Parametric Study of Piled Raft Foundations Performance in Layered Soil Subjected to Uniform Vertical Loading

Biya Degefu Teji

A Thesis Submitted to the Department of Civil Engineering,
School 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 2023
Adama, Ethiopia

Parametric Study of Piled Raft Foundations: Performance in Layered Soil Subjected to Uniform Vertical Loading

Biya Degefu Teji

Advisor: Argaw asha (PhD)

A Thesis Submitted to the Department of Civil Engineering,

School 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 2023
Adama, Ethiopia

DECLARATION

I hereby declare that this Master Thesis entitled "**Parametric Study of Piled Raft Foundations Performance in Layered Soil Subjected to Uniform Vertical Loading**" 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.

Biya Degefu Teji	____________________	____________________
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 "**Parametric Study of Piled Raft Foundations Performance in Layered Soil Subjected to Uniform Vertical Loading**" prepared under my guidance by Biya Degefu Teji.

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 "**Parametric Study of Piled Raft Foundations Performance in Layered Soil Subjected to Uniform Vertical Loading**" by Biya Degefu.

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 Biya Degefu have read and evaluated the thesis entitled "**Parametric Study of Piled Raft Foundations Performance in Layered Soil Subjected to Uniform Vertical Loading**" 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 School Graduate Committee (SGC).

____________________	____________________	____________________
Department Head	Signature	Date
____________________	____________________	____________________
School Dean	Signature	Date
____________________	____________________	____________________
Office of Postgraduate Studies,	Dean Signature	Date

ACKNOWLEDGEMENT

Foremost, I would like to thank my Almighty God and his Mother Saint Mary 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. Additionally, I appreciate the support of Mr. Brhane Gebru beside my adviser. 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 Adama Science and Technology University for sponsoring my postgraduate studies and funding 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.

ABSTRACT

Rapid urbanization has necessitated the construction of large civil structures, often on soft soil sites, that can cause settling, especially in urban areas with limited rock sites. Strict safety regulations require minimal differential settlement in high-rise buildings, despite their considerable weight. For the past four to five decades, piled raft foundations have been successfully used throughout the world to maximize civil engineering structure foundations by creating a composite foundation in which the piles are used as settlement reducers and share the load from the superstructure with the raft. In these foundations, piles act as settlement reducers and share the superstructure's load with the raft. Due to the complex soil-structure interaction in pile raft foundations and the absence of field data, numerical approaches are frequently needed. In this study, the load-settlement behavior of piled raft from previous numerical works was analytically simulated to validate the 3D finite element model. The performance of a rectangular combination piled raft system is evaluated in layered soil subjected to uniform vertical loading. The analysis is conducted using the powerful finite element-based program Plaxis 3D to examine the effects of various parameters. A parametric study is also carried out to investigate the response of piled-raft foundations, including the influence of raft thickness, number of piles, pile length, spacing of piles, and pile diameter. It was observed that by increasing raft thickness from 0.7 to 1.7m, the differential settlement was reduced by 78.21% for the case of the 16-pile number. However, the maximum settlement increased by 2.81%. By increasing the number of piles from 4 to 16, the maximum settlement amount was reduced by 22.09% for 4D pile spacing. Additionally, from the total settlement reduction obtained by increasing pile length, a 19.49% reduction was achieved by increasing the pile length from 9m to 15m in the case of 5D pile spacing. Hence, the findings from the current research can serve as a framework for examining and developing large piled-raft foundations.

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

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

R_{total},s	Settlement dependent on the total resistance of pile and raft
R_{raft},s	Settlement-dependent resistance of raft
R_{pile},k,j	Settlement-dependent resistance of pile
α_{pr}	piled raft coefficient
c	Cohesion
D	Depth of pile
ψ	Dilatancy angle
δ	Angular distortion
K_{rs}	Raft soil stiffness ratio
σ_{ii}	Normal stress
γ	Unit weight
E	Modulus of elasticity
v	Poisson's ratio
σ_f	Failure Normal stress
τ_f	Failure shear stress
ø	Friction angle
h	Group efficiency
f_{avg}	Average unit frictional resistance
Q_{pt}	The load carried at the pile tip
Q_s	The load carried by skin friction of the pile
Q_p	Load carrying capacity of the pile
Q_{pr}	Load carrying capacity of unpiled raft
a_r, b_r	model parameters for the normalized hyperbolic
n	Number of piles
P_g	The perimeter of the cross-section block
X_g	Pile group effect factor
L_p	Pile length
L_r	Raft length
B_r	Raft width
$Q_{g(u)}$	The ultimate load-bearing capacity of each pile without the group effect
B_g	Pile group width
A_g	Pilee 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

CHAPTER ONE

1. INTRODUCTION

1.1. Background

The rapid urbanization of recent decades has increased the need for large civil structures, such as high-rise buildings, bridges, power plants, and industrial facilities. However, many of these structures are being built on soft soil sites, which can result in ground settling, particularly in urban areas where there are few rock sites available. Given the strict safety regulations, the allowable differential settlement of the structure in high-rise buildings is very small, despite the tremendous weight of the structure. Adequate foundations are essential to transfer loads from the superstructure to the substructure.

Buildings are constructed from the ground up, but if the foundation fails, the entire building could collapse or fail in many other ways. In cases where a heavy structure is built on weak soil, a shallow raft foundation may not meet the design criteria, necessitating load transmission to a deeper, more capable layer. Piled foundations have been developed to support the excessive loads caused by superstructures and to prevent excessive settlements. However, due to the load-sharing mechanism between piles, rafts, and soil, it is not feasible to construct foundations using only piles or rafts. This would lead to high construction costs and excessive differential settlement, respectively. Consequently, "Piled Raft Foundations," a combination of two distinct systems, have been created (Clancy & Randolph, 1993).

In recent years, there has been an increased focus on the use of sustainability principles in engineering design. Piled raft foundations have been shown to offer several benefits in this regard, including the use of less material than conventional foundations, reduced construction time and associated costs, and a smaller environmental impact. Additionally, the use of piled raft foundations can help to reduce the amount of excavation required, which can limit the impact on the environment and surrounding communities. As such, the use of piled raft foundations can be seen as a sustainable alternative to conventional 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. Therefore, numerical approaches are often utilized to solve these problems, particularly with the development of advanced understanding and high-performance computing tools (Poulos, 2001a).

There are three broad classes of numerical analysis methods for piled raft foundation systems: (1) simplified calculation methods, (2) approximate computer-based methods, and (3) more rigorous computer-based methods. Among these methods, 3D linear/nonlinear finite element or finite difference methods are the most feasible (Poulos, 2001a). Nonlinear 3D finite element and finite difference analyses have been carried out recently. Nevertheless, difficulties in modeling the soil-structure interface continue to be a challenge in this 3D finite element and finite difference analyses.

The main difficulty in applying numerical methods to piled raft foundation systems lies in selecting appropriate input parameters to provide effective output results. By performing a back analysis on well-documented case histories, the process of determining suitable values for these input parameters can be altered. In parametric analyses, different parameters are analyzed to investigate the behavior of piled raft foundation systems under axial loads. Many studies in the literature focused on the parameters such as pile number, pile length, pile diameter, pile spacing ratio, pile location, pile stiffness, load distribution, load level, raft thickness, raft dimensions, and soil type (Yamashita et al., 2011).

Another important factor in the design of piled raft foundations is the type of soil present at the site. Different soil types have varying characteristics that can impact the performance of the foundation. For instance, in soft soils, it may be necessary to increase the length or number of piles to ensure adequate support for the structure. Similarly, in areas with high water content, the soil may be susceptible to settlement, and it may be necessary to increase the raft thickness to prevent differential settlement. A thorough understanding of the soil conditions is therefore critical in the design and construction of piled raft foundations (Nguyen et al., 2013).

It is important to note that the behavior of piled raft foundations is still not fully understood, and there is ongoing research to better understand the interaction between the pile, raft, and soil. Recent studies have suggested that there may be a need to consider the influence of factors such as pile spacing, pile arrangement, and soil-structure interaction on the behavior of piled raft foundations. In addition, further research is needed to evaluate the impact of these factors on the long-term performance of piled raft foundations (Lee et al., 2015).

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

Due to the heavy weight of the building, using a raft foundation in many cases only results in excessive settlements that are not acceptable due to serviceability limit state requirements. However, systematically positioning piles beneath the raft can diminish these settlements to acceptable levels. Moreover, the overall bearing capacity of the foundation system is enhanced along with the reduction in settlements (Roshan & Shooshpasha, 2014). 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 (Poulos, 2001b).

Most of our country's research has primarily focused on comparing the effectiveness of pile raft foundations with standalone pile and raft structures. This is beneficial in determining the most appropriate option based on factors such as economic feasibility, settlement reduction, and other considerations. However, once a pile raft foundation design is chosen, it necessitates the evaluation of various parameters, including raft thickness, pile length, pile diameter, pile spacing, pile orientation, load levels, and more. Although most research focuses on square raft models, real-world scenarios demonstrate that structures deviate from this standard form, requiring a variety of foundation shapes, typically approximating a rectangular form.

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 Objectives

The general objective of this study is to investigate the performance of piled raft foundations in layered soil under uniform vertical loading through a comprehensive parametric study.

1.3.2. Specific Objectives

- Assess the settlement performance of piled raft foundation in response to uniform vertical loading;
- Perform and compare settlement analyses for various piled raft foundation configurations, considering variations in pile spacing, diameter, length, and number;
- Investigate the settlement behavior of piled rafts with different raft thicknesses.

1.4. Significant of the Study

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. This research contributes to the analysis and design of piled raft foundations.

Through numerical model tests, this study offers valuable insight into the settlement behavior of rafts on settlement-reducing piles and the load-sharing dynamics between piles and rafts. These findings can potentially provide practical guidelines for the cost-effective design of rafts on settlement-reducing piles, benefiting both the construction industry and future infrastructure projects that utilize such foundational designs.

1.5. Scope of the Study

A uniformly distributed vertical load that acted on the foundation system was the only consideration in the parametric study of pile raft foundation as a displacement control on weak soils in Addis Ababa. For this study, no further fieldwork or lab testing was conducted; instead, all relevant information was gathered from the design office and different literature. The study focused solely on static analysis, excluding dynamic analysis, such as the effects of vibration and seismic loads on piled raft foundations, since the study area is located in earthquake zone 3.

1.6. Limitation of the Study

The collected data did not have complete information; as a result, this study employed various correlation equations and standards extracted from different literature.

1.7. Organization of the Study

The study was organized mainly into five chapters. The first chapter introduces the background, the statement of the problem, the objectives, and the scope of the study. The second chapter was mainly a literature review that stated the study's matter. This section covers reviews on the concept of pile raft foundation; design philosophy of pile raft foundation; design considerations in pile raft foundation; method of analysis for pile raft foundation; load carrying behavior of pile raft foundation; parametric studies; finite element modeling of pile raft foundation; soil distribution in Addis Ababa; and research gaps were covered. The methodology for the study is presented in the third chapter, which includes the input subsoil, pile, and raft material parameters, along with the suggested constitutive behavior that controls them. Additionally, a numerical model used for the study is discussed. The fourth chapter relied on the presentation, analysis, and interpretation of results. The fifth chapter was concerned with the conclusion and recommendations.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Introduction

The objective of any foundation is to transmit the load to the soil to provide safety, reliability, and serviceability to the structure (Sinha & Hanna, 2017). In the design of the foundation, the first alternative is a shallow foundation, which can support a superstructure's weight without experiencing severe total or differential settlements, as long as the topsoil has enough bearing strength to do so. However, even in areas with poor subsoil conditions, the demand for Highrise buildings and high-loaded superstructures has expanded quickly in recent decades. As a result, there is a greater demand for foundations with strong bearing capacities and low total and differential settling values.

The transfer of loads can be improved through the use of different types of foundations. Raft foundations are a common solution for distributing the weight of a building evenly across its base. In instances where soil pressure is low, or building loads are heavy, spread footings may not be enough and a raft foundation might be more cost-effective. Although raft foundations can meet the required bearing capacity, they may not limit differential and total settlements within acceptable limits. An alternative option for heavy load transfer is the use of deep foundations such as pile foundations. These are used when there are no firm bearing layers within reachable depths and the loading is uneven. The pile foundation takes the load deeper into the ground, and the length of the pile may need to be long to accommodate the load-bearing capacity.

The challenges posed by either raft or pile foundations can be avoided by using a combined pile raft foundation (CPRF) system, which combines both types of foundations for more economical and efficient results (R. T. Johnson et al., 2019). 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.

Over the past few decades, the evaluation of piled raft foundations has advanced to consider the collective contribution of both the piles and the raft to create a more effective system. Piles are structural components made from steel, concrete, or timber, used when the upper soil layers are too weak or compressible to support the superstructure's weight, with piles used to transmit the load to the underlying bedrock or stronger soil layer (Das, 2011). Conversely, raft foundations cover the entire building area, transmitting the entire structural load and reducing differential settlements. Piles are generally lengthy and slender, and they transfer foundation loads through soil layers of low bearing capacity to deeper soil and rock layers with high bearing capacity (Srilakshmi & Darshan Moudgalya, 2013).

2.2. The Concept of Pile Raft Foundation

Shallow foundations like rafts are suitable for competent soils near the surface. However, excessive settlement can occur even with adequate safety factors against bearing capacity failure. To control raft settlements, bearing pressures can be reduced. Piled rafts are composite foundations that utilize piles as settlement reducers and load sharers with the raft. The load is transferred from the raft to the shallow soil and pile heads and then diffused to deeper soil through the pile shaft and base. Full-scale model tests under various conditions and configurations are necessary to investigate the interaction among the foundation components (Sinha, 2013).

A piled raft foundation is a composite system where both piles and the raft share the load. The number of piles in a conventional piled foundation can be reduced significantly by considering the contribution of the raft. The piles provide most of the foundation's stiffness, while the raft provides additional load capacity. Adding piles to a raft foundation can enhance its performance when the raft alone does not meet the design requirements, such as settlement requirements.

According to Poulos (2016), using strategically located piles with a raft foundation can improve load capacity and settlement performance. The traditional design assumes 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. However, a small number of piles can cause bending moments and stresses in the pile heads (El-Garhy et al., 2013). Overall, introducing piles to an unpiled raft foundation improves bearing capacity and reduces settlement.

Three options are available for supporting a heavy building on a thick clay deposit. Load-bearing piles can be used if the clay layer has very poor shear strength, while a raft foundation can be used if the clay layer has adequate strength. When the clay layer has intermediate strength, a piled raft can be used to reduce settlements and minimize distress to adjacent structures (Maharaj & Gandhi, 2004).

2.2.1. Soil-Structure Interaction in the Context of CPRF Components

The piled raft foundation is comprised of three load-bearing components, specifically piles, raft, and subsoil. Based on their respective rigidity, the raft distributes the overall load transmitted from the structure to the topsoil and the connected piles (Ata et al., 2015). The use of the CPRF design concept is only applicable to subsoil types that lack very strong and stiff layers at the pile bases compared to the layer directly below the raft. If not, the limited movement of the pile base will draw stresses, ultimately leading to conventional end-bearing piles, as seen in cases where the pile base is in solid rock (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; Katzenbach et al., 2007).

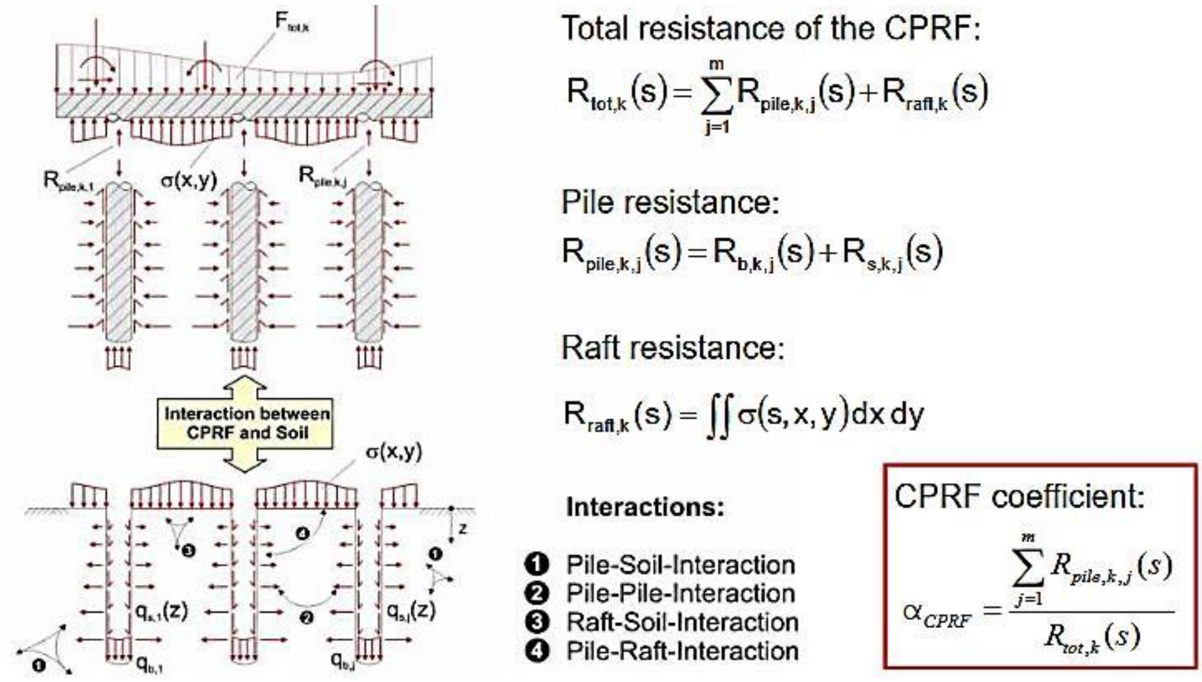


Figure 2.1: Typical Piled Raft Foundation load-bearing elements; soil-structure interaction (Katzenbach et al., 2007)

The study of CPRF systems consists in taking into account the interactions between the different elements in the system (Figure 2.1). Pile-soil interaction is the soil behavior surrounding the pile under loading that affects the pile's capacity and the load distribution to other piles or the raft. Pile-pile interaction is the interaction between neighboring piles in a group, affecting their load-carrying capacity and transfer of loads to adjacent piles. Raft-soil interaction is the interaction between the soil and the raft of a piled raft foundation, affecting the magnitude and distribution of the loads transferred to the piles and the foundation's settlement behavior. Pile-raft interaction is the interaction between the piles and the raft in a piled raft foundation, affecting the distribution of loads within the foundation and the pile's capacity, and the foundation's settlement behavior. The stiffness of the raft and the relative stiffness of the piles are important factors in pile-raft interaction (Nguyen et al., 2013).

2.2.2. Advantage of Pile Raft Foundation

Piled raft foundations are designed to minimize settlements by utilizing piles to provide most of the stiffness at serviceability loads, while the raft element provides additional capacity at ultimate loading. In cases where the raft provides additional capacity, it is possible to reduce the required number of piles. The raft can also provide redundancy to the piles in case some of them are defective or weaker or encounter unfavorable subsoil conditions. The presence of the raft facilitates a certain degree of load redistribution from the impacted piles to the unaffected ones, thereby decreasing the possible impact of pile "weakness" on the overall performance of the foundation (Katzenbach et al., 2007).

An additional benefit of piled rafts is that the pressure exerted by the raft on the soil can enhance the lateral stress between the piles beneath it and the surrounding soil, ultimately increasing the load capacity of a pile compared to those that stand freely. When designing this type of foundation system, a geotechnical evaluation must take into account not only the individual capacities of the pile and raft components but also their combined capacity and interaction during serviceability loading. Piled rafts are best utilized when the raft can supply sufficient load capacity, but the settlement and/or differential settlements of the raft alone exceed the permissible values (Poulos et al., 2011).

According to Poulos (2001), soil profiles consisting of relatively stiff clays or relatively dense sands are favorable for piled raft foundations. In both cases, the raft can offer a considerable percentage of the necessary load capacity and rigidity, with the piles serving to improve the foundation's performance rather than being the primary source of support.

2.3. Piled Raft Design Philosophy

Directly casting a pile cap on the ground can lead to block-type failure, which is beneficial. Within a group of piles, interaction effects initiate slippage between the soil and each pile at its base. However, if the pile cap directly impacts the soil surface, relative slippage cannot happen at shallow levels, leading to the ultimate limit state characterized by the complete punching failure of the entire soil block encompassing the piles. (Franke, 1991).

Randolph (1994) identifies three distinct design methodologies for piled rafts.

2.3.1. Conventional Approach

The conventional approach for foundation design involves uniformly distributing piles over the foundation area to form a pile group that carries the majority of the load, with some consideration for the load transferred from the raft to the ground. This technique is appropriate for Small Piled Rafts that require pile support from a capacity standpoint (Kambala, 2010). The piles are intended to support the bulk of the load, with the raft's contribution primarily to the ultimate load capacity (Poulos, 2001b).

2.3.2. Creep Piling Approach

The Creep Piling Approach involves designing piles to operate at a working load where significant creep occurs, usually 70-80% of the ultimate load capacity. The goal is to take advantage of the compensation in effective stress from the excavated soil by including enough piles to reduce the net contact pressure between the raft and soil. This approach maximizes pile capacity to control the amount of load carried by the raft, and the spacing of the piles is adjusted accordingly (Algulin & Pedersen, 2014).

2.3.3. Differential Settlement Control Approach

The conventional and creep piling methods both involve uniformly distributing piles under the raft to limit absolute settlement. However, a more targeted approach to minimizing differential settlements involves strategically placing the piles to reduce differential settlements without significantly reducing the average settlement (Poulos, 2001b). Figure 2.2 illustrates the load settlement behavior of piled rafts designed based on the three design philosophies.

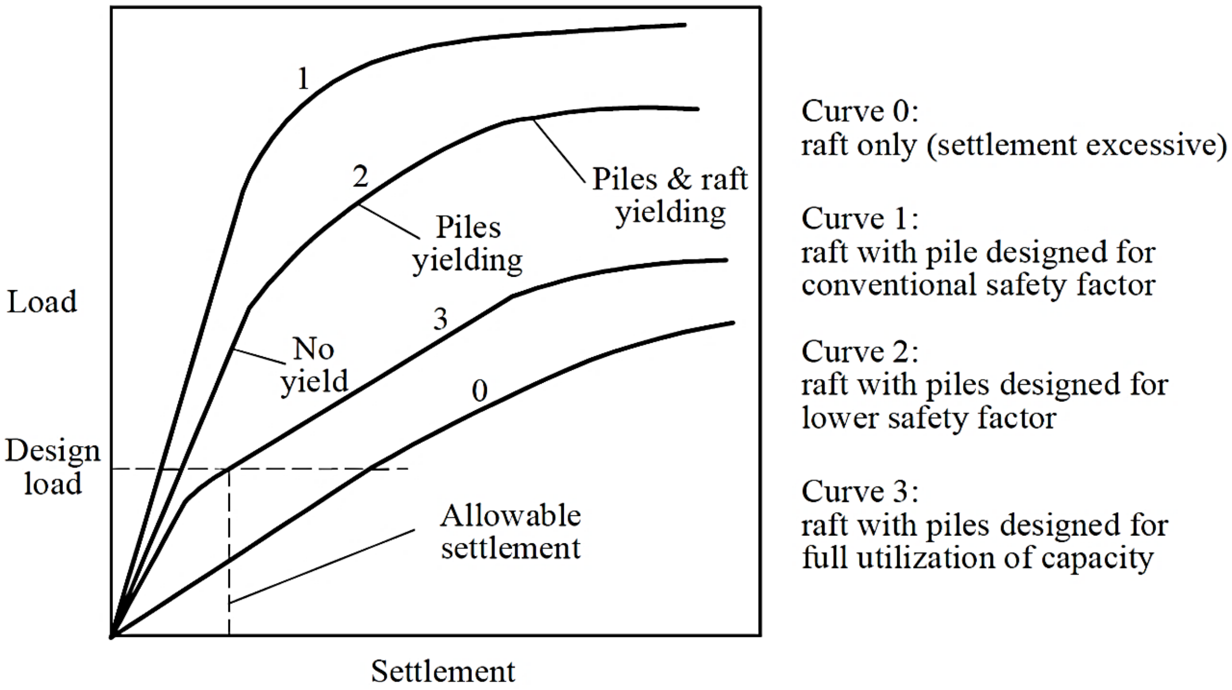


Figure 2.2: Load-settlement behavior for a piled raft, comparing different design philosophies (Poulos, 2001b)

The behavior of a raft alone, which exhibits excessive settlement at the design load, is shown by curve 0. Curve 1 illustrates a conventional piled raft design, where the behavior of the piled raft is governed by the pile group behavior. The creep piling approach, where fewer piles operate at a lower factor of safety and therefore load the raft more, is shown by curve 2. Curve 3 depicts the system of utilizing piles as settlement reducers, where the full capacity of the piles is utilized at the design load. The design shown in Curve 3 is preferred for economic reasons.

2.4. Design Consideration

The design of a piled raft foundation system requires the consideration of several important aspects to ensure an optimum design. These aspects, as highlighted by Poulos (2001), 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. Favorable and Unfavorable Circumstances for Piled Raft

Piled rafts are most effective when the raft alone cannot meet the required load capacity but can provide adequate stiffness and when the soil profiles consist of relatively stiff clays or dense sands. In such cases, the raft provides a significant proportion of the required load capacity, with the piles enhancing the foundation's performance. On the other hand, situations with soft clays or loose sands near the surface, soft compressible layers at shallow depths, soil profiles undergoing consolidation settlements, or swelling movements due to external causes are unfavorable 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 (Poulos, 2001b).

2.5. Method of Analysis

There are various methods for analyzing piled raft foundations, as described by (Poulos, 2000). These methods can be broadly categorized into three classes: simplified calculation methods, approximate computer-based methods, and rigorous computer-based methods. Simplified methods involve hand calculations that use theoretical solutions for the elastic continuum of a raft and piles. This approach involves making several assumptions about soil behavior and loading conditions. Approximate computer-based methods are also based on elastic theory, and 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 & Kouzer, 2015; Van Impe & Lungu, 2001). 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 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.

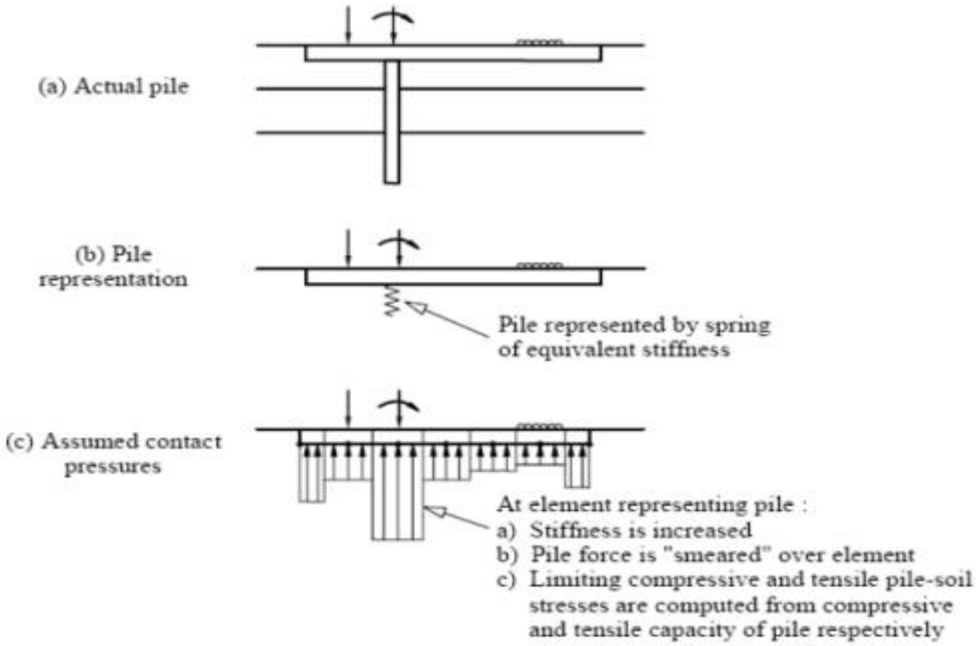


Figure 2.3: Representation of piled raft via GASP analysis (Poulos, 1991)

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. 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.

2.5.3.1. 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. (1994) highlighted that the application of joint elements is restricted in the soil-structure contact.

2.5.3.2. 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, 2011). The ultimate load carried by the pile is given by:

$$\mathrm{R}_{\mathrm{ck}} = \frac{R_{cm}}{x} \tag{2.1}$$

$$\mathrm{R}_{\mathrm{c}} = \frac{R_{ck}}{g_t} \tag{2.2}$$

$$R_c = \frac{R_{bk}}{g_b} + \frac{R_{sk}}{g_s} \tag{2.3}$$

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

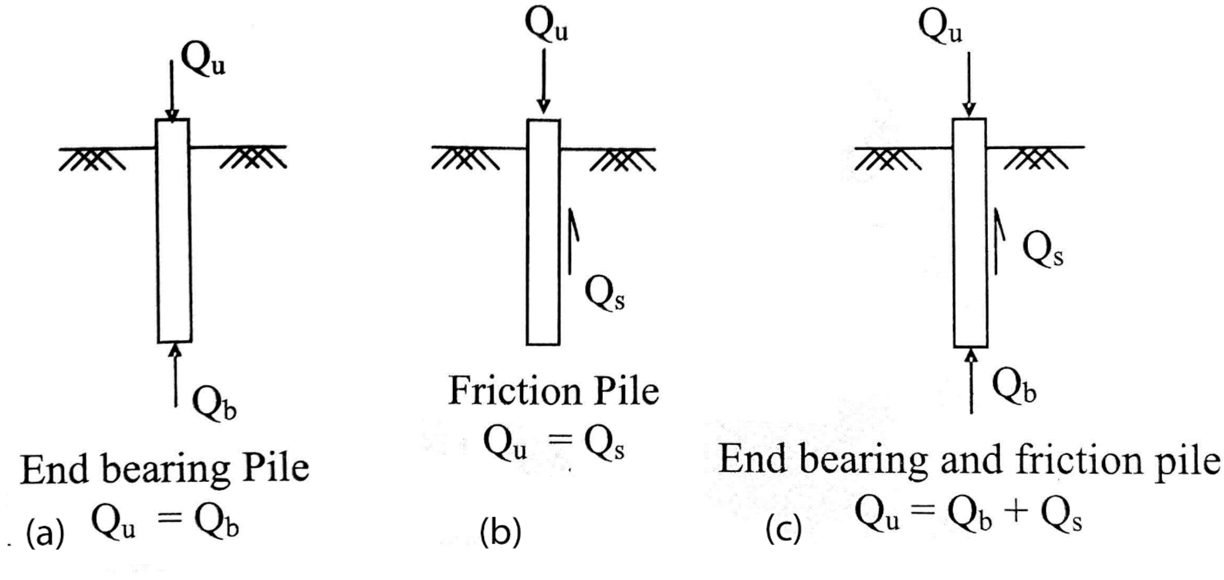


Figure 2.4: The mechanisms of the load transfer to the soil piles: (a) point or end-bearing piles, (b) friction piles, and (c) combined (Das, 2011)

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: -

$$L_g=(n_1-1)s + 2(D/2) \quad (2.4)$$

$$B_g=(n_2-1)s + 2(D/2) \quad (2.5)$$

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, 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:

$$Q_{g(u)}= f_{avg}* P_g* L \tag{2.6}$$

$$P_g=2s(n_1+n_2-2)+4D \tag{2.7}$$

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:

$$Q_{g\,(u)} =h*N*Q_{(u)} \tag{2.8}$$

$$Q_{\,(u)=}f_{avg}* P_s* L \tag{2.9}$$

$$h=\frac{Q_{g(u)}}{NQ_{(u)}}=\frac{2(n_1+n_2+2)s+4D}{f_{avg}*p_{pile}*L} \tag{2.10}$$

$$Q_{g(u)}=\frac{2(n_1+n_2+2)s+4D}{f_{avg}*p_{pile}*L}(N*Q_{(u)}) \tag{2.11}$$

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.

AGI (1984) suggests adopting h= 1, except for those cases for which piles were bored without care. Concerning piles in cohesive soils, Viggiani (2000) suggests assuming h= 0.6-0.7.

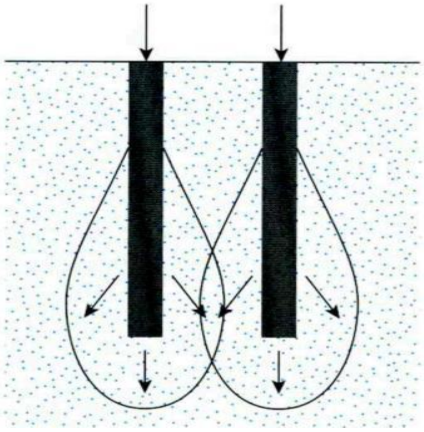


Figure 2.5: Stress overlaps between two piles

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:

$$Q_{pr}=Q_p+Q_r \tag{2.12}$$

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: -

$$Q_{pr}=h_r*Q_{ur} + h_p*Q_{pg} = h_r*Q_{ur} + h_p(x_g*N*Q_{sp}) \tag{2.13}$$

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

$$h_r = Q_r / Q_{ur} \tag{2.14}$$

$$h_p = Q_p / Q_{gp} \tag{2.15}$$

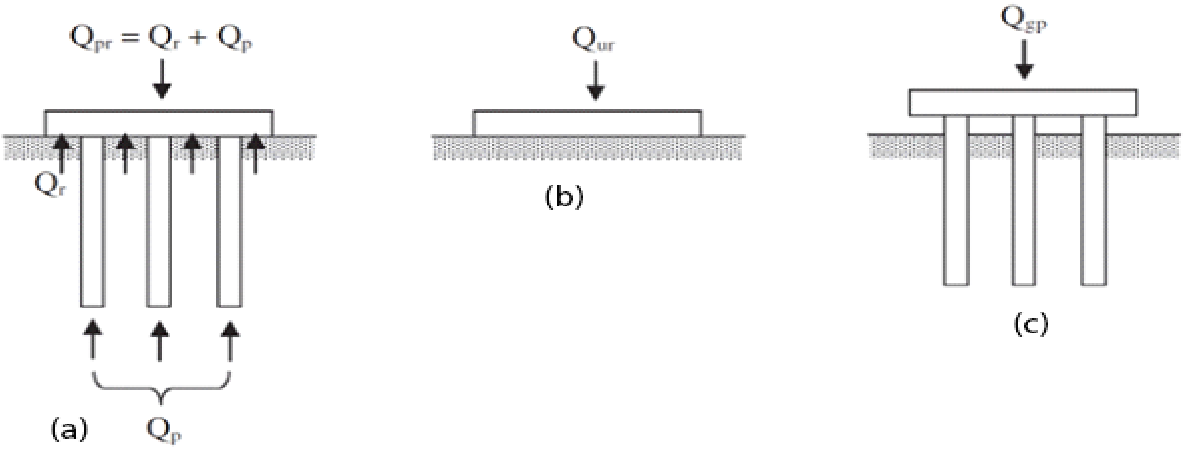


Figure 2.6: A typical configuration of (a) piled raft; (b) unpiled raft; and (c) group piles (Lee et al., 2014)

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.

$$h_r\text{=1-3}\left(\frac{{A_g}/{A_r}}{{S_p}/{D_p}}\right) \qquad (2.16)$$

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.

$$\alpha_p\text{=}\frac{Q_p}{Q_{pr}} = \frac{Q_p}{Q_r+Q_p} = \text{1-}\frac{Q_r}{Q_{pr}} \qquad (2.17)$$

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:

$$Q = \frac{s}{a+b+s} \tag{2.18}$$

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:

$$\frac{Q_r}{Q_{r,u}} = \frac{\frac{s}{B_r}}{a_r+b_r\left(\frac{s}{B_r}\right)} \tag{2.19}$$

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):

$$\frac{Q_p}{Q_{p,u}} = \frac{\frac{s}{D_p}}{a_p+b_p\left(\frac{s}{d_p}\right)} \tag{2.20}$$

Where:

Q_P =load imposed on piles

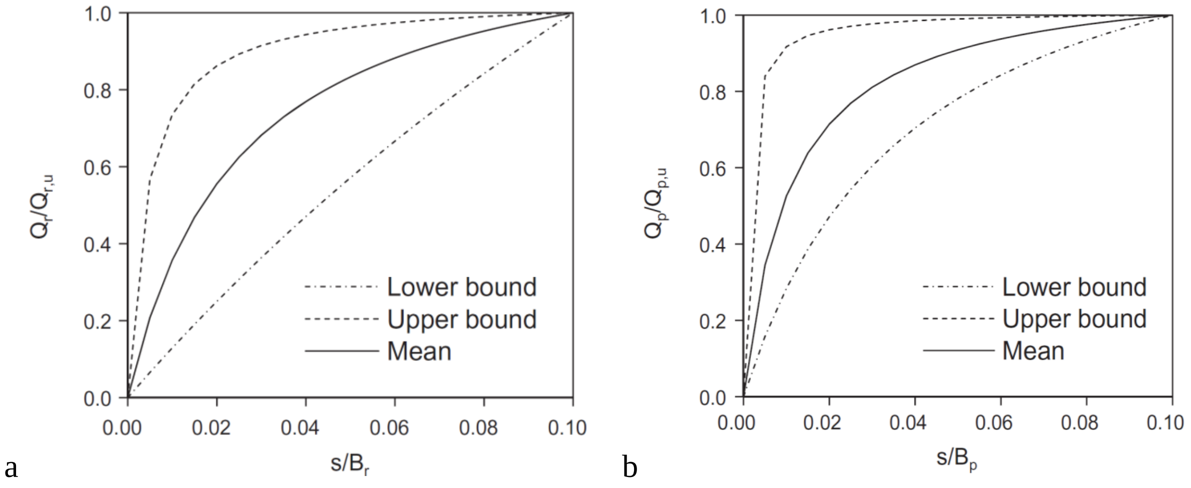
$Q_{P,\,u}$ =the ultimate load capacity of piles

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



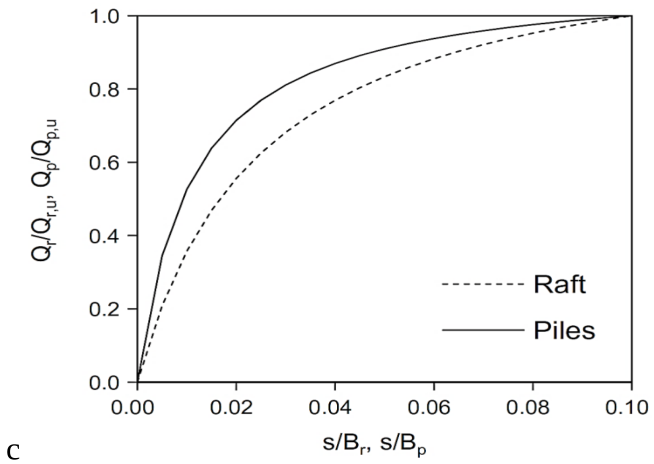


Figure 2.7: Normalized load–settlement curves of (a) raft; (b) piles; and (c) raft and piles Lee et al. (2014)

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

2.7.2.1. 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) explain that the stiffness of the raft can be determined by:

$$K_f = \left[\frac{E_f}{E_s}\right]\left[\frac{2t}{s}\right]^3 \tag{2.21}$$

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.

2.7.2.2. 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.

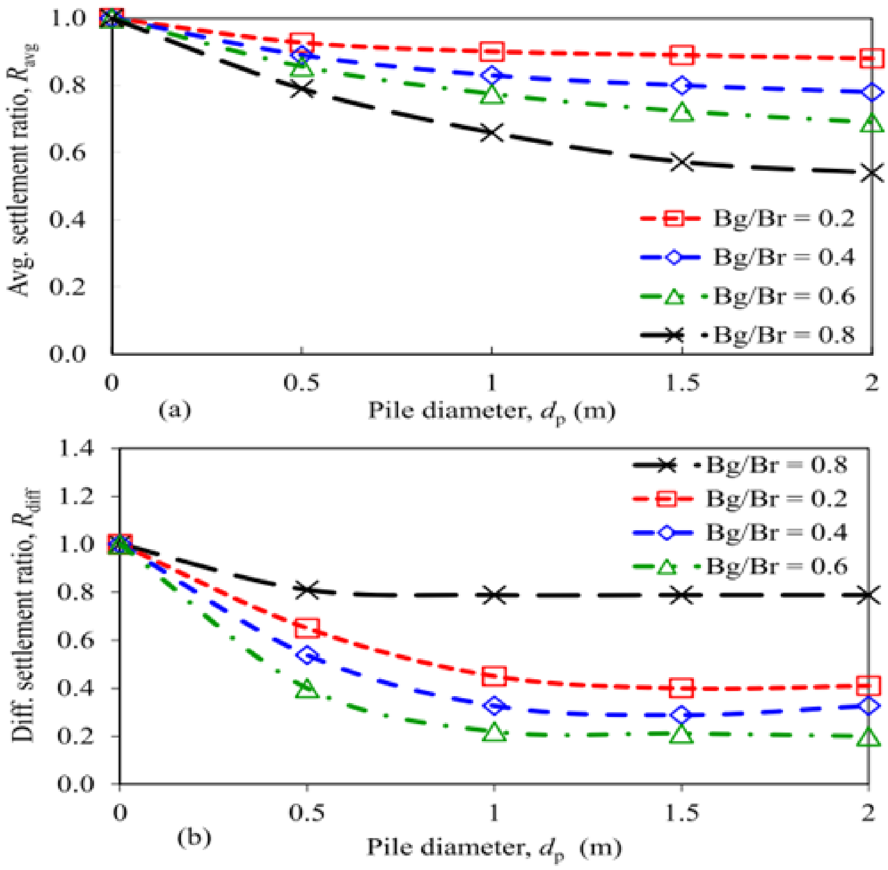


Figure 2.8: Effect of pile diameter on (a) average settlement ratio and (b) differential settlement ratio (Mali & Singh, 2018)

2.7.2.3. 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; Oh et al. (2009) 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. (2015) 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

Samee (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.

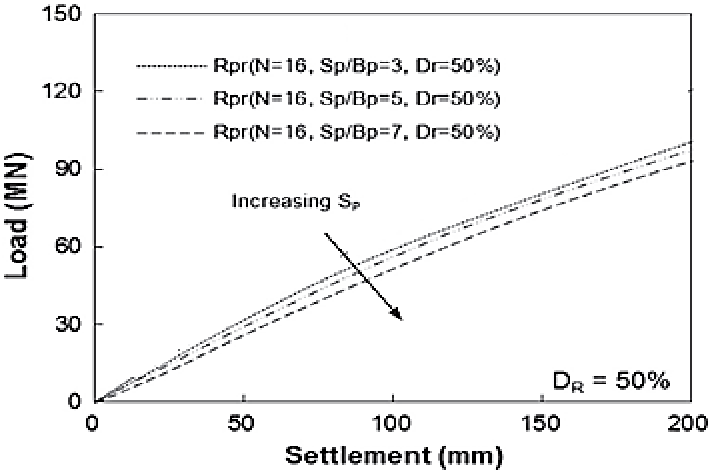


Figure 2.9: Decomposed load–settlement curves of the piled raft with different pile spacing (Lee et al., 2015)

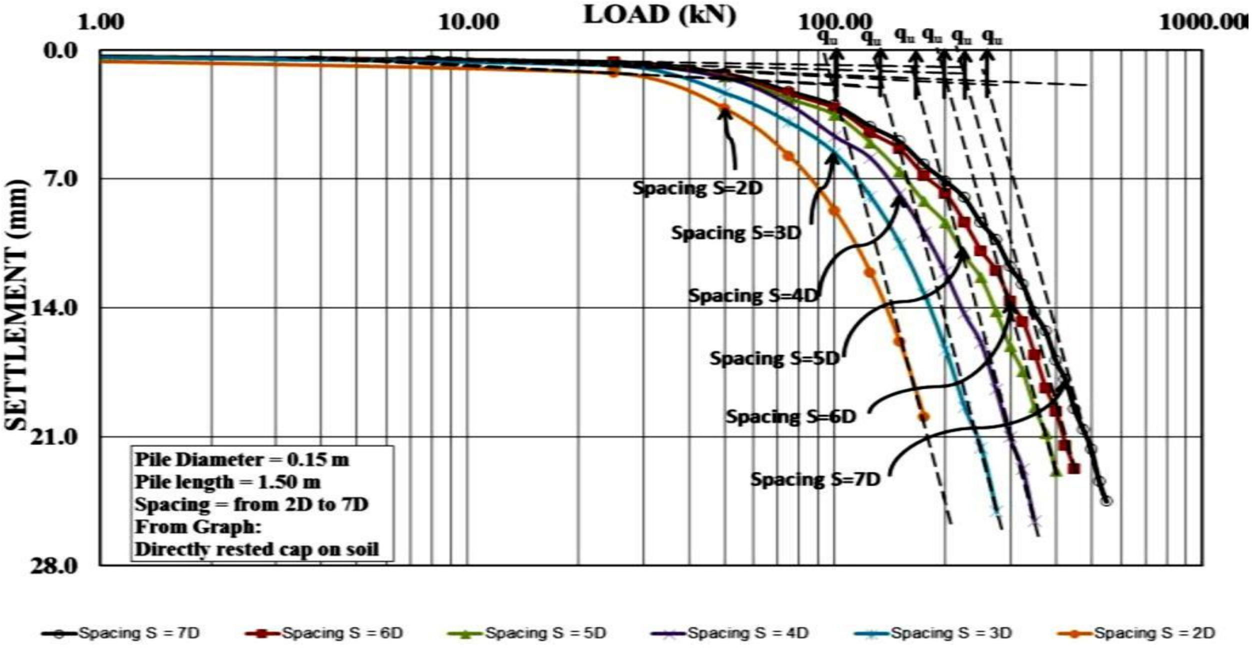


Figure 2.10: Settlement vs load for different pile spacing (Samee, 2018)

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.

2.7.2.4. 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.

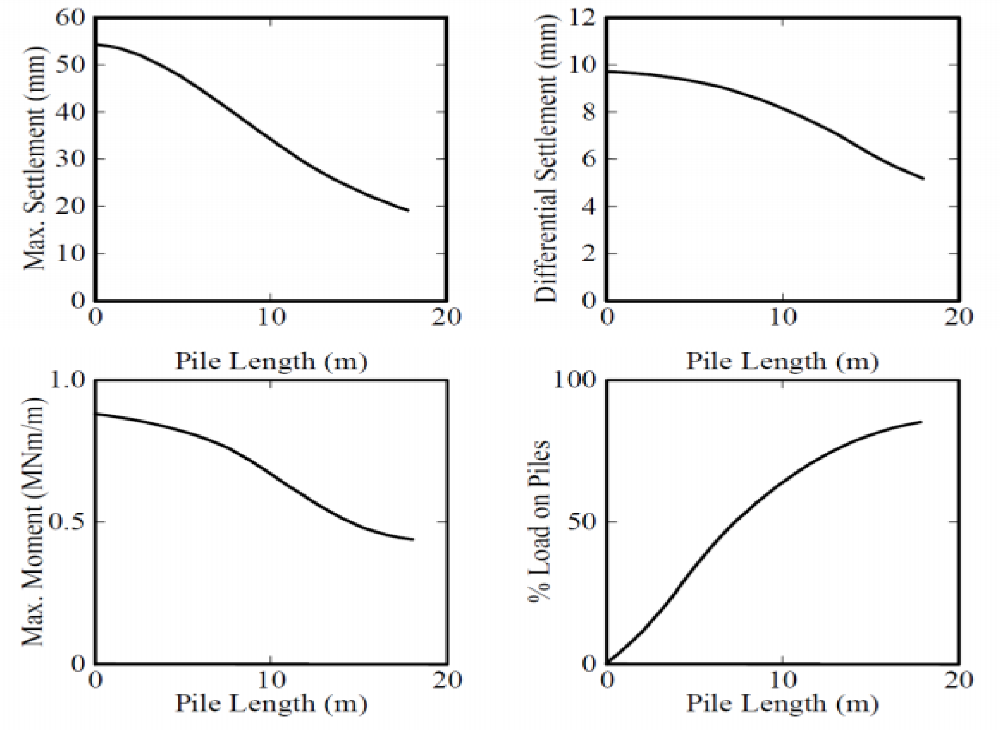


Figure 2.11: Effect of pile length on the foundation (Van Impe & Lungu, 2001)

Van Impe & Lungu (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.

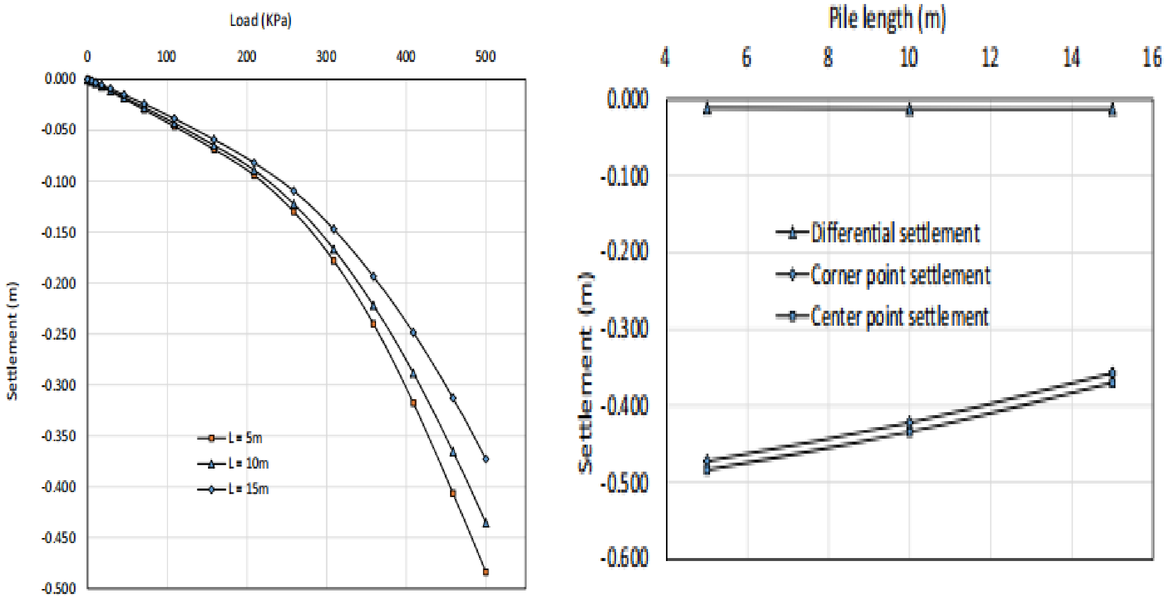


Figure 2.12: Load settlement curve for different pile lengths (Sinha & Hanna, 2017)

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.

2.7.2.5. 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.

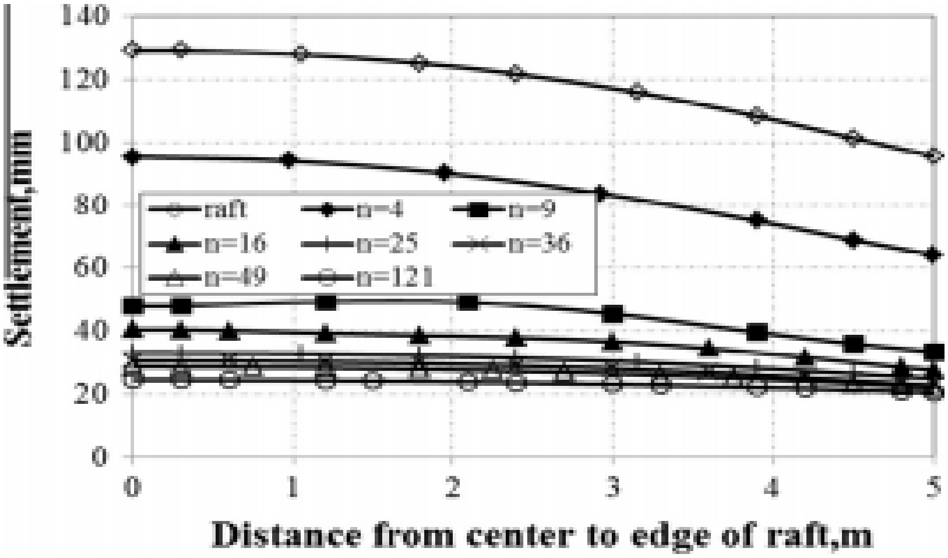
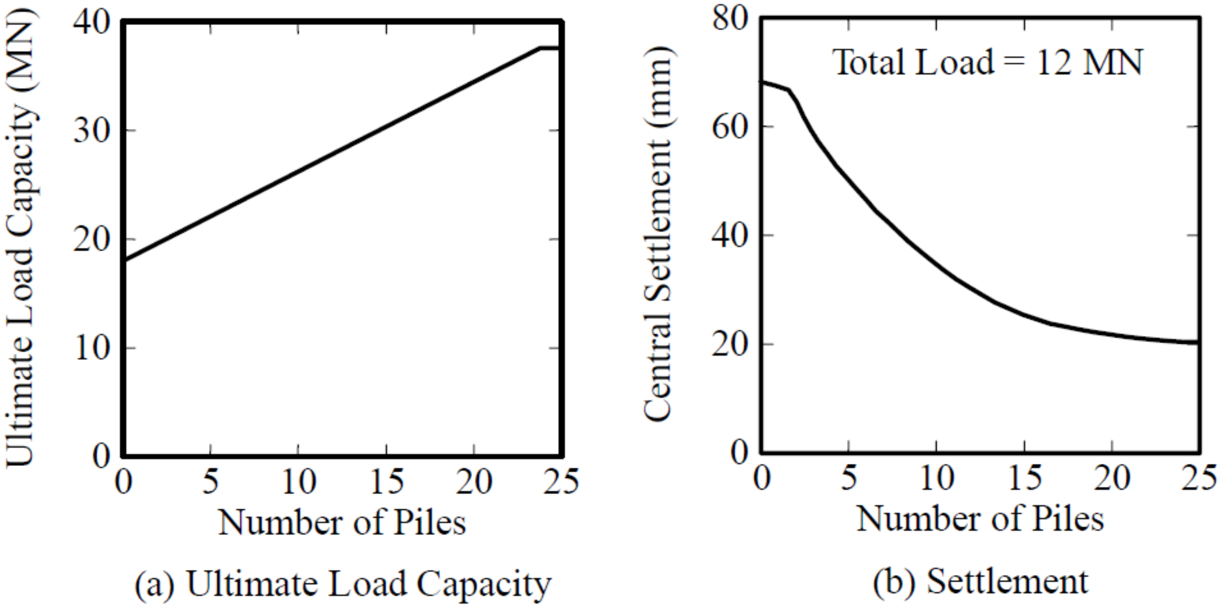


Figure 2.13: Normalized Settlement vs the number of piles (Ata et al., 2015)

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.



(a) Ultimate Load Capacity

(b) Settlement

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 et al., 2020; Ghiasi et al., 2018; Othman & Mohtar, 2021).

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 (R. T. Johnson et al., 2019; 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., 2016).

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 (Classic Consulting Engineers PLC, 2016).

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 (Classic Consulting Engineers PLC, 2016).

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 THREE

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 accomplish these objectives, several steps were followed. First, a detailed literature review was conducted to gain a deep understanding of pile raft foundations, including relevant parameters, methods, and the effects of these parameters on the settlement of the structure. Next, representative data were gathered from geotechnical design offices, companies specializing in geotechnical investigations, and government agencies concerned with these matters. 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.

In this study, an experimental research design was selected to achieve the objectives set out in the problem statement. The study was conducted through a simulation analysis, and the results were presented using graphs, tables, and written statements. To carry out this study, a desk study was mainly employed. Various relevant literature, books, and case studies on the research issue were reviewed to inform the quantitative research. 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.

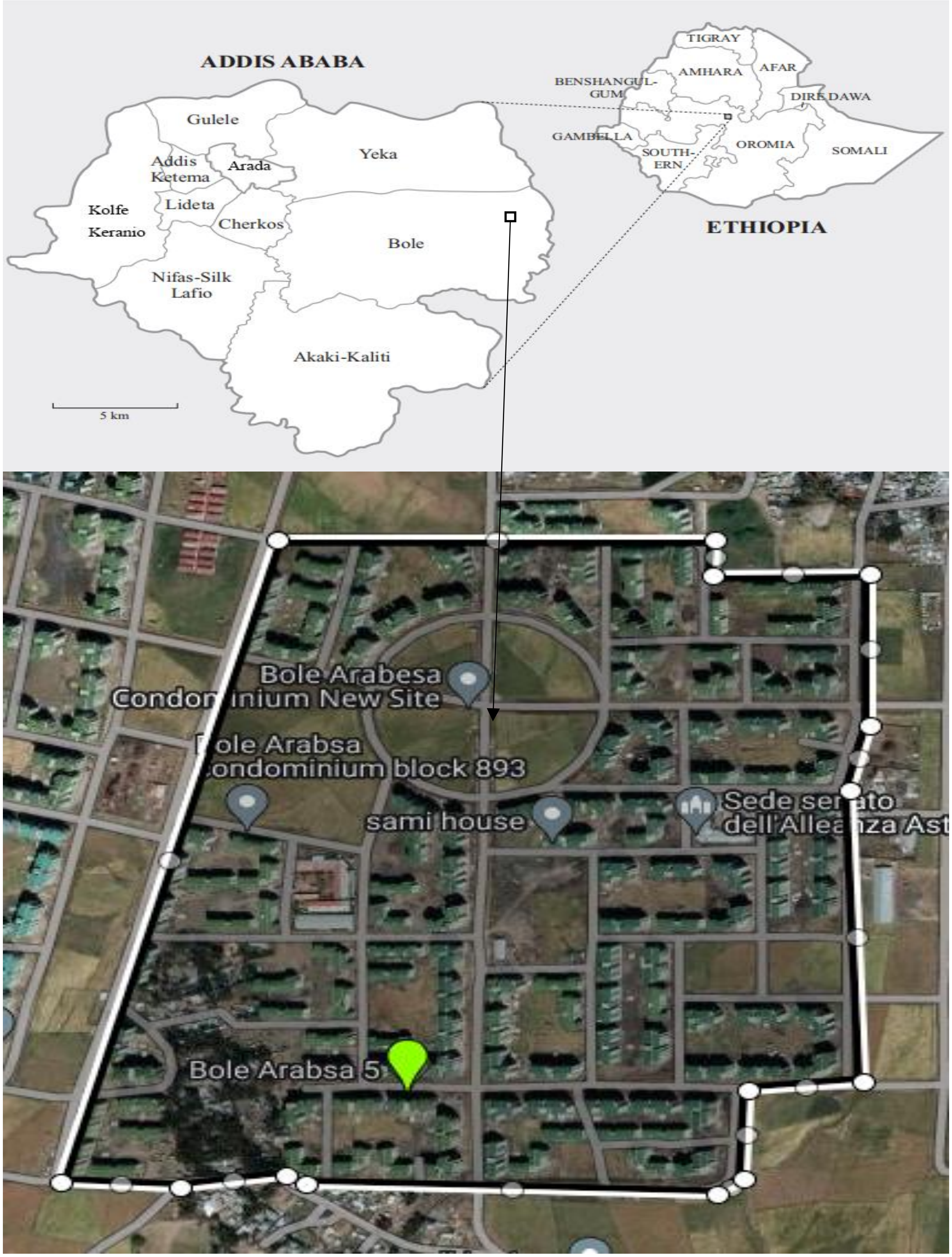
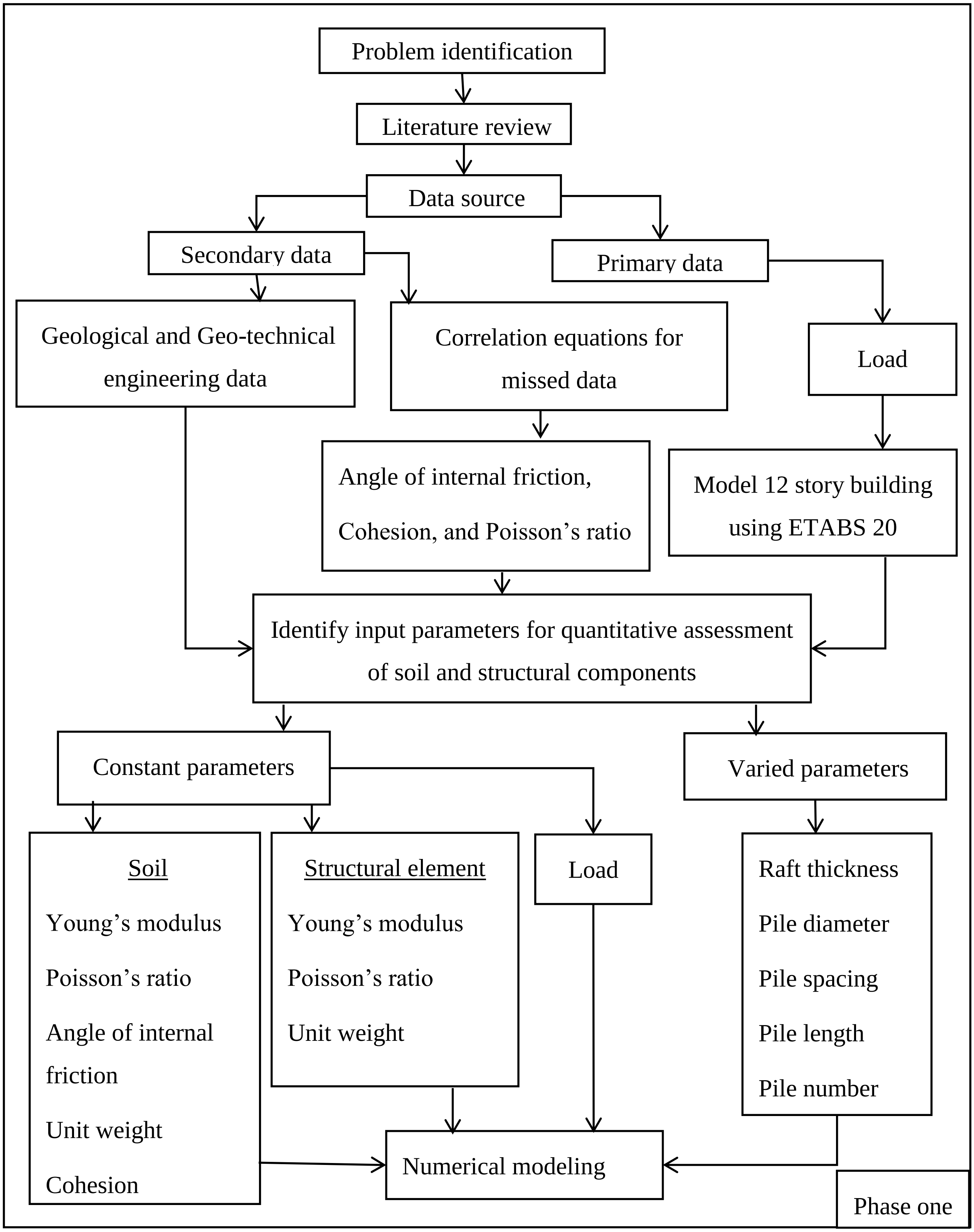


Figure 3.1: Detail of the study area


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
Pile number
Numerical modeling
Phase one

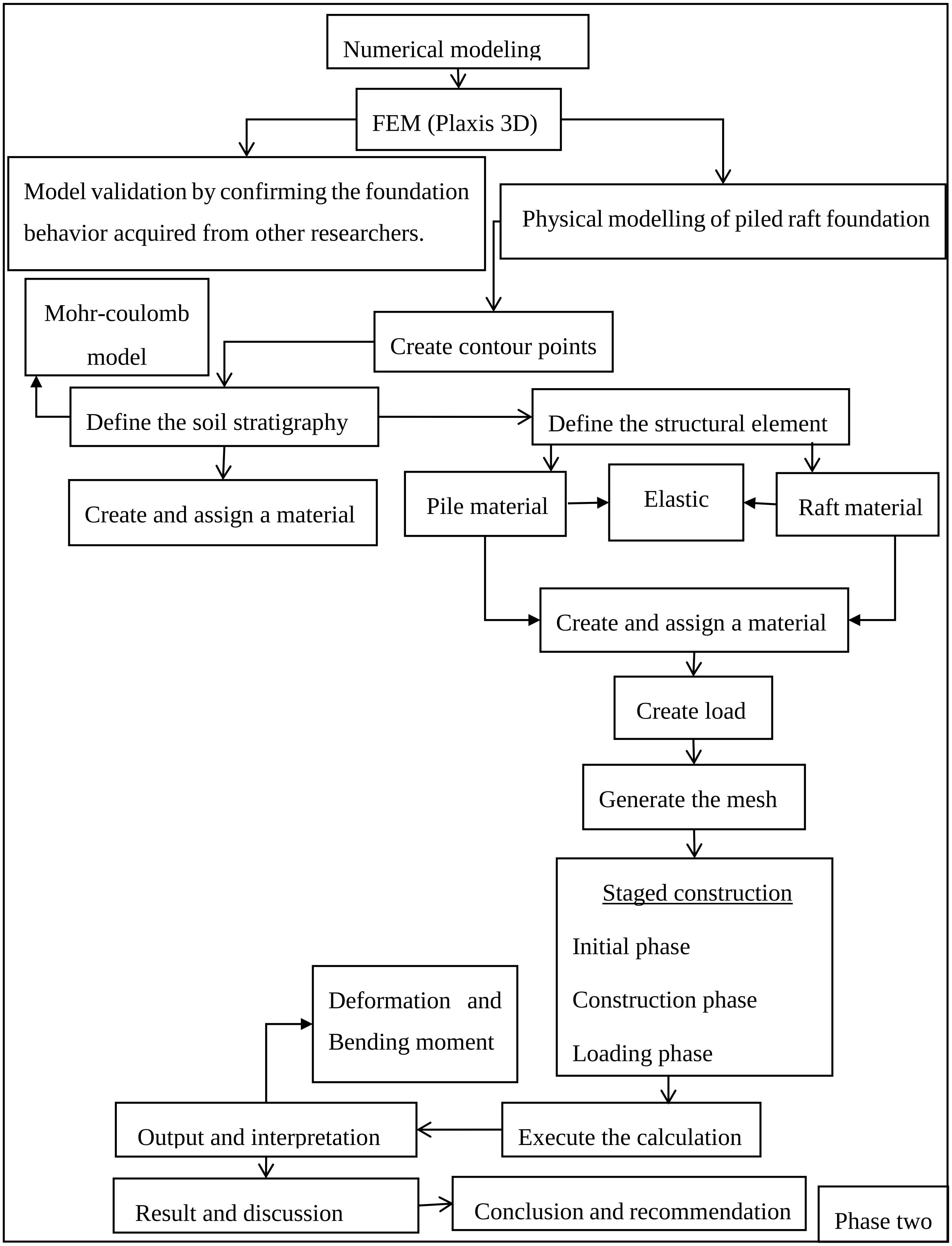


Figure 3.2: Design methodology (procedure)

3.3. Sampling Technique

In this study, the sampling process involved employing non-probabilistic methods, specifically purposive sampling techniques. The researchers selected samples that were readily accessible and able to address the research objectives. Additionally, purposive sampling was used to target objects that represented the study area and research issues. The goal of this sampling approach was to guarantee that the chosen samples were representative of the objective and gap of the study, allowing the study's findings to be applicable to similar contexts. 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 paper, a comprehensive analysis and parametric study of piled raft foundations were conducted using the powerful finite element-based software PLAXIS 3D CONNECT Edition V20. The selection was made on various parameters from the components of the piled raft system; some were kept constant, while others were varied based on their effects on the response of the piled raft system. 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.

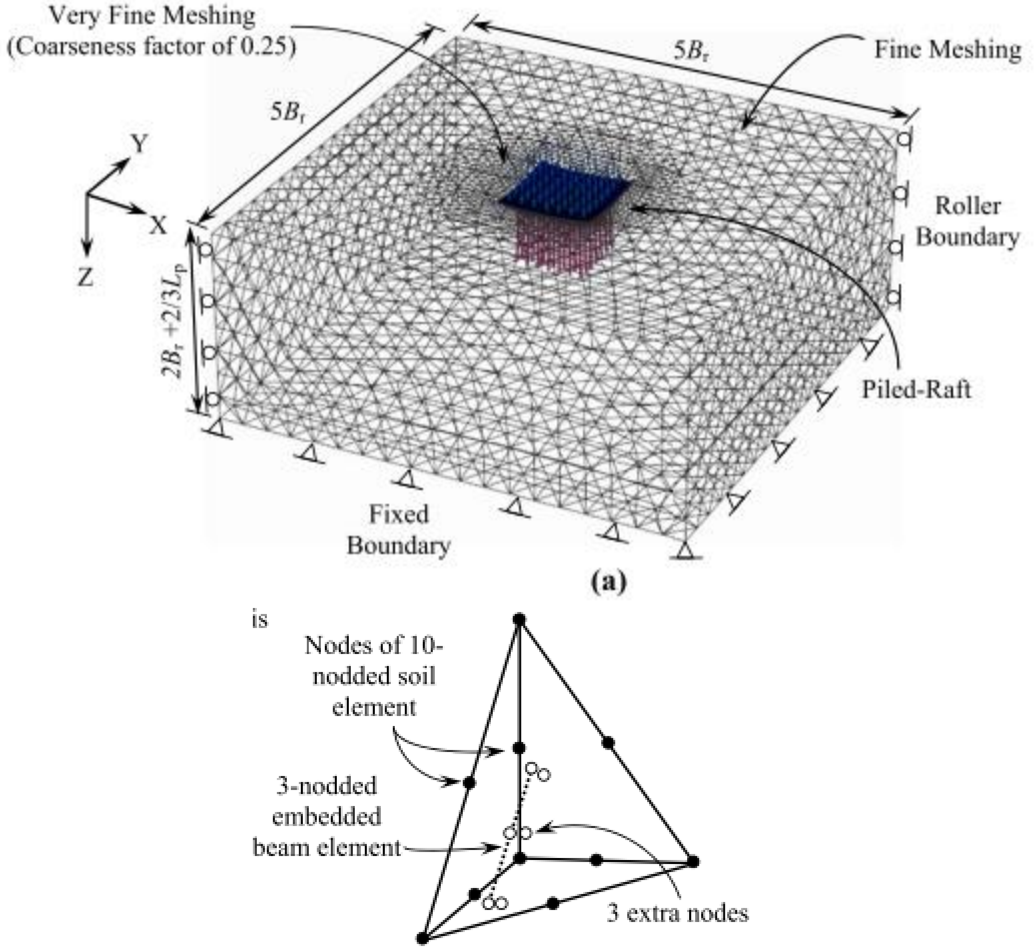
3.6. Development of Finite Element Numerical Model in PLAXIS 3D

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.

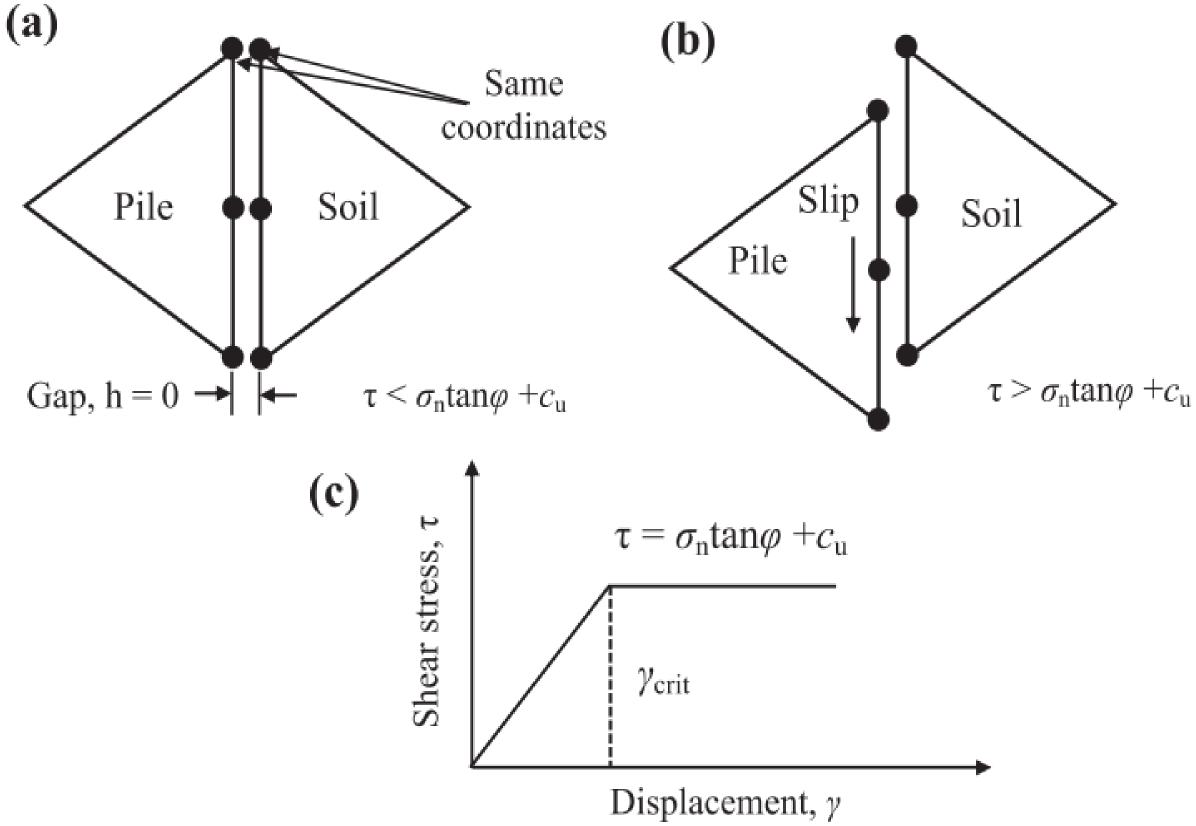


Figure 3.4: Pile-soil interface modeling technique (a) no slip, (b) slip, and (c) Coulomb frictional law (Jeong et al., 2004)

3.6.3. Input Parameter for Numerical Analysis

3.6.3.1. 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 & Rétháti, 1974; Obrzud & Truty, 2012). Cohesion, angle of friction, and Poisson's ratio were determined using a correlation equation developed by R. Kumar et al. (2016).

3.6.3.2. 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.

3.6.3.3. 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 EBCS (1995). The research began by using a 0.6m diameter for the piles, which was then increased to 0.8m and 1m. According to EBCS (1995), 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.

3.6.3.4. 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 & Shooshpasha, 2014). 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; Mosie, 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

Trail No.	Mesh coarseness	Number of elements	Maximum central settlement (m)
1	Very coarse	1685	0.1501
2	Coarse	3012	0.1526

3	Medium	7941	0.1558
4	Fine	19765	0.1596
5	Very fine	50426	0.1605

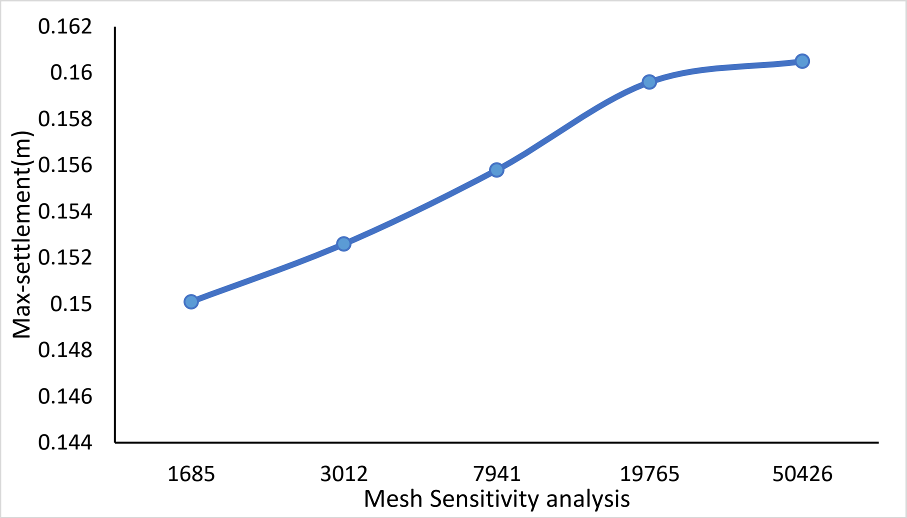


Figure 3.5: Effect of mesh coarseness on maximum central settlement

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), Mali & Singh (2018), and Sinha & Hanna (2017). 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	-	-

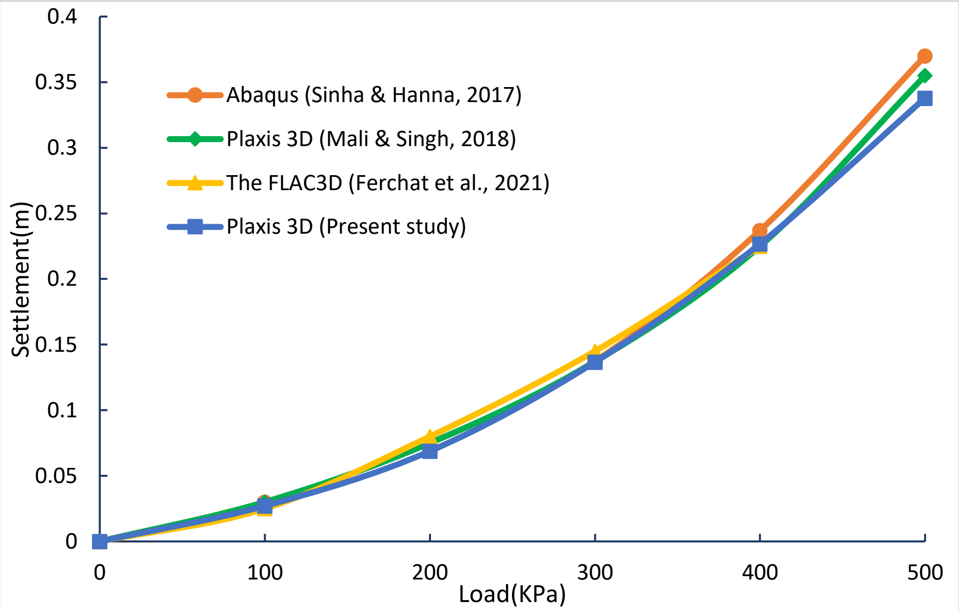


Figure 3.6: Comparison of the current study's results and previous numerical studies on load-settlement behavior of piled raft

CHAPTER FOUR

4. RESULT AND DISCUSSION

4.1. General

An extensive parametric investigation was conducted to examine the behavior of a piled raft (PR) foundation system under vertical loading in a layered soil profile, accounting for the 3D interactions between the soil, piles, and raft. The study considered variables like pile diameter, spacing, length, number, and raft thickness in a rectangular raft. To evaluate the interaction effects of the piled raft for drained soil conditions, various foundation types were taken into account, including piled raft (PR) and unpiled raft (UR). 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 numbers 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 pile-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	-	-

Dilatancy ψ, (°)	0	5.7	-	-

Table 4.2: Geometric configurations of pile-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		4, 9, 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

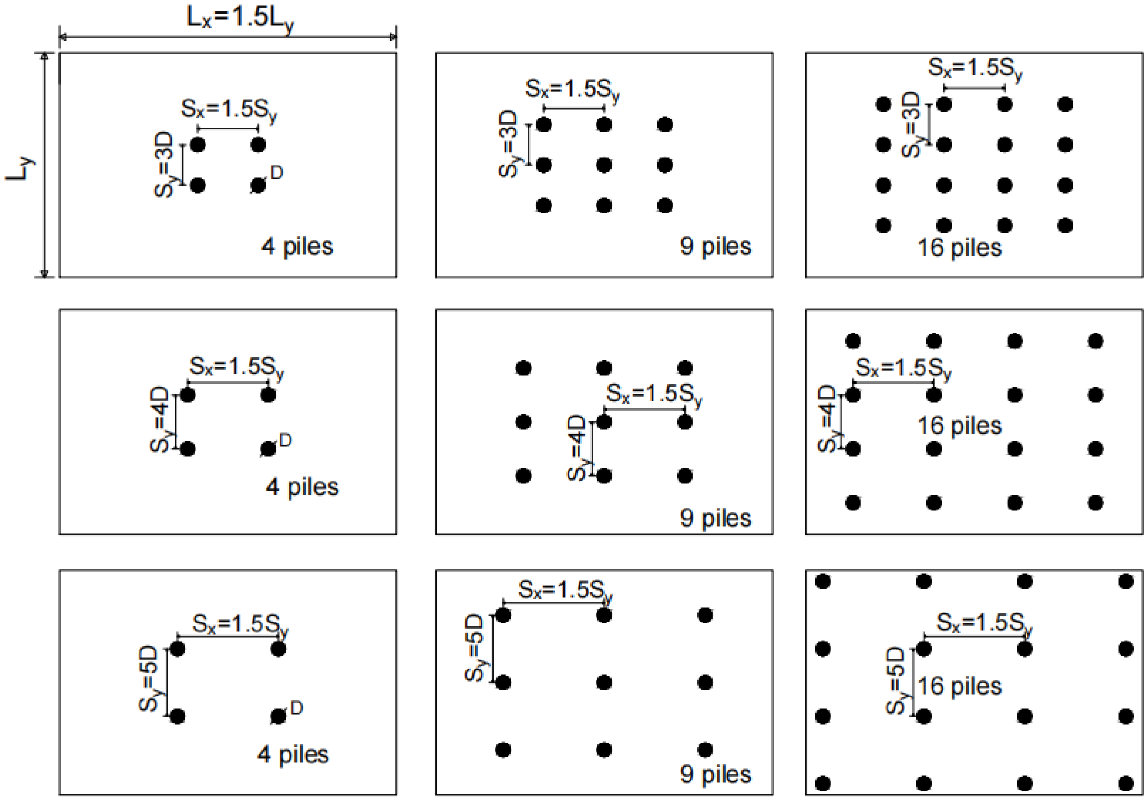


Figure 4.1: Example of piled rafts considered for parametric analysis

4.2. Unpiled Raft Behavior

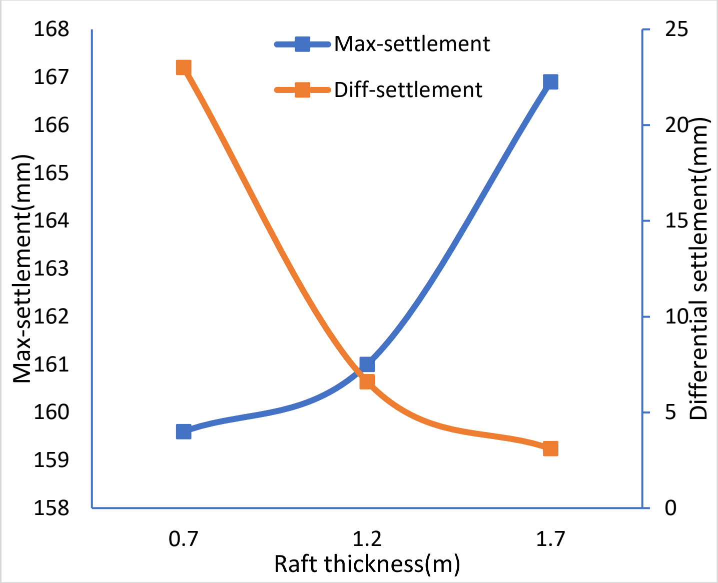
A 15m by 10m rectangular raft is situated on a layered soil profile at the site. The subsoil Consists of a 5m-thick top layer of medium to very stiff high-plastic silty clay and a subsequent layer of medium-dense to very-dense silty sand extending downward. In designing a foundation system, the raft thickness is a crucial parameter to consider, especially for unpiled raft foundations. The behavior of piled raft is dependent on the flexibility or stiffness of the raft. In the present study, the raft-to-soil stiffness ratio by Viggiani (2001) has been used to assess the flexibility and stiffness of the raft. This ratio is presented in Equation (4.1).

$$K_{rs} = \frac{4*E_r*(1-\nu_s{}^2)}{3*E_s*(1-\nu_r{}^2)} * \frac{t_r{}^3}{B_r{}^3} \tag{4.1}$$

where E_r is Young's modulus of the raft; v_s is the Poisson's ratio of soil; E_s is Young's modulus of soil, v_r is the Poisson's ratio of the raft; B_r is the width of the raft, and t_r is the thickness of raft.

Hence, it is noticeable from Equation 4.1 that as the raft thickness increases, so does the ratio of raft-to-soil stiffness. Additionally, a K_{rs} value of 0.001 signifies perfect flexibility, a K_{rs} value between 0.001 and 1 represents intermediate flexibility, and a K_{rs} value greater than or equal to 1 denotes perfect stiffness (Viggiani, 2001). For this study, the calculated K_{rs} values for raft thicknesses of 0.7, 1.2, and 1.7 m are 0.1311, 0.66, and 1.878, respectively. The raft with a thickness of 0.7 m is relatively more flexible compared to the other thicknesses. A comparable trend was noted in the research conducted by Mali & Singh (2018); however, the K_{rs} values were smaller in contrast to the present study, attributable to the wider raft width.

This study investigated the behavior of a rectangular unpiled raft foundation imposed on a uniformly distributed vertical load of 360kPa, varying the raft thickness at 0.7m, 1.2m, and 1.7m. Figure 4.2 shows that the maximum settlement increased as the thickness of the raft increased due to the increase in self-weight, which added more load to the soil. However, an increase in raft thickness also led to a decrease in differential settlement. This can be attributed to the increase in raft rigidity, allowing for the load to be distributed more evenly on the soil. Therefore, a thicker raft can better withstand vertical loads and reduce the potential for differential settlement, which is essential for the stability and safety of the structure (Mali & Singh, 2020). Therefore, the thickness of the raft must be carefully considered to ensure a balance between maximum settlement and differential settlement, as well as the overall stability of the foundation system.

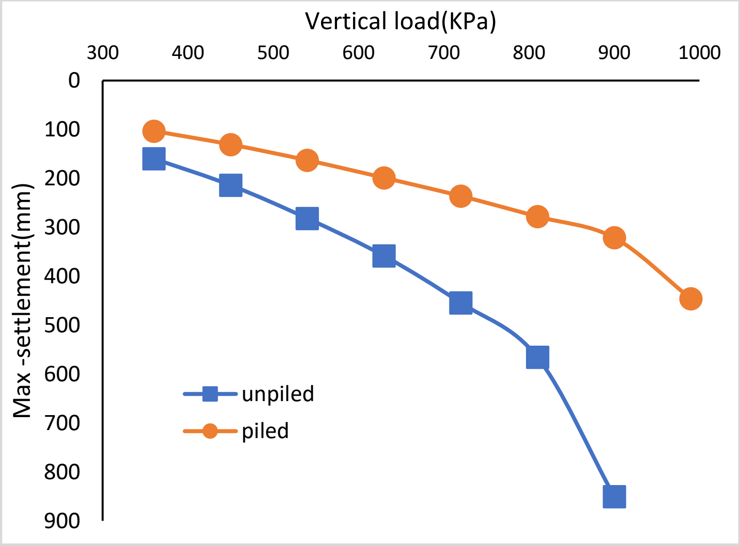


Raft thickness (m)	Max-settlement (mm)	Diff-settlement (mm)
0.7	159.6	23
1.2	167.1	6.6
1.7	173.4	3.1

Figure 4.2: Raft thickness vs raft settlement

4.3. Piled Raft Behavior

The study aimed to understand the load-settlement relationship, which is crucial for determining the behavior of any foundation system. A rectangular unpiled raft with a thickness of 0.7m was tested under varying uniformly distributed load intensities to investigate its response. Furthermore, for a piled raft scenario, 16 piles with a diameter of 0.8m, a spacing of 3D, and a length of 9m were added to the unpiled raft foundation.



Load (KN/M^2)	Max-settlement(mm)	
	Unpiled raft	Piled raft
360	159.6	103.1
540	281.7	162.8
720	454.2	236
900	850.2	321.3

Figure 4.3: Settlement v_s load of the unpiled and piled raft foundation

Specifically, the raft was subjected to loads of 360kPa, 540kPa, 720kPa, and 900kPa, which resulted in maximum settlements of 159.6mm, 281.7mm, 454.2mm, and 850.2mm for the unpiled raft, and 103.1mm, 162.8mm, 236mm, and 321.3mm for the piled raft, respectively. When the load increased by 50% from the initial 360 kPa to 540 kPa, the settlement experienced a 78.38% increase (unpiled) and 57.9% (piled). Upon doubling the load to 720 kPa, the settlement increased by 184.58% (unpiled) and 128.9% (piled). Lastly, when the load escalated to two and a half times the initial value of 360 kPa, reaching 900 kPa, the settlement experienced a 432.7% increase (unpiled) and 211.64% (piled). This observation demonstrates a trend of increased settlement with higher applied loads, as illustrated in Figure 4.3.

This is due to soil particle compression when a load is applied to the soil surface. The vertical pressure increases, forcing the soil particles closer together and causing the overall volume of the soil beneath the raft to decrease, leading to gradual settlement. Thus, as the applied load on the raft increases, so does the level of compression experienced by the soil, ultimately resulting in a higher rate of settlement.

4.3.1. 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 0.7 m, 1.2 m, and 1.7 m were used in the models. The piles had a fixed length of 9 m, and the pile diameter and spacing were set at 0.8 m and 3 times of pile diameter, respectively, under applied loading of 360 Kpa. The analysis considered the effect of raft thickness for unpiled conditions, as well as those with 4, 9, and 16 piles. By varying these parameters, a comprehensive evaluation of maximum settlement and differential settlement of piled rafts with different raft thicknesses was conducted, as displayed in Table 4.3.

4.3.1.1. Effect of Raft Thickness on Settlement

According to the data presented in Figure 4.4, it can be observed that the maximum settlement of the raft foundation increases with an increase in the thickness of the raft. And it is true for both the unpiled and piled cases. The reason for this can be attributed to the increase in the self-weight of the raft as its thickness increased. The added weight leads to an increase in the load transferred to the foundation, which in turn results in higher settlement values.

In contrast, when considering piled raft foundations, it can be seen that the maximum settlement is lower compared to the unpiled case. This is due to the load being shared between the piles and the raft, resulting in a reduced load transferred to the foundation. This sharing of the load is known to increase the stiffness of the system, thereby reducing the maximum settlement value. Furthermore, it was observed that as the number of piles in the foundation increases, the settlement values decrease. This can be attributed to the additional support provided by the increased number of piles, which helps to distribute the load more evenly.

Table 4.3: Comparison of maximum and differential settlements for different raft thicknesses and pile numbers

Raft thickness(m)	Maximum settlement(mm)				Differential settlement(mm)			
	unpiled	n=4	n=9	n=16	unpiled	n=4	n=9	n=16
0.7	159.6	134	116.4	103.1	23	5.1	4.2	12.85
1.2	161	136.5	120.4	103.3	6.6	3.5	1.8	5.15
1.7	166.9	142.4	125	106	3.1	3.4	1.4	2.8

As illustrated in Figure 4.5, unlike maximum settlement, differential settlement tends to decrease with increasing raft thickness. The observation is consistent for both piled and unpiled raft foundations and can be attributed to the increased rigidity of the raft as its thickness is increased. The greater stiffness of the thicker raft helps distribute the load more evenly to the soil, which in turn reduces the differential settlement.

For an unpiled raft, increasing the raft thickness from 0.7 m to 1.2 m increases the maximum settlement by 0.877% and decreases the differential settlement by 71.3%. However, increasing the raft thickness from 1.2 m to 1.7 m increases the maximum settlement by 3.66% and decreases the differential settlement by 53%. Similarly, for a piled raft with 16 piles, increasing the raft thickness from 0.7 m to 1.2 m increases the maximum settlement by 0.194% and decreases the differential settlement by 60%. However, increasing the raft thickness from 1.2 m to 1.7 m increases the maximum settlement by 2.61% and decreases the differential settlement by 45.63%.

However, when the number of piles is increased, the differential settlement behavior becomes more complex. Specifically, the analysis results revealed that the differential settlement decreased when the number of piles increased from 4 to 9. The reduction is due to the fact that as the number of piles increases, the load is distributed more uniformly over the foundation, resulting in less differential settlement. However, from pile number 9 to 16, the differential settlement increases. This phenomenon can be explained by considering the ratio of the width of the grouped pile to the width of the raft (B_g/B_r). As the ratio increases, the edge piles experience less load compared to the center piles, which in turn leads to higher differential settlement values (Mali & Singh, 2018). Therefore, it is important to consider the pile arrangement when designing piled raft foundations and to carefully select the raft thickness to ensure optimal performance.

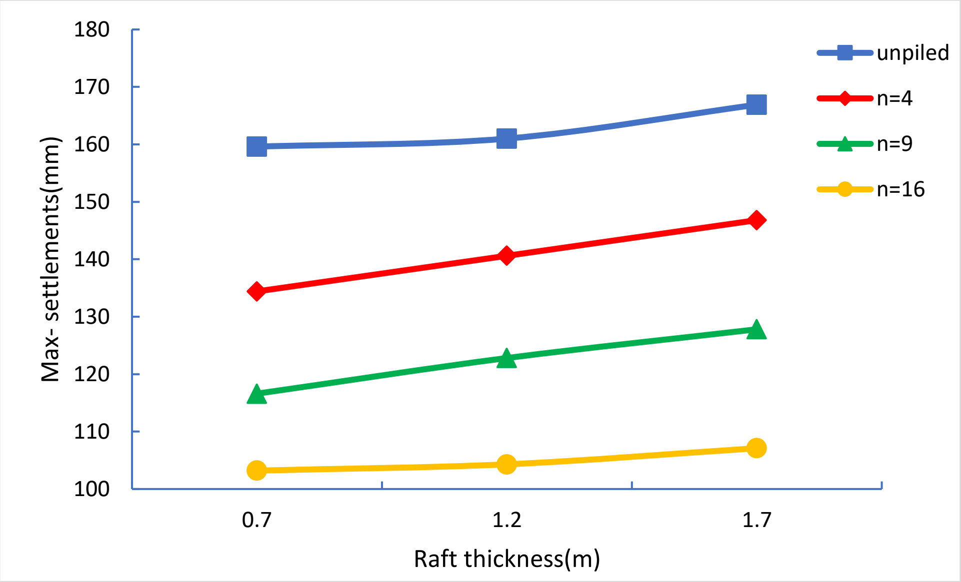


Figure 4.4: Effect of raft thickness on maximum settlement for different pile numbers

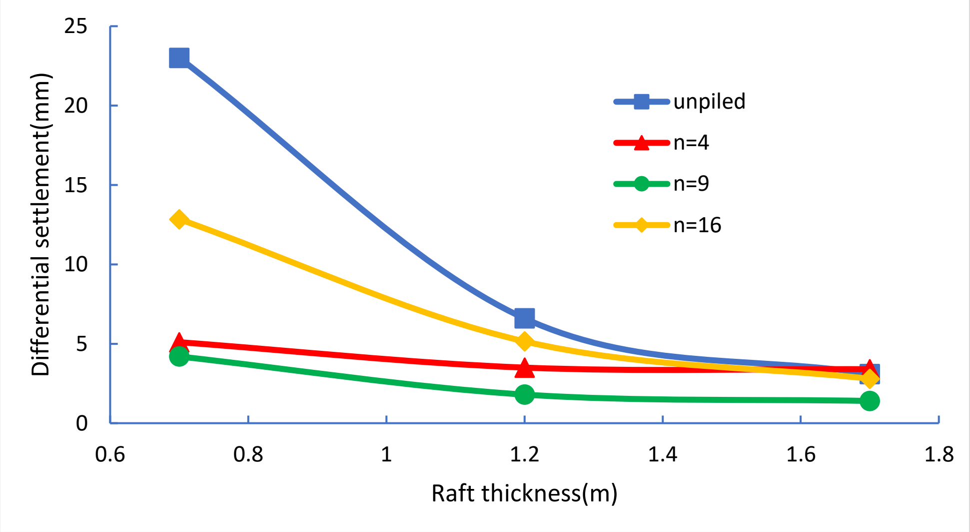


Figure 4.5: Effect of raft thickness on differential settlement for different pile numbers

4.3.1.2. Effect of Raft Thickness on load-sharing ratio

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 4.6. 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.

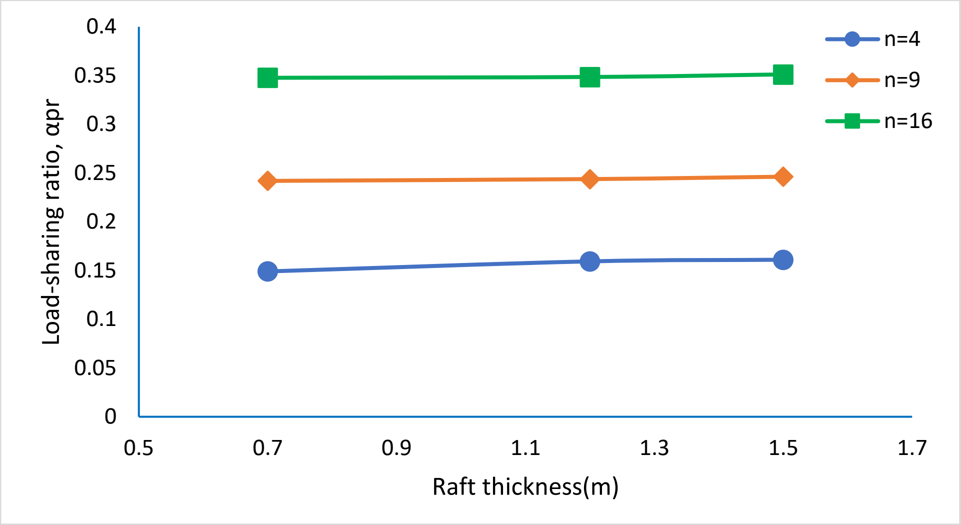


Figure 4.6: Effect of raft thickness on load sharing ratio for different pile numbers

4.3.2. 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. To thoroughly assess the performance of the piled rafts with different pile diameters, maximum settlement, differential settlement, and maximum bending moment were considered as evaluation criteria.

4.3.2.1. Effect of Pile Diameter on Settlement

Table 4.4 clearly shows the impact of the maximum and differential settlement on the size and number of piles. The experimental results presented in Figure 4.7 demonstrate a clear and important trend: an increase in pile diameter leads to a decrease in the maximum settlement. The finding can be attributed to the fact that an increase in pile diameter leads to a corresponding increase in the surface area of the pile, which in turn increases skin friction. Moreover, as the base area of the pile also increases, this further contributes to an increase in base resistance, thereby reducing the maximum settlement. These observations hold true regardless of the number of piles in the configuration. When the pile diameter increases from 0.6m to 0.8m, the maximum settlement decreases by 1.32%, 5.75%, and 6.27% for 4, 9, and 16 piles, respectively. Furthermore, when the pile diameter increases from 0.8m to 1m, the maximum settlement declines by 5% and 4.03% for 4 and 9 piles, respectively.

Table 4.4: Comparison of maximum and differential settlements for different pile diameters and pile numbers

Pile diameter(m)	Maximum settlement(mm)			Differential settlement(mm)		
	n=4	n=9	n=16	n=4	n=9	n=16
0.6	135.8	123.5	110.0	8.3	4.7	3.5
0.8	134	116.4	103.1	5.1	4.2	12.85
1	127.3	111.7		5.7	10.1	

However, the trend in differential settlement exhibits a more complex pattern, as it is influenced by both the pile diameter and the number of piles. For instance, when the pile configuration consists of four and nine piles, differential settlement initially decreases and subsequently rises with an increase in pile diameter. On the other hand, in a 16-pile setup, differential settlement increases as the pile diameter increases, as shown in Figure 4.8.

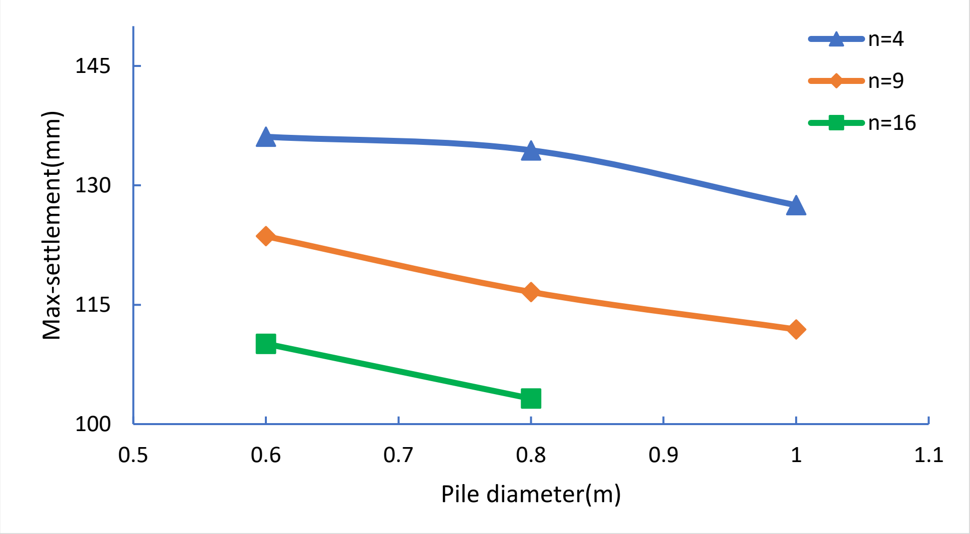


Figure 4.7: Effect of pile diameter on maximum settlement for different pile numbers

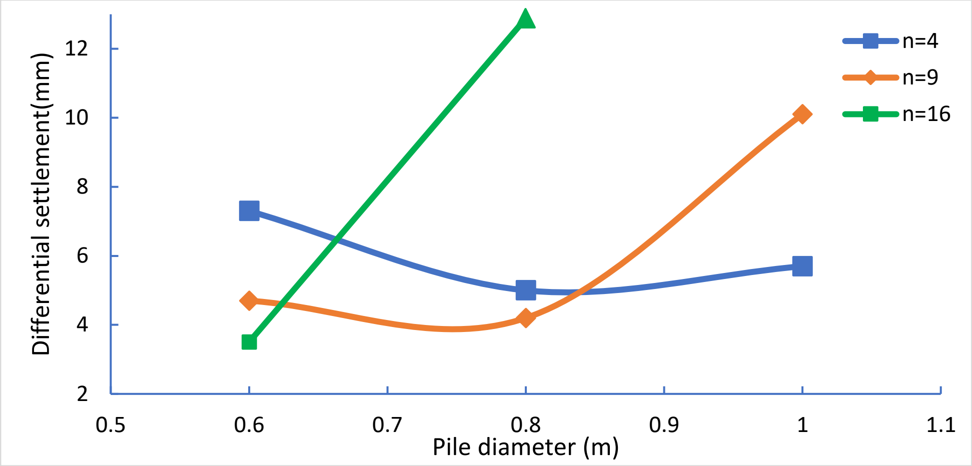


Figure 4.8: Effect of pile diameter on differential settlement for different pile numbers

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.

4.3.2.2. Effect of Pile Diameter on load-sharing ratio and Bending Moment

Figure 4.9 shows, Increasing the diameter of the pile generally leads to an increase in the load sharing ratio of the pile. 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.

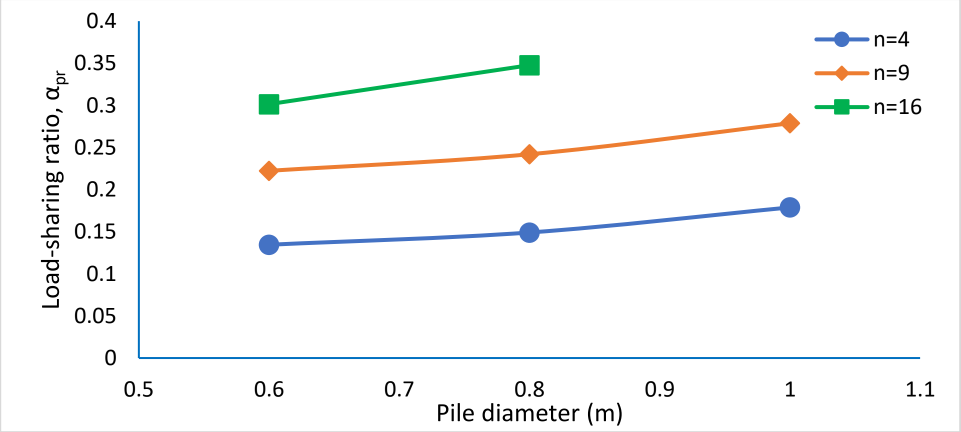


Figure 4.9: Effect of pile diameter on load sharing ratio for different pile numbers

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. An unpiled raft only exhibits a sagging moment, whereas a piled raft also experiences a hogging moment at the locations of the piles. This primarily occurs because of the upward reaction force from the piles, which counteracts the raft's bending at that specific point.

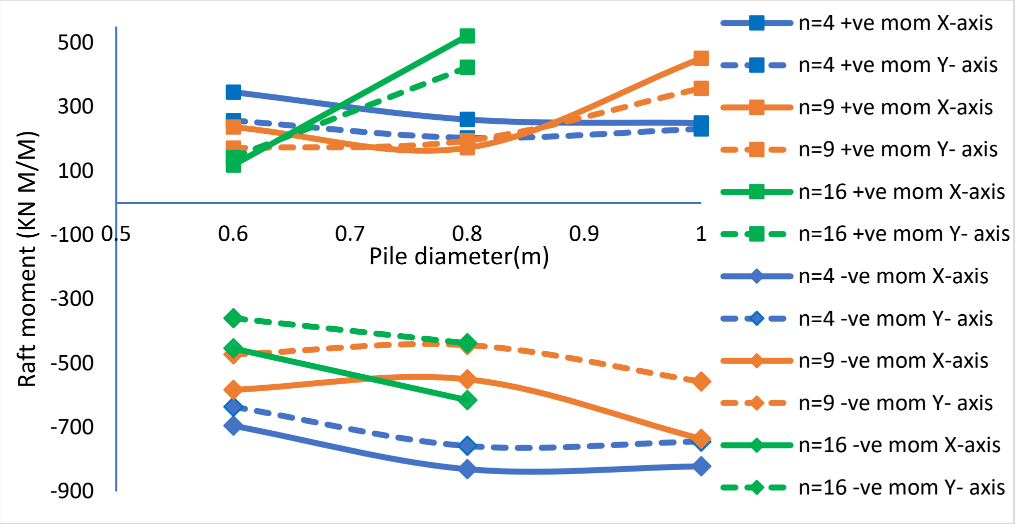


Figure 4.10: Effect of pile diameter on the maximum bending moment for different pile numbers

The piled raft exhibits both positive and negative values for the maximum bending moment, indicating the presence of sagging and hogging behavior. The Figure 4.10 illustrates that an increase in pile diameter leads to an increase in negative bending moment for 16 piles. 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.

In the case of a 4-pile and 9-pile configuration, the behavior of the maximum negative bending moment differs from that of 16 piles. Specifically, when the pile diameter increases from 0.6m to 0.8m, the maximum negative bending moment initially increases for the 4-pile arrangement while it decreases for the 9-pile arrangement. However, when the pile diameter further increases to 1m, the maximum negative bending moment decreases for the 4-pile setup, whereas it increases for the 9-pile configuration. This can be attributed to the combined effects of the width of the grouped pile (Bg) and the spacing of the piles. As the pile diameter increases, both the spacing and width of the group piles increase, which results in a change in the position for the development of the maximum negative bending moment. Additionally, unlike the other two pile numbers (4 and 16), the center of the raft is supported by the piles in the case of a 9-pile number, further contributing to the observed behavior.

The maximum positive bending moment is primarily influenced by the length or width of the raft, as the positive moment develops between support and the moment is a load multiple of length. For a pile number of four, the maximum positive moment develops outside the pile group due to the small ratio of the width of the pile group to the width of the raft (Bg/Br). This means that when the pile diameter increases, the cantilever side of the raft decreases, resulting in a decrease in the positive moment.

However, for a pile number of 16, the ratio (Bg/Br) increases, causing the maximum positive moment to develop between piles. As the pile diameter increases, the spacing of the piles increases, which in turn increases the maximum positive moment. The behavior of the positive bending moment for a nine pile is similar to that of the maximum negative moment, which is due to the effect of the width of the grouped pile (Bg) and pile spacing. As the pile diameter increases, both the spacing and width of the group pile increase, altering the position for the development of the maximum bending moment. Additionally, the results demonstrate that in both cases of the moment, the value of the moment in the long axis was greater than that of the shorter axis under most conditions.

4.3.3. Effect of Pile Spacing

The objective of the investigation was to analyze how the spacing of piles affects the performance of piled rafts. The models employed three different pile spacings 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 4, 9, and 16 piles. A comprehensive analysis of the maximum settlement, differential settlement, and maximum bending moment of piled rafts with varying pile spacings was conducted by modifying these parameters.

4.3.3.1. Effect of Pile Spacing on Settlement

It is evident that for any number of piles, the maximum settlement decreases as the pile spacing increases, as demonstrated in Figure 4.11. 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, resulting in an expanded area covered by the piles (Ag). As the area covered by the piles (Ag) increases, they become more evenly distributed beneath the entire area of the raft (Ar), leading to a decrease in the maximum settlement of the pile-raft. With lower pile spacing, piles were primarily concentrated towards the central section of the raft, even though the load was distributed across the entire raft. As a result, the difference in the maximum settlement was more significant for lower pile spacing compared to larger pile spacing (Mali & Singh, 2020).

Table 4.5: Comparison of maximum and differential settlements for different pile spacing and pile number

	Maximum settlement(mm)			Differential settlement(mm)		
Pile spacing (Sy)	n=4	n=9	n=16	n=4	n=9	n=16
3D	135.8	123.5	110	8.3	4.7	3.5
4D	132.2	118	105.7	7.3	5.3	14.84
5D	129.9	115.7	106.3	7.6	12.7	31.61

Based on Table 4.5, the maximum settlement was reduced from 3D to 4D pile spacing by 2.65%, 4.45%, and 3.91% for 4, 9, and 16 pile numbers, respectively. Similarly, when the pile spacing increases from 4D to 5D, the maximum settlement declines by 1.74%, 1.95%, and 0.567% for 4, 9, and 16 pile numbers, respectively. Out of these, the 9-pile number has the best settlement reduction rate compared to the others when the spacing of the pile increases. However, this doesn't necessarily mean it's the best settlement reducer overall because it is evident that as the pile number increases, the settlement also decreases, as demonstrated by the results.

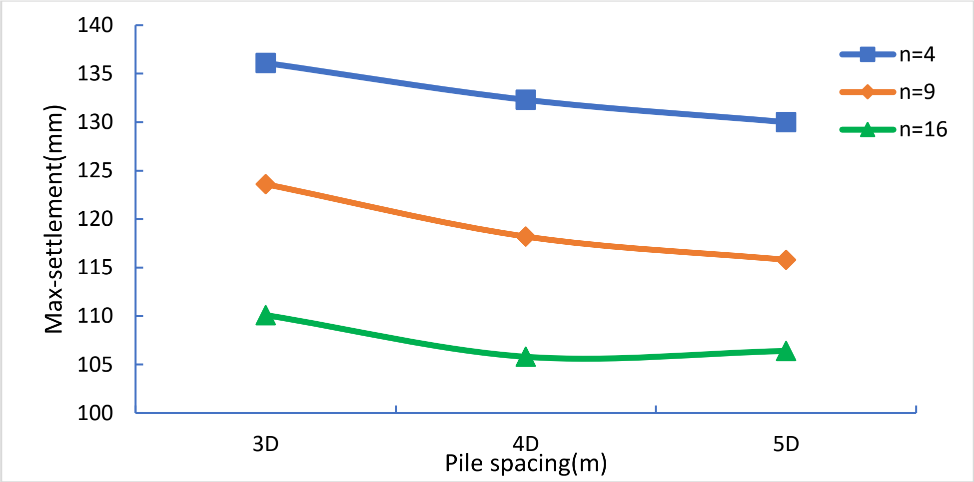


Figure 4.11**:** Effect of pile spacing on maximum settlement for different pile numbers

The experimental results presented in Figure 4.12 reveal a clear trend in the behavior of differential settlement as the pile spacing increases. Interestingly, the trend is opposite to that observed for maximum settlement. Specifically, it can be observed that for a 9 and 16 number of piles, the differential settlement increases as the pile spacing increases. This observation can be attributed to the fact that with an increase in pile spacing, the piles tend to move away from the center of the raft, leading to an increase in the pile group area (Ag) and a subsequent decrease in the central settlement of the raft. As a result, the piles start behaving as individual elements rather than a cohesive group. This causes edge piles to experience less load compared to the center piles, leading to an uneven distribution of load and an increase in differential settlement. However, in the case of 4 piles, differential settlement decreases at first and then increases as pile spacing increases.

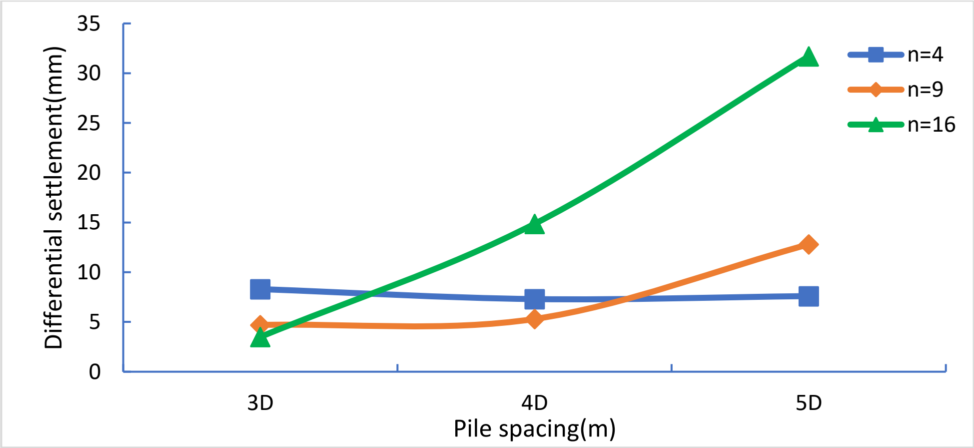


Figure 4.12: Effect of pile spacing on differential settlement for different pile numbers

4.3.3.2. Effect of Pile Spacing on Load Sharing ratio and Bending Moment

The efect of pile spacing on load-sharing ratio for diferent load confgurations and piled raft confguration is shown in Figure 4.13. when pile spacing increase the load sharing ratio also increase. This could attribute the mobilization of higher relative movement between piles and soil and maximum load capacities, since at larger pile spacing piles start to behave as individual element. Therefore, piles should be placed strategically so that the maximum load capacities of the raft and piles can be utilized.

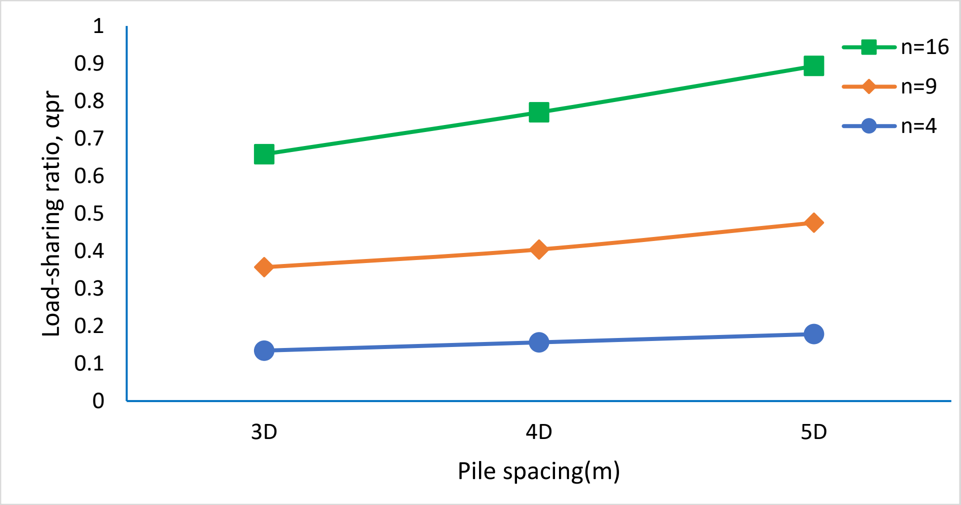


Figure 4.13: Effect of pile spacing on load-sharing ratio for different pile numbers

Figure 4.14 illustrates the effect of pile spacing on both the maximum negative and positive bending moment of a raft with different pile numbers. For a smaller number of piles, such as four and nine piles, the maximum negative moment decreases initially as the pile spacing increases from 3D to 4D, then increases when the pile spacing increases from 4D to 5D. The reason for this is similar to the effect of pile diameter, as discussed previously. As pile spacing increases, the grouped pile width also increases, affecting the negative bending moment value.

However, when the pile number becomes 16, the maximum negative moment behaves differently in both the longer and shorter axis of the raft. Since as the pile number increases, the cantilever portion of the raft decreases, which in turn decreases the contribution of soil in supporting the load. Consequently, the load is supported more by the piles than the soil, resulting in an increased bending moment for the raft.

The maximum positive bending moment decreases when the pile spacing increases for four piles but increases for 16 piles. However, in the case of nine piles, it decreases when the pile spacing increases from 3D to 4D and increases when the pile spacing increases from 4D to 5D. The reason for these trends is similar to the case of pile diameter, as discussed previously.

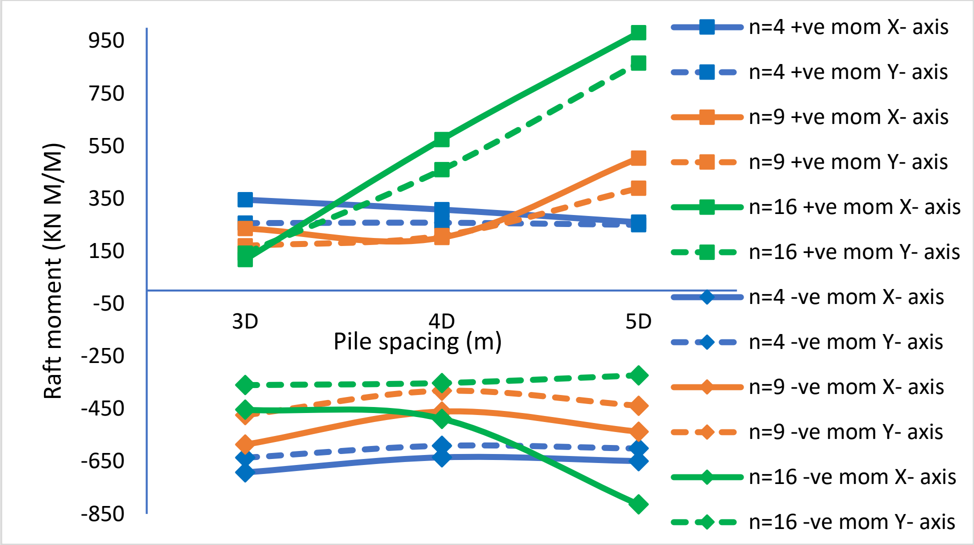


Figure 4.14: Effect of pile spacing on the maximum bending moment for different pile numbers

4.3.4. Effect of Pile Length

The study aimed to examine the impact of pile length on the behavior of piled raft foundations. 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 9 piles with lengths of 9m, 12m, and 15m and a spacing of three, four, and five times 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.

4.3.4.1. Effect of Pile Length on Settlement

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 under a uniform load of 360 Kpa for pile spacing of 3D. For other pile spacings, the maximum settlement also decreased, as shown in Figure 4.15. 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.

The behavior of differential settlement differs from that of maximum settlement with varying pile lengths and spacings. The results in Figure 4.16 demonstrate that, with a 5D pile spacing, increasing the pile length reduces the differential settlement. Conversely, for 3D pile spacing, the differential settlement increases with an increase in pile length. This behavior can be attributed to the small pile spacing causing piles to concentrate at the center and act as a single pile, resulting in an uneven distribution of load to the soil. When piles have smaller diameters and are closely spaced, their individual load-carrying capacity is reduced. To preserve the necessary load-bearing capacity, the pile length usually needs to be increased. Similar findings were reported by Akl et al. (2014), an increase in pile length has an effect of increasing the differential settlement at working stress level for the pile configurations with uniform distribution of piles and piles concentrated at edges. Additionally, for a 4D pile spacing, differential settlement initially decreases and then increases again when the pile length increases.

Table 4.6: Comparison of maximum and differential settlements for different pile lengths and pile spacing

Pile length(m)	Maximum settlement(mm)			Differential settlement(mm)		
	Sy=3D	Sy=4D	Sy=5D	Sy=3D	Sy=4D	Sy=5D
9	123.5	118	115.7	4.7	5.3	12.7
12	113.8	109.4	102.8	13	4.8	11.26
15	108.8	99.2	93.23	13.75	6.73	9.06

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.

As the piles extend deeper, they transfer a greater load to the stiffer silty sand stratum, potentially causing increased differential settlement. This phenomenon is particularly apparent in areas where the raft is supported by the silty clay layer, like the cantilever part of the raft, as the contrast between the different layers' responses to loading can lead to an uneven distribution of settlement. Additionally, Pile spacing also affects the differential settlement. If the piles are too closely spaced, they may not be able to support the load of the structure evenly. This can lead to differential settlement.

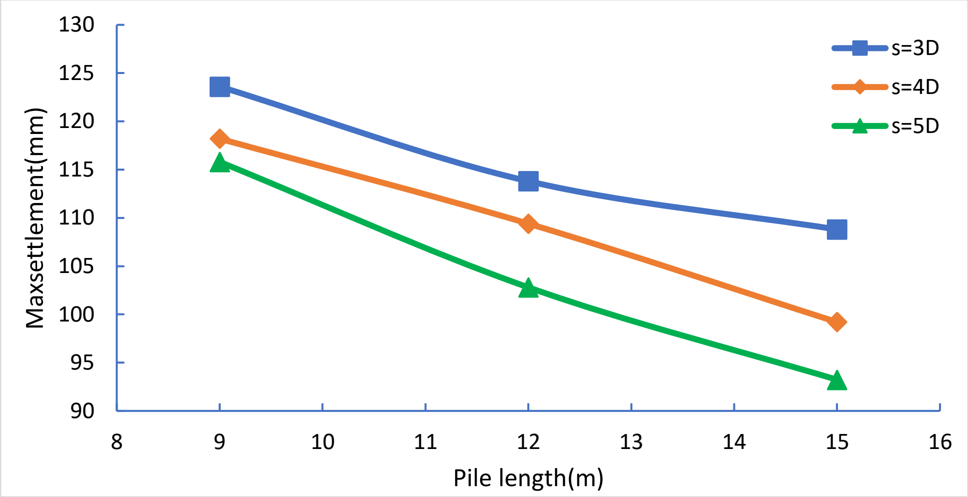


Figure 4.15**:** Effect of pile length on maximum settlement for different pile spacing

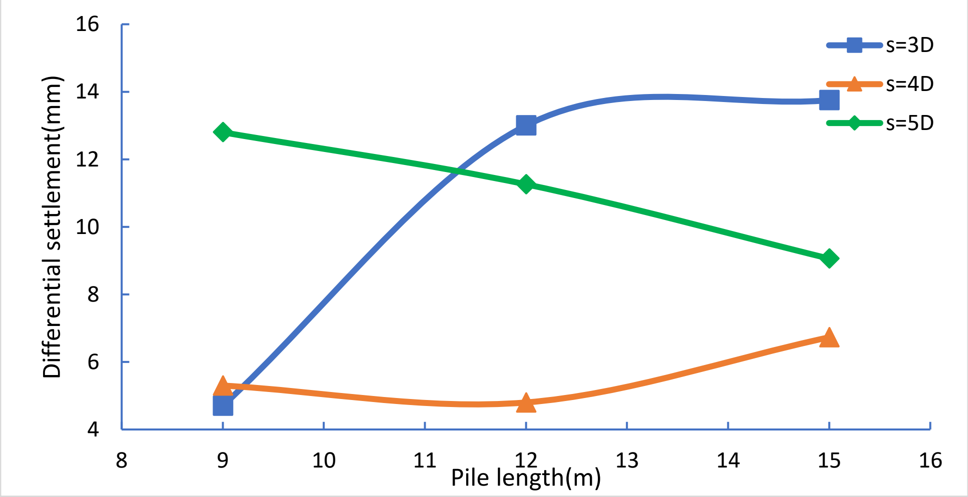


Figure 4.16: Effect of pile length on differential settlement for different pile spacing

Based on the findings presented in Table 4.6, it is evident that an increase in pile length from 9m to 12m results in a decrease in maximum settlement by 7.85%, 7.29%, and 11.14% for pile spacings of 3D, 4D, and 5D, respectively. Similarly, when the pile length increases from 12m to 15m, the maximum settlement declines by 4.4%, 9.32%, and 9.31% for pile spacings of 3D, 4D, and 5D, respectively. In this context, a 5D pile spacing provides the most significant reduction in the maximum settlement as the pile length increases. However, it should be noted that, in most cases, the differential settlement for 5D spacing is greater than that of 4D spacing but smaller than that of 3D spacing. This indicates that although the 5D pile spacing reduces the maximum settlement the most with increasing pile length, it may not provide the best balance between maximum and differential settlement in comparison to other spacing options. 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.

4.3.4.2. Effect of Pile Length on Load-Sharing Ratio and Bending Moment

Increasing the length of a pile generally leads to an increase in the load sharing ratio as shown in Figure 4.17. 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.

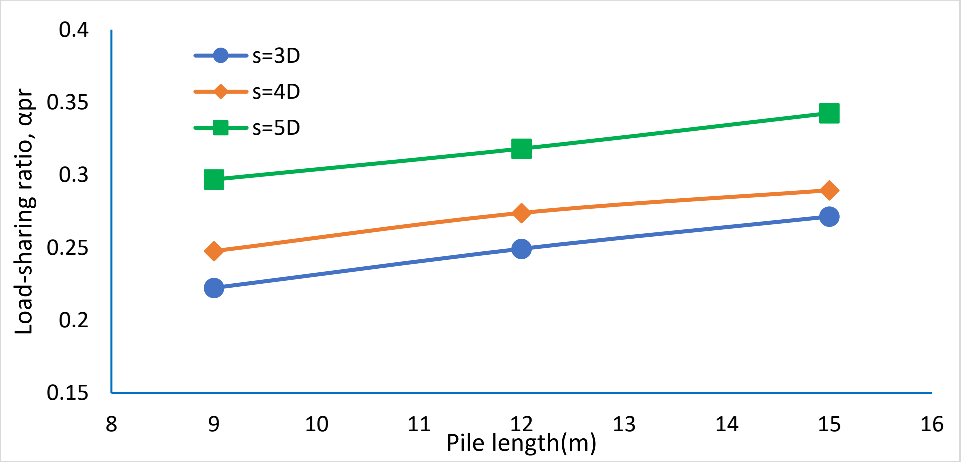


Figure 4.17: Efect of pile length on load-sharing ratio for different pile spacing

Figure 4.18 illustrates that the maximum negative bending moment increases as the pile length increases. As the pile length increases, the stiffness and resistance of the foundation system against deformations also increase, resulting in a reduction in the overall deflection of the raft foundation. Consequently, the negative bending moments, which occur at the top face of the raft due to deflection, tend to increase. And with an increase in pile length, the raft's load is carried more by the piles and less by the soil, which results in stiffer supports for the raft. This stiffer support system leads to a better load distribution, increasing in the negative moment.

The maximum positive bending moment decreases when the pile length increases. 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 positive 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 the positive moment in the raft foundation. When the pile length increases, the piles interact with different layers of soil that may have varying strengths and stiffnesses. The load distribution and settlement behavior of the pile group can be affected by changes in soil properties, which in turn influences the bending moment response in the raft foundation.

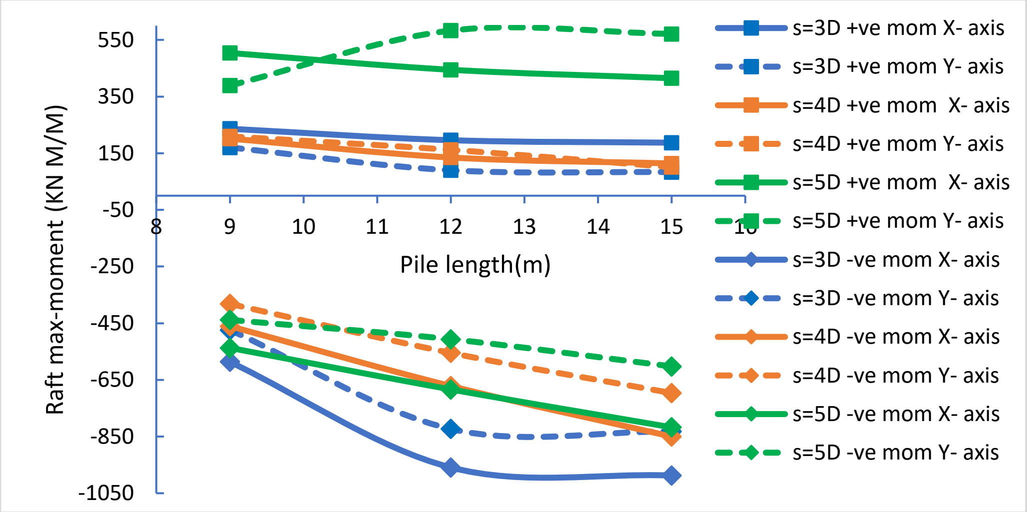


Figure 4.18: Effect of pile length on the maximum bending moment for different pile spacing

When the pile spacing is small, a positive bending moment develops outside the pile group. 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. As a result, the positive bending moment decreases.

In the case of 5D spacing, the positive bending moment on the shorter side is greater than that on, the longer side because, as defined in the methodology, the longer side spacing is 1.5 times the shorter side ($S_x = 1.5S_y$). When the pile length increases, the contribution of soil in supporting the raft decreases because most of the load is supported by the pile, which increases the positive bending moment compared to the longer side of the raft.

4.3.5. Effect of Number of piles

To investigate the influence of pile number and spacing on the performance of piled rafts, models with 4, 9, and 16 piles were created with 3D, 4D, and 5D pile spacing. The main objective of the study was to assess the maximum settlement and differential settlement of the foundations. The models maintained a fixed raft thickness of 0.7m, a pile diameter of 0.6m, and a pile length of 9m. They were subjected to a 360 Kpa load. As presented in the preceding sections, the effects of pile number on maximum and differential settlement were analyzed in detail concerning other parameters.

The study results suggest that both pile number and spacing have a significant impact on the performance of piled rafts. Specifically, increasing the number of piles results in a decrease in the maximum settlement, as shown in Figure 4.19. This is due to the load being distributed over a larger area, leading to a reduction in the settlement. However, the behavior of differential settlement varies with pile spacing, as illustrated in Figure 4.20. In general, increasing pile spacing leads to an increase in differential settlement. Nevertheless, this trend is not uniform and depends on the pile spacing and number. The results further demonstrate that the performance of piled rafts is primarily related to the area covered by the pile group (Ag).

In Table 4.7, it can be observed that the maximum settlement decreases from 4 piles to 9 piles by 9.06%, 10.74%, and 10.93% for pile spacings of 3D, 4D, and 5D, respectively. Additionally, the maximum settlement declines from 9 piles to 16 piles by 10.93%, 10.42%, and 8.12% for the corresponding pile spacings of 3D, 4D, and 5D. Consequently, the most effective pile spacing for reducing maximum settlement while increasing the number of piles is 4D. However, the differential settlement for 4D pile spacing is smaller than that of 5D pile spacing, but it behaves differently when compared to 3D. Therefore, careful consideration of pile number and spacing is crucial in designing piled raft foundations to achieve the desired level of performance.

Table 4.7: Comparison of maximum and differential settlements for different pile numbers and pile numbers

Number of piles	Maximum settlement(mm)			Differential settlement(mm)		
	Sy=3D	Sy=4D	Sy=5D	Sy=3D	Sy=4D	Sy=5D
4	135.8	132.2	129.9	8.3	7.3	7.6
9	123.5	118	115.7	4.7	5.3	12.7
16	110	105.7	106.3	3.5	14.84	31.61

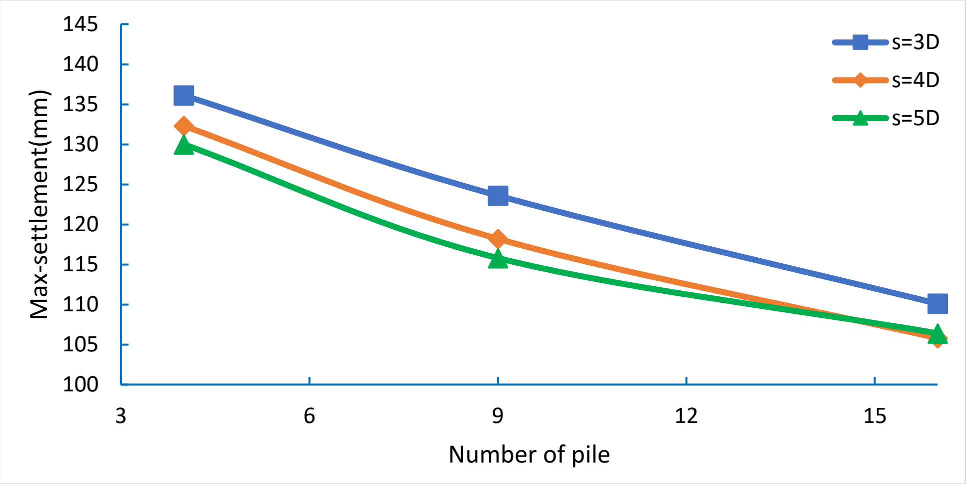


Figure 4.19**:** Effect of pile number on maximum settlement for different pile spacing

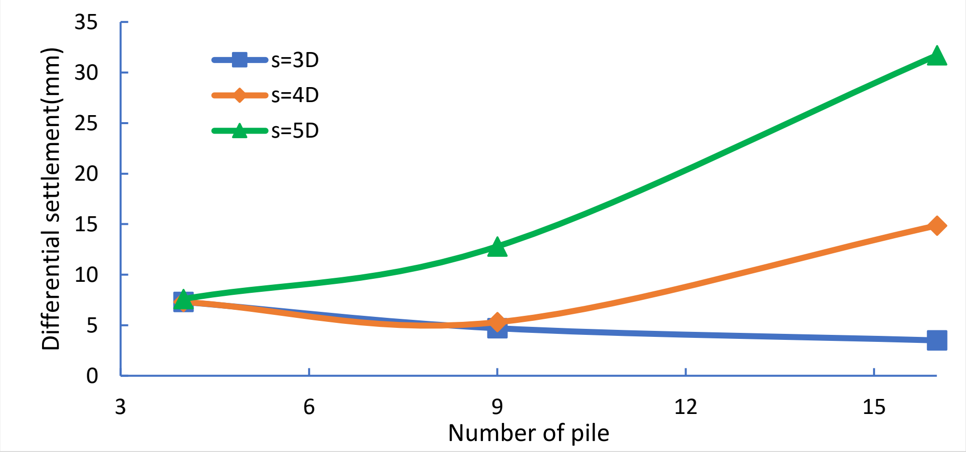


Figure 4.20: Effect of pile number on differential settlement for different pile spacing

The efect of number of piles on load-sharing ratio is shown in Figure 4.21. It can be seen that for any pile spacing with increases in number of piles, load-sharing ratio increases gradually. This can be explained by the fact that as the number of piles increases, the load is distributed more evenly among them, which increases the load sharing ratio of pile.

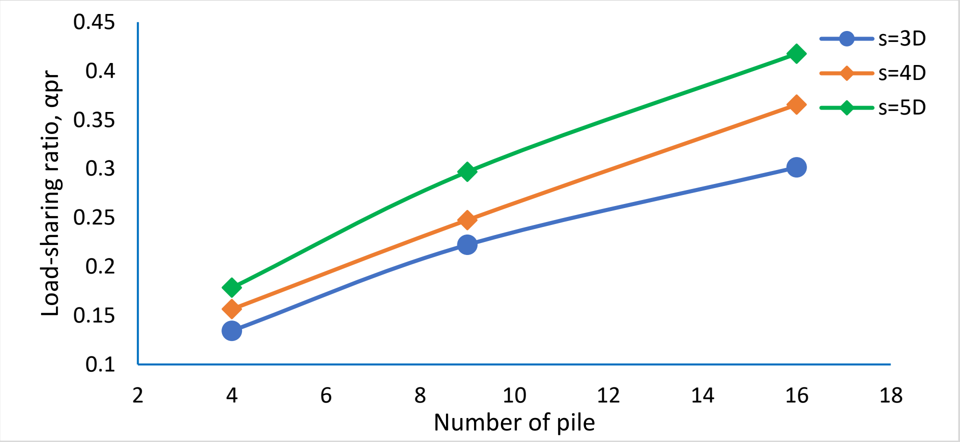


Figure 4.21: Efect of pile numbrt on load-sharing ratio for different pile spacin

Figure 4.22 demonstrates the effect of pile number on bending moment, which also behaves similarly to the effect of pile spacing discussed earlier. The underlying reasons behind these effects are also comparable. For pile spacings of 3D and 4D, the maximum negative bending moment decreases along both axes of the raft as the number of piles increases. However, for a pile spacing of 5D, the maximum negative bending moment decreases with an increasing number of piles along the shorter axis while first decreasing and then increasing along the longer axis as the number of piles increases. This variation is due to the changing position of the maximum bending moment as the pile spacing and the pile number differ, which is related to the width of the pile group (Bg). As for the maximum positive bending moment, there is a decrease with an increasing number of piles when the pile spacing is 3D and an increase when the spacing is 5D along both axes. However, for a pile spacing of 4D, the behavior is different, initially decreasing and then increasing as the number of piles increases.

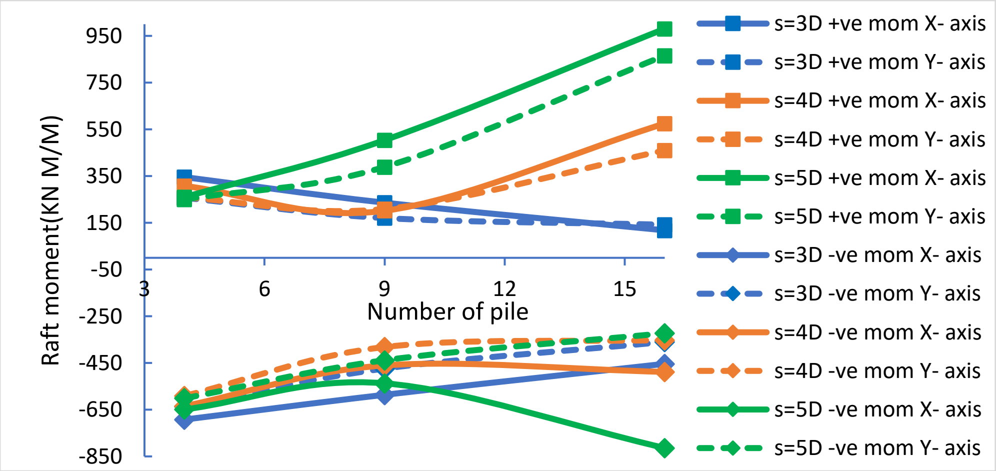


Figure 4.22: Effect of pile number on the maximum bending moment for different pile spacing

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATION

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, and bending moment of the foundations. The effects of various parameters, such as pile diameter, pile spacing, pile number, pile length, and raft thickness, are investigated.

The following conclusions can be drawn from numerical analysis:

- ✓ The behavior of an unpiled and 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 differential settlement decreased by 86.52% for unpiled, 37.26% for 4 piles, 61.9% for 9 piles, and 78.2% for 16 piles when raft thickness increased from 0.7m to 1.7m.
- ✓ Increasing raft thickness also led to a higher self-weight, contributing to a greater maximum settlement, which increased by 4.59% for unpiled, 9.55% for 4 piles, 9.79% for 9 piles, and 3.88% for 16 piles. 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 6.26% and 9.55% for 4 and 9 piles (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 4.34%, 6.3%, and 3.36% for 4, 9, and 16 piles, 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 11.9%, 15.93%, and 19.42% for pile spacings of 3D, 4D, and 5D, respectively. Differential settlement varied with pile lengths and spacings while bending moments increased negatively and decreased positively with longer piles. Performance was influenced by load distribution, foundation stiffness, deflection, and soil layer interactions.
- ✓ The study on piled raft performance revealed the significant impact of pile number and spacing on maximum and differential settlement. Increasing pile numbers from 4 to 16 reduced maximum settlement by 19%, 20.04%, and 18.17% for pile spacings of 3D, 4D, and 5D, respectively. However, differential settlement varied with specific pile spacing and number. The area coverage of the pile group (Ag) also notably affected overall performance. Thus, engineers and designers had to carefully consider pile number and spacing to optimize performance and minimize settlements.
- ✓ A significant observation in this study, besides the parameters, was the impact of the ratio between the pile group width and the raft width (Bg/Br) on the differential settlement and the bending moment of the raft. As the ratio of the pile group width to the width of the raft (Bg/Br) changed, both the differential settlement and the bending moment exhibited different behaviors. Therefore, the performance of piled rafts was mainly related to the area covered by the pile group (Ag).

5.2. Recommendation

The following recommendations are given for future researchers who want to study the effects of different parameters on piled raft foundations:

- ✓ Conduct a comprehensive literature review to identify other parameters that affect the behavior of piled raft foundations besides the five parameters studied in this research (raft thickness, pile number, pile diameter, pile length, and pile spacing).
- ✓ For this research, small raft sizes were used. In the future, it is recommended to use large raft foundations to investigate the effect of the pile number and spacing more extensively.
- ✓ Perform laboratory experiments and validate the numerical results obtained from PLAXIS 3D using different soil types and loading conditions.
- ✓ Explore the response of piled raft foundations under complex loading patterns such as eccentric and lateral.

- ✓ Include dynamic analysis in the study to account for the effects of vibration and seismic loads on piled raft foundations.
- ✓ Extend the study to complex soil strata conditions such as multi-layered, heterogeneous, or anisotropic soils.

Special Acknowledgment

This research project founded by Adama Science and Technology University under grand number:

ASTU/SM-R/789/23

Adama, Ethiopia

REFERENCE

AGI. (1984). *Raccomandazioni Sui Pali Di Fondazione*. Associazione Geotecnica Italiana. Padova: Servizi Grafici Editoriali.

Akl, A. Y., Mansour, M. H., & Moustafa, H. K. (2014). Effect of changing configurations and lengths of piles on piled raft foundation behaviour. *Civil Engineering and Urban Planning: An International Journal*, *1*(1).

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*.

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)*.

Alnuaim, A. M., El Naggar, H., & El Naggar, M. H. (2013). 3D Modeling of Piled Raft Foundation Subjected To Vertical Loading. *The 3rd Specialty Conference on Material Engineering & Applied Mechanics Part of CSCE Annual Conference (Montreal 2013)*.

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.

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. B. J., Kumarswamy, S., Swolfs, W. M., Waterman, D., Chesaru, A., & Bonnier, P. G. (2016). PLAXIS 2016. *PLAXIS Bv, 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.

Classic Consulting Engineers PLC. (2016). *Geotechnical Investigation Report for Bole Arabsa V site*.

Coyle, H. M., & Castello, R. R. (1981). New design correlations for piles in sand. *Journal of the Geotechnical Engineering Division*, *107*(7), 965–986.

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

EBCS. (1995). *EBCS-7-foundations*. Ministry of Works & Urban Development.

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.

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. (2021). 3D numerical analysis of piled raft interaction in drained soft clay conditions. *Arabian Journal of Geosciences*, *14*, 1–12.

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.

Ghiasi, M., Farhoudi, R., & & Shafieifar, M. (2018). Numerical modeling of piled raft foundations using Plaxis 3D. *Geomechanics and Engineering*, *15(3)*, 451–468.

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.

Imple, V. (2001). Methods of analysis of piled raft foundations. *International Society of Soil Mechanics and Geotechnical Engineering*.

Janbu, N. (1976). Static bearing capacity of friction piles. *Sechste Europaeische Konferenz Fuer Bodenmechanik Und Grundbau*, *1*.

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, D. E. (2014). 14 Descriptive statistics. *Research Methods in Linguistics*, 288.

Johnson, R. T., Varghese, R. M., & Joseph, J. (2019). 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). 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., & Choudhury, D. (2016). Estimation of engineering properties of soils from field SPT using random number generation. *INAE Letters*, *1*, 77–84.

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).*

Kuwabara, F. (1989). An elastic analysis for piled raft foundations in a homogeneous soil. *Soils and Foundations*, *29*(1), 82–92.

Lee, J., Kim, Y., & Jeong, S. (2010). Three-dimensional analysis of bearing behavior of piled raft on soft clay. *Computers and Geotechnics*, *37*(1–2), 103–114. https://doi.org/10.1016/j.compgeo.2009.07.009

Lee, J., Park, D., & Choi, K. (2014). Analysis of load sharing behavior for piled rafts using normalized load response model. *Computers and Geotechnics*, *57*. 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.

Maharaj, D. K., & Anshuman, A. (2004). The effect of raft size and pile length on load-settlement behaviour of axisymmetric piled raft foundation. *Electronic Journal of Geotechnical Engineering*.

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). 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.

Mali, S., & Singh, B. (2020). 3D numerical modeling of large piled-raft foundation on clayey soils for different loadings and pile-raft configurations. *Studia Geotechnica et Mechanica*, *42*(1), 1–17.

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.

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

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

Oh, E. Y. N., Lin, D. G., Bui, Q. M., Huang, M., Surarak, C., & Balasubramaniam, A. S. (2009). Numerical analysis of piled raft foundation in sandy and clayey soils. *Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4)*, 1159–1162.

Othman, N. N. A., & Mohtar, N. (2021). Effect of raft thickness on the behavior of piled raft foundation on soft soil. *Geomechanics and Engineering, 23(1)*, 23–37.

Poulos, H. G. (1991). Analysis of piled strip foundations. *International Conference on Computer Methods and Advances in Geomechanics. 7*, 183–191.

Poulos, H. G. (2000). 16. Practical design procedures for piled raft foundations. In *Design applications of raft foundations*. https://doi.org/10.1680/daorf.27657.0016

Poulos, H. G. (2001a). Methods of analysis of piled raft foundations. *A Report Prepared on Behalf of Technical Committee TC18 of Piled Foundations*.

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

Poulos, H. G. (2016). Tall building foundations: design methods and applications. In *Innovative Infrastructure Solutions* (Vol. 1, Issue 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).

Prakoso, W. A., & Kulhawy, F. H. (2001). Contribution to piled raft foundation design. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(1), 17–24.

Prat, M., Bisch, E., Millard, A., Mestat, P., & Cabot, G. (1995). *The modeling of the structures (La modelisation des ouvrages)*. Hermes Publishing House (Maison d'édition Hermes), Paris/France.

Randolph, M. F., & Wroth, C. P. (1978). Analysis of deformation of vertically loaded piles. *Journal of the Geotechnical Engineering Division*, *104*(12), 1465–1488.

Reul, O., & Randolph, M. F. (2004). Design Strategies for Piled Rafts Subjected to Nonuniform Vertical Loading. *Journal of Geotechnical and Geoenvironmental Engineering*, *130*(1), 1–13. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:1(1)

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.

Samee, A. E. (2018). Effect of Pile Spacing On Ultimate Capacity and Load Shearing for Piled Raft Foundation. *International Journal of Applied Engineering Research*, *13*, 4–6.

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

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

Skempton, A. W., & MacDonald, D. H. (1956). The allowable settlements of buildings. *Proceedings of the Institution of Civil Engineers*, *5*(6), 727–768.

Srilakshmi, G., & Darshan Moudgalya, N. S. (2013). Analysis of piled raft foundation using finite element method. *International Journal of Engineering Research and Science & Technology*, *2*(3), 89–96.

Sulaiman Al-Ne'aimi, R. M., & Hussain, M. S. (2021). Numerical modeling and parametric study of piled rafts foundations. *Arabian Journal of Geosciences*, *14*, 1–13.

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*, *20*(2), 331–343. https://doi.org/10.1007/s00773-014-0286-x

Tsuchida, T., Kitade, K., Tanaka, M., Kang, G., & Kaya, K. (2020). Evaluation of design shear strength of intermediate soil for construction of breakwater at Port of Sakai. *Soils and Foundations*, *60*(1), 239–256. https://doi.org/10.1016/j.sandf.2019.11.011

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. (2000). ‘Analysis and Design of Piled Foundations. *First Arrigo Croce Lecture, Naples, December*.

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

Vu, A.-T., & Matsumoto, T. (2016). Experimental and numerical study on small-size piled raft foundation models subjected to cyclic horizontal loading. *Geotechnics Sustainable Infrastructure Development-Geotec Hanoi. ISBN 978-604-82-0013, 8*.

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 Int. Conf. on SMFE*, *1*, 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 & Réthàti, 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)

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

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

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

$\nu = 0.125 + 0.0125\text{N}$ 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

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

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

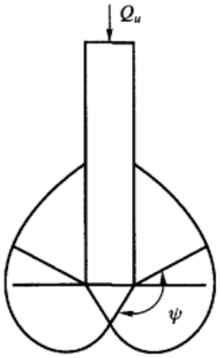


Figure A.1: The shapes of failure surfaces at the tips of piles as assumed by Meyerhof

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)

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

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

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

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

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

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

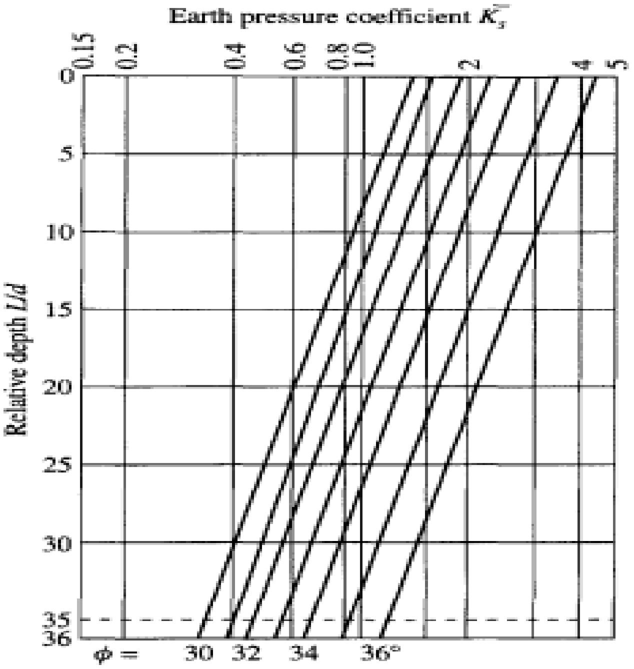


Figure A.2: Coefficient K versus L/d, **δ** = 0.8 *φ* (Coyle & Castello, 1981)

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 Plaxis 3D and ETABS

Table B.1: Comparison of bending moment for different pile diameters and pile numbers

Maximum bending moment (KN M/M)

	Diameter(m)	n=4		n=9		n=16	
		m11	m22	m11	m22	m11	m22
Negative moment	0.6	-695.4	-636.1	-583.1	-473.2	-454.2	-360
	0.8	-830.7	-758.3	-550.4	-443.8	-615.2	-438
	1	-822	-744.5	-736	-557.6		
Positive moment	0.6	345.1	256.6	236	170.2	117.7	141.9
	0.8	259.8	202.7	171.6	193.9	520.5	422.3
	1	249	230.4	450.3	357		

Table B.2: Comparison of bending moment for different pile spacing and pile number

Maximum bending moment (KNM/M)

	Pile spacing (Sy)	n=4		n=9		n=16	
		m11	m22	m11	m22	m11	m22
Negative moment	3D	-695.4	-636.1	-583.1	-473.2	-454.2	-360
	4D	-636.7	-591.8	-460.8	-382	-486.8	-351.1
	5D	-650.7	-602.1	-537.9	-438.8	-813.5	-322.2
Positive moment	3D	345.1	256.6	236	170.2	117.7	141.9
	4D	307.5	257.7	201.7	209.6	575	460
	5D	259.4	249.6	503.4	388.8	980.2	865.1

Table B.3: Comparison of bending moment for different pile lengths and pile spacing

Maximum bending moment (KNM/M)

	Pile length(m)	Sy = 3D		Sy = 4D		Sy = 5D	
		m11	m22	m11	m22	m11	m22
Negative moment	9	-583.1	-473.2	-460.8	-382	-537.9	-438.8
	12	-959	-823.1	-671.7	-554.8	-683.6	-506.5
	15	-987.4	-832.3	-850	-696.5	-817.4	-602.4
Positive moment	9	236	170.2	201.7	209.6	503.4	388.8
	12	195.8	89.68	134.8	161.9	444.4	582.7
	15	187.1	83.42	113.8	100.7	414.6	571

Table B.4: Comparison of bending moment for different pile numbers and pile spacing

Maximum bending moment (KNM/M)							
	Number of piles	Sy=3D		Sy=4D		Sy=5D	
		m11	m22	m11	m22	m11	m22
Negative moment	4	-695.4	-636.1	-636.7	-591.8	-650.7	-602.1
	9	-583.1	-473.2	-460.8	-382	-537.9	-438.8
	16	-454.2	-360	-486.8	-351.1	-813.5	-322.2
Positive moment	4	345.1	256.6	307.5	257.7	259.4	249.6
	9	236	170.2	201.7	209.6	503.4	388.8
	16	117.7	141.9	575	460	980.2	865.1

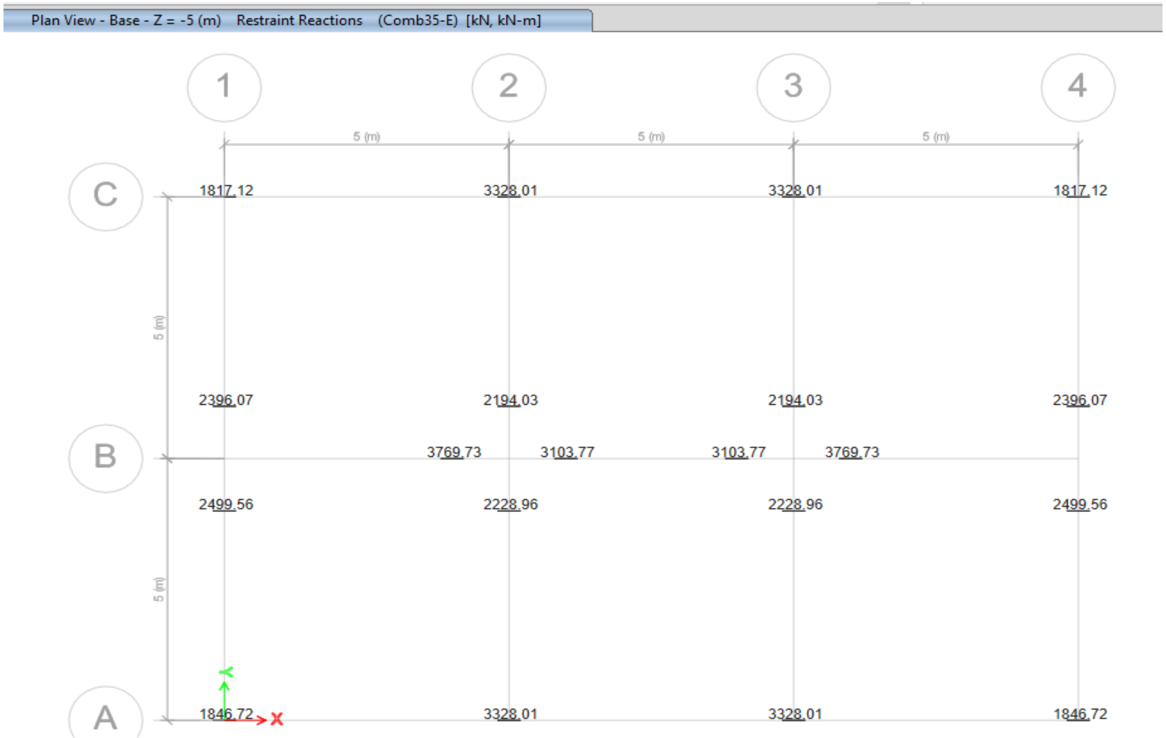


Figure B.1: Reaction force obtained from ETAS output

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

Appendix C: Different Software Models

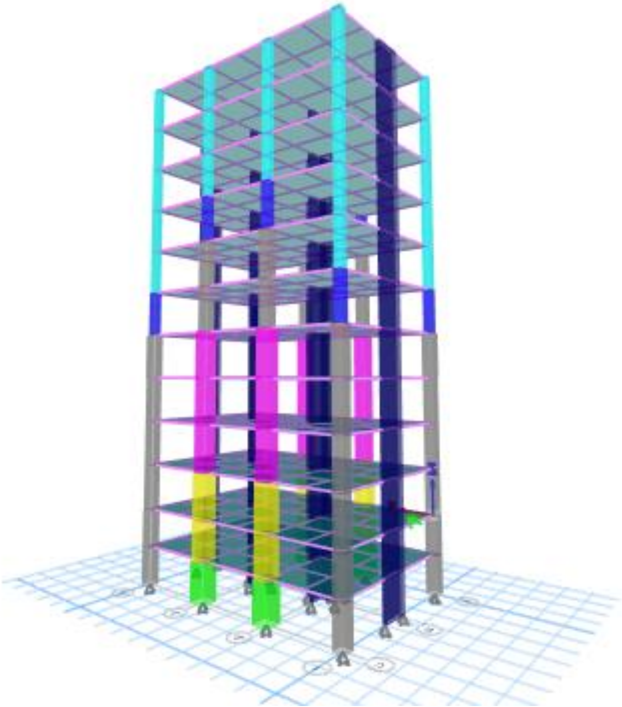


Figure C.1: Design 12 story building using ETABS software

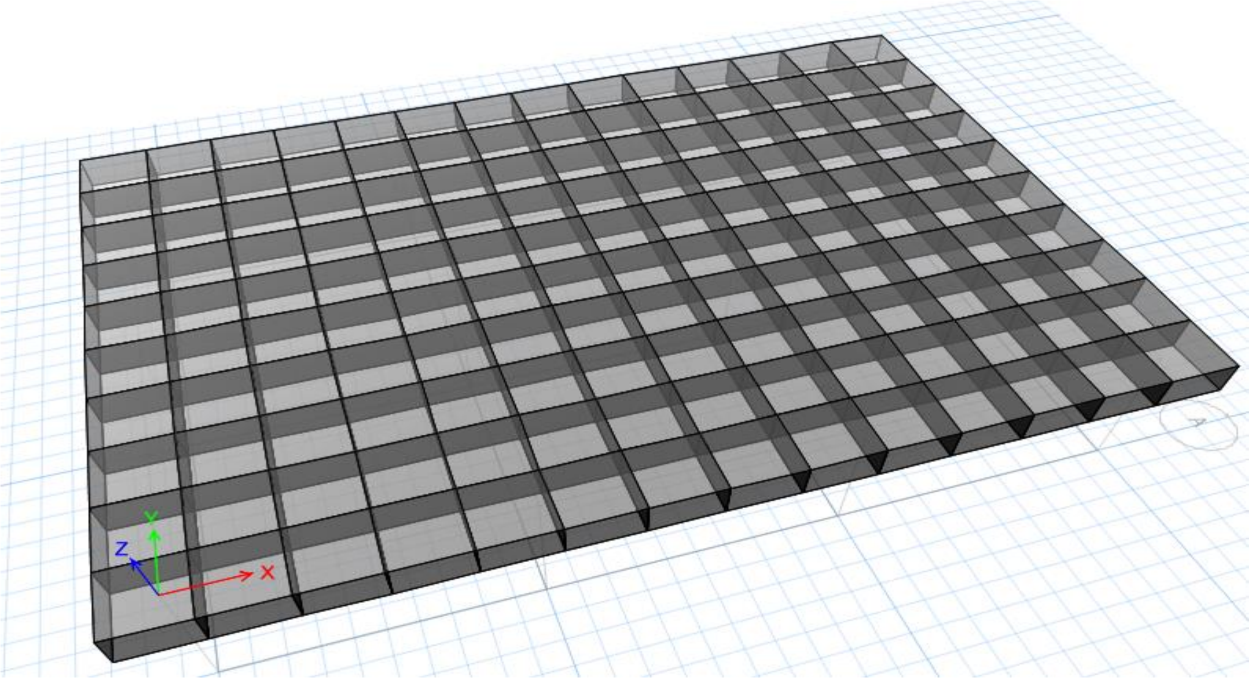


Figure C.2: Design raft foundation using SAFE software

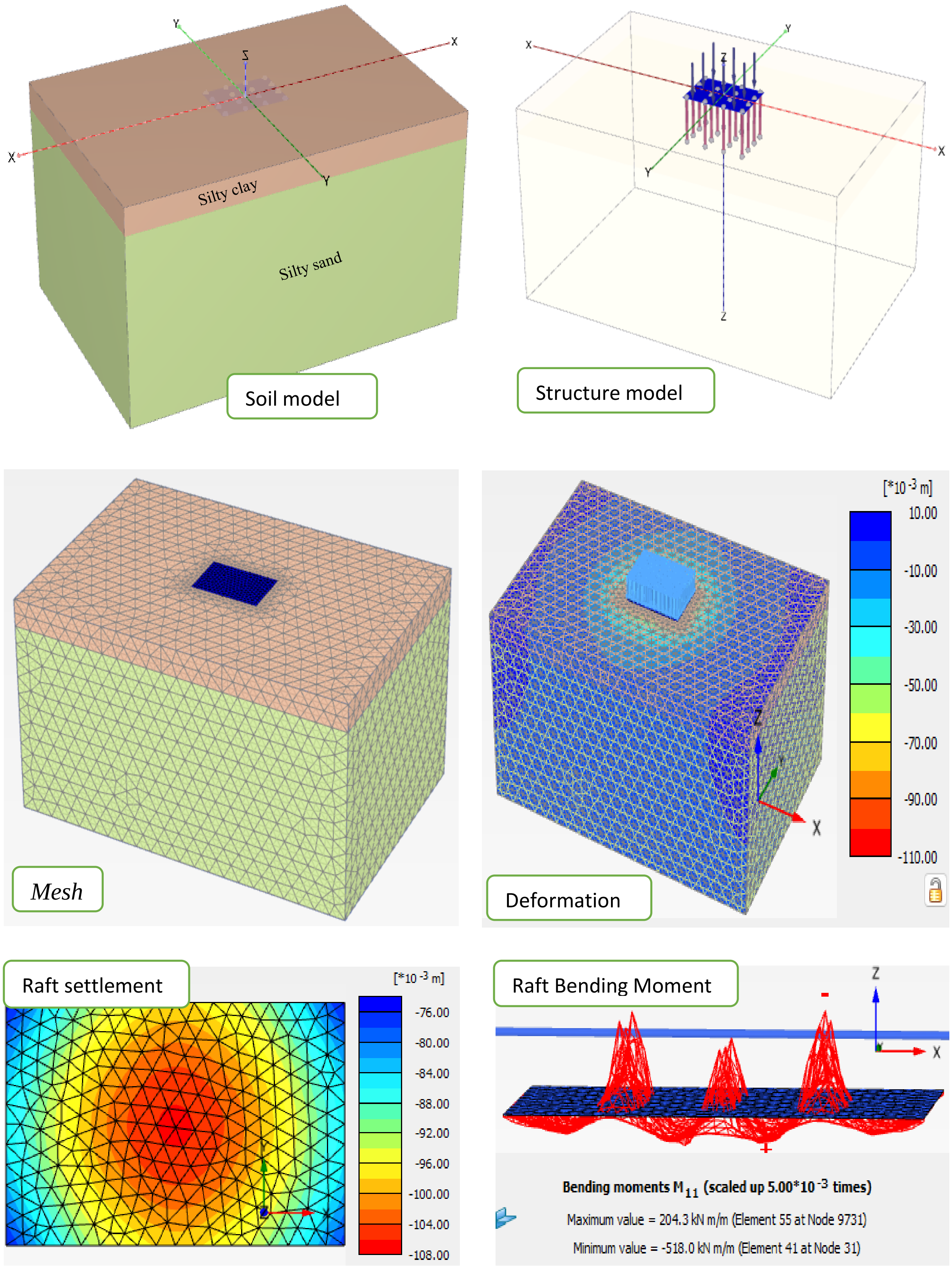


Figure C.3: Numerical modeling using PLAXIS 3D software

Appendix D: Borehole Data

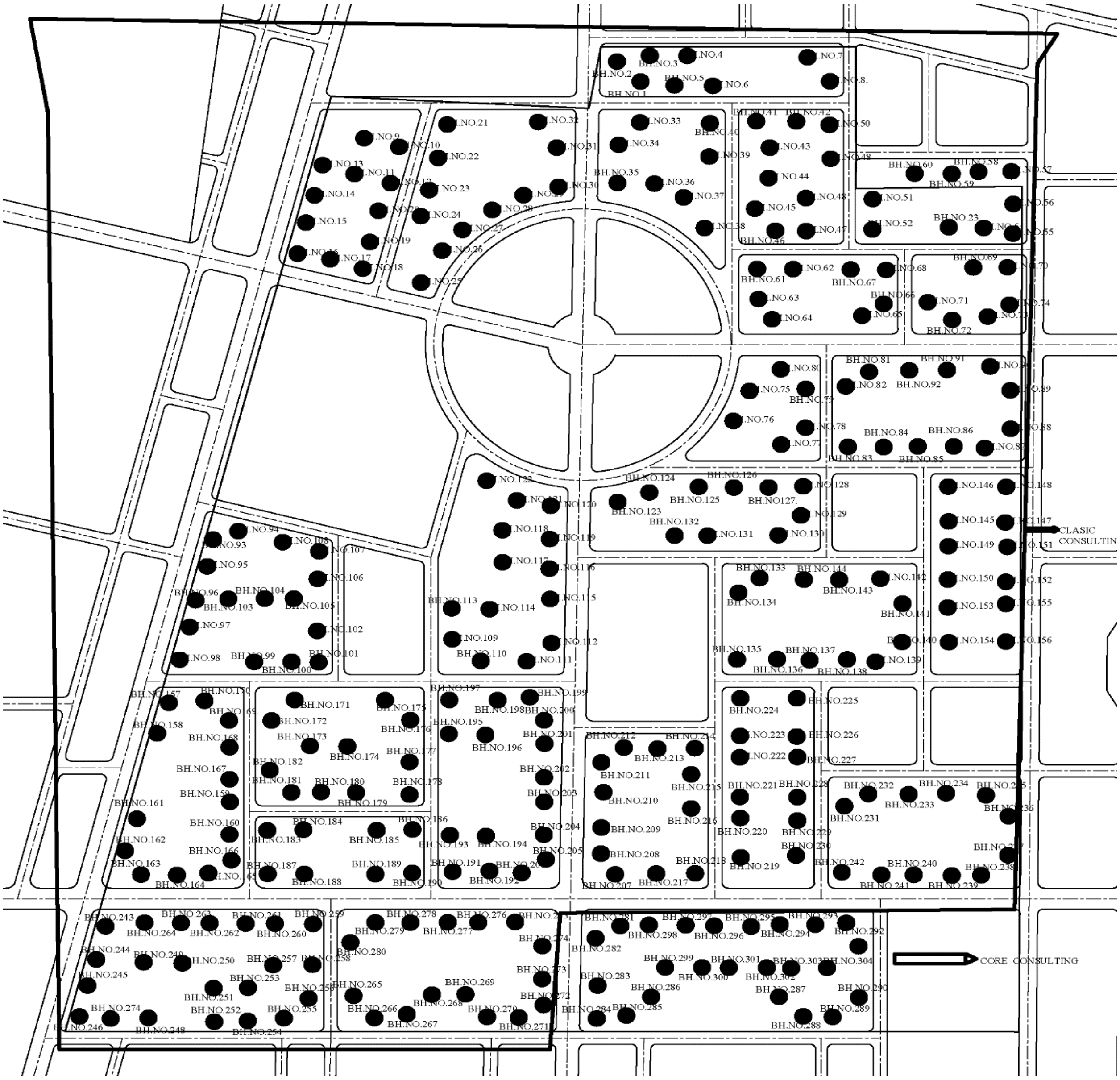


Figure D.1: Placement of boreholes for Bole Arabsa V

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

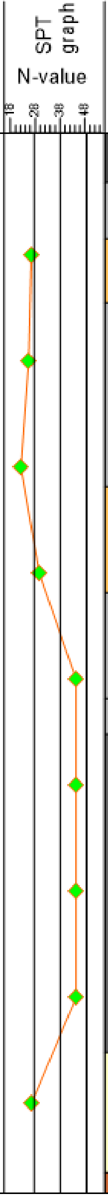
SPT (N) value for silty sand = 30

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

Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)
1.50	100			
3.00	100			
4.50	100			
6.00	100			
6.50	100			
7.30	100			
8.00	100			
9.00	100			
10.00	100			
11	100			
12	100			
13	100			
14	100			
15	100			

Sample depth	Sample type	SPT	N
1.5 1.95	D	4,6,7	13
3 3.45	D	5,6,6	12
4.5 4.95	D	4,3,6	9
6 6.45	D	7,8,8	16
7.5 7.95	D	R	30
9 9.45	D	R	30
10.5 10.95	D	R	30
12 12.45	D	R	30
13.5 13.95	D	5,6,7	13



Soil/Rock description	Ground water level (m)
Dark grey silty Clay [Black Cotton soil]	
Greyish white silty Clay	
Yellowish brown clayey silty Sand	
Reddish to greyish white silty Clay	
Yellowish brown silty Clay	
Greyish white silty sandy Gravel with some rock	
Greyish white to reddish brown clayey silty Sand	
Greyish black silty Sand	
Yellowish silty Clay	
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

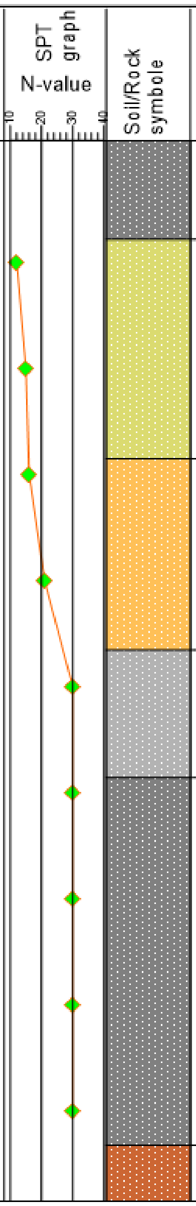
SCR=Solid Core Recovery
RQD=Rock Quality Designation
AFS=Average Fracture Spacing

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

Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)
1.50	100			
3.00	100			
4.50	100			
6.00	100			
6.50	100			
7.30	100			
8.00	100			
9.00	100			
10.00	100			
11	100			
12	100			
13	100			
14	100			
15	100			

Sample depth	Sample type	SPT	N
1.5 1.95	D	5,6,6	12
3 3.45	D	6,7,8	15
4.5 4.95	D	6,7,9	16
6 6.45	D	8,10,11	21
7.5 7.95	D	R	30
9 9.45	D	R	30
10.5 10.95	D	R	30
12 12.45	D	R	30
13.5 13.95	D	R	30



Soil/Rock description	Ground water level (m)
Dark grey silty Clay [Black Cotton soil]	
Greyish green to yellowish Red silty Clay	
Yellowish brown silty Clay with some sand	
Greyish white silty Sand	
Greyish black silty Sand	
Reddish brown silty Clay	

Depth (m): 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Driller: Assefa Ababu

Logged by: Haile Meskel

Checked by: Haile Meskel

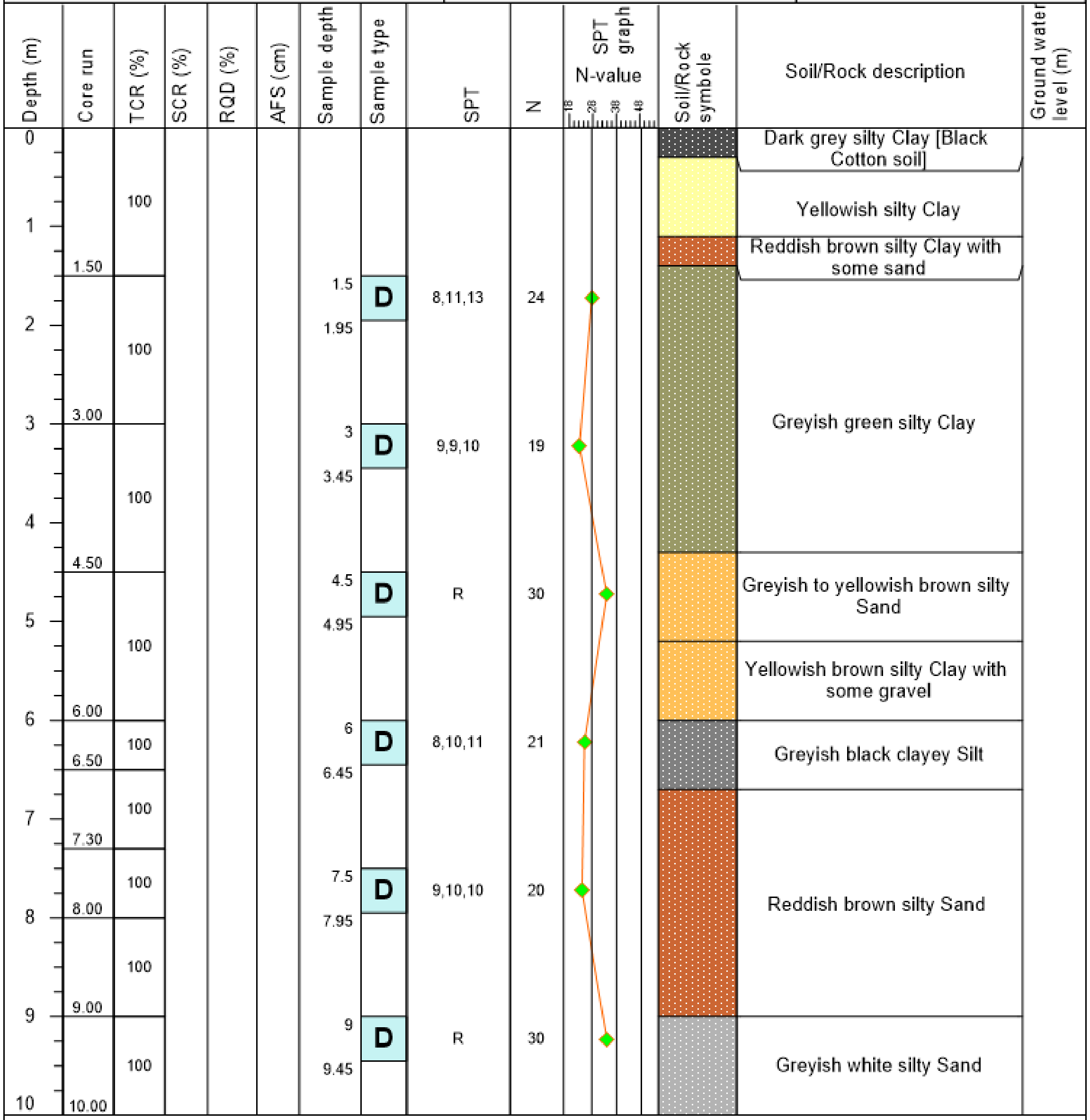
Note:

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



Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)	Sample depth	Sample type	SPT	N
1.50	100							
3.00	100				1.5 1.95	D	8,11,13	24
4.50	100				3 3.45	D	9,9,10	19
6.00	100				4.5 4.95	D	R	30
6.50	100				6 6.45	D	8,10,11	21
7.30	100							
8.00	100				7.5 7.95	D	9,10,10	20
9.00	100							
10.00	100				9 9.45	D	R	30

Soil/Rock description
Dark grey silty Clay [Black Cotton soil]
Yellowish silty Clay
Reddish brown silty Clay with some sand
Greyish green silty Clay
Greyish to yellowish brown silty Sand
Yellowish brown silty Clay with some gravel
Greyish black clayey Silt
Reddish brown silty Sand
Greyish white silty Sand

Driller: Assefa Ababu

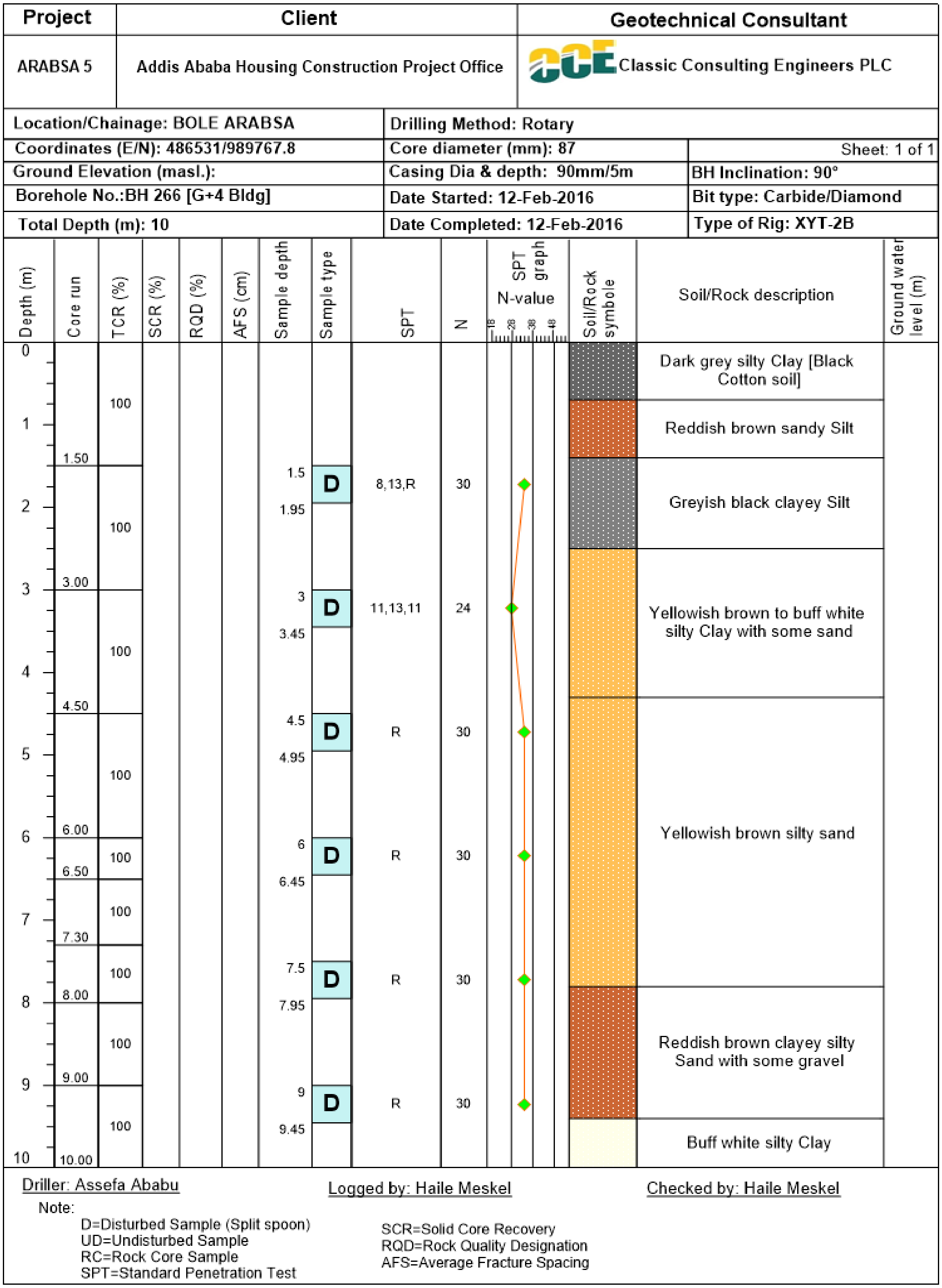
Logged by: Haile Meskel

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

Core run	TCR (%)	SCR (%)	RQD (%)	AFS (cm)
1.50	100			
3.00	100			
4.50	100			
6.00	100			
6.50	100			
7.30	100			
8.00	100			
9.00	100			
10.00	100			

Sample depth	Sample type	SPT	N
1.5 1.95	D	8,13,R	30
3 3.45	D	11,13,11	24
4.5 4.95	D	R	30
6 6.45	D	R	30
7.5 7.95	D	R	30
9 9.45	D	R	30

Soil/Rock description:

- Dark grey silty Clay [Black Cotton soil]
- Reddish brown sandy Silt
- Greyish black clayey Silt
- Yellowish brown to buff white silty Clay with some sand
- Yellowish brown silty sand
- Reddish brown clayey silty Sand with some gravel
- Buff white silty Clay

Driller: Assefa Ababu

Logged by: Haile Meskel

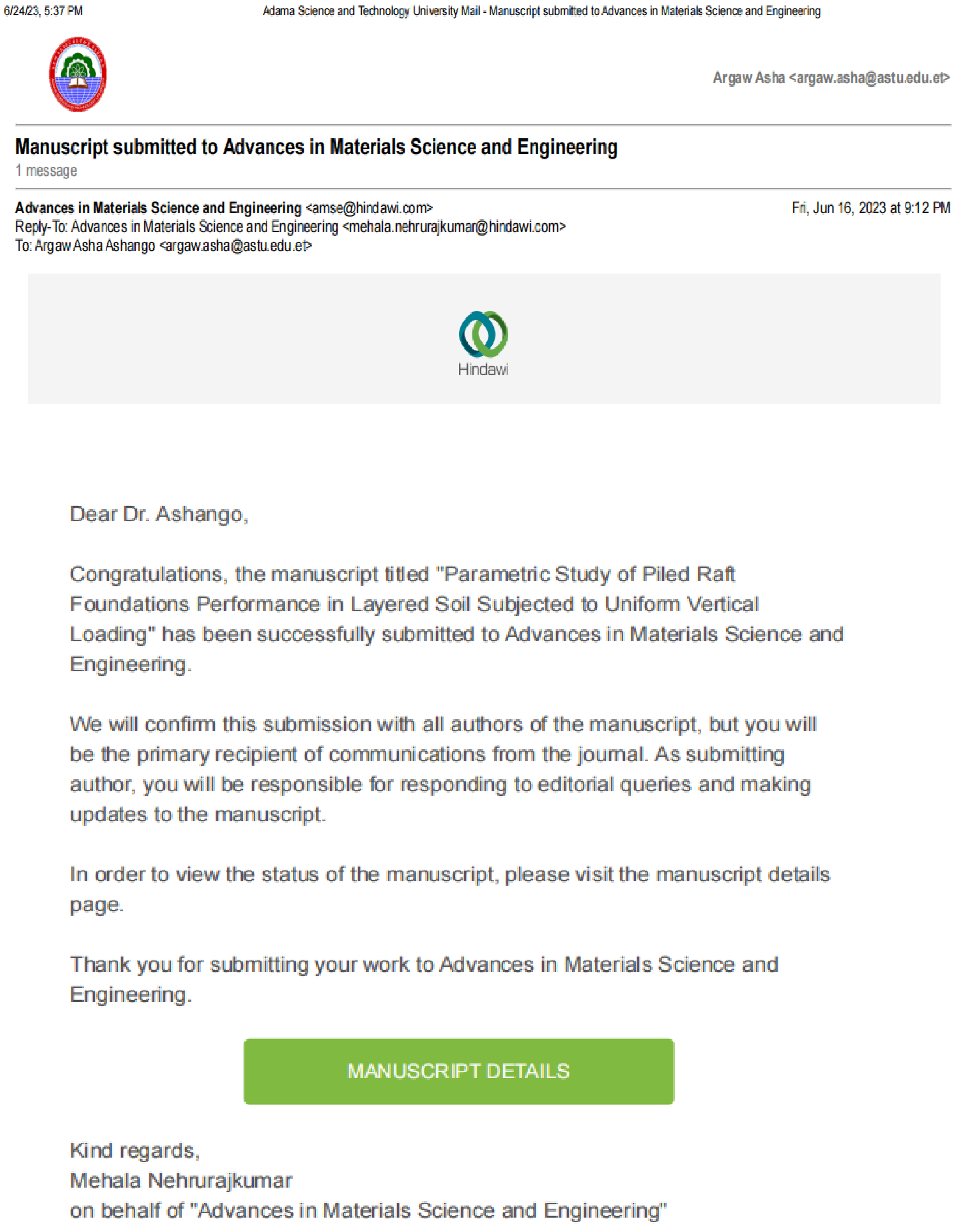
Checked by: Haile Meskel

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

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



6/24/23, 5:37 PM Adama Science and Technology University Mail - Manuscript submitted to Advances in Materials Science and Engineering

Argaw Asha <argaw.asha@astu.edu.et>

Manuscript submitted to Advances in Materials Science and Engineering

1 message

Advances in Materials Science and Engineering <amse@hindawi.com> Fri, Jun 16, 2023 at 9:12 PM
Reply-To: Advances in Materials Science and Engineering <mehala.nehrurajkumar@hindawi.com>
To: Argaw Asha Ashango <argaw.asha@astu.edu.et>

Hindawi

Dear Dr. Ashango,

Congratulations, the manuscript titled "Parametric Study of Piled Raft Foundations Performance in Layered Soil Subjected to Uniform Vertical Loading" has been successfully submitted to Advances in Materials Science and Engineering.

We will confirm this submission with all authors of the manuscript, but you will be the primary recipient of communications from the journal. As submitting author, you will be responsible for responding to editorial queries and making updates to the manuscript.

In order to view the status of the manuscript, please visit the manuscript details page.

Thank you for submitting your work to Advances in Materials Science and Engineering.

MANUSCRIPT DETAILS

Kind regards,
Mehala Nehrurajkumar
on behalf of "Advances in Materials Science and Engineering"