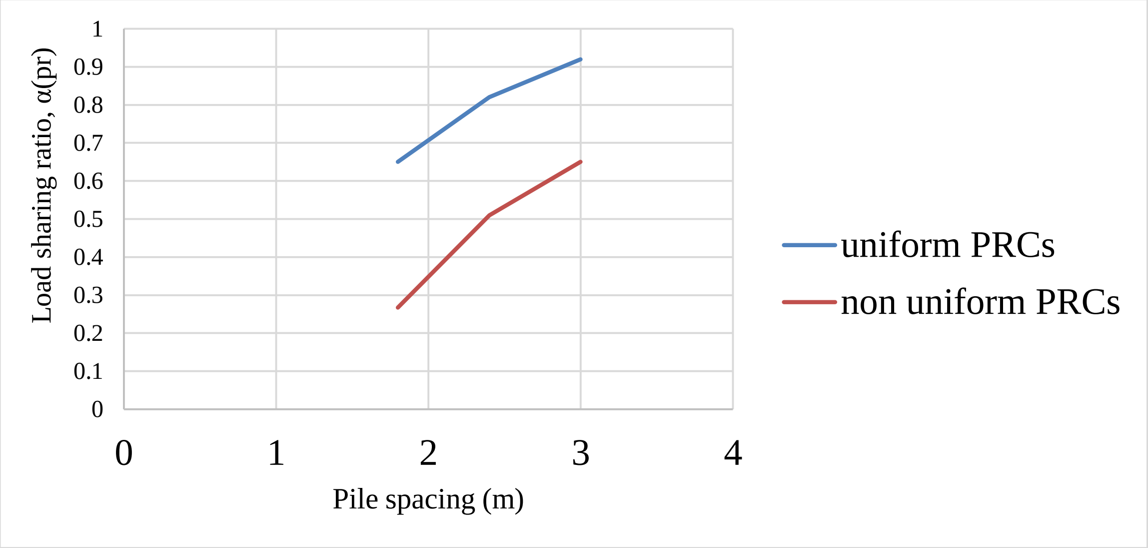


Figure 4.6: Effect of pile spacing on load-sharing ratio for different PRCs

In general, when we see Figure 4.6 the graph presents the relationship between pile spacing and load sharing ratio (α(pr)) for both uniform and non-uniform piled-raft configurations (PRCs). As pile spacing increases from 1.8 to 3 meters, the load sharing ratio shows an upward trend for both configurations, indicating improved load distribution with increased spacing. However, uniform PRCs consistently exhibit a higher load sharing ratio compared to non-uniform PRCs across all spacing intervals. At a spacing of 3 meters, the load sharing ratio for uniform PRCs approaches 0.8, while non-uniform PRCs remain below 0.5. This analysis suggests that uniform pile arrangements are more effective in distributing loads evenly, which is critical for enhancing the stability and performance of foundations. The results highlight how crucial it is to take pile arrangement into account when designing a foundation in order to maximize load sharing.

Effect of Pile Spacing on Maximum Bending Moment of Different PRCs

Table 4.9 illustrates the effect of pile spacing on bending moment of a raft with uniform and non-uniform piled raft configurations. As the pile spacing increases from 3D to 4D then maximum bending moment is also increased, also increases when the pile spacing increases from 4D to 5D. The reason for this is similar to the effect of pile diameter, as it has been discussed under the effect of pile diameter. As pile spacing increases, the grouped pile width also increases, affecting the maximum bending moment value.

Table 4.9: Effect of pile spacing on maximum bending moment for different PRCs

Pile spacing (m)	Maximum Bending Moment (kN.M/M)	
	Uniform PRCs	Non-uniform PRCs
3D	486.1	231.6
4D	620.8	613.2
5D	1256.0	1081.2

Based on table 4.9, the analysis of maximum bending moments for uniform and non-uniform pile raft configurations reveals significant percentage increases between the specified pile spacing. For uniform PRCs, the maximum bending moment increases from 486.1 kN·m/m at 3D to 620.8 kN·m/m at 4D, resulting in a percentage increase of approximately 27.6%. Between 4D and 5D, it further rises to 1256.0kN·m/m, representing a substantial increase of about 102.0%. In contrast, for non-uniform PRCs, the maximum bending moment increases from 231.60kN·m/m at 3D to 613.20kN·m/m at 4D, which is an increase of approximately 164.5%. From 4D to 5D, the moment increases from 613.20kN·m/m to 1081.20kN·m/m, yielding a percentage increase of around 76.30%. These results indicate that while both configurations experience notable increases in bending moments with greater pile spacing, non-uniform PRCs exhibit a more dramatic rise from 3D to 4D compared to uniform PRCs.

The general trend observed in the maximum bending moments for both uniform and non-uniform piled raft configurations indicates that increasing pile spacing consistently results in higher bending moments for both types of configurations. For uniform PRCs, the bending moments rise steadily from 486.10kN·m/m at 3D to 620.80kN·m/m at 4D, and then significantly to 1256.0kN·m/m at 5D, highlighting a pronounced increase, particularly between 4D and 5D. In contrast, non-uniform PRCs show a dramatic increase from 231.6 kN·m/m at 3D to 613.20kN·m/m at 4D, which is notably higher in percentage terms compared to the uniform configuration. However, the increase from 4D to 5D, while still substantial, is less pronounced than the jump observed in the previous interval, rising to 1081.20kN·m/m. Overall, while both configurations experience increases in bending moments with greater pile spacing, non-uniform PRCs demonstrate a more significant initial increase, suggesting different structural behaviors under varying loading conditions.

4.3.3. Effect of Raft Thickness

The study intended to examine the impact of raft thickness on the performance of piled rafts. Three different raft thicknesses, namely 0.7m, 1.2m, 1.7m and 2.0m were used in the models. The piles had a fixed length of 9m, and the pile diameter and spacing were set at 0.8m and 3 times of pile diameter, respectively, under applied loading of 360KPa. The number of piles also kept constant 16. The analysis considered the effect of raft thickness for different piled raft configurations, as well as those with uniform pile lengths. By varying these parameters, a comprehensive evaluation of maximum settlement, differential settlement, load sharing ratio and maximum bending moment of different piled raft configurations with different raft thicknesses was conducted and presented below. The comparison of the effects on the uniform piled raft configurations and non-uniform piled raft configurations has been done.

Effect of Raft Thickness on Settlement of Different PRCs

As the raft thickness grows, it is evident from the data shown in Figure 4.7 that the maximum settling of the raft foundation also increases which is true for both uniform and non-uniform PRCs. This is explained by the fact that as the raft's thickness increased, so did its self-weight. Higher settlement values are the outcome of the increased load transferred to the foundation as a result of the additional weight.

Based on Table 4.10, the maximum settlement was increased for 0.7 to 1.2 of raft thickness by 0.19% and 0.69% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Similarly, when the raft thickness increases from 1.2 to 1.7, maximum settlement has been raised by 2.60% for uniform piled-raft configurations and 0.29% for non-uniform piled-raft configurations. Out of these, these non-uniform piled-raft configuration has lower maximum settlement increased rate slightly compared to uniform piled-raft configurations when the thickness of the raft increases.

Table 4.10: Effects of raft thickness on settlement of different piled raft configurations

Raft thickness(m)	Maximum settlement(mm)	
	Uniform PRCs	Non – uniform PRCs
0.7	103.1	101.0
1.2	103.3	101.7
1.7	106	102.0
2.0	106.8	104.0

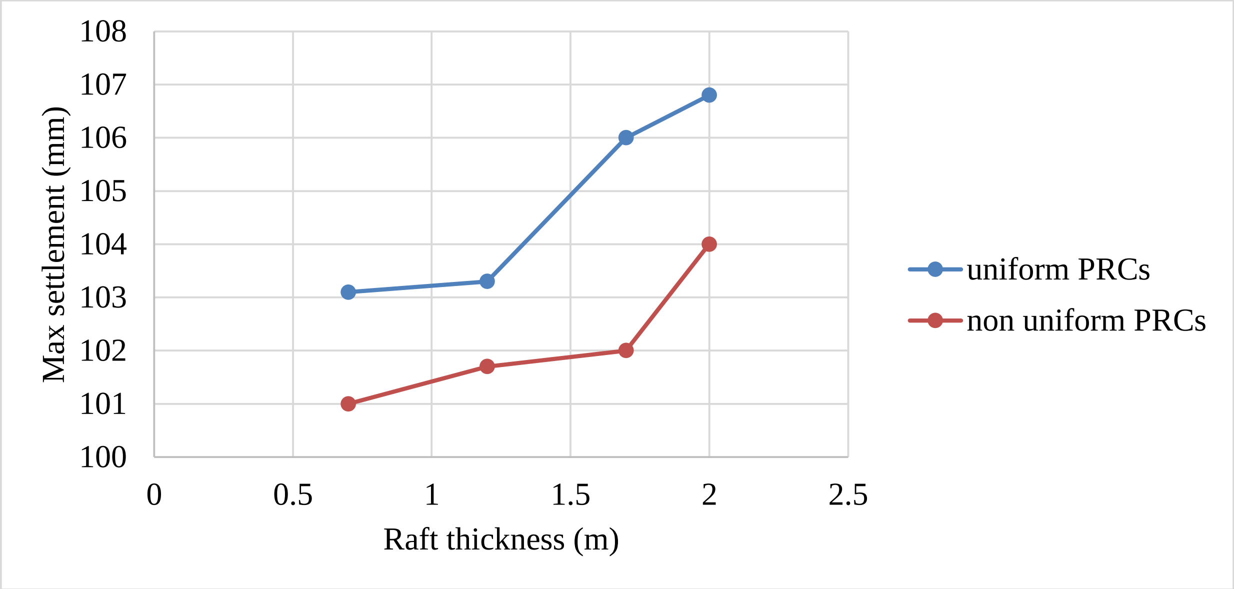


Figure 4.7: Effect of raft thickness on max. settlement of different PRCS

Based on Table 4.11, differential settlement was decreased for 0.7 to 1.2 of raft thickness by 59.92% and 57.26% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Similarly, when the raft thickness increases from 1.2 to 1.7, the differential settlement has been increased by 45.60% for uniform piled-raft configurations and 46.31% for non-uniform piled-raft configurations.

In general, when we see Figure 4.7 the trend of maximum settlement of both piled raft configurations of uniform and non-uniform piled raft, when raft thickness increases, maximum settlement is also increased. It is intended to compare effects of raft thickness on maximum settlement of uniform and non-uniform piled raft configurations, non-uniform length of piled raft configurations performance has lower maximum settlement slightly as compared to uniform piled raft configurations, as it can be depicted from the graph below.

Table 4.11: Effect of raft thickness on differential settlement of different PRCs

Raft thickness (m)	Differential settlement (mm)	
	Uniform PR	Non-uniform PR
0.7	12.85	14.25
1.2	5.15	6.09
1.7	2.8	3.27
2.0	2.6	2.5

In contrast to maximum settlement, differential settlement tends to decrease as raft thickness increases, as shown in Figure 4.8. Because the raft becomes more stiff as its thickness increases, this finding holds true for both uniform piled and non-uniform piled raft designs of foundations. The thicker raft's increased rigidity aids in more uniformly distributing the load to the earth, hence lowering differential settling.

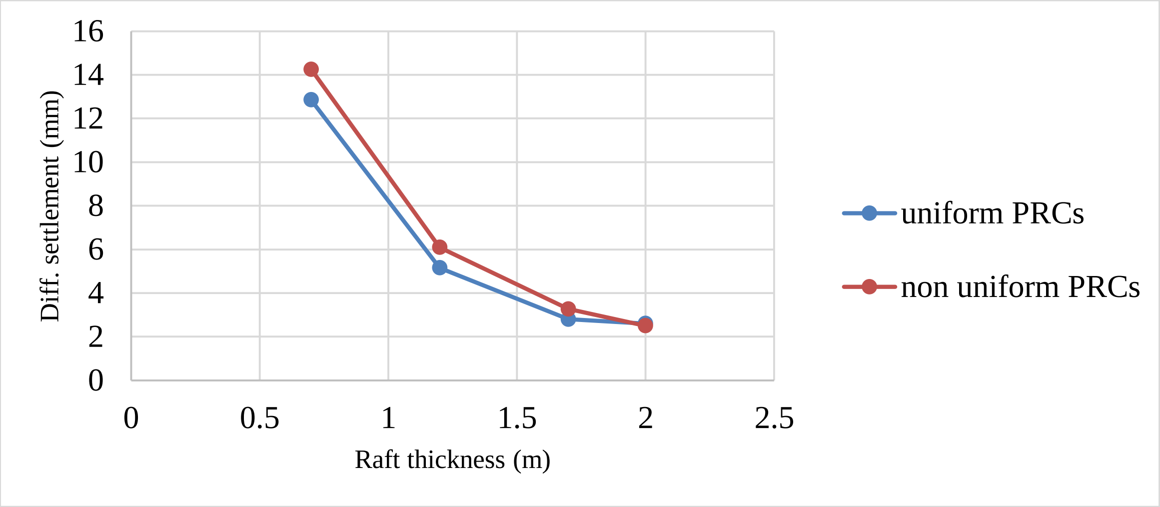


Figure 4.8: Effect of raft thickness on differential settlement of different PRCs

Effect of Raft Thickness on Load Sharing Ratio of Different PRCs

Increasing the thickness of the raft in a foundation system supported by piles generally results in a slightly higher load sharing ratio of the piles as shown in Figure 4.9. This is primarily due to the increased self-weight of the thicker raft, which imposes a greater demand on the piles to carry the load. The additional weight of the raft leads to a more significant transfer of load to the piles, resulting in a higher load sharing ratio in all number of piles.

In general, when we see Figure 4.9 the trend of load sharing ratio of both piled raft configurations of uniform and non-uniform piled raft, when raft thickness increases, the load sharing ratio is increased. It is intended to compare effects of raft thickness on load sharing ratio of uniform and non-uniform piled raft configurations, non-uniform length of piled raft configurations performance has lower load sharing ratio as it can be depicted from the graph below.

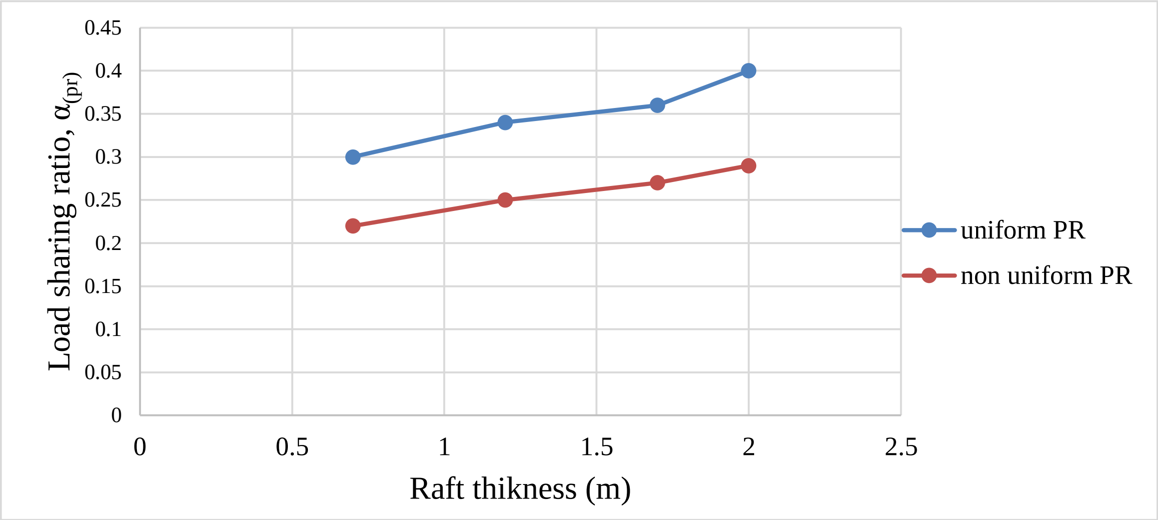


Figure 4.9: Effect of raft thickness on load sharing ratio, α_{pr} of different PRCs

Based on Table 4.12, load sharing ratio was increased for 0.7 to 1.2 of raft thickness by 13.33 % and 13.63 % for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Similarly, when the raft thickness increases from 1.2 to 1.7, load sharing ratio has been increased by 5.88% for uniform piled-raft configurations and 8% for non-uniform piled-raft configurations. Out of these, these non-uniform piled-raft configuration has better load-sharing ratio, $\alpha_{(pr)}$ increased rate compared to uniform piled-raft configurations when the thickness of the raft increases.

Table 4.12: Effect of raft thickness on load sharing ratio, $\alpha_{(pr)}$ of different PRCs

Raft thickness(m)	Load sharing ratio, $\alpha_{(pr)}$	
	Uniform PRCs	Non-uniform PRCs
0.7	0.30	0.22
1.2	0.34	0.25
1.7	0.36	0.27
2.0	0.40	0.29

Effect of Raft Thickness on Maximum Bending Moment PRCs

Normally, the raft foundation is designed for maximum bending moment and maximum shear force values. Thus in the present study, the maximum bending moment and maximum shear force values are taken into account (Ferchat et al., 2021).

Table 4.13: Effect of raft thickness on maximum bending moment of different PRCs

Raft thickness (m)	Maximum Bending Moment (kN.M/M)	
	Uniform PRCs	Non-uniform PRCs
0.7	486.1	521.4
1.2	612.7	659.8
1.7	663.4	684.3

Based on Table 4.13, the maximum bending moment was increased for 0.7 to 1.2 raft thickness by 26.04 % and 26.54 % for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Similarly, when the raft thickness increases from 1.2 to 1.7, the maximum bending moment has been increased by 8.27 % for uniform piled-raft configurations and 3.71 % for non-uniform piled-raft configurations. Out of these, these non-uniform piled-raft configuration has lower maximum bending moment increased rate compared to uniform piled-raft configurations when the thickness of the raft increases.

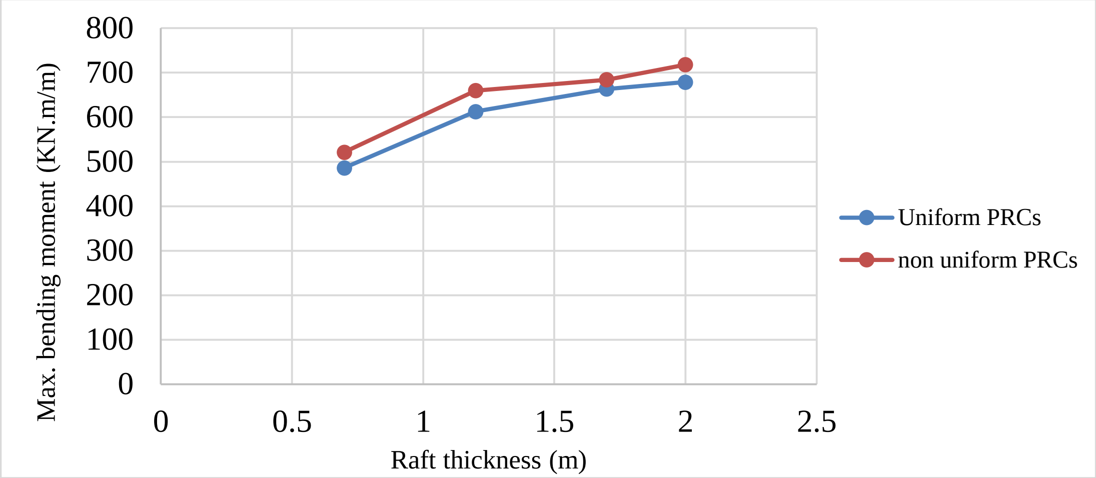


Figure 4.10: Effect of raft thickness on maximum bending moment of different PRCs

Increasing the thickness of the raft in a foundation system supported by piles generally results in a slightly higher maximum bending moment of the different piled raft foundation, as shown in Figure 4.10. This is primarily due to the increased self-weight of the thicker raft, which imposes a greater demand on the piles to carry the load. The additional weight of the raft leads to a more significant transfer of load to the piles, resulting in a higher maximum bending moment in all different piled raft configurations of both uniform and non-uniform piled raft configurations.

4.3.4. Effect of Pile Diameter

In this study, the effect of pile diameter on the performance of piled rafts was investigated by modeling three different pile diameters 0.6 m, 0.8 m, and 1.0 m. The raft thickness was kept constant at 0.7 m, while other parameters were consistent with the previous analysis including number of piles which is 16. To thoroughly assess the performance of the piled rafts with different pile diameters, maximum settlement, differential settlement, and maximum bending moment of different piled-raft configurations of uniform piled raft configurations and non-uniform piled raft configurations were considered as evaluation criteria.

Effect of Pile Diameter on Settlement of Different PRCs

The effect of the maximum settlement on the various piled raft configurations is seen in Table 4.14. A distinct and significant trend emerged from the experimental data shown in Figure 4.11: the maximum settlement decreases as pile diameter increases. The conclusion can be explained by the fact that when pile diameter rises, the pile's surface area also increases, which raises skin friction of the pile base. Additionally, when the pile's base area grows, base resistance rises as well, lowering the maximum settlement of different piled raft configurations of both uniform and non-uniform piled raft configurations.

These observations hold true regardless of the different piled raft in the configuration, whether uniform or non-uniform piled raft configurations. When the pile diameter increases from 0.6m to 0.8m, the maximum settlement decreases by 6.20 % and 1.56 % for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Furthermore, when the pile diameter increases from 0.8m to 1m, the maximum settlement declines by 1.6 % and 0.79 % for uniform piled raft configurations and non-uniform piled raft configurations, respectively.

Table 4.14: Comparison of maximum settlements for different pile diameters of different PRCs

Pile diameter (m)	Maximum settlement (mm)	
	Uniform PRCs	Non-uniform PRCs
0.6	110.0	102.6
0.8	103.1	101.0
1.0	101.9	100.2

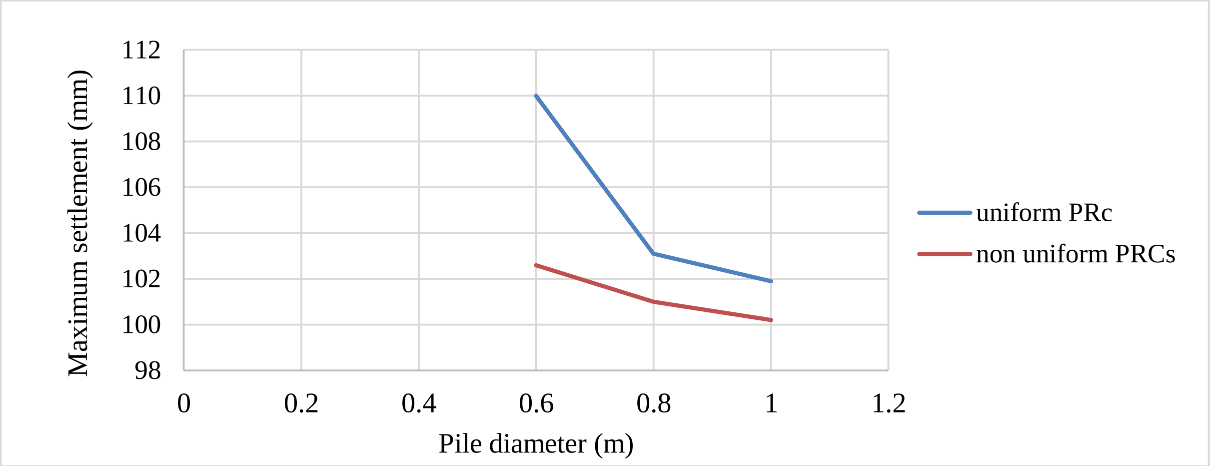


Figure 4.11: Comparison of maximum settlements for different pile diameters

However, the trend in differential settlement exhibits a more complex pattern, as it is influenced by the pile diameter and both the configurations types of uniform piled raft configurations and non-uniform piled raft configurations. For instance, when the pile configuration consists of non-uniform piled raft configurations, differential settlement initially increases and subsequently rises with an increase in pile diameter. On the other hand, in a uniform piled raft configurations, differential settlement increases as the pile diameter increases, as shown in Figure 4.12.

In general, when we see Figure 4.12 the trend of differential settlement of both piled raft configurations of uniform and non-uniform piled raft configurations, when pile diameter increases, differential settlement is increased. It is intended to compare effects of pile diameter on differential settlement of uniform and non-uniform piled raft configurations.

Table 4.15: Comparison of differential settlement for different pile diameters

Pile diameter (m)	Differential settlement (mm)	
	Uniform PRCs	Non-uniform PRCs
0.6	3.5	15.63
0.8	12.85	14.25
1	13.11	12.45

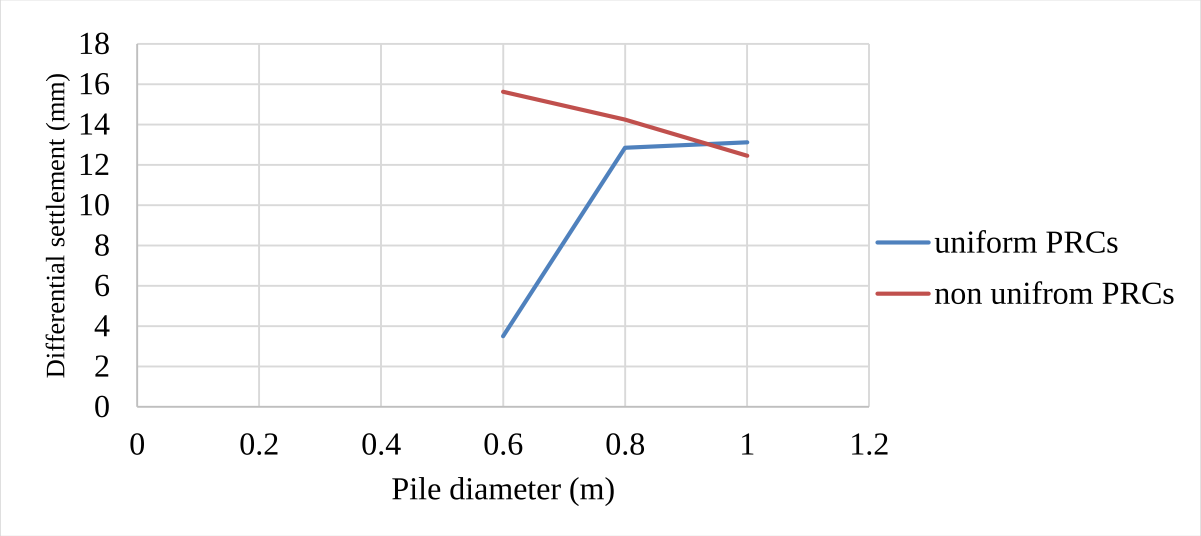


Figure 4.12: Comparison of differential settlement for different pile diameters

In the case of uniform piled raft configurations the change in differential settlement behavior can be attributed to the ratio of the pile group width to the raft width (Bg/Br). As the pile diameter increases, the spacing between the piles also increases due to the constant multiplier of diameter. Consequently, as the pile diameter and the number of piles increase, the group width also increases, resulting in an increase in Bg/Br. This means that edge piles experience less load compared to the center piles, leading to an uneven distribution of load and an increase in differential settlement. However, in case of non-uniform piled raft configurations, it is different trend. As pile diameter increases the differential settlement decreased. At the beginning the amount of differential settlement was large because the central piles experience more load as compared to edge load so that the outer piles are longer than central piles and as pile diameter increased the differential settlement decreased.

Effect of Pile Diameter on Load Sharing Ratio of Different PRCs

Figure 4.13 shows, increasing the diameter of the pile generally leads to an increase in the load sharing ratio of the pile for both uniform piled-raft configurations and non-uniform piled-raft configurations. This is primarily because a larger diameter pile has a higher load-bearing capacity, improved stiffness, and enhanced load transfer capabilities, allowing it to carry a greater proportion of the total load to all numbers of piles.

Table 4.16: Effect of pile diameter on load sharing ratio for different PRCs

Pile diameter (m)	Load sharing ratio,α_{pr}	
	Uniform PRCs	Non-uniform PRCs
0.6	0.30	0.19
0.8	0.34	0.25
1	0.36	0.27

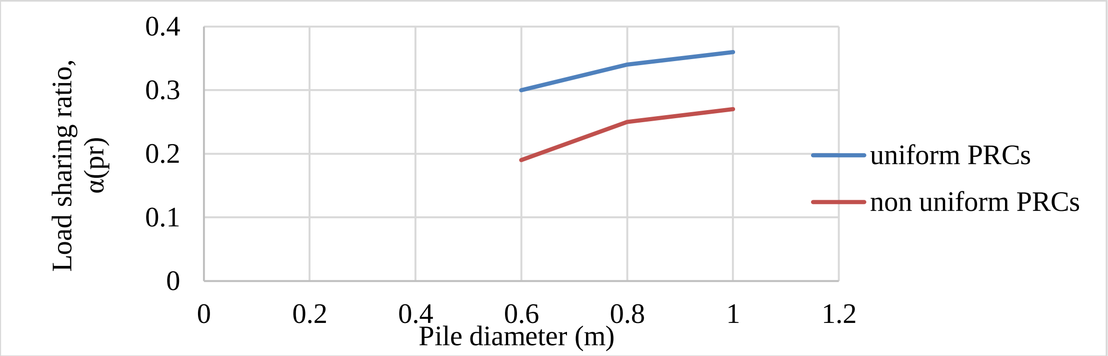


Figure 4.13: Effect of pile diameter on load sharing ratio for different PRCs

Based on Table 4.16, load sharing ratio was increased for 0.6 to 0.8 pile diameter by 13.30% and 31.60% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Similarly, when the pile diameter increases from 0.8 to 1, load sharing ratio has been increased by 5.88% for uniform piled-raft configurations and 8.0% for non-uniform piled-raft configurations. Out of these, these non-uniform piled-raft configuration has better load-sharing ratio, (α_{pr}) increased rate compared to uniform piled-raft configurations when the spacing of the pile increases.

In general, when we see Figure 4.13 the trend of load sharing ratio of both piled raft configurations of uniform and non-uniform piled raft configurations, when pile diameter increases, load sharing ratio is increased. The non-uniform length of piled raft configurations performance has lower load sharing ratio as compared to uniform piled raft configurations as it can be depicted from the graph. This is due to the increase of pile spacing as pile diameter increases. When pile spacing increases the edge piles experience less loads so they have lower load capacity. The load sharing ratio is lower for non-uniform piled raft configurations as compared to uniform piled raft configurations.

Effect of Pile Diameter on Maximum Bending Moment

The development of the bending moment in the raft is a crucial factor for the structural design. Poulos (2001b) also indicated that the maximum bending moment generated in the raft should be part of the design considerations for the piled raft system.

Table 4.17: Effect of pile diameter on the maximum bending moment for different PRCs

Pile diameter (m)	Maximum bending moment (kN.M/M)	
	Uniform PRCs	Non-uniform PRCs
0.6	486.1	547.3
0.8	612.7	521.4
1.0	663.4	507.3

Based on Table 4.17, the maximum bending moment was increased for 0.6 to 0.8 pile diameter by 26.04% and 4.73% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. Similarly, when the pile diameter increases from 0.8 to 1, the maximum bending moment has been increased by 8.30% for uniform piled-raft configurations and 2.70% for non-uniform piled-raft configurations. Out of these, these non-uniform piled-raft configuration has better maximum bending moment increased rate compared to uniform piled-raft configurations when the diameter of the pile increases.

The table 4.17 illustrates that an increase in pile diameter leads to an increase in negative bending moment for 16 piles for both uniform and non-uniform piled raft configurations. One reason for this phenomenon is that a larger pile diameter results in a more significant contact area between the pile and the raft, leading to a higher transfer of loads from the raft to the piles, which contributes to the increase in the negative bending moment. Additionally, an increase in pile diameter causes a larger area of soil to be displaced during installation, resulting in increased soil resistance to pile displacement. Consequently, the pile must displace more soil to achieve the same amount of settlement, leading to a higher mobilization of soil resistance. This increased mobilization of soil resistance contributes to the rise in the negative bending moment of the raft.

4.3.5. Effect of Pile Length

The study aimed to examine the impact of pile length on the behavior of piled raft foundations under different piled raft configurations of both uniform piled raft and non – uniform piled raft configurations. To evaluate the impact of pile length on maximum settlement, differential settlement, and bending moment behavior of piled raft foundation, a basic model consisting of 16 piles with lengths of 9 m, 12 m and 15 m and spacing of three times (Sy = 3D) the pile diameter along the shorter side of the raft was used, while the longer side had a spacing of 1.5 times the shorter side spacing. The model had a pile diameter of 0.6 meters and a raft thickness of 0.7 meters and was subjected to an applied loading of 360 KPa.

Effect of Pile Length on Settlement of Different PRCs

The study showed that increasing the pile length from 9 m to 15 m resulted in a decrease in the maximum settlement of the foundation from 123.6 mm to 108.8 mm for uniform piled-raft configurations and 106.0 mm to 78.85 mm for non-uniform piled raft configurations under a uniform load of 360 Kpa for pile spacing of 3D along the shorter side. Similar findings were reported by Maharaj & Anshuman (2004) in their investigation of the settlement performance of piled rafts using NLAXIFEM software. However, their study considered larger pile length-to-diameter ratios, resulting in a greater change in settlement values. The reduction in the maximum settlement at the center of the raft was attributed to the increase in the mobilized shaft resistance from piles. As the pile length increases, it leads to a higher mobilization of shaft friction, which in turn causes a reduction in the maximum settlement at the foundation's center.

Table 4.18: Comparison of maximum settlements for different pile lengths and pile spacing for different PRCs

Pile length (m)	Maximum settlement (mm)	
	Uniform PRCs	Non-uniform PRCs
9	123.5	106.0
12	113.8	88.58
15	108.8	78.85

Longer piles, however, can be more susceptible to bending and buckling as they seek to transfer the applied loads through the silty clay to the underlying stiffer silty sand; this effect is due to slenderness problems of the pile for sand soils, where the pile length is large, and the diameter is small. This can result in an increased differential settlement between the piles as they try to accommodate the load differentials. As the pile length increases, so does the extent of the interaction between the pile and the soil layers. The settlement response within the silty-clay layer may vary depending on the depth to which piles are driven into the underlying silty sand layer.

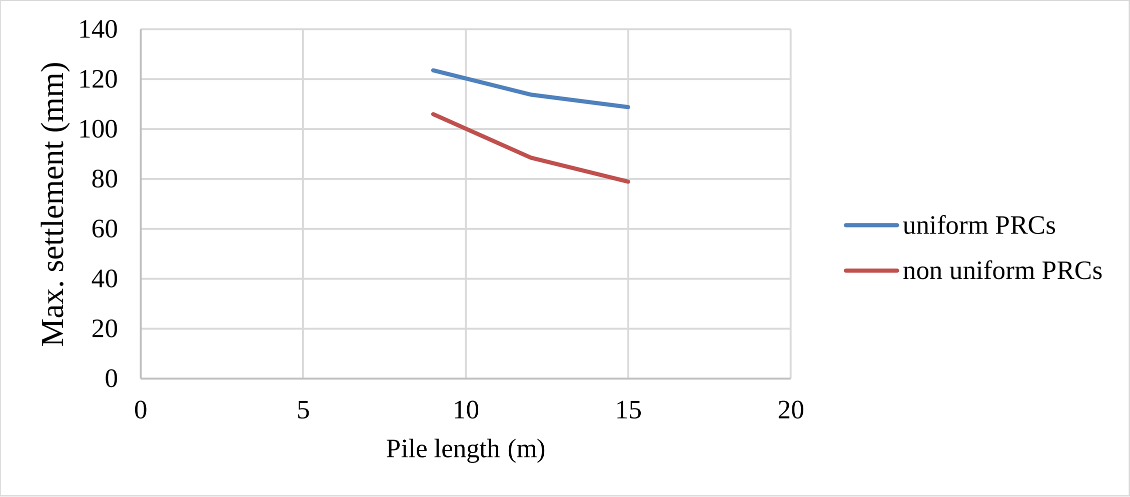


Figure 4.14: Comparison of maximum settlements for different pile lengths and pile spacing for different PRCs

Based on the findings presented in Table 4.18, it is evident that an increase in pile length from 9m to 12m results in a decrease in maximum settlement by 7.85 % for uniform piled raft configurations and 17.42 % for non-uniform piled raft configurations. Similarly, when the pile length increases from 12m to 15m, the maximum settlement declines by 4.4% and 9.73% for uniform piled raft configurations and non-uniform piled raft configurations, respectively. In practical terms, it might be helpful to consider both maximum and differential settlement reductions to choose the best pile spacing to suit different design requirements and soil conditions.

In general, when we see Figure 4.14 the trend of maximum settlement of both piled raft configurations of uniform and non-uniform piled raft configurations, when pile length increases, maximum settlement is decreased. It is intended to compare effects of pile length on maximum settlement of uniform and non-uniform piled raft configurations, non-uniform length of piled raft configurations performance has lower settlements as it can be depicted from the graph.

Effect of Pile Length on Load-Sharing Ratio of Different PRCs

Increasing the length of a pile generally leads to an increase in the load sharing ratio as shown in Table 4.19. Longer piles have greater embedment depths, allowing them to resist higher loads and transfer them effectively to the soil. The increased length provides a larger surface area for load transfer, enabling the pile to carry a greater proportion of the total load. Additionally, longer piles often have higher load-bearing capacities and increased stiffness, further enhancing their ability to share the load with neighboring piles. Therefore, as the pile length increases, the load sharing ratio tends to increase as well.

Based on the findings presented in Table 4.19, it is evident that an increase in pile length from 9m to 12m results in increase in load sharing ratio by 13.6 % for uniform piled raft configurations and 91.01 % for non-uniform piled raft configurations. Similarly, when the pile length increases from 12m to 15m, the load sharing ratio increases by 24.0 % and 66.66 % for uniform piled raft configurations and non-uniform piled raft configurations, respectively.

Table 4.19: Effect of pile length on load sharing ratio, α_{pr} of different PRCs

Pile length (m)	Load-Sharing Ratio, α_{pr}	
	Uniform PRCs	Non-uniform PRCs
9	0.22	0.267
12	0.25	0.51
15	0.31	0.17

Effect of Pile Length on Maximum Bending Moment of Different PRCs

The maximum bending moment decreases when the pile length increases for both uniform piled raft configurations and non-uniform piled raft configurations. As the pile length increases, the load carried by the raft foundation is transferred deeper into the ground, which tends to decrease the load on the raft itself, resulting in a lower moment. This occurs because longer piles can distribute loads more efficiently in the underlying soil strata, reducing the bearing pressure on the raft foundation. The properties of the soil surrounding the piles can also influence moment in the raft foundation. When the pile length increases, the piles interact with different layers of soil that may have varying strengths and stiffness. The load distribution and settlement behavior of the pile group can be affected by changes in soil properties, which in turn influences bending moment response in the raft foundation.

Table 4.20: Effect of pile length on maximum bending moment of different PRCs

Pile length (m)	Maximum Bending Moment (KN.m/m)	
	Uniform PRCs	Non-uniform PRCs
9	236	200.2
12	195.8	158.4
15	187.1	139.7

When the pile length is small, bending moment develops outside the pile group for both uniform piled raft configurations and non-uniform piled raft configurations. As the pile length increases, the soil experiences a greater load than before, which allows it to support the load more effectively with the pile for both uniform piled raft configurations and non-uniform piled raft configurations. As a result, bending moment decreases for both uniform and non-uniform piled raft configurations. Based on the findings presented in Table 4.20, it is evident that an increase in pile length from 9m to 12m results in a decrease in maximum bending moment by 17.03% and 11.14 % for uniform piled raft configurations and non-uniform piled raft configurations, respectively.

CHAPTER 5

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

This study uses a three-dimensional finite-element model to evaluate the performance of piled-raft foundations on layered soil profiles. The model is implemented in PLAXIS 3D software and simulates the maximum settlement, differential settlement, load sharing ratio and maximum bending moment of the piled raft foundations with various types of piled raft configurations. The effects of various parameters, such as raft thickness, pile spacing, pile diameter and pile length are evaluated.

The following conclusions can be drawn from numerical analysis:

- ✓ Non-uniform piled raft configurations have more settlement reduction rate when pile spacing is considered as a parametric study over uniform piled raft configurations. Therefore, it is recommended to use non-uniform piled raft configurations over uniform piled-raft configurations when the reduction of maximum settlement is concerned.
- ✓ The behavior of an un-piled, uniform piled and non-uniform piled rectangular raft foundation was significantly affected by the applied load and raft thickness. An increase in load resulted in greater settlement due to heightened soil compression, while a thicker raft could lessen differential settlement by evenly spreading the load on the soil. The maximum settlement increased by 184.58% for un-piled, 57.90% for uniform piled-raft configurations and 68.08% for non-uniform piled raft configurations when applied uniformly distributed load increased from 360KPa to 540KPa.
- ✓ Increasing raft thickness also led to a higher self-weight, contributing to a greater maximum settlement, which increased by 0.19% for uniform piled raft configurations and 0.69% for non-uniform piled raft configurations. Thus, it was essential to carefully determine the raft thickness to balance maximum and differential settlement, ensuring the overall stability and safety of the foundation system.
- ✓ A larger pile diameter greatly impacted piled raft's performance, reducing maximum settlement by 6.20% and 1.56% for uniform and non-uniform piled raft configurations, respectively (0.6m to 1m) due to an increased surface area and base resistance.

Differential settlement and bending moments depended on factors like pile group to raft width ratio, pile spacing, and raft dimensions.

- ✓ The research showed that pile spacing crucially affected piled raft foundations' settlement and bending moment, influenced by factors like pile numbers and group pile width (Bg). Increased spacing (from 3D to 5D) led to reduced maximum settlement by 3.0% and 3.30% for uniform and non-uniform piled raft configurations, respectively, while causing opposite effects on differential settlement and complex impacts on bending moments.
- ✓ Increasing pile length from 9m to 15m reduced maximum settlement by 7.85% and 17.42% for uniform and non-uniform piled raft configurations, respectively of pile spacing of 3D respectively. Performance was influenced by load distribution, foundation stiffness, deflection, and soil layer interactions.
- ✓ The effect of the ratio of the raft width to the pile group width (Bg/Br) on the bending moment of the raft and differential settlement was a noteworthy finding in this study, aside from the parameters. Both the differential settling and the bending moment showed distinct responses when the ratio of the pile group width to the raft width (Bg/Br) varied. Consequently, the area covered by the pile group (Ag) had a major impact on the performance of piled rafts.

5.2. Recommendation

Future researchers who wish to examine the impact of various parameters on piled raft foundations are advised to follow these recommendations:

- ✓ In addition to the four parameters examined in this study (raft thickness, pile diameter, pile length, and pile spacing), conduct a thorough literature survey to find additional factors that influence the behavior of piled raft foundations under different piled raft configurations specifically when central piles are longer than the outer piles.
- ✓ Small raft sizes were used for this study. It is recommended that large raft foundations be used in the future to further examine the impact of pile number and spacing.
- ✓ Use various soil types and loading conditions to conduct laboratory tests and verify the numerical findings produced by PLAXIS 3D.

- ✓ Examine how piled raft foundations react to intricate loading patterns like lateral and eccentric.
- ✓ To take into consideration the impact of seismic loads and vibration on piled raft foundations, incorporate dynamic analysis into the study.

REFERENCES

Al-Juaidi, A. H., Ahmed, M. F., & Al-Mahaidi, R. (2020). Numerical analysis of piled raft foundation on soft clay using PLAXIS 3D , 20(10),. International Journal of Geomechanics, 20(10).

Algulin, J., & Pedersen, B. (2014). Modelling of a piled raft foundation as a plane strain model in PLAXIS 2D. *Master of Science, Department of Civil and Environment Eng, Division of Geo-Engineering, Chalmers University, Sweden*.

Alnuaim, A. M., El Naggar, H., & El Naggar, M. H. (2013). 3D modeling of piled raft foundation subjected to vertical loading. *Proceedings, Annual Conference - Canadian Society for Civil Engineering*, *5*(January), 3807–3815.

Ata, A., Badrawi, E., & Nabil, M. (2015). Numerical analysis of unconnected piled raft with cushion. *Ain Shams Engineering Journal*, *6*(2), 421–428.

Bhaduri, A., & Choudhury, D. (2020). Serviceability-Based Finite-Element Approach on Analyzing Combined Pile–Raft Foundation. *International Journal of Geomechanics*, *20*(2). https://doi.org/10.1061/(ASCE)GM.1943-5622.0001580

Bhartiya, P., Chakraborty, T., & Basu, D. (2022). Load-settlement response of piled raft foundations in sand. *Geomechanics and Geoengineering*, *17*(4), 1260–1283. https://doi.org/10.1080/17486025.2021.1928767

Bourgeois, E., de Buhan, P., & Hassen, G. (2012). Settlement analysis of piled-raft foundations by means of a multiphase model accounting for soil-pile interactions. *Computers and Geotechnics*, *46*, 26–38. https://doi.org/10.1016/j.compgeo.2012.05.015

Brinkgreve, R., Swolfs, W., & Engin, E. (2015). PLAXIS user’s manual, version 6.1. *Balkema, Rotterdam, The Netherlands*.

Cerato, A. B., & Lutenegger, A. J. (2006). Bearing capacity of square and circular footings on a finite layer of granular soil underlain by a rigid base. *Journal of Geotechnical and Geoenvironmental Engineering*, *132*(11), 1496–1501.

Clancy, P., & Randolph, M. F. (1993). An approximate analysis procedure for piled raft foundations. *International Journal for Numerical and Analytical Methods in Geomechanics*, *17*(12), 849–869. https://doi.org/10.1002/NAG.1610171203

Das, B. M. (2011). Principles of Foundation Engineering. 7th. Pacific Grove: Brooks/Cole-Thomson Learning.

Deb, P., & Pal, S. K. (2019). Analysis of Load Sharing Response and Prediction of Interaction Behaviour in Piled Raft Foundation. *Arabian Journal for Science and Engineering*, *44*(10), 8527–8543. https://doi.org/10.1007/s13369-019-03936-1

Dejen, G. (2017). *The Assessment of 20/80 Condominium Housing Projects in Addis Ababa: The case of Bole and Akaky Kaliti Sub cities*. https://doi.org/10.20372/NADRE:3449

El-Garhy, B., Galil, A. A., Youssef, A. F., & Raia, M. A. (2013). Behavior of raft on settlement reducing piles: Experimental model study. *Journal of Rock Mechanics and Geotechnical Engineering*, *5*(5), 389–399. https://doi.org/10.1016/J.JRMGE.2013.07.005

El, A., & Nashaat, S. W. (2018). Redistribution of Load between Soil and Piles underneath Piled Raft Foundation. *International Journal of Applied Engineering Research ISSN*, *13*(9), 973–4562. http://www.ripublication.com

Farouk, A. (2011). High rise buildings and how they affect countries progression. *E-IataorC Leader*, *2011*, 1–14.

Ferchat, A., Benmebarek, S., & Houhou, M. N. (2018). Numerical Analysis of Piled Raft Interaction in Soft Clay. *Advances in Science, Technology and Innovation, January 2014*, 337–339. https://doi.org/10.1007/978-3-030-01665-4_78

Ferchat, A., Benmebarek, S., & Houhou, M. N. (2021). 3D numerical analysis of piled raft interaction in drained soft clay conditions. *Arabian Journal of Geosciences*, *14*(5). https://doi.org/10.1007/S12517-021-06783-3

Franke, E., Lutz, B., & El-Mossallamy, Y. (1994). Measurements and numerical modelling of high rise building foundations on Frankfurt Clay. *Vertical and Horizontal Deformations* *of Foundations and Embankments*, 1325–1336.

Hanisch, J., Katzenbach, R., & König, G. (2002). *Kombinierte Pfahl-Plattengründungen*. John Wiley & Sons.

Horikoshi, K., & Randolph, M. F. (1996). Centrifuge modelling of piled raft foundations on clay. *Geotechnique*, *46*(4), 741–752. https://doi.org/10.1680/GEOT.1996.46.4.741

Jayarajan, P., & Kouzer, K. M. (2015). Analysis of piled raft foundations. Indian Journal of Science, 16(51), 51–57.

Jeong, S., Lee, J., & Lee, C. J. (2004). Slip effect at the pile–soil interface on dragload. *Computers and Geotechnics*, *31*(2), 115–126.

Johnson, R. T., Varghese, R. M., & Joseph, J. (2019a). Parametric study on the behavior of combined pile raft foundation founded on multi-layered soil using plaxis 3d. In *Lecture Notes in Civil Engineering* (Vol. 15). Springer Singapore. https://doi.org/10.1007/978-981-13-0562-7_24

Johnson, R. T., Varghese, R. M., & Joseph, J. (2019b). Parametric study on the behavior of combined pile raft foundation founded on multi-layered soil using plaxis 3d. *Lecture Notes in Civil Engineering*, *15*, 217–225. https://doi.org/10.1007/978-981-13-0562-7_24

Kambala, S. N. R. (2010). *Piles as settlement reducers in raft* [Doctoral dissertation].

Katzenbach, R., Gutberlet, C., & Bachmann, G. (2007). Soil-Structure Interaction aspects for ultimate limit state design of complex foundations. *First International Symposium on Geotechnical Safety & Risk*.

Kézdi, Á., & Rétháti, L. (1974). Handbook of soil mechanics (Vol. 1). Elsevier Amsterdam.

Kumar, R., Bhargava, K., Letters, D. C.-I., & 2016, undefined. (2016). Estimation of engineering properties of soils from field SPT using random number generation. *SpringerR Kumar, K Bhargava, D ChoudhuryINAE Letters, 2016•Springer*, *1*(3–4), 77–84. https://doi.org/10.1007/s41403-016-0012-6

Kumar, U. (2018). Assessment Of Non-Uniform Length Of Piles In Piled Raft Foundation Subjected To Non-Uniform Loading. *International Journal for Research in Engineering Application & Management (IJREAM).*, 0–3.

Kuwabara, F. (1989). Elastic analysis for piled raft foundations in a homogeneous soil. *Soils and Foundations*, *29*(1), 82–92. https://doi.org/10.3208/sandf1972.29.82

Lee, J., Park, D., & Choi, K. (2014). Analysis of load sharing behavior for piled rafts using normalized load response model. *Computers and Geotechnics*, *57*, 65–74. https://doi.org/10.1016/J.COMPGEO.2014.01.003

Lee, J., Park, D., Park, D., & Park, K. (2015a). Estimation of load-sharing ratios for piled rafts in sands that includes interaction effects. *Computers and Geotechnics*, *63*, 306–314. https://doi.org/10.1016/j.compgeo.2014.10.014

Lee, J., Park, D., Park, D., & Park, K. (2015b). Estimation of load-sharing ratios for piled rafts in sands that includes interaction effects. *Computers and Geotechnics*, *63*, 306–314. https://doi.org/10.1016/J.COMPGEO.2014.10.014

Maharaj, D. K., & Gandhi, S. R. (2004). Non-linear finite element analysis of piled-raft foundations. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, *157*(3), 107–113. https://doi.org/10.1680/GENG.2004.157.3.107

Mali, S., & Singh, B. (2018). Behavior of large piled-raft foundation on clay soil. *Ocean Engineering*, *149*, 205–216.

Mosie, A. T. (2022). Assessment of High Rise Building Construction in Addis Ababa City. *American Journal of Construction and Building Materials*, *6*(1), 11–16.

Mulatu, B. (2019). *A STUDY OF RULES AND REGULATIONS ORGANIZING THE PRACTICE OF GLASS FAÇADE BUILDINGS IN ADDIS ABABA, ETHIOPIA.* https://www.academia.edu/download/96156414/2019_BIRUCK_MULATU_MSC_IN_ADVANCED_ARCHITECTURAL_DESIGN_THESIS_SUBMISSIONS.pdf

Nguyen, D. D. C., Jo, S. B., & Kim, D. S. (2013). Design method of piled-raft foundations under vertical load considering interaction effects. *Computers and Geotechnics*, *47*, 16–27. https://doi.org/10.1016/j.compgeo.2012.06.007

Nguyen, D., Jo, S., Geotechnics, D. K.-C. and, & 2013, undefined. (2013). Design method of piled-raft foundations under vertical load considering interaction effects. *ElsevierDDC Nguyen, SB Jo, DS KimComputers and Geotechnics, 2013•Elsevier*, *47*, 16–27. https://doi.org/10.1016/j.compgeo.2012.06.007

Obrzud, R., & Truty, A. (2012). The Hardening Soil Model—A Practical Guidebook Z Soil PC 100701 report, revised 31.01. Obrzud R. Truty A.

Poulos, H. G. (2000). 16. Practical design procedures for piled raft foundations. *Design Applications of Raft Foundations*, 425–467. https://doi.org/10.1680/DAORF.27657.0016

Poulos, H. G. (2001a). Piled raft foundations: design and applications. *Géotechnique, 51*(2), 95–113. https://doi.org/10.1680/GEOT.2001.51.2.95

Poulos, H. G. (2001b). Piled raft foundations: Design and applications. *Geotechnique, 51*(2), 95–113. https://doi.org/10.1680/GEOT.51.2.95.40292

Poulos, H. G. (2016). Tall building foundations: design methods and applications. *Innovative Infrastructure Solutions*, *1*(1). https://doi.org/10.1007/S41062-016-0010-2

Poulos, H. G., Small, J. C., & Chow, H. (2011). Piled raft foundations for tall buildings. *Geotechnical Engineering*, *42*(2).

Poulos HG. (1991). Analysis of piled strip foundations. *International Conference on Computer Methods and Advances in Geomechanics*, 183–191.

Prakoso, W. A., & Kulhawy, F. H. (2001). Contribution to Piled Raft Foundation Design. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(1), 17–24. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:1(17)

Randolph, M. F., & Wroth, C. P. (1978). ANALYSIS OF DEFORMATION OF VERTICALLY LOADED PILES. *ASCE J Geotech Eng Div*, *104*(12), 1465–1488.

https://doi.org/10.1061/AJGEB6.0000729

Roshan, A., & Shooshpasha, I. (2014). Numerical analysis of piled raft foundations in soft clay. *EJGE*, *19*, 4541–4554.

Russo, G. (1998). Numerical analysis of piled rafts. *International Journal for Numerical and Analytical Methods in Geomechanics*, *22*(6), 477–493.

Sanzeni, A., & Danesi, E. G. (2022). Field tests and interpretation of screw micropiles subjected to axial loading in cohesive soil. *International Journal of Geotechnical Engineering*, *16*(4), 391–399. https://doi.org/10.1080/19386362.2021.1920738

Sinha, A., & Hanna, A. M. (2017). 3D Numerical Model for Piled Raft Foundation. International Journal of Geomechanics, 17(2). https://doi.org/10.1061/(asce)gm.1943-5622.0000674

Sinha, A. (2013). 3D Modeling of piled raft foundation. *(Doctoral Dissertation, Concordia University).*

Srilakshmi, G., of, N. D. M.-I. J., & 2013, undefined. (2013). Analysis of piled raft foundation using finite element method. *Academia.EduG Srilakshmi, NS Darshan MoudgalyaInternational Journal of Engineering Research and Science & Technology, 2013•academia.Edu*.

Taghavi Ghalesari, A., Barari, A., Fardad Amini, P., & Ibsen, L. B. (2015). Development of optimum design from static response of pile–raft interaction. *Journal of Marine Science and Technology (Japan)*, *20*(2), 331–343. https://doi.org/10.1007/s00773-014-0286-x

Teji, B. D., & Ashango, A. A. (2023). Performance Optimization of Piled Raft Foundations in Layered Soil under Uniform Vertical Loading Using Plaxis 3D. *Advances in Materials Science and Engineering*, *2023*. https://doi.org/10.1155/2023/6693876

Van Impe, W. F., & Lungu, I. (2001). Methods of analysis of piled raft foundations. International Society of Soil Mechanics and Geotechnical Engineering, Technical Committee TC18 on Piled Foundations.

Viggiani, C. (2001). Analysis and design of piled raft foundations. First Arrigo Croce Lecture, Rivista Italiana Di Geotechnica, 47–75.

Yamashita, K., Yamada, T., & Hamada, J. (2011). Investigation of settlement and load sharing on piled rafts by monitoring full-scale structures. *Soils and Foundations*, *51*(3), 513–532. https://doi.org/10.3208/sandf.51.513

Zeevaert, L. (1957). Compensated friction-pile foundation to reduce the settlement of buildings on the highly compressible volcanic clay of Mexico City. *Proc. 4th ICSMFE, London*, *2*, 81–86.

APPENDIX

Appendix A: Empirical Equations and Standard Values for Missing Data

Table A.1: Typical values of soil Young's modulus for different soils according to USCS (MPa) (based on Obrzud & Truty, 2012 complied from Kézdi & Réthái, 1974 and Prat et al., 1995)

USCS	Description	Loose	Medium	Dense	
GW, SW	Gravels/Sand well-graded	30-80	80-160	160-320	
SP	Sand, uniform	10-30	30-50	50-80	
GM, SM	Sand/Gravel silty	7-12	12-20	20-30	
USCS	**Description**	**Very soft to soft**	**Medium**	**Stiff to very stiff**	**Hard**
ML	Silts with slight plasticity	2.5 - 8	10-15	15 -40	40 - 80
ML, CL	Silts with low plasticity	1.5 - 6	6-10	10-30	30 -60
CL	Clays with low-medium plasticity	0.5 - 5	5-8	8-30	30 - 70
CH	Clays with high plasticity	0.35 - 4	4-7	7-20	20 - 32
OL	Organic silts	-	0.5 -5	-	-
OH	Organic clays	-	0.5 -4	-	-

Correlation equation for cohesion (C), angle of internal friction (φ), and Poisson’s ratio (ν) using SPT N value (R. Kumar et al., 2016).

$C = -2.2049 + 6.484N$ N = 2 - 30 (Cohesive soil) (A.1)

$C = -16.5 + 2.15N$ N = 10 - 30 (Intermediate soil) (A.2)

$\varphi = 7N$ for N<=4 (A.3)

$\varphi = 27.12 + 0.2857N$ for N=4 to 50 (A.4)

$\nu = 0.2 + 0.01N$ N= 0 - 20 loose granular soil (A.5)

$\nu = 0.2 + 0.005N$ N= 20 - 50 dense granular soil (A.6)

$\nu = 0.15 + 0.0167N$ N= 0 - 6 Soft Clay (A.7)

$\nu = 0.125 + 0.0125N$ N= 6 - 30 stiff clay (A.8)

A soil whose sand content is from 50% to 80%, or coral-mixed soil, is classified as typical intermediate soil (Tsuchida et al., 2020).

Skin Resistance and Base Resistance

Janbu's Method of Determining Q_b

$$Q_b = \left(cN^*{}_c + q''{}_o N^*{}_q\right)A_b \tag{A.15}$$

Where: -

c = unit cohesion

q'' = effective vertical pressure at the base level of the pile

$N^*{}_c$ and $N^*{}_q$ = bearing capacity factors

A_b = base area of the pile

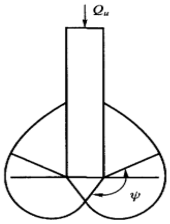


Figure A.1: The shapes of failure surfaces at the tips of piles as assumed by Meyerhof

Table A.2: Bearing capacity factors N^*_q and N^*_c by Janbu (1976)

ψ=	75^0		90^0		105^0	
φ	N^*_q	N^*_c	N^*_q	N^*_c	N^*_q	N^*_c
0	1	5.74	1	5.74	1	5.74
5	1.5	6.25	1.57	6.49	1.64	7.33
10	2.25	7.11	2.47	8.34	2.71	9.7
20	5.29	11.78	6.4	14.83	7.74	18.53
30	13.6	21.82	18.4	30.14	24.9	41.39
35	23.08	31.53	33.3	46.12	48.04	67.18
40	41.37	48.11	64.2	75.31	99.61	117.52
45	79.9	78.9	134.87	133.87	227.68	226.68

Where ψ = angle as shown in Fig. A.1. This angle varies from 60° in soft compressible soil to 105° in dense sand.

Skin Resistance Q_f by Coyle and Castello (1981)

$$Q_f = A_s q'_o K_s \tan\boldsymbol{\delta} \qquad (A.18)$$

where q'_o = average effective overburden pressure and $\boldsymbol{\delta}$ = angle of wall friction = 0.8 φ. The value of Ks can be obtained in Fig. A.2. This method is used for 30^0 to 36^0 φ values.

For others, β -Method or the Effective Stress Method of Computing Skin Resistance was used

In this method, the unit skin friction f_s is defined as

$$f_s = K_s \tan\boldsymbol{\delta} q'_o = \beta q'_o \qquad (A.16)$$

as per Jaky (1944) $\beta = (1-\sin\varphi')\tan \varphi'$ for normally consolidated clay

$$Q_f = f_s * p \qquad (A.17)$$

Where: -

f_s = unit skin friction

β = the skin factor

$\boldsymbol{\delta}$ = normally consolidated clay

q'_o = mean effective vertical stress between the ground surface and pile tip

p = perimeter of the pile

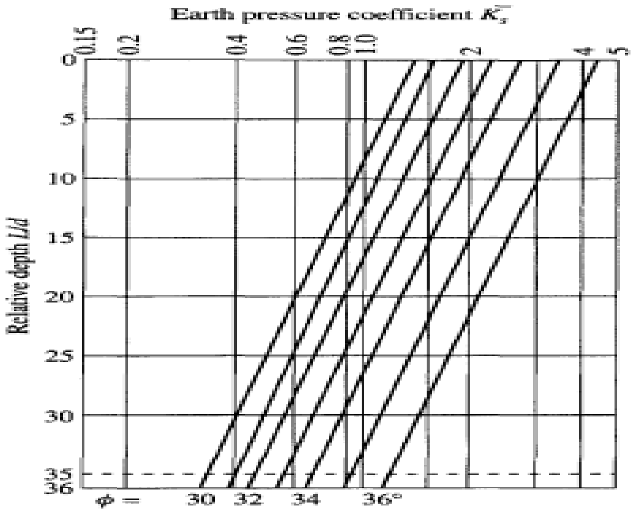


Figure A.2: Coefficient K versus L/d, **δ** = 0.8 *φ* (Coyle & Castello, 1981)

Table A.3: Base resistance and skin resistance value for this study

Pile length(m)	Pile diameter(m)	Base resistance, Q_b (KN)	Skin resistance, Q_f (KN/M)
15	0.6	4508.951	233.1574
15	0.8	8015.913	406.5308
15	1	12524.86	597.8394
12	0.6	3775.841	242.6886
12	0.8	6712.607	404.481
12	1	10488.45	581.4415
9	0.6	3042.732	248.0179
9	0.8	5409.301	363.7596
9	1	8452.032	516.704
5	0.6	-	10.98841
5	0.8	-	14.65122
5	1	-	18.31402

Table A.4: Tolerable settlements of buildings in mm (Skempton & MacDonald, 1956)

Criterion	Isolated foundation	Rafts
Angular distortion (cracking)	1/300	
Greatest differential settlement(mm)		
Clays	45 (35)	
Sands	32 (25)	
Maximum settlement(mm)		
Clays	75	75-125 (65-100)
Sands	50	50-75 (35-65)

Table A.5: Settlement value for validation from literature and current study

	Total settlement(m)			
Load (KPa)	Sinha & Hanna (2017)	Sinha & Hanna (2018)	Ferchat et al. (2021)	present study
0	0	0	0	0
100	0.03	0.03	0.025	0.02708
200	0.075	0.075	0.08	0.0688
300	0.1375	0.137	0.145	0.1367
400	0.237	0.225	0.225	0.2268
500	0.37	0.355	-	0.3379

Appendix B: Output Values from ETABS

Figure B.1: Reaction force obtained from ETAS output

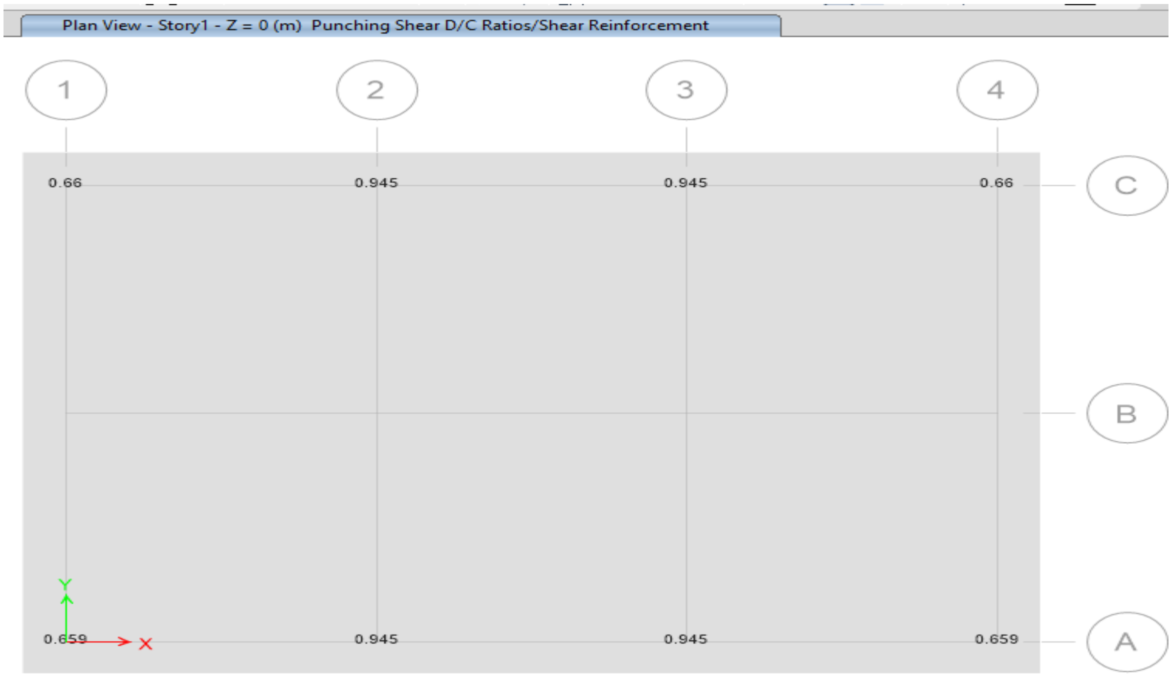


Figure B.2: The ratio of applied shear force to the punching shear resistance from SAFE output

Appendix C: Different Software Models

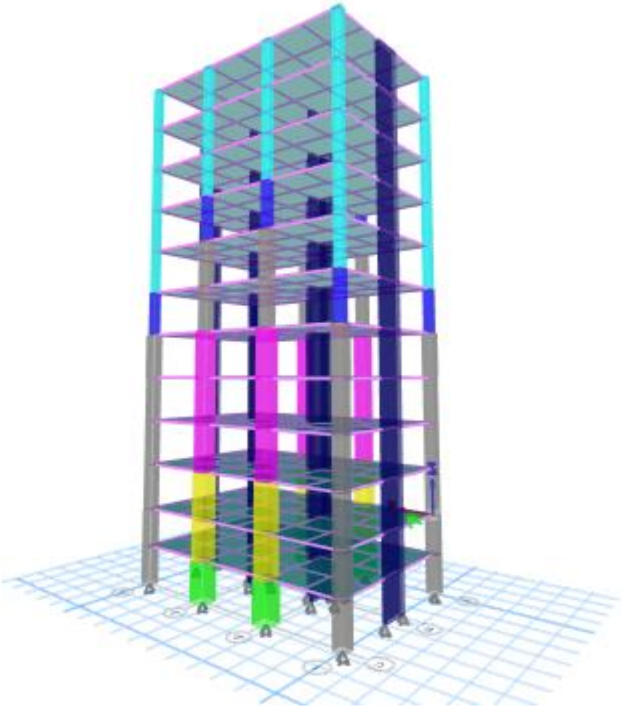


Figure C.1: Design 12 story building using ETABS software

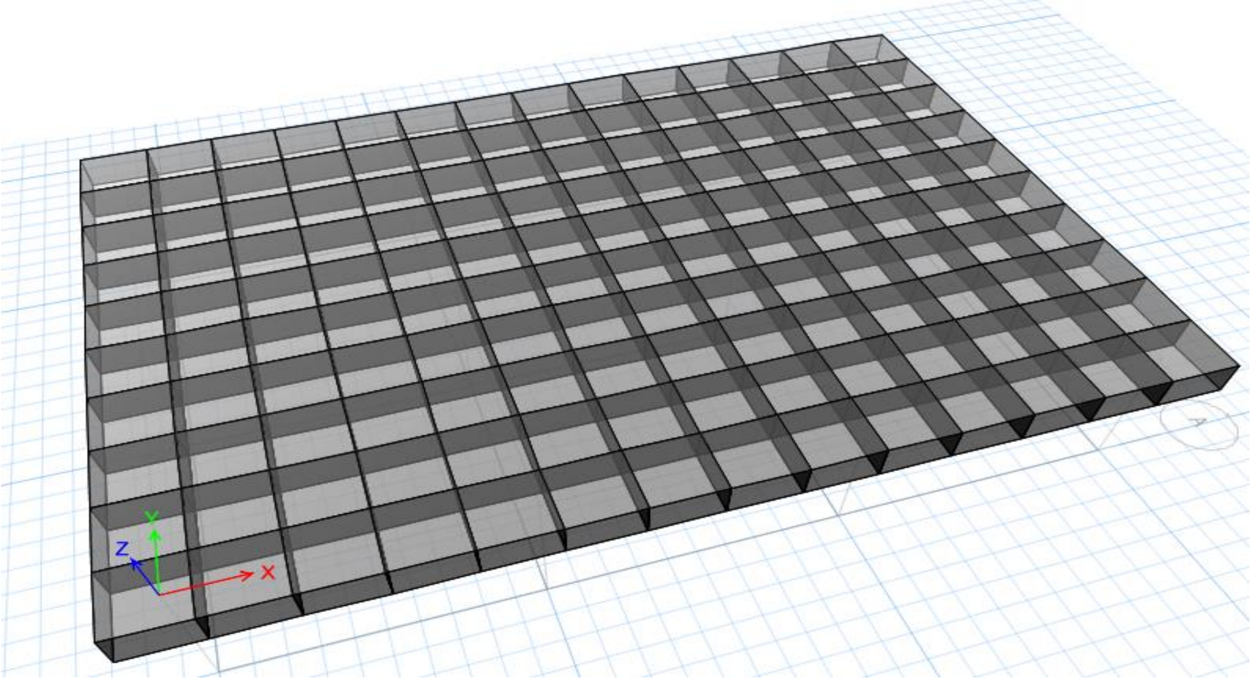
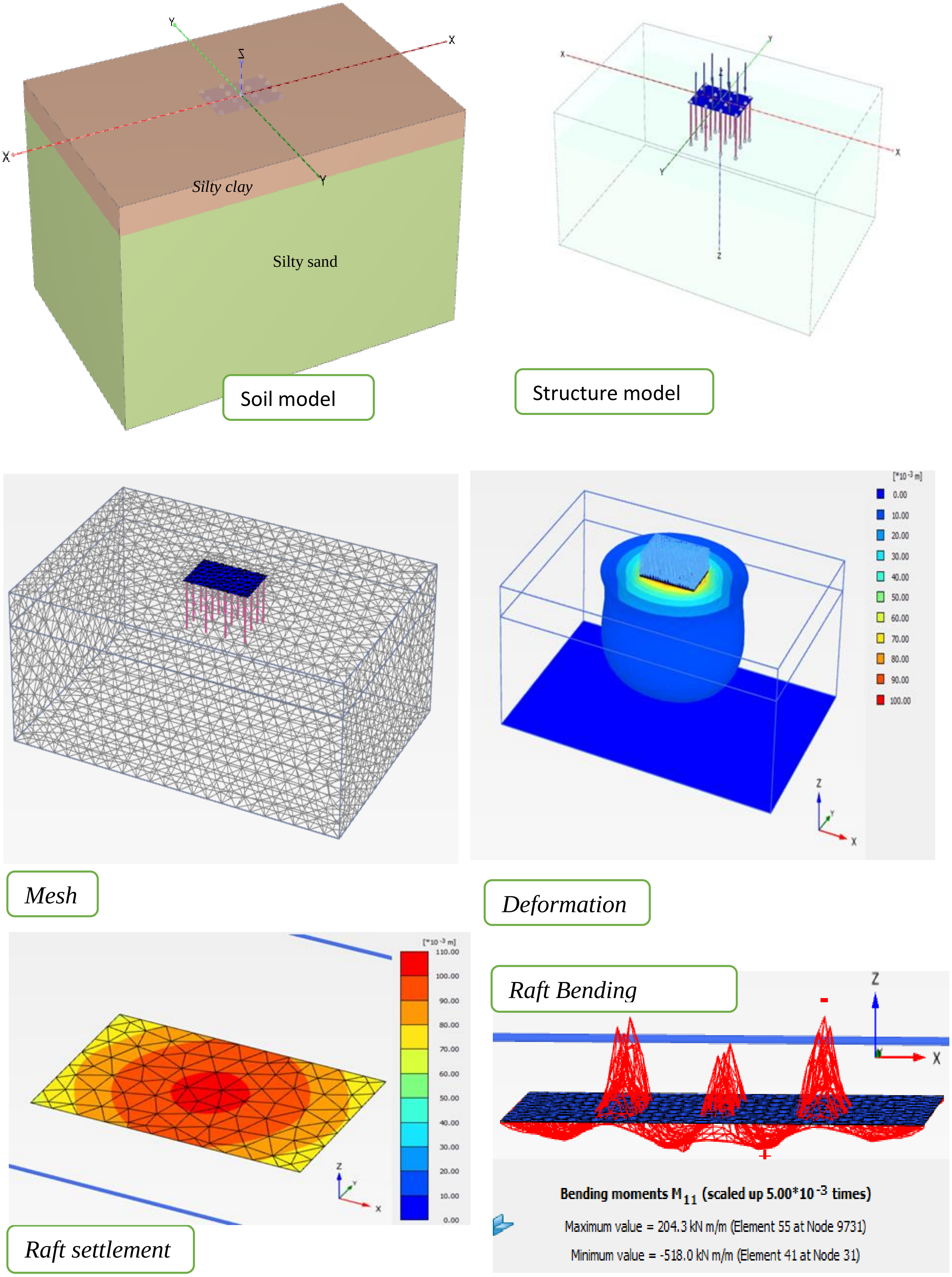


Figure C.2: Design raft foundation using SAFE software



Bending moments M_{11} (scaled up $5.00*10^{-3}$ times)

Maximum value = 204.3 kN m/m (Element 55 at Node 9731)

Minimum value = -518.0 kN m/m (Element 41 at Node 31)

Figure C.3: Numerical modeling using PLAXIS 3D software

Appendix D: Borehole Data

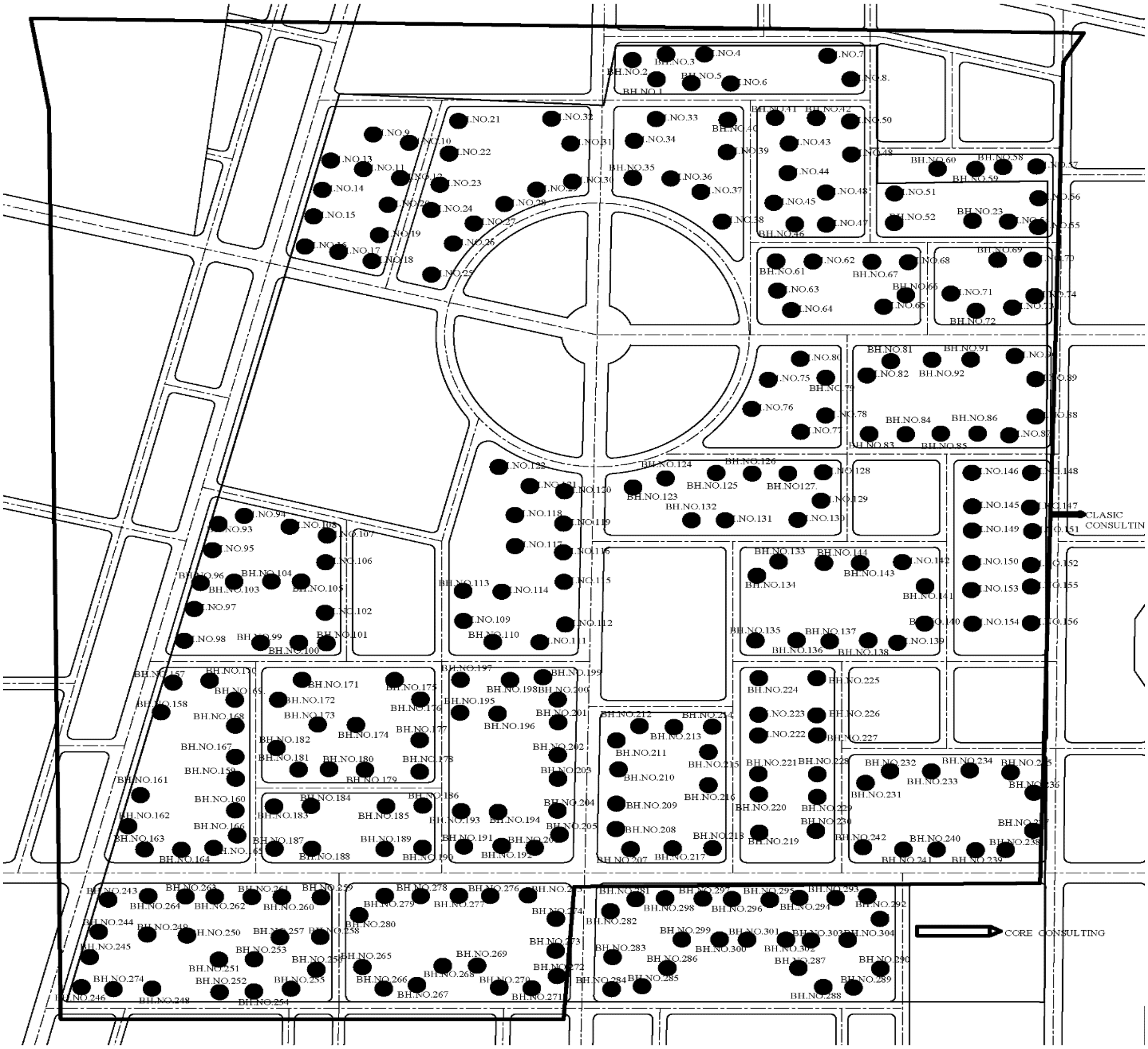


Figure D.1: Placement of boreholes for Bole Arabsa V

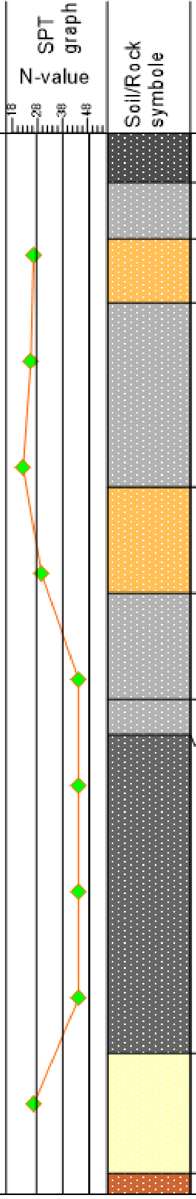
The mode is a statistical concept representing the most frequently occurring value or observation within a dataset. It is widely employed in descriptive statistics as a measure of central tendency, complementing the mean and median (D. E. Johnson, 2014). Consequently, the mode was utilized in the present study to represent the SPT N value.

SPT (N) value for silty clay = 12

SPT (N) value for silty sand = 30

Project	Client	Geotechnical Consultant
ARABSA 5	Addis Ababa Housing Construction Project Office	Classic Consulting Engineers PLC

Location/Chainage: BOLE ARABSA	Drilling Method: Rotary	
Coordinates (E/N): 486256/990087.85	Core diameter (mm): 87	Sheet: 1 of 1
Ground Elevation (masl.): -	Casing Dia & depth: 90mm/5m	BH Inclination: 90°
Borehole No.:BH 10 [G+7 Bldg]	Date Started: 28-Jan-2016	Bit type: Carbide/Diamond
Total Depth (m): 15	Date Completed: 28-Jan-2016	Type of Rig: XYT-2B



Depth (m)	Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)	Sample depth	Sample type	SPT	N	Soil/Rock description	Ground water level (m)
0 1	1.50	100								Dark grey silty Clay [Black Cotton soil] Greyish white silty Clay	
2 3	3.00	100				1.5 1.95	D	4,6,7	13	Yellowish brown clayey silty Sand Reddish to greyish white silty Clay	
4	4.50	100				3 3.45	D	5,6,6	12		
5 6	6.00	100				4.5 4.95	D	4,3,6	9	Yellowish brown silty Clay	
	6.50	100				6 6.45	D	7,8,8	16		
7	7.30	100								Greyish white silty sandy Gravel with some rock	
8	8.00	100				7.5 7.95	D	R	30		
9	9.00	100								Greyish white to reddish brown clayey silty Sand Greyish black silty Sand	
10	10.00	100				9 9.45	D	R	30		
11	11	100				10.5 10.95	D	R	30		
12	12	100									
13	13	100				12 12.45	D	R	30	Yellowish silty Clay	
14	14	100				13.5 13.95	D	5,6,7	13		
15	15	100								Reddish brown silty Sand with	

Driller: Assefa Ababu Logged by: Haile Meskel Checked by: Haile Meskel

Note:

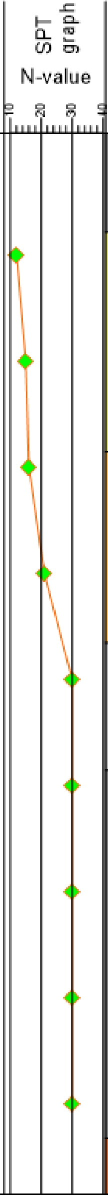
D=Disturbed Sample (Split spoon)
UD=Undisturbed Sample
RC=Rock Core Sample
SPT=Standard Penetration Test

SCR=Solid Core Recovery
RQD=Rock Quality Designation
AFS=Average Fracture Spacing

Project	Client	Geotechnical Consultant
ARABSA 5	Addis Ababa Housing Construction Project Office	Classic Consulting Engineers PLC

Location/Chainage: BOLE ARABSA	Drilling Method: Rotary	
Coordinates (E/N): 486244.23/990043.62	Core diameter (mm): 87	Sheet: 1 of 1
Ground Elevation (masl.): -	Casing Dia & depth: 90mm/5m	BH Inclination: 90°
Borehole No.:BH 23 [G+7 Bldg]	Date Started: 5-Feb-2016	Bit type: Carbide/Diamond
Total Depth (m): 15	Date Completed: 5-Feb-2016	Type of Rig: XYT-2B

Depth (m)	Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)	Sample depth	Sample type	SPT	N	Soil/Rock symbole	Soil/Rock description	Ground water level (m)
0 1	1.50	100								▒	Dark grey silty Clay [Black Cotton soil]	
2 3	3.00	100				1.5 1.95	D	5,6,6	12	▒	Greyish green to yellowish Red silty Clay	
4	4.50	100				3 3.45	D	6,7,8	15			
5 6	6.00	100				4.5 4.95	D	6,7,9	16	▒	Yellowish brown silty Clay with some sand	
	6.50	100				6 6.45	D	8,10,11	21			
7	7.30	100										
8	8.00	100				7.5 7.95	D	R	30	▒	Greyish white silty Sand	
9	9.00	100										
10	10.00	100				9 9.45	D	R	30	▒	Greyish black silty Sand	
11	11	100				10.5 10.95	D	R	30			
12	12	100										
13	13	100				12 12.45	D	R	30			
14	14	100				13.5 13.95	D	R	30			
15	15	100								▒	Reddish brown silty Clay	



Driller: Assefa Ababu

Logged by: Haile Meskel

Checked by: Haile Meskel

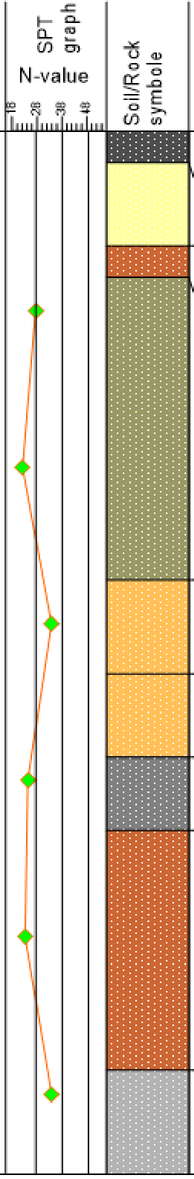
Note:

D=Disturbed Sample (Split spoon)
UD=Undisturbed Sample
RC=Rock Core Sample
SPT=Standard Penetration Test

SCR=Solid Core Recovery
RQD=Rock Quality Designation
AFS=Average Fracture Spacing

Project	Client	Geotechnical Consultant
ARABSA 5	Addis Ababa Housing Construction Project Office	Classic Consulting Engineers PLC

Location/Chainage: BOLE ARABSA	Drilling Method: Rotary	
Coordinates (E/N): 486533/989945.5	Core diameter (mm): 87	Sheet: 1 of 1
Ground Elevation (masl.):	Casing Dia & depth: 90mm/5m	BH Inclination: 90°
Borehole No.:BH 185 [G+4 Bldg]	Date Started: 12-Feb-2016	Bit type: Carbide/Diamond
Total Depth (m): 10	Date Completed: 12-Feb-2016	Type of Rig: XYT-2B



Depth (m)	Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)	Sample depth	Sample type	SPT	N	Soil/Rock description	Ground water level (m)
0 1	1.50	100								Dark grey silty Clay [Black Cotton soil] Yellowish silty Clay Reddish brown silty Clay with some sand	
2	3.00	100				1.5 1.95	D	8,11,13	24	Greyish green silty Clay	
3 4	4.50	100				3 3.45	D	9,9,10	19		
5	6.00	100				4.5 4.95	D	R	30	Greyish to yellowish brown silty Sand Yellowish brown silty Clay with some gravel	
6	6.50	100				6 6.45	D	8,10,11	21	Greyish black clayey Silt	
7	7.30	100								Reddish brown silty Sand	
8	8.00	100				7.5 7.95	D	9,10,10	20		
9	9.00	100									
10	10.00	100				9 9.45	D	R	30	Greyish white silty Sand	

Driller: Assefa Ababu

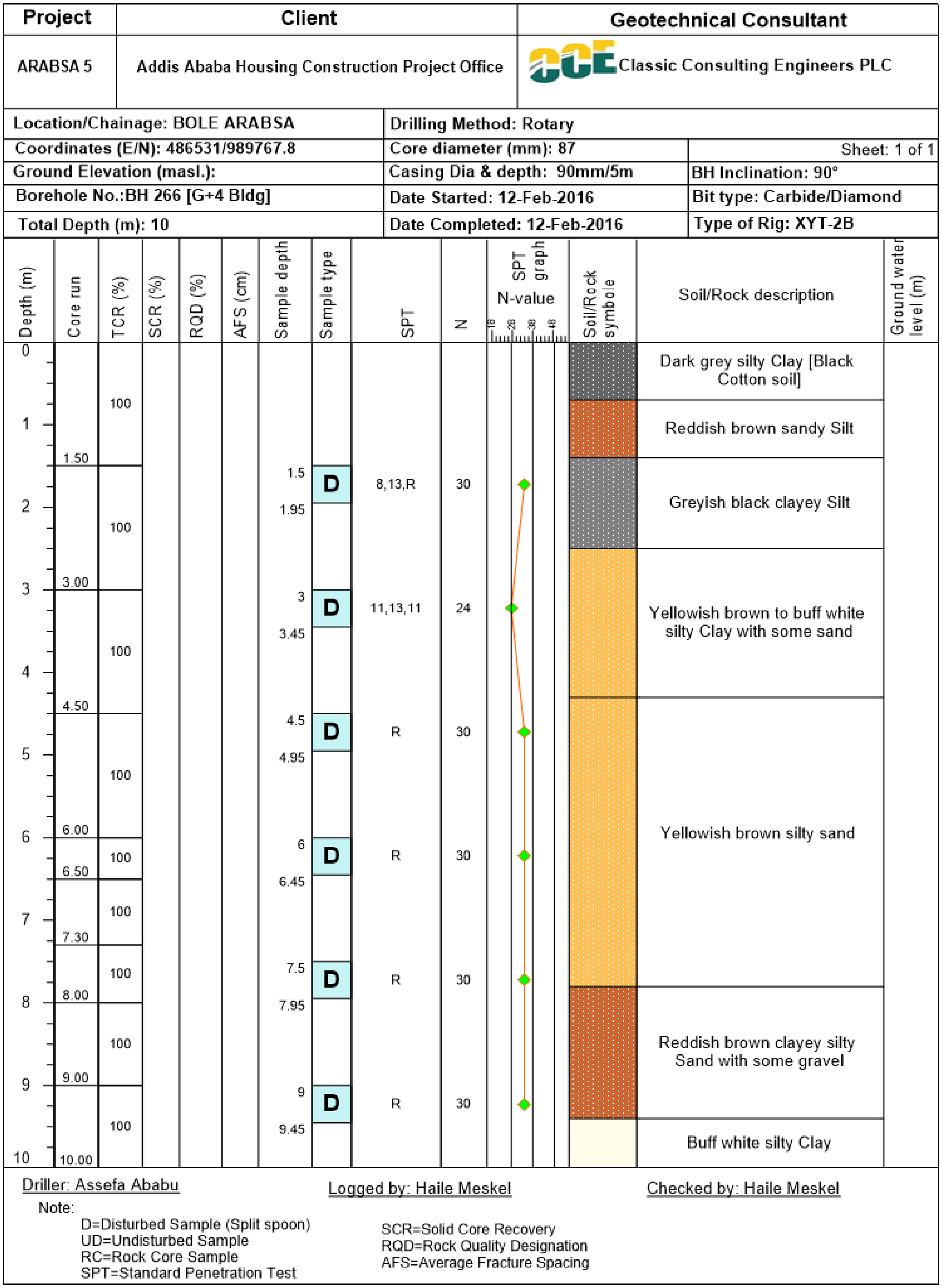
Logged by: Haile Meskel

Checked by: Haile Meskel

Note:

D=Disturbed Sample (Split spoon)
UD=Undisturbed Sample
RC=Rock Core Sample
SPT=Standard Penetration Test

SCR=Solid Core Recovery
RQD=Rock Quality Designation
AFS=Average Fracture Spacing



Project	Client	Geotechnical Consultant
ARABSA 5	Addis Ababa Housing Construction Project Office	Classic Consulting Engineers PLC

Location/Chainage: BOLE ARABSA	Drilling Method: Rotary	
Coordinates (E/N): 486531/989767.8	Core diameter (mm): 87	Sheet: 1 of 1
Ground Elevation (masl.):	Casing Dia & depth: 90mm/5m	BH Inclination: 90°
Borehole No.:BH 266 [G+4 Bldg]	Date Started: 12-Feb-2016	Bit type: Carbide/Diamond
Total Depth (m): 10	Date Completed: 12-Feb-2016	Type of Rig: XYT-2B

Depth (m)	Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)	Sample depth	Sample type	SPT	N	SPT graph N-value	Soil/Rock symbole	Soil/Rock description	Ground water level (m)
0												Dark grey silty Clay [Black Cotton soil]	
1	1.50	100										Reddish brown sandy Silt	
2	3.00	100				1.5 1.95	D	8,13,R	30			Greyish black clayey Silt	
3	4.50	100				3 3.45	D	11,13,11	24			Yellowish brown to buff white silty Clay with some sand	
4													
5	6.00	100				4.5 4.95	D	R	30			Yellowish brown silty sand	
6	6.50	100				6 6.45	D	R	30				
7	7.30	100											
8	8.00	100				7.5 7.95	D	R	30			Reddish brown clayey silty Sand with some gravel	
9	9.00	100				9 9.45	D	R	30			Buff white silty Clay	
10	10.00	100											

Driller: Assefa Ababu

Logged by: Haile Meskel

Checked by: Haile Meskel

Note:

D=Disturbed Sample (Split spoon)
UD=Undisturbed Sample
RC=Rock Core Sample
SPT=Standard Penetration Test

SCR=Solid Core Recovery
RQD=Rock Quality Designation
AFS=Average Fracture Spacing

Figure D.2: Bore log sample from Bole Arabsa borehole