INVESTIGATION OF LOAD SHARING BEHAVIOR OF PILED RAFT WITH PILE TIPS FINITE DIFFERENCE METHOD: A CASE STUDY OF THE NEW BUILDING BANK OF ABYSSINIA HEADQUARTERS ADDIS ABABA

Adisu Degif Akneda

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

Office of Graduate Studies
Adama Science and Technology University

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

January, 2024

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master thesis entitled **"Investigation Of Load Sharing Behavior Of Piled Raft With Pile Tips Finite Difference Method: A Case Study Of The New Building Bank Of Abyssinia Headquarters Addis Ababa"** is my original work. That is, it has not been submitted for the award of any 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.

Adisu Degif Akneda	______________________	______.
Name of student	Signature	Date

RECOMMENDATION

I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled **"Investigation Of Load Sharing Behavior Of Piled Raft With Pile Tips Finite Difference Method: A Case Study Of The New Building Bank Of Abyssinia Headquarters Addis Ababa"** prepared under my/our guidance by Adisu Degif submitted in partial fulfillment of the requirements for the degree of Masters of Science in Civil Engineering. Therefore, I/we recommend the submission of a revised version of the thesis to the department following the applicable procedures.

Argaw Asha (Ph.D.)	___________________	________.
Major Advisor/Supervisor	Signature	Date
________________________	___________________	__________
Co-advisors/ Co-supervisor	Signature	Date

APPROVAL PAGE

I/we, the advisors of the thesis entitled **“Investigation Of Load Sharing Behavior Of Piled Raft With Pile Tips Finite Difference Method: A Case Study Of The New Building Bank Of Abyssinia Headquarters Addis Ababa”** and developed by Adisu Degif hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Argaw Asha (Ph.D.)	__________________	________.
Major Advisor/Supervisor	Signature	Date
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APPROVAL OF BOARD OF REVIEWERS

We, the undersigned, members of the Board of Examiners of the thesis by Adisu Degif have read and evaluated the thesis entitled **"Investigation Of Load Sharing Behavior Of Piled Raft With Pile Tips Finite Difference Method: A Case Study Of The New Building Bank Of Abyssinia Headquarters Addis Ababa"** and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Civil Engineering.

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ABBREVIATIONS AND ACRONYMS

A	Global displacement vector
B_r	Width of the raft
CPT	Cone penetration test
CPRF	Combined piled raft footing
E_s	Stress-strain modulus
E_{sh}	Stress-strain modulus horizontal
E_{sv}	Stress-strain modulus value
FLAC	Fast lagrangian analysis of continua
FEM	Finite element method
K	Global stiffness matrix
K_r	Stiffness of raft
K_{pr}	Stiffness of piled raft
K_p	Stiffness of the pile group
K_{pr}	Stiffness of piled raft
K_p	Stiffness of the pile group
K_r	Stiffness of the raft alone
L	Length of the raft
N_{cor}	Corrected N value
Pa	Average atmospheric pressure
Pup	Ultimate load capacity of the piles in the group
S`	Design settlement
S_{pr}	Settlement of piled raft
S_r	Settlement of raft without piles
SPT	Standard penetration test
X	Proportion of load carried by the piles
γ	Unite weight
Z	Depth
Σz	Overburden pressure at a depth z below the foundation level
$\Delta\sigma z$	Additional vertical stress due to the loads from the superstructure
α_{cp}	Raft – pile interaction factor
3D	Three times diameter of the pile
6D	Six times diameter of the pile

ABSTRACT

The abstract of the thesis presents a detailed investigation into the load-sharing behavior of a piled raft foundation with pile tips using a finite difference method. Here are the key points summarized from the abstract:The thesis focuses on investigation the of the load-sharing behavior of a piled raft foundation with pile tips at the New Building Bank of Abyssinia Headquarters in Addis Ababa using the finite difference method. Emphasis on understanding how superstructure loads are distributed between piles and the raft in a piled raft foundation. Piled raft foundations offer increased load capacity and reduced settlements in a cost-effective manner compared to traditional foundation concepts. The study focuses on the contributions of the raft to the bearing behavior of the piled raft foundation and the mechanisms of load sharing between the raft and piles. Key points highlighted in the abstract include: The primary aim is to analyze the load-sharing behavior of a piled raft foundation with pile tips, specifically at the mentioned site in Addis Ababa. The study employs the finite difference method to model and analyze the behavior of the foundation system, considering the interaction between the raft, piles, and soil. The investigation is conducted at the New Building Bank of Abyssinia Headquarters in Addis Ababa, providing a real-world context for the analysis. Emphasis is placed on understanding how loads are distributed between the raft and piles in the piled raft foundation system with pile tips. The findings of the study are expected to contribute to the knowledge and understanding of the load-sharing mechanisms in piled raft foundations, particularly with the inclusion of pile tips. In summary, the abstract sets the stage for a detailed investigation into the load-sharing behavior of a specific piled raft foundation with pile tips at a notable construction site, utilizing the finite difference method for analysis and evaluation.

***Key words**: Piled raft foundation, load sharing, pile tips, finite difference method.*

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

One of the most important aspects of civil engineering projects is a foundation system. Carefully and properly designed foundations surely lead to a safe, efficient, and economic project. Foundation systems are divided into two: shallow and deep foundations. Selection of the foundation system mainly depends on the nature of the structure and type of earth material. In piled-raft foundations, the piles are used as elements to enhance the behavior of the raft to satisfy the design requirements, and they are typically not considered carriers for the total structural load.The function of any foundation is to transmit the load to the soil to provide safety, reliability, and serviceability to the structure. As the use of piled raft foundations as an alternative to conventional piled foundations for tall buildings has been increasing, different techniques have been developed for performing analyses over the last decade. In piled rafts, the raft directly interacts with soil and is supported by a group of piles of various configurations. Such foundations will be subjected to the vertical loadings transferred directly from the structure and horizontal loadings mostly due to wind loads. These loads are transferred to the soil through the raft and the piles. The conventional pile design philosophy is based on that the piles carry the entire load and are accepted as a group, no contribution is made by the raft to the ultimate load capacity. However, a combination of shallow and deep foundations can be a cost-effective design approach. The piled raft foundation is a combination of a deep pile group and a shallow raft foundation that has gained increasing recognition in very recent years. In a piled raft foundation, the total load coming from the superstructure is partly carried by piles, and the remaining load is taken by the raft through contact with the soil. The design of a piled raft is based on the soil-structure interaction between the constituting elements, however, the piled raft subsoil interaction problem is highly complicated as it depends on a large number of parameters like pile-raft geometry, pile spacing, subsoil type, etc. Hence, it needs 3D analysis to account for these factors. In this study, raft contributions to the bearing behavior of piled raft foundations and load-sharing mechanisms between rafts and piles in the case of pile tips resting on a hard stratum are investigated. In addition, a parametric study has been conducted to see the effect of the weak layer located in the hard stratum below the pile tips on piled raft behavior. In this study, the Bank of Abyssinia headquarter building has been taken as a case study. The complex geometry and interaction of a piled-raft foundation can be accounted for using Finite diffrence Method modeling. So, this method will be used for modeling and analyzing the piled raft foundation system. Before detailed modeling, a preliminary assessment of the foundation has been carried out using a simplified method.Piled raft foundations provide an economical foundation option for circumstances where the performance of the raft alone does not satisfy the design requirements. Under these situations, the addition of a limited number of piles may improve the ultimate load capacity, the settlement and differential settlement performance, and the required thickness of the raft.

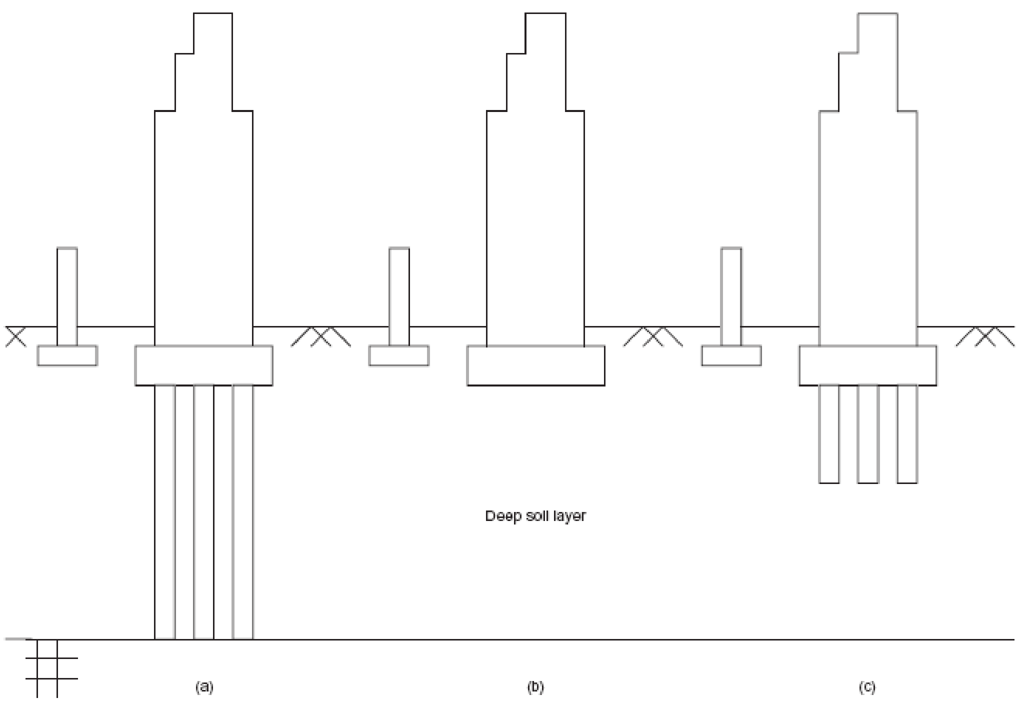


Figure 1**:** Concept of Pile Raft Foundation (a) Piles; (b) Raft and; (c) Piled Raft (Basile, 1999)

1.2 Statement of the Problem

The main problem statement for this paper is the lack of proper consideration and understanding of the selection criteria for piled raft foundations in construction projects in

Ethiopia. While poor soil bearing capacity is typically the primary reason for choosing piled raft foundations, this decision is not consistently based on this aspect in the country. This lack of adherence to best practices in foundation selection can potentially lead to safety and stability issues in high-rise buildings and civil structures. Furthermore, there is a need to assess the settlement and load-sharing behavior of piled raft foundations, specifically focusing on the construction of the Bank of Abyssinia (BOA) headquarters. Understanding how these foundations perform under vertical loads is crucial for ensuring the overall structural integrity of such projects. By evaluating the specific case of the BOA headquarters, valuable insights can be gained that will be beneficial for future projects utilizing similar foundation systems.

1.3Research Objective:

Investigate the load-sharing behavior of piled rafts with pile tips in the construction of the BOA headquarters in Addis Ababa.

1.4Specific objectives

- Evaluate the load transfer mechanisms within the piled-raft foundation system at the BOA headquarters construction site in Addis Ababa.
- Investigate the pile capacity of the piled-raft foundations under vertical loads, considering the specific soil conditions and design parameters of the BOA headquarters project.
- Analyze the contribution of the raft to the maximum and differential settlements of the foundation in the context of the high-rise building construction at the BOA headquarters.
- Determine the load-sharing behavior between the pile and the raft with pile tips in the piled-raft foundation system of the BOA headquarters project.

1.5 Significance of the study

- Develop a better contribution of the raft on the maximum and differential settlements of the foundation.
- Explore the previous work done abroad and increase the confidence of geotechnical engineers to apply the load-sharing behavior between the raft and the piles in Ethiopia.
- Used as a reference for future

- ❖ To understand the load-sharing nature of piled-raft under vertical load;
- ❖ Assess the design condition of the buildings under vertical loading;
- ❖ To contribute its part to the area

1.6 Scope and Limitation of study on research

This study is limited to investigating the contribution of rafts, on settlement, load-sharing behavior, and bearing capacity of piled raft foundations when the pile tips rest on a hard stratum. The analysis is limited to the case of the Bank of Abyssinia (BOA) head quarter building under gravity loading only. It is also restricted to assessing the failure behavior of piled raft in cases where a weak stratum is located below the pile tip

1.6 Thesis Organization

Chapter 1 presents the general background of the use of piled raft foundations to support different types of structures and the advantages of using such foundations. Chapter 2 also highlights the currently available means for analyzing and designing piled raft foundations. A review of previous studies on piled raft foundations is also presented in this chapter. Chapter 3 presents information about the case study building and its surroundings. It also contains information about geotechnical conditions at the site. The determination of soil parameters used for modeling the foundation is also included in this chapter. A preliminary assessment of the foundation a using simplified method has been presented. It is to investigate the adequacy of the raft alone, concerning ultimate bearing capacity and settlement requirements. Presents details of the numerical model. This model was used to analyze the piled raft foundation. In addition, the validity of the developed model for other models available in the literature is also included in Chapter 4 presents the analysis results and discussions of the piled raft foundation. It has been discussed in terms of load-settlement and load-sharing-settlement curves. Conclusions and recommendations of the whole work have been summarized in Chapter 5 and References are also added at the end of this chapter.

1.7 Methodology

All the necessary secondary data that helps with the modeling and analysis of the piled-raft foundation was collected from investigation reports conducted in the lab and field tests. Different correlation techniques were also used to determine soil parameters that were not included in the soil investigation report. Software modeling and analysis of the data The finite element software **FLAC3D 6.00** was selected for simulating the raft, pile, and piled raft foundation. The behavior of piled-raft foundations was analyzed based on different constitutive material behaviors. The material behavior of soil was modeled with a non-linear material constitutive model, whereas the raft and piles were modeled with a linear elastic constitutive model. Finally,, the results are interpreted, conclusions drawn, and recommendations made based on the obtained results.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Piled Raft Foundation is a composite foundation system consisting of three bearing elements; piles, raft, and subsoil, that combines the bearing effect of both foundation elements raft and piles. Due to combining the different elements of strictures (raft and piles) in one system, piled raft foundations are regarded as very complex systems. The complexity of this type of foundation is caused by the presence of four interaction factors involved in the system these are pile-to-soil, pile-to-pile, raft-to-soil, and pile-to-raft interactions Fig 2. (Long, 2018).In foundation design, rafts, pile groups, and piled rafts are commonly used to support structures. Extensive research work has been carried out and published in the past decades, and different analysis methods have been developed that can be classified into several categories namely (i) Empirical Method; (ii) Analytical Method, and; (iii) Numerical Method. The lack of experimental evidence, the disparity between theoretical evaluation and field measurements, and the urge to develop more rational techniques have prompted many researchers to investigate the areas of the analysis of piled raft foundations(Paulo & Paulo, 2010). A wide variety of loading and site conditions have been considered and various approaches of analysis have been followed. In this chapter, a brief review of the techniques developed for the analysis of; (i) Raft Foundation; (ii) Pile Group Foundation, and; (iii) Piled-Raft Foundation are presented. These have been classified into the following two categories:

i) Raft Behavior
ii) Pile Group Behavior
iii) Piled Raft Behavior

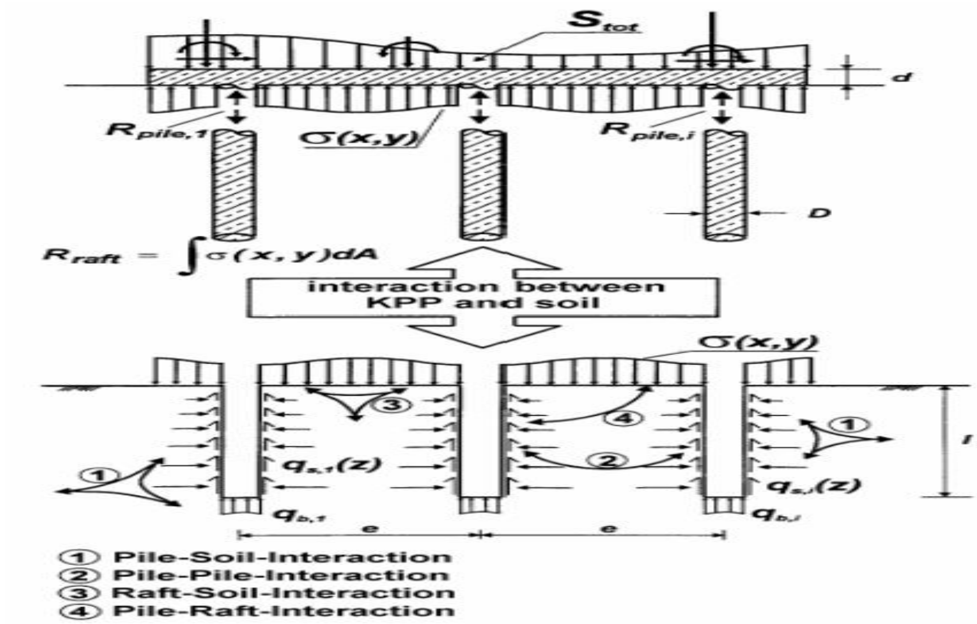


Figure 2:Piled-Raft Foundation and the interactions among the bearing elements (Jardine et al., 1986)

The bearing behavior of the piled raft foundation is described by the pile-raft coefficient αpr which is defined by the ratio between the sums of the characteristic pile resistance to the characteristic value of the total resistance

$$\mathrm{Kpr} = \frac{\mathrm{Kp} + \mathrm{Kr}\,(1 - \alpha\mathrm{cp})}{1 - \alpha\mathrm{cp}\; 2\,\frac{\mathrm{Kr}}{\mathrm{Kp}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq}\ 2.1)$$

where, Kpr = stiffness of piled raft

Kp = stiffness of the pile group

Kr = stiffness of the raft alone

2.2 Design Concepts piled raft foundation

Reviewed the design philosophy and design consideration of the piled raft foundation as follows. (Sinha, 2013)

2.2.1 Design Philosophy

Numerous works have been done and are still in progress to develop a definite design strategy for piled raft foundations (Reul & Randolph, 2000). Categorized the various design philosophies into three different design approaches. a) The conventional approach, in which, the foundation is designed as a pile group with regular spacing over the entire foundation area, to carry the major portion of the load (60 – 75% of the total structural load) and allowance is made for the raft to transmit some load directly to the ground. The conventional approach has the limitation that any design by this philosophy will remain inevitably in an elastic regime, where the piles are loaded below their shaft capacity and piles are evenly distributed over the whole foundation area. The shaft capacity of the group pile is "extremely difficult and has not been resolved yet" (Roy & Saha, 2011). Moreover, the allowance for the raft to transmit the load is not defined in this approach, which they let for engineering judgment. b) Creep piling approach, proposed by (Roy & Saha, 2011), in which, piles are designed to operate at a working load, at which significant creep starts to occur (typically at about 70 – 80% of its ultimate load-bearing capacity). To reduce the net contact pressure between the raft and soil, adequate piles are added to reduce the pre-consolidation pressure of the clay. The creep piling approach again sets the limitation of operating the pile below the creep load, which is, as mentioned above, 70% to 80% of the ultimate load-bearing capacity. However, the ultimate capacity is based on conventional group theory, which is under investigation. Moreover, the reduction of net contact pressure between the raft and soil using pile addition will refrain the raft from transmitting the load to its full capacity directly to the soil. c) Differential settlement control approach, in which, pile supports are designed tactfully to minimize differential settlement rather than reducing average settlement significantly. The differential settlement control approach could be the economic one, as piles are located strategically to reduce the differential settlement. It will require less number of piles, in comparison to the other two approaches. However, to cause the differential settlement to occur, the utilization of the ultimate bearing capacity of each of the single individual piles in the group is required, which is not yet established and cannot be captured by any analytical method developed so far. The goal, to use the ultimate bearing capacity according to the requirement of raft-pile-soil interaction, can be achieved by the numerous-geotechnical methods by simulating the complex nature of piled raft foundation.

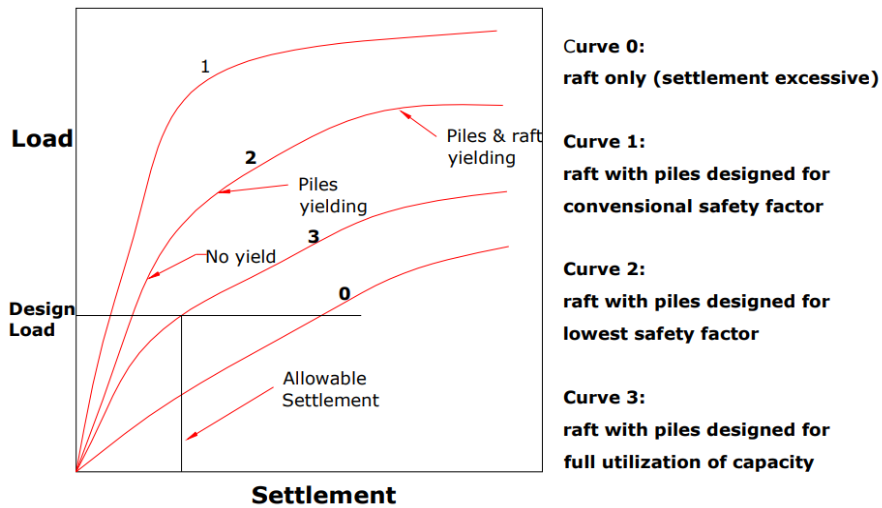
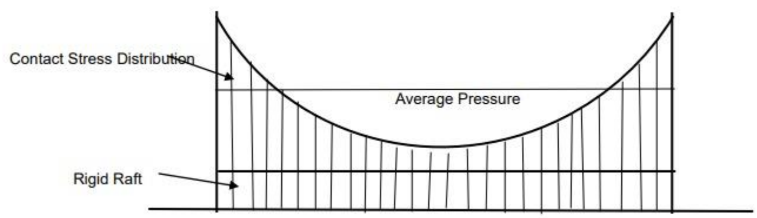


Figure 3: Load settlement Curves for piled raft foundation according to varies design philosophies. (Poulos, 2002)



Contact Stress Distribution for Rigid Raft

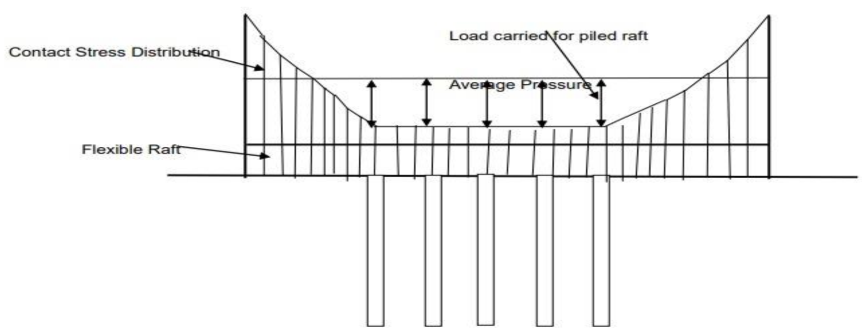


Figure 4: Design Approach for piles to reduce Differential Settlements (Deb & Pal, 2021)

2.2.2 Design Considerations

termed piled raft foundation as a Combined Piled Raft Foundation (CPRF), which consists of three bearing elements, piles, raft, and subsoil (Katzenbach & Turek, 2004). The stiffness of the raft and pile, the soil properties, and the dimension and strategy of pile location play a significant role in the design of a piled raft foundation system.

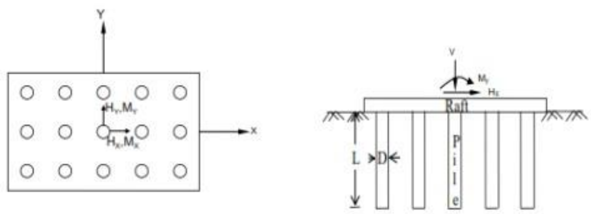


Figure 5: Illustrates the general piled raft foundation with its overall forces and moments.

The following design issues must be taken into consideration, to design a successful piled raft foundation.

1.Ultimate geotechnical capacity under vertical, lateral, and moment loadings,

2.Maximum and total settlements,

3.Differential settlement and angular rotation,

4.Lateral movement and stiffness,

5.Load sharing between the piles and raft,

6.Raft moment and shear for the structural design of the raft and its stiffness

7.Pile loads and moments for the structural design of the piles and their stiffness.

Figure 5 Piled Raft foundation system A sound prediction of a piled raft foundation behavior implies a full interaction between piles, raft, and soil. Hence, the following factors must be considered.

1) The raft characteristics (its relative stiffness – flexibility, rigidity, shape - dimension).
2) Pile characteristics (number, layout, length, diameter, stiffness)
3) Applied load characteristics (concentrated or distributed load and its level related to the ultimate capacity)

4) Soil characteristics (soil profile, layers, and their stiffness, the ultimate soil bearing capacity) Therefore, it is essential to develop a design method for pile raft foundation, which includes the following capabilities

1) Piles-raft-soil interaction in a logical manner, including the interaction of pile -pile, raft-pile, pile-raft, raft-soil, and pile-soil,

2)Variation of number, location, and characteristics of the pile,

3) Load sharing of pile and raft and,

4)Full utilization of the ultimate pile load capacity in compression and tension as well as the nonlinear load-deflection behavior of the foundation. (Poulos, 2002) also states the same Design Philosophies for piled raft foundations as that of (Ayuluri & Krishna, 2017).

2.2.3 Method of Analysis

According to the report made by H.G. Poulos on behalf of TC18 International Society of Soil Mechanics and Geological Engineering, July 2001, several methods of analyzing piled rafts have been developed, and some of these have been summarized by (Reul & Randolph, 2000). Three broad classes of analysis methods have been identified:

A) Simplified calculation methods,

B) Approximate computer-based methods,

C) More rigorous computer-based methods.

Simplified methods include those (Burland & Broms, 1976), (Reul & Randolph, 2000),(Poulos, 2001) and (Reul, 2004) . All involve a number of simplifications in relation to the modeling of the soil profile and the loading conditions on the raft. Methods employing a "plate on springs" approach, in which the raft is represented by a plate and the piles as springs (Poulos & Small, 1997) (Tran et al., 2012). The more rigorous methods include.Boundary element methods, in which both the raft and the piles within the system are discretized, and use is made of elastic theory (Mahdi et al., 2022). Methods combining boundary elements for the piles and finite element analysis for the raft (Investigator & Paikowsky, 1999) (Malhotra et al., 2019). Simplified finite element analyses, usually involving the representation of the foundation system as a plane strain problem(Sinha, 2013) or an axisymmetric problem (Mahdi et al., 2022) and corresponding finite difference analyses via the commercial program FLAC (Hemada & National, 2017). Three-dimensional finite and finite difference analyse element analyses(Hemada & National, 2017); s via the commercial program FLAC 3D. In the following section, a more detailed description will be given of a limited number of the above methods, and these will then be used to analyze a relatively simple hypothetical problem.

2.3 Piled Raft Foundations

2.3.1 Simplified Analysis Methods

2.3.1.1 Poulos-Davis-Randolph (PDR) Method (1980)

For assessing the vertical bearing capacity of a piled raft foundation using simple approaches, the ultimate load capacity can generally be taken as the lesser of the following two values:

1) The sum of the ultimate capacities of the raft plus all the piles
2) The ultimate capacity of a block containing the piles and the raft, plus that of the portion of the raft outside the periphery of the piles.

For estimating the load-settlement behavior, an approach similar to that described can be adopted (Reul & Randolph, 2000). However, a useful extension to this method can be made by using the simple method of estimating the load sharing between the raft and the piles, as outlined by (Reul & Randolph, 2000). The definition of the pile problem considered by Randolph is shown in Figure 2 Using his approach, the stiffness of the piled raft foundation can be estimated as follows:

$$Kpr = \frac{Kp + Kr(1 - \alpha cp)}{1 - \alpha cp\ 2\frac{Kr}{Kp}} \dots\dots\dots\dots\dots\dots\dots\dots\dots \text{Eq. } 2.2$$

Where, Kpr = stiffness of piled raft

Kr = stiffness of the raft alone

Kp = stiffness of the pile group

αcp = raft – pile interaction factor.

The raft stiffness Kr and pile group stiffness can be estimated from elastic theory. The single pile stiffness is computed from elastic theory and then multiplied by a group stiffness efficiency factor which is estimated approximately from elastic solutions. The proportion of the total applied load carried by the raft is:

$$\frac{Pr}{Pt} = \frac{Kr(1-\alpha cp)}{Kp+Kr(1-\alpha cp)} \dots\dots\dots\dots\dots \text{Eq. } 2.3$$

Where: Pr= load carried by the raft and

Pt = total load

The raft-pile interaction factor αcp can be estimated as follows:

$$\alpha cp \;=\; 1-\frac{\ln\left(\frac{rc}{ro}\right)}{\zeta} \quad \dots\dots\dots\dots\dots\dots\dots\dots \text{Eq. } 2.4$$

where rc = average radius of pile cap and

ro = radius of pile

The above equations are used to develop a tri-linear load-settlement curve as shown in Figure 2. First, the stiffness of the piled raft is computed from equation (2.5) for the number of piles being considered. This stiffness will remain operative until the pile capacity is fully mobilized. Making the simplifying assumption that the pile load mobilization occurs simultaneously, the total applied load, P1, at which the pile capacity is reached, is given by:

$$P1 \;=\frac{Pup}{1-X} \dots\dots\dots\dots\dots\dots\dots \text{Eq. } 2.5$$

Where P_{up} = ultimate load capacity of the piles in the group

X = proportion of load carried by the piles (Equation 2.5).

Beyond point A in Figure 2.the stiffness of the foundation system is that of the raft alone (Kr), and this holds until the ultimate load capacity of the piled raft foundation system is reached point B in Figure 2. At that stage, the load-settlement relationship becomes horizontal. Thus load – settlement curves for a raft with various numbers of piles can be computed.

2.3.1.2 Burland's Approach

Burland (1995) has developed the following simplified process of design: Estimate the total long-term load-settlement relationship for the raft without piles The design load P_0 gives a total settlement S_0. Assess an acceptable design settlement Sa, which should include a margin of safety.P1 is the load carried by the raft corresponding to Sa. The load excess $P_0 – P_1$ is assumed to be carried by settlement-reducing piles. The shaft resistance of these piles will be fully mobilized and therefore no factor of safety is applied. However, Burland suggests that a 'mobilization factor' of about 0.9 be applied to the 'conservative best estimate' of ultimate shaft capacity, Psu. If the piles are located below columns that carry a load over Psu, the piled raft may be analyzed as a raft on which reduced column loads act. At such columns, the reduced load Qr is:

$$Qr = Q - 0.9\,Psu \ \ldots\ldots\ldots\ldots\ldots..(Eq. 2.6)$$

The bending moments in the raft can then be obtained by analyzing the piled raft as a raft subjected to the reduced loads Qr. The process for estimating the settlement of the piled raft is not explicitly set out by Burland, but it would appear reasonable to adopt the approximate approach of Randolph (1994) in which:

$$Spr = Sr * \frac{Kr}{Kpr} \ldots\ldots\ldots\ldots\ldots (Eq. 2.7)$$

Where,

S_{pr} = settlement of piled raft

S_r = settlement of raft without piles subjected to the total applied to load

K_r = stiffness of raft

K_{pr} = stiffness of piled raft.

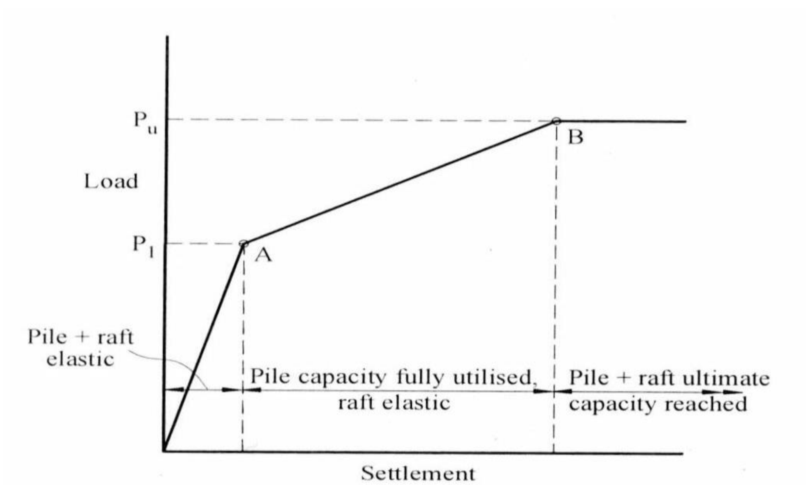


Figure 6: Simplified Load-Settlement Curve for Preliminary Analysis

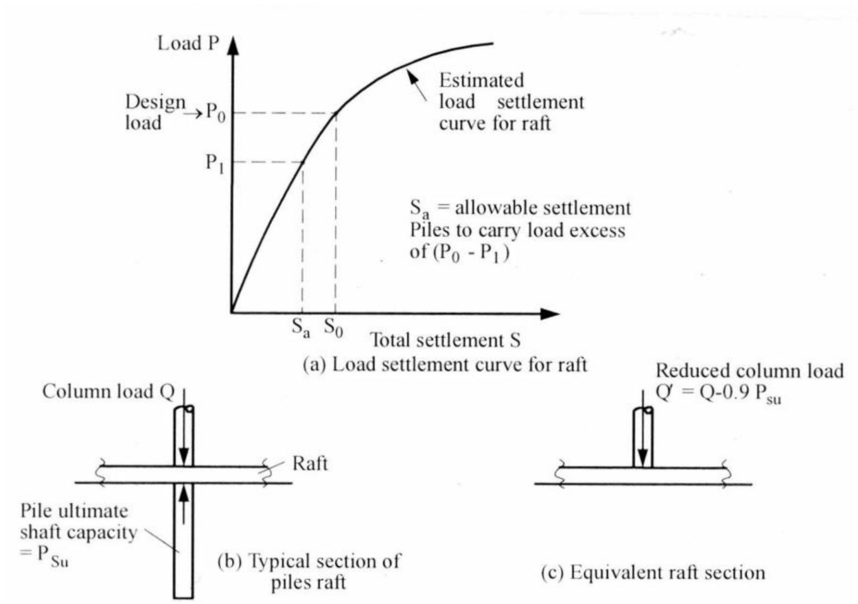


Figure 7: Burland's Simplified Design Concepts

$$\text{spr} = \text{sr} * \frac{\text{kr}}{\text{kpr}} \dots\dots\dots\dots\dots (\text{Eq. } 2.8)$$

Where:-

Spr = settlement of piled raft;

Sr = settlement of raft without piles subjected to the total applied load;
Kr = stiffness of raft;
Kpr= stiffness of piled raft;
Kpr =can be estimated using

$$\text{kpr} = \frac{\frac{\text{kp} + \text{kr}(1 - \alpha\text{cp})}{(1 - \alpha\text{cp})2\text{kr}}}{2\text{kp}} \dots\dots\dots\dots\dots (\text{Eq. } 2.10)$$

Where: Kpr = stiffness of piled raft
Kp = stiffness of the pile group
Kr = stiffness of the raft alone
αcp= raft – pile interaction factor.

2.3.2 Approximation Method

A) Strip Springs Approach (GASP) was presented by Poulos (1991) as illustrated in Figure 4 A section of the raft is represented by a strip and the supporting piles by springs. An approximate allowance is made for all four components of interaction.

(i) Raft-Raft Elements;

(ii) Pile-Pile Elements;

(iii) Raft-Pile Elements and;

(iv) Pile-Raft Elements.

The effects of the parts of the raft outside the strip section being analyzed are taken into account by computing the free-field soil settlements due to these parts. These settlements are then incorporated into the analysis and the strip section is analyzed to obtain the settlements and moments due to the applied loading on that strip section and the soil settlements due to the sections outside the Raft. The method has been implemented via a computer program GASP (Geotechnical Analysis of Strip with Piles) and has given settlement which is in reasonable agreement with more complete methods of analysis. However, it does have some significant limitations, especially as it cannot consider torsional moments within the raft.

(Poulos, 2001) developed a program GARP (Geotechnical Analysis of Raft with Piles) which employed a Finite Difference Method for the raft with the consideration of the interaction effects between the piles and raft. Allowances were made for the piles to reach their ultimate capacities and local bearing failure of the raft.

B) In Plate on Springs Approach (GARP)

Of analysis, the raft is represented by an elastic plate, the soil is represented by an elastic continuum and the piles are modeled as interacting springs. Some of the early approaches in this category neglected some of the components of interaction and gave pile-raft stiffness which was too large. (Poulos, 2016)has employed a Finite Difference Method for the plate and has allowed for the various interactions via approximate elastic solutions. This analysis has been implemented via a program GARP (Geotechnical Analysis of Raft with Piles). Allowance has been made for layering of the soil profile, the effects of piles reaching their ultimate capacity (both in compression and tension), the development of bearing capacity failure below the raft, and the presence of free-field soil settlements acting on the foundation system. The approximations involved are similar to those employed in the program GASP for piled strips.

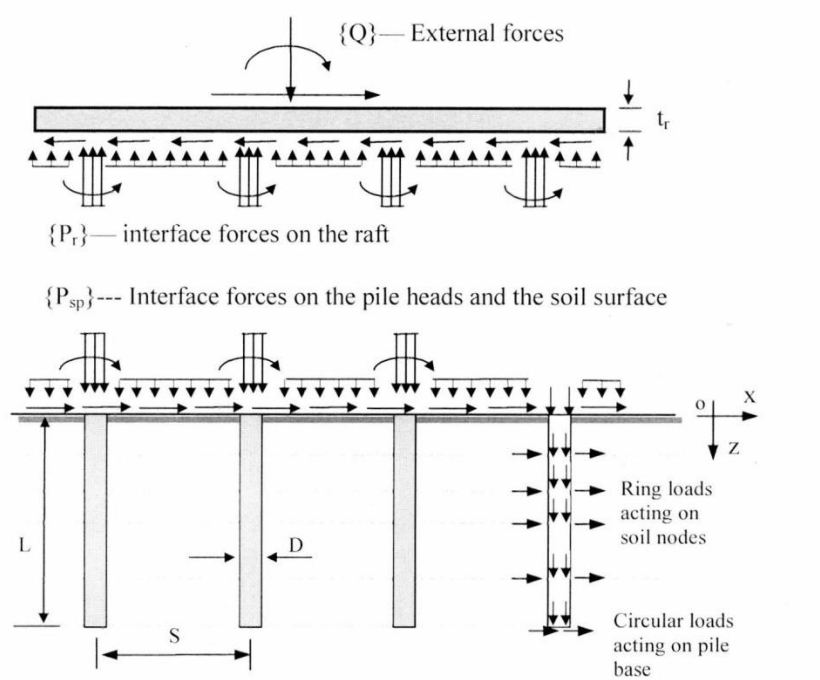


Figure 8: Representation of piled strip problem via GASP Analysis

A later version of GARP has replaced the finite difference analysis for the raft with a finite element analysis and has employed a modified approach to consider the development of the ultimate load capacity in the piles. Most analyses of piled rafts are based on the raft being treated as a thin plate. have examined the effect of the method of modeling the raft as a thin plate and analyzed a typical problem using firstly, a three-dimensional finite element program and then secondly, by making the raft 0.3m thick, and assigning the raft modulus to that part of the finite element mesh representing the raft (Poulos, 2002). It was assumed in the analysis that there was no slip between the raft and the soil or between the piles and the soil. It was found that there was not a great deal of difference in the computed deflections for the raft, for both a stiff raft and a flexible raft.

2.3.3 More Rigorous Computer Methods

In the preliminary design stage only bearing capacity and average settlement of rafts are considered as discussed in section (2.2). This helps to decide the number of piles required and where these piles should be located, but other issues such as differential settlement, raft shear force and bending moment, distribution of load among the piles, etc. are not considered. So it is necessary to carry out a more detailed design to assess the detailed distribution of settlement and decide upon the optimum locations and arrangement of the piles. The raft bending moments and shears, and the pile loads, should also be obtained for the structural design of the foundation. The numerical methods employed to simulate the complex piled raft foundation are mainly the Finite Element Method (FEM), Boundary Element Method (BEM), Finite Difference Method (FDM), or a combination of two or more of these methods.

3.3.3.1 Finite Difference Method

Poulos (1994) employed Finite Difference Method (FDM) to analyze the raft behavior of a piled raft foundation. The rectangular rigid raft of constant stiffness was discretized into nodes and elements, for which, the equation of plate bending was expressed in incremental finite difference form. At this stage, Poulos concluded that the published theorem for the Finite Difference Coefficient are in “error”, especially for the edges and corner of the raft, and do not satisfy vertical equilibrium. However he made some approximation to overcome this limitation. This analysis considers the concentrated and applied moment load as uniformly distributed load. Load displacement curves were used to obtain the vertical displacement of the soil at the junctions of the piles. The load displacement curves for the interaction of two rigid circular cap pile unit were initially obtained and then applied for all pile cap unit by super position theory as mentioned in section 2.3.3. However, this elastic 44 superposition theory is valid, only when the piles are located along a circumference and subjected to the same load (Mendonca et al. 2000). The limitations of 2-D thin plate theory and other approximations used, have already been discussed in section 2.3.3. Besides the work of Poulos (1994), no more analysis using Finite Difference Method was found in available published documents. This may be due to the lack in the development of a reliable Finite Difference Method formulation, as mentioned by Poulos (1994).

2.3.3.2 Two – Dimensional Numerical Analysis (FLAC) Methods

This category is exemplified by the analyses described by,(Fai & Eng, 2017)and (Malhotra et al., 2019), and (Hakro et al., 2022a) In the former case, the commercially available program FLAC has been employed to model the piled raft, assuming the foundation to be a two-dimensional (plane strain) problem or an axially symmetric three-dimensional problem. In both cases, significant approximations need to be made, especially for the piles, which must be "smeared" to a wall and given an equivalent stiffness equal to the total stiffness of the piles being represented. Problems are also encountered in representing concentrated loadings in such an analysis since these must also be smeared. Unless the problem involves uniform loading on a symmetrical raft, it may be necessary to carry out analyses for each of the directions to obtain estimates of the settlement profile and the raft moments. As with the plate-on-springs approach, this analysis cannot give torsional moments in the raft.

2.3.3.3 Three – Dimensional Numerical Analysis

A complete three-dimensional analysis of a piled raft foundation system can be carried out by finite element analysis (Katzenbach & Turek, 2004) or by use of the commercially available computer program FLAC 3D. In principle, the use of such a program removes the need for the approximate assumptions inherent in all of the above analyses. Some problems remain, however, about the modeling of the pile-soil interfaces, and whether interface elements should be used. If they are, then approximations are usually involved in the assignment of joint stiffness properties. Apart from this difficulty, the main problem is the time involved in obtaining a solution, in that a non-linear analysis of a piled raft foundation can take several days, even on a modern computer running at 450 MHz. Such analyses are therefore more suited to obtaining benchmark solutions against which to compare simpler analysis methods, rather than routine design tools. But according to (Hakro et al., 2022a) review of different analysis methods of Piled Rafts, we found more rigorous computer methods summarized as follows.

2.4. Settlement of Piled Raft Foundation

The settlement of the piled raft foundation reviewed by Gebregziabher (2011) is as follows. The settlement of the piled raft foundation is dependent on the total resistance of the foundation unit, R_{tot}, k(s) is the sum of the resistances of all the individual piles and the raft, or equivalently:

$$\mathrm{Rtot,k(s)} = \sum_{j-1}^{m} \mathrm{Rpile,k,j(s)} + \mathrm{Rraft,k(s)} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,2.11})$$

The resistance of the individual piles Rpile,k,j(s)is computed as the sum of the base and skin friction resistances:

$$\mathrm{Rpile,k,j(s)} = \mathrm{Rb,k,j\,(s)} + \mathrm{Rs,k,j\,(s)} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,2.12})$$

The resistance of the raft Rraft, k(s) can be determined by integrating the settlement-dependent pressure σ(x, y) over the (raft-soil) contact area:

$$\text{Rraft}, \text{k (s)} = \iint \sigma(\text{s}, \text{x}, \text{y})\text{dxdy} \ldots \ldots \ldots \ldots \ldots .. (\text{Eq. } 2.13)$$

The total external load F_{tot}, k is carried partly by the piles and partly by the contact pressure developed between the raft and the soil. The proportion of the load carried by the pile and raft is usually expressed using the CPRF coefficient α_{pr}. The value of αpr varies between 0 and 1, the lowest and highest values representing the case of the unpiled raft and free-standing pile groups respectively. The primary purpose of the piles in most CPRF designs is the reduction of settlements. In the case of large pile groups or CPRF-supporting heavy structures, the optimization criteria of design are the reduction of differential settlements (Nepelski, 2020). Hence the design of CPRF shall be in such a way that the settlements comply with specifications of local and international building standards. While handling the serviceability of a building, it would be necessary to consider the following settlement measures: Maximum settlements Max: usually occurs at the midpoint of the raft of a CPRF with piles of uniform dimensions acted upon by uniform loads. In that case, its magnitude will be equal to the midpoint settlements M

$$\text{SMax} = \text{SM} \ldots \ldots \ldots \ldots \ldots .. (\text{Eq. } 2.14)$$

1) Minimum settlement S_{Min}: usually occurs at the corner of the raft of a CPRF with piles of uniform dimensions acted upon by uniform loads, in which case its magnitude will be equal to the corner settlement SC

$$\text{SMin} = \text{SC} \ldots \ldots \ldots \ldots \ldots .. (\text{Eq. } 2.15)$$

2) Differential settlement ΔS is defined as the difference between the maximum and minimum settlements

$$\Delta\text{S} = \text{SMax} - \text{SM} \ldots \ldots \ldots \ldots \ldots .. (\text{Eq. } 2.16)$$

Maximum angular distortion δ/L is defined as the differential settlement between two points divided by the distance between them.

2.4.1 Tolerable Raft Settlement of Buildings

Foundation settlements must be estimated with great care for buildings, bridges, towers, power plants, and similar high-cost structures. For structures such as fills, earth dams, levees, braced sheeting, and retaining walls, a greater margin of error in the settlements can usually be tolerated. The principal components of ΔH are particle rolling and sliding, which produce a change in the void ratio, and grain crushing, which alters the material slightly. Only a very small fraction of ΔH is due to elastic deformation of the soil grains. Settlements are usually classified as follows:

1. Immediate, or those that take place as the load is applied or within a period of about seven days.
2. Consolidation, or those that are time-dependent and take months to years to develop. Mac Donald and Skempton (1955) recommended maximum values in parentheses tolerable differential settlement and angular distortion of buildings.

Table 1: Angular and differential settlement max limit (Bowles, 1997) Criterion

Criterion	Rafts Max. Differential settlement, mm
Angular distortion (cracking)	1/300
Greatest differential settlement	45
Clay	
Sand	32

2.4.2.Design of Settlement Reducing Piles

While designing the settlement reducing piles, some concepts should be decided to pay special attention to (Poulos, 2002) and (ASCE, 2012). These issues are listed by Poulos as follows:

A) Maximum settlement
B) Differential settlement
C) load capacities for vertical, lateral, and moment loading
D) Pile loads and moments

Raft moments and shears In the design process, for the settlement reducing piles, special attention should be given to avoid overdesign since it can cause as much trouble as designing under capacity (Hameedi, 2005). However, since piles are only there to reduce settlements, they do not contribute to the bearing capacity. Hence, the unpiled raft should be sufficient from the bearing capacity point of view and it should provide a factor of safety of at least three (Poulos & Small, 1997). Unfortunately, engineers have been designing the systems based on the principle that an adequate number of piles should be placed to carry the structural weight. However, they should be thinking in terms of settlements and the placement should be done according to the acceptable settlement limits (Ilamparuthi, 2009). While designing the settlement-reducing piles, the load sharing between raft and piles should be taken into account since the piles are not placed to provide bearing capacity. However, the settlement behavior of the raft directly changes when the piles are present so, this load sharing becomes more important. This load sharing is based on the stiffness of the soil and raft and the pile settlements (Mendoza et al., 2014). The load-sharing behavior of the system highly depends on the working conditions of the piles, i.e. the factor of safety values applied to the piles. There is some detailed analysis of case histories in the literature which give reasonable explanations about the relation between load sharing and the load carrying performances of the piles and rafts. In the paper presented by (Russo, 2018), some case histories were investigated. It has been seen that when piles are loaded to 50 percent of their ultimate capacities, the load carried by the raft drops to almost one-half of the total load whereas when they are loaded to 80 percent or above of their ultimate capacities, the piles carry a lower proportion of the load (Russo, 2018).

2.4.3. Finite Element Method

The finite element method is one of the most powerful tools for the analysis of piled rafts. It requires the discretion of both the structural foundation system and the soil. To reduce the computational effort, problems are sometimes simplified to an axisymmetric problem or a plane-strain problem. The first solution which employed the finite element method for the analysis of foundation structures was obtained by (Katzenbach & Turek, 2004). The behavior of the raft was obtained by the finite element technique in which the raft was divided into several rectangular elements joined at a discrete number of nodal points. The soil was modeled either by the Winkler model in which interactions between springs were not considered or by the elastic continuum model in which separation between the raft and the soil was not allowed when negative reactions existed. The stiffness matrix for the whole system was formed by combining the stiffness of the soil with the stiffness matrix of the plate bending elements. Contact stresses were represented by equivalent forces applied at nodal points of the finite element mesh. extended the approach to a multi-layered soil system with isotropic or crossanisotropic properties(Amornfa et al., 2022). The layered soil system was divided into several horizontal layers of uniform thickness with infinite lateral extent. The loaded surface of the soil mass was discretized into surface elements corresponding to the raft elements, and the raft was modeled by finite elements. The contact between the raft and the soil was assumed to be smooth. suggested that in the analysis of raft foundations, the structure, foundation, and supporting soil have to be analyzed as a system (Katzenbach & Turek, 2004). The stiffness of the structure can influence the distribution of loads and moments transferred to the raft. Results have revealed that there were significant differences in the behavior of the raft predicted by the use of different soil models for the supporting soil. The flexibility of the raft has significant effects on the distribution of column loads and moments. Results have shown that the linear elastic continuum model provided a more realistic solution to the behavior of the raft and is more preferable to use in modeling the supporting soil. Compatibility of the pile and soil displacements, the load deformation relationship of the pile was determined and expressed as

$$\{\mathrm{Q}\} = ([\mathrm{Kp}] + [\mathrm{Ks}])\{\mathrm{wp}\} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.}\ 2.17)$$

Where,

[Kp] = stiffness matrix of piles

[Ks] = stiffness matrix of the soil obtained by inverting the soil flexibility matrix,

[Fs], i.e. $[Ks] = [Fs] - 1$

{wp} = vector of deformations at the pile nodes

{Q} = vector of external applied loads

The reinforcing effect of all piles in the group was considered in the formulation. Non-homogeneity of the soil was taken into account by incorporating continuously varying soil stiffness into the numerical integration process during the formulation of the element stiffness matrices. The soil non-linearity was assumed to be elastic-plastic and was analyzed by limiting the shear forces or lateral soil pressures to some values and the excess soil forces at the nodes were then redistributed to other nodes. An early example of the analysis of a piled raft was given by (Deb & Kumar, n.d.), in which a model with eight nodded isoparametric elements was used. In the analysis, an approximation of the equivalent stiffness of the pile group was made such that each concentric row of piles was modeled by a continuous annulus with an overall stiffness that was equivalent to the sum of the stiffness of the individual piles. The soil was assumed to be a linear elastic isotropic material with the modulus increasing linearly with depth. To incorporate the additional stiffening effect of the superstructure into the analysis, an equivalent raft thickness which had the same bending stiffness as the combined raft and the superstructure was introduced. However, Hooper's results have shown that the contribution of the stiffening effect of the superstructure on the behavior of the piled raft was relatively small. applied this method to the analysis of a rigid raft resting on a pile group embedded in a homogeneous medium (Watcharasawe et al., 2015). The piles and the soil were assumed to be a weightless linearly elastic homogeneous media. presented a numerical method to examine the behavior of a rigid piled raft embedded in non-homogeneous soil (Ukritchon et al., 2016). The raft was discretized into square sub-elements. The base of the raft was assumed to be perfectly smooth. The soil was assumed to be a linearly elastic, isotropic material and Young's Modulus was assumed to increase linearly with depth. The piles were assumed to have a circular cross-section and were discretized into two nodded elements at the pile-soil interface. Interactions between the piles, the raft and the soil were taken into account and the vertical deformation of the soil was determined by the principle of superposition. Employed the finite element method to examine the behavior of a raft supported by a single pile at the Centre (Lkinani & Eddy, 2014) . In the analysis, the cap was assumed to be circular and to contact the soil perfectly.. The cap, the pile, and the surrounding soil medium were modeled by finite elements. The pile was assumed to be linearly elastic and the soil was assumed to be either elastic or elastic perfectly plastic. A weak zone around the pile with lower strength and modulus was introduced to account for the slip at the pile-soil interface. described a structural model that employed the finite element method for the geometrical modeling of the continuum, an elastic-plastic constitutive model to describe the soil behavior, and a step-by-step analysis for numerical simulation (Katzenbach et al., 2010). The piles were modeled by 3-

dimensional isoparametric finite elements and the raft was modeled by shell elements. Realistic stress-strain behavior of the soil was simulated by a constitutive model for the soil which consisted of two main yield-surface segments: a pressure-dependent perfectly plastic shear failure surface and a compression cap yield surface. used the same structural model to carry out parametric studies on the behavior of piled rafts in Frankfurt Clay(Katzenbach & Turek, 2004). proposed the use of iterative techniques with the finite element method to examine the behavior of a non-uniformly loaded piled raft (Mahmoud & Elarabi, 2012). Unlike the traditional techniques, this approach can reduce the size of the stiffness matrices, thus reducing the number of equations to be solved in the system presented a three-dimensional elastic-plastic finite element method for the analyses of piled raft foundations in over consolidated clay – Frankfurt clay(Ambassa & Amba, 2020). The analysis was implemented by the program paxis3d. In the finite element method, the soil was modeled by hexahedron elements, and the piles were modeled by triangular prism elements. The circular piles were modeled by square piles with the same shaft circumference. The interfaces between the raft and soil and between the pile and soil were modeled by thin solid continuum elements and were assumed to be perfectly rough. The soil was modeled by a cap model to simulate the non-linear behavior. The cap model consisted of three yield surface segments: the pressure-dependent, perfectly plastic shear failure surface, the compression cap yield surface, and the transition yield surface. The same model was used by these authors to perform a parametric study of a piled raft with different pile configurations subjected to non-uniform vertical loading(Deb & Kumar, n.d.). presented the results of a three-dimensional nonlinear finite element analysis of a piled raft foundation under a uniformly distributed load (Deb & Pal, 2019). Based on analysis it had been found that the ultimate load-carrying capacity of the flexible raft increased with an increase in soil modulus and length of the pile. Piles lengths even less than the width of flexible rafts had been found effective in reducing differential settlement. The increase in soil modulus had been found to reduce the overall settlement and differential settlement. It had been found that although the increase in soil modulus reduced the overall settlement, differential settlement increased with an increase in soil modulus for the same overall settlement.

proposed a non-linear finite element method for the analysis of a piled raft subjected to a uniformly distributed load (Lodha & Solanki, n.d.). This method combined an incremental iterative procedure with a Newton-Raphson method to solve the non-linear equations involved in a plasticity analysis. The raft, pile, and soil were discretized into eight nodded brick elements.

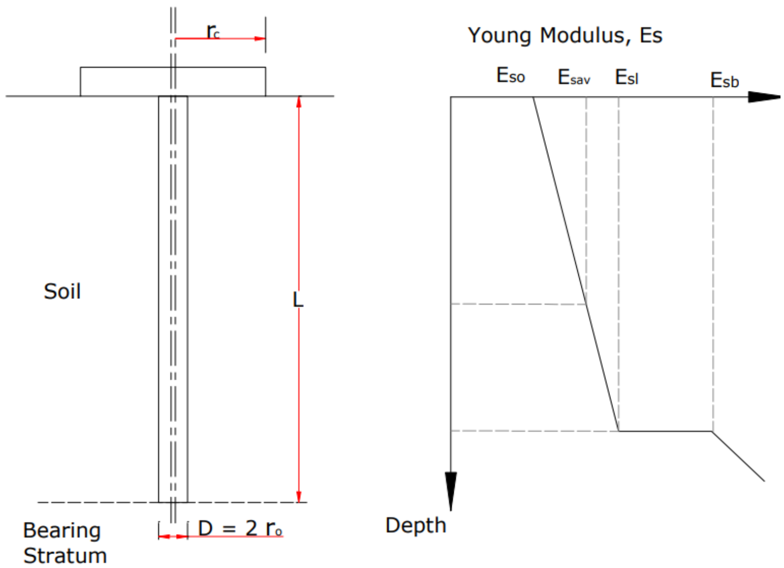


Figure 9: Simplified representation of Piled-raft unit(Poulos & Small, 1997)

$$\frac{pr}{pt} = \frac{kr(1-\alpha cp)}{kp + kr(1-\alpha cp)} = x \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 2.18)$$

Where: Pr = load carried by the raft

Pt = total applied load.

The raft – pile interaction factor αcp can be estimated as follows:

$$\alpha\text{cp} = 1 - \ln\left(\frac{\text{rc}}{\text{ro}}\right)\zeta \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 2.19)$$

Where: r_c = average radius of pile cap, (corresponding to an area equal to the raft area divided by the number of piles)

r_o = radius of pile

$$\Phi\gamma\upsilon\rho\varepsilon\ 12\ = \ln\left(\frac{rm}{ro}\right) \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 2.20)$$

$$rm = \{0.25 + \xi\ [2.5\ \rho\ (1-\nu) - 0.25)\ *\ L \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 2.21)$$

$$\zeta = \frac{\text{Esl}}{\text{Esb}} \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 2.22)$$

$$\rho = \frac{Esav}{Esl} \ldots\ldots\ldots\ldots\ldots..(Eq. 2.23)$$

v = Poisson's ratio of soil

L = pile length E_{sl} = soil Young's modulus at the level of pile tip

E_{sb} = soil Young's modulus of bearing stratum below pile tip

E_{sav}= average soil Young's modulus along pile shaft.

2.5 Advantage of Piled Raft Foundation

in piled raft foundations piles are used as settlement control elements with most of the stiffness at serviceability loads and the raft element providing additional capacity at ultimate loading (Hakro et al., 2022). Consequently, it is generally possible to reduce the required number of piles when the raft provides this additional capacity. In addition, if there are one or more defective or weaker piles, in the subsoil the presence of the raft allows some measure of redistribution of the load from the affected piles to those that are not affected. Another feature of piled rafts is that the pressure applied from the raft on to the soil can increase the lateral stress between the underlying piles and the soil, and thus can increase the ultimate load capacity of a pile as compared to free-standing piles (Katzenbach et al., 2010)

2.6 Related studies

The performance of piled raft foundations is affected by many factors. These factors occur as a result of soil, pile, and raft characteristics. Many researchers have examined the performance of piled rafts considering the effects of soil type, pile dimensions and configurations, and raft dimensions on its load sharing and load settlement behavior. From the literature, the most parameters that affect the Load sharing and settlement behavior of piled rafts are relative stiffness among the foundation components. The relative stiffness of the foundation also depends on the stiffness of the soil, dimension, and configuration of the foundation components.

The modulus of the pile wall was computed from the term equivalent modulus which was a function of the number of piles, width or diameter of the pile, and soil modulus. The study concluded that the ratio between the width of the raft and the length of the pile played an important role in the settlement behavior of the piled raft. The piled raft with a ratio equal to unity was very effective in reducing overall settlement, where as a ratio of 0.5 was very effective in minimizing the differential settlement. Further, it was concluded that a pile-to-raft area ratio of 5% to 6% was adequate to reduce the overall settlement. The results were mostly in the form of non-dimensional parameters. While the contribution was very useful as a parametric study, it has only a very limited application. The procedure would be ideal for a single group of the large number of piles, in a row (Ukritchon & Keawsawasvong, 2016). An experimental study was carried out by (Ukritchon et al., 2016) to understand load sharing mechanism of piled raft foundations and he found that the load-sharing mechanism between piles and raft depends on pile – subsoil stiffness. According to his finding, at an initial stage the applied load is taken by the piles since piles are stiffer than soil, then when the piles reach their ultimate load capacity the excess load is carried by the raft. A three dimension finite element analysis was performed on sand to investigate load-sharing behavior between the piles and raft and he concluded that soil property, raft geometry, and pile geometry (diameter, length, spacing of piles) are some of the parameters that affect load sharing behavior of piled raft foundation (Xie & Chi, 2020). Piles take more loads at small spacing and rafts take more loads at large spacing of piles but pile spacing greater than 7D is ineffective. A finite element analysis of piled raft foundation in the sand under vertical load has been carried out to study the load sharing behavior between raft and piles by considering the different configurations of piles beneath the raft and he suggests that the load sharing mechanism between piles and raft in piled raft foundation depends on the ratio stiffness of the pile group to the stiffness of the raft. In addition to this, settlement of the foundations plays an important role in distributing the load between the foundation elements (e.g. raft and the piles). For example, the load carried by the raft can increase with the increase in the settlement of any particular piled-raft system. Therefore, predicting the settlement of piled-raft foundations is the first step to determining the load sharing between the piles and the raft. A series of 2D numerical analyses of piled raft foundations have been performed by (Ai et al., 2017). The effects of raft thickness, soil modulus, and pile spacing on load sharing of piled rafts were studied through this numerical study. The result reveals that the percentage of load shared by the raft increases with increasing pile spacing and soil modulus and decreases with increasing raft thickness The thinner the raft the more deflect that increases contact between raft and soil which increases the load shared by the raft. In soft soil, whatever load comes to the raft is taken care of by the pile through skin friction and alternatively, if the soil is hard, whatever load comes to the raft is taken care of by the underneath raft soil. A parametric study has been carried out by (Sinha, 2013). On the performance of piled raft considering different parameters using finite element method. The result reveals that raft settlement increases with the increase in pile spacing and decreases with the increase in the pile size and length whereas the settlement of the raft decreases with the increase of the angle of shearing resistance and the cohesion of the soil. For pile spacing greater than 6 times the pile size, the system tends to function as a raft foundation Several case studies have been carried out by to investigate the effect of piled raft area ratio on load sharing mechanism of piled raft foundation using finite element method (The et al., 2019). The author concludes that the ratio of total piles area to raft area has an important influence on load sharing of piled raft component. The pile's load sharing varies from (15%) at the piles-raft ratio of about (1 %) corresponding to pile spacing of (7D) to (42%) at a piles/raft ratio equals to (7%) corresponding to a close pile spacing of (3D) which means that the piles are taking more loading share and there is a tendency to behave as a mere piled system as the spacing between piles is reduced. A detailed 3D analysis of piled raft foundations has been conducted by to examine the effect of raft flexibility, width of raft, and diameter of piles on load sharing behavior of piles and raft using the finite element method (Paulo & Paulo, 2010). The result showed that the percentage of load shared by the piles increases as pile diameter increases and decreases as raft width increases. But raft flexibility has significantly affected the load shared by piles and raft. Flexibility of raft is depending on raft thickness and pile spacing. The variation in load carried by the pile is noticeable at S/D=4; the load carried by the piles is about 35% and 45% for raft thickness, t= 0.3 m and t= 2 m, respectively. The raft flexibility, Kf = 0.2 and 8.73 for these two cases. On the other hand, Kf = 0.29 and 0.02 if the spacing is S/D=10 for the same raft thickness values. Due to the narrow range of Kf for the large spacing case, the variation in percentage of load carried by the piles is insignificant, and it is approximately 25%. Therefore, from this result one may notice that piles spacing have a great influence on load sharing behavior of piled raft foundations. A parametric study has been carried out (Amornfa, 2022) on the load-sharing behavior of piled rafts considering different parameters using finite different methods. The parametric study results show that the load-carrying ratio of the raft depends on the number of piles of the pile group and the level of loading applied to the piled-raft foundation (the raft may carry 15% to 70% of the total applied load to the piled raft).The load carried by the raft increases when the loading to the piled raft increases and the number of piles decreases.

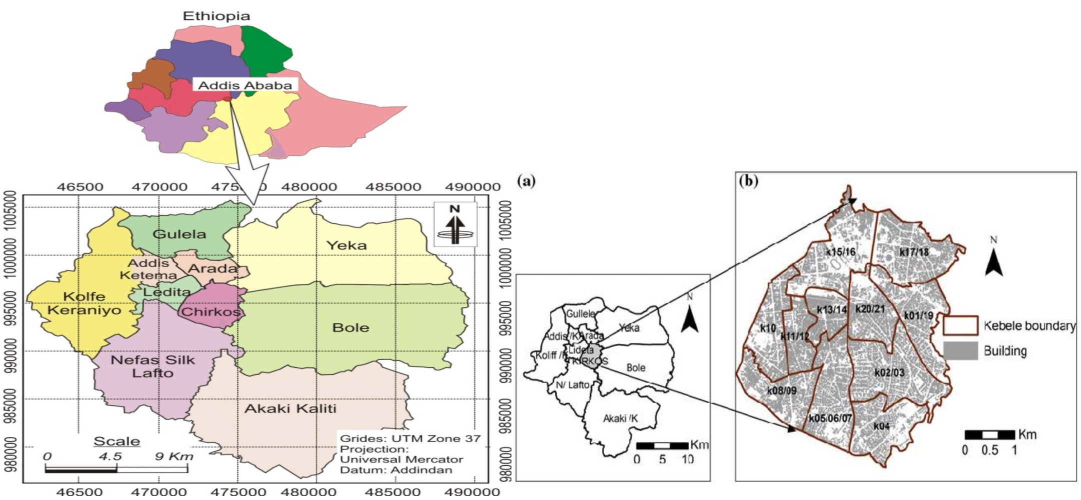
CHAPTER THREE

MATERIALS AND METHOD

3.1. Description of Study Area

The study was conducted in Addis Ababa specifically in kirkose sub city, which is one found on the south eastern margin of the city. It shares boundaries with Bole sub-city in the East, Lieta sub city and Nifas Silk Lafto sub cities in the North West and Arada sub city in the North. The lowest point is 2,050 meters in the Southern periphery and the maximum elevation is 2,331 meters above sea level. The Sub city has 11 Woredas and covers total plot area of 123 km^2 (Eshetu, 2017). The geographical location of the area is found at approximately on 9° 0'7''N latitude and 38°45'46''E longitude. The area has annual average temperature ranges from 10℃ to 22℃ with a total average annual rainfall of 1117.10 mm. The geological history of the studied area is an integral part of the evolution and development of the Ethiopian Plateau and the Rift system, because of its location at the western margin of the Main Ethiopian Rift (MER). The area is covered by different volcanic rocks with both acidic and basic compositions and overlain by fluvial and residual soils varying in thickness from a few centimeters to several meters below natural ground level. Black cotton soil is the predominant soil type (Muche, 2019).

The New Headquarters Building Bank of Abyssinian (BOA) project is located in central Addis Ababa, Kirkos sub-city, around the Mexico square. The tower building will be the tallest building in East Africa with a height of 270 meters above ground residing on a plot of 9700 meters square of land near Mexico square. The total built-up area of the Bank of Abyssinia headquarters complex is 174 thousand meters square. The main tower comprises a total of 60 floors (56 floors above ground and four floors underground). The underground functions mainly include a mechanical parking area, vault and equipment rooms, and a vehicle lobby area. The sky garden is at the top of the tower building. The top of the tower building also caters to the bank's logo with a hollow glass curtain wall of a diamond structure. The building complex mainly includes an office, a podium that has nine floors above ground, a lobby area, a mall, a cinema, and a lecture hall. The building complex has also another block of 20-story buildings above ground and two stories underground. Bank of Abyssinia headquarters building will become a landmark in Ethiopia, a new gathering and a focal point in Addis Ababa, and the most eye-catching night scene in the capital city. The landmark, Bank of Abyssinia headquarters project will infuse additional vitality into Addis Ababa and bring tangible benefits to the bank stakeholders. It is our conviction, that with the expertise and experience of China state Construction Engineering Company and the unreserved support of the Bank of Abyssinia management and project team, the Bank of Abyssinia headquarters will be built according to the contract and schedule.



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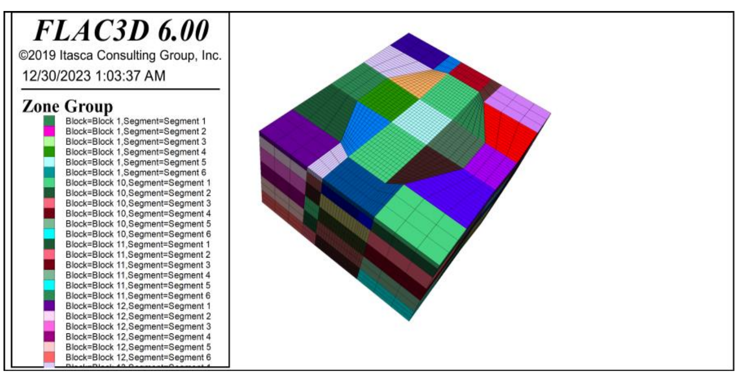

(b)

Figure 10: a) study area map b) geometric foundation model c) 3d view of bu

(c)

3.1.1 Weather and climate of study area

According to Berhanu et al., (2014), the climate in Ethiopia is geographically quite diverse which most commonly follows varied topography and is categorized in to five different sub zones based on altitude, rainfall, and temperature variation. It ranges from the high cold area named "wurch" to the highly hot climatic condition area known as "Berha" having different physical measurement characteristics such as altitude, mean annual precipitation, and temperature as shown in table 2

Table 2:Climate zones of Ethiopia and their physical characteristics (Berhanu et al., 2014)

Zones	Altitude (m)	Mean annual rainfall (mm)	Mean annual temperature (°C)
Wurich (cold to moist)	>3200	900-2200	Below 11.5
Dega (cool to humid)	2300-3200	900-1200	11.5-17.5
Weynadega (cool sub-humid)	1500-2300	800-1200	17.5-20
Kola (warm semi-arid)	500-1500	200-800	20-27.5

3.1.2 Geological conditions of the site

The subsurface profile of the site and the engineering properties of the soil strata are investigated by Construction Design Share Company. The company carried out Core drilling of forty (14) boreholes with a maximum drilling depth of 98m along with in situ and laboratory tests. The following geological layers have been identified by the company according to apendex d.

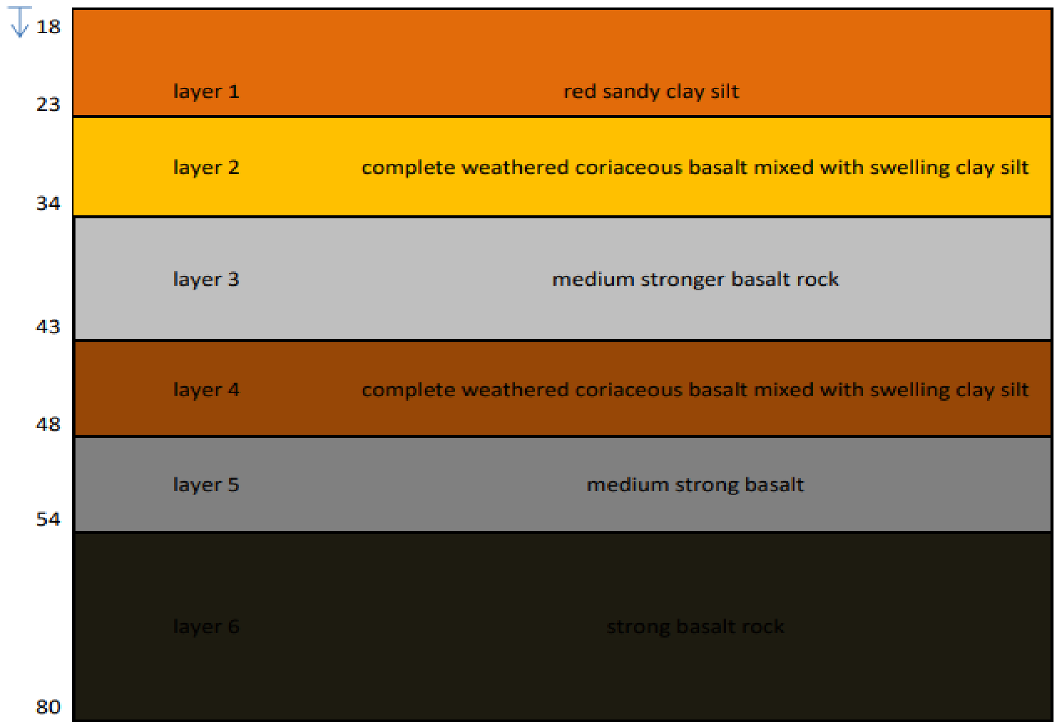

Figure 11: soil profile below the foundation level

Based on the provided information about the subsurface profile and borehole data, it is important to consider the following aspects in the analysis and design of the piled-raft foundation system for the BOA headquarters project: The average groundwater level has been identified as 8 meters below the natural ground level. This information is crucial for determining the effective stresses acting on the foundation elements and for assessing potential changes in pore water pressures during construction and long-term operation. Submerged Unit Weight: Since the foundation is located 18 meters below the ground surface, the submerged unit weight of the soil (γ’) should be considered in the analysis to account for the influence of the groundwater on the foundation behavior. Soil Layers: The subsurface profile from Boreholes BH6, BH7, and BH8 provides valuable information about the soil strata beneath the main tower foundation. The presence of different soil layers, including sandy clayey silt, completely weathered basalt mixed with swelling clay, and medium-strong basalt, indicates varying soil properties that must be carefully considered in the foundation design. The thickness and distribution of each soil layer, as described in the borehole data, should be accurately characterized to assess their load-bearing capacities, settlement characteristics, and interaction with the foundation elements. The presence of swelling clay within the weathered basalt layer requires special attention due to its potential for volume changes and differential settlements, which could affect the overall stability and performance of the foundation system. Understanding how load transfer mechanisms operate within the different soil layers and between the piles and raft is essential for ensuring effective load distribution and minimizing potential settlement issues in the piled-raft foundation system.By considering these factors and conducting a detailed analysis based on the provided subsurface data, it will be possible to optimize the design and performance of the piled-raft foundation system for the BOA headquarters project in Addis Ababa.

3.2 Determination of basic soil parameter for the numerical model

Almost all of the soil parameters used for the analysis of the foundation are obtained from geotechnical reports; however, some necessary data are not included in the investigation report. Therefore the parameters that could not be obtained directly from the laboratory tests, have been indirectly derived by using empirical correlations based on the recommendations of different literature, international geotechnical codes, and standards. The data used for this study can be categorized into the following groups;

1) Stiffness parameters; modulus of elasticity (Es)and Poisson's ratio (ν)

2) Shear strength parameters; angle of internal friction(ϕ) and soil cohesion(c)

3) Unit weight or density of the soil(γ)

4) Consolidation parameters

1) Stiffness parameters

3.2.1Stiffness Modulus (Es)

The stiffness modulus Es is a basic parameter that describes the load-settlement behavior of soils and governs the results of settlement related problems. Several methods are available for estimating the stiffness modulus of soil as described by (Bowles, 1996). Unconfined compression tests, tri-axial compression tests, and in situ tests are among the test methods. The geotechnical investigation report has included stiffness modulus values for the different layers but some of them are not conducted. The elastic modulus of three layers; red sandy clayey silt (Layer 1) and completely weathered rock (layers 2&5) were not given in the soil investigation report. Therefore, elastic moduli of layers (1& 2) have been determined using German code (Eq.3.1) (DIN4094-1, 2010). The elastic modulus of the completely weathered rock (layer 2&5) is taken from literature recommendations given by (Ghee & Guo, 2010). After the modulus elasticity (Es) is determined from correlation then, it is converted to E using (Eq.3.1) which is used as input value in FLAC3D software. The result is summarized in Table 3. Using code provisions: German code (DIN4094-1, 2010)

$$ES = \mu Pa\left(\sigma z + \frac{0.5\Delta\sigma z}{Pa}\right)^{w} \ldots\ldots\ldots\ldots\ldots..(Eq.3.1)$$

Where: μ = stiffness coefficient depends on the value of N- SPT

w = stiffness exponent depends on soil type

σ z = overburden pressure at a depth z below the foundation level

Δσ z = additional vertical stress due to load from the superstructure at a depth z

Pa = atmospheric pressure taken as 101.4 kN/m2 according to Hayward and Oguntoyinbo (1987)

$$E = Es\left(1 - v - \frac{2v^2}{1 - v}\right) \ldots\ldots\ldots\ldots\ldots..(Eq.3.2)$$

b) Poisson’s Ratio, ν Poisson’s ratio is a property of materials that describes the volume change of the material in a direction perpendicular to the application of a load. It is defined as the ratio of the lateral expansion to the axial compression of soils. (Bowles, 1996) recommend a range of values of Poisson’s ratio between 0.4 and 0.5 for most clay and 0.2 to 0.4 for medium to dense cohesion less soil. In this research, the value of Poisson”s ratio used for the different layers is given in Table 3.

Table 3: Poisson’s ratio value used for the different layers

	Layer1	Layer2	Layer3	Layer4	Layer5	Layer6
SPT(N)	28	44	>50	44	>50	>50
Depth to its center (m)	0.5	5	-	22	-	-
Poisson”s ratio(ν)	0.3	0.3	0.25	0.3	0.25	0.25
Stiffness coef.( )	450	450	-	450	-	-
Exponent coef.(w)	0.6	0.6	-	0.6	-	-

Overburden pressure in kN/m2	153.5	-	-	-	-	-
Additional vertical stress in kN/m2	990	-	-	-	-	-
Stiffness modulus(Es) in MN/m2	138.92	-	-	-	-	-
Young‟s modulus (E) in MN/m2	121.061	400	1000	400	1000	1500

3.3.2. Shear Strength Parameters

Shear strength parameters, namely, angle of internal friction (∅') and cohesion (c') are taken from the literature recommendation given by (Braiud, 2013). The shear parameters of the selling clayey silt were taken for layers 2 and 4 (completely weathered basalt mixing with swelling clayey silt), by assuming the worst-case layer

Based on the information provided, the shear strength parameters for layers 2 and 4, which consist of completely weathered basalt mixing with swelling clayey silt, are assumed to be taken from literature recommendations by (Braiud, 2013). The shear parameters of the swelling clayey silt are considered for these layers, assuming the worst-case scenario.

1. Angle of Internal Friction (∅'):

The angle of internal friction (∅') is a critical parameter that characterizes the shear resistance of a soil. It represents the maximum angle at which a soil can remain stable before failure occurs. For the swelling clayey silt in layers 2 and 4, the angle of internal friction (∅') can be obtained from the literature recommendations provided by (Braiud, 2013)or other relevant sources. The value of ∅' for the swelling clayey silt layer is essential for determining the shear strength and stability of the soil under various loading conditions.

2. Cohesion (c'):

Cohesion (c') is another important shear strength parameter that represents the cohesive forces present in the soil. It is particularly significant in cohesive soils like clayey silt. The cohesion value (c') for the swelling clayey silt in layers 2 and 4 can be derived from literature recommendations or empirical correlations based on the characteristics of the soil. The cohesion value influences the shear strength of the soil and plays a crucial role in determining its stability and bearing capacity.

By utilizing the shear strength parameters (angle of internal friction Ø' and cohesion c') obtained from literature recommendations by (Braiud, 2013)for the swelling clayey silt in layers 2 and 4, the numerical model can incorporate these values to accurately simulate the behavior and response of the soil layers in the FLAC3D software for the BOA headquarters project in Addis Ababa.

3.3.3. Unit weight or density of the soil

The total unit weight provided in Table 4 for layers 2 and 4, consisting of completely weathered basalt mixing with swelling clayey silt, is essential for determining the soil density in the FLAC3D software. The total unit weight represents the combined weight of the soil and any water content present, impacting the overall stability and behavior of the soil layers during analysis and simulations.The Soil density is another soil property that the software takes as in put data. Therefore the total unit weight of all layers was taken from the investigation report and given in

Table 4: Shear strength parameters of the soil

	Frictional angle Φ[º]	Cohesion c[KN^2]	Total unit weight [KN^3]
Red sandy clayey silt[layer1]	27	25	17
Completely weathered basalt mixed with swelling clayey sit [Layer 2]	42.8	25	22
Medium-strong rock basalt [Layer 3]	45	5000	24
Completely weathered basalt mixed with swelling clayey silt [Layer 4]	42.8	25	22
Medium-strong rock basalt [Layer 5]	45	5000	24
Strong rock basalt [Layer 6]	45	5000	28

3.3.4. Consolidation parameter

Consolidation parameters that are required for this study are compression index (Cc) and swelling index (Cr) since these parameters are required to determine cap hardening in the cap plasticity constitutive model. The soil properties of some layers were not included in the soil investigation report made by CDSC. Therefore their properties (Cc and Cr) were determined using empirical correlations. There are different correlation methods available in the literature for determining these parameters. Cc is related to liquid limit (LL) by (Arora, 1987). The values of Cc and Cr are also given in range. In this study, these parameters are taken from the range specified by (Basile, 1999). The values of Cc and Cr for each layer are crucial for understanding the consolidation behavior of the soil and its response to loading conditions in the FLAC3D software simulation. These values are given in Table 5 shown below.

Table 5: Consolidation parameters of the soil

Soil strata	**Compression index(Cc)**	**Swelling index(C)**
Red sandy clayey silt(layer1)	0.2	0.028
Completely weathered coriaceous basalt. It is locally decomposed into silt clay (Layers 2 and 4)	0.15	0.022
Medium strong basalt rock(Layer 3 and 5)	0.1	0.015
Strong basalt rock(Layer 6)	0.1	0.015

3.4 General Flow Chart of the Study

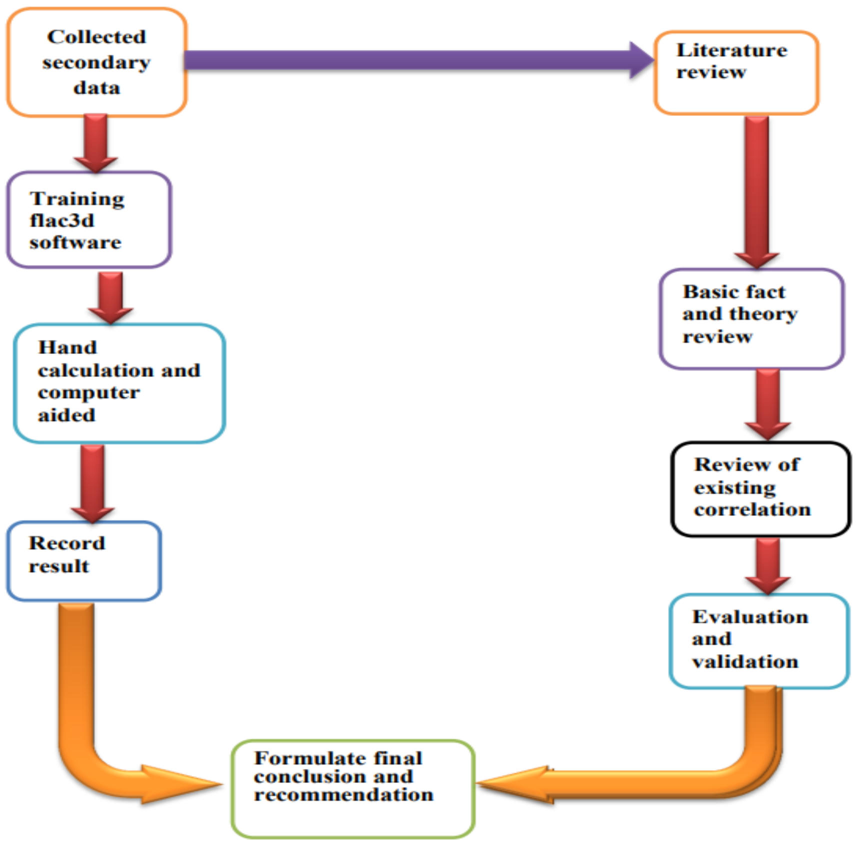

Figure 12: Summarized methodology chart of the structure

The general flow chart of the study can be outlined as follows:

Review existing literature on cap plasticity constitutive models and their application in geotechnical engineering. Identify key parameters and concepts related to cap hardening behavior in soils. Develop a cap plasticity constitutive model based on the obtained soil properties and calibration data from laboratory tests. Implement the model in FLAC3D software for numerical simulations. Define the boundary conditions, loading scenarios, and material properties for the numerical simulations. Specify the consolidation parameters for each soil layer based on Table 5. Perform numerical simulations using FLAC3D to analyze the cap hardening behavior of the soil under different loading conditions. Evaluate the stress distribution, deformation patterns, and settlement predictions of the soil layers. Compare the numerical simulation results with the laboratory test data to validate the accuracy and reliability of the cap plasticity model. Adjust model parameters if necessary to improve the model's predictive capabilities. Analyze the simulation results to understand the cap hardening behavior of the soil layers. Interpret the influence of different factors (e.g., loading magnitude, soil properties) on the soil's response. Summarize the key findings of the study regarding cap hardening behavior in soils. Provide recommendations for practical applications and further research in this area. This flow chart outlines the sequential steps involved in the study, from literature review and laboratory testing to numerical simulations, model validation, analysis, and conclusion. It provides a structured framework for conducting and analyzing the research on cap hardening behavior in soils using a cap plasticity constitutive model.

CHAPTER FOUR

RESULT AND DISCUSSION

The aim of the investigation of load sharing behavior of a piled raft with pile tips using the finite difference method in the case study of the new building Bank of Abyssinia headquarters in Addis Ababa is to analyze and understand how the load is distributed between the piled raft and the piles supporting the foundation system. This study aims to assess the interaction between the raft and piles, as well as how the presence of pile tips influences the load sharing mechanism.Key objectives of this investigation may include:

1. Analyzing the load distribution between the piled raft and individual piles in the foundation system.
2. Assessing the influence of pile tips on the load transfer mechanism within the foundation system.
3. Investigating the behavior of the foundation system under different loading conditions and soil properties.
4. Evaluating the overall performance and stability of the foundation system under various scenarios.
5. Providing insights into optimizing the design and construction of piled raft foundations with pile tips for similar projects.

By conducting this investigation, valuable information can be obtained regarding the load sharing behavior of piled raft foundations with pile tips, which can help improve the design and performance of similar foundation systems in future construction projects.

4.1. Design Of Piled Raft Using Simplified Method

Designing a piled-raft foundation using a simplified method involves considering the Before the detailed geotechnical design, a feasibility assessment is necessary by considering various foundation schemes. This is to investigate the adequacy of the raft alone, both regarding ultimate bearing capacity and settlement. If the raft alone is not adequate, the number of piles required below it which satisfy the design requirements will be determined using a simplified method. A geotechnical assessment was carried out for the following foundation schemes:

1) A raft alone, without piles;

2) A raft with 15 piles;
3) A raft with 30 piles;
4) A raft with 45 piles
5) A raft with 60 piles

For the preliminary assessment, the piles were assumed to be 2m in diameter and extend to the medium-strong basalt with an average length of about 8m. The raft was converted approximately to a rectangular plate 30m by 46m in plan, and 3m in thickness. The raft capacity is estimated using EBCS-8 and it can carry a maximum pressure of 2.16MPa.This indicates that the total superstructure load can be carried by the raft alone with an average settlement of 6.86 cm. The capacity of a single pile is determined using the α method for its shaft and its end resistance is taken from the compressive test results. This gives a total capacity of 11.54MN. Settlement and load sharing between the piles and the raft are also investigated using the stiffness of the piled raft, raft, and piles. The result shows that the raft can carry 24.11% and 14.37% of the total load for 15 and 60 numbers of piles respectively.

4.1.1 Assessment of bearing capacity of the raft and piles

The assessment of the bearing capacity of the raft and piles in a piled-raft foundation design is crucial to ensure that the foundation system can safely support the applied loads without excessive settlement or failure. Here are some key considerations for assessing the bearing capacity of the raft and piles:

1. Raft Bearing Capacity:

- Calculate the ultimate bearing capacity of the raft based on the soil properties, raft dimensions, and applied loads.
- Consider factors such as shape and size of the raft, depth of embedment, and soil strength parameters in determining the bearing capacity.
- Use appropriate bearing capacity calculation methods, such as the Terzaghi's bearing capacity equation, to estimate the ultimate bearing capacity of the raft.

2. Pile Bearing Capacity:

- Determine the ultimate bearing capacity of individual piles based on their dimensions, length, material properties, and soil conditions.

- Consider pile-soil interaction effects, such as skin friction and end-bearing capacity, in calculating the pile bearing capacity.
- Use methods like static pile load tests, dynamic load tests, or empirical formulas to estimate the ultimate bearing capacity of piles.

3. Combined Analysis:
   - Perform a combined analysis of the raft and piles to assess the overall bearing capacity of the foundation system.
   - Consider the interaction between the raft and piles in distributing the loads and resisting settlement.
   - Verify that the combined bearing capacity of the raft and piles is sufficient to support the applied loads without exceeding allowable settlement criteria.
4. Factor of Safety:
   - Apply appropriate factors of safety to account for uncertainties in soil properties, load assumptions, and design parameters.
   - Ensure that the calculated bearing capacities of the raft and piles have an adequate factor of safety to account for variations in soil behavior and loading conditions.
5. Verification:
   - Verify the calculated bearing capacities of the raft and piles against relevant design codes and standards to ensure compliance with safety and serviceability requirements.
   - Consider conducting additional analyses or tests, such as finite element analysis or load tests, to validate the calculated bearing capacities if needed.

By carefully assessing the bearing capacity of both the raft and piles in a piled-raft foundation design, engineers can ensure that the foundation system is structurally sound and capable of supporting the intended loads with acceptable levels of settlement and stability.

a) Raft-bearing capacity

The adequacy of the raft alone in terms of bearing capacity and settlement should be investigated first before adapting the piled raft system. As mentioned above, the actual geometry of the raft is simplified to an equivalent rectangle (30m by 46m). The soil profile and the location of the raft and piles are given in Figure 16 below. The ultimate capacity of the raft alone can be determined using EBCS-7(Eq.4.1) in case of drained condition (long term).

$$quit = cNc\, sc + q'Nq\, sq + 0.5\gamma' N\gamma s\gamma r\gamma \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.3)$$

Where: $Nq = e^{\pi \tan\varphi} \tan^2(45 + \frac{\varphi}{2}) \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.4)$

$$Nc = (Nq - 1) \cot \varphi \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.5)$$

$$N\gamma = (Nq - 1)\tan\varphi \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.6)$$

$$Sc = 1 + 0.2(B'/ L') \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.7)$$

$$Sq = 1 + 0.2(B'/ L')\sin\varphi \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.8)$$

$$S\gamma = 1 - 0.3(B'/ L') \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.9)$$

$$r\gamma = 0.7B' \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.10)$$

Taking the soil parameter from Table 6 and substituting it into (Eq. 3.3), the ultimate bearing capacity of the raft (q_{ult}) becomes q_{ult} = 6MPa. Taking a factor of safety of 3 the allowable bearing capacity (qa) is 2 MPa. Since the basement is not backfilled the allowable bearing capacity is increased by the effective stress that is removed from the foundation level.; Where:

$q' = \gamma' h \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.11)$

h = foundation depth and

γ ' = Effective unit weight)

$q' = \gamma' h = (17.7 - 9.8) * 18 = 142.2\ q = a\ 2 + 0.142 = 2.142 MPa$

Multiplying this stress (qa) by the area of the raft gives 3024MN. The total superstructure load on the foundation including the raft weight is 1426 GN. The capacity of the raft is much greater than the given super structural load. Therefore the raft can carry double as much load. It can be said that bearing capacity failure may not occur in this building. Table 6: Summary of soil parameters used for simplified design method

$$\boldsymbol{e} = \mathrm{e1}\left(\frac{L}{d}\right) * \mathrm{c1}\left(\frac{Ep}{G}\right) * \mathrm{c2}\left(\frac{s}{d}\right) * \mathrm{c3}(v) * \mathrm{c4}(\rho) \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.12)$$

The single pile stiffness is calculated using (Eq.3.12) and gives 4.75 GPa. The total pile group stiffness is determined as shown in Table 6.

Where: Gs = soil shear modulus at the depth Lp , Lp = pile length, r_o = pile radius,

$\eta = r\,b / ro \ldots\ldots\ldots\ldots\ldots\ldots (Eq. 3.13)$

rb = pile radius at its base $\zeta = Gs / Gb$, Gb = shear modulus of the soil below the pile base,

$\rho = \frac{\left(G_{\frac{1}{2}}\right)}{G}$ medium shear modulus at the soil layer around the pile,

$$Kp = \frac{Gsro\left(\frac{4\eta}{(1-v)\xi} + \frac{2\pi}{\zeta}\frac{Lp}{a}\frac{tanh\ \mu\boldsymbol{L}p}{\mu Lp}\right)}{1 + \frac{1}{\pi\lambda}\frac{4\eta}{(1-v)\xi}\frac{Lp}{a}\frac{tanh\mu Lp}{\mu Lp}} \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 3.14)$$

$$\lambda = \frac{Ep}{Gs} \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 3.15)$$

$$\zeta = \ln\left(\frac{rm}{ro}\right) \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 3.16)$$

$$rm = Lp\{0.25 + \xi[2.5\rho(1-\upsilon) - 0.25]\} \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 3.17)$$

$$\mu Lp = \frac{Lp}{ro}\sqrt{\frac{2}{\zeta\lambda}} \ldots\ldots\ldots\ldots\ldots..(\text{Eq. } 3.18)$$

Table 6: Table piled raft stiffness

SN.	Number of piles	Average Spacing (m)	Singe pile stiffness, Kp(GN/m)	Efficiency component e	Group efficiency R = n^{1-e}	Group pile stiffness Kpg(GN/m)
1	15	11	5.48	0.488	4	19
2	30	7.7	5.48	0.533	4.89	23.25
3	45	6.3	5.48	0.561	5.32	25.26
4	60	5.4	5.48	0.589	5.38	25.56

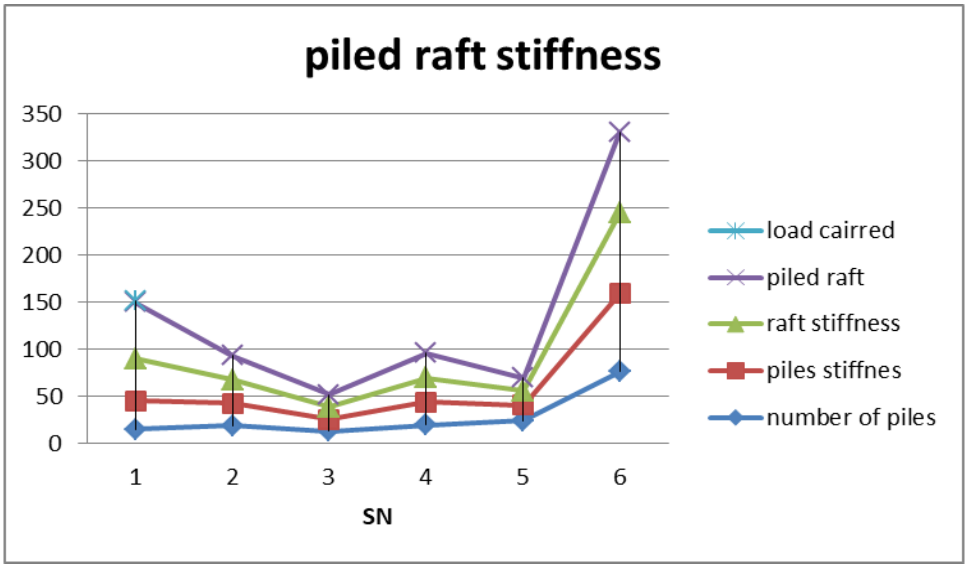

Figure 13 piled raft stiffness

To determine the value of the raft stiffness Kr, first the equivalent soil Modulus and Poisson's ratio are determined by the approximate graphical design method given by (Ayuluri & Krishna, 2017). By weighting the elastic parameters of each layer in a multi-layered system according to its influence on settlement an equivalent modulus and Poisson's ratio can be determined for the overall system. This is by assuming that the summation of the total settlement of layered soil is equated with the settlement of an equivalent single homogeneous layer. The 6 layers are converted to a single layer using this approach and give an equivalent soil modulus of, Es = 0.3MPa.The Detailed procedures for converting the 6 layers into single a homogenous layer are included in Appendix C. On the other hand, the stiffness of the raft is determined using (Eq.3.19) and yields Kr = 12.91Gpa.

$$\mathrm{kr} = \frac{\mathrm{Esd}}{(1 - \mathrm{v}^2)\mathrm{IEIF}} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,3.19})$$

Where:

K_r = Raft stiffness,

d = equivalent diameter of the raft,

v = Poisson's ratio of the soil

E_r = Equivalent elastic modulus of soil,

E_s = Elastic modulus of the raft,

t = thickness of the raft,

Z_E = depth of the foundation,

I_F = correction factor for rigidity,

I_E = correction factor for embedment

$$\mathrm{IE} = 1 - \frac{1}{3.5\exp(1.22\mathrm{v} - 0.4)\left[\frac{d}{Ze} + 1.6\right]} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,3.20})$$

$$\mathrm{IF} = \frac{\pi}{4} + \frac{1}{4.66 + 10 * \mathrm{KF}} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,3.21})$$

$$KF = \frac{ER}{ES} * \left(\frac{2t}{d}\right)^3 \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,3.22})$$

Once the stiffness of the pile group and the raft are determined, the overall stiffness (K_{pr}) of the piled raft and the load sharing ratio (X and $\boldsymbol{\alpha}_{pr}$) between the raft and piles can be established. The values of $\mathbf{K}_{pr}$ and **X** are calculated using (Eq.3.23 and 3.24) respectively. The load-sharing ratio between the raft and piles is given in Table 7.

$$kpr = \frac{1 - 0.6\left(\frac{Kr}{Kp}\right)}{1 - 0.6\left(\frac{Kr}{Kp}\right)} Kp \ \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,3.23})$$

$$\frac{Pr}{Pt} = \frac{0.2}{1 - 0.8\left(\frac{Kr}{KP}\right)}\left(\frac{Kr}{KP}\right) = X \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.\,3.24})$$

Where: K_{pr} K_p K_r , and are stiffness of piled raft, single pile, and raft respectively

Table 7: Piled raft stiffness and load sharing ratio between raft and pile

SN.	Number of piles	Group pile stiffness Kpg(GN/m)	Raft stiffness Kr (GN/m	Piled raft stiffness Kpr (GN/m)	Load carried by the raft (X) in %	Load carried by the piles (αpr =100% - X)
1	15	19	12.91	19.77	24.11	75.89
2	30	23.3	12.91	23.95	16.74	83.26
3	45	25.3	12.91	25.93	14.64	85.36
4	60	25.6	12.91	26.22	14.37	85.63

b) Load settlement curve The overall piled raft stiffness (Kpr) and the load sharing ratio (αpr) by piles that are determined in Table 7. are key parameters for developing the tri-linear load-settlement curve of the piled raft foundation. This tri-linear load settlement curve has been determined using (Eq.3.27 and 3.28). Let Pu be the ultimate load capacity of the pile group and α_{pr} = load sharing ratio by the pile group, the load carried by the pile group (PA) can be determined by (Eq.3.25)

$$\mathrm{pa} = \frac{\mathrm{pu}}{\alpha\mathrm{pr}} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.}\,3.25)$$

If the total applied load on the foundation is less than or equal to P_A (Eq. 3.26), the settlement of the piled raft is governed by the stiffness of the piled raft (P_R) and it is estimated using (Eq.3.26). If the total applied load is greater than P_A, the settlement is governed by the raft stiffness and it is determined using (Eq.3.266). The average settlement of the piled raft is estimated for various loads (up to nearly two times the actual load) as shown in Table 3. and one can be observed from the result the raft settlement of 6.86 cm is decreased to 3.65 cm by adding 60 piles below it for the actual load of the foundation.

For P ≤PA $\mathrm{s} = \frac{\mathrm{p}}{\mathrm{Kpr}} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.}\,3.26)$

For p > PA $s = sA + \frac{p-PA}{Kr} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.}\,3.27)$

$$sA = \frac{PA}{Kpr} \ldots\ldots\ldots\ldots\ldots..(\mathrm{Eq.}\,3.28)$$

Table 8: Average settlement of piled rafts with different numbers of piles

Number of piles below the raft	**0**	**15**	**30**	**45**	**60**
Average settlement (cm) at (P = 100MN)	0.86	0.51	0.417	0.386	0.381
Average settlement (cm) at (P = 200MN)	1.71	1.11	0.835	0.771	0.763
Average settlement (cm) at (P = 400MN)	3.43	2.63	1.67	1.54	1.52
Average settlement (cm) at (P = 600MN)	5.14	4.34	3.31	2.31	2.22
Average settlement (cm) at (P = 900MN)	6.86	6.26	5.23	4.6	3.65
Average settlement (cm) at (P = 1200MN)	10.29	9.49	8.46	7.42	6.44
Average settlement (cm) at (P = 1500MN)	12.86	12.1	11.03	9.99	9.015

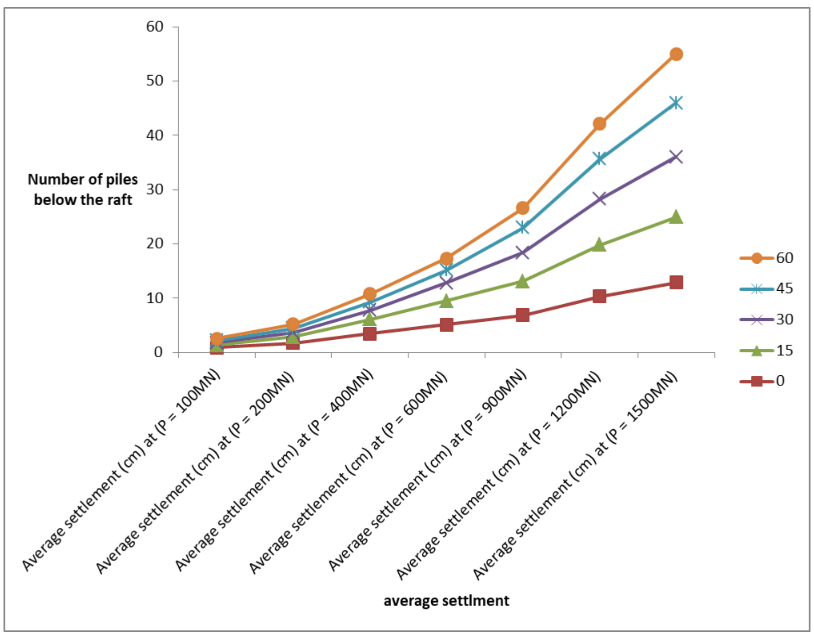

Figure 14: Load settlement relation of the piled raft for preliminary designed

The load settlement curve of the piled raft system is shown in Figure 15. this curve reveals that in the first stage of the curve (the first linear relationship between load settlements) the total settlement is governed by the pile group and raft, then in the second stage of the curve the piled raft is governed by the raft alone and it settles continuously after the ultimate capacity of the raft and piles is reached.

4.1.2 Finite difference Modelling And Analysis Of The Piled Raft Foundation

Finite difference modeling and analysis of a piled-raft foundation system involves discretizing the foundation and surrounding soil into a grid of finite elements to simulate the behavior of the structure under applied loads. Here are the key steps involved in conducting a finite difference analysis of a piled-raft foundation:

1. Define the Geometry and Soil Properties:

- Define the geometry of the foundation system, including the raft dimensions, pile locations, and soil layers.
- Assign appropriate soil properties to each layer, such as soil type, density, stiffness, and strength parameters.

2. Discretization:

- Discretize the foundation system and surrounding soil into a grid of finite elements to represent the structure numerically.
- Use a suitable mesh size to capture the complex interactions between the raft, piles, and soil.

3. Boundary Conditions:

- Apply appropriate boundary conditions to simulate the interaction between the foundation system and the underlying soil layers.
- Consider factors such as soil-structure interaction effects, pile-soil interaction, and lateral constraints.

4. Load Application:

- Apply the design loads, including dead loads, live loads, wind loads, and seismic loads, to the foundation system.
- Consider the distribution of loads on the raft and piles based on structural configurations and loading conditions.

5. Material Models:
   - Define material models for the soil and structural elements to capture their mechanical behavior under loading.
   - Use constitutive models that represent the nonlinear stress-strain relationships of soil and structural materials.
6. Analysis:
   - Perform a finite difference analysis using numerical methods to solve the equilibrium equations for the foundation system.
   - Consider time-dependent effects, such as consolidation settlement, creep, and dynamic loading conditions if applicable.
7. Results Interpretation:
   - Analyze the results of the finite difference model to assess the performance of the piled-raft foundation system.
   - Evaluate factors such as settlement, stress distribution, pile-soil interaction, and overall stability of the foundation.
8. Sensitivity Analysis:
   - Conduct sensitivity analyses to investigate the effects of variations in input parameters, such as soil properties, loading conditions, and design configurations.
   - Assess the influence of different factors on the behavior and performance of the piled-raft foundation system.
9. Validation:
   - Validate the results of the finite difference analysis against field measurements, empirical data, or analytical solutions to ensure the accuracy and reliability of the model.
   - Make adjustments to the model parameters or assumptions based on validation results to improve the predictive capabilities of the analysis.

By following these steps in conducting a finite difference modeling and analysis of a piled-raft foundation system, engineers can gain valuable insights into the behavior and performance of the foundation under various loading conditions and make informed decisions regarding design modifications or improvements.

4.2 Formulation of Finite diference Method (FDM)

In the context of the study on the load-sharing behavior of piled raft foundations, the Finite Difference Method (FDM) was not explicitly used. Instead, the Finite Element Method (FEM) was employed to model and analyze the behavior of piled-raft foundations. However, if you are interested in understanding the formulation of the Finite Difference Method (FDM) for a different application or topic, I can provide a general overview of how FDM is typically formulated:

1. Problem Setup:

- The FDM is commonly used to solve partial differential equations (PDEs) or ordinary differential equations (ODEs) by discretizing the domain into a grid of points.

2. Discretization:

- The domain is divided into a grid with points spaced at regular intervals in each dimension. The derivatives in the differential equation are approximated using finite differences at these grid points.

3. Finite Difference Approximations:

- Different types of finite difference approximations, such as forward, backward, or central differences, are used to approximate derivatives based on neighboring grid points.

4. Discretized Equations:

- By substituting these finite difference approximations into the original differential equations, a system of algebraic equations is obtained that can be solved numerically.

5. Boundary Conditions:

- Boundary conditions are applied at the edges of the domain to constrain the solution and ensure it satisfies the problem requirements.

6. Solution Method:

- The resulting system of equations is typically solved using iterative methods like Gauss-Seidel, Jacobi, or more advanced techniques like multigrid methods.

7. Convergence and Accuracy:

- The accuracy of the solution depends on the grid resolution and the order of the finite difference approximations used. Convergence studies are often performed to ensure the solution approaches the true solution as the grid is refined.

8. Implementation:

- The FDM formulation is implemented in programming languages like MATLAB, Python, or Fortran to solve specific problems efficiently.

Overall, the Finite Difference Method is a powerful numerical technique for solving differential equations by discretizing them into algebraic equations based on finite difference approximations. It is widely used in various fields such as fluid dynamics, heat transfer, structural analysis, and many more.

4.2.1 Element type

Different element types are available in FLAC3D software (i.e., beam, shell, and solid elements) which are implemented based on the nature of projects. The most commonly used in 3D analysis are tetrahedral or hexahedral continuum elements (Vakili 2015). These have been found very successful in predicting the behavior of piled raft foundations. For each type of element, there are normally linear or quadratic elements with full or reduced integration. In general, quadratic elements are more accurate than linear elements but more expensive in calculations if the same mesh is used. Linear hexahedral elements with reduced integration (C3D8R) in FLAC3D can be used in large-scale and complex analyses, on the balance of accuracy and efficiency (Sinha 2013). However, higher-order elements are recommended for more accurate purposes when the computational resource is not a problem. Due to a lack of high processor computer resources, linear hexahedral elements with reduced integration (C3D8R) were used in this study to model the different layers of soil and linear wedge elements with reduced integration (C3D8R) for the soil around the piles and the piles and raft themselves as well.

4.2.2 Boundary conditions

The boundaries of the soil in the model must be constrained in the vertical and lateral directions where the displacement of the soil due to the foundation load is negligible. To minimize the boundary effects in the model many authors suggested different locations of these boundaries. The horizontal length extent of 30D (30 times the pile diameter) and vertical depth extent of 2L (two times the pile length) is sufficient after which no appreciable stress and strain variation effect was observed (Sinha, 2013). Therefore, the boundaries of the model were placed at sufficient distances from the foundation so that the influence of the boundaries on the deformations of the foundation is minimized. The horizontal boundaries are constrained by the location of shoring walls (which retain the excavated depth) when the wall location is greater than (30D) and at 30D when the wall is nearer than 30D. The vertical boundary is fixed at a depth of 5L(5 times the pile length) from the bottom of the raft. Three separate boundary conditions were imposed onto the model. Due to symmetry, the problem is reduced to half of its original size. Nodes on both lateral boundaries of the model are fixed against horizontal movement (x = 0 and y = 0), yet free to move in the vertical direction. Meanwhile, nodes on the bottom boundary of the model are fixed in all directions (x =y = z = 0), whereas the top boundary is free to move in all directions. Nodes on the plane of symmetry are restrained from moving normally to the plane of symmetry but can move along the plane of symmetry as shown in Figure 15.

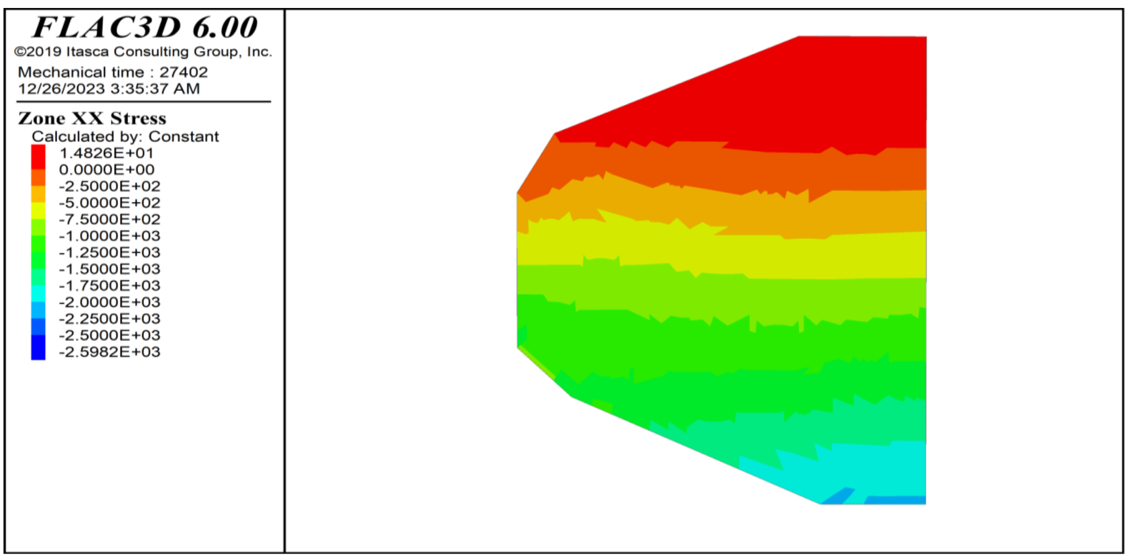

Figure 15: Boundary conditions

4.2.3 Sensitivity analysis

The sensitivity analysis conducted on the influence of the finite element mesh size on the bearing behavior of a piled raft foundation involved varying the number and sizes of elements while keeping material properties and other parameters constant. The analysis aimed to understand how the mesh coarseness affects the results, particularly the total maximum settlement in the foundation.

The study considered five different finite element meshes, each with a specific number of elements and sizes. The results of this sensitivity analysis are summarized in Table 9, which provides information on the generated number of elements and the total maximum settlement in the foundation for each mesh configuration.

This analysis is crucial as the finite element mesh plays a significant role in accurately capturing the behavior of the foundation system. By varying the mesh size and density, researchers can assess how the discretization of the model influences the calculated settlements and load-sharing behaviors. The results from this sensitivity analysis will help in determining an optimal mesh configuration that provides reliable and accurate predictions of the foundation's performance under different loading conditions.

Table 9: Influence of mesh size on maximum Total settlement

Model	Mesh Coarseness	Number of elements	Maximum settlement(m)	Time required to complete
Model 1	Coarse mesh	9360	70	10 minutes
Model 2	Coarse mesh	37500	73	25minutes
Model 3	Medium mesh	47860	76.65	45minutes
Model 4	Medium mesh	60522	81.23	1h8 minute

Table: Shows the influence of mesh density on the total settlement of the building. As we see from this figure maximum settlement increases with an increases number of element till the number of elements reaches 37500, after that an increase in a number of elements has no significant effect on the maximum settlement of the building. It can be said that mesh is converged with 47860 elements because there is no significant change in deformation when the number of elements increases to 60522. Therefore model 4 (medium mesh) was used to investigate the general behavior of the piled raft foundation.

4.2.4 Contact interface

When we model foundations, the contact condition between the soil and the structures must be specified to simulate its realistic behavior. The soil structure interaction is the main driving factor of the load-sharing mechanism that requires proper modeling to achieve accurate numerical results (Shamsi et al., 2022). There are two types of modeling techniques used for the pile–soil, and raft-soil interfaces. One is a slip element and the other is a thin layer element. Advanced finite element code such as FLAC3D has a special contact element (slip element) that may be used at the soil structure interface. Due to its simplicity slip element is preferred by (Xiang & Zareian, 2018) and (Hu et al., 2004). Unfortunately, this contact element is costly in terms of time and computer memory. It has also some convergence problems. Alternatively, a thin solid continuum element was used to simulate the contact zone between soil and raft, and between soil and the large-diameter bored instead of special interface elements. In the thin layer element method, the contact between structure and soil was described as perfectly rough. This means that no relative motion takes place between the nodes of the finite elements that represent the structure and those of the finite elements that represent the layer of soil. The material behavior in the contact area (the thin element) was simulated by the material behavior of the soil. (Reul, 2004) use thin-layer element at thepile–soil interface and obtain a good agreement between the results of pile shaft resistance predicted by bearing capacity theory and the results calculated by numerical analyses. In this study, thin solid continuum elements of thickness 0.1 times the pile diameter are used at the pile-soil interface and a thickness of 0.1 times the raft thickness at the raft-soil interface, following recommendations by (Reul, 2004).

4.2.5 Loading

The present study focuses on the behavior of piled raft foundation systems under vertical loads. The load configuration is one of the crucial parameters that affect the failure mechanism of the foundation. The superstructure load is transferred through the shear walls (core walls) and columns, acting on the top of the raft. Any load in FLA3D whether it is self-weight or external applied load is applied in incremental time step. The following steps are used for applying boundary conditions and different types of loading conditions. There are six steps in this model, these are

1. initial step
2. Primary load step
3. . Excavation step
4. Pile installation step
5. Raft installation step and
6. Loading step

1. Initial step (type initial condition)

The initial step is used to apply the boundary conditions and the initial stress state field of the soil. In analyzing most structures, it is appropriate to begin with a complete mesh of stress-free unreformed elements and subsequently apply the specified loads to obtain the desired stress state. However, buried structures are exceptional in that their response depends on the history of the loading, i.e. in-situ state of stress in the ground (Schnaid, 2005). Therefore it is important to apply initial conditions (pre-defined stress) before applying any external loads. In defining the stress field, vertical stress at two points should be defined and the variation between those two points is considered linear (Staff et al., 1992). Here, vertical stress at a point (σ'v) is determined by considering the number of soil layers that lie above the point considered (n) and given by:

$$\sigma v = \sum_{k=1}^{n} (\rho g h 1 - u) \ldots \ldots \ldots \ldots \ldots . . (\text{Eq.} 4.1)$$

Where: σv = effective vertical stress ρ = density of soil g = gravity hi = thickness of the soil(ith layer) u = pore water pressure n = number of soil layer For the given effective vertical stress field there is a corresponding effective horizontal stress and this can be determined by multiplying the effective vertical stress with effective earth coefficient (Ko). KO can be approximated by $KO = 1 - sin\phi$.

2. Primary load step (type Geostatic)

The geostatic stress field procedure is used in FLAC3D to verify that the initial geostatic stress field is in equilibrium with gravity loads and boundary conditions, or to iterate if necessary, to obtain equilibrium conditions. The geostatic stress field procedure is normally used as the first step of a geotechnical analysis. In this step, all the structural elements, such as the raft and the piles are removed or deactivated and gravity load is applied only to the soil. Ideally, the gravity loads and initial stresses should exactly equilibrate and produce zero deformations.

3. Excavation step (type static general)

The soil excavation can be modeled by deactivating the corresponding finite elements in the model. When the elements are deactivated in the analysis, the contribution of mass and stiffness of that element is removed from the global Mass and Stiffness matrix. The excavated soil above the foundation level was removed in this step to account for the relief pressure. In addition, bore holes were created for the piles to be installed by deactivating all the elements at the pile location as shown in Figure 16.

These steps are essential for accurately simulating the behavior of foundations in FLAC3D simulations.

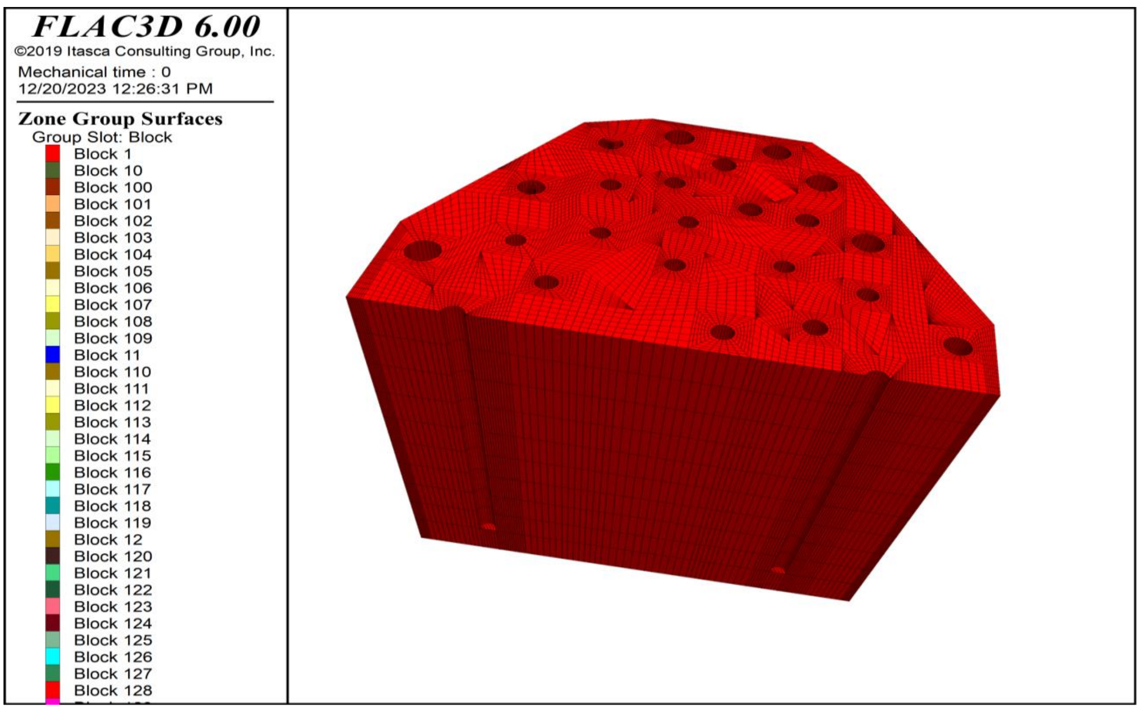

Figure 16: Excavation of soil at the locations of piles (enlarged view at pile and raft location

4. Pile installation step (type static general)

In this step installation of the foundation piles is simulated by activating the piles (previously deactivated at step 2) in place of finite elements representing the pile which is removed or deactivated from soil elements in the preceding step (step 3) as shown in Figure 16

Figure 17: Pile installation step (enlarged view at pile and raft location)

5. Raft installation (type static general) In this step installation of the foundation raft is simulated by activating what is previously deactivated at step 2 as shown in Figure 4.3.

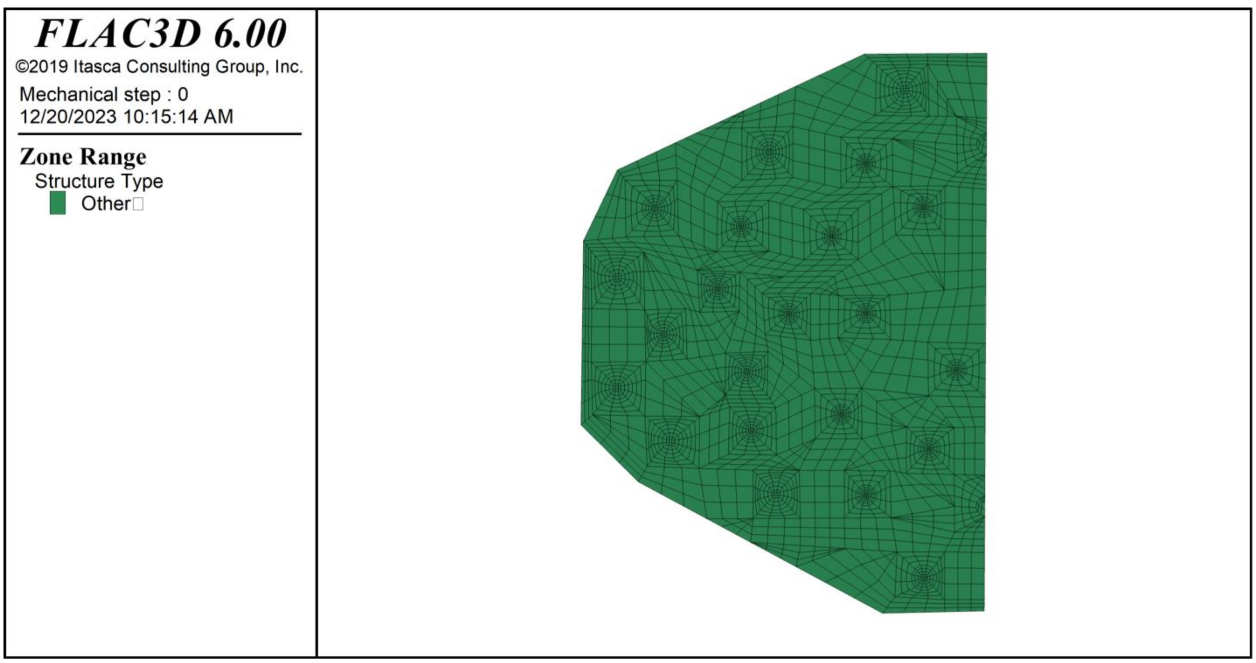

Figure 18: Raft installation step (enlarged view at pile and raft location)

6. Loading step (type static general) the super structural load is applied on the raft through the shear wall and columns. The application of load on the developed model is carried out using pressure rather than nodal loads. Nodal loads have a problem of excessive deformation in the node of application (Sabetamal et al., 2014). So in this model pressure loads are chosen for application of the load to avoid excessive deformation. Another reason for choosing pressure

load is to simulate the real loads applied on the raft from columns and superstructure on the raft

Table 10: Summary of basic concrete parameters used for the software

	Modulus of Elasticity	Poisson's ratio	Effective Unit weight
Symbols and units	E[GN/m2]	V	γ'[kN/m3]
Raft	35	0.2	15
Pile	36	0.2	15

Table 11: Summary of basic soil parameters used for the software

	Sym.	Layer1	Layer2	Layer3	Layer4	Layer5	Layer6
Modulus of Elasticity	E [MN/m2]	121	400	1000	400	1000	1500
Effective Unit weight	γ' [kN/m3]	7	12	14	12	14	18
Poisons ratio(ν)	-	0.3	0.3	0.25	0.3	0.25	0.25
Cohesion	C [kN/m2]	25	25	5000	5000	5000	5000

Layer1 [Red sandy clayey silt], Layer 3&5 [Medium strong rock basalt], Layer 6 [Strong rock basal], Layer 2&5[Completely weathered basalt mixed with swelling clayey silt]

4.3 Model validation

Model validation is a crucial step in the design and analysis of piled raft foundation systems to ensure that the numerical models accurately represent the behavior of the actual system. Here are three key aspects of model validation for piled raft foundations:

1. Field Testing and Instrumentation: Field testing and instrumentation are essential for validating numerical models of piled raft foundations. By comparing the predicted behavior from the numerical model with field measurements, engineers can assess the accuracy of the model and identify any discrepancies. Common field tests include load tests, settlement monitoring, and pile integrity testing. These tests provide valuable data for calibrating the numerical model and verifying its predictive capabilities.

2. Back-analysis of Case Histories: Back-analysis involves using historical data from previous projects to validate numerical models of piled raft foundations. By comparing the predicted

behavior of the model with actual performance data from case histories, engineers can assess the model's reliability and accuracy. Back-analysis helps identify any discrepancies between the predicted and observed behavior, leading to adjustments in the model parameters or assumptions to improve its accuracy.

3. Sensitivity Analysis: Sensitivity analysis is a critical component of model validation for piled raft foundations. By varying input parameters such as soil properties, material properties, and loading conditions, engineers can assess the impact of these factors on the model predictions. Sensitivity analysis helps identify key parameters that significantly influence the behavior of the foundation system and allows engineers to refine the model to better represent the actual conditions. By conducting sensitivity analysis, engineers can improve the robustness and reliability of the numerical model for piled raft foundations.

Overall, model validation for piled raft foundation systems involves field testing, back-analysis of case histories, and sensitivity analysis to ensure that the numerical models accurately represent the behavior of the actual system. By validating the models through these methods, engineers can enhance their confidence in the design and analysis of piled raft foundations and ensure that they perform as intended in real-world applications.

The software which is used for developing the model must be validated before its result is accepted and applied to simulate real-world problems. Validation is the only way to justify the predictions of a numerical model to the true physics concerned (Sinha, 2013). To check the validity of the results the model (FLA3D), an example of piled-raft foundations was analyzed. The model reported in the American Society of Civil Engineers (ASCE) Technical Committee – 18 (TC -18) report in (Poulos, 2001), has been used in this thesis for validation purpose. Fig. 19 shows the layout of the piled-raft foundation considered in this analysis. Figure 19: Layouts of piled-raft foundations taken from(Poulos, 2001). As shown in Figure 19 the raft dimension is 10m by 10 m with 0.5m thickness and the 9 piles are 10m in length and 0.5m in diameter. One-quarter of the foundation has been taken into account for simulation purposes. The middle three piles in the transverse direction were subjected to the concentrated load of 2MN, while the edge piles were subjected to the concentrated load of 1MN.

In the provided text, the process of model validation for a piled-raft foundation system using the FLA3D software is described. The validation process involves comparing the results obtained from the numerical model with those from a validated model reported in the ASCE Technical Committee – 18 (TC -18) report by Poulos in 2001. The layout of the piled-raft foundation considered in the analysis includes a raft dimension of 10m by 10m with a thickness of 0.5m and nine piles of 10m length and 0.5m diameter.

To validate the FLA3D model, one-quarter of the foundation layout is simulated, with the middle three piles in the transverse direction subjected to a concentrated load of 2MN, and the edge piles subjected to a concentrated load of 1MN. By comparing the results obtained from the FLA3D model with those from the validated model reported by Poulos, the accuracy and reliability of the numerical model can be assessed.

It is essential to conduct such validation studies to ensure that the numerical model accurately represents the behavior of the actual piled-raft foundation system. Validation helps in justifying the predictions of the numerical model based on the true physics involved in the system and enhances confidence in using the model for simulating real-world problems.

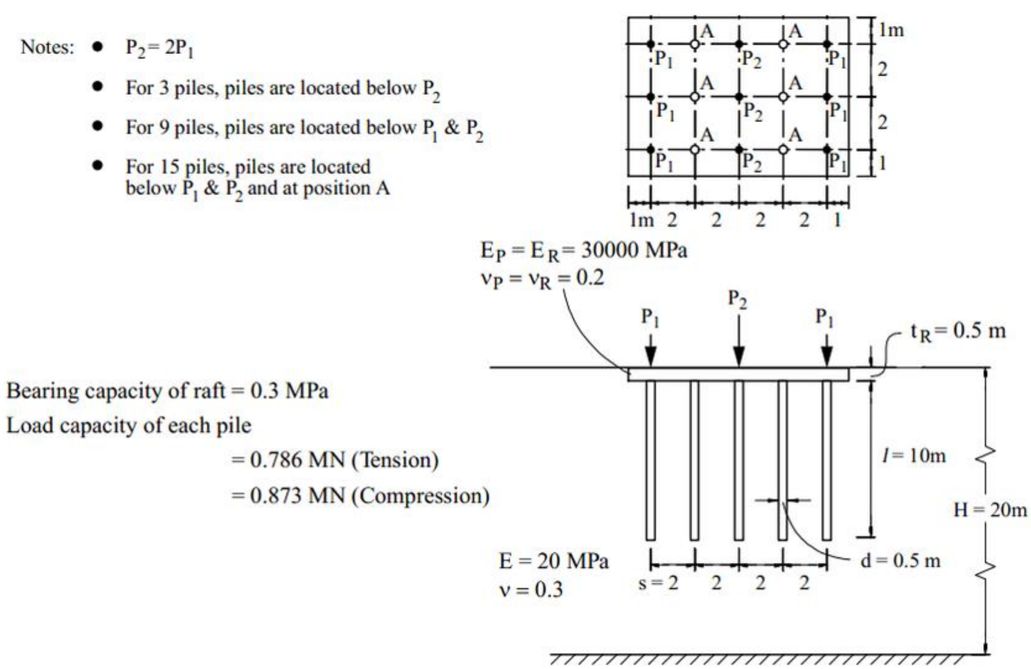

Figure 19: Layouts of piled-raft foundations taken from(Poulos, 2001)

Table 12: The result of the settlement contour simulated in this model.

Model	Central Settlement (mm)	Corner pile Settlement(mm)
FLAC 2D Predicted by Poulos(2001)	65.9	60.5
FLAC 3D Predicted by Poulos(2001)	39.9	35.8
PDR Method	36.8	-
GASP	33.8	22
GARP5	34.2	26
PLAXIS 2D Predicted by Omeman(2013)	32	26
In this thesis	37.6	7.5

The main objective of this study is to investigate the contribution of the raft to the bearing behavior of piled raft foundation and to assess load-sharing mechanisms between the raft and piles. As shown in Chapter 3, a FLA3D model has been developed to study the behavior of piled raft foundations in case of pile tips resting on a stiff stratum. In addition, to ensure the reliability of the results obtained by the developed model, a comparison study was carried out between the results given by (Poulos, 2016) and those obtained from the current FE model with similar real structure geometry, loading, and properties. The scope of this study is to investigate the contribution of the raft, on the settlement, and load sharing behavior of the piled raft foundation and to assess its failure behavior in cases where a weak stratum is located under the hard stratum below the pile tips. Therefore, the results obtained by the developed model are related to these parameters. Furthermore, discussions are made by considering comparisons to previous works related to the specific topic under consideration.

4.4 Behavior of the raft alone

The raft was analyzed assuming that it could support the entire load. Figure 6.1shows the contour of the vertical settlement. It undergoes total settlement of 5.1 cm and differential settlement of 1.14 cm. When this result is compared with the result of the simplified method, the simplified method gives higher settlement (6.86 cm). The maximum, minimum and tilting of the foundation is given in Table 4.1. As expected the location of the maximum and minimum settlements of the raft occur at the center and corner respectively. It is usually the differential settlement rather than total settlement which causes damage to structures. To accommodate the structure itself from harmful distortion, (EBCS 8, 1995)and (Bowles, 1996) limit the maximum differential settlement and tilting of any building are 75% of total settlement and 1/500 respectively. It should be noted that the maximum differential settlement and tilting of the building are less than the maximum specified allowable value. Therefore these results cause no negative effect on the serviceability of the building. As discussed in the Chapte 3, the adequacy of the raft alone in terms of bearing capacity and settlement requirements should be investigated first before adapting the piled raft system. The results showed that the raft can carry double as much the superstructure load. Settlement of the raft is also within the acceptable limit given by EBCS- 8 and (Bowles, 1996) recommendations. Therefore, it can be concluded that the raft is adequate both in terms of bearing terms of bearing capacity and settlement requirements.

Table 13: Maximum and minimum settlement

Maximum settlement [mm]	Minimum settlement [mm]	Differential settlement [mm]	Tilting
37.6	7.5	30.1	0.0004

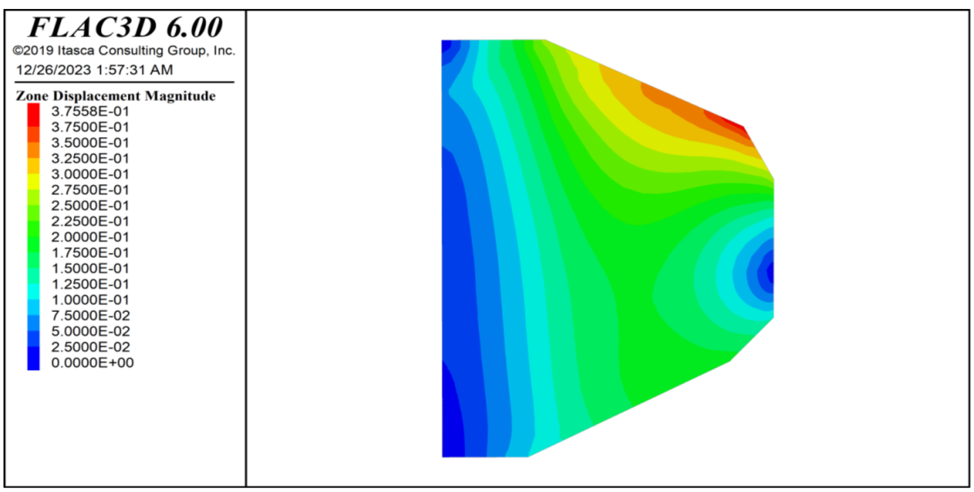

Figure 20: Contours of vertical displacement the raft at full load (units: m)

4.5 General behavior of piled raft foundation

A piled raft foundation combines the benefits of both pile foundations and raft foundations to provide an efficient and cost-effective solution for supporting structures on challenging soil conditions. The general behavior of a piled raft foundation involves the interaction between

the raft, piles, and underlying soil to distribute loads, control settlement, and ensure structural stability. Here are some key aspects of the general behavior of piled raft foundations:
However this belled shape was not considered in the model. The length of the bored pile varies (ranging from 5m to 10 m) to reach the hard stratum. The variable soil profile was simplified to horizontal because of its difficulty to consider in the model. To assess the behavior of the piled raft under consideration, two cases have been taken. In the first case, the actual length of piles was considered. In this case, some piles did not reach the hard stratum due to simplification made for the soil formation. In the second case, an average length of the piles was analyzed. Here all pile tips are extended up to the hard stratum. Case 1: Using the actual length of the piles shows the contours of settlement of the raft at total working load. The location of the maximum and minimum settlements of the raft occur at the center and corner respectively. The results of the analysis show the maximum and minimum settlements of the raft as 4.23 cm and 2.7 cm respectively. This gives a 1.53 cm maximum differential settlement and/1695 tilting of the building as shown in Table 4.4. It can be noticed that the maximum settlement of the piled raft foundation is almost the same as the maximum settlement of the raft alone. The maximum settlement reduction of the raft by adding 46 bored piles below it is less than 1cm. In addition, maximum differential settlement and tilting of the piled raft foundation and the raft alone are also the same. So, based on the result, it can be concluded that inserting piles below the raft has no contribution to settlement reduction.

Table 14: maximum differential settlement and tilting

Maximum settlement [mm]	Minimum settlement [mm]	Differential settlement [mm]	Tilting
34.6	27	15.3	0.058

The maximum axial load is at the top of the pile; it reduces with depth and minimum at the tip of the pile. The axial load carried by the piles at the center of the raft is very small compared to the piles around the edges. Similar behavior was also reported by(Mendoza et al., 2014). This is due to pile group effects. The central pile became less stiff and the axial load carried by it will be smaller as compared to the piles around the edges. Case 2: Using the average length of the piles Settlement contours of the raft are shown in Figure 6.4. The results of the analysis show maximum and minimum settlements of the raft are 3.46cm and 2.7 cm respectively. This gives a 1.5 cm maximum differential settlement and/2439 tilting of the building. These results are similar to the results of case 1. Therefore the simplification made for the soil formation has no significant effect on settlements of the foundation.As mentioned earlier, in the model some piles were not extended up to the hard stratum. To see the effect of soil layer at pile tips on axial load distribution one typical pile location has been taken for comparison. Axial load distribution of the pile when the soil layer at the pile tip is varied. As shown in the figure axial load distribution of the pile is almost twice when its tip is resting on the hard stratum as compared to when its tip is resting on a weak stratum.

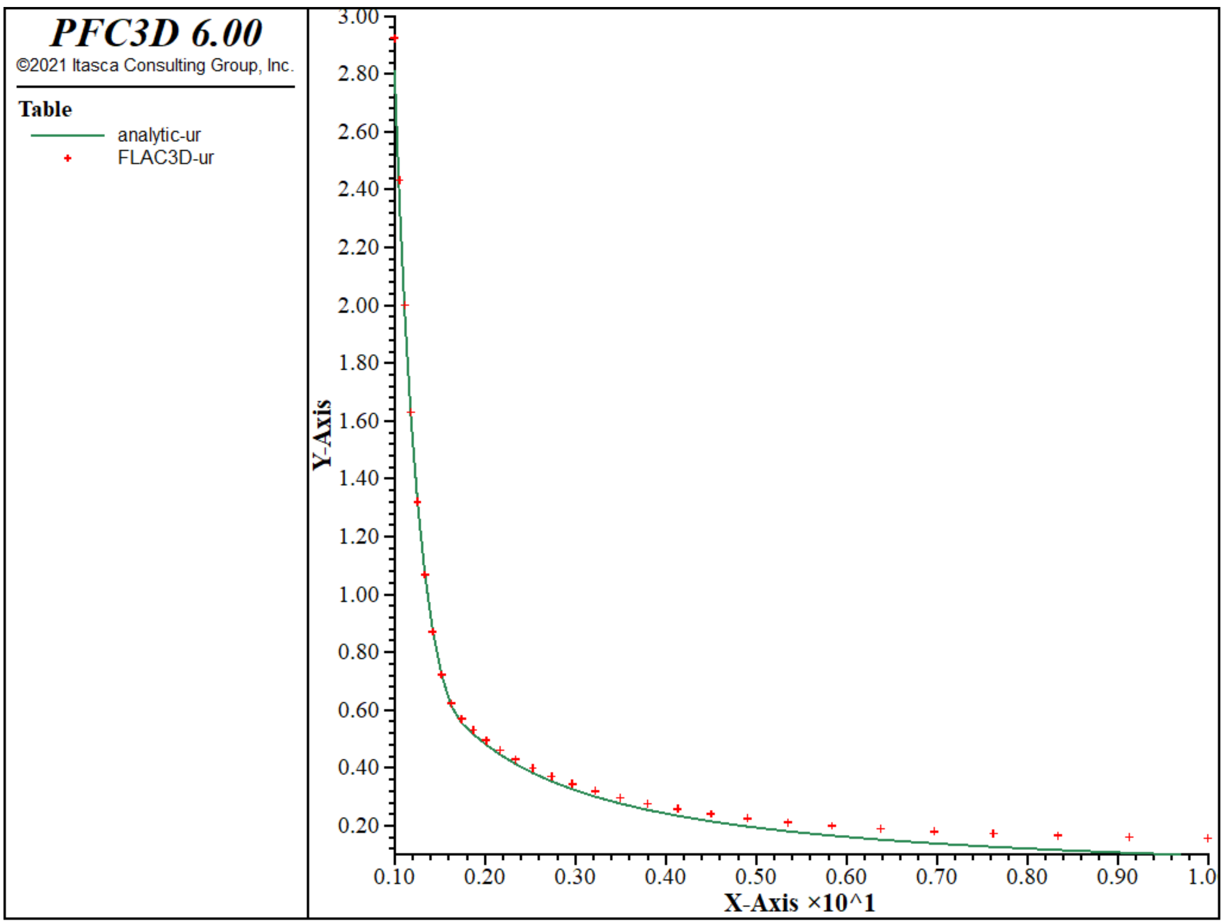

Figure 21:6Load sharing behavior of piled raft foundation

4.6Load sharing behavior of piled raft foundation

The percentage of load taken by each component (raft & piles) depends on several factors such as soil property, raft geometry, pile geometry (diameter, length), and its spacing. In this study, investigation was made for the actual soil properties of the site and the actual geometry of the foundation system. Table 15 shows the computed settlement of the piled raft foundation, the total gravity load transferred from the superstructure to the raft, and the load sharing rations between piles and raft.

To calculate the percentage of a specific load in relation to the total load, you can use the following formula:

Percentage of specific load = (Specific load / Total load) * 100

Where:

- Specific load is the value of the load you are interested in calculating the percentage for.
- Total load is the sum of all loads or the total value you are comparing against.

Simply plug in the values for the specific load and total load into the formula, then multiply the result by 100 to get the percentage.

To calculate the load applied on a raft in meganewtons (MN), you can use the following formula:

Load = Pressure x Area

Where:

- Load is the total load applied on the raft in meganewtons (MN).
- Pressure is the pressure acting on the raft in megapascals (MPa) or newtons per square meter (N/m^2).
- Area is the total area of the raft in square meters (m^2) over which the load is distributed.

You can determine the pressure acting on the raft based on the specific load applied or other relevant factors. Once you have the pressure and area values, you can multiply them to calculate the total load applied on the raft in meganewtons.

The load sharing ratio of piles refers to how the load is distributed among multiple piles in a pile group. The load sharing ratio can be calculated using the following formula:

Load Sharing Ratio = Load Carried by Individual Pile / Total Load on Pile Group

Where:

- Load Sharing Ratio is the ratio of the load carried by an individual pile to the total load on the pile group.

- Load Carried by Individual Pile is the load that a single pile in the group is supporting.
- Total Load on Pile Group is the total load acting on the entire pile group.

By calculating the load sharing ratio, you can determine how the load is distributed among the piles in a group and assess the contribution of each pile to supporting the total load.

The load sharing ratio of a raft foundation, denoted as X, can be calculated using the following formula:

X = (Load Carried by Raft / Total Load on Raft Foundation) * 100%

Where:

- X is the load sharing ratio of the raft foundation expressed as a percentage.
- Load Carried by Raft is the total load that the raft foundation is supporting.
- Total Load on Raft Foundation is the sum of all loads acting on the raft foundation.

By using this formula, you can determine the percentage of the total load that is being carried by the raft foundation. This information is important for understanding how the load is distributed and shared among the various components of the foundation system.

The total settlement of a raft foundation can be calculated using the following formula:

Total Settlement = (Σ (Load * Settlement) / Total Load on Raft Foundation)

Where:

- Total Settlement is the total settlement of the raft foundation in millimeters.
- Load is the individual load acting on the raft foundation.
- Settlement is the settlement corresponding to each load.
- Σ represents the summation of all individual load settlements.
- Total Load on Raft Foundation is the sum of all loads acting on the raft foundation.

This formula calculates the total settlement of the raft foundation by considering the settlement contribution of each load based on their magnitude and distribution. It provides valuable information for assessing the overall stability and performance of the foundation system.

Table 15: Shows load-sharing behavior between piles and rafts with applied vertical load

Percentage of the total load in (%)	Load applied on the raft [MN]	Load shared by the piles[MN]	Load sharing ratio of piles ( )	in % Load sharing ratio of raft (X)	in % Total settlement [mm]
10	160.8	176	100	0	5.99
20	256.86	295	100	0	9.5
35	400.8	465	98.3	1.7	14.8
65	688.8	754	95.2	4.8	26.23
80	832.8	880	93.6	6.4	33.82
95	976.8	1030	93.1	6.9	36.49
100	1024.8	1090	92.9	7.1	42.3

As we can see from Table 15. at the total superstructure load, load sharing ratio by the piles, αpr is 92.9% for case 1(using actual pile length). For Case 2(average pile length) αpr gives 96%. When the results of the FE method are compared with the simplified method, the simplified method underestimates the load shared by the piles. It gives 84.36% of the total load transferred by the piles. This is due to many simplifications being made in the simplified method. The piled raft coefficient was not only dependent on the system geometries of the foundation but also the load level for most cases. The load sharing between the raft and the piles as a function of the total applied load reported Similar behavior was reported by(Katzenbach et al., 2010). At a small load level, almost the entire superstructure load is carried by the piles (horizontal portion of the graph) shown in the figure. When the load of the superstructure is small, the settlement of the foundation is also small; at this stage load shared by the raft is insignificant or small because interaction between the raft and the soil is negligible. When the magnitude of the load increases load carried by the piles decreases and becomes almost constant as shown in the figure. At this stage, the ultimate capacities of the piles are reached after that if there is any additional load it will be taken by the raft. When the total load of the structure increases settlement of the building also increases, as a result of the raft–soil interaction, the contact pressure below the raft increases. At this stage, the load-sharing ratio by the piles decreases, and the load-sharing ratio of the raft increases. Generally as shown in the figure the load shared by the piles is greater than 93%, this shows almost all the superstructure load are transferred by the piles. This is due to the tip of the piles resting on the medium-strong rock; the entire load is transferred to the rock through the piles. In addition, the settlement of the foundation is also very small, as a result, the raft–soil interaction has no significant effect, and the load shared by the raft is negligible.

According to piled raft foundation guideline(Burland & Broms, 1976), the application of piled raft foundation is effective in cases where the soil under the raft is not very weak in comparison to that under the pile tip. Thus it is common to define the dimensionless stiffness ratio Esoil layer at pile tips / Etop layer as the ratio of stiffness of the soil layers at the tip of the piles to that at the top of piles or just under the raft. The guideline restricts the use of the Piled raft foundation for the range of Esoil layer at pile tips / Etop laye greater than 10, because the contribution of the raft is very small (piles raft coefficient αpr is >0.9 to all cases). But in this study, the actual stiffness ratio of the soil layers at the tip of the piles to that at the top of piles or just under the raft (Esoil layer at pile tips / Etop laye) is 8.26/1. For this stiffness ratio load shared by the piles, αpr is 92.9%. This value is nearly acceptable as compared with the recommendation given by the piled raft guideline. To apply the recommendation given by the piled raft foundation guideline for stratified soil condition, in the case of pile tips resting on a hard stratum, a parametric study was carried out. Five different stiffness rations $E_{soil\ layer\ at\ pile\ tips}$ / $E_{top\ laye}$ were analyzed. These ratios are three above the limit value (10/1) and three below the limit value. Only the stiffness of the weak layer (beneath the raft) is varied keeping the stiffness of the hard stratum (where the pile tips resting).

In FLAC3D, the stiffness ratio is a parameter that is used to define the relative stiffness of different materials or components in the model. The stiffness ratio is typically defined as the ratio of the Young's modulus (E) of one material to the Young's modulus of another material. It is used to represent the relative stiffness between different materials in the model and can have a significant impact on the behavior and interaction of these materials.

The stiffness ratio is often used in geotechnical engineering and rock mechanics simulations to represent the differences in stiffness between rock layers, soil types, or other materials in the model. By adjusting the stiffness ratio, you can control how materials interact with each other, how loads are transferred between different components, and how deformations are distributed within the system.

In FLAC3D, you can define the stiffness ratio for different materials by specifying the Young's modulus values for each material and then setting the stiffness ratio parameter accordingly. By adjusting the stiffness ratio values, you can simulate a wide range of scenarios where materials with different stiffness properties are present in the model.

It is important to carefully consider and calibrate the stiffness ratio parameter in your FLAC3D model to accurately represent the relative stiffness of materials and ensure that the simulation results reflect the real-world behavior of the system being analyzed. The stiffness ratio can play a crucial role in determining the overall response and stability of the model under different loading conditions.

The stiffness ratio is a measure of the relative stiffness between the soil layer at the pile tip and the soil layer at the pile top. It is calculated by dividing the stiffness of the soil layer at the pile tip (Esoil layer at pile tip) by the stiffness of the soil layer at the pile top (Etop layer at pile tip). This ratio helps to assess how the stiffness of the soil changes along the depth of the pile and can be used to optimize the design of the pile foundation. The load shared by the piles interaction factor, often denoted as δ, is a measure of how the load is distributed among a group of piles in a pile foundation system. This factor represents the percentage of the total load that each pile in the group carries based on its interaction with neighboring piles. The load shared by the piles interaction factor is typically expressed as a percentage, ranging from 0% to 100%. A higher interaction factor indicates a more even distribution of the load among the piles in the group, while a lower interaction factor suggests that some piles may be carrying a disproportionately higher load compared to others. The interaction factor takes into account various factors such as pile spacing, pile stiffness, soil properties, and pile group configuration. It is an important consideration in the design of pile foundations to ensure that the load is distributed effectively among the piles to prevent overstressing of individual piles and ensure overall stability and performance of the foundation system.

The formula to calculate the load shared by the piles interaction factor in percentage is:

Interaction Factor (%) = Load carried by individual pile/Total load on the group of piles× 100%

This formula calculates the percentage of the total load that each pile in a group of piles carries based on its interaction with neighboring piles. The load carried by an individual pile can be determined based on factors such as pile stiffness, spacing, soil properties, and the overall configuration of the pile foundation system. The total load on the group of piles is the sum of all loads that the piles are designed to support collectively.

Table 16: shows the analyzed cases of different stiffness ratios with load sharing ratios by the piles.

S.N	Stiffness ratio =$E_{soil\ layer\ at\ pile\ tips}$ / $E_{top\ laye}$	Load shared by the pile's αpr in %
1	25	100
2	20	99.8
3	12.5	96.5
4	8.33	92.25
5	2	86.3

Based on the provided data of stiffness ratios and the corresponding percentage of load shared by the pile's apron, it appears that there is a trend where as the stiffness ratio decreases, the percentage of load shared by the pile's apron also decreases. This relationship suggests that the stiffness ratio of the soil layer at the pile tips relative to the top layer has a significant influence on how the load is distributed and shared by the pile's

From the data, it can be observed that as the stiffness ratio decreases from 25 to 2, the percentage of load shared by the pile's apron decreases from 100% to 86.3%. This indicates that a lower stiffness ratio results in a lower percentage of load being shared by the pile's apron, implying that a greater proportion of the load is carried by the soil layer at the pile tips compared to the top layer. This relationship between stiffness ratio and load sharing behavior highlights the importance of considering soil properties and layering when designing piled-raft foundations to ensure proper load distribution and structural stability.The effects of the stiffness of the top weak layer on the load-sharing ratio of the piles have been studied using the stiffness ratio-versus-load shared by the piles.

For lower stiffness ratios (Esoil layer at pile tips / Etop laye < 10), the percentage of load carried by the piles increases linearly with increasing Esoil layer at pile tips / Etop layer as shown in the figures and becomes 100% for Esoil layer at pile tips / Etop laye values greater than 20.

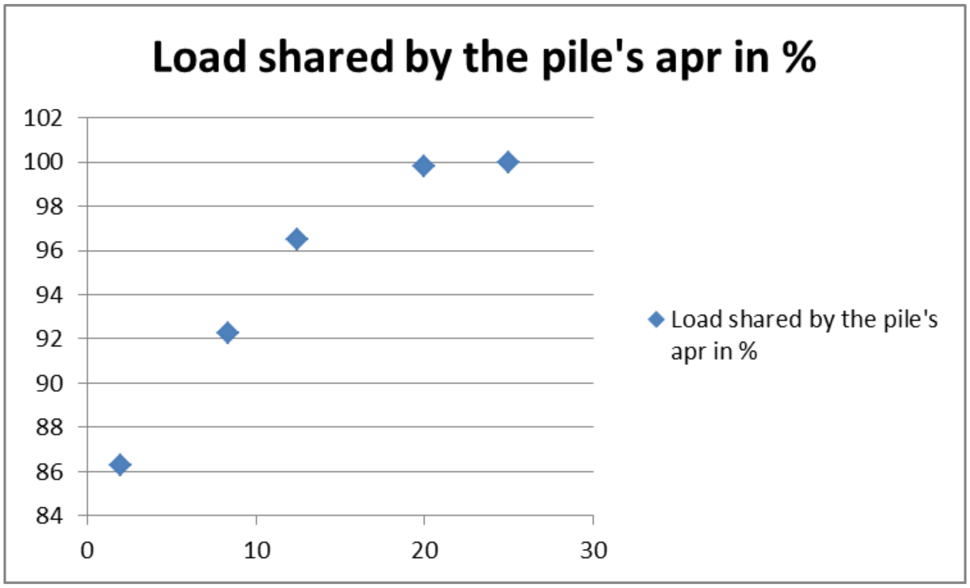

Figure 22: Shows the effects of stiffness ratio on the load-sharing behavior of pile

4.7 Effect of the raft–soil interaction on the behavior of piled raft foundation

a) Effect of the raft–soil interaction on settlements of the building To see the effect of the raft-soil interaction on an individual group of piles behavior, the piles with raft have been analyzed with the same material properties of soil and pile as considered in the piled raft foundation. The same discretization has been used; only the raft-soil interaction was ignored (the contact between raft and soil is not allowed). In the analysis, the magnitude and way of application of the loads on the raft are the same as in the piled raft foundation analysis (with full contact between raft and soil). Figure 16 shows the contours of settlement of the raft at total working load. The positions of the maximum and minimum settlements are slightly altered from their location. The maximum settlement is shifted from the center point. It is located almost on the corner of the symmetry line shown in the figure. The results of the analysis show maximum and minimum settlements of the raft are 4.28 cm and 2.72 cm respectively as shown in Table 14. The maximum differential settlement and tilting of the whole building are 1.56 cm and 0.00061 respectively. It should be noted that although the raft–soil interaction is ignored in the model, the maximum differential settlement and tilting of the building are similar to the results obtained by considering the raft-soil interaction. It can be concluded that the raft soil interaction does not affect the foundation behavior. As mentioned earlier the pile tips are located on the medium-strong layer, as a result, the settlement of the foundation became small. Due to this reason the raft–soil interaction is not active.

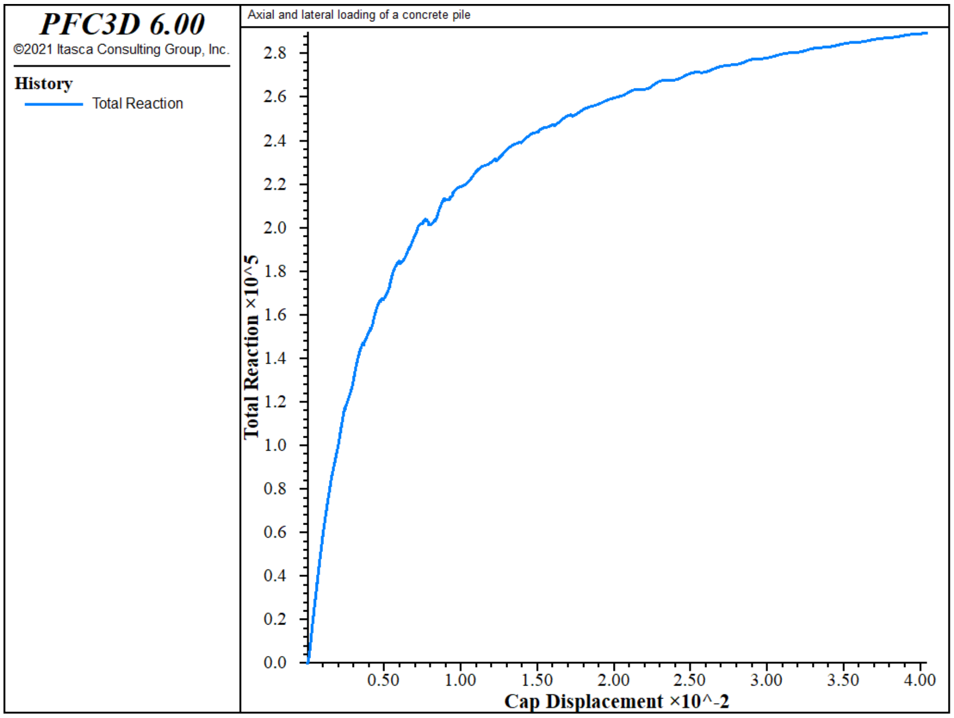

Figure 23: pile axial loads and contour

b) Effect of raft–soil interaction on axial load distribution of piles Here we cannot talk about load sharing mechanism; since the contact between raft and soil was ignored all loads are carried by the pile groups. To see the effect of raft–soil interaction on the axial load distribution of piles, the two previously selected piles (one from the center and one from the edge) were chosen. The comparison of axial load distribution between these piles is also plotted in Figure 22 As expected, the maximum axial load is at the top of the pile; it reduces with depth and minimum at the tip of the pile. The axial load carried by both piles is almost the same both in their magnitude and their pattern. This shows that the raft–soil interaction has no significant effect on the axial load distribution of the piles.

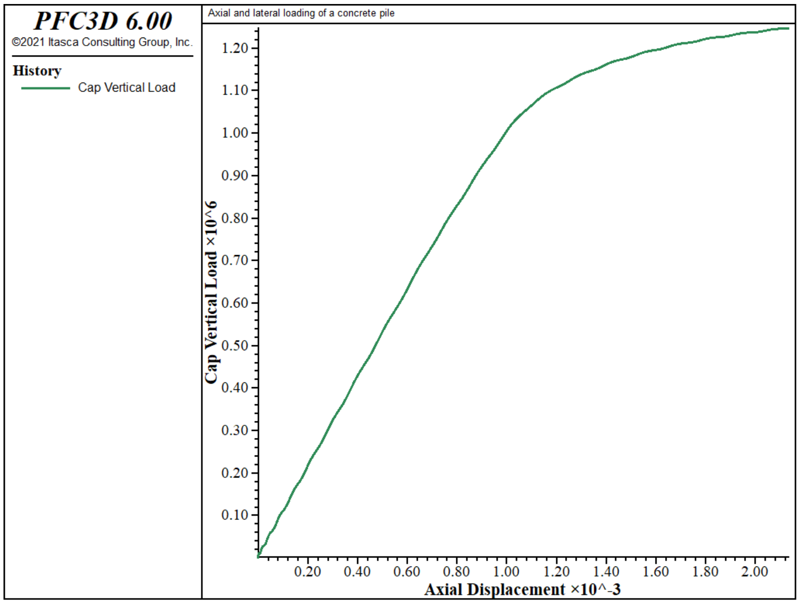

Figure 24: Axial load distributions of piles a) Central piles b) Edge piles c) Effect of raft–soil interaction on load-settlement behavior of the building

Fig 25 shows the typical load-settlement curves for the selected key node of a piled raft foundation unit with and without considering the raft–sil interaction. As it can be shown in the graph both curves exhibit the same stiffness. This indicated that the raft–soil interaction has no significant contribution

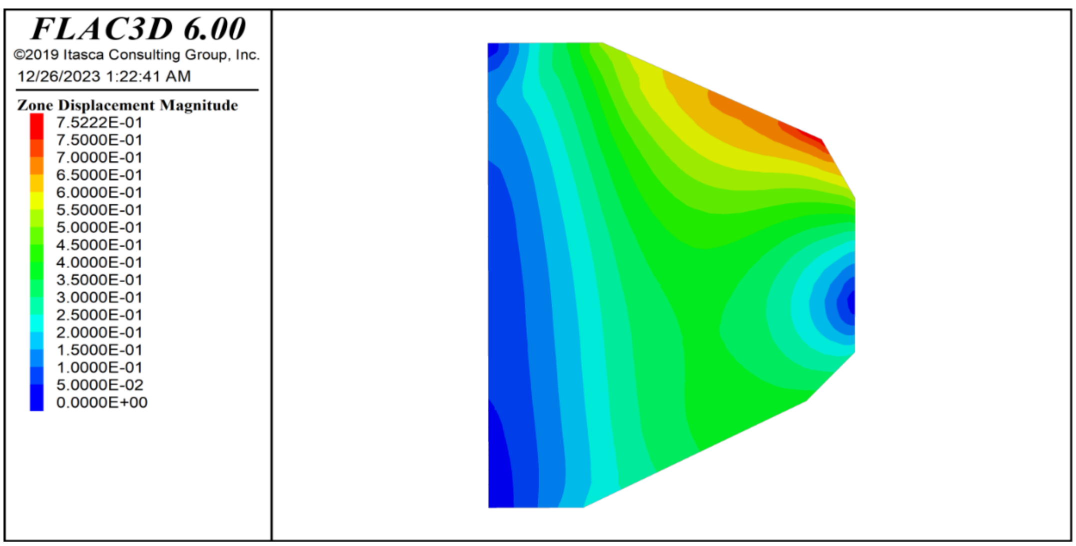

Figure 25: Effects of raft – soil interaction on load displacement behavior of the piled raft foundation

4.7.1 Effect of weak layer on the behavior of piled raft foundation

The study investigated the effect of the weak layer's location on settlements and load-sharing behavior by varying its position while keeping other parameters constant. Five different locations were considered: at the pile tips and below the pile tips at 1m, 3m, 6m, and 14m depths. The influence of the weak layer on settlements was found to decrease with increasing stiffness ratio (E_weak layer / E_soil layer at pile tips), becoming insignificant for values greater than 0.5 for all weak layer locations. The study also varied the stiffness of the weak layer while keeping other parameters constant. Four different stiffness ratios of the weak layer to the stiffness of hard strata were considered. For lower stiffness ratios (<0.2), both maximum and differential settlements decreased abruptly with increasing stiffness ratio, indicating that a slight reduction in soil stiffness in the weaker range led to excessive settlement increases. Contour plots of raft settlements showed that the positions of maximum and minimum settlements were not significantly altered by stiffness variation. Maximum and differential settlements decreased with increasing stiffness ratio, with the weak layer's influence becoming negligible for stiffness ratios >0.5.The effect of weak layer location on settlements was found to be negligible when the weak stratum was located below 8m for all stiffness ratios considered. The study concluded that the behavior of the piled raft foundation is not significantly affected by a weak layer located below 8m, provided the relative stiffness between the weak and hard strata is greater than 0.5. For all stiffness ratios considered in the study (0.05 to 0.8), the presence of a weak stratum did not have a substantial impact on the behavior of the piled raft if located below 8m.

Overall, the study highlights the importance of considering both the location and stiffness of weak layers when analyzing the settlements and load-sharing behaviors of piled raft foundations, with a focus on how these factors interact to influence foundation performance.

The effect of this weak layer clearly showed on total and differential settlement of the foundation. Location of the weak layer has more effect on settlement rather than the relative stiffness of weak to hard strata.

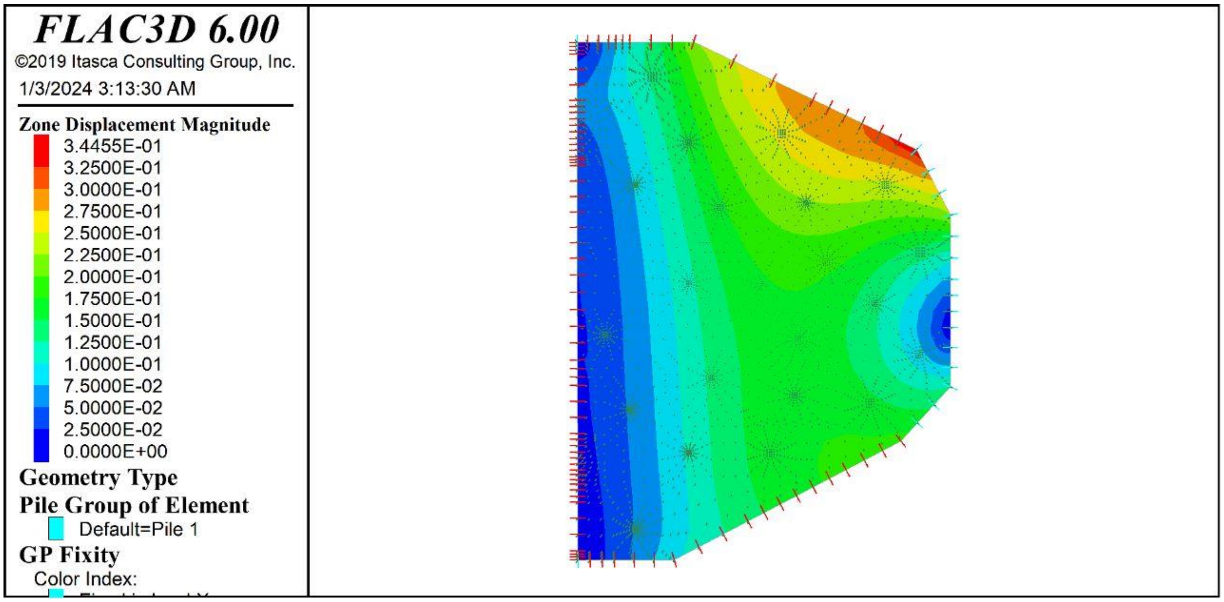

Figure 26: Shows maximum and differential settlements of the building with location of the weak layer under pile tips

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1CONCLUSIONS

The conclusions drawn from the study on the load-sharing behavior of piled raft foundations with consideration of weak layers beneath the raft and below pile tips using the Finite difference Method are summarized as follows:

- The thesis outlines a two-stage design process for piled raft foundations, involving an initial assessment using a simplified method followed by detailed design and behavior assessment using the Finite difference Method.
- A three-dimensional numerical model was developed using FLAC3D software to analyze piled-raft foundations, accounting for interactions among piles, raft, and soil. The model was validated against existing literature and showed reasonable agreement with other numerical models.
- The analysis revealed that while the raft alone can support superstructure loads with acceptable settlements, the addition of piles reduced the raft's contribution significantly. Only 7% of the total load was transferred by the raft when analyzed with 46 piles.
- Inserting piles below the raft did not contribute to settlement reduction if the pile tips were resting on a hard stratum. The raft had minimal impact on load sharing and settlement when pile tips.
- Load sharing between the raft and piles was influenced by the stiffness ratio of piles to raft and settlement of the foundation. The load carried by the raft increased notably with higher raft settlement.
- The study's results on load shared by the raft aligned closely with recommendations from piled raft foundation guidelines, particularly regarding the stiffness ratio of top and bottom layers affecting load distribution between piles and raft.

In summary, the study provides valuable insights into the load-sharing behavior of piled raft foundations, emphasizing the impact of weak layers, pile tips, and settlement on load distribution between the raft and piles. The findings offer practical implications for the design and analysis of piled-raft foundations in construction projects.

5.2RECOMMENDATIONS

Based on the conclusions drawn from the study on the load sharing behavior of piled raft foundations considering weak layers, the following recommendations can be made:

- Conduct further research to investigate the behavior of piled raft foundations in the presence of weak layers with varying characteristics and depths. This will help in understanding the influence of different weak layers on the load sharing behavior and settlement of the foundation system.
- Validate the findings of the numerical modeling through field studies and monitoring of actual piled raft foundations constructed on sites with weak layers. This will provide practical insights into the performance of piled raft foundations in real-world conditions.
- Develop or refine design guidelines for piled raft foundations considering the effect of weak layers. Guidelines should address the interaction between piles, raft, and weak layers to ensure safe and efficient design of piled raft foundations in geotechnically challenging conditions.
- Conduct detailed settlement analysis to assess the settlement behavior of piled raft foundations with weak layers. Investigate the influence of settlement on load sharing between the raft and piles to optimize the design for stability and performance.
- Consider the stiffness ratio between the top layer (raft) and bottom layer (soil layer at pile tip) when designing piled raft foundations. Ensure that the stiffness ratio is within an acceptable range to optimize load sharing between the raft and piles based on the specific site conditions
- Implement strict quality control measures during the construction of piled raft foundations to ensure proper installation of piles and raft components. Monitoring settlement during and after construction is crucial to assess the performance of the foundation system.
- Collaborate with geotechnical experts and structural engineers to integrate geotechnical considerations into the design and construction of piled raft foundations. A

multidisciplinary approach will help in addressing complex challenges associated with weak layers and optimizing foundation performance.

By implementing these recommendations, designers and engineers can enhance their understanding of piled raft foundations in the presence of weak layers and improve the design, construction, and performance of foundation systems in geotechnically challenging environments.

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APPENDIX-A

Laboratory test result

Twenty undisturbed soil sample

no	BH NO	depth m	LL (%)	PL (%)	PI(%)	Free swell (%)	Organic content (%)	swelling pressure (KN/M3)	Natural Moisture Content
1		5.5	-	-	-	-	-	-	40.3
2	1	20	74.5	52	63	-	-	-	56.33
3	1	42	103	52	37	-	-	-	22.44
4	1	4.7	67.9	29	41	230	-	460	16.09
5	3	7.5	86.1	43	88	90	-	-	28.16
6	5	8.4	141	49	36	160	-	360	32.98
7	5	23	78.8	36	72	230	-	280	38.26
8	6	6	119	53	53	110	-	-	72.25
9	6	23	-	-	-	-	-	-	34.23
10	6	39	-	-	-	-	-	-	39.67
11	6	42	-	-	-	-	-	-	28.78
12	6	44	78.1	40	25	120	9.8	-	22.09
13	7	4	73	35	38	130	-	-	33.09
14	7	41	-	-	-	-	-	-	42.04
15	7	42	78.5	36	47	140	-	-	42.23
16	7	41	89.9	33	56	-	-	-	32.46
17	8	49	85.1	25	48	-	-	-	36.3
18	8	18	67.5	57	44	150	4.62	-	78.9
19	8	5.1	95.7	-	40	120	-	-	34.79
20	9	43	65.9	-	35	-	-	-	24.87
21	9	24	-	-	-	-	-	-	41.3

Twenty undisturbed soil sample

no	BH NO	depth m	Natural Unit Weight Kg/M3	UNCONFINED COMPRESSIVE STRENGTH (KN/M3)	Direct Shear Test		Triaxial Shear Test	
					CKN/M3	Φ degree	C KN/M3	Φ Degree
1		5.5	1760	84	-	-	14	23
2	1	19.7	1619	-	18	18		
3	1	42	1689	-	-	-	18	18
4	1	4.7	1545	-	-	-	16	20
5	3	7.5	1789	154	-	-	38	26
6	5	8.4	1687	71	-	-	26	8
7	5	23	1989	134	-	9	32	12
8	6	6	1544		-	6	29	26
9	6	22.5	1660	251	80	-	-	-
10	6	39.4	1690	262	95	16	27	18
11	6	42	1970	275	-	-	-	26
12	6	44	1915	-	82	-	34	17
13	7	4	1545	386	-	-	22	24
14	7	40.5	1680	-	-	17	32	-
15	7	41.5	1870	-	-	13		-
16	7	40.5	1820	-	87	-		13
17	8	48.5	1790	-	32	-	34	22
18	8	18	1749	-	-	-	2	17
19	8	5.1	1538	-	-	-	24	16
20	9	43	1718	-	-	-	-	-
21	9	23.7	1670	142	-	-	-	-

project	headquarters building of boa				
client	China state construction engineering Ethiopia PLC				
location	A.A Mexico 7 rock sample				
				rock strength test	
no	bh no			compressive strength kn/m2	module of elasticity kn/m3
		death (m)	unit weight kg/m3		
1	10			27703	2028000
2	10	27	2670	31240	243852
3	10	45	2781	49680	3508483
4	10	52.3	2856	57878	1963182
5	10	58	2813	32630	1660000
6	10	66.5	2775	47465	1808682
7	10	72	2828	49527	1608782

APPENDIX-B

Structural load and Pile lengths

All Loads are in kN	
C_1	35863
C_2	35243.3
C_3	31995.3
C_4	28138.6
C_5	25829.1
C_6	25572.6
C_7	32276.2
C_8	28199.2
C_9	30206.3
C_{10}	34430.9
C_{11}	25560.5
C_{12}	25200.3
C_{13}	26431.5
C_{14}	27084.5
C_{15}	29990.6
C_{16}	32757.6
Pall =	487884.7
Note : C = Column load Pall = Shear wall load	

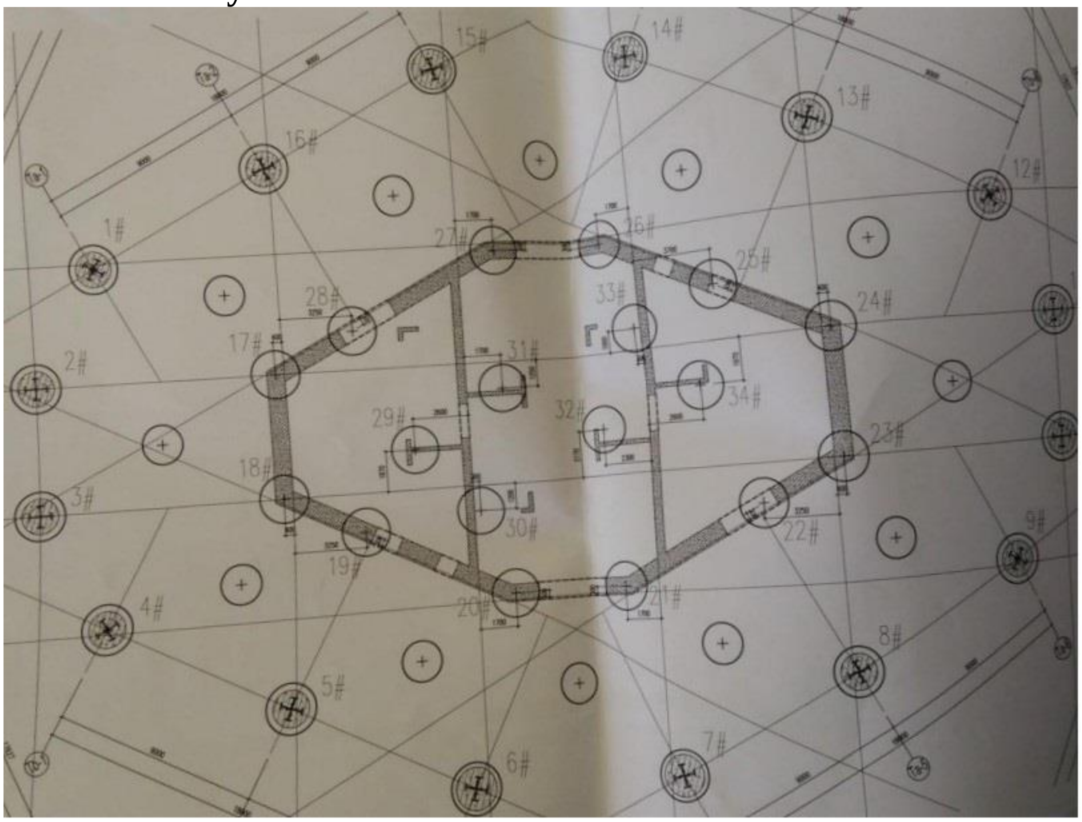
Pile lengths

pile no	pile length	Pile no	pile length
1	7.5 m	25	8.7 m
2	9.8 m	26	7.7 m
3	8.76 m	27	9.7 m
4	7.78m	28	6.8 m
5	8.98 m	29	8.8 m
6	8.84 m	30	8.6 m
7	7.5 m	31	8.9 m
8	6.6 m	32	8.6 m
9	8.1 m	33	8.5 m
10	5.9 m	34	8.8 m
11	5.4 m	35	7.9m
12	5.3 m	36	6.3 m
13	7.8m	37	5.3 m
14	8.4 m	38	7.7 m
15	8.5 m	39	7.5 m
16	7.6 m	40	5.8 m
17	6.3 m	41	6.4 m
18	8.9 m	42	7.4 m
19	9.3 m	43	7.48 m
20	9.2 m	44	7 m
21	8.8 m	45	5.58 m
22	7.5 m	46	4.5 m
23	8.6 m	47	7 m

no	BH NO	depth m	Natural Unit Weight Kg/M3	UNCONFINED COMPRESSIVE STRENGTH (KN/M3)	Direct Shear Test		Triaxial Shear Test	
					C KN/M3	Φ degree	C KN/M3	Φ Degree
1		5.5	1760	84	-	-	14	23
2	1	19.7	1619	-	18	18		
3	1	42	1689	-	-	-	18	18
4	1	4.7	1545	-	-	-	16	20
5	3	7.5	1789	154	-	-	38	26
6	5	8.4	1687	71	-	-	26	8
7	5	23	1989	134	-	9	32	12
8	6	6	1544		-	6	29	26
9	6	22.5	1660	251	80	-	-	-
10	6	39.4	1690	262	95	16	27	18
11	6	42	1970	275	-	-	-	26
12	6	44	1915	-	82	-	34	17
13	7	4	1545	386	-	-	22	24
14	7	40.5	1680	-	-	17	32	-
15	7	41.5	1870	-	-	13		-
16	7	40.5	1820	-	87	-		13
17	8	48.5	1790	-	32	-	34	22
18	8	18	1749	-	-	-	2	17
19	8	5.1	1538	-	-	-	24	16
20	9	43	1718	-	-	-	-	-
21	9	23.7	1670	142	-	-	-	-

APPENDIX-C

Foundation layout



APPENDIX-D

Borehole log section