Numerical Analysis of load – Settlement Response of Piled Raft Foundation in Layered Soil Using Plaxis 3D Numerical Model

Sicko Jara Usha

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

Office of Graduate Studies
Adama Science and Technology University

November, 2025
Adama, Ethiopia

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Advisor: Biruk Gissila (PhD)

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DECLARATION

I declare that this MSc. thesis entitled “**Numerical Analysis of load – Settlement Response of Piled Raft Foundation in Layered Soil Using Plaxis 3D Numerical Model** "is my work and has not been submitted to any university for a similar purpose. The references used in this thesis are duly recognized by proper citations.

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I, the advisor of this MSc thesis, hereby certify that I have closely advised the student while developing this thesis and read the draft entitled "**Numerical Analysis of load – Settlement Response of Piled Raft Foundation in Layered Soil Using Plaxis 3D Numerical Model**" prepared under my guidance by Sicko Jara Usha Therefore, I recommend the submission of the thesis to the department for further review and evaluation.

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I, the advisors of the thesis entitled "**Numerical Analysis of load – Settlement Response of Piled Raft Foundation in Layered Soil Using Plaxis 3D Numerical Model**" and developed by Sicko Jara Usha, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Sicko Jara Usha have read and evaluated the thesis entitled "**Numerical Analysis of load – Settlement Response of Piled Raft Foundation in Layered Soil Using Plaxis 3D Numerical Model**" 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 (specialization in Geotechnical Engineering).

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Abstract

Urban growth has led to large buildings on soft soil due to limited firm building site and rocky ground formations, causing excessive and differential settlement issues in cities with less stable base. Strict safety rules require minimal uneven settlement in high-rise buildings. Piled raft foundations have become a popular solution, using piles to reduce settlement and share the building's weight. In this study the analysis of load-settlement behavior of piled raft foundation using numerical methods was carried out. The performance of a rectangular piled raft system is evaluated in layered soil subjected to uniform vertical loading. The analysis is conducted using the powerful finite element-based program Plaxis 3D to examine the effects of various parameters. A parametric study is also conducted to investigate the response of piled-raft foundations, including the influence of raft thickness, pile length, and pile spacing, while keeping the pile diameter and the number of piles constant. The results from the analysis indicated that by applying a piled raft to an un-piled raft foundation with a raft thickness of 2 m, the maximum settlement was reduced from 102.7 mm to 77.57mm, and the differential settlement also decreased from 11.9 mm to 2.09 mm. This represents a decrease of 24.47% and 82.44%, respectively, for a case with 2D pile spacing and an 18 m pile length. By increasing the pile spacing from 2D to 3D, the maximum settlement was reduced by 17.18% for an 18 m pile length and a 3 m raft thickness. Furthermore, a total settlement reduction of 24.18% was achieved by increasing the pile length from 10.8 m to 18 m, under the conditions of 3D pile spacing and a 3 m raft thickness. Hence, the findings from this research can serve as a framework for developing large combined piled-raft foundations to support heavy building structures and provide a methodological approach for future projects involving complex soil-structure interactions.

Keywords: Piled-Raft, Settlements, Plaxis 3D, High-rise building and Soil-structure interaction

Table of Contents

List of Figures

List of Tables

List of Abbreviations

2D - Two Dimensional
3D - Three Dimensional
A- Area
AASHTO – American Association Society of Highway and Transport Organization
Ap - Total area with in unit cell
A_r – Area Replacement ratio
ASTM – American Society for Testing and Materials BSI – British Standard Methods of Test for Soil
B – Footing Size
D - Diameter of pile
De - effective Diameter
Ec – Modulus Elasticity of Concrete
E - Easting
Es – Modulus Elasticity of soil
FEM - Finite Element Method
Ø – Friction Angle
FEM - Finite Element Modeling
H – Layer Thickness
KN/M - Kilo Newton per Meter
KN - Kilo Newton
KPa - Kilo Pascal
L – Length of Pile
L/D-Length to Diameter Ratio
N - Number of pile
N - Northing
n - Stress concentration factor
S - Center to Center Spacing
S/D - Spacing over Diameter Ratio
SPT – Standard Penetration Test
S – Pile Spacing
UDL – Uniformly Distributed Load
T – Raft Thickness

CHAPTER ONE

Introduction

1.1.Background

Due to the growth of the economy and a shortage of land resources, many high-rise buildings have been constructed in major cities. However, many of these structures are being constructed on soft soil sites, which can lead to ground settling, especially in urban areas where there are few rock sites available. In foundation design, the two basic requirements are to limit the total settlement of the structure to a small value and to exclude differential settlement. However, it should be noted that heavy structures can become excessively displaced if they are constructed in soft soils. It is crucial to select suitable foundation types for any building or structure in order for it to last for a long time, and the building may experience serious structural problems if the foundation is not properly constructed.

Selecting appropriate types of foundation is crucial for the longevity of any building or structures and the building may experience serious structural problems if the foundation is not properly constructed. Shallow foundations, such as strip footings and raft foundations, are appropriate for stable soil conditions where the load can be spread over a relatively shallow area. However, when the soil is weak the bearing capacity might not be enough to support a heavy structure causing significant settlement. Essentially, a piled foundation is a deep foundation made up of long, slender columns (piles) driven or drilled into the ground. By transferring the load to this deeper, stronger layer, the piles prevent excessive settlement and possible structural damage. A shallow raft foundation may not be sufficient when heavy structures are built on weak soils because excessive settlement is possible. Piled foundations are used in such cases to transfer the loads to deeper soil.

The use of only piles or rafts foundation is efficient due to the load sharing between piles, rafts and the soil. Pandey G. et al. (2024) stated that relying solely on piles or rafts raises the risk of either very high costs or significant differential settlement. As a result, "Piled Raft Foundations" were developed, combining two distinct systems (Clancy P. et al, 1993). Piled rafts are foundations made up of three load-bearing elements: piles, rafts, and soil. Because the raft is stiff, it distributes the structure's total load as contact pressure over the piles in the ground. By using piled rafts, total as well as differential settlements have been reduced. A raft foundation often induces excessive settlements that are unacceptable due to serviceability concerns. By placing piles under the raft in a systematic manner, such settlements can be reduced to acceptable levels. Besides settlement reduction, the bearing capacity of the whole system of foundations also increases.

In combined piled raft foundation, load distribution is governed by complex interactions between structural elements (i.e., pile-piles, pile-rafts, and raft-piles) and their geometries. For the first time, piles were introduced below the raft to reduce its settlement (Burland et al., 1977). Researchers later performed some prominent investigations on piled raft foundation using analytical methods, 3D finite element analysis, and small scale model tests to idealize the behaviour of this foundation (Clancy and Randolph, 1993; El Sawwaf, 2010; Fattah et al., 2013; Ghalesari and Rasouli, 2014; Kumar and Choudhury, 2018; Mali and Singh, 2018; Park and Lee, 2015; Poulos and Davids, 2005; Sawada and Takemura, 2014; Sinha and Hanna, 2017). A 3D finite element (FE) analysis has been widely used to analyze piled raft foundation responses in clayey soils. Using 3D FE modelling, Reul and Randolph (2003) investigated three case histories related to a piled raft foundation resting on clayey soil. According to de Sanctis and Mandolini (2006), the load bearing capacity of piled raft foundation was also examined using a 3D finite element method. A Piled raft foundation resting on soft/stiff clay was also analyzed by several other researchers using 3D finite element to understand the load bearing and load sharing responses and different settlement criteria (Singh and Singh, 2020; Sinha and Hanna, 2017; Cho et al., 2012; Deb and Pal, 2019; Mali and Singh, 2018).

In this study the numerical analysis of piled raft foundation rested in layered soft/stiff clayey soil using plaxis 3D were presented for identifying the responses of piled raft foundation under a heavy structures. This research analysed the influence of pile length of pile, pile spacing and raft thickness on settlement reduction and axial load resisting capabilities. The investigation examines into the potential of this method to enhance load-bearing capacity and reduce settlement by examining the impact of modifying these diverse parameters within a specified existing soil condition for the incorporation of piled raft foundation. This task is executed through the utilization of PLAXIS 3D, a three-dimensional finite element software. Within the research location, there is a widespread distribution of soft to stiff clay deposits extending to significant depths, characterized by weak strength and high compressibility. Thus, application of piled raft foundation type for minimizing excessive settlement and eliminating differential settlement emerges as exceedingly crucial. The load-bearing capacity of a piled raft foundation is recognised to the frictional characteristics of the pile length, the cohesion and frictional attributes of the surrounding soils, as well as the thickness and flexibility or rigidity features of the raft part transmitting stresses to the corresponding pile.

Therefore, this research tries to investigate the effect of numerical modelling analysis of piled raft foundation on settlement reduction characteristics. Then following identification of index as well as engineering properties of both materials with the help of collected secondary data's from consulting offices, analysis of settlement reduction of the given soil due to utilization of piled raft foundation on layered soil, using numerical methods, was studied in detail and finally, the conclusions of the research and future prospects are forwarded.

1.2.Statement of The problem

The global rise in urbanization and population growth has created a significant demand for housing, leading to the construction of high-rise buildings in numerous areas. This trend is also evident across Africa, where cities work to support their growing populations. In Ethiopia, the heightened demand for housing has led to the development of many high-rise structures. A prime example of this is the ECX 3B+G+35 building, which illustrates the country's commitment to addressing the increasing demand for urban infrastructure. The recent structures that will be built in big cities like Addis Ababa will be high-rise buildings in whatever soil is available, whether soft soils or hard strata. In Addis Ababa, most high rise buildings have raft or pile foundations, which are expensive (Teji, Biya et al., 2023). Despite having adequate bearing capacity, the raft foundation is subject to excessive settlement. The conventional design methods for pile groups result in a greater number of piles under the raft. It is possible to reduce this number with the concept of piled rafts. Whenever an appropriate foundation design can be applied to soil conditions, piled rafts have proved to be an efficient solution. Using this method of calculation is very conservative; the basic principle is that the foundation structure should contain as many piles as would be required to reduce the settlement to an acceptable level. Furthermore, the design engineers of piled raft foundations continue to use commercial structural software such as ETABS and SAP2000, which cannot model the interactions and come up with inaccurate estimates of foundation settlements, raft bending moments, and pile loads due to the lack of ability to model these interactions. When a structure needs to be supported on weak or compressible soil, or when significant loads cannot be handled by a raft foundation alone, piled raft foundations are ideal. These foundations combine the best features of both raft and pile foundations, making them cost-effective and robust even if the cost analysis neither is nor carried out under this study.

Therefore, the introduction of piled raft foundation into feeble soil as a heavy structural load support goes beyond a mere substitution process, as it can lead to alterations in material characteristics. In the current investigation, a numerical evaluation of the load-settlement behaviour of piled raft foundation in layered soil in Addis Ababa city was conducted using a Plaxis 3D Model. The study applied finite element analysis by subjecting static loads to examine the impact of settlement reduction under various conditions, with subsequent discussion of the findings. A three-dimensional representation of a heavy super structural load support was developed, and the outcomes of the finite element analysis concerning settlement analysis for each case were deliberated.

1.3.Research Questions

1. Is it possible to investigate the effect of using different raft thicknesses in piled raft foundations for settlement reduction?
2. To what extent is the utilization of piled raft foundations capable of improving the settlement properties of the given soil under heavy structural loads?
3. Is there an optimum pile length and pile spacing for piled raft foundations in layered soil?
4. How do variations in pile length, spacing, and raft thickness impact settlement characteristics in piled raft foundations on layered clayey soil compared using numerical model parameters?

1.4.Objectives

1.4.1.General Objectives

The primary objective of this research is to analyze the effectiveness of a piled raft foundation in reducing settlement in layered clayey soil by utilizing the PLAXIS 3D finite element modeling software. The study aims to quantify how this foundation design can enhance the load-bearing capacity and minimize differential settlement in such soil conditions.

1.4.2. Specific Objectives

1. Investigate the effect of varying raft thicknesses in un-piled and piled raft foundations on settlement reduction.
2. To evaluate the extent to which piled raft foundations improve the settlement properties of the soil under heavy structural loads.
3. To determine the optimum pile length and spacing for piled raft foundations in layered soil.
4. Analyze the impact of variations in pile length, spacing, and raft thickness on settlement characteristics in piled raft foundations, using numerical model parameters for comparison.

1.5. Significance of the study

A piled raft foundation allows carrying super structural loads with restrained settlement. Piled raft foundations are significant because they combine the benefits of both raft and pile foundations, offering a cost-effective and efficient solution for supporting structures, especially in challenging soil conditions. They reduce overall settlement, minimize differential settlement, and thereby bearing capacity become significantly improved. This makes them particularly useful for high-rise buildings and structures built on soft or unstable soil. By acknowledging this contribution, the overall length of the piles may be considerably reduced. In addition to this primary importance, the study also explores critical parameters of the foundation, such as pile diameter, number of piles, spacing, and raft thickness, which all influence the performance of piled raft foundations. Through numerical model tests, this study offers valuable insight into the settlement behavior of rafts on settlement-reducing piles. Upon completion of this thesis, companies constructing high rise building especially on weak or layered clayey soil should be benefited from reduced foundation cost. And also they get insight about design and construction of piled raft foundation. This study enhances the design of piled raft foundations by exploring critical parameters, demonstrating cost-efficiency, and providing insights into settlement behavior for high-rise buildings on weak soils.

1.6. Scope and limitation of the study

1.6.1. Scope of the study

Basically the study focuses application of piled raft foundation in layered clayey soil for settlement reduction analyzed using Plaxis 3D numerical model. Hence, in order to achieve the objectives of the research purely numerical analysis method was followed. A uniformly distributed vertical load that acted on the foundation system was the only consideration in the parametric study of pile raft foundation as a displacement control on layered soil found in Addis Ababa. For this study, no further fieldwork or lab testing was conducted; instead, all relevant information was gathered from the design office and different literature. The study focused solely on static load analysis. In this study the effect of dynamic load such as vibration and seismic loads were did not considered. Finally by using the optimum amount in terms of number, length, L/D ratio of pile and varying raft thickness inside the soil volume; analysis of settlement reduction properties using plaxis 3D numerical model were carried out both before and following the inclusion of pile. Finally, the results and findings of the research will be analyzed, organized and presented.

1.6.2. Limitation of the study

- In this study, the effect of using a piled raft foundation for settlement reduction was examined using a numerical model such as PLAXIS 3D. However, if a fully functional model testing laboratory were available, conducting laboratory tests would provide valuable comparative data.
- Due to limited data and time constraint, this study did not consider the effects of dynamic load, lateral load, and eccentricity. Future research should incorporate the effects of dynamic load, lateral load, and eccentricity to provide a more comprehensive understanding of piled raft foundations.
- In this study, small raft sizes with a constant number of piles and pile diameter were modeled. Future studies should use larger raft foundations and vary pile diameter and number to better investigate their effects.

1.7. Thesis organization and outline

This thesis comprises five chapters. The first chapter serves as the introduction, outlining the study's background, problem statement, objectives, and the scope and limitations of the research. The second chapter presents a literature review, focusing on the theoretical framework and the application of piled raft foundations for managing heavy structural loads and reducing settlement, particularly in clayey soils. It covers the concept of piled raft foundations as a mechanism for improving soil settlement, the design philosophy and considerations for piled raft techniques, methods of analysis, the settlement reduction capabilities of these foundations, parametric studies, finite element modeling, soil distribution in the study area, and identifies existing research gaps. The third chapter details the methodology, including the input parameters for subsoil, raft, and pile materials, as well as the suggested constitutive behaviors governing these elements. A brief overview of the numerical model employed in the study is also provided. The fourth chapter focuses on presenting, analyzing, and interpreting the results, discussing the behavior of piled raft foundations constructed on layered soils through full-scale three-dimensional finite element analyses using Plaxis 3D. Finally, the fifth chapter concludes the study with findings and recommendations based on the numerical analysis, followed by a list of references.

CHAPTER TWO

Literature review

2.1. Introduction

A proper foundation is essential for structures to stay stable, safe, and long-lasting. The foundation provides stability, distributes the weight of the building, and protects it from the effects of the environment. A well-designed foundation ensures a building's structural integrity and prevents costly repairs. It is important to consider several factors when choosing a foundation type for a building, such as soil conditions, building load, and site-specific factors. Foundation depth is influenced by soil bearing capacity, water table level, and nearby structures. Moreover, the type, height, and seismic activity of the structure also influence the decision-making process. When designing foundations, a geotechnical engineer considers shallow foundations to support simple structures. In cases where the structure's weight increases and the soil bearing capacity compromises the structure's stability, other foundation types must be considered (Da Fonseca et al., 2012). Rajapakse, R. (2015) stated that raft and pile foundations are used to handle heavy loads and uneven soil conditions in construction. Raft foundations are a good choice for evenly distributing building loads when soil pressure is low or building loads are high, making them more cost-effective than spread footings in these cases. However, he explained that they may not be enough to prevent settlement. For situations with weak bearing layers and uneven loads, deep pile foundations are more suitable, as they transfer loads to deeper, more stable soil layers.

In conditions with low bearing capacity and substantial settlements, piles are an effective solution. Pile caps are commonly used to connect the pile heads when designing piles for foundation support. The pile cap is designed solely for structural capacity. However, the pile cap also impacts the foundation system beyond just connecting pile heads and load transfer. Various studies have confirmed the important contribution of soil support under the pile cap, even in soils with low support capacity, as observed by several authors (V.R.P. Koteswara *et al.,* 2020, A.O. Alshenawy *et al.,* 2016). According to Garcia, J. R. et al. (2024), the role of the pile cap becomes especially important if the cap is in direct contact with the foundation soil.

Katzenbach et al. (2005) emphasized that the challenges associated with either raft or pile foundations can be avoided by using a combined pile-raft foundation (CPRF) system, which merges both types of foundations for more cost-effective and efficient results. A piled raft foundation was first designed by Zeevaert (1957) for Mexico City's Latino Americana tower in 1957. According to Parmar (2025), pile raft foundations combine the advantages of pile foundations with raft foundations, and are increasingly used for structures requiring high load capacity and settlement control, especially in challenging soil conditions. Their advantages over traditional pilings and raft foundations include load distribution, settlement reduction, and cost-effectiveness in high-rise buildings, bridges, and offshore structures.

2.2. The concept of piled raft foundation

The use of piled rafts is increasing to support different types of heavy infrastructure facilities. Essentially, piled raft foundation relies on both piles and raft for load transfer. The effectiveness of a piled raft foundation depends on a robust system design based on soil conditions. D.K. Malviya et al. (2023) found that a piled raft system performs most efficiently when the capacities of its component elements are fully utilized. Moreover, they stated that in a piled raft system, the raft mainly acts as a bearing element, mobilizing its capacity through interaction with the soil underneath. This bearing interaction is most effectively mobilized when the soil at shallow depths has sufficient stiffness. When the surface soil profile is relatively stiff clay or dense sand, a piled raft foundation provides adequate load capacity (D.K. Malviya et al, 2023).

As a result of combining piles and rafts, this innovative approach enhances load-bearing capacity and reduces settlement over either element alone. This foundation solution, particularly when soil conditions are tough, distributes load between piles and rafts, resulting in a more cost-effective and efficient solution. As stated by Burland et al (1977), pile rafts provide an effective method of minimizing settlements and differential settlements, improving the bearing capacity of shallow foundations, and reducing bending moments on rafts in an efficient manner. Piled rafts are characterized by complex soil-structure interactions between structure, piles, rafts, and subsoil. In traditional foundation designs, either the raft or piles carried the entire load. Instead, piled raft foundations carry the entire load, at either end of the foundation. This approach involves integrating the piles and rafts together, considering their combined interaction as a means of ensuring the structure's stability and managing settlements. In this way, piles can be used more efficiently, potentially exceeding their individual design capacities.

Nguyen D. et al. (2013) highlighted the importance of the stiffness of both the raft and piles, and their relative stiffness, when describing piled raft foundations. Load bearing capacity and settlement characteristics of the foundation are significantly influenced by pile-raft interaction between the raft and piles. A study by Kacprzak, G. M. et al. (2024) found that there were four types of interactions between piles and rafts: pile - pile, pile - raft, pile - soil, and raft - soil. Figure 2.1 also clearly shows the interaction that developed in piled raft foundations.

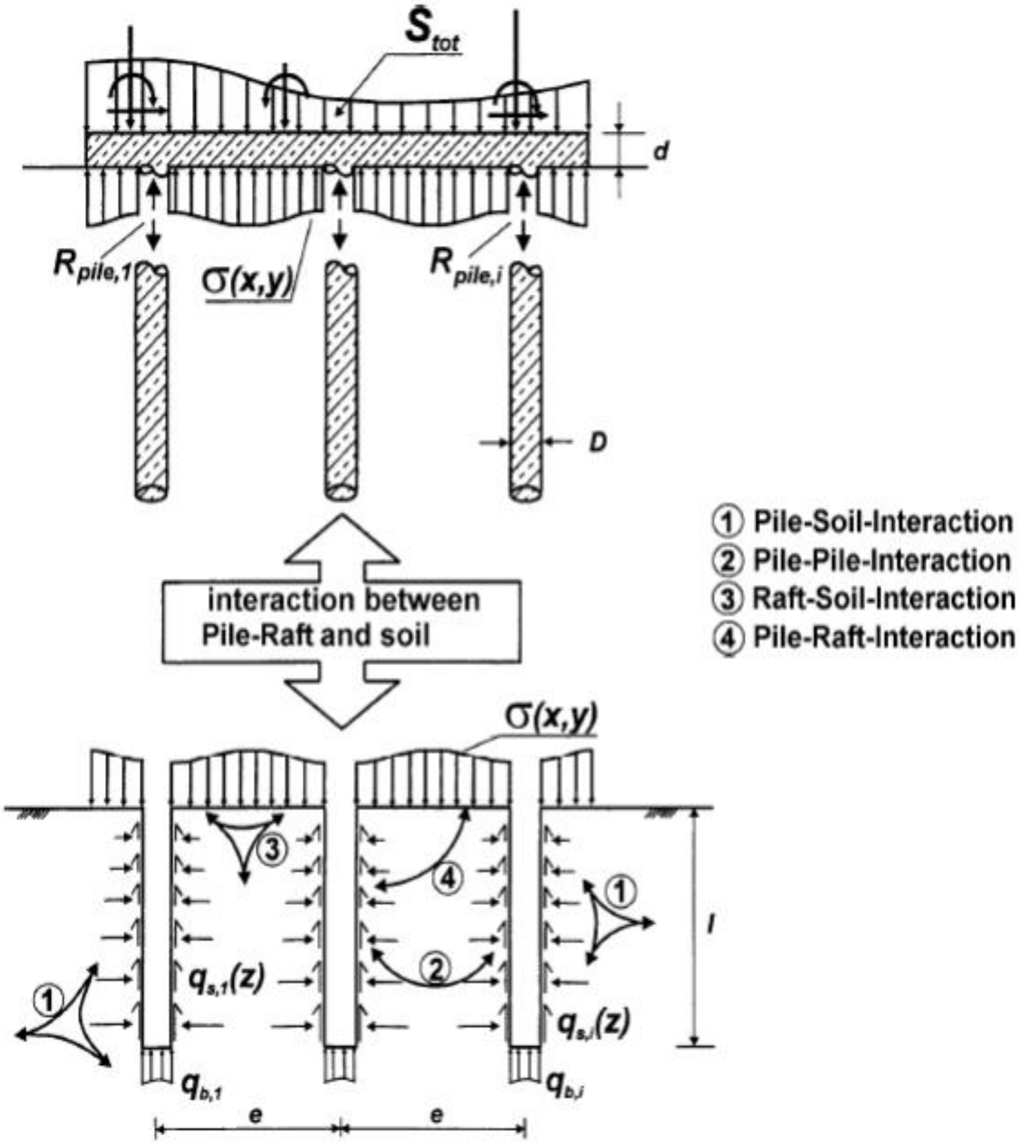


Figure 2.1: Interactions between pile, raft and soil in a piled raft foundation (Kacprzak, G. M. et al., 2024)

A pile-soil interaction occurs when the soil surrounding a pile under load affects its capacity and how the load is distributed among piles or the raft. A pile-pile interaction occurs when loads are transferred from one pile to another, affecting the capacity and transfer of loads. The raft-soil interaction is the interaction between the soil and the raft of a piled raft foundation, affecting the magnitude and distribution of loads transferred to the piles as well as the settlement behavior of the foundation. As the piles and the raft interact within a piled raft foundation, it affects the load distribution inside the foundation, the pile's capacity, and the settlement behavior of the foundation.

2.2.1. Function of piles in piled raft foundation

Pile foundations can lead to significant cost savings without compromising foundation performance or safety. According to Fleming K. et al. (2008), the stress applied to the subsoil medium from the raft increases the confining pressure for the piles under the raft, ultimately improving the load bearing capabilities. Additionally, these piles maintain good stiffness of the foundation, reducing settlement and increasing the capacity of piled raft systems (Fleming K. et al., 2008). As a result, piled rafts require fewer piles than pile groups to satisfy the same capacity and settlement demands. The figure below shows a typical configuration of different foundation systems subjected to superstructure, wind, and earthquake loads. According to Figure 2.2, in raft foundations (Figure 2.2.a), the load coming from the superstructure is transferred to the subsoil through contact pressure held between the raft and soil.

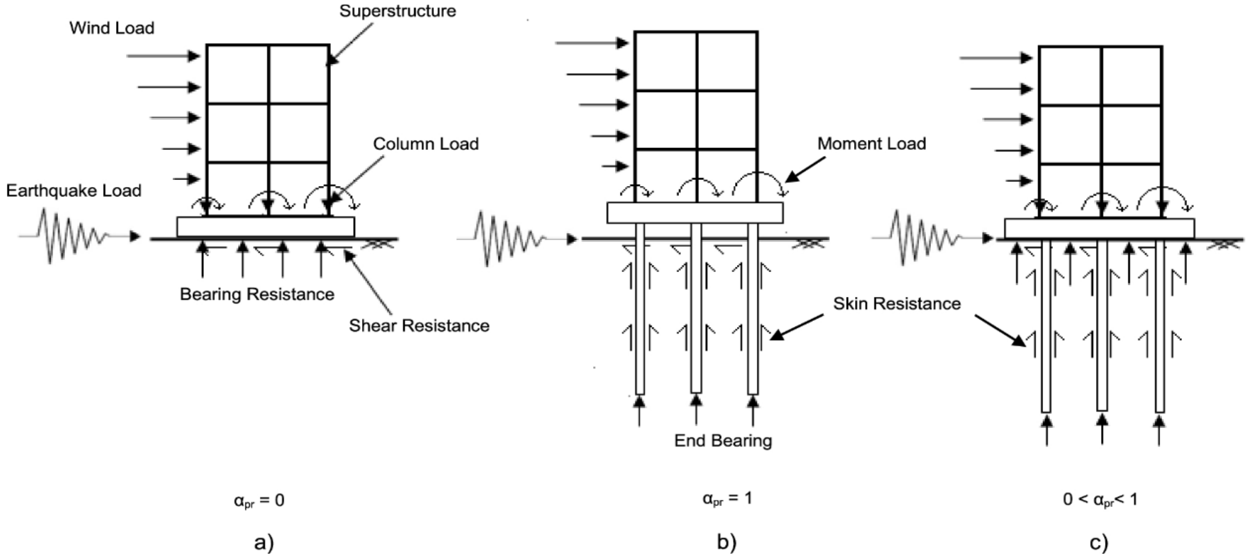


Figure 2.2: Typical configuration of a) unpiled raft; b) pile group; c) piled raft (D.K. Malviya et al, 2023)

A typical pile group (Figure 2.2.b) does not allow the raft to come in contact with soil, and the load bearing behavior of the raft part is not considered in the design process. According to Tomlinson et al. (2007), in a standard pile group, the entire load is transferred to the soil via frictional resistance and the end bearing properties of the piles. In contrast, in a piled raft system (see Figure 2.2.c), the total load is shared between the raft's bearing resistance and the skin friction and end bearing of the piles, creating complex interactions between the soil, piles, and raft. In traditional designs for piled rafts, the pile group typically bears most of the load, while the raft is designed to contribute to load distribution. In this approach, the additional piles serve as bearing members that enhance the raft's bearing capacity. Piles are strategically positioned under areas of heavy load and across the central part of the uniformly loaded raft to minimize localized deformations and reduce differential settlement across the system. Thus, piles not only function as settlement reducers but also enhance the overall load-bearing capacity of the foundation. Table 2.1: shows the summarized different function of pile in piled raft foundation system.

Table 2.1: Function of pile in piled raft foundation (D.K. Malviya et al, 2023)

Property	**Pile function in piled raft sytem**
Bearing Capacity	Piles under the raft enhance the load-bearing performance of the foundation system
Maximum contact pressure	Piles can be effectively utilized if the maximum contact pressure beneath the raft surpasses the permissible design limit for the soil
Application	Piles in a piled raft are suitable when the local settlement beneath the superstructure exceeds the acceptable limit.
Efficiency	Piles in a piled raft are effectively utilized when the maximum moment in the raft, resulting from the column loads of the superstructure, surpasses the permissible limit for the raft.

2.3. Mechanism of piled raft foundation

A piled raft foundation is a practical and cost-effective solution for heavy and tall structures, which usually experience a combination of vertical, lateral, and moment loads due to the vertical self-weight of the foundation system, superstructure, soil fill, and surface surcharge (Chanda D. et al., 2017). A study by Katzenbach, et al. (2000), found that the response of the piled raft, as a result of its interaction with soil, piles, and rafts, is complex and multifaceted. They also pointed out that the load-carrying and settlement responses to piled rafts are different from the individual responses to piles and rafts, since piled rafts respond differently to load and settlement. Additionally, they suggested that the total resistance of the foundation (Rtot) must not be less than the total load of the superstructure (Stot). As a result, the foundation's resistance can be calculated by adding the resistance of all piles together with the resistance of the raft (Rraft). It is expressed as follows (Katzenbach, et al., 2000):

$$R_{tot} = R_{raft} + \sum_{i=1}^{n} R_{pile,i} \geq S_{tot} \quad \text{……………………………………………...2.1}$$

Where: $\sum_{i=1}^{n} R_{pile.i}$ is the sum of all pile resistance

According to Garcia (2018), in a piled raft foundation system, the load distribution across piles and rafts is represented by using a coefficient α_{pr} and it is expressed as follows (eqn 2.2):

$$\alpha_{Pr} = \frac{\sum_{i=1}^{n} Q_{pile,i}}{Q_{Pr}} \quad \text{…………………………………………………………….....2.2}$$

Qpr and Qpile,i, represent the total load applied to the piled raft and the total load absorbed by ith pile, respectively, while α_{pr} represents the part of the total load carried by piles. Raft foundations with $\alpha_{pr} = 0$ and pile foundations with $\alpha_{pr} = 1$. The piled raft lies in the range $0 < \alpha_{pr} < 1$. In a piled raft foundation system, conventional rafts and piled foundations can be considered the limiting cases.

2.4. Load settlement response of un-piled and piled raft foundation

Based on considering different types of design philosophies the load settlement response of both unpiled and piled raft foundation investigated as per Poulos H.G. (2000) is as shown in figure 2.3. According to the figure, Curve C_{UPR} shows the response of the unpiled raft. At the design load, the raft settles excessively as shown by the C_{UPR} curve from figure below. Curve $C_{1,PR}$ represents the conventionally designed piled raft, in which the piles act primarily as bearing members and a significant portion of the design load is carried by the piles. A creep piling is represented by curve $C_{2,PR}$ in which piles operate at 70–80% of their ultimate load capacity. Compared to the conventional design of piled rafts, the raft contributes more to load sharing in this design philosophy. Based on design loads, curve $C_{3,PR}$ shows the nonlinear response of a piled raft using piles as settlement reducers. Additionally, the complete utilization of the load capacities of both the piles and the raft makes this design more cost-effective compared to the design methods presented in C1, $_{\mathrm{PR}}$, and C2, $_{\mathrm{PR}}$.

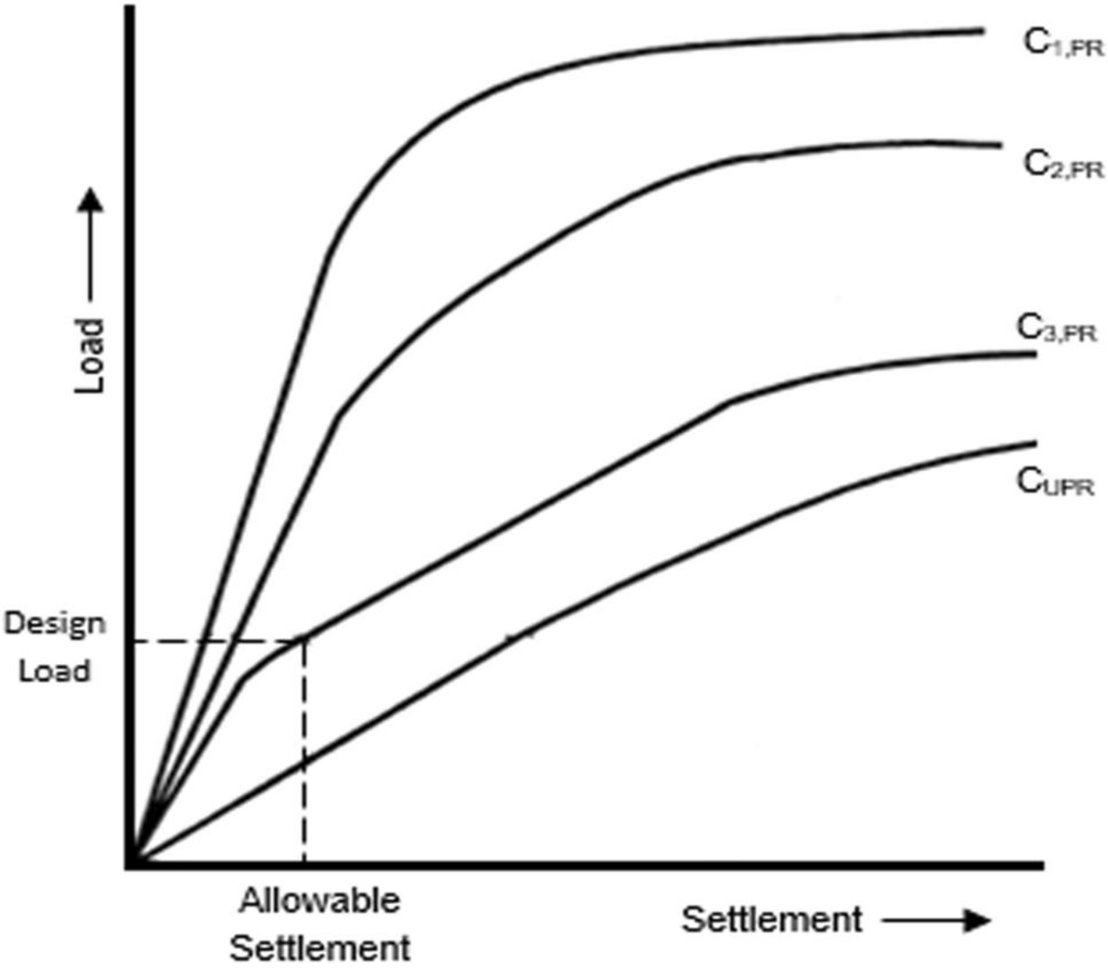


Figure 2.3: Load settlement curve both for un-piled and piled raft foundation (Poulos H.G., 2000)

2.5. Settlement estimation of piled raft foundation

According to D.K. et al. (2023) piled raft foundations are designed to reduce settlement, especially in situations where a raft alone might experience excessive settlement. While piles are primarily used to reduce settlement, they can also carry some of the load. Determination of both total and differential settlement of piled raft foundation for long term performance of the provided superstructure is significantly important. Piled raft foundation settlement behavior depends on various factors, including the loading condition, pile spacing, raft and pile geometry, relative stiffness between raft and soil, and pile arrangement schemes.

Elwakil A. Z. (2016) examined how various parameters—such as loading conditions, pile spacing, raft and pile geometry, the relative stiffness between the raft and subsoil, and pile arrangement—affect the settlement behavior of piled rafts through both numerical and experimental investigations. Their findings suggest that increasing the number of piles leads to a reduction in the settlement of the pile-raft system. Yang J. (2019) further indicated that uniformly distributed piles beneath the raft significantly help minimize differential settlement in piled rafts. Sinha A. et al. (2017) noted that the impact of confinement within the pile group diminishes at approximately 6D pile spacing in cohesive soils and between 6–12D spacing in cohesionless soils. They also found that closely spaced piles under column loads effectively decrease both total and differential settlements in piled raft foundations. Chow YK (1987) found that the average settlement of piled rafts decreases as pile length and spacing increase while keeping the number of piles constant. Additionally, differential settlements in piled rafts are reduced with an increase in soil stiffness. Increasing the raft thickness and raft–soil stiffness ratio results in decreasing differential settlement but is found to increase the average settlement of the pile–raft system (El-Garhy B.2013, Patil J.D.2016).

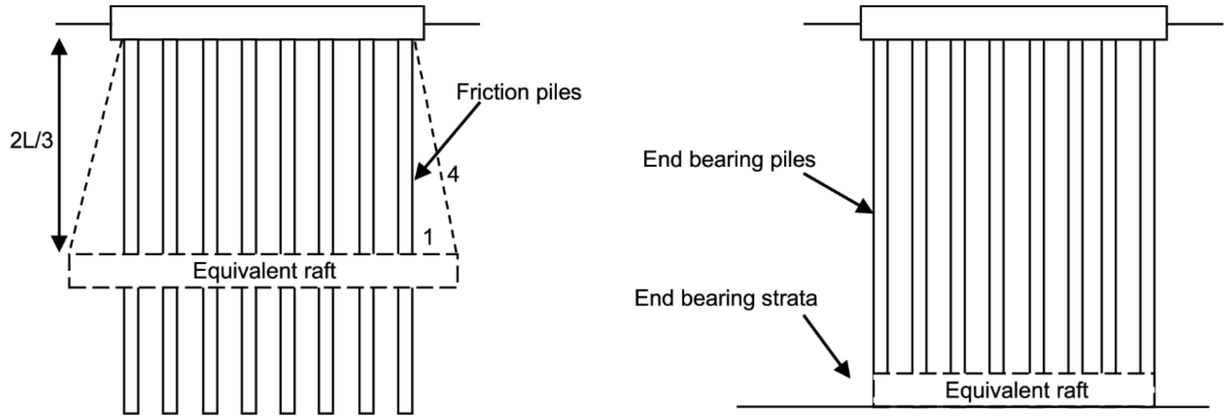
2.6. Methods of settlement estimation for piled raft foundation

The settlement assessment of piled rafts is complicated due to the interaction among foundation elements and the variability of their stiffness. Total and differential settlements of pile-rafts are calculated and compared to the allowable limits during the design process. Various approximate methods exist for estimating the settlement of pile raft foundations. This section reviews different approximate techniques for estimating piled raft settlement. Several approaches can be employed to estimate the settlement of piled raft foundation systems, including analytical, numerical, and empirical methods. These methods consider the intricate interactions among the raft, piles, and soil, encompassing both the pile-soil interactions and the raft-soil interactions. It has been suggested that the piles and raft can be viewed as springs that interact, or that it can be viewed as an equivalent pier (Phung L., 2016).

2.6.1. Equivalent raft method

As a result of the equivalent raft method, pile raft foundation settlement analysis is simplified by replacing the pile group and surrounding soil with an equivalent raft. By doing this, settlement calculations can be done using standard raft foundation methods, but with parameters adjusted for pile-soil interaction.

According to N. T. Dung et al. (2010), the equivalent raft method is primarily used to estimate the settlement of pile groups in homogeneous and layered soils. It was also discovered that this method can be used to estimate the initial settlement of rigid piled raft foundation systems. As illustrated in Figure 2.4, the equivalent raft method involves substituting the pile group supporting the raft with an equivalent raft positioned at two-thirds of the embedded length for friction piles and at the pile base for end-bearing piles.



a) Friction pile group **b) End bearing pile group**

Figure 2.4: Load sharing and settlement behaviour of piled raft foundation using equivalent raft approach (Randolph M.F., 1994)

According to Randolph MF (1994), this method is limited in its ability to calculate differential settlement in the foundation system because it uses average settlement estimation for the piled raft foundation system. Additionally, they found that the average settlement at ground level (wav) is the sum of raft settlement (wraft) and pile elastic compression above the equivalent raft level (Δw). And determination of average settlement as per equivalent raft method is given as equation below (Randolph M.F., 1994):

$\omega_{av} = \omega_{raft} + \Delta_{\omega}$…………………………………………………………………...2.3

Under this method, a rigid raft is uniformly loaded with piles of uniform distribution and geometric properties. N.T. Dung et al. (2010) investigated that this method has the advantage of taking into account soil stiffness variations below the raft level. It is especially relevant when there is a layer of softer soil beneath the pile base. A piled raft with end bearing piles mobilizes the load of the foundation system through end bearings with little contribution from raft or pile friction in load sharing; therefore, piled rafts with end bearing piles are rare on a real construction site. Furthermore, the method provides total settlement rather than differential settlement for piled raft systems. Also, this method does not consider the flexibility of the raft in settlement estimation and is only applicable for rigid piled raft systems (N. T. Dung et al, 2010). However, Poulos H. G. (2000) identified that using the equivalent raft approach methods to determine settlement tends to significantly overestimate settlement when dealing with a relatively small number of piles. He also noted that the method does not account for changes in soil stress around the piles resulting from raft-soil interaction, which is a limitation. Nonetheless, the method provides a reasonable estimate of the initial settlement of the pile-raft system when the piles are frictional and possess uniform geometry, stiffness, and spacing across the raft. Additionally, this method is more suitable when settlement reducer or creep piling design philosophies are followed for piled raft foundations (Poulos HG (2000).

2.6.2. Poulos-Davis-Randolph (PDR) method

This method includes estimating the load sharing between the raft and the piles and hyperbolic load-deflection relationships for the pile and the raft (Poulos H.G., et al, 1980, Randolph M.F., 1994). According to Poulos H.G., et al (1980), hyperbolic load settlement provides a more realistic overall response to load settlement.

A typical load settlement response of piled raft system proposed by is as shown in Figure 2.5. Figure 2.5, confirms that up to point A the pile capacity has become fully mobilized and the load applied (P_A) to the piled raft system is shared by the pile and raft. The settlement (SA) at this point is determined as follows (Randolph M.F., 1994):

$$S_A = \frac{P_A}{K_{Pr}} \qquad \text{..2.4}$$

Where: $\boldsymbol{K}_{\mathbf{pr}}$ is the stiffness of piled raft systems.

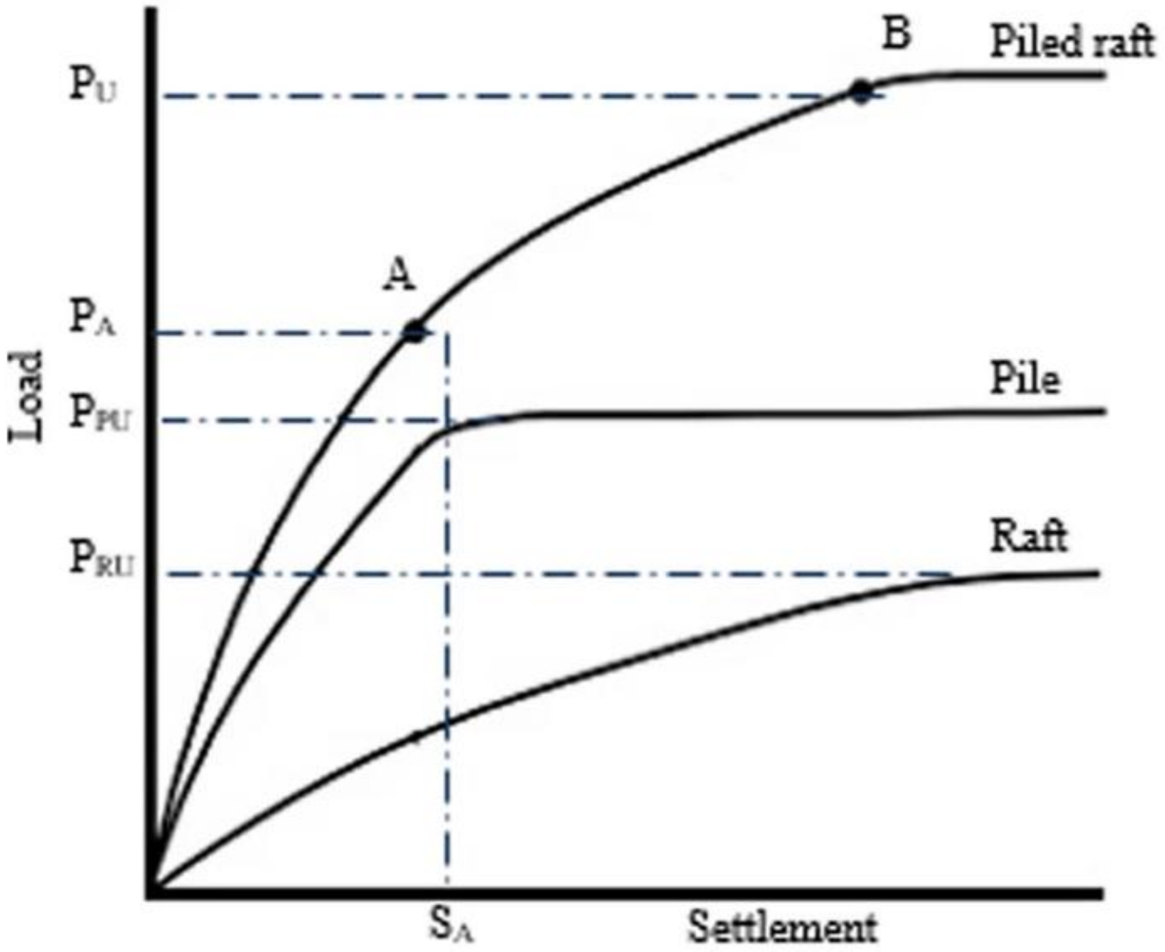


Figure 2.5: Load settlement curve for piled raft (Poulos H. G., 2000)

Nguyen et al. (2013) used the load settlement response of a single pile and an unpiled raft to determine the stiffness of the pile and raft, respectively. They combined these stiffnesses with pile–soil–pile and pile–soil–raft interaction factors to calculate the pile–raft stiffness factor. After point A, the load increment (P–PA) on the piled raft is carried solely by the raft, with the pile acting as a settlement reducer. The settlement (S) of the piled raft after point *A* is estimated based on equation 2.5 as given below (Nguyen et al., 2013):

$$S = \frac{P_A}{K_{Pr}} + \frac{P - P_A}{K_r} \quad \text{………………………………………………..2.5}$$

According to Nguyen et al. (2013) the design load for piled raft (P_A) at the ultimate capacity of the pile (P_{PU}) and pile–raft stiffness (K_{pr}) can be determined using the following equation:

$$P_A = \frac{P_{Pu}}{\beta_P} \text{ and } K_{Pr} = XK_P \quad \text{……………………………………….2.6}$$

X represents the proportion of pile stiffness contributing to total piled raft stiffness, and Ɓp depicts the proportion of load carried by piles in a piled raft system. As described by Randloph (1993), the approximate expression can be used to estimate factors as follows:

$$X \approx \frac{1-0.6(K_r/K_p)}{1-0.64(K_r/K_P)} \qquad \text{2.7}$$

$$\beta_P = \frac{1}{(1+\propto)} \qquad \text{2.8}$$

$$\alpha = \frac{0.2}{1-0.8\left(\frac{K_r}{K_P}\right)}\left(K_r/K_p\right) \qquad \text{2.9}$$

If the piled raft system exhibits hyperbolic behavior, the secant stiffness of the piles (Kp) and the raft (Kr) is expressed as follows (Randloph, 1993):

$$K_P = K_{Pi}(1 - R_a\, P_P/P_{PU}) \qquad \text{2.10}$$

$$K_R = K_{Ri}\left(1 - R_{fR}\, P_R/P_{RU}\right) \qquad \text{2.11}$$

where K_{pi} is the initial tangent stiffness of the pile group; R_{fp} is the hyperbolic factor for the pile group; P_p is load carried by piles; P_{pu} is ultimate capacity of piles; K_{ri} is initial tangent stiffness of raft; R_{fr} is the hyperbolic factor of the raft; P_r is load carried by raft; and P_{ru} is ultimate capacity of the raft. This approach is limited to considering uniformly loaded, perfectly flexible, and perfectly rigid rafts. It can be used to estimate the average load settlement relationship for piled rafts, but not differential settlements. The creep piling design philosophy of piled raft analysis is applied to this method, which utilizes the total capacity of the piles (D.K. Malviya et al., 2023).

2.6.3. Equivalent pier method

The equivalent pier method simplifies pile group analysis by representing them as a single, equivalent pier. By treating the pier as a single unit with equivalent stiffness and load displacement characteristics, this approach simplifies calculation of pile group behavior, particularly settlement (Rotta et al., 2017). Horikoshi K. et al. (1999) described the equivalent pier method as an easy method for determining pile stiffness, which is useful for estimating settlement of rigid piled raft foundation systems. As shown in the Figure 2.6, this method replaces each pile with a pier of equivalent diameter (deq), of equal length (Horikoshi K. et al., 1999).

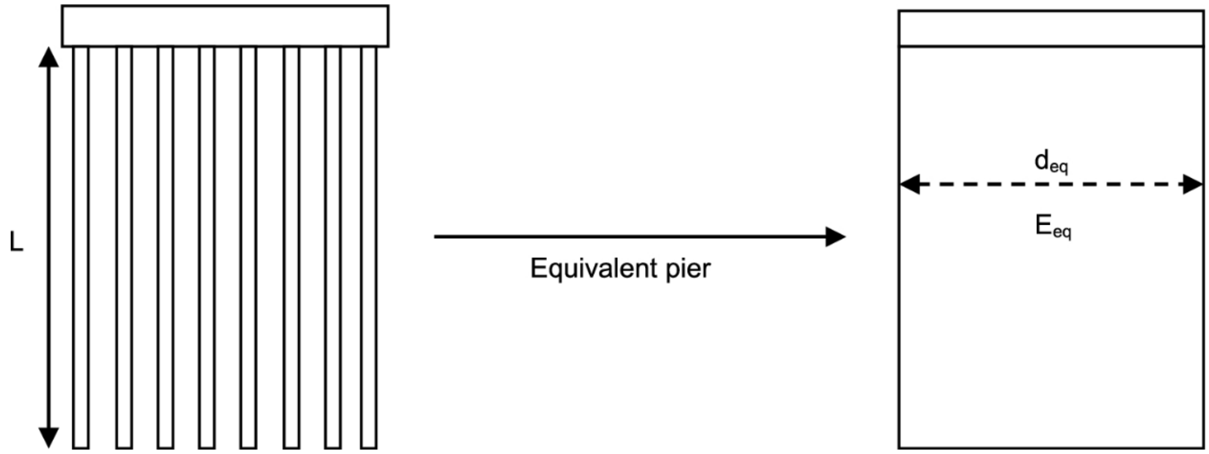


Figure 2.6: Load sharing and settlement behaviour of piled raft foundation using equivalent pier approach

Moreover, the equivalent diameter of the pier for friction piles (d) and end bearing ($d_{e,\ \mathrm{eb}}$) determined as per Rotta et al (2017) is as shown below:

$$d_{e,f} = 1.27A_G^{0.5} \quad \text{...........} 2.12$$

$$d_{e,eb} = 1.13A_G^{0.5} \quad \text{...........} 2.13$$

According to Rotta et al. (2017) the plan area of the pile group (A_G) is the summation of the total cross-sectional area of piles (A_P) and the plan area of soil (A_{soil}) surrounding the piles and the relation among them is as shown below:

$$A_G = A_P + A_{soil} \quad \text{...........} 2.14$$

In equivalent piers, the Young's modulus of the pile (Ep) and the soil (Es) are effectively homogenized. Following are the steps for calculating Eeq (Rotta et al, 2017):

$$E_{eq} = E_P\left(\frac{A_P}{A_g}\right) + E_s\left(1 - \frac{A_P}{A_g}\right) \quad \text{...........} 2.15$$

Randolph M. (1994) concluded that this method is suitable for estimating settlement on uniformly loaded rigid foundations with small pile groups. In addition, the equivalent pier approach may be applied for piles with a large number of piles by replacing the full pile group with a set of equivalent piers. The study found, however, that this method is only suitable for estimating the average settlement of piled rafts with unequal lengths.

2.6.4. Settlement ratio method

In the settlement ratio method, the settlement of a pile group is estimated by comparing it to the settlement of a single pile under similar loading conditions. Basically, the settlement of a single pile is multiplied by the group settlement ratio (Rs) that accounts for pile interactions (Poulos H.G., et al., 1980). According to Zhang Q et al (2012) this method is useful in estimating the settlement of piled rafts having rigidly attached rafts with symmetric pile groups. They also stated that in this method, a single pile (δ_{single}) settlement at the average load level is multiplied by a factor R_s to estimate the pile group settlement (δ_{group}) and the relation among them is as shown below:

$$\delta_{group} = \delta_{single} R_s \quad \text{2.16}$$

This method is primarily suited for the conventional piled raft design approach, where the piles serve as bearing elements, supporting a significant portion of the total load with minimal contribution from the raft, and are evenly spaced across the entire raft. It calculates the overall settlement but does not address differential settlement. The method is quick and facilitates straightforward settlement estimation for the initial design (Zhang Q et al., 2012).

2.7. Load sharing behaviour of piled raft foundation

Piled raft foundations distribute the load between the raft and piles based on soil properties, pile length and number, and raft stiffness. This interaction allows for a more efficient and cost-effective foundation design compared to using either piles or a raft alone.

The piled raft foundation system consists of multiple piles and a raft, each with different geometries and load-carrying capacities, resulting in uneven load sharing when subjected to the superstructure's load. Cho J et al. (2012) observed that the load sharing between the piles and the raft in a piled raft system varies under these conditions. They defined the load sharing ratio of the pile (LSRP) as the proportion of the load carried by the piles to the total load on the foundation, and the load sharing ratio of the raft (LSRR) as the proportion of the load supported by the raft to the total load.

Various parameters such as pile length, diameter, number, spacing, stiffness, and the raft's thickness and stiffness significantly influence load sharing in a piled raft system (Cho J et al., 2012). Additionally, Kwon O et al. (2006) found that the load-settlement behavior of the piled raft is similar for point and uniform loading in soft clays, with only minor differences observed in stiff clays. The pile's ultimate capacity is mobilized much earlier, contributing to load sharing until this point, after which the raft bears the remaining load until it reaches its ultimate capacity (Kwon O et al., 2006).

2.7.1. Approximate Computer based Method

To accurately predict settlement and load sharing for a specific pile arrangement, raft dimensions, loading conditions, and soil profile, numerical methods with suitable modeling techniques and reliable parameters can be employed. These numerical analysis methods are effective in addressing a range of piled raft issues. Several computer programs, including GRUPPALO, GARP (Geotechnical Analysis of Raft with Piles), GASP (Geotechnical Analysis of Strip with Piles), NAPRA (Nonlinear Analysis of Piled Rafts), PRAB (Piled Raft Analysis with Batter Piles), and HyPr, are commonly used for the settlement analysis of piled raft systems. Mandolini and Viggiani (1997) used GRUPPALO, a boundary element method-based computer code, to analyze pile groups and free-standing piled rafts. Russo et al. (2013) used GARP and NAPRA for the settlement analysis of Burj Khalifa. GARP employs a plate-on-spring approach to analyze piled rafts.

During investigation, they assumed that the raft, pile, and soil are represented as elastic plates, interacting springs, and elastic continuum, respectively. This method is applicable to both flexible and rigid rafts and to homogeneous and layered soil profiles. Moreover, they concluded that this method allows for applying uniform and point loads on the raft. Poulos (1991) used a strip-on-springs approach to analyze piled raft foundations. The raft is modeled as a strip, and supporting piles are modeled as springs. This approximate method provides reasonable agreement with other methods in settlement estimation of piled raft foundations. Its limitation is that it cannot consider the moments in the raft. NAPRA computes the behavior of piled rafts subjected to any combination of uniformly distributed or concentrated loads and moments (Russo et al., 1998). PRAB is based on elasticity theory and has been used for axially and laterally loaded piled raft foundations in both heterogeneous (Kitiyodom P. et al., 2003) and homogeneous (Kitiyodom P. et al., 2002) soil media. Clancy (1993) developed a computer code, HyPr, for a flexible piled raft on homogeneous soil of finite depth. This method considers the complex interactions between the piled raft components and can estimate both average and differential settlements.

2.7.2. Rigorous Computer – based Method

A computer-based approach, particularly Finite Element Method (FEM) and Finite Difference Method (FDM), provides a powerful tool for analyzing piled raft foundations, enabling more detailed and accurate design optimization. To simulate the complex interactions between rafts, piles, and soil, Deka et al (2014) used numerical modeling techniques, particularly the Finite Element Method (FEM). Moreover, they found that this approach provided a more accurate representation of foundation behavior under various loading conditions than simplified analytical approaches. Moreover, this method achieves more realistic and accurate results than any other method, making it a suitable option for analysis when precise results are desired (Deka et al., 2014).

Various studies revealed that it is possible to analyze both uniform and non-uniform loading condition of the foundation through using finite element analysis method (Hooper J., 1973, Rabiei M. et al., 2016, Reul O. et al., 2004). Mendonca A.V. et al. (2000) concluded that these analysis techniques are the most effective for determining settlements and load distributions within piled raft foundations. In boundary element method analysis, the raft is modeled as a thin plate element, the soil is represented as an elastic linear homogeneous half-space, and the pile is treated as a single element. Additionally, it has been observed that these numerical methods demand significant computational memory and fast processors, so they should be used judiciously during the initial stages of designing the piled raft foundation.

2.7.3. Software Based Analysis Method

A three-dimensional elasto-plastic finite element method used for the analyses of piled-raft foundations was presented by Reul et al (2003). ABAQUS was used to implement the finite-element analysis. Figure 2.7 shows the structural model based on the finite element method for this analysis.

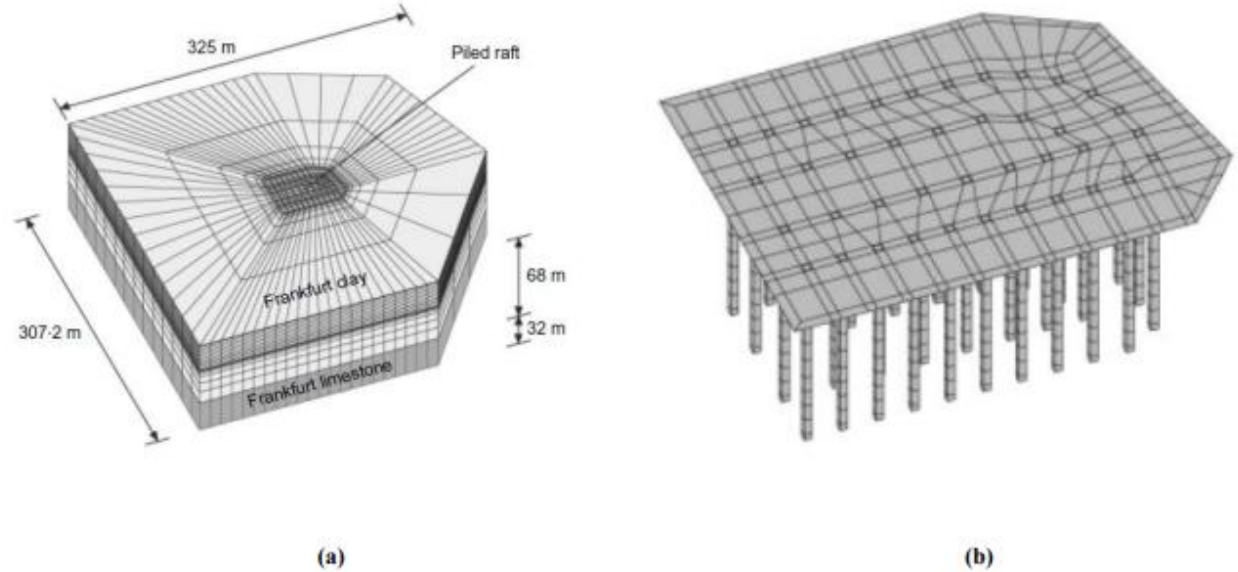


Figure 2.7: A three dimensional PLAXIS software used a) finite element mesh of the system b) finite element mesh of the piled raft foundation system (Reul et al, 2003)

As it is seen from the Figure 2.7, modelling the soil and foundation with finite elements allows the soil-structure interaction to be treated in the most rigorous manner. In this example, the soil is represented by solid brick elements and the piles by wedge elements of first order. A first order shell element of square and triangular shape with reduced integration has been used to model the raft. In the case of soil beneath the foundation level, only finite element models are used. In addition to the foundation level, the weight of the soil above the foundation level is also considered. In place of circular piles, square piles with the same shaft circumference have been installed. Considering drained shear parameters simplifies soil into a one-phase medium instead of a multiphase medium (Reul et al, 2003).

2.7. Factors that affect piled raft foundation

The optimization of a piled raft foundation is clearly influenced by many factors. Jamil et al. (2022) identified that type, stiffness, and density of the soil properties; structural loads, including the magnitude and type of vertical and lateral forces; and foundation design parameters, such as raft thickness, pile number, length, diameter, spacing (S/D ratio), and the specific locations of the piles within the raft are the different factors that affect the overall settlement reduction capacity of the piled raft foundation. Furthermore, the interaction between the piles and the raft, as well as between the piles themselves and the soil, is crucial to determining performance and load sharing.

2.7.1. Raft Thickness

A thin or flexible raft deforms more than a thick or rigid one, increasing contact with the subsoil and thus increasing the reaction force. As a result, the subsoil could undergo significant deformation. In addition to affecting differential settlement, raft thickness also affects maximum settlement and axial forces in pile foundations. In general, as per Tổng et al. (2020) thicker rafts increases the maximum settlement due to the increased self-weight, but also it improves the stiffness of the system, resulting in reduced differential settlement and greater contribution to the total load sharing. The stiffness of the raft according to Alnuaim et al. (2013) could be determined as follows:

$$K_f = \left[E_f/E_s\right]\left(\frac{2t}{s}\right)^3 \quad \text{...}2.17$$

Where: K_f is stiffness of the raft, E_f and Es is rafts young's modulus and average elastic modulus of the soil respectively, t is raft thickness and s is pile spacing

According to the equation (Alnuaim et al., 2013), raft stiffness and raft thickness are directly related. In their study, Alnuaim et al. (2013) classified rafts by their flexibility into three categories: rigid rafts, flexible rafts, and intermediate rafts, depending on the kf values between 0.01 and 10. Based on their flexibility raft can be perfectly rigid (if $k_f > 10$), perfectly flexible (if $k_f < 0.01$), and intermediate flexibility if the k_f values falls between 0.01 to 10. Additionally, they performed centrifugal tests to determine the load carried by the raft for two different pile spacing and various raft thicknesses as a function of total displacement of the piled raft. They observed that at a pile spacing to diameter ratio of 4, the load supported by the raft varied significantly, being approximately 65% and 55% for raft thicknesses of 0.3 m and 2 m, respectively. This difference was caused by a high variation in kf, which was about 0.05 and 2.2 for the two raft thicknesses.

Conversely, at pile spacing to diameter ratio of 10, the values of kf were quite similar, around 0.004 and 0.07 for raft thicknesses of 0.3 m and 1.25 m, respectively, resulting in a narrower variation of about 75% in the load carried by the raft. This occurs because a thicker raft at larger spacing is more flexible, leading to increased interaction between the raft and soil compared to a similar raft with smaller pile spacing (Alnuaim et al., 2013).

2.7.2. Pile spacing

Pile spacing affects pile raft foundations in several ways, such as altering load distribution between piles and rafts, affecting overall settlement, and impacting stiffness of the system. According to Yirsaw et al (2023) with increased pile spacing, more loads is transferred to the raft, resulting in greater raft load sharing, while with more closely spaced piles, the piles take on more load. There is no single optimal spacing for foundations; instead, it depends on soil conditions, desired load distribution, and foundation stiffness requirements. In a study by Alnuaim et al (2013), rafts with small pile spacing experience less deformation at the center than those with large pile spacing. Using a 3x3 group of piles with varying pile spacing, Oh et al (2009) found that settlement increased with increasing pile spacing. The researchers recommended a pile spacing of 2D-3D for further research (Maharaj et al, 2004, Oh et al, 2009). Saif Azhar et al. (2020) investigated the behaviour and performance of the combined piled raft foundation by changing the parameters like pile spacing using SAFE software. For their case studies, when the pile center-to-centre spacing is varied from 2.5D to 6D, which are 0.75m to 1.80m, 1.50m to 3.60m, and 2.25m to 5.40m for pile diameters of 0.3m, 0.6m, and 0.9m, respectively, the maximum and differential settlements results are as shown in Figure 2.8.

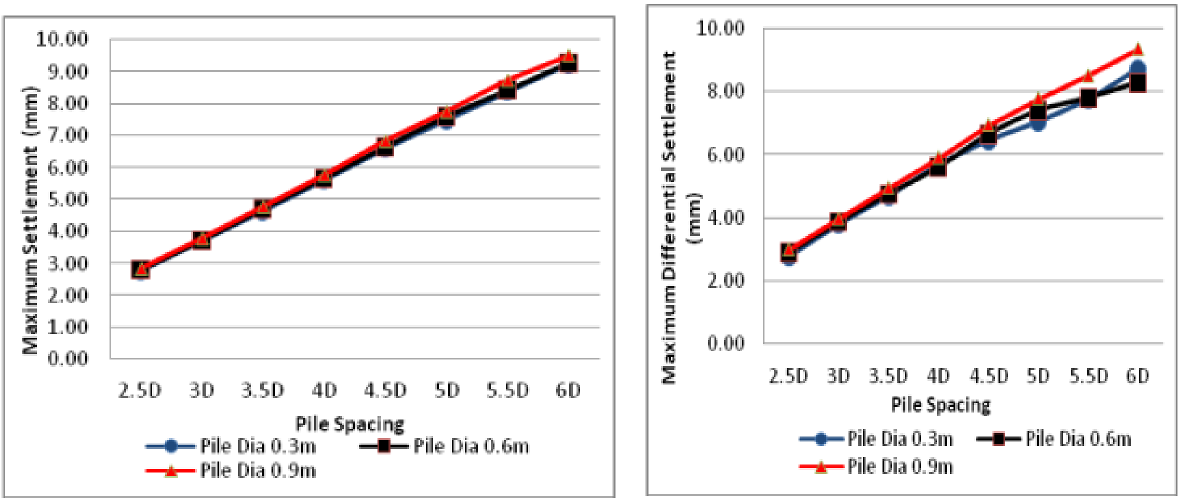


Figure 2.8: Effect of pile spacing on maximum settlement and maximum differential settlement (Saif Azhar et al. 2020)

Figure 2.8 also shows a linear increase in maximum settlement and maximum differential settlement as a result of increasing pile spacing (Saif Azhar et al. 2020). Mali et al. (2021) used Plaxis 3D numerical model to investigate the effect of pile spacing on center settlement ratio for different pile group configurations is shown in Figure 2.9 (a) and (b). Their study shows that with an increase in pile spacing to pile depth ratio (Sp/dp) from 3 to 5, the center settlement ratio decreases for the 4 × 4 configuration. The center settlement ratio decreased as the pile spacing (Sp) increased because of uniform load distribution among the piles. However, for 2 x 2 pile configuration, as Sp/dp ratio increased from 3 to 4, the center settlement ratio remained constant, and thereafter, it decreased at Sp/dp ratio 5.

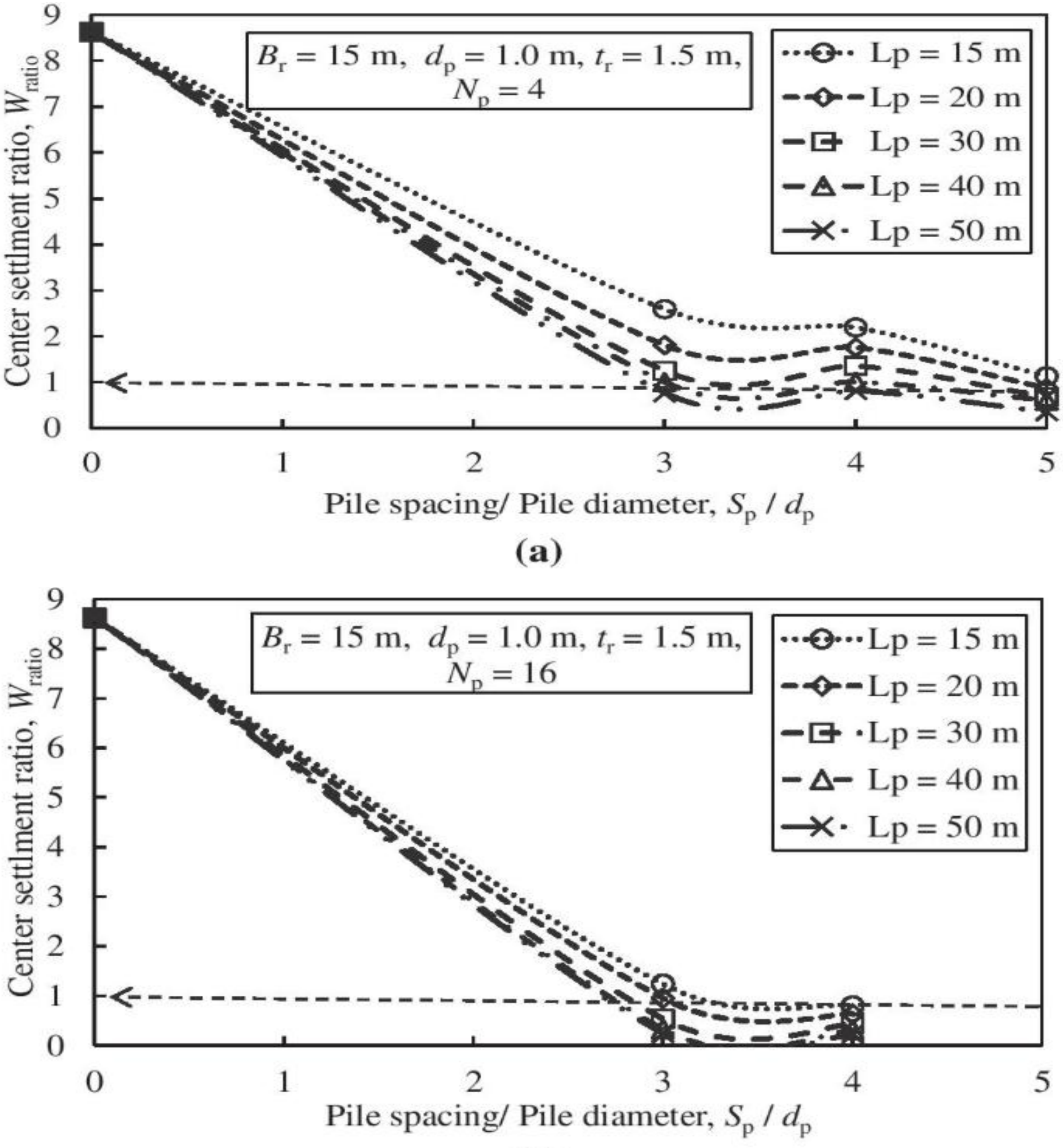


Figure 2.9: Center settlement ratio versus Sp/dp ratio: (a) 2 × 2 pile groups and (b) 4 × 4 pile group

2.7.3. Pile Length

The length of the piles significantly influences the settlement behavior of piled raft foundations. While longer piles generally lead to a decrease in total settlement, they may also result in an increase in differential settlement between the piles and the raft. According to Hoang et al. (2024) increasing pile length in a piled raft foundation it decreases overall settlement, increases load-bearing capacity, and increases the percentage of load carried by the piles, however, it becomes less effective at a point, called the critical depth, after which more increases yield diminishing returns. As a result, the raft's bending moment is reduced, but the shear force was increased. Kumar (2018) found that a non-uniform pile length in a piled raft foundation can meet the minimum settlement requirement. Moreover, he concluded that cost for foundation preparation was significantly reduced due to implementation of piled raft type design approach. Study by Zhang et al. (2012) indicated that the length of piles in piled raft foundations has a substantial impact on load distribution, overall settlement, and differential settlement. Future studies should explore a wider variety of pile lengths and configurations to enhance the effectiveness of piled raft foundations across different soil types and load conditions.

2.8. Review of related literature

A pile raft foundation is composed of piles and rafts, where rafts act as pile caps. In addition to the raft, there are a number of piles that support the raft. Afterwards, the combined assembly is loaded both vertically and laterally. By using rafts and piles, these loads are transferred to the soil. A piled raft foundation system distributes load between the piles and the raft, in contrast to traditional piled or raft foundations where only piles are utilized to minimize total and differential settlements, often overlooking the raft's contribution. In piled raft systems, piles mainly serve to reduce settlement, while load sharing between the piles and raft is of secondary importance. By adjusting various factors such as pile diameter, spacing, length, and raft thickness, the total and differential settlement of the piled raft system can be maintained within acceptable limits. A number of studies have been performed on parametric studies of piled raft foundation while subjected at different conditions:

Reul and Randolph (2004) studied 259 different piled raft configurations using three-dimensional elastoplastic finite element analyses. In this study, the pile positions, number of piles, pile length, and the raft-soil stiffness ratio, as well as the load distribution on the raft, were varied. The parametric study considered square unpiled rafts and piled rafts with an edge length of B = 38 m. Three basic pile configurations were examined. Pile Configuration 1 has piles uniformly distributed under the entire raft area. Pile Configuration 2 places the piles only in the central area. Pile Configuration 3 has piles under both the central area and the edges of the raft. The number of piles was varied between n = 9 and n = 169, and the pile length between Lp = 10 m and Lp = 50 m. The pile diameter was kept constant at dp = 1.0 m. Pile spacing varied between s = 3 m and s = 6 m. The raft-soil stiffness ratio ranged from about 0.008 (nearly fully flexible) to approximately 54 (nearly rigid), where K is defined by Horikoshi & Randolph, (1998).

Reul and Randolph (2004) conducted a study involving 259 different piled raft configurations using three-dimensional elasto-plastic finite element analyses. They varied factors such as pile positions, the number of piles, pile lengths, and the raft-soil stiffness ratio, along with the load distribution on the raft. The parametric study focused on square un-piled rafts and piled rafts with an edge length of B = 38m. Three primary pile configurations were analyzed: Configuration 1 featured piles evenly distributed across the raft area; Configuration 2 had piles concentrated only in the central region; and Configuration 3 included piles both in the central area and along the edges of the raft. The number of piles ranged from n = 9 to n = 169, with pile lengths varying between Lp = 10 m and Lp = 50 m. The pile diameter remained constant at Dp = 1.0 m, and pile spacing ranged from S = 3 m to S= 6 m. The raft-soil stiffness ratio was adjusted between Krs ~ 0.008 (approximately fully flexible) and Krs ~ 54 (roughly rigid), where K is defined by Horikoshi and Randolph (1998). The authors concluded that from their analysis the optimized design of a foundation depends on the subsoil conditions, the load configuration, and the load level. Moreover, they concluded that for similar pile length the reduced average settlement was observed for the case of smaller number of piles rather that of higher number of piles. Furthermore, they found that comparing with unpiled raft foundation piled raft foundation shows a greater reduction in average settlement values due to installation of piles in all configurations.

Wiesner and Brown (1980) conducted an experimental investigation on raft foundation models embedded in overconsolidated clay to evaluate the accuracy and applicability of methods based on elastic continuum theory for predicting the behaviour of piled-raft foundations subjected to vertical loading. The study involved precise measurements of settlements, strains, and bending moments in the raft. Their findings revealed that the theoretical predictions, which assume the soil behaves as a linearly elastic continuum, provided satisfactory results in predicting the performance of piled-raft foundations, demonstrating the robustness of this simplified approach for practical use.

According to Nirmal et al (2014), piled raft foundations are a cost-effective solution when raft foundations can meet the bearing capacity requirement but fail to keep differentials and maximum settlements below the maximum allowable limit. According to previous studies, increasing the thickness of rafts or the length of piles decreased the settlement of rafts, but decreasing the distance between piles increased settlement of rafts. In this study, permuted pile arrangements were used instead of uniform ones, resulting in improved performance of piled raft systems. An analysis of piled raft foundations is presented in this paper using PLAXIS 3D with permuted pile arrangements. Models and analyses were conducted for three different pile diameters. In this study, a 10 storey building founded on medium density sand was analyzed. A variety of pile combinations were modeled and analyzed for piling rafts. According to the comparison of results, installing high capacity piles in the regions with the highest load concentration and reinforcing the remainder of the raft with medium capacity piles has the most significant effect on reducing maximum settlement and differential settlement. As part of this study, a few general trends in the behavior of piled rafts have been examined. Moreover, they concluded that it is advisable to provide piles with a different diameter than with equal diameter irrespective of soil type, and that the interior region should receive piles with a larger diameter in order to reduce the maximum settlement and differential settlement. The study concluded that the piles configurations in raft (piled raft) have the most important effect on significantly reducing maximum settlement and the differential settlement, particularly by concentrating the piles in the centre of raft.

Vu, Anh et al (2014) highlighted the settlement behaviour of piled raft foundation through using Plaxis 3D finite element program. In their study the effects of pile number, pile length, pile layout and pile spacing on the behaviour of piled raft foundation were studied in detail. The result from numerical study revealed that Piled raft foundation has much more efficiency to reduce settlement than that of traditional unpiled raft foundation. Moreover, they found that the value of vertical deformation decreased as the result of the increasing pile number, pile length, pile spacing and vice versa. And they concluded that pile layout has showed a significant effect on both value and location of maximum settlement of piled raft foundation.

SrinivasaReddy et al (2017) presented application of PLAXIS 3D finite element software to analyse piled raft foundation on clayey soil to investigate the behaviour of piled raft system in soils under different loading conditions. According to their study the settlement was measured at the centre of the models of pile raft with (single, two, three & four) piles and the behaviour of piled raft foundation with respect to the effect of number of piles, spacing between piles, elastic of modulus and raft size on the load carrying capacity of piled raft foundation system are assessed. They concluded that as the number of pile beneath the raft increases then the bearing capacity of the piled raft become significantly improved. Moreover, they concluded that in comparison to shallow (raft) foundations, piled rafts reduce effectively the settlements.

Research from Latakia University (2024) used the Plaxis 3D program to model the pile-raft of a 16-story residential building in Latakia, Syria, in order to determine the percentage contribution of both the raft and the piles to the total loads of the building. It was compared with the proposed simplified method for calculating the raft's contribution, which is based on the principle of the additional effect of the piles as raft columns, thereby reducing their settlement. The raft's contribution reached 21.11%, leading to a reduction in the number of piles to 99 with 2m spacing, instead of 120 piles with 1.8m spacing when the raft's contribution was neglected. Moreover, in this study they concluded that it is possible to consider this method safe to use compared to the Poulos method, which gave a higher percentage of the raft contribution, reaching 36.8%, compared to the analytical model of PLAXIS 3D program, which reached 28.36%.

Using the finite element-based program Plaxis 3D, Biya et al (2023) investigated the response of piled-raft foundations depending on the thickness of the rafts, the number of piles, the length of the piles, the spacing of the piles, and the diameter of the piles. In this study uniform vertical loading found from Addis Ababa study area were applied on layered soils (medium to very stiff high plastic silty clay and medium to very dense silty sand soil). This model includes a continuum of soil, a rectangular raft foundation (1.5 Lr/Br, 10 m Br, and 15 m Lr), an interface component, and a 360 kPa uniformly distributed load (UDL); a drained analysis was utilized since no water was encountered in boreholes. The raft's edge lateral boundaries were set twice its width, limiting soil displacement horizontally (but allowing vertical displacement). The results showed that keeping the pile number as 16 then increasing the raft thickness from 0.7 m to 1.7 m a reduced in the differential settlement by 78.21% were observed. Conversely, the maximum settlements were increased by 2.81%. Besides, the result from their study revealed that as increasing the number of piles from 4 to 16 then the maximum settlement were reduced by 22.09% for a pile spacing of 4D. Moreover, as increasing the pile length from 9 m to 15 m the result showed that there is a 19.49% reduction in the total settlement while spacing the pile with a distance of 5D.

According to Nguyen et al. (2014), for large pile rafts in sand, a 3D numerical analysis was conducted, and it was suggested that piles should be piled more densely at the load center for a uniform load, along the column for a column load, and along the load line for a line load.

A review of recent investigations on the effect of application of piled raft foundation as a further settlement reduction compared to un-piled raft foundation were presented. Using Plaxis 3D Foundation, Elarabi (2012) investigated the applicability of piling rafts in soft clay under undrained conditions. In the case of piled rafts, he discovered that increasing pile spacing leads to a larger settlement.

Ta LD et al (1996) investigated piled rafts in layered soils. In order to simulate the piles in the layered soil, a numerical method called the finite layer method was used. The study concluded that in layered soil, pile load distribution is affected by layers' relative thicknesses and stiffnesses.

A summary table that offers a concise overview of recent research efforts is also presented in Table 2.1. The table summarizes how researchers conducted their investigation, identifying which soil was used to construct piled raft foundation. Detail review of the application of different types of numerical model to analyse piled and unpiled raft foundation at various parametric studies and explaining how the numerical alaysis process was executed were presented in a summarized table from, and presenting the main findings drawn from their studies.

Table 2.2: Summarized review of previous works

Reference	**Soil Type**	**Numerical type**	**Piled and unpiled raft foundation and their geometry with parametric studies**	**Main Conclusion**
Abdel et al (2020)	Frankfurt over-consolidated clay	Plaxis 3D	Piled raft foundation evaluated interms of total settlement, differential settlement and the pile skin friction	It was found that the chosen foundation system “plied raft foundation” for Messeturm was an optimized solution for the proposed building
Batuhan et al (2023)	Five different material	Plaxis 2D and 3D	The load-settlement behavior, including maximum and differential settlements, as well as pile loads and bending moments, was compared against field measurements.	The results show that 3D models predict load settlement more accurately than 2D models. Additionally, it was concluded that 2D models yield conservative results.
Joseph, J. (2018)	Multi – layered soil	Plaxis 3D	A parametric study was conducted to examine how the diameter and spacing of piles, along with different raft thicknesses, affect settlement reduction.	The foundation experiences greater settlement compared to a piled raft foundation. Additionally, raft thickness has minimal impact on reducing total and differential settlements.
Ahmed, M. et al (2014)	Suitable to cohesion less soil	Plaxis 3D	Parameters such as construction phasing, sequential loading, building aspect ratios,	The study found that the interaction between the building foundation, soil field, and superstructure

			soil failure models, and the thickness ratio of the soil's stiff layer are taken into account.	significantly impacts the structure.
Vijaykumar et al (2014)	Clayey Sand	Plaxis 3D	Parameters such as the number, length, diameter, and spacing of piles have been included in the analysis of the piled raft foundation system.	The total load supported by the piled raft is distributed between the piles and the raft. As a result, the stresses and bending moments in the piles are significantly reduced. An increase in the length and number of piles enhances the load-carrying capacity of the system increases and the settlement decreases.
Yirsaw et al (2022)	Stiff clay	FLAC 3D	Analyzed 28 piled raft configurations at various length and diameter of pile,	Increasing the distance between piles increases the raft load sharing distribution by 11.5% while reducing settlement. Further increasing pile length is ineffective for settlement reduction

2.9. Gaps identified while reviewing previous related works

Overall, previous research indicates that the use of piled raft foundations in clayey soils is crucial for minimizing settlement under heavy loads, and recent studies have produced noteworthy findings regarding their effectiveness for settlement improvement. As a result of the literature review, piled raft foundation is effective at improving load-bearing capacity and reducing settlement of weak to stiff soils. In order to achieve optimal performance, various factors, such as soil type, pile spacing, and pile diameter, must also be taken into account during the design process.

Nonetheless, there have been limited studies focusing on the influence of key parameters such as pile length (Lp), pile spacing (Sp), pile diameter (dp), and the number of piles (Np) on the settlement and load-bearing characteristics of piled raft foundations in clay soils while subjected under heavy structural load. Additionally, the impact of these parameters on the optimal design of small piled raft foundations is not well documented and requires further investigation.Most current research on the parametric analysis of piled raft foundations has concentrated on square-shaped rafts, which do not truly reflect the typical shape of many structures. Furthermore, there is insufficient research on local soil conditions and their impact on the performance of piled raft foundations in Ethiopia.

Consequently, it is essential to examine the behavior of rectangular piled raft foundations, especially in the weak soil types prevalent in Addis Ababa and other areas of Ethiopia.

Chapter three

Research Methodology

3.1. Introduction

The purpose of this section is to develop a method for using a numerical model to simulate a piled raft foundation that supports heavy structural loads on stiff, clayey soil. A description of the study area is provided. A realistic boundary condition is adopted, including restraints, the groundwater table, applied loads, and the method used to model the piled raft foundation. Using secondary data from the study area, a material parameter is calibrated for the soil profile. Additionally, a material parameter is presented for the raft and pile foundation components. Furthermore, this section describes the study area and the process undertaken to achieve the general and specific objectives of the study. To accomplish these objectives, several steps were followed.

First, a detailed literature review was conducted to gain an in-depth understanding of the application of piled raft foundations in reducing settlement for deep foundations resting on clayey soil and then relevant parameters, methods, and their effects on structural settlement were investigated in detail.

Next, representative data were collected from geotechnical design offices, specialized geotechnical investigation companies, and government agencies concerned with these matters. Based on the depth, the number of boreholes, and the extent of the area covered, the research zone where moderate soil could be present was determined using the collected data. Parameters for the numerical modelling of the foundation system using Plaxis 3D were identified. A numerical model was then developed for piled raft foundation type application in selected soils, through considering various parameters. Results and discussions were based on the model's output. Finally, conclusions and recommendations were made. Figure 3.2 presents a flow chart of this research more clearly.

3.2. Description of study area

The proposed 3B+ G+35 Mixed use Building project site is located in Addis Ababa, at Lagare close to Ethiopian Insurance Company at the northern side of the Federal Housing Corporation and in front of the Ethiopian Maritime office. Location of the site in Google map is presented in

Figure 3.1. The project location is characterized by flat topographical feature and approximately rectangular in plan shape. There are no any visible geomorphologic features such as gullies and river cuts.

Figure 3.1: Location map of the project site in Google map

The Capital city Addis Ababa is the hub of a vast region of immense economic potentials accessible by means of railway and expressway. Due to these facts, the urbanization is rapid in the different directions of the city and investors are attracted to invest in the town and the nearby areas. Currently, many civil engineering structures such as roads, bridges, Industry Park and multistory buildings including international hotels and commercial centers are under construction in the city. On the other hand, the town has been vulnerable to geological hazards like erosion and associated landslides, ground fissure and flooding during rainy season. Regarding seismicity of the project location, according to the Ethiopian Building Code Standard (ES EN 1998-1:2015) Ethiopia is subdivided into five seismic zones (Zone 0, 1, 2, 3, 4 and 5). The seismic hazard zone 0 is the least hazardous zone or zero seismicity whereas zone 5 is very high seismicity Zone. Zone 5 is located in the main Ethiopian rift system and almost all epicenters are located within this zone 5. Since Addis Ababa city, including the project sites, are located within seismic Zone-3 having a ground acceleration ratio of 0.1, the design and construction of facility with this zone should be seismic hazards corresponding to a reference return period of 475 years (10 % probability of accidence in 50 years).

3.3. Data Collection

This research used both primary and secondary data sources for data collection. Primary data is a load calculation at the base from 37-story building designed and analysed using ETABS software (See Appendix 1). Secondary data came from a comprehensive review and analysis of publications, literature, journals, books, and case studies about pile raft foundation design and analysis. Furthermore, a desk study of data from design offices (Lula Engineering-Design-Building Renovate Consulting) such as geotechnical investigation report was conducted to gather relevant information on the subject. In addition to ensuring the study's objectives are met, secondary data sources offer a cost-effective and time-efficient way of obtaining information on the research topic.

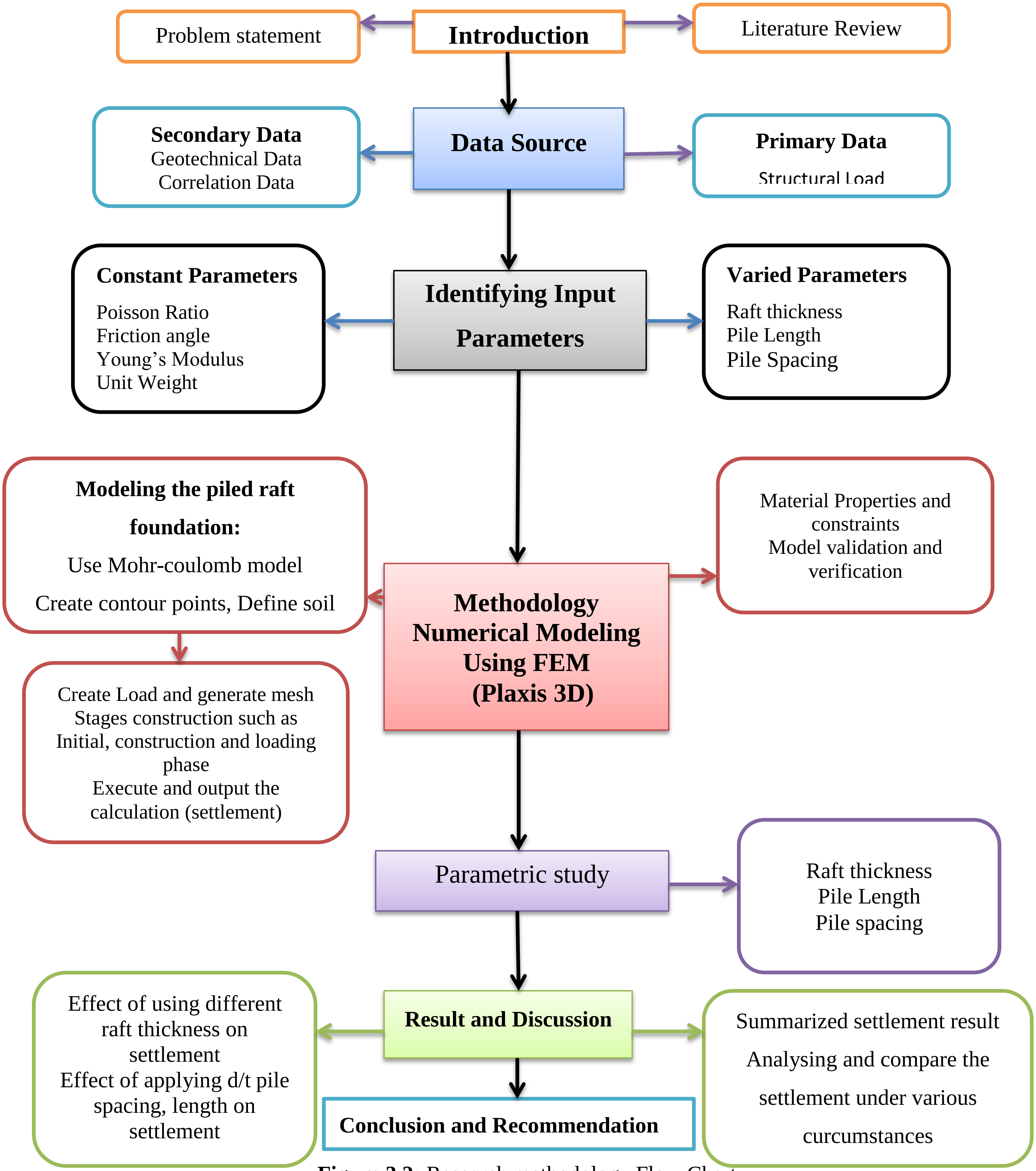


Figure 3.2: Research methodology Flow Chart

3.4. Using PLAXIS 3D to develop a Finite Element Numerical Model

This research paper conducted a comprehensive analysis and parametric study of a piled raft foundation constructed on clayey soil using the powerful finite element-based software PLAXIS 3D CONNECT Edition Version 20 (V20). In order to perform a numerical analysis with Plaxis 3D, various parameters were selected based on the components of the effect of applying a piled raft foundation system; some parameters were kept constant, while others were varied based on how they affected the reduction of settlement by soil, raft and pile interaction. Several parameters were varied, including raft thickness, pile spacing, pile length, and pile number. Throughout the study, soil properties as well as structural elements like the raft and pile remained constant.

3.4.1. The soil Parameters

This study examined the application of the piled raft system on mainly clayey soils by collecting soil data from geotechnical investigation consulting offices. Modelling the soil as an Elasto-plastic Mohr-Coulomb medium was used to represent material non-linearity. For the provided project site, a multi-layer soil model was developed from 4 borehole data, with the primary type being a plastic clayey and silt sand soil type. These boreholes extended to more than **18**m of maximum depth from the ground surface. In their report, some boreholes did not reveal any subsurface water during drilling, while others showed shallow groundwater at depths starting from 2 meters. This presence is likely due to the wet season, which can lead to flooding in the boreholes, and may also be influenced by the water used during drilling required for penetrating hard rock. However, the impact of groundwater was not taken into account during the analysis.

The geotechnical parameters for the layer were sourced from collected data, and missing information was estimated using empirical equations derived from the Standard Penetration Test (SPT) and laboratory shear test values of the boreholes. Kumar R. et al (2016) illustrated that empirical relationships based on the SPT N value are commonly used because of their simplicity and usefulness in estimating parameters such as cohesion, angle of friction, Poisson's ratio, shear wave velocity, and bearing capacity. Moreover, they concluded that standard penetration test (SPT) is a widely used method for general soil characterization. The Young's modulus, cohesion, angle of friction, and Poisson's ratio of the layers were not provided in the soil investigation report. Therefore, the Young's modulus of the given soil layer was determined using Appendix 2 as reported in USCS (Kézdi & Réthári, 1974; Obrzud & Truty, 2012)**.** Cohesion, angle of friction, and Poisson’s ratio were determined using a correlation equation developed by Kumar R. et al. (2016).

3.4.2. Development of Raft Part Material Properties and Parameters

The raft was treated as a flat slab with uniform thickness resting on the ground surface. During the modeling of the raft, it was found that its volume was considerably smaller than that of the surrounding soil mass. As a result, smaller mesh elements were used for the raft. A rectangular raft foundation with a length-to-width ratio of 1.5 (Lr/Br = 1.5) was considered. The initial raft thickness was determined using SAFE 20 software, which incorporated loads from the ETABS output to counteract punching forces. Thicknesses of 2 m, 2.5 m, and 3 m were analyzed. Relevant raft properties were obtained from previous journal articles and publications.

In plaxis 3D, the raft part of the foundation structure is modelled as a plate element and its properties are as given in the Table 3.1. Its properties were acquired from ECX (Ethiopian Commodity Exchange) office building project Profile for Lula Engineering-Design-Building Renovate Consulting. The three dimensional view of raft foundation is shown in Figure 3.3 and summary of the parameters developed for the raft foundation as a plate is presented in Table 3.1.

Table 3.1: Raft properties adopted for all subsequent finite element analysis

Parameter	**Value**
Material Model	Elastic
Raft thickness	2m to 3m
Bulk Unit weight (KN/m^3)	25
Modulus of Elasticity, E (mPa)	25000
Friction Angle (^{0})	42
Dilatancy Angle	12
Poisons Ratio	0.15

3.4.3. Development of Pile Part Material Properties and Parameters

In this study, piles were modelled similarly to the raft. Each building frame's raft was assumed to be supported by a group of piles with circular cross-sections. Small-diameter bored piles were defined as those with a diameter of 600 mm or less, while large-diameter bored piles had diameters greater than 600 mm, as per CES-2015. This research used piles with a 1 m diameter. According to ES 7-2015, for bored cast-in-situ piles, the spacing should be at least 3 times the pile diameter but not less than 1.10 m. Therefore, the study began with 2D spacing on the shorter side of the raft, which later increased to 2.5 and 3 times the pile diameter. Simultaneously, a spacing of 1.5 times the shorter side spacing was used for the longer side of the raft. Pile length was another parameter used to analyze the settlement of the structure. Since this research focuses on settlement, a large piled raft with Br > Lp was chosen, with an Lp of 18 m, then reduced to 14.4 m and 10.8 m. Another factor considered in the analysis was the number of piles, with only 24 piles utilized.

In the present study, circular piles were considered. C25/30 concrete grade and S-400 steel were used with a Poisson's ratio of 0.15 for concrete. In this study, the effect of the number of piles, pile spacing, the end of pile at soil with varying stiffness, length of piles on settlement, and swelling of foundation were examined. Summary of the parameters developed for the pile foundation part as embedded beam row element is as shown in Table 3.2.

Table 3.2: Pile properties adopted for all subsequent finite element analysis

Parameter	**Value**
Material Model	Elastic
Pile diameter	1m
Design Element	Embedded Beam row
Pile Length	18m and varies
Bulk Unit weight (KN/m^3)	25
Modulus of Elasticity, E (mPa)	25000
Friction Angle (^{0})	42
Dilatancy Angle	12
Poisons Ratio	0.15

Figure 3.3 shows a three-dimensional view of inclusion of a single column loading on a given footing.

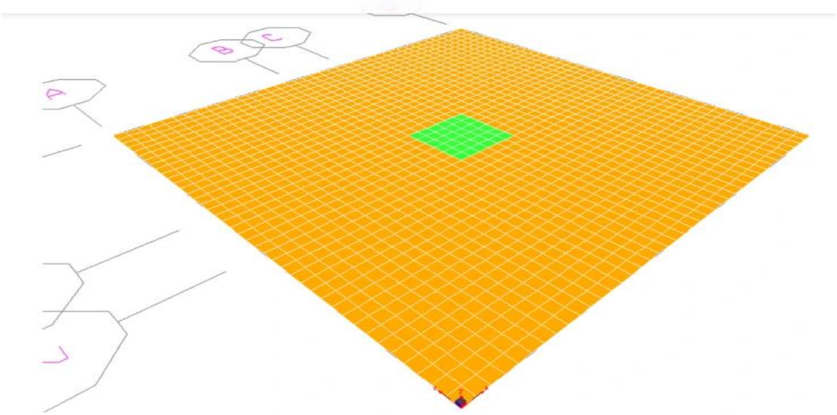


Figure 3.3: 3D view of piled raft foundation loading as uniformly distributed load (UDL) on footing

3.4.4. Material properties of layered soil

Based on one borehole data extending up to 2 meters from the surface, the analysis was using a Mohr–Coulomb numerical model as Elasto-plastic medium and modelling a layer of subsoil was carried out. The geotechnical parameters were derived from collected data, and missing information was calculated using empirical equations. As shown in the table below, Young's modulus, cohesion, angle of friction, Poisson's ratio and other parameters were determined.

Table 3.3: Soil properties adopted for all subsequent finite element analysis

Soil Parameter	**Soil layer-1**	**Soil Layer-2**
Material Model	MC	MC
Depth	0.0m-10m	10m-18m
Drainage condition	Drained	Drained
Bulk Unit weight (KN/M3)	18.3	18.8
Cohesion (kPa)	41.7	23
Modulus of Elasticity, E (mPa)	50	50
Friction Angle (^{0})	23.7	28
Dilatancy Angle	-	-
Poisons Ratio	0.45	0.35

3.4.5. Finite Element and Boundary Conditions

A finite element model's accuracy depends not only on the sophistication of the material model, but also on the boundary conditions of the domain, the number and type of elements within the domain, and other modelling issues.

The structural model includes a soil continuum with undisturbed boundary conditions, a piled raft foundation, an interface component, and a uniformly distributed load of 520.37kPa from 1,063,244.49KN of distributed load. This study modelled rectangular raft foundation geometry with a width of 12m and a length of 18m, where B and L correspond to the width and length of the chosen raft for modelling, respectively from a building foot print width of 36.35m and 56.21m length.

A typical finite element mesh is shown in Figure 3.4. The design office report indicates that groundwater was not encountered in all boreholes. Hence, in this study, the water table was not considered, and drained analyses were performed. At the edge of the raft, the model's lateral soil domain boundaries were set at a distance equal to twice the raft's width and were restricted against horizontal movement (i.e., horizontal displacement) while allowing vertical movement (i.e., vertical displacement) of the soil. In a raft foundation, the pressure bulb (see Figure 3.5) was created with a size up to double the raft's width, whereas in a pile group, it was formed at two-thirds of the pile length. Consequently, the bottom soil boundary had a vertical distance equal to twice the raft's width plus two-thirds of the pile length, and it was restricted in both horizontal and vertical movements. As shown from figure 3.4, the excavation's depth is determined as 2B + 2/3(pile maximum length). These parameters are utilized for modelling the excavation area using Plaxis 3D.

The examination and analysis of a unit or group of pile inclusion on the given layered soil consists of three phases: the initial phase, the construction phase, and the loading phase.

- During the initial phase, which involves setting up the initial geometry configurations and the corresponding stress field, the soil domain was activated.
- In the construction phase, the piled-raft geometry was activated.
- And in the loading phase, the applied load was introduced and executed.

A preliminary analysis of the un-piled raft under the imposed load revealed that the chosen lateral boundaries of the soil domain were adequate, as the area of plastic strain in the soil was equal to the raft's width (Br) laterally from the edge of the raft (Mirand et al.,2021). The code for finite elements in Plaxis 3D was used to create the entire 3D model. This code automatically generates the finite element mesh using a triangulation procedure, but global and local mesh refinements may be defined to ensure a good quality of the mesh (Brinkgreve et al., 2008). Soil and pile were modelled as a continuum element consisting of 10-noded tetrahedral elements.

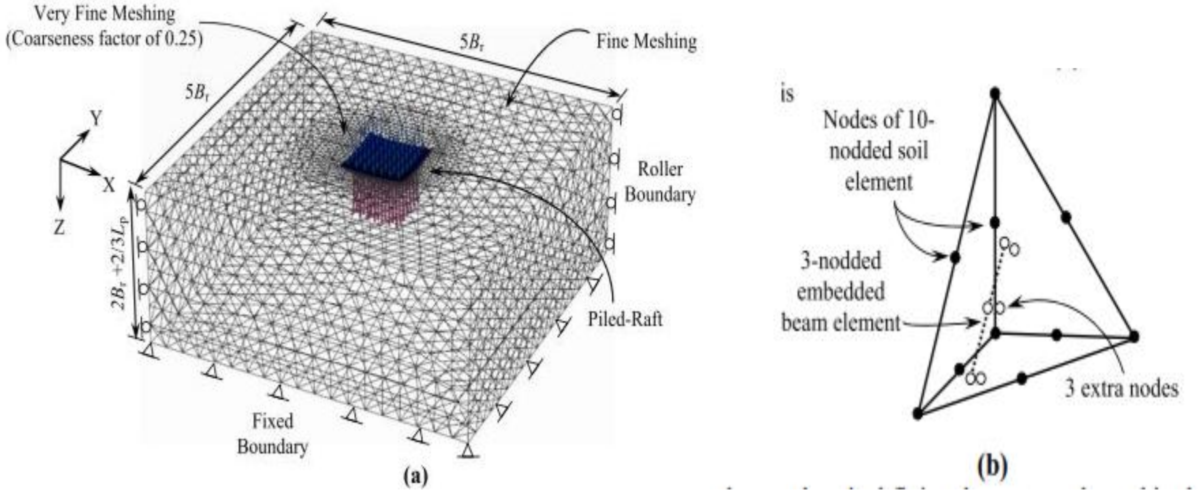


Figure 3.4: (a) Boundary and typical finite element mesh used in the parametric study, and (b) 10-node tetrahedral element with 3-node embedded beam element (Mali & Singh, 2018)

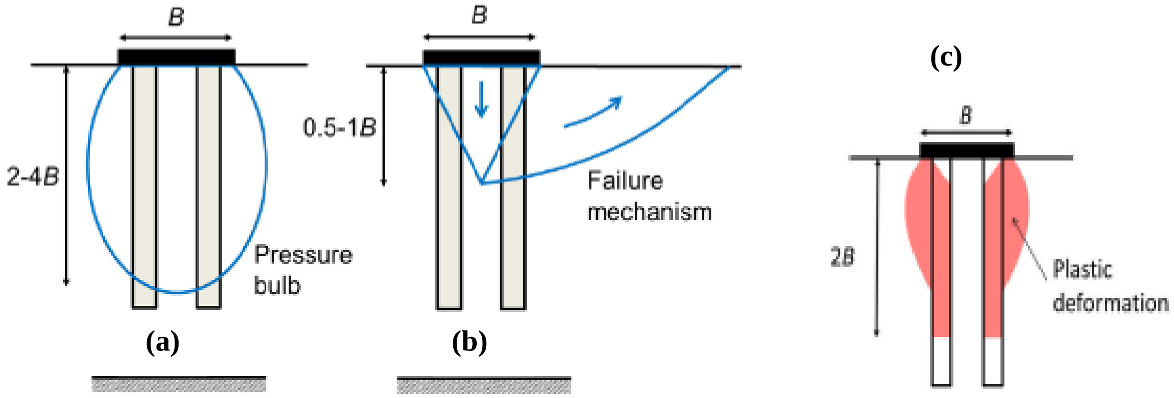


Figure 3.5: Justification of critical pile column length in a homogeneous soil layer: (a) Settlement reduction in elastic materials linked to pressure distribution; (b) Bearing capacity; (c) Settlement reduction in elasto-plastic materials related to plastic deformation (Mirand et al, 2021)

3.4.6. Constitutive Numerical Modeling the Piled Raft Foundation

Castillo et al. (2024) defined that the constitutive numerical model defines how materials behave under load within a numerical simulation, which allows engineers to predict the characteristics of materials and structures. Material properties such as elasticity, plasticity, and strength are mathematically described by these models, which link stress to strain to capture complex behaviors such as hardening, softening, and time-dependent deformations. It has the advantage of requiring a few input parameters, all of which can be calculated from standard soil tests, which is a key advantage of the Mohr-Coulomb model. Figure 3.4 shows that soil in the Mohr-Coulomb model was represented by 10-node tetrahedral elements as well as elastic perfectly plastic elements. A variety of parameters were required for this modelling, including cohesion, the internal friction angle, the Young's modulus, and the Poisson's ratio.

The Mohr-Coulomb failure criteria state that soils fail when their mobilized shear stress exceeds their shear strength. To simplify the analysis process, constant material parameter values were used for the soil domain. Based on Vishwakarma et al (2017) specifications for modeling concrete slabs, the raft parts of the foundation were modeled as area elements (shells). Load transferred from the column was treated as a concentrated point load. This point load, however, is uniformly distributed (UDL) over the cross-sectional area of the raft in the mathematical model.

In finite-element modelling, the plate (shell) is discretised and the soil was modelled as a spring with equivalent stiffness. According to Li, J et al (2024) using Finite Element Modeling (FEM), a thin plate or shell structure is divided into smaller, manageable "finite elements." Simultaneously, the underlying soil is simplified and represented as a series of connected springs, where the spring's stiffness reflects the soil's resistance to deformation in real life. Soil-structure interaction problems are often solved using this method, which simplifies complex soil behavior into a more computationally tractable form for FEM analysis.

In this study the raft was modeled using triangular plate elements. Meshing these plates yields six-node triangular plate elements with six degrees of freedom. Similarly, the pile part of the foundation is modeled as embedded beam elements. These embedded beams are composed of beam components combined with unique interface elements that facilitate interaction with the surrounding soil. Once meshed, these beam elements transform into 3-node line elements with six degrees of freedom for each node, including three translational and three rotational movements.

Moreover, Ninicet et al (2014) employed a numerical technique in which a structural element like a pile is represented by beam elements within a soil finite element model. They observed that soil-structure interaction is simulated by specially specified interface elements of these beams that interact with surrounding soil. As a result of this approach, it is possible to have an efficient analysis of geotechnical structures by separating the beam meshes from the solid meshes, as well as accurately predicting how piles and soil transfer loads and deform. Due to their high modulus of elasticity, rafts and piles (connected each other through applying rigid connection) maintain an elastic state during investigation, leading to their classification as linearly elastic.

In this analysis, the interface element is represented by the interface reduction factor (R_{inter}). Wang et al (2024) explained that, in finite element analysis (FEA), the interface reduction factor (Rinter) represents the reduced shear strength and stiffness of interface elements (such as soil and structural elements) as compared to adjacent soil and it is obtained by dividing the ultimate shear resistance held between soil and the corresponding concrete by the limit shear resistance. Moreover, they showed that a Rinter value of 1.0 indicates a perfectly bonded, fully developed interface, while a value closer to 0.0 indicates virtually frictionless contact. In Figure 3.6, the pile-soil interface technique is illustrated. These two figures illustrate the conditions of "no slip" and "slip" between the soil and pile, respectively.

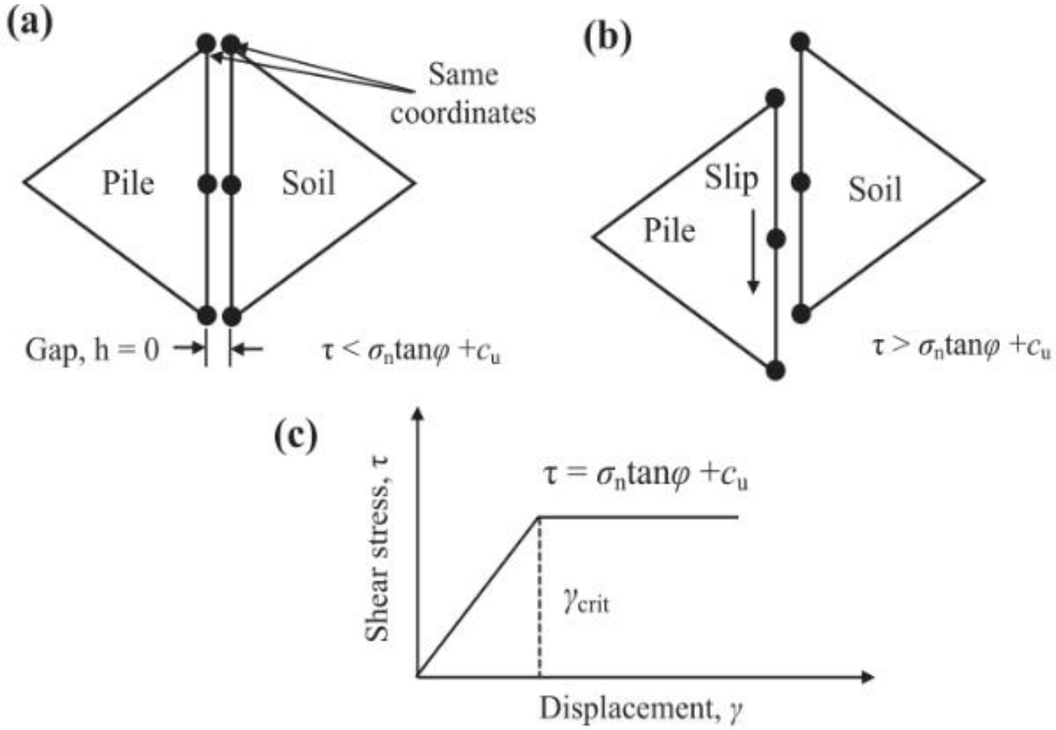


Figure 3.6: Pile-soil interface modeling technique (a) no slip, (b) slip, and (c) Coulomb frictional law (Jeong et al., 2004)

Interface elements are available in PLAXIS 3D foundation to model the interaction between smooth and rough surfaces i.e. between the raft and soil. Interface elements can simulate gap and slip displacements, which are normal and parallel to the interface, respectively. The loss of strength at the interface is modeled with a reduction factor (R_{inter}), which relates the interface strength to the soil strength through friction angle (ϕ) as below (Wang et al, 2024):

$$tan\varphi_i = R_{inter} tan\varphi_{soil} \leq tan\varphi_{soil} \ldots\ldots 3.1$$

According to the Plaxis 3D manual, sand and concrete interface recommendations range from 0.8-1, whereas clay and concrete recommendations range from 0.7-1. Thus, in this study the interface between raft and soil is considered as smooth with Rinter values of 0.8. Modelling pile - soil interactions was carried out using node pairs instead of single nodes in 3-node line elements. In each pair, one node is part of the beam element, and the other is a point in the 10-node wedge element belonging to the soil element. Interface elements are primarily used to simulate displacement discontinuities between structural elements and soil mass. Wang et al (2024) demonstrated that in the finite element formulation, the coordinates of each pair of nodes are identical, indicating that the interface element has zero thickness (h = 0) (see Figure 3.6(a)). The Mohr-Coulomb failure criterion is followed by interface elements, and when the soil's shear stress is equal to its yield shear strength ($\tau_f = c + \sigma_n \tan\phi$), slippage occurs at the interface (Figure 3.6(c)). As seen from Figure 3.6(C) elastic shear behavior exists until the shear stress reaches a critical value (γ_{crit}), after which the shear displacement increases without an accompanying rise in shear stress (Figure 3.6(c)). It is important to introduce interface elements to simulate displacement discontinuities between structural concrete elements and the soil mass (Rafael et al (2017).

3.5. Mesh Sensitivity Analysis

A mesh sensitivity analysis was conducted to investigate the effect of element number on the accuracy of the finite element model. The number of pile, pile size, and pile spacing are varied under raft thickness in subsequent parametric studies. It was performe to compare the accuracy of medium and fine meshes against very fine meshes. The vertical displacement was examined for the mesh sensitivity analysis as the settlement performance of the piled raft is the primary focus of this thesis work. It is possible to influence the results of the finite element model by changing the number of elements. In order to examine this effect, five different finite element meshes were tested on a biased mesh system with varying element sizes and numbers as shown in table 3.4.

Table 3.4: Effect of the number of elements on maximum settlement

Trial Number	Mesh Coarseness	Number of Elements	Maximum Settlement (m)
1	Very coarse	1685	0.1501
2	Coarse	3012	0.1526
3	Medium	7941	0.1558
4	Fine	19765	0.1596
5	Very fine	50426	0.1605

Figure 3.5 and Table 3.4 shows that the maximum central settlement increases with an increase in elements until it reaches 19,765 elements. Once the maximum central settlement reaches this point, the number of elements has almost no impact. As a result, the fourth trial model was selected for further analysis. The soil domain was covered with a fine mesh, while the structural components were covered with a mesh that was considerably finer. Its coarseness factor between fine and very fine mesh is 0.09%, which indicates that the element size in this very fine mesh is 0.09% times smaller than that in the fine mesh.

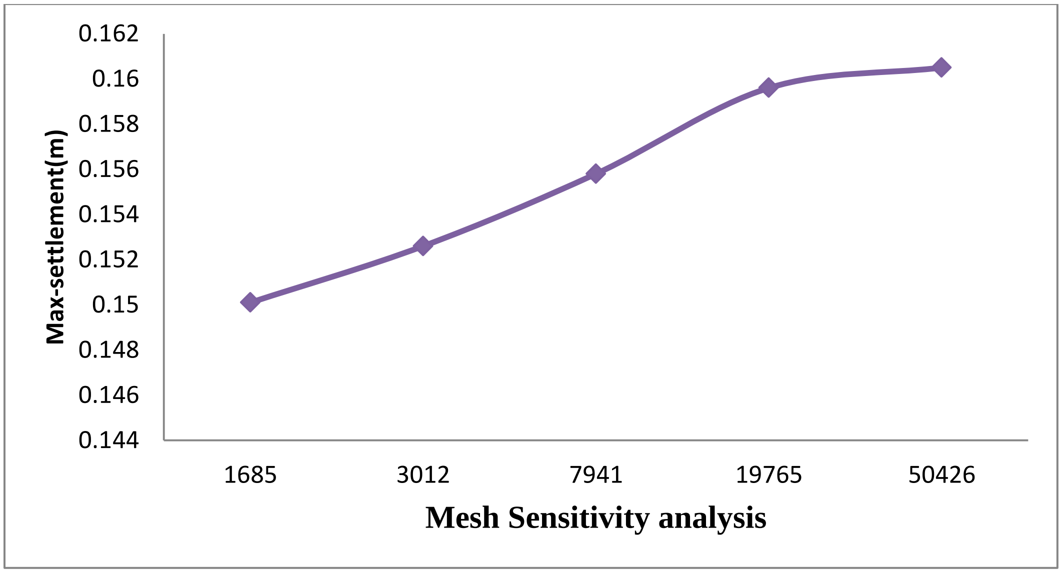


Figure 3.7: Effect of mesh coarseness on maximum central settlement

The extremely fine mesh was created with a 0.25 coarseness factor, which indicates that the element size in this very fine mesh is 0.25 times smaller than the element in the fine mesh. The use of a finer mesh gave slightly higher settlements, but the differences were negligible. Mesh sensitivity analyses were performed to confirm the accuracy of the mesh.

3.6. Model Validation

In this research, the model validity approach was tested by comparing the numerical findings to existing literatures such as Ferchat et al. (2021), Mali & Singh (2018), and Sinha & Hanna (2017). A study of the application of piled raft foundation to selected layered soil profile was presented. In order to achieve the objectives, a piled raft system with a rectangular raft measuring 12 x 18 m and a 2m, 2.5m and 3m thickness was modeled. This raft, fully embedded in soft clay soil, rests on 24 circular piles that are 1.0 m in diameter and 18m, 14.4m and 10.8m long respectively and piles are evenly distributed beneath the raft, having a spacing (Sp) of 2,2.5 and 3 times pile diameter (D) where pile diameter is taken as 1m. In order to simulate loading, a uniform vertical load was applied to the foundation surface. All subsequent numerical modeling analyses utilized a small strain formulation and a staged construction approach. Work planes are defined as horizontal planes (x-z planes) at specific vertical levels (y-levels), where geometry points, lines, structures, and loads can be identified. In PLAXIS 3D, every model begins with an initial phase, which includes only the soil clusters and does not activate other structural components. This phase calculates the stresses and deformations arising solely from the soil clusters under the influence of gravity load. A series of finite Element Analysis was carried out using PLAXIS 3D foundation code to examine the effect of key design parameters upon the settlement performance.

The key design material parameters and considerations are illustrated in **Table 3.1 and 3.2**. In addition, the preliminary checks for sensitivity analysis have also dictated. **Figure 3.8** shown below compares the current study of the load-settlement behaviour of the piled raft foundation generated by numerical model analysis with the Plaxis results generated by Mali et al. (2018), and Ferchat et al. (2021). As it is seen from the figure, load-settlement analysis of present work approximately aligns with previous works. Therefore, present numerical study's results are in good agreement with those of previous numerical studies.

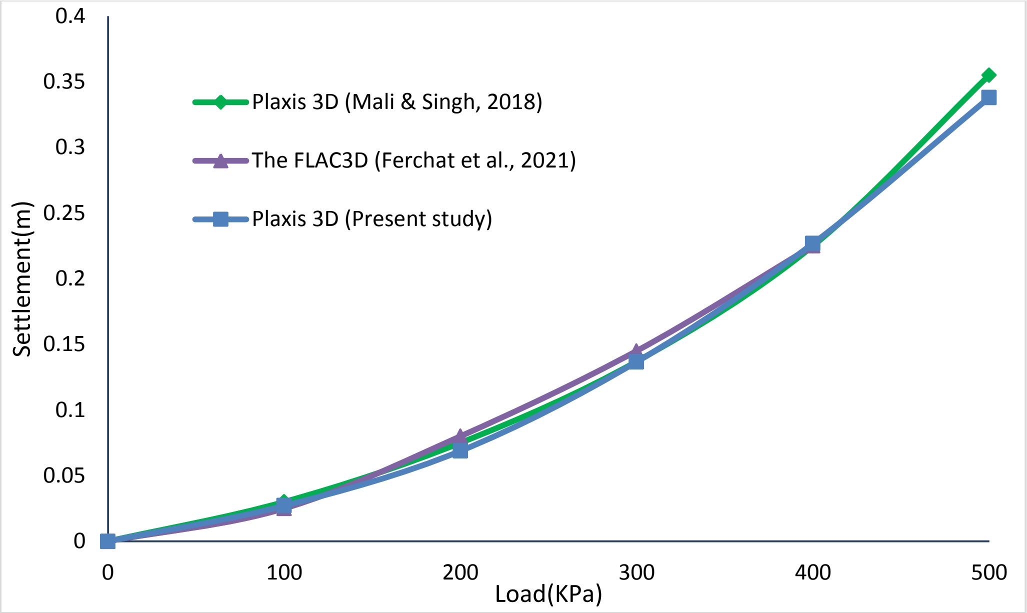


Figure 3.8: Comparison of the current study's results and previous numerical studies on load-settlement behaviour of the given soil.

3.7. Design Consideration

In Ethiopia, engineers should consider optimizing piled raft foundations in high settlement soils by conducting comprehensive geotechnical assessments to evaluate soil characteristics and groundwater conditions. This involves employing numerical modeling to tailor pile configurations—such as diameter, spacing, and raft thickness—to enhance load distribution and minimize settlement effectively. Additionally, selecting durable materials resistant to local environmental factors is crucial. Integrating ongoing monitoring systems will enable real-time assessment of settlement and structural performance, facilitating timely interventions. Ultimately, fostering local expertise through training will empower engineers to confidently implement these innovative foundations, ensuring safety and cost-effectiveness in construction.

CHAPTER FOUR

RESULT AND DISCUSSION

4.1. Introduction

With PLAXIS 3D, 30 Finite Element Analyses were conducted to analyze the settlement behaviour of piled raft foundation in several configurations. The purpose of this study is to verify the effectiveness of piled raft foundation and to better understand the settlement behaviour of piled raft foundation on layered clayey soil. The effect of parametric studies such as pile space, length and raft thickness focuses mainly on the settlement performance of piled raft under heavy working loads was executed. This is because foundation design on clayey soil is usually governed by settlement rather than bearing capacity criteria, due to its high compressibility nature of clay soil (Priebe, 1979). The study considered variables like pile spacing, length, number, and raft with a rectangular type and raft thickness. In order to minimize the storage and time required for numerical computations, smaller foundation dimensions were considered in this study, along with the general dimensions commonly used by most researchers and standards. Figure 4.1 shows an example of pile inclusion along with provided raft considered in the present parametric study for different length of pile and their spacing (See Appendix-3).

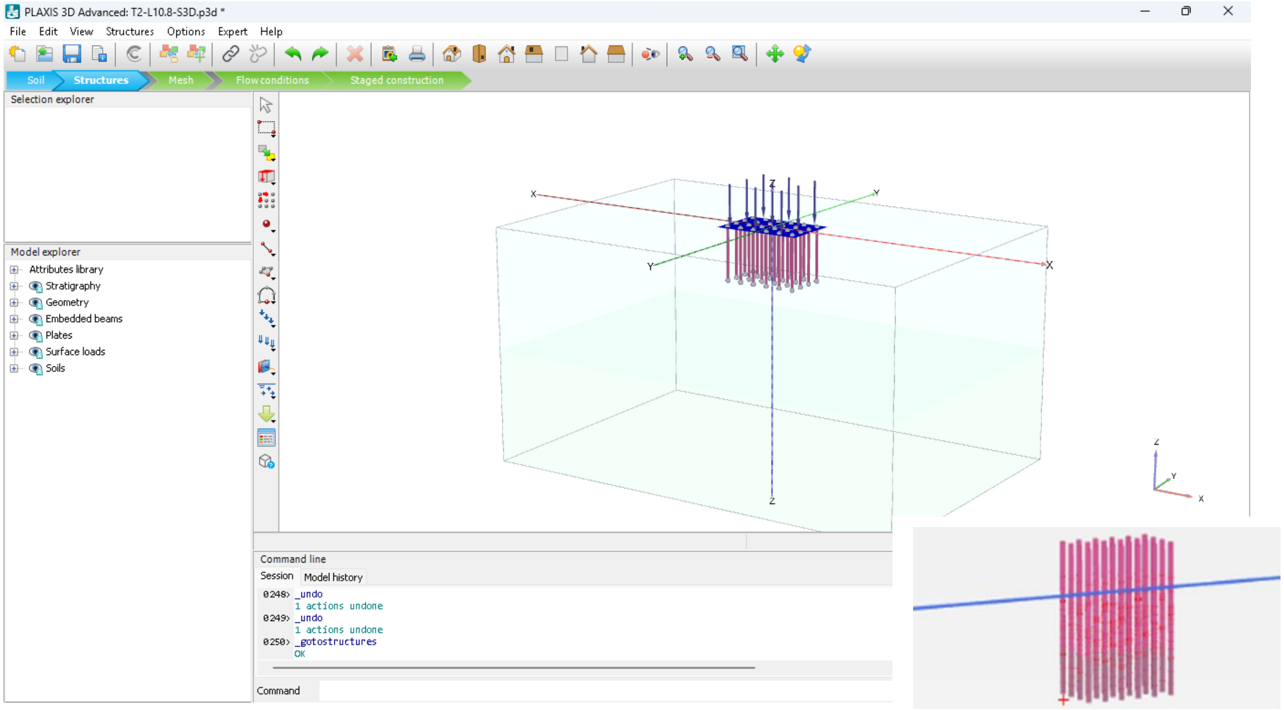


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Figure 4.1: Sample of modeling of piled raft foundation on a given soil

Table 4.1 and Table 4.2 summarize the foundation and soil parameters, as well as the geometric configurations of the pile-raft model used in the parametric analysis, respectively. A detailed result of the analysis is presented in this chapter along with details on the influence of key design parameters, analysis of the results of the numerical modelling as well as the discussion of the outcomes were presented.

Table 4.1: Important material properties used for parametric parameter analysis of piled –raft system

Parameters	**Soil Property**		**Concrete Property**	
	Soil 1	**Soil 2**	**Pile**	**Raft**
FE Model	Elasto-Plastic		Linear Isotropic	
Young's Modulus, E (MPa)	50	50	25000	25000
Poisson's Ratio,	0.45	0.35	0.25	0.25
Angle of internal friction, Ø'(°)	23.7	28		
Unit weight, γ,kN/m3	18.3	18.8	25	25
Cohesion, ' (kPa)	41.7	23		
Dilatancy Angle (o)				

Different geometric configuration of piled raft foundation for parametric analysis is shown in table 4.2. For parametric study of a piled raft foundation, the effect of key geometric arrangement such spacing of piles, pile length, and raft thickness on settlement should be investigated. To realize various raft stiffness level by using common approaches like distribution uniform pile, the influence of pile spacing under the raft area, and adjusting pile length-to-diameter ratios is also significantly considered.

Table 4.2: Geometric arrangement for piled-raft foundation for parametric study

Parameters	**Unit**	**Arrangement and Value**
Raft Width (Br)	m	12
Raft Length (Lr)	m	18
Raft Thickness (Tr)	m	2, 2.5 and 3
Number of Pile	No	24
Pile Length (Lp)	m	Lr, 0.8(Lr) and 0.6(Lr)
Pile Spacing (Sp)	m	2(D), 2.5 (D) and 3(D)
Pile Diameter (Dp)	m	1

4.1.1. Settlement results using a numerical model by Plaxis 3D at different conditions

Table 4.3 shows the amount of settlement obtained under various conditions by varying the raft thickness, spacing of pile, and pile length using PLAXIS 3D numerical model.

Table 4.3: Settlement results of piled raft foundation subjected to an applied load of 520.37kPa using Plaxis 3D numerical model

Raft -Length-Spacing Combination(T=Raft Thickness, L=Pile Lenth, S=Pile Soacing and D=Pile Diameter)	Maximum Settlement (m)	Minimum Settlement (m)	Positive Moment in the Short Direction (KN-m/m)	Negative Moment in the Short Direction(KN-m/m)	Positive Moment in the Long Direction (KN-m/m)	Negative Moment in the Long Direction(KN-m/m)	Differential Settlement(mm)
T2 (2meter raft Thickness)	0.1027	0.0908	3546	-43.66	2055	-60.07	0.0119
T2-L18-S2D	0.07757	0.07548	557.5	-251.5	553.9	-346.5	0.00209
T2-L18-S2.5D	0.07061	0.06717	1223	-88.94	839.8	-80.34	0.00344
T2-L18-S3D	0.06628	0.06038	2748	-153.4	1752	-78.43	0.0059
T2-L14.4-S2D	0.0856	0.08336	766.8	-1.668	681.2	-238.5	0.00224
T2-L14.4-S2.5D	0.08011	0.07456	1427	-2.0	867.3	-119.8	0.00555
T2-L14.4-S3D	0.07518	0.06851	2814	-49.45	1756	-128.8	0.00667
T2-L10.8-S2D	0.09541	0.09182	998.8	-18.3	928.9	-400	0.00359
T2-L10.8-S2.5D	0.0907	0.08401	1815	-5.12	1052	-3.029	0.00669
T2-L10.8-S3D	0.0857	0.07804	3048	-124.8	1790	-119.4	0.00766
T2.5 (2.5m Raft thickness)	0.105	0.09553	3832	-55.69	2149	-66.45	0.00947
T2.5-L18-S2D	0.07999	0.07830	554.1	-279.9	567.1	-379.3	0.00169
T2.5-L18-S2.5D	0.07255	0.07002	1345	-81.07	855.2	-86.56	0.00253
T2.5-L18-S3D	0.06711	0.06318	3137	-110.3	1851	-64.88	0.00393
T2.5-L14.4-S2D	0.0881	0.08647	805.8	-0.7803	701.2	-266.1	0.00158
T2.5-L14.4-S2.5D	0.08223	0.0778	1568	6.366	896.9	-121.1	0.00443
T2.5-L14.4-S3D	0.0765	0.07203	3182	-7.850	1845	-117.6	0.0045
T2.5-L10.8-S2D	0.09795	0.09512	1066	-15.32	966.3	4.541	0.00283
T2.5-L10.8-S2.5D	0.09304	0.08777	1984	-7.383	1089	2.867	0.00527
T2.5-L10.8-S3D	0.08748	0.08192	3436	-76.63	1883	-109.2	0.00556
T3 (3m Raft Thickness)	0.1078	0.09932	4001	-64.23	2181	-70.01	0.00848
T3-L18-S2D	0.08252	0.08101	554.7	-305.8	586.1	-411.8	0.00151
T3-L18-S2.5D	0.07464	0.07258	1401	-88.49	870	-96.03	0.00206
T3-L18-S3D	0.06834	0.06546	3379	-85.66	1911	-52.62	0.00288
T3-L14.4-S2D	0.09066	0.08937	814.5	-4.183	718.8	-295.6	0.00129
T3-L14.4-S2.5D	0.08458	0.08071	1624	7.576	910.6	-127.1	0.00387
T3-L14.4-S3D	0.07836	0.0749	3408	-3.066	1898	-110.5	0.00346
T3-L10.8-S2D	0.1008	0.09835	1092	-18.45	993.4	7.456	0.00245
T3-L10.8-S2.5D	0.09554	0.09094	2038	-8.221	1116	2.629	0.0046
T3-L10.8-S3D	0.08968	0.08511	3669	-49.02	1936	-102	0.00457

4.2. Observations about un-piled rafts behaviour

Unpiled raft foundation is used as a baseline for comparison during designing piled raft foundations. Therefore, to analyse raft with different thickness without piling 18m by 12m rectangular raft is situated on a layered soil profile at the site. The subsoil, observed from geotechnical investigation report, consists of a 25m-thick top layer of medium to very stiff high-plastic silty clay and a subsequent layer of medium-dense to very-dense silty sand extending downward. For designing unpiled raft foundation, the thickness of the raft spreads the entire building load over a large area to reduce ground pressure, which is an important parameter to consider. Furthermore, the flexibility or stiffness nature of raft can determine the behaviour of piled raft foundation. The present study assessed the raft's stiffness and flexibility using Viggiani's (2001) raft-to-soil stiffness ratio. And the equation for raft to soil stiffness ration is as shown below:

$$K_{rs} = \frac{4 * E_r * (1 - V_s^2)}{3 * E_s * (1 - V_r^2)} \times \frac{t_r^3}{B_r^3} \qquad \text{……4.1}$$

Where: E_r is Young's modulus of the raft; v_s is the Poisson's ratio of soil; E_s is Young's modulus of soil, v_r is the Poisson's ratio of the raft; B_r is the width of the raft, and t_r is raft thickness. The soil-to-raft stiffness ratio equation indicates that as raft thickness increases, so does the raft-to soil stiffness ratio. The result of Viggiani (2001) indicated that Krs values of 0.001 indicate perfect flexibility, 0.001 to 1 indicate intermediate flexibility, and 1 indicates perfect stiffness respectively. For the present study result of raft-soil stiff ness ratio (Krs) for raft thickness of 2m, 2.5m and 3m were as shown below.

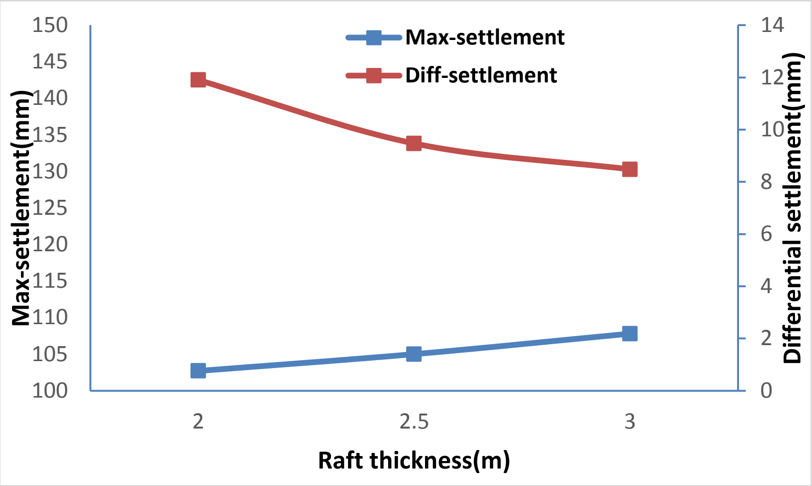
Table 4.4: Calculated Stiffness values for different raft thickness

Raft thickness (m)	**Raft-to-soil stiffness ratio (Krs)**
2m	2.6996
2.5m	5.272
3m	9.114

As it is seen from Table 4.4 the calculated Krs values for raft thicknesses of 2m, 2.5, and 3 m are 2.6996, 5.272, and 9.114 respectively. The raft with a thickness of 2m is relatively more flexible compared to the other thicknesses. Therefore, for all raft thicknesses since values of raft-to-soil are greater than one, the raft for study is classified as a perfect stiff material in which the obtained result is in agreement with the research conducted by Mali & Singh (2018). This is due to that a thicker raft has more structural rigidity and can distribute loads over larger area of the underlying soil or pile. Thus, settlement becomes reduced and improved stability is achieved. As Ramchandra (2020) points out, increasing the raft thickness reduces the load on individual piles and helps equalize settlement across the whole structure by increasing resistance to bending.

Similarly, in this study the effect of 520.37kPa application of a uniform load distribution and utilization of raft without pile having a thickness of 2m, 2.5m and 3m were examined. Figure 4.2 shows plaxis 3D numerical results for maximum and differential settlement of unpiled raft foundation with a raft thickness of 2m, 2.5m and 3m respectively. The result from Figure 4.2 shows that for the unpiled raft with a thickness of 2m, 2.5m and 3m values of maximum settlement increased to 102.7mm, 105mm and 107.8mm respectively. This is caused by the thickness of the raft incrementing, which increases its self-weight, adding more loads to the soil. Conversely, during raft thickness increment values of differential settlement become decreased to 11.9mm, 9.47mm and 8.48mm respectively.

Mali et al. (2020) found that as increasing raft thickness total and differential settlement would significantly decreased. This can be attributed from increased raft thickness by providing greater stiffness and a more uniform load distribution across the soil, thereby resisting compression more effectively. Therefore, a thicker raft can withstand vertical loads and reduce the potential for differential settlement, which is essential for the stability and safety of the structure (Mali et al, 2020). However, excessive thickness can lead to a constant settlement values once a certain limit is reached and can significantly increase the unpiled raft self- weight, which may contribute to an increase in total settlement. Therefore, the thickness of the raft must be carefully considered to ensure a balance between maximum vertical settlement and differential settlement, as well as the overall stability of the structure.

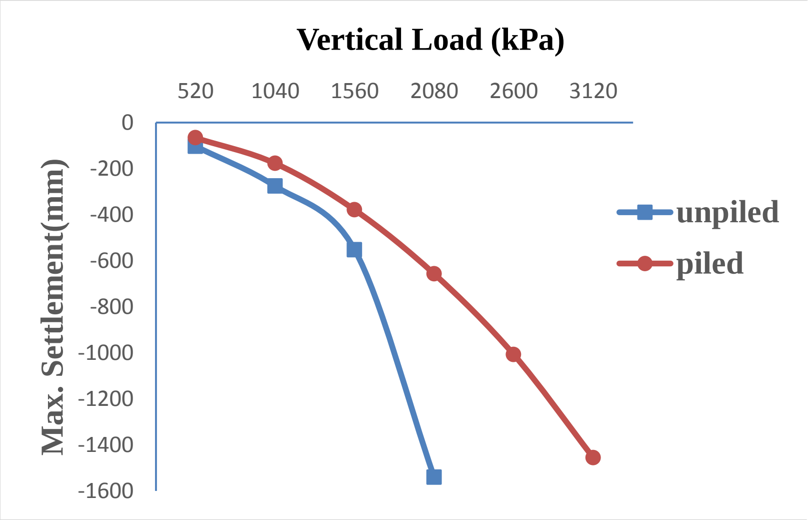


Raft Thickness(m)	Max Settl (mm)	Diff. Settl (mm)
2	102.7	11.9
2.5	105	9.47
3	107.8	8.47

Figure 4.2: Maximum and Differential settlements against raft thickness

4.3. Effect of load increment on piled and un-piled raft system on maximum settlement

Bralović et al. (2022) stated that under increasing applied loads, a piled raft foundation settles according to its load-settlement relationship, which is affected by the raft and pile load sharing. Initially, the piles carry most of the load and limit settlement. But as the applied load increases, the raft takes on a larger share of the load. They concluded that, final settlement of piled and unpiled raft system is influenced by several factors such as pile spacing, length, and soil properties. Therefore in this study effect of load increment on piled and unpiled raft system on maximum settlement were investigated. Figure 4.3 shows values of maximum settlement for piled and unpiled raft system against the applied loads.



Load	unPiled	piled
(kN)	Max. Set(mm)	Max. Set (mm)
520.37	102.7	66.28
1040	275.7	176.8
1560	552	378.8
2080	1540	656.9
2600	-	1007
3120	-	1445

Figure 4.3: Maximum settlement versus applied load for piled and un-plied raft system

As it can be seen from figure 4.3, during the raft is subjected under 520.37kPa, 1040kPa, 1560kPa and 2080kPa load application, results maximum settlements values of 102.7mm, 176.8mm, 378.8mm, and 656.9mm in case of un-piled raft system, and 66.28mm, 275.7mm, 552mm, and 1540mm for piled raft system respectively.

When the load increased from 520.37kPa to 1040kPa by 50% the settlement experienced about 165.45% increment for piled raft system and 168.45% for un-piled raft system respectively. Upon doubling the load to 1560kPa, the settlement increased by 437.48% (unpiled) and 471.5% (piled). The figure illustrates that, for unpiled foundation, as vertical load increases, maximum settlement increases extremely. The curve for unpiled raft foundation shows a steep decline, indicating that unpiled raft foundations experience substantial settlement under higher loads. Whereas, for piled raft foundation the maximum settlement for piled raft foundations also increases with vertical load, but at a much slower rate compared to unpiled foundations and the curve is flatter, suggesting that piled foundations provide better load-bearing capacity and result in less settlement under similar loading conditions.

Moreover, when the load increases values of settlement for both piled and unpiled raft systems were extremely increased as presented on Figure 4.3. This occurs due to soil particle compression when a load is applied to the soil surface. The vertical pressure increases, pushing the soil particles closer together and causing the overall volume of the soil beneath the raft to decrease, which leads to gradual settlement. Therefore, as the load on the raft increases, the soil experiences more compression, resulting in a higher rate of settlement. From figure 4.4, comparing the unpiled raft system with the piled raft foundation shows greater load-bearing capacity and reduced settlement, with the load versus settlement distribution being more uniform.

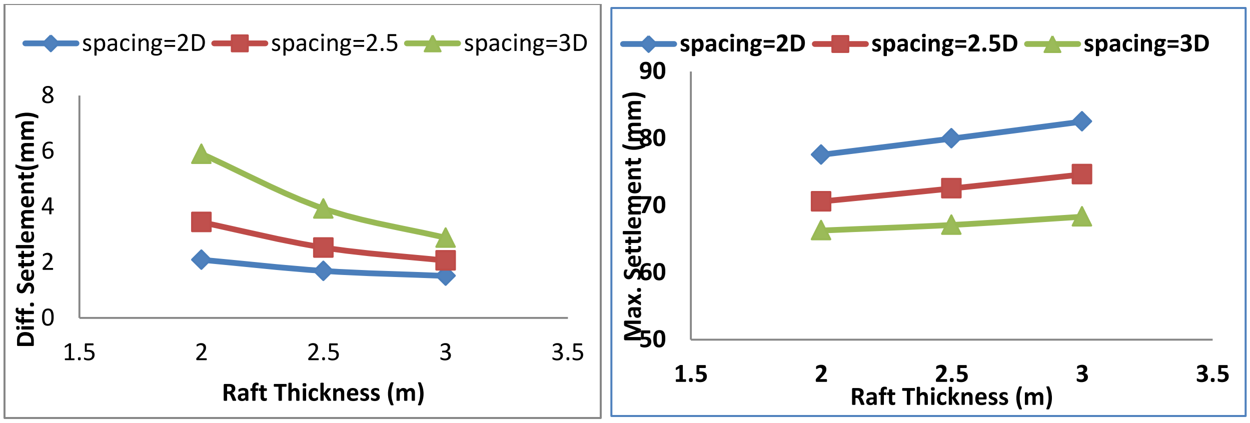
4.4. Effect of raft thickness of piled raft system on maximum and differential settlement

This study examined the influence of raft thickness on the settlement reduction capability of piled raft system. To achieve three different raft thicknesses, namely 2m, 2.5m, and 3m were used during numerical modeling. The piles had a fixed length of 18 m, with pile diameter of 1m respectively, under 520.37 kPa axial load application. Table 4.5 presents values of maximum and differential settlement for piled raft system against the applied loads. By varying parameters like raft thickness and pile length though taking other as a constant, a comprehensive evaluation of maximum settlement and differential settlement of piled rafts were carried out, as displayed in Table 4.5.

Table 4.5: Values of maximum and differential settlement against raft thickness

Raft Thickness (m)	**Maximum Settlement (mm)**			**Differential Settlement (mm)**		
	Pile Spacing(2D)			Pile Spacing(2D)		
	L=18m	L=14.4m	10.8m	L=18m	L=14.4m	10.8m
2	77.57	85.6	95.41	2.09	2.24	3.59
2.5	79.99	88.1	97.95	1.69	1.58	2.83
3	82.52	90.66	100.8	1.51	1.29	2.45
Raft Thickness (m)	**Maximum Settlement (mm)**			**Differential Settlement (mm)**		
	Pile Spacing(2.5D)			Pile Spacing(2.5D)		
	L=18m	L=14.4m	10.8m	L=18m	L=14.4m	10.8m
2	70.61	80.11	90.7	3.44	5.55	6.69
2.5	72.55	82.23	93.04	2.53	4.43	5.27
3	74.64	84.58	95.54	2.06	3.87	4.6
Raft Thickness (m)	**Maximum Settlement (mm)**			**Differential Settlement (mm)**		
	Pile Spacing(3D)			Pile Spacing(3D)		
	L=18m	L=14.4m	10.8m	L=18m	L=14.4m	10.8m
2	66.28	75.18	85.7	5.9	6.67	7.77
2.5	67.11	76.5	87.48	3.93	4.5	5.56
3	68.34	78.36	89.68	2.88	3.46	4.57

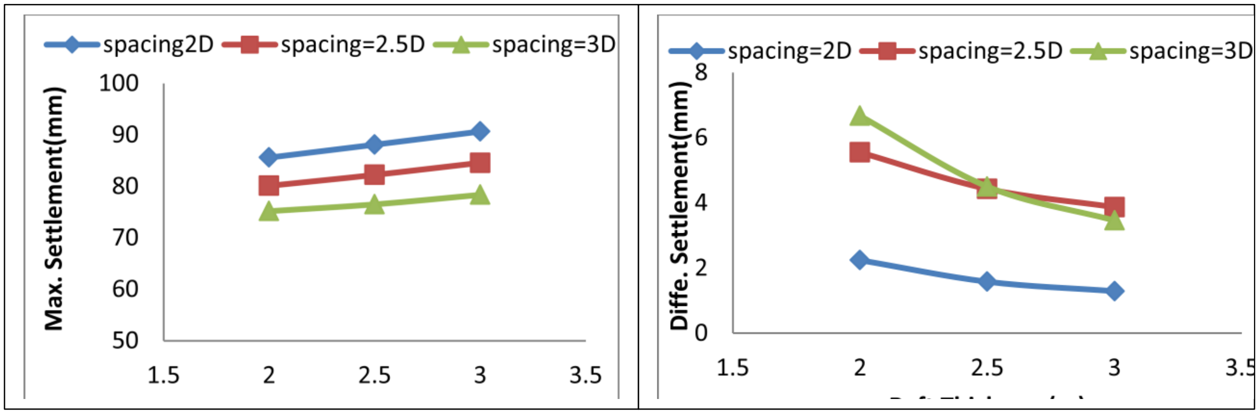
Figure 4.4 shows numerical results for the maximum and differential settlement of the piled raft system. From the figure, it can be observed that the values of maximum settlement increase when the raft thickness increases. Conversely, values of differential settlement were considerably reduced when the raft thickness increased. As it can be seen from Figure 4.4(a) when raft thickness increased from 2m to 2.5m and 3m while taking pile length as 18m then values of maximum settlement were increased from 66.28mm to 67.11mm and 68.34mm for 3D pile spacing, from 60.61mm to 72.55 and 74.64mm for 2.5D pile spacing and from 77.57mm to 79.99mm and 82.52mm for 2D pile spacing respectively. Conversely, by realizing from Figure 4.4(b), values of differential settlements were considerably reduced from 5.9mm to 3.93mm and 2.88mm for 3D pile spacing, from 3.44mm to 2.53mm and 2.06mm for 2.5D pile spacing, and from 2.09mm to 1.69mm and 1.51mm for 2D pile spacing, respectively.



a) Maximum settlement Vs Raft thickness **b) differential settlement Vs Raft thickness**

Figure 4.4: Settlement vs raft thickness of 18m pile length at various raft thickness

Similarly, Figure 4.5 presents numerical result for the maximum and differential settlement of the piled raft system for 14.4m pile length. It can be observed from the figure that maximum settlement values increase as the raft thickness increases. Conversely, differential settlement values decrease significantly with increasing raft thickness. As shown in Figure 4.5(a), when the raft thickness increases from 2m to 2.5m and 3m while keeping the pile length at 14.4m, the maximum settlement values increase from 75.18mm to 76.5mm and 78.36mm for 3D pile spacing, from 80.11mm to 82.23mm and 84.58mm for 2.5D pile spacing, and from 85.6mm to 88.1mm and 90.66mm for 2D pile spacing. Conversely, as seen in Figure 4.5(b), differential settlement values decrease substantially from 6.67mm to 4.5mm and 3.46mm for 3D pile spacing, from 5.5mm to 4.43mm and 3.87mm for 2.5D pile spacing, and from 2.24mm to 1.58mm and 1.29mm for 2D pile spacing, respectively.



a) Maximum settlement Vs Raft thickness **b) differential settlement Vs Raft thickness**

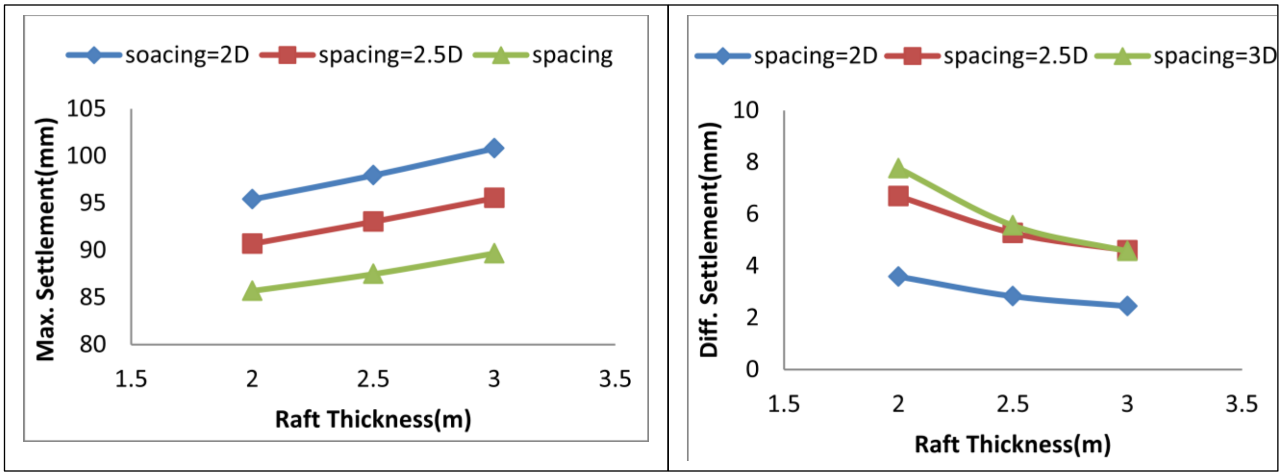
Figure 4.5: Settlement vs raft thickness of 14.4m pile length at various raft thickness

Moreover, Figure 4.6 presents numerical result for the maximum and differential settlement of the piled raft system for 10.8m pile length. From figure it can be clearly seen that similar trend were observed for maximum and differential settlement values. From Figure 4.6(a), when the raft thickness increases from 2m to 2.5m and 3m while keeping the pile length at 10.8m, the maximum settlement value increased from 85.7mm to 87.48mm and 89.68mm for 3D pile spacing, from 90.7mm to 93.04mm and 95.54mm for 2.5D pile spacing, and from 95.41mm to 97.95mm and 100.8mm for 2D pile spacing. On the contrary, from Figure 4.6(b), differential settlement values decrease considerably from 7.77mm to 5.56mm and 4.57mm for 3D pile spacing, from 6.69mm to 5.56mm and4.57mm for 2.5D pile spacing, and from 3.59mm to 2.83mm and 2.45mm for 2D pile spacing, respectively.

In general it can be concluded that when raft thickness increased for piled raft system then settlement value become increased on the contrary, differential settlement were reduced significantly. The reason for settlement increment when raft thickness increases is that thicker rafts have a larger area and more volume, leading to more contact with the soil and a greater capacity to deform the soil during load transfer from raft to soil with the help of pile interaction.

Conversely, when the raft thickness increases, the piled raft system becomes more rigid with higher values of relative stiffness. These enable the raft to distribute the concentrated load from the superstructure to piles and underlying soil, making the settlement uniform. For this reason, differential settlement decreases significantly when the raft thickness is increased for the piled raft system.

In a piled raft system, Ezz-Eldeen et al. (2024) reported that the average settlement increases with increased raft thickness, but differential settlement is significantly reduced. In addition, the study found that the stiffer, thicker raft distributed loads more evenly across the piles and soil, resulting in a more uniform deformation profile. It was concluded that the stiffer and more equally distributed raft minimized differential settlement.



a) Maximum settlement Vs Raft thickness **b) differential settlement Vs Raft thickness**

Figure 4.6: Maximum and differential settlement vs raft thickness of 10.8m pile length at various raft thickness

4.5. Effect of pile spacing on settlement reduction for piled raft foundation system

In this study detailed analysis of the effects of pile spacing on piled rafts system was examined. The models employed three different pile spacing's along the shorter side of the rectangular raft, specifically 2D, 2.5D, and 3D, while the longer side had a spacing of 1.5 times that of the shorter side. The piles were 18 meters long, with a diameter of 1 meters and a 2m raft thickness, and were subjected to an applied load of 520.37Kpa. Based on table 4.6, a comprehensive analysis of the maximum settlement, differential settlement, and maximum bending moment of piled rafts with varying pile spacing was carried out.

Table 4.6: Maximum and differential settlement values against pile spacing

pile spacing (D=1m)	**Maximum Settlement (mm)**			**Differential Settlement (mm)**		
	pile length =18m					
	T=2m	T=2.5m	T=3m	T=2m	T=2.5m	T=3m
2	77.57	79.99	82.52	2.09	1.69	1.51
2.5	70.61	72.55	74.64	3.44	2.53	2.66
3	66.28	67.11	68.34	5.9	3.93	2.88

The numerical results for piled raft settlement for using different pile spacing are shown in Figure 4.7. As can be seen in Figure 4.7, the maximum settlement values decreased significantly with increased pile spacing. From Figure 4.7, when pile spacing is increased from 2D to 2.5D and 3D while taking the pile length as 18m, the maximum settlement values decrease from 77.57mm to 70.61mm and 66.28mm, decreasing the settlement by 17.03% at 3D pile spacing for a 2m raft thickness, from 79.99mm to 72.55mm and 67.11mm, decreasing the settlement by 19.19% at 3D pile spacing for 2.5m raft thickness and from 82.52mm to 74.64mm and 68.34mm, decreasing the settlement by 20.75% at 3D pile spacing for 3m raft thickness respectively.

It is evident that for any number of piles, the maximum settlement decreases as the pile spacing increases, as revealed in Figure 4.7. Mali et al. (2020) found that when the pile spacing increases with a given number of piles, the width of the pile group (Bg) also increases, resulting in an expanded area covered by the piles (Ag). As the area covered by the piles (Ag) increases, they become more evenly distributed beneath the entire area of the raft (Ar), leading to a decrease in the maximum settlement of the pile-raft system. Furthermore, they found that with lower pile spacing, piles tended to concentrate toward the center of the raft, despite the load being distributed evenly across the raft. Accordingly, the maximum settlement was larger for lower pile spacing compared to larger pile spacing (Mali et al., 2020). In a piled raft foundation, El-Samny et al. (2020) found that increasing pile spacing generally decreases settlement, increases the load carried by the raft, and reduces the load on individual piles. A closer spacing (e.g., 2D-3D) results in a more uniform distribution of load among piles, whereas a wider spacing (e.g., 4D-4.5D) causes the raft to carry a larger percentage of the total load and reduce settlement more effectively and they concluded that a large spacing of pile, however, can reduce the benefit of pile systems (Oh et al. 2009 and El-Samny et al. 2020).

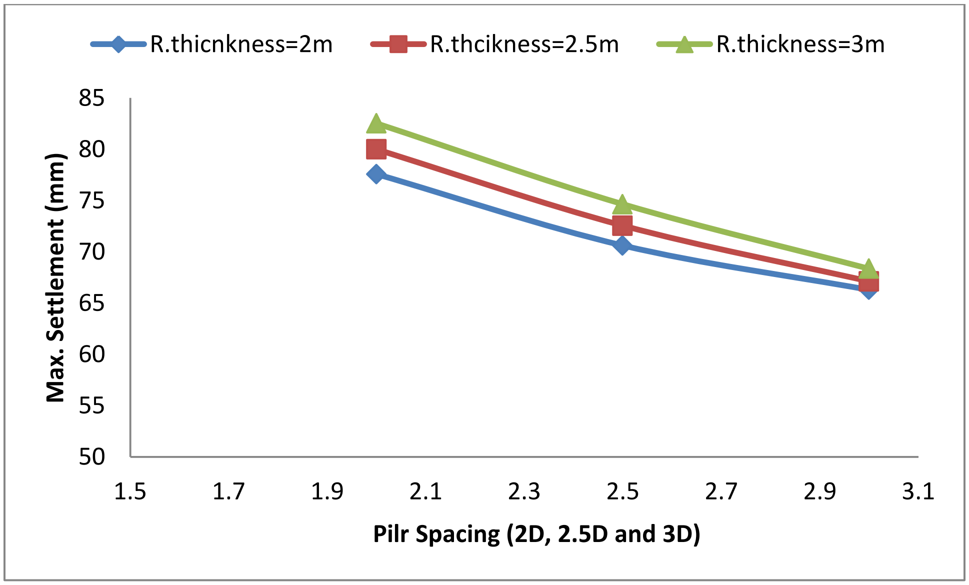


Figure 4.7: Effect of pile spacing on maximum settlement

According to Suro et al. (2016), pile spacing impacts pile raft settlement, with optimal spacing (often 3-times pile diameter) minimizing settlement by balancing individual pile support and group interaction. In addition, they suggested that too little spacing can result in increased settlement due to reduced soil compaction and result in decreased in differential settlement due to increased pile group effects. Whereas, too much spacing (> 4D) can also result in greater settlement as fewer piles share the load, causing less combined raft-soil-pile interaction, while too little pile spacing can (Oh et al. 2009).

From Figure 4.8, when pile spacing is increased from 2D to 2.5D and 3D while taking the pile length and pile diameter (D) as 18m and 1m, values of differential settlement were increased from 2.09mm to 3.44mm and 5.9mm, increasing the settlement by 182.29% at 3D pile spacing for a 2m raft thickness, from 1.69mm to 2.53mm and 2.66mm, increasing the settlement by 57.39% at 3D pile spacing for 2.5m raft thickness and from 1.51mm to 2.66mm and 2.88mm, increasing the settlement by 90.73% at 3D pile spacing for 3m raft thickness respectively. Based on the results presented in Figure 4.9, differential settlement values demonstrate a clear trend as pile spacing increases. Interestingly, the trend is opposite to the maximum settlement trend. It can be observed that for 2m, 2.5m and 3m raft thickness, the differential settlement increases as the pile spacing increases. In the case of increased pile spacing, the piles tend to move away from the center of the raft, leading to an increase in the pile group area (Ag) and a subsequent decrease in the central settlement of the raft. As a result, the piles start behaving as individual elements rather than a cohesive group. This causes edge piles to experience less load compared to the center piles, leading to an uneven distribution of load and an increase in differential settlement (Biya et al. 2023, Mali et al., 2020). To examine the behavior of piled raft foundations in stiff clay, Mali and Singh (2018) applied the 3D finite element method. And they found that as the spacing of the piles increases up to a certain value, differential settlement decreases, and then increases. Therefore, the optimal pile spacing for the piled raft system could be decisive. If the spacing is beyond the optimal, the piles become less effective as a group, and the load is distributed less efficiently, results to increased bending moments in the raft and consequently an increase in differential settlement. The researchers recommended a pile spacing of 2D-3D (Maharaj et al, 2004, Oh et al, 2009).

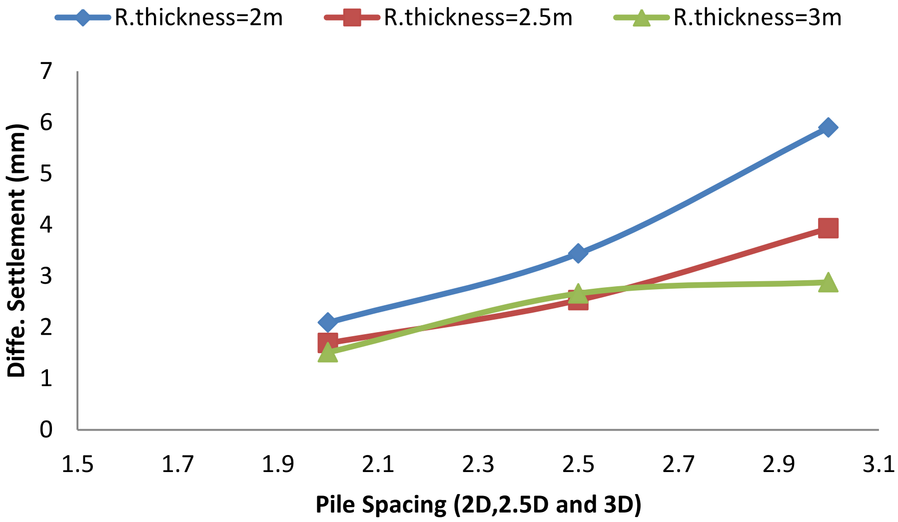
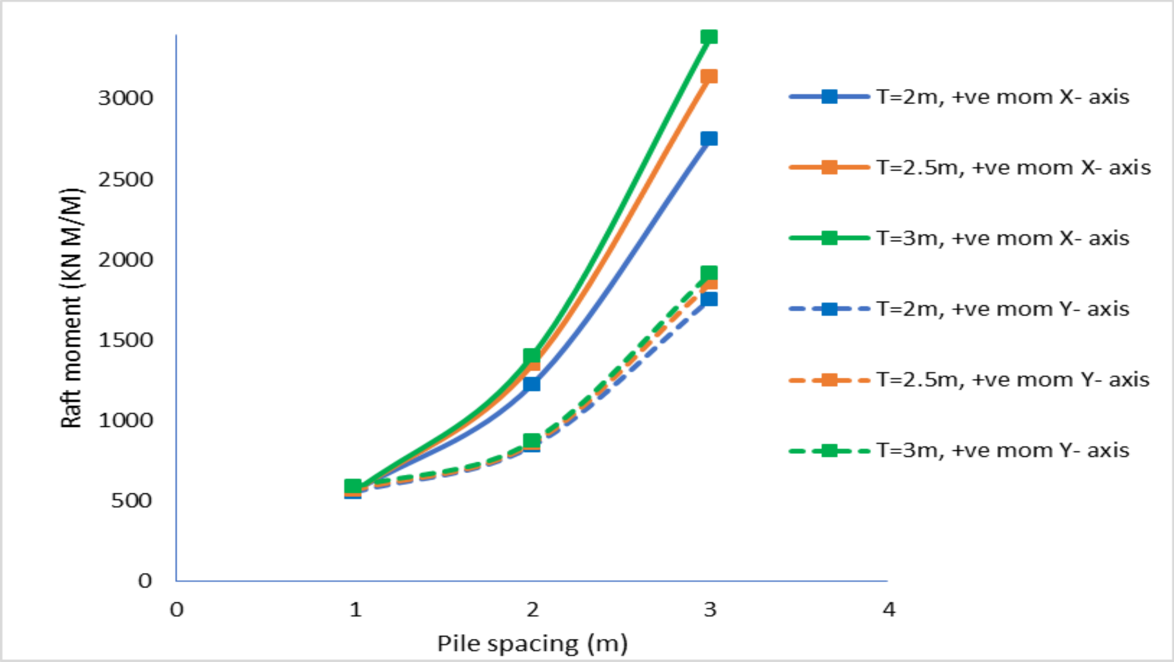


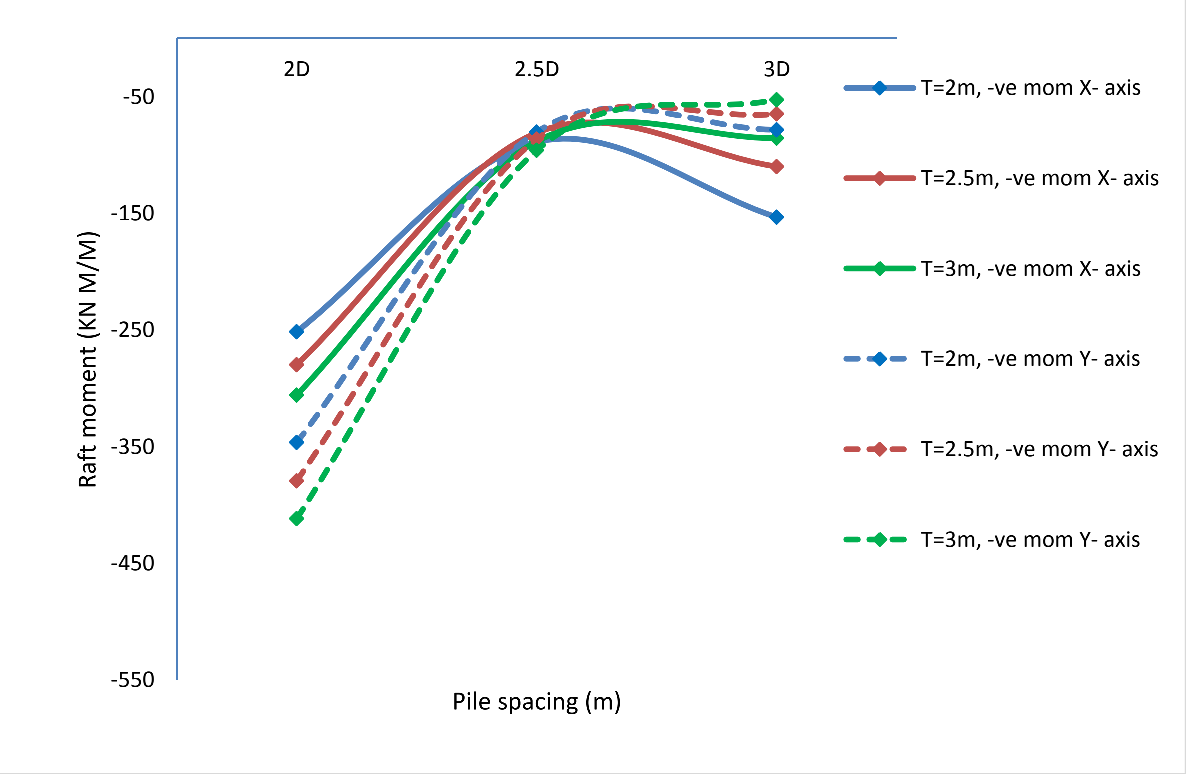
Figure 4.8: Effect of pile spacing on differential settlement

4.6. Effect of Pile Spacing on Bending Moment of Piled Raft Foundation

The bending moment (*M*) developed in the raft foundations are considered as crucial entity for reinforcement design of piled raft foundation. According to Poulos (2001b), maximum bending moments in the raft should be considered when designing a piled raft system. He also reported that the maximum bending moment in the raft increases with increases in raft thickness. Hakro et al. (2022) found that unpiled rafts experience sagging moments caused by soil settlement, while piled rafts can also experience hogging moments at the piles because their upward reaction force supports the raft locally, inverting the curvature and causing tension at specific points on the top surface. The numerical results for piled raft positive and negative bending moment for using different pile spacing are shown in Figure 4.9.



a) Pile spacing Vs maximum positive bending moment for different raft thickness



b) Pile spacing Vs maximum positive bending moment for different raft thickness

Figure 4.9: Effect of pile spacing on the maximum bending moment for different raft thickness

From figure 4.9, whereas taking pile length and pile diameter with constant values of 18m and 1m respectively, for 2m and 2.5m raft thickness the maximum negative moment along the short (X-direction) decreases initially as the pile spacing increases from 2D to 2.5D, then increases when the pile spacing increases from 2.5D to 3D. On the other hand, for 3m raft thickness, and 3D pile spacing along the short direction and also for 2m, 2.5m and 3m raft thickness in the long (Y-direction) maximum negative moment is continuously decreased when the pile spacing increases from 2D, 2.5D and 3D respectively.

Generally, as the thickness of the raft of a piled raft foundation increased from 2.5m to 3m for 2.5D and 3D pile spacing, the maximum negative moment in the short direction become increased. This is because thicker, stiffer rafts can less deform and accommodate load distribution, leading to greater bending moments and higher localized stresses, particularly in situations where negative curvature is caused by external loads or settlements. There is, however, a limit thickness where this effect may diminish, as the raft behaves more rigidly and moments remain constant (Kumar et al. 2020). When pile spacing increases, negative bending moments decrease, probably because as pile spacing increases, grouped pile width also increases, impacting the negative bending moments (biya et al. 2023).

Additionally, when pile spacing increases with the raft thickness increment, the maximum positive bending moment is increased. According to El-Samny et al. (2020), increasing pile spacing in a piled raft foundation increases positive bending moments. In addition, they explained that a wider pile spacing results in less support from the piles, causing the raft to bear a larger portion of the load directly, causing greater bending of the structure. With the increase in pile spacing from 2D to 2.5D and 3D, more raft-soil interaction occurs, which helps distribute the load. Despite this, this can also increase the load on the raft and result in a greater bending moment in the structure (Malviya et al., 2024).

4.7. Effect of Pile Length on Maximum and Differential Settlement of Piled Raft Foundation

In this study detailed analysis of the effects of pile length on piled rafts system was carriedout. The models employed three different pile length specifically 18m, 14.4m, and 10.8. The piles were 2D, 2.5D and 3D spaced. To analyze pile length effect 2m raft thickness were considered, and piled raft foundation were subjected to an applied load of 520.37Kpa. Based on table 4.7, a comprehensive analysis of the maximum settlement and differential settlement of piled rafts with varying pile spacing was carried out.

Table 4.7: Values of maximum and differential settlement against pile length

Pile Length (m)	**Raft Thickness=2m**					
	Maximum Settlement (mm)			**Differential Settlement (mm)**		
	S=2D	S=2.5D	S=3D	S=2D	S=2.5D	S=3D
18	77.57	70.61	66.28	2.09	3.44	5.9
14.4	86.6	80.11	75.18	2.24	5.55	6.67
10.8	95.41	90.7	85.7	3.59	6.69	7.66

From Figure 4.10, when pile length is increased from 10.8m to 14.4m and 18 while taking the raft thickness and pile diameter (D) as 2m and 1m respectively, values of maximum settlement were decreased from 95.41mm to 86.6mm and 77.57mm, decreasing the settlement by 18.6% at 18m pile length for S=2D pile spacing, from 90.7mm to 80.11mm and 70.61mm, decreasing the settlement by 22.15% at 18m pile length for S=2.5D pile spacing and from 85.7mm to 75.18mm and 66.28mm, decreasing the settlement by 22.67% at 18m pile length for S=3D pile spacing respectively. According to the results, maximum settlement is significantly increased when pile length is reduced. Consequently, this is due to the pile length's insufficiency to reach stronger strata. A shorter pile can result in increased settlement when compared to a longer pile that effectively transfers load to more stable soil (Drill Master, 2024).

Furthermore, if the pile is too short, its skin friction capacity may not be fully mobilized, and the end-bearing contribution may be limited. As a result, the pile capacity is reduced, and a greater portion of the load is carried by the raft and soil surrounding it, resulting in increased settlement. In their study, O'Brien et al. (2012) found that when piles are shorter, the raft bears more of the total load. As a result of this increased stress concentration on the raft, the raft can experience greater bending moments and shear forces. Therefore, when pile length is reduced then settlements increased.

According to Kacprzak et al. (2025), the behavior of a piled raft foundation is highly dependent on the interaction between the piles and the surrounding soil. When piles are shorter, they may not interact with the soil effectively, resulting in a less rigid foundation system and a greater likelihood of settlement. Soil type also affects pile length's effect on settlement. Longer piles reduce settlement in soft clay or loose sand by transferring loads to deeper, more stable layers. Shorter piles may be sufficient to provide adequate support in stiffer soils, though the benefit of increasing pile length may be less pronounced (Basha et al., 2022).

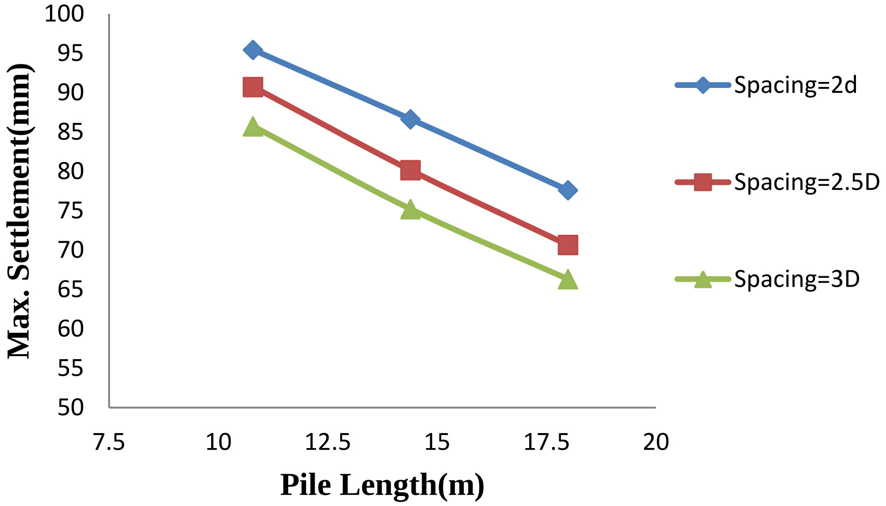


Figure 4.10: Effect of pile length on maximum settlement

From Figure 4.11, when pile length is increased from 10.8m to 14.4m and 18 values of differential settlement were decreased from 3.59mm to 2.24mm and 2.09mm, decreasing the settlement by 41.78% at 18m pile length for S=2D pile spacing, from 6.69mm to 5.55mm and 3.44mm, decreasing the settlement by 48.58% at 18m pile length for S=2.5D pile spacing and from 7.66mm to 6.67mm and 5.9mm, decreasing the settlement by 22.97% at 18m pile length for S=3D pile spacing respectively.

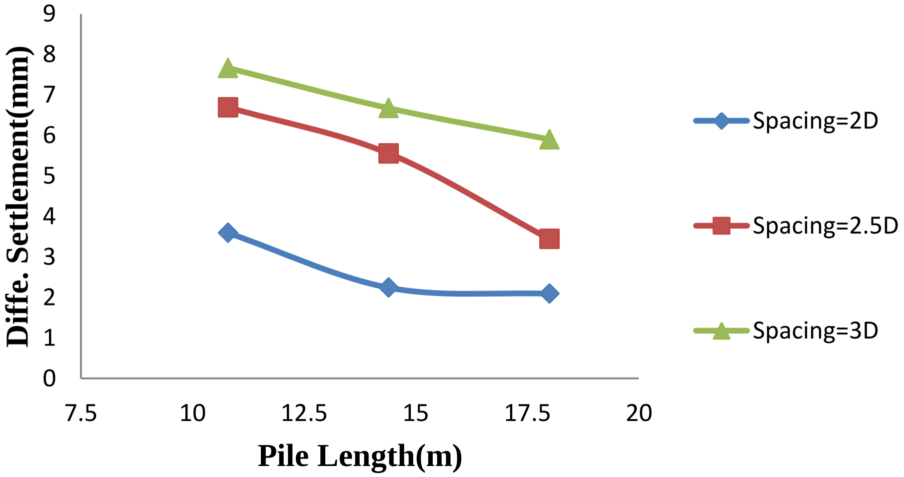


Figure 4.11: Effect of pile length on differential settlement values

As can be seen from Figure 4.11, differential settlement increases with decreasing pile length. As pile length decreases, piles are less able to transfer loads to deeper, stable soil layers, increasing stress on rafts and surrounding soil. As a result of this uneven distribution of stress, the foundation settles at a greater differential settlement.

4.8. Effect of Pile length on Bending Moment of Piled Raft Foundation

Table 4.8: Bending moment values against pile length

Maximum bending moment(KNM/M), raft thickness =2m							
	Pile length(m)	S=2D		S=2.5D		S=3D	
Negative moment		m11	m22	m11	m22	m11	m22
	18	-251.5	-346.5	-88.94	-80.34	-153.4	-78.43
	14.4	-1.668	-238.5	-2	-119.8	-49.45	-128.8
	10.8	-18.3	-400.55	-5.12	-3.03	-124.8	-119.4
Positive moment	18	557.5	553.9	1223	839.8	2748	1752
	14.4	766.8	681.2	1427	867.3	2814	1756
	10.8	998.8	928.9	1815	1052	3048	1790

From figure 4.12, whereas taking raft thickness and pile diameter with constant values of 2m and 1m respectively, for S=2D, S=2.5D and S=3D pile spacing the maximum positive moment along both short and long axis (X and Y-direction) increased when the pile length is decreased from 18m to 14.4m and 10.8m respectively. From the result it can be concluded that as the pile length is become reduced then values of maximum positive moments were increased. In a piled raft foundation, decreasing pile length can increase the positive bending moment within both the pile and the raft. There are several reasons for this, such as when piles are shorter, they may not reach as deep into competent soil layers, which mean the raft must carry a larger proportion of the load, so positive bending moments are greatly increased. Asefa et al. (2022) stated that when the pile length is decreased, the shorter piles offer less resistance to deformation, which can lead to a less uniform distribution of the load and less soil contact for friction. Therefore, the piles are more prone to bending from raft loads and can create differential settlement, increasing stress and bending moments within the pile group and the connected raft. Moreover, Hoang et al. (2024) found that when pile length is decreased, piles are more sensitive to variations in soil properties, leading to differential settlement and higher bending moments.

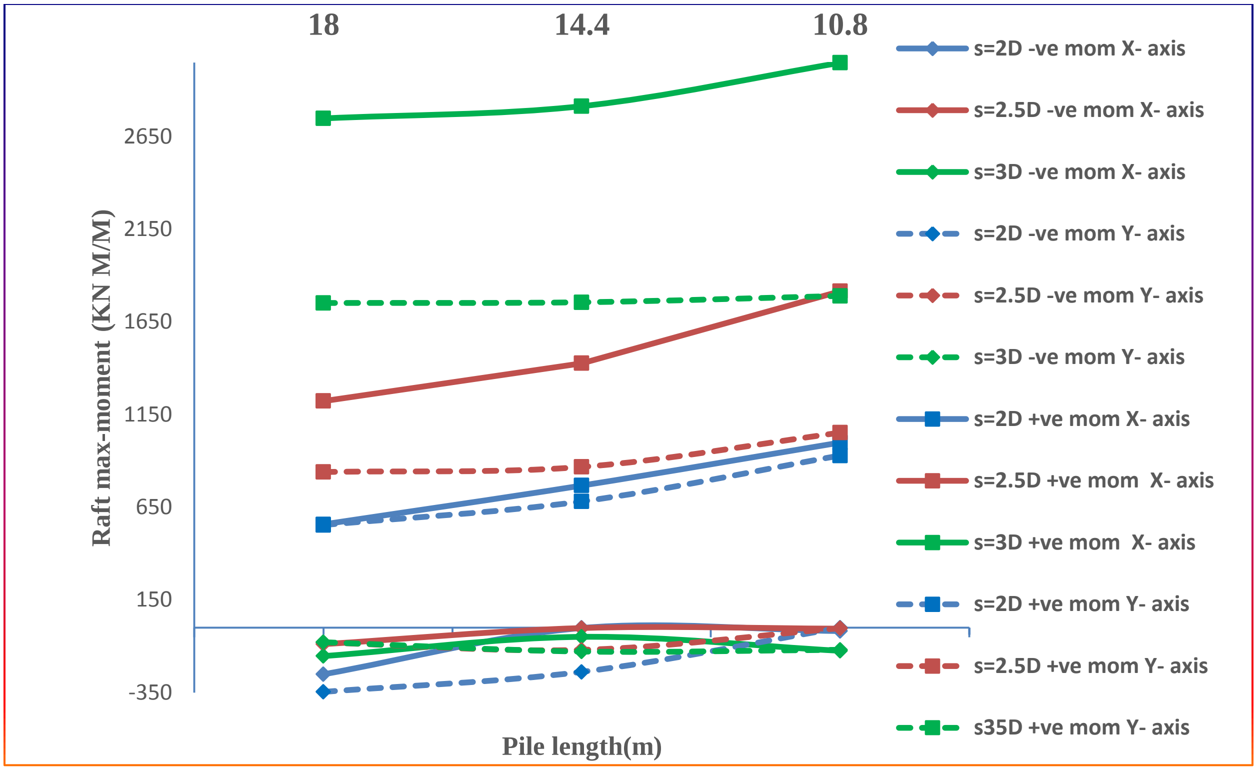


Figure 4.12: Effect of pile length on positive and negative bending moment

Generally, decreasing pile length can raise the positive bending moment in the raft because the raft ends up supporting a larger part of the structural load. Shorter piles offer less support and are more affected by soil condition variations, which can lead to increased stress and bending in the raft structure.

In pile raft foundations, negative bending moments can behave in complex ways. Figure 4.12 and Table 4.8 show that the negative moment value decreases greatly when the pile length decreases from 18m to 14.4m, and then increases when the pile length decreases to 10.8m. Several factors contribute to this, such as a shorter pile, which can lead to a more flexible raft, which can adapt to load changes more easily when the pile length is decreased. Negative bending moments can be temporarily reduced by this flexibility, especially at the edges where they tend to be highest (Hoang et al., 2024). According to El-Garhy et al. (2013), the initial decrease in negative moments can be followed by an increase in negative moments as the raft settles unevenly as a result of varying support from shorter piles. Furthermore, they found that localized settlements may cause negative moments to increase at the edges when adapting to the new loading conditions. In general, decreasing pile length in a piled raft foundation can lead to a decrease in negative bending moments initially due to increased load distribution to the raft. However, as differential settlement occurs and positive bending moments rise, negative moments can subsequently increase, reflecting the complex interplay between load distribution, raft flexibility, and soil interaction. Understanding these dynamics is crucial for effective design and analysis.

Chapter 5

Conclusion and Recommendation

5.1. Conclusion

In challenging soil environments and complex loading conditions, piled raft foundations are a preferred choice for many civil engineering projects. In this study, the load-settlement response of piled raft foundations was studied using numerical methods such as PLAXIS 3D, considering parameters such as raft thickness, pile spacing, and pile length. During study, a comprehensive parametric study using numerical methods and detailed structural analysis are essential to ensure that the chosen pile spacing; pile length and raft thickness effectively minimizes settlement and provides adequate support for the structure. Based on the observations presented in this paper, the following conclusions can be drawn:

- For unpiled raft foundation when the raft thickness increases from 2m to 2.5m and 3m, then values of maximum settlement were increased from 102.7mm to 105mm and 107.8mm. Conversely, values of differential settlement were reduced from 11.9mm to 9.47mm and 8.47mm, reduced by 28.8% for 3m raft thickness respectively. This indicates that greater raft thickness enhances overall stability by minimizing differential settlement despite a marginal increase in total settlement.
- Figure 4.4 illustrates that at lower loads, both foundations experience settlement, but piled raft foundations exhibit significantly lower maximum settlement values. As the load increases, the gap between the curves widens, demonstrating the effectiveness of piled raft foundations in managing higher loads with reduced settlement. Overall, this indicates that piled raft foundations are superior for heavy structures.
- When the unpiled raft foundation is piled with 18m pile lengths, a 1m pile diameter, and 3m pile spacing, the maximum settlement values are reduced from 102.7mm, 105mm, and 107.8mm to 66.28mm, 67.11mm, and 68.34mm for raft thicknesses of 2m, 2.5m, and 3m. Similarly, differential settlement also reduced from 11.9mm, 9.47mm and 8.47mm to 5.9mm, 3.93mm and 2.88mm. Piling the unpiled raft foundation significantly reduces maximum settlement, with reductions of 34.46%, 36.08% and 36.67% across raft thicknesses of 2m, 2.5m, and 3m.

- When pile spacing is increased from 2D to 2.5D and 3D, while maintaining a pile length of 18m, the maximum settlement values decrease from 77.57mm to 70.61mm and 66.28mm, resulting in a 17.03% reduction in settlement at 3D pile spacing for a 2m raft thickness. Conversely, the values of differential settlement increase from 2.09mm to 3.44mm and 5.9mm, representing an increase of 182.29% at 3D pile spacing. Increasing pile spacing reduces maximum settlement significantly, while differential settlement increases substantially.
- The study shows that pile spacing and raft thickness significantly impact bending moments in piled raft foundations. Initially, increasing spacing reduces maximum negative moments, but a larger raft thickness raises them. Additionally, wider spacing increases positive moments due to decreased pile support.
- Increasing the pile length from 10.8m to 14.4m and then to 18m, while keeping the raft thickness at 2m and pile diameter at 1m, reduces maximum settlement from 95.41mm to 86.6mm and 77.57mm. This results in an 18.6% decrease in settlement at 18m pile length for 2D pile spacing. Similarly, differential settlement decreased from 3.59mm to 2.24mm and then to 2.09mm, resulting in a reduction of 41.78%. Longer pile lengths significantly reduce both maximum and differential settlement values.
- Decreasing pile length in a piled raft foundation increases positive bending moments while initially reducing negative moments. As shorter piles provide less support and adaptability to soil variations, this can lead to differential settlement and eventual increases in negative moments. Understanding these interactions is essential for effective structural design and analysis.

5.2. Recommendation

- The study primarily focuses on numerical analysis; however, conducting laboratory experiments to validate the numerical results obtained from PLAXIS 3D using various soil types and loading conditions could also be explored.
- To enhance the understanding of piled raft foundations under complex loading patterns, such as eccentric and lateral loads, it is recommended to conduct additional numerical simulations.

- Due to time constraints, this study assumes pile diameter and pile number as a constant. However, it is recommended to investigate the effects of these parameters by varying them during numerical analysis.
- Future research should include a cost comparison of piled raft foundations with un-piled rafts and piles alone.

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Appendix-1: Load calculation from ETABS for 3B +35 building (wall Supported)

5.4 MAT and PILE DESIGN FOUNDATION DESIGN

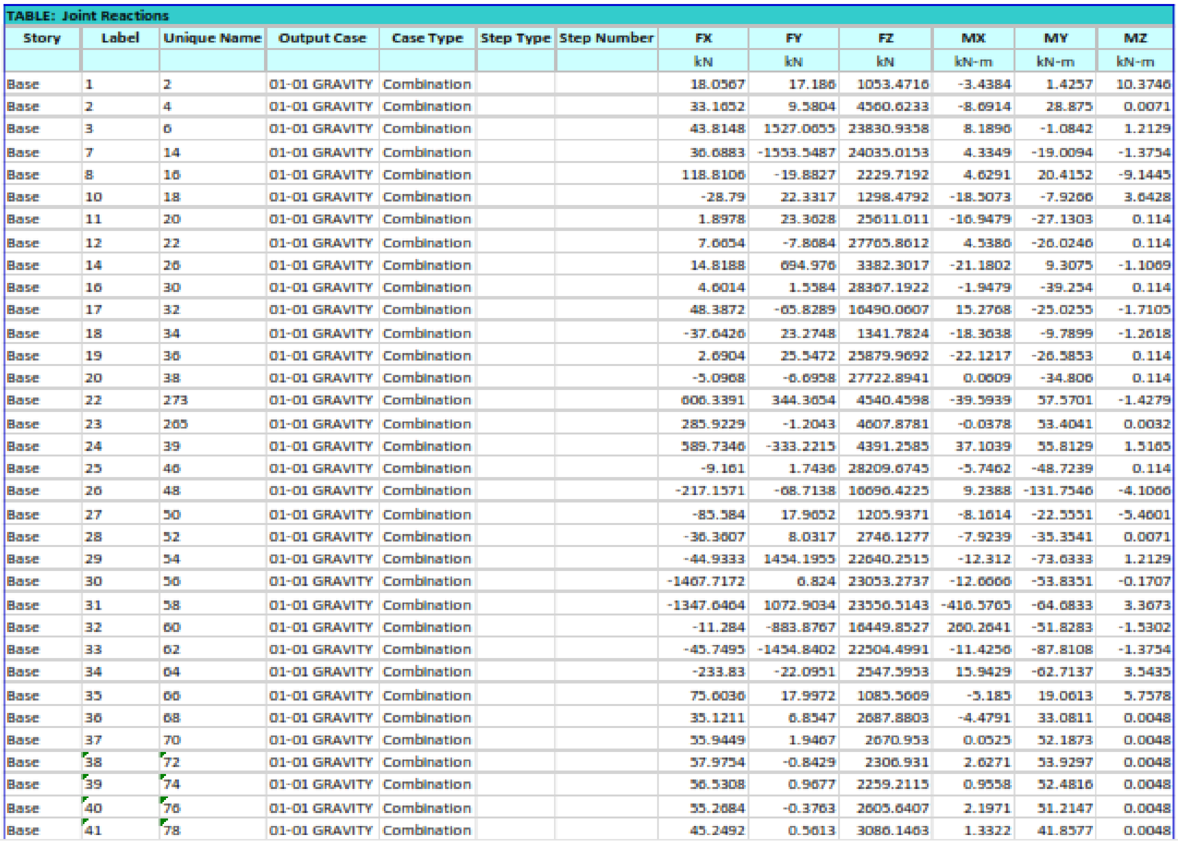
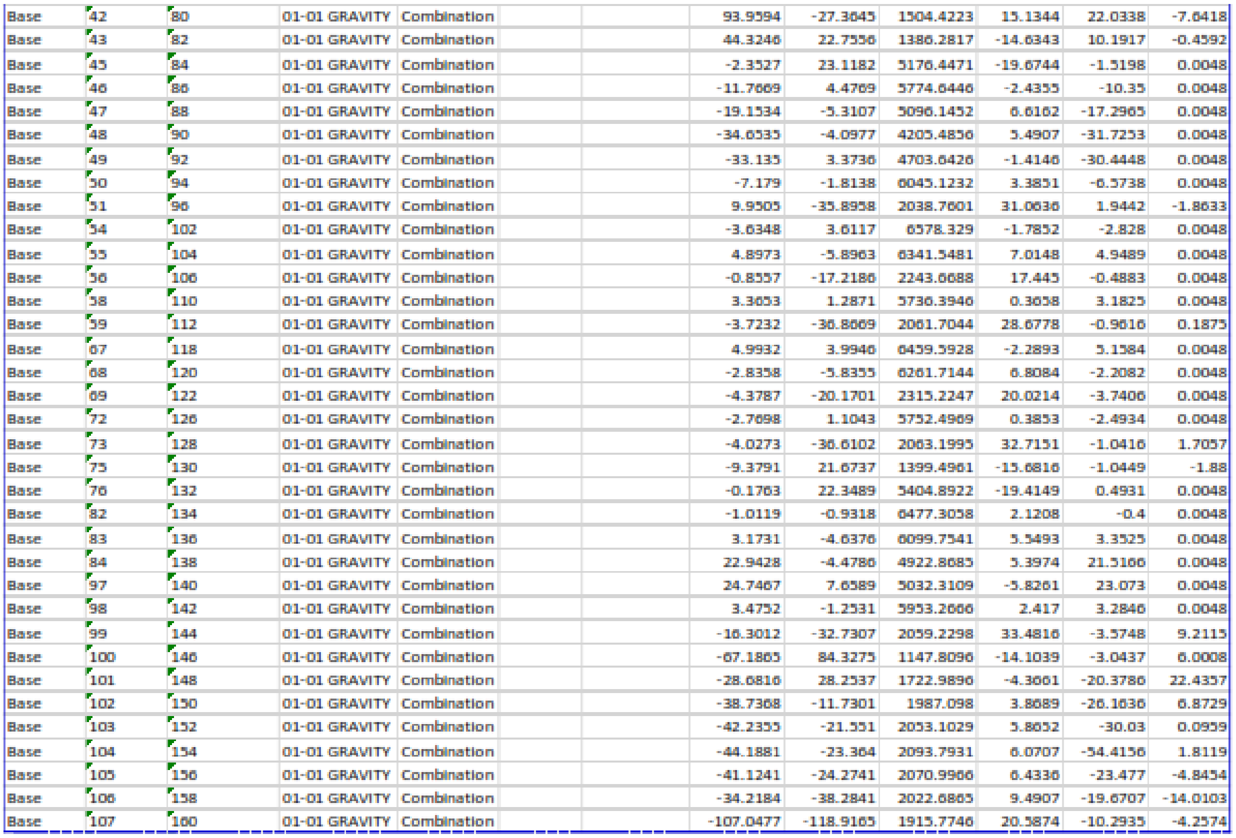
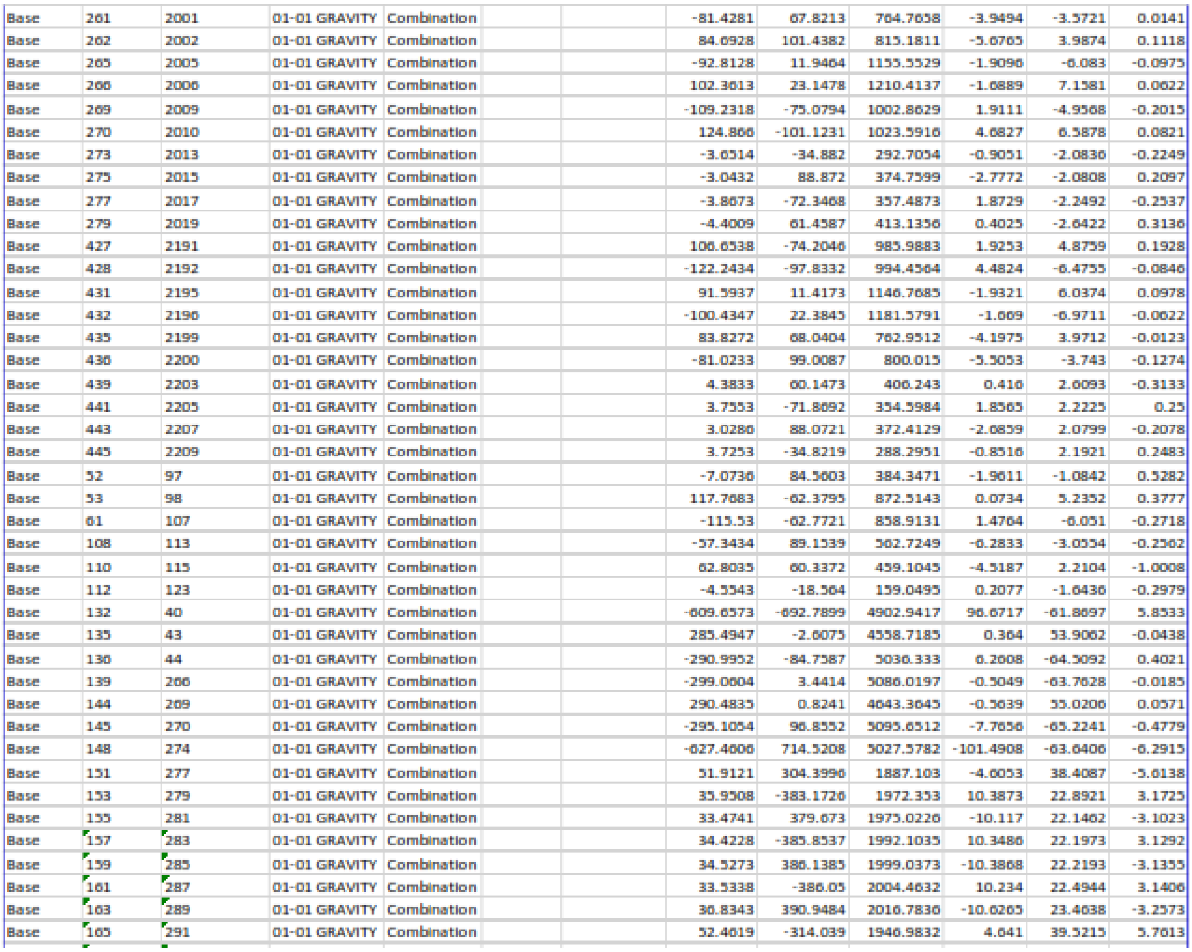


TABLE: Joint Reactions

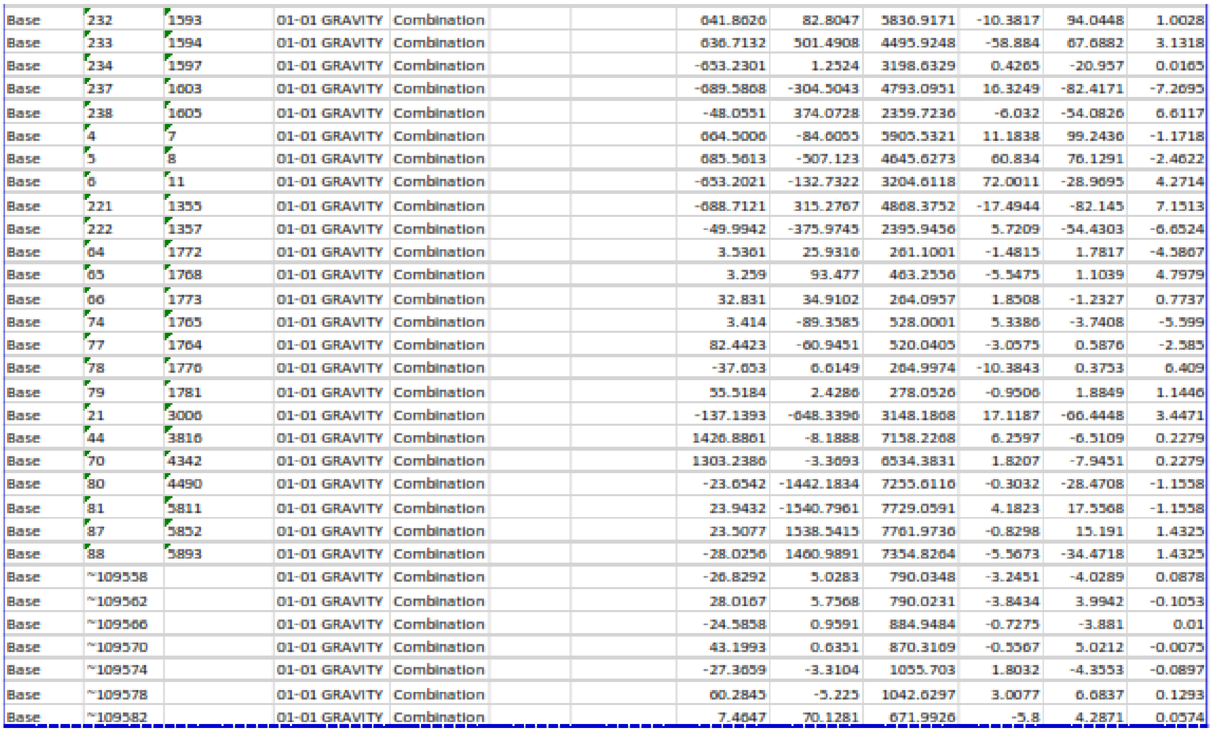
Story	Label	Unique Name	Output Case	Case Type	Step Type	Step Number	FX	FY	FZ	MX	MY	MZ
							kN	kN	kN	kN-m	kN-m	kN-m
Base	1	2	01-01 GRAVITY	Combination			18.0567	17.186	1053.4716	-3.4384	1.4257	10.3746
Base	2	4	01-01 GRAVITY	Combination			33.1652	9.5804	4560.6233	-8.6914	28.875	0.0071
Base	3	6	01-01 GRAVITY	Combination			43.8148	1527.0655	23830.9358	8.1896	-1.0842	1.2129
Base	7	14	01-01 GRAVITY	Combination			36.6883	-1553.5487	24035.0153	4.3349	-19.0094	-1.3754
Base	8	16	01-01 GRAVITY	Combination			118.8106	-19.8827	2229.7192	4.6291	20.4152	-9.1445
Base	10	18	01-01 GRAVITY	Combination			-28.79	22.3317	1298.4792	-18.5073	-7.9266	3.6428
Base	11	20	01-01 GRAVITY	Combination			1.8978	23.3628	25611.011	-16.9479	-27.1303	0.114
Base	12	22	01-01 GRAVITY	Combination			7.6654	-7.8684	27765.8612	4.5386	-26.0246	0.114
Base	14	26	01-01 GRAVITY	Combination			14.8188	694.976	3382.3017	-21.1802	9.3075	-1.1069
Base	16	30	01-01 GRAVITY	Combination			4.6014	1.5584	28367.1922	-1.9479	-39.254	0.114
Base	17	32	01-01 GRAVITY	Combination			48.3872	-65.8289	16490.0607	15.2768	-25.0255	-1.7105
Base	18	34	01-01 GRAVITY	Combination			-37.6426	23.2748	1341.7824	-18.3638	-9.7899	-1.2618
Base	19	36	01-01 GRAVITY	Combination			2.6904	25.5472	25879.9692	-22.1217	-26.5853	0.114
Base	20	38	01-01 GRAVITY	Combination			-5.0968	-6.6958	27722.8941	0.0609	-34.806	0.114
Base	22	273	01-01 GRAVITY	Combination			606.3391	344.3654	4540.4598	-39.5939	57.5701	-1.4279
Base	23	265	01-01 GRAVITY	Combination			285.9229	-1.2043	4607.8781	-0.0378	53.4041	0.0032
Base	24	39	01-01 GRAVITY	Combination			589.7346	-333.2215	4391.2585	37.1039	55.8129	1.5165
Base	25	46	01-01 GRAVITY	Combination			-9.161	1.7436	28209.6745	-5.7462	-48.7239	0.114
Base	26	48	01-01 GRAVITY	Combination			-217.1571	-68.7138	16696.4225	9.2388	-131.7546	-4.1066
Base	27	50	01-01 GRAVITY	Combination			-85.584	17.9652	1205.9371	-8.1614	-22.5551	-5.4601
Base	28	52	01-01 GRAVITY	Combination			-36.3607	8.0317	2746.1277	-7.9239	-35.3541	0.0071
Base	29	54	01-01 GRAVITY	Combination			-44.9333	1454.1955	22640.2515	-12.312	-73.6333	1.2129
Base	30	56	01-01 GRAVITY	Combination			-1467.7172	6.824	23053.2737	-12.6666	-53.8351	-0.1707
Base	31	58	01-01 GRAVITY	Combination			-1347.6464	1072.9034	23556.5143	-416.5765	-64.6833	3.3673
Base	32	60	01-01 GRAVITY	Combination			-11.284	-883.8767	16449.8527	260.2641	-51.8283	-1.5302
Base	33	62	01-01 GRAVITY	Combination			-45.7495	-1454.8402	22504.4991	-11.4256	-87.8108	-1.3754
Base	34	64	01-01 GRAVITY	Combination			-233.83	-22.0951	2547.5953	15.9429	-62.7137	3.5435
Base	35	66	01-01 GRAVITY	Combination			75.6036	17.9972	1085.5609	-5.185	19.0613	5.7578
Base	36	68	01-01 GRAVITY	Combination			35.1211	6.8547	2687.8803	-4.4791	33.0811	0.0048
Base	37	70	01-01 GRAVITY	Combination			55.9449	1.9467	2670.953	0.0525	52.1873	0.0048
Base	38	72	01-01 GRAVITY	Combination			57.9754	-0.8429	2306.931	2.6271	53.9297	0.0048
Base	39	74	01-01 GRAVITY	Combination			56.5308	0.9677	2259.2115	0.9558	52.4816	0.0048
Base	40	76	01-01 GRAVITY	Combination			55.2684	-0.3763	2605.6407	2.1971	51.2147	0.0048
Base	41	78	01-01 GRAVITY	Combination			45.2492	0.5613	3086.1463	1.3322	41.8577	0.0048



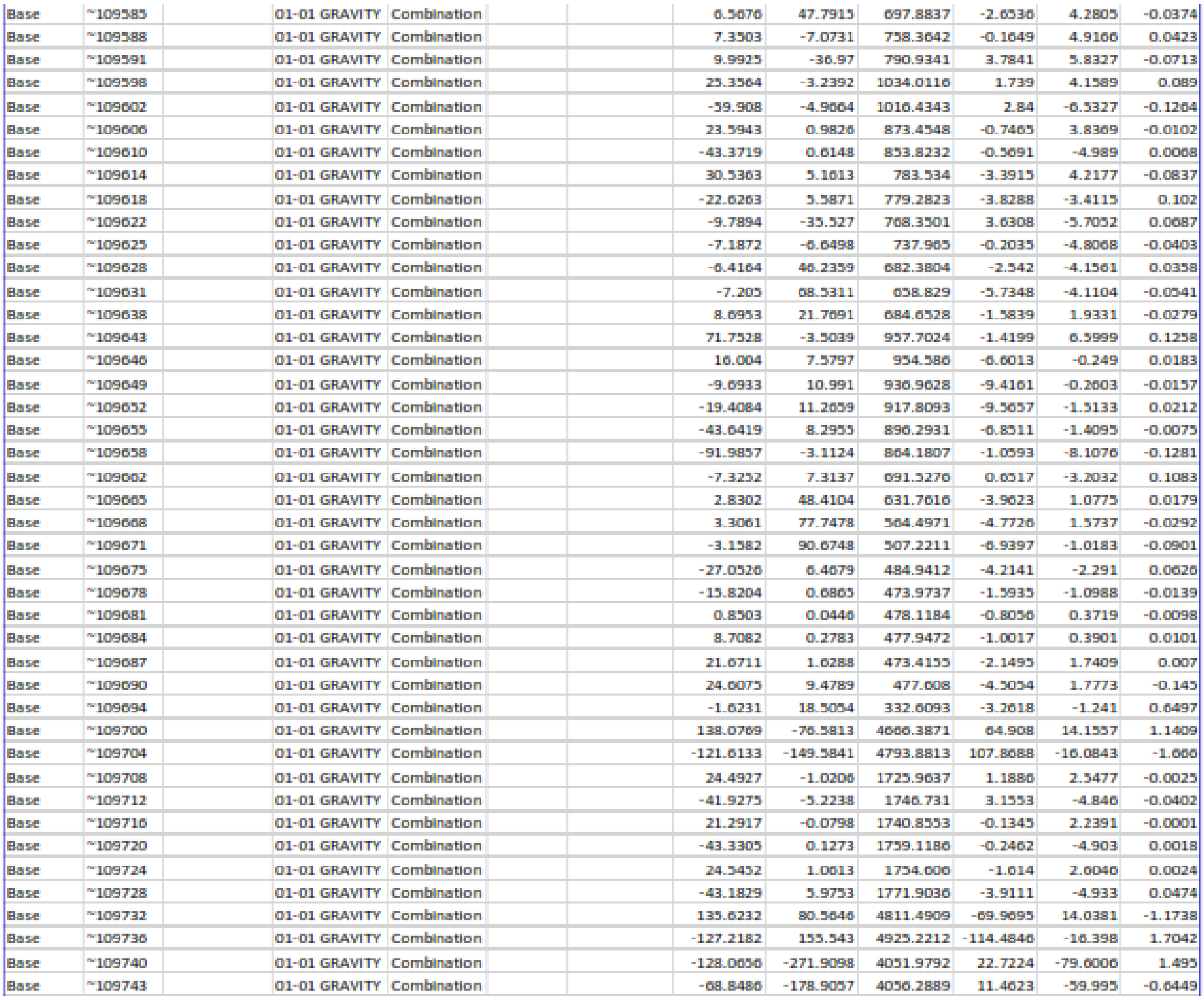
Base	42	80	01-01 GRAVITY	Combination			93.9594	-27.3645	1504.4223	15.1344	22.0338	-7.6418
Base	43	82	01-01 GRAVITY	Combination			44.3246	22.7556	1386.2817	-14.6343	10.1917	-0.4592
Base	45	84	01-01 GRAVITY	Combination			-2.3527	23.1182	5176.4471	-19.6744	-1.5198	0.0048
Base	46	86	01-01 GRAVITY	Combination			-11.7669	4.4769	5774.6446	-2.4355	-10.35	0.0048
Base	47	88	01-01 GRAVITY	Combination			-19.1534	-5.3107	5096.1452	6.6162	-17.2965	0.0048
Base	48	90	01-01 GRAVITY	Combination			-34.6535	-4.0977	4205.4856	5.4907	-31.7253	0.0048
Base	49	92	01-01 GRAVITY	Combination			-33.135	3.3736	4703.6426	-1.4146	-30.4448	0.0048
Base	50	94	01-01 GRAVITY	Combination			-7.179	-1.8138	6045.1232	3.3851	-6.5738	0.0048
Base	51	96	01-01 GRAVITY	Combination			9.9505	-35.8958	2038.7601	31.0636	1.9442	-1.8633
Base	54	102	01-01 GRAVITY	Combination			-3.6348	3.6117	6578.329	-1.7852	-2.828	0.0048
Base	55	104	01-01 GRAVITY	Combination			4.8973	-5.8963	6341.5481	7.0148	4.9489	0.0048
Base	56	106	01-01 GRAVITY	Combination			-0.8557	-17.2186	2243.6688	17.445	-0.4883	0.0048
Base	58	110	01-01 GRAVITY	Combination			3.3653	1.2871	5736.3946	0.3658	3.1825	0.0048
Base	59	112	01-01 GRAVITY	Combination			-3.7232	-36.8669	2061.7044	28.6778	-0.9616	0.1875
Base	67	118	01-01 GRAVITY	Combination			4.9932	3.9946	6459.5928	-2.2893	5.1584	0.0048
Base	68	120	01-01 GRAVITY	Combination			-2.8358	-5.8355	6261.7144	6.8084	-2.2082	0.0048
Base	69	122	01-01 GRAVITY	Combination			-4.3787	-20.1701	2315.2247	20.0214	-3.7406	0.0048
Base	72	126	01-01 GRAVITY	Combination			-2.7698	1.1043	5752.4969	0.3853	-2.4934	0.0048
Base	73	128	01-01 GRAVITY	Combination			-4.0273	-36.6102	2063.1995	32.7151	-1.0416	1.7057
Base	75	130	01-01 GRAVITY	Combination			-9.3791	21.6737	1399.4961	-15.6816	-1.0449	-1.88
Base	76	132	01-01 GRAVITY	Combination			-0.1763	22.3489	5404.8922	-19.4149	0.4931	0.0048
Base	82	134	01-01 GRAVITY	Combination			-1.0119	-0.9318	6477.3058	2.1208	-0.4	0.0048
Base	83	136	01-01 GRAVITY	Combination			3.1731	-4.6376	6099.7541	5.5493	3.3525	0.0048
Base	84	138	01-01 GRAVITY	Combination			22.9428	-4.4786	4922.8685	5.3974	21.5166	0.0048
Base	97	140	01-01 GRAVITY	Combination			24.7467	7.6589	5032.3109	-5.8261	23.073	0.0048
Base	98	142	01-01 GRAVITY	Combination			3.4752	-1.2531	5953.2666	2.417	3.2846	0.0048
Base	99	144	01-01 GRAVITY	Combination			-16.3012	-32.7307	2059.2298	33.4816	-3.5748	9.2115
Base	100	146	01-01 GRAVITY	Combination			-67.1865	84.3275	1147.8096	-14.1039	-3.0437	6.0008
Base	101	148	01-01 GRAVITY	Combination			-28.6816	28.2537	1722.9896	-4.3661	-20.3786	22.4357
Base	102	150	01-01 GRAVITY	Combination			-38.7368	-11.7301	1987.098	3.8689	-26.1636	6.8729
Base	103	152	01-01 GRAVITY	Combination			-42.2355	-21.551	2053.1029	5.8652	-30.03	0.0959
Base	104	154	01-01 GRAVITY	Combination			-44.1881	-23.364	2093.7931	6.0707	-54.4156	1.8119
Base	105	156	01-01 GRAVITY	Combination			-41.1241	-24.2741	2070.9966	6.4336	-23.477	-4.8454
Base	106	158	01-01 GRAVITY	Combination			-34.2184	-38.2841	2022.6865	9.4907	-19.6707	-14.0103
Base	107	160	01-01 GRAVITY	Combination			-107.0477	-118.9165	1915.7746	20.5874	-10.2935	-4.2574



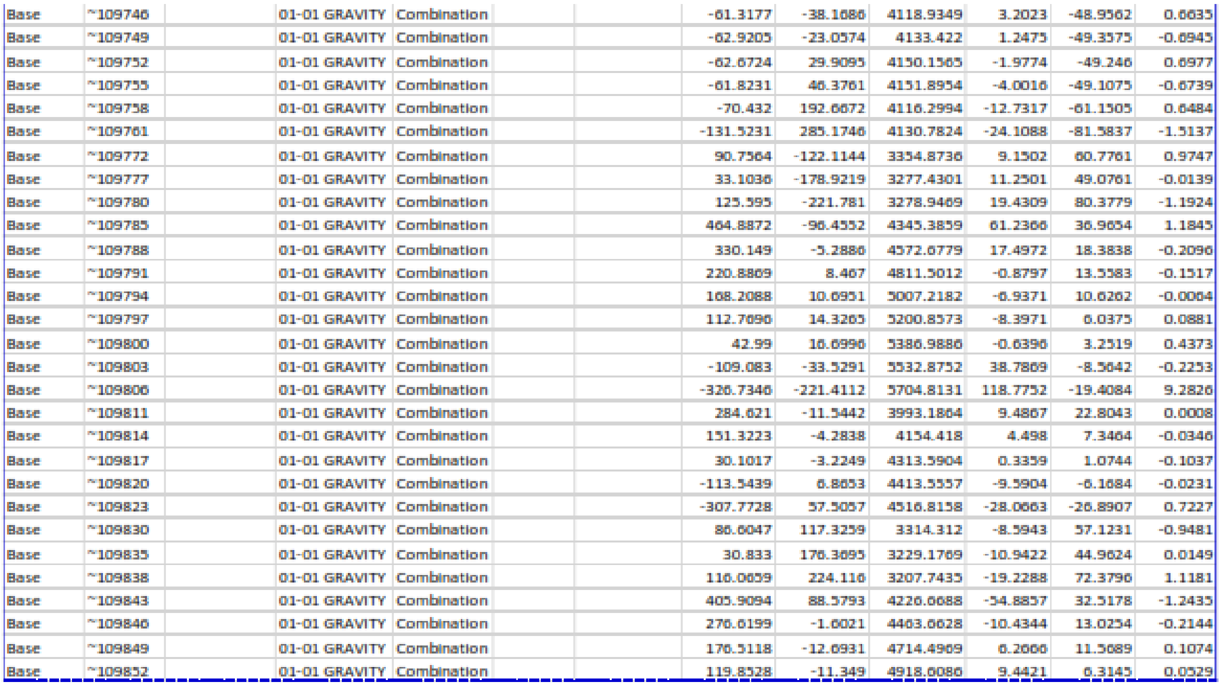
Base	261	2001	01-01 GRAVITY	Combination			-81.4281	67.8213	764.7658	-3.9494	-3.5721	0.0141
Base	262	2002	01-01 GRAVITY	Combination			84.6928	101.4382	815.1811	-5.6765	3.9874	0.1118
Base	265	2005	01-01 GRAVITY	Combination			-92.8128	11.9464	1155.5529	-1.9096	-6.083	-0.0975
Base	266	2006	01-01 GRAVITY	Combination			102.3613	23.1478	1210.4137	-1.6889	7.1581	0.0622
Base	269	2009	01-01 GRAVITY	Combination			-109.2318	-75.0794	1002.8629	1.9111	-4.9568	-0.2015
Base	270	2010	01-01 GRAVITY	Combination			124.866	-101.1231	1023.5916	4.6827	6.5878	0.0821
Base	273	2013	01-01 GRAVITY	Combination			-3.6514	-34.882	292.7054	-0.9051	-2.0836	-0.2249
Base	275	2015	01-01 GRAVITY	Combination			-3.0432	88.872	374.7599	-2.7772	-2.0808	0.2097
Base	277	2017	01-01 GRAVITY	Combination			-3.8673	-72.3468	357.4873	1.8729	-2.2492	-0.2537
Base	279	2019	01-01 GRAVITY	Combination			-4.4009	61.4587	413.1356	0.4025	-2.6422	0.3136
Base	427	2191	01-01 GRAVITY	Combination			106.6538	-74.2046	985.9883	1.9253	4.8759	0.1928
Base	428	2192	01-01 GRAVITY	Combination			-122.2434	-97.8332	994.4564	4.4824	-6.4755	-0.0846
Base	431	2195	01-01 GRAVITY	Combination			91.5937	11.4173	1146.7685	-1.9321	6.0374	0.0978
Base	432	2196	01-01 GRAVITY	Combination			-100.4347	22.3845	1181.5791	-1.669	-6.9711	-0.0622
Base	435	2199	01-01 GRAVITY	Combination			83.8272	68.0404	762.9512	-4.1975	3.9712	-0.0123
Base	436	2200	01-01 GRAVITY	Combination			-81.0233	99.0087	800.015	-5.5053	-3.743	-0.1274
Base	439	2203	01-01 GRAVITY	Combination			4.3833	60.1473	406.243	0.416	2.6093	-0.3133
Base	441	2205	01-01 GRAVITY	Combination			3.7553	-71.8692	354.5984	1.8565	2.2225	0.25
Base	443	2207	01-01 GRAVITY	Combination			3.0286	88.0721	372.4129	-2.6859	2.0799	-0.2078
Base	445	2209	01-01 GRAVITY	Combination			3.7253	-34.8219	288.2951	-0.8516	2.1921	0.2483
Base	52	97	01-01 GRAVITY	Combination			-7.0736	84.5603	384.3471	-1.9611	-1.0842	0.5282
Base	53	98	01-01 GRAVITY	Combination			117.7683	-62.3795	872.5143	0.0734	5.2352	0.3777
Base	61	107	01-01 GRAVITY	Combination			-115.53	-62.7721	858.9131	1.4764	-6.051	-0.2718
Base	108	113	01-01 GRAVITY	Combination			-57.3434	89.1539	562.7249	-6.2833	-3.0554	-0.2562
Base	110	115	01-01 GRAVITY	Combination			62.8035	60.3372	459.1045	-4.5187	2.2104	-1.0008
Base	112	123	01-01 GRAVITY	Combination			-4.5543	-18.564	159.0495	0.2077	-1.6436	-0.2979
Base	132	40	01-01 GRAVITY	Combination			-609.6573	-692.7899	4902.9417	96.6717	-61.8697	5.8533
Base	135	43	01-01 GRAVITY	Combination			285.4947	-2.6075	4558.7185	0.364	53.9062	-0.0438
Base	136	44	01-01 GRAVITY	Combination			-290.9952	-84.7587	5036.333	6.2608	-64.5092	0.4021
Base	139	266	01-01 GRAVITY	Combination			-299.0604	3.4414	5086.0197	-0.5049	-63.7628	-0.0185
Base	144	269	01-01 GRAVITY	Combination			290.4835	0.8241	4643.3645	-0.5639	55.0206	0.0571
Base	145	270	01-01 GRAVITY	Combination			-295.1054	96.8552	5095.6512	-7.7656	-65.2241	-0.4779
Base	148	274	01-01 GRAVITY	Combination			-627.4606	714.5208	5027.5782	-101.4908	-63.6406	-6.2915
Base	151	277	01-01 GRAVITY	Combination			51.9121	304.3996	1887.103	-4.6053	38.4087	-5.6138
Base	153	279	01-01 GRAVITY	Combination			35.9508	-383.1726	1972.353	10.3873	22.8921	3.1725
Base	155	281	01-01 GRAVITY	Combination			33.4741	379.673	1975.0226	-10.117	22.1462	-3.1023
Base	157	283	01-01 GRAVITY	Combination			34.4228	-385.8537	1992.1035	10.3486	22.1973	3.1292
Base	159	285	01-01 GRAVITY	Combination			34.5273	386.1385	1999.0373	-10.3868	22.2193	-3.1355
Base	161	287	01-01 GRAVITY	Combination			33.5338	-386.05	2004.4632	10.234	22.4944	3.1406
Base	163	289	01-01 GRAVITY	Combination			36.8343	390.9484	2016.7836	-10.6265	23.4638	-3.2573
Base	165	291	01-01 GRAVITY	Combination			52.4619	-314.039	1946.9832	4.641	39.5215	5.7613



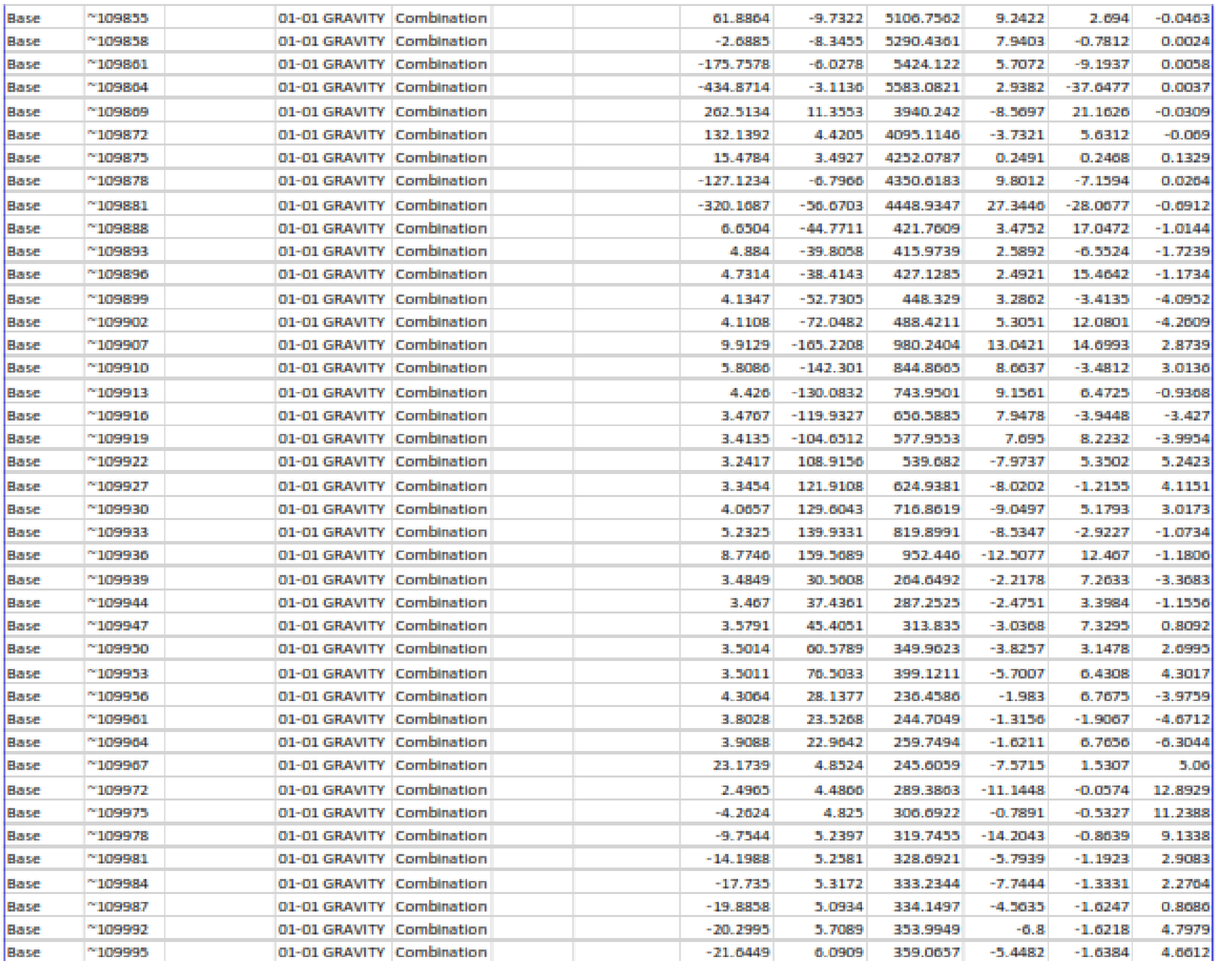
Base	232	1593	01-01 GRAVITY	Combination			641.8626	82.8047	5836.9171	-10.3817	94.0448	1.0028
Base	233	1594	01-01 GRAVITY	Combination			636.7132	501.4908	4495.9248	-58.884	67.6882	3.1318
Base	234	1597	01-01 GRAVITY	Combination			-653.2301	1.2524	3198.6329	0.4265	-20.957	0.0165
Base	237	1603	01-01 GRAVITY	Combination			-689.5868	-304.5043	4793.0951	16.3249	-82.4171	-7.2695
Base	238	1605	01-01 GRAVITY	Combination			-48.0551	374.0728	2359.7236	-6.032	-54.0826	6.6117
Base	4	7	01-01 GRAVITY	Combination			664.5006	-84.6055	5905.5321	11.1838	99.2436	-1.1718
Base	5	8	01-01 GRAVITY	Combination			685.5613	-507.123	4645.6273	60.834	76.1291	-2.4622
Base	6	11	01-01 GRAVITY	Combination			-653.2021	-132.7322	3204.6118	72.0011	-28.9695	4.2714
Base	221	1355	01-01 GRAVITY	Combination			-688.7121	315.2767	4868.3752	-17.4944	-82.145	7.1513
Base	222	1357	01-01 GRAVITY	Combination			-49.9942	-375.9745	2395.9456	5.7209	-54.4303	-6.6524
Base	64	1772	01-01 GRAVITY	Combination			3.5361	25.9316	261.1001	-1.4815	1.7817	-4.5867
Base	65	1768	01-01 GRAVITY	Combination			3.259	93.477	463.2556	-5.5475	1.1039	4.7979
Base	66	1773	01-01 GRAVITY	Combination			32.831	34.9102	264.0957	1.8508	-1.2327	0.7737
Base	74	1765	01-01 GRAVITY	Combination			3.414	-89.3585	528.0001	5.3386	-3.7408	-5.599
Base	77	1764	01-01 GRAVITY	Combination			82.4423	-60.9451	520.0405	-3.0575	0.5876	-2.585
Base	78	1776	01-01 GRAVITY	Combination			-37.653	6.6149	264.9974	-10.3843	0.3753	6.409
Base	79	1781	01-01 GRAVITY	Combination			55.5184	2.4286	278.0526	-0.9506	1.8849	1.1446
Base	21	3006	01-01 GRAVITY	Combination			-137.1393	-648.3396	3148.1868	17.1187	-66.4448	3.4471
Base	44	3816	01-01 GRAVITY	Combination			1426.8861	-8.1888	7158.2268	6.2597	-6.5109	0.2279
Base	70	4342	01-01 GRAVITY	Combination			1303.2386	-3.3693	6534.3831	1.8207	-7.9451	0.2279
Base	80	4490	01-01 GRAVITY	Combination			-23.6542	-1442.1834	7255.6116	-0.3032	-28.4708	-1.1558
Base	81	5811	01-01 GRAVITY	Combination			23.9432	-1540.7961	7729.0591	4.1823	17.5568	-1.1558
Base	87	5852	01-01 GRAVITY	Combination			23.5077	1538.5415	7761.9736	-0.8298	15.191	1.4325
Base	88	5893	01-01 GRAVITY	Combination			-28.0256	1460.9891	7354.8264	-5.5673	-34.4718	1.4325
Base	~109558		01-01 GRAVITY	Combination			-26.8292	5.0283	790.0348	-3.2451	-4.0289	0.0878
Base	~109562		01-01 GRAVITY	Combination			28.0167	5.7568	790.0231	-3.8434	3.9942	-0.1053
Base	~109566		01-01 GRAVITY	Combination			-24.5858	0.9591	884.9484	-0.7275	-3.881	0.01
Base	~109570		01-01 GRAVITY	Combination			43.1993	0.6351	870.3169	-0.5567	5.0212	-0.0075
Base	~109574		01-01 GRAVITY	Combination			-27.3659	-3.3104	1055.703	1.8032	-4.3553	-0.0897
Base	~109578		01-01 GRAVITY	Combination			60.2845	-5.225	1042.6297	3.0077	6.6837	0.1293
Base	~109582		01-01 GRAVITY	Combination			7.4647	70.1281	671.9926	-5.8	4.2871	0.0574



Base	~109585		01-01 GRAVITY	Combination			6.5676	47.7915	697.8837	-2.6536	4.2805	-0.0374
Base	~109588		01-01 GRAVITY	Combination			7.3503	-7.0731	758.3642	-0.1649	4.9166	0.0423
Base	~109591		01-01 GRAVITY	Combination			9.9925	-36.97	790.9341	3.7841	5.8327	-0.0713
Base	~109598		01-01 GRAVITY	Combination			25.3564	-3.2392	1034.0116	1.739	4.1589	0.089
Base	~109602		01-01 GRAVITY	Combination			-59.908	-4.9664	1016.4343	2.84	-6.5327	-0.1264
Base	~109606		01-01 GRAVITY	Combination			23.5943	0.9826	873.4548	-0.7465	3.8369	-0.0102
Base	~109610		01-01 GRAVITY	Combination			-43.3719	0.6148	853.8232	-0.5691	-4.989	0.0068
Base	~109614		01-01 GRAVITY	Combination			30.5363	5.1613	783.534	-3.3915	4.2177	-0.0837
Base	~109618		01-01 GRAVITY	Combination			-22.6263	5.5871	779.2823	-3.8288	-3.4115	0.102
Base	~109622		01-01 GRAVITY	Combination			-9.7894	-35.527	768.3501	3.6308	-5.7052	0.0687
Base	~109625		01-01 GRAVITY	Combination			-7.1872	-6.6498	737.965	-0.2035	-4.8068	-0.0403
Base	~109628		01-01 GRAVITY	Combination			-6.4164	46.2359	682.3804	-2.542	-4.1561	0.0358
Base	~109631		01-01 GRAVITY	Combination			-7.205	68.5311	658.829	-5.7348	-4.1104	-0.0541
Base	~109638		01-01 GRAVITY	Combination			8.6953	21.7691	684.6528	-1.5839	1.9331	-0.0279
Base	~109643		01-01 GRAVITY	Combination			71.7528	-3.5039	957.7024	-1.4199	6.5999	0.1258
Base	~109646		01-01 GRAVITY	Combination			16.004	7.5797	954.586	-6.6013	-0.249	0.0183
Base	~109649		01-01 GRAVITY	Combination			-9.6933	10.991	936.9628	-9.4161	-0.2603	-0.0157
Base	~109652		01-01 GRAVITY	Combination			-19.4084	11.2659	917.8093	-9.5657	-1.5133	0.0212
Base	~109655		01-01 GRAVITY	Combination			-43.6419	8.2955	896.2931	-6.8511	-1.4095	-0.0075
Base	~109658		01-01 GRAVITY	Combination			-91.9857	-3.1124	864.1807	-1.0593	-8.1076	-0.1281
Base	~109662		01-01 GRAVITY	Combination			-7.3252	7.3137	691.5276	0.6517	-3.2032	0.1083
Base	~109665		01-01 GRAVITY	Combination			2.8302	48.4104	631.7616	-3.9623	1.0775	0.0179
Base	~109668		01-01 GRAVITY	Combination			3.3061	77.7478	564.4971	-4.7726	1.5737	-0.0292
Base	~109671		01-01 GRAVITY	Combination			-3.1582	90.6748	507.2211	-6.9397	-1.0183	-0.0901
Base	~109675		01-01 GRAVITY	Combination			-27.0526	6.4679	484.9412	-4.2141	-2.291	0.0626
Base	~109678		01-01 GRAVITY	Combination			-15.8204	0.6865	473.9737	-1.5935	-1.0988	-0.0139
Base	~109681		01-01 GRAVITY	Combination			0.8503	0.0446	478.1184	-0.8056	0.3719	-0.0098
Base	~109684		01-01 GRAVITY	Combination			8.7082	0.2783	477.9472	-1.0017	0.3901	0.0101
Base	~109687		01-01 GRAVITY	Combination			21.6711	1.6288	473.4155	-2.1495	1.7409	0.007
Base	~109690		01-01 GRAVITY	Combination			24.6075	9.4789	477.608	-4.5054	1.7773	-0.145
Base	~109694		01-01 GRAVITY	Combination			-1.6231	18.5054	332.6093	-3.2618	-1.241	0.6497
Base	~109700		01-01 GRAVITY	Combination			138.0769	-76.5813	4666.3871	64.908	14.1557	1.1409
Base	~109704		01-01 GRAVITY	Combination			-121.6133	-149.5841	4793.8813	107.8688	-16.0843	-1.666
Base	~109708		01-01 GRAVITY	Combination			24.4927	-1.0206	1725.9637	1.1886	2.5477	-0.0025
Base	~109712		01-01 GRAVITY	Combination			-41.9275	-5.2238	1746.731	3.1553	-4.846	-0.0402
Base	~109716		01-01 GRAVITY	Combination			21.2917	-0.0798	1740.8553	-0.1345	2.2391	-0.0001
Base	~109720		01-01 GRAVITY	Combination			-43.3305	0.1273	1759.1186	-0.2462	-4.903	0.0018
Base	~109724		01-01 GRAVITY	Combination			24.5452	1.0613	1754.606	-1.614	2.6046	0.0024
Base	~109728		01-01 GRAVITY	Combination			-43.1829	5.9753	1771.9036	-3.9111	-4.933	0.0474
Base	~109732		01-01 GRAVITY	Combination			135.6232	80.5646	4811.4909	-69.9695	14.0381	-1.1738
Base	~109736		01-01 GRAVITY	Combination			-127.2182	155.543	4925.2212	-114.4846	-16.398	1.7042
Base	~109740		01-01 GRAVITY	Combination			-128.0656	-271.9098	4051.9792	22.7224	-79.6006	1.495
Base	~109743		01-01 GRAVITY	Combination			-68.8486	-178.9057	4056.2889	11.4623	-59.995	-0.6449



Base	~109746		01-01 GRAVITY	Combination			-61.3177	-38.1686	4118.9349	3.2023	-48.9562	0.6635
Base	~109749		01-01 GRAVITY	Combination			-62.9205	-23.0574	4133.422	1.2475	-49.3575	-0.6945
Base	~109752		01-01 GRAVITY	Combination			-62.6724	29.9095	4150.1565	-1.9774	-49.246	0.6977
Base	~109755		01-01 GRAVITY	Combination			-61.8231	46.3761	4151.8954	-4.0016	-49.1075	-0.6739
Base	~109758		01-01 GRAVITY	Combination			-70.432	192.6672	4116.2994	-12.7317	-61.1505	0.6484
Base	~109761		01-01 GRAVITY	Combination			-131.5231	285.1746	4130.7824	-24.1088	-81.5837	-1.5137
Base	~109772		01-01 GRAVITY	Combination			90.7564	-122.1144	3354.8736	9.1502	60.7761	0.9747
Base	~109777		01-01 GRAVITY	Combination			33.1036	-178.9219	3277.4301	11.2501	49.0761	-0.0139
Base	~109780		01-01 GRAVITY	Combination			125.595	-221.781	3278.9469	19.4309	80.3779	-1.1924
Base	~109785		01-01 GRAVITY	Combination			464.8872	-96.4552	4345.3859	61.2366	36.9654	1.1845
Base	~109788		01-01 GRAVITY	Combination			330.149	-5.2886	4572.6779	17.4972	18.3838	-0.2096
Base	~109791		01-01 GRAVITY	Combination			220.8869	8.467	4811.5012	-0.8797	13.5583	-0.1517
Base	~109794		01-01 GRAVITY	Combination			168.2088	10.6951	5007.2182	-6.9371	10.6262	-0.0064
Base	~109797		01-01 GRAVITY	Combination			112.7696	14.3265	5200.8573	-8.3971	6.0375	0.0881
Base	~109800		01-01 GRAVITY	Combination			42.99	16.6996	5386.9886	-0.6396	3.2519	0.4373
Base	~109803		01-01 GRAVITY	Combination			-109.083	-33.5291	5532.8752	38.7869	-8.5642	-0.2253
Base	~109806		01-01 GRAVITY	Combination			-326.7346	-221.4112	5704.8131	118.7752	-19.4084	9.2826
Base	~109811		01-01 GRAVITY	Combination			284.621	-11.5442	3993.1864	9.4867	22.8043	0.0008
Base	~109814		01-01 GRAVITY	Combination			151.3223	-4.2838	4154.418	4.498	7.3464	-0.0346
Base	~109817		01-01 GRAVITY	Combination			30.1017	-3.2249	4313.5904	0.3359	1.0744	-0.1037
Base	~109820		01-01 GRAVITY	Combination			-113.5439	6.8653	4413.5557	-9.5904	-6.1684	-0.0231
Base	~109823		01-01 GRAVITY	Combination			-307.7728	57.5057	4516.8158	-28.0663	-26.8907	0.7227
Base	~109830		01-01 GRAVITY	Combination			86.6047	117.3259	3314.312	-8.5943	57.1231	-0.9481
Base	~109835		01-01 GRAVITY	Combination			30.833	176.3695	3229.1769	-10.9422	44.9624	0.0149
Base	~109838		01-01 GRAVITY	Combination			116.0659	224.116	3207.7435	-19.2288	72.3796	1.1181
Base	~109843		01-01 GRAVITY	Combination			405.9094	88.5793	4226.0688	-54.8857	32.5178	-1.2435
Base	~109846		01-01 GRAVITY	Combination			276.6199	-1.6021	4463.6628	-10.4344	13.0254	-0.2144
Base	~109849		01-01 GRAVITY	Combination			176.5118	-12.6931	4714.4969	6.2666	11.5689	0.1074
Base	~109852		01-01 GRAVITY	Combination			119.8528	-11.349	4918.6086	9.4421	6.3145	0.0529



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Base	~109861		01-01 GRAVITY	Combination			-175.7578	-6.0278	5424.122	5.7072	-9.1937	0.0058
Base	~109864		01-01 GRAVITY	Combination			-434.8714	-3.1136	5583.0821	2.9382	-37.6477	0.0037
Base	~109869		01-01 GRAVITY	Combination			262.5134	11.3553	3940.242	-8.5697	21.1626	-0.0309
Base	~109872		01-01 GRAVITY	Combination			132.1392	4.4205	4095.1146	-3.7321	5.6312	-0.069
Base	~109875		01-01 GRAVITY	Combination			15.4784	3.4927	4252.0787	0.2491	0.2468	0.1329
Base	~109878		01-01 GRAVITY	Combination			-127.1234	-6.7966	4350.6183	9.8012	-7.1594	0.0264
Base	~109881		01-01 GRAVITY	Combination			-320.1687	-56.6703	4448.9347	27.3446	-28.0677	-0.6912
Base	~109888		01-01 GRAVITY	Combination			6.6504	-44.7711	421.7609	3.4752	17.0472	-1.0144
Base	~109893		01-01 GRAVITY	Combination			4.884	-39.8058	415.9739	2.5892	-6.5524	-1.7239
Base	~109896		01-01 GRAVITY	Combination			4.7314	-38.4143	427.1285	2.4921	15.4642	-1.1734
Base	~109899		01-01 GRAVITY	Combination			4.1347	-52.7305	448.329	3.2862	-3.4135	-4.0952
Base	~109902		01-01 GRAVITY	Combination			4.1108	-72.0482	488.4211	5.3051	12.0801	-4.2609
Base	~109907		01-01 GRAVITY	Combination			9.9129	-165.2208	980.2404	13.0421	14.6993	2.8739
Base	~109910		01-01 GRAVITY	Combination			5.8086	-142.301	844.8665	8.6637	-3.4812	3.0136
Base	~109913		01-01 GRAVITY	Combination			4.426	-130.0832	743.9501	9.1561	6.4725	-0.9368
Base	~109916		01-01 GRAVITY	Combination			3.4767	-119.9327	656.5885	7.9478	-3.9448	-3.427
Base	~109919		01-01 GRAVITY	Combination			3.4135	-104.6512	577.9553	7.695	8.2232	-3.9954
Base	~109922		01-01 GRAVITY	Combination			3.2417	108.9156	539.682	-7.9737	5.3502	5.2423
Base	~109927		01-01 GRAVITY	Combination			3.3454	121.9108	624.9381	-8.0202	-1.2155	4.1151
Base	~109930		01-01 GRAVITY	Combination			4.0657	129.6043	716.8619	-9.0497	5.1793	3.0173
Base	~109933		01-01 GRAVITY	Combination			5.2325	139.9331	819.8991	-8.5347	-2.9227	-1.0734
Base	~109936		01-01 GRAVITY	Combination			8.7746	159.5689	952.446	-12.5077	12.467	-1.1806
Base	~109939		01-01 GRAVITY	Combination			3.4849	30.5608	264.6492	-2.2178	7.2633	-3.3683
Base	~109944		01-01 GRAVITY	Combination			3.467	37.4361	287.2525	-2.4751	3.3984	-1.1556
Base	~109947		01-01 GRAVITY	Combination			3.5791	45.4051	313.835	-3.0368	7.3295	0.8092
Base	~109950		01-01 GRAVITY	Combination			3.5014	60.5789	349.9623	-3.8257	3.1478	2.6995
Base	~109953		01-01 GRAVITY	Combination			3.5011	76.5033	399.1211	-5.7007	6.4308	4.3017
Base	~109956		01-01 GRAVITY	Combination			4.3064	28.1377	236.4586	-1.983	6.7675	-3.9759
Base	~109961		01-01 GRAVITY	Combination			3.8028	23.5268	244.7049	-1.3156	-1.9067	-4.6712
Base	~109964		01-01 GRAVITY	Combination			3.9088	22.9642	259.7494	-1.6211	6.7656	-6.3044
Base	~109967		01-01 GRAVITY	Combination			23.1739	4.8524	245.6059	-7.5715	1.5307	5.06
Base	~109972		01-01 GRAVITY	Combination			2.4965	4.4866	289.3863	-11.1448	-0.0574	12.8929
Base	~109975		01-01 GRAVITY	Combination			-4.2624	4.825	306.6922	-0.7891	-0.5327	11.2388
Base	~109978		01-01 GRAVITY	Combination			-9.7544	5.2397	319.7455	-14.2043	-0.8639	9.1338
Base	~109981		01-01 GRAVITY	Combination			-14.1988	5.2581	328.6921	-5.7939	-1.1923	2.9083
Base	~109984		01-01 GRAVITY	Combination			-17.735	5.3172	333.2344	-7.7444	-1.3331	2.2764
Base	~109987		01-01 GRAVITY	Combination			-19.8858	5.0934	334.1497	-4.5635	-1.6247	0.8686
Base	~109992		01-01 GRAVITY	Combination			-20.2995	5.7089	353.9949	-6.8	-1.6218	4.7979
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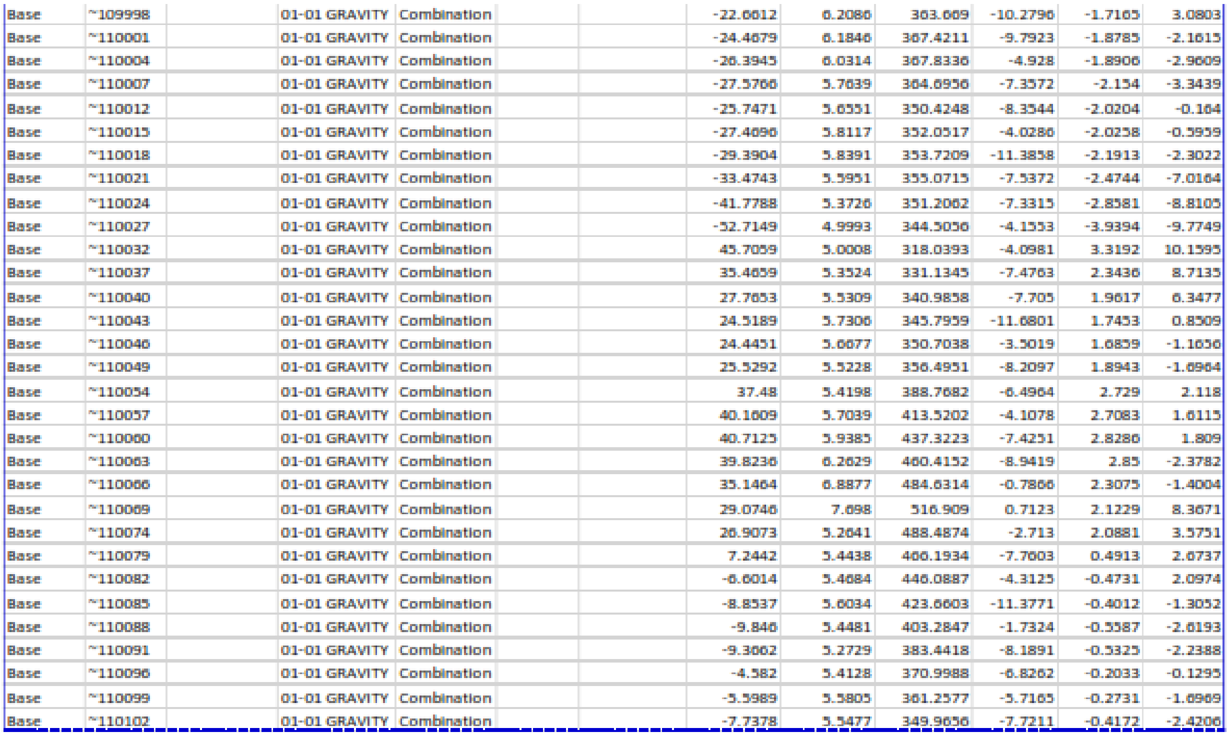

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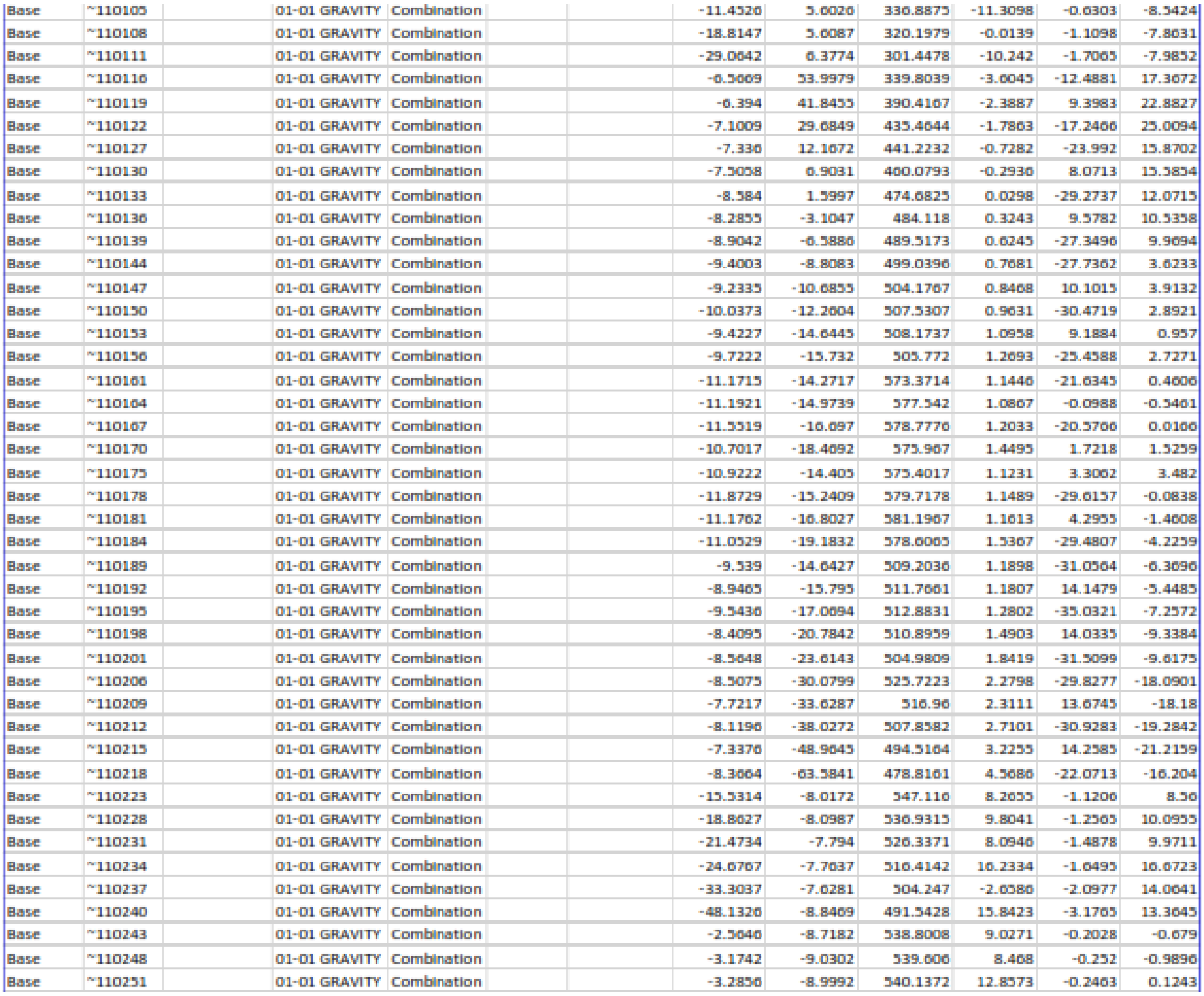
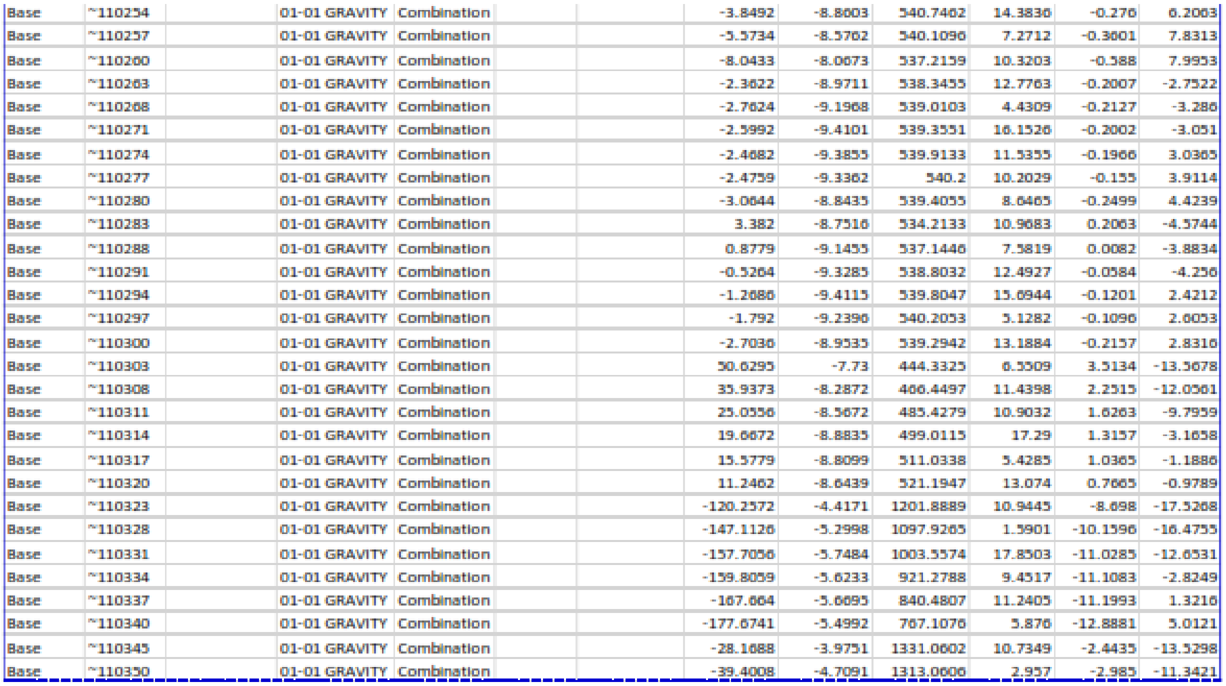
Base	~110004		01-01 GRAVITY	Combination			-26.3945	6.0314	367.8336	-4.928	-1.8906	-2.9609
Base	~110007		01-01 GRAVITY	Combination			-27.5766	5.7639	364.6956	-7.3572	-2.154	-3.3439
Base	~110012		01-01 GRAVITY	Combination			-25.7471	5.6551	350.4248	-8.3544	-2.0204	-0.164
Base	~110015		01-01 GRAVITY	Combination			-27.4696	5.8117	352.0517	-4.0286	-2.0258	-0.5959
Base	~110018		01-01 GRAVITY	Combination			-29.3904	5.8391	353.7209	-11.3858	-2.1913	-2.3022
Base	~110021		01-01 GRAVITY	Combination			-33.4743	5.5951	355.0715	-7.5372	-2.4744	-7.0164
Base	~110024		01-01 GRAVITY	Combination			-41.7788	5.3726	351.2062	-7.3315	-2.8581	-8.8105
Base	~110027		01-01 GRAVITY	Combination			-52.7149	4.9993	344.5056	-4.1553	-3.9394	-9.7749
Base	~110032		01-01 GRAVITY	Combination			45.7059	5.0008	318.0393	-4.0981	3.3192	10.1595
Base	~110037		01-01 GRAVITY	Combination			35.4659	5.3524	331.1345	-7.4763	2.3436	8.7135
Base	~110040		01-01 GRAVITY	Combination			27.7653	5.5309	340.9858	-7.705	1.9617	6.3477
Base	~110043		01-01 GRAVITY	Combination			24.5189	5.7306	345.7959	-11.6801	1.7453	0.8509
Base	~110046		01-01 GRAVITY	Combination			24.4451	5.6677	350.7038	-3.5019	1.6859	-1.1656
Base	~110049		01-01 GRAVITY	Combination			25.5292	5.5228	356.4951	-8.2097	1.8943	-1.6964
Base	~110054		01-01 GRAVITY	Combination			37.48	5.4198	388.7682	-6.4964	2.729	2.118
Base	~110057		01-01 GRAVITY	Combination			40.1609	5.7039	413.5202	-4.1078	2.7083	1.6115
Base	~110060		01-01 GRAVITY	Combination			40.7125	5.9385	437.3223	-7.4251	2.8286	1.809
Base	~110063		01-01 GRAVITY	Combination			39.8236	6.2629	460.4152	-8.9419	2.85	-2.3782
Base	~110066		01-01 GRAVITY	Combination			35.1464	6.8877	484.6314	-0.7866	2.3075	-1.4004
Base	~110069		01-01 GRAVITY	Combination			29.0746	7.698	516.909	0.7123	2.1229	8.3671
Base	~110074		01-01 GRAVITY	Combination			26.9073	5.2641	488.4874	-2.713	2.0881	3.5751
Base	~110079		01-01 GRAVITY	Combination			7.2442	5.4438	466.1934	-7.7603	0.4913	2.6737
Base	~110082		01-01 GRAVITY	Combination			-6.6014	5.4684	446.0887	-4.3125	-0.4731	2.0974
Base	~110085		01-01 GRAVITY	Combination			-8.8537	5.6034	423.6603	-11.3771	-0.4012	-1.3052
Base	~110088		01-01 GRAVITY	Combination			-9.846	5.4481	403.2847	-1.7324	-0.5587	-2.6193
Base	~110091		01-01 GRAVITY	Combination			-9.3662	5.2729	383.4418	-8.1891	-0.5325	-2.2388
Base	~110096		01-01 GRAVITY	Combination			-4.582	5.4128	370.9988	-6.8262	-0.2033	-0.1295
Base	~110099		01-01 GRAVITY	Combination			-5.5989	5.5805	361.2577	-5.7165	-0.2731	-1.6969
Base	~110102		01-01 GRAVITY	Combination			-7.7378	5.5477	349.9656	-7.7211	-0.4172	-2.4206



Base	~110105		01-01 GRAVITY	Combination			-11.4526	5.6026	336.8875	-11.3098	-0.6303	-8.5424
Base	~110108		01-01 GRAVITY	Combination			-18.8147	5.6087	320.1979	-0.0139	-1.1098	-7.8631
Base	~110111		01-01 GRAVITY	Combination			-29.0642	6.3774	301.4478	-10.242	-1.7065	-7.9852
Base	~110116		01-01 GRAVITY	Combination			-6.5669	53.9979	339.8039	-3.6045	-12.4881	17.3672
Base	~110119		01-01 GRAVITY	Combination			-6.394	41.8455	390.4167	-2.3887	9.3983	22.8827
Base	~110122		01-01 GRAVITY	Combination			-7.1009	29.6849	435.4644	-1.7863	-17.2466	25.0094
Base	~110127		01-01 GRAVITY	Combination			-7.336	12.1672	441.2232	-0.7282	-23.992	15.8702
Base	~110130		01-01 GRAVITY	Combination			-7.5058	6.9031	460.0793	-0.2936	8.0713	15.5854
Base	~110133		01-01 GRAVITY	Combination			-8.584	1.5997	474.6825	0.0298	-29.2737	12.0715
Base	~110136		01-01 GRAVITY	Combination			-8.2855	-3.1047	484.118	0.3243	9.5782	10.5358
Base	~110139		01-01 GRAVITY	Combination			-8.9042	-6.5886	489.5173	0.6245	-27.3496	9.9694
Base	~110144		01-01 GRAVITY	Combination			-9.4003	-8.8083	499.0396	0.7681	-27.7362	3.6233
Base	~110147		01-01 GRAVITY	Combination			-9.2335	-10.6855	504.1767	0.8468	10.1015	3.9132
Base	~110150		01-01 GRAVITY	Combination			-10.0373	-12.2604	507.5307	0.9631	-30.4719	2.8921
Base	~110153		01-01 GRAVITY	Combination			-9.4227	-14.6445	508.1737	1.0958	9.1884	0.957
Base	~110156		01-01 GRAVITY	Combination			-9.7222	-15.732	505.772	1.2693	-25.4588	2.7271
Base	~110161		01-01 GRAVITY	Combination			-11.1715	-14.2717	573.3714	1.1446	-21.6345	0.4606
Base	~110164		01-01 GRAVITY	Combination			-11.1921	-14.9739	577.542	1.0867	-0.0988	-0.5461
Base	~110167		01-01 GRAVITY	Combination			-11.5519	-16.697	578.7776	1.2033	-20.5766	0.0166
Base	~110170		01-01 GRAVITY	Combination			-10.7017	-18.4692	575.967	1.4495	1.7218	1.5259
Base	~110175		01-01 GRAVITY	Combination			-10.9222	-14.405	575.4017	1.1231	3.3062	3.482
Base	~110178		01-01 GRAVITY	Combination			-11.8729	-15.2409	579.7178	1.1489	-29.6157	-0.0838
Base	~110181		01-01 GRAVITY	Combination			-11.1762	-16.8027	581.1967	1.1613	4.2955	-1.4608
Base	~110184		01-01 GRAVITY	Combination			-11.0529	-19.1832	578.6065	1.5367	-29.4807	-4.2259
Base	~110189		01-01 GRAVITY	Combination			-9.539	-14.6427	509.2036	1.1898	-31.0564	-6.3696
Base	~110192		01-01 GRAVITY	Combination			-8.9465	-15.795	511.7661	1.1807	14.1479	-5.4485
Base	~110195		01-01 GRAVITY	Combination			-9.5436	-17.0694	512.8831	1.2802	-35.0321	-7.2572
Base	~110198		01-01 GRAVITY	Combination			-8.4095	-20.7842	510.8959	1.4903	14.0335	-9.3384
Base	~110201		01-01 GRAVITY	Combination			-8.5648	-23.6143	504.9809	1.8419	-31.5099	-9.6175
Base	~110206		01-01 GRAVITY	Combination			-8.5075	-30.0799	525.7223	2.2798	-29.8277	-18.0901
Base	~110209		01-01 GRAVITY	Combination			-7.7217	-33.6287	516.96	2.3111	13.6745	-18.18
Base	~110212		01-01 GRAVITY	Combination			-8.1196	-38.0272	507.8582	2.7101	-30.9283	-19.2842
Base	~110215		01-01 GRAVITY	Combination			-7.3376	-48.9645	494.5164	3.2255	14.2585	-21.2159
Base	~110218		01-01 GRAVITY	Combination			-8.3664	-63.5841	478.8161	4.5686	-22.0713	-16.204
Base	~110223		01-01 GRAVITY	Combination			-15.5314	-8.0172	547.116	8.2655	-1.1206	8.56
Base	~110228		01-01 GRAVITY	Combination			-18.8627	-8.0987	536.9315	9.8041	-1.2565	10.0955
Base	~110231		01-01 GRAVITY	Combination			-21.4734	-7.794	526.3371	8.0946	-1.4878	9.9711
Base	~110234		01-01 GRAVITY	Combination			-24.6767	-7.7637	516.4142	16.2334	-1.6495	16.6723
Base	~110237		01-01 GRAVITY	Combination			-33.3037	-7.6281	504.247	-2.6586	-2.0977	14.0641
Base	~110240		01-01 GRAVITY	Combination			-48.1326	-8.8469	491.5428	15.8423	-3.1765	13.3645
Base	~110243		01-01 GRAVITY	Combination			-2.5646	-8.7182	538.8008	9.0271	-0.2028	-0.679
Base	~110248		01-01 GRAVITY	Combination			-3.1742	-9.0302	539.606	8.468	-0.252	-0.9896
Base	~110251		01-01 GRAVITY	Combination			-3.2856	-8.9992	540.1372	12.8573	-0.2463	0.1243



Base	~110254		01-01 GRAVITY	Combination			-3.8492	-8.8003	540.7462	14.3836	-0.276	6.2063
Base	~110257		01-01 GRAVITY	Combination			-5.5734	-8.5762	540.1096	7.2712	-0.3601	7.8313
Base	~110260		01-01 GRAVITY	Combination			-8.0433	-8.0673	537.2159	10.3203	-0.588	7.9953
Base	~110263		01-01 GRAVITY	Combination			-2.3622	-8.9711	538.3455	12.7763	-0.2007	-2.7522
Base	~110268		01-01 GRAVITY	Combination			-2.7624	-9.1968	539.0103	4.4309	-0.2127	-3.286
Base	~110271		01-01 GRAVITY	Combination			-2.5992	-9.4101	539.3551	16.1526	-0.2002	-3.051
Base	~110274		01-01 GRAVITY	Combination			-2.4682	-9.3855	539.9133	11.5355	-0.1966	3.0365
Base	~110277		01-01 GRAVITY	Combination			-2.4759	-9.3362	540.2	10.2029	-0.155	3.9114
Base	~110280		01-01 GRAVITY	Combination			-3.0644	-8.8435	539.4055	8.6465	-0.2499	4.4239
Base	~110283		01-01 GRAVITY	Combination			3.382	-8.7516	534.2133	10.9683	0.2063	-4.5744
Base	~110288		01-01 GRAVITY	Combination			0.8779	-9.1455	537.1446	7.5819	0.0082	-3.8834
Base	~110291		01-01 GRAVITY	Combination			-0.5264	-9.3285	538.8032	12.4927	-0.0584	-4.256
Base	~110294		01-01 GRAVITY	Combination			-1.2686	-9.4115	539.8047	15.6944	-0.1201	2.4212
Base	~110297		01-01 GRAVITY	Combination			-1.792	-9.2396	540.2053	5.1282	-0.1096	2.6053
Base	~110300		01-01 GRAVITY	Combination			-2.7036	-8.9535	539.2942	13.1884	-0.2157	2.8316
Base	~110303		01-01 GRAVITY	Combination			50.6295	-7.73	444.3325	6.5509	3.5134	-13.5678
Base	~110308		01-01 GRAVITY	Combination			35.9373	-8.2872	466.4497	11.4398	2.2515	-12.0561
Base	~110311		01-01 GRAVITY	Combination			25.0556	-8.5672	485.4279	10.9032	1.6263	-9.7959
Base	~110314		01-01 GRAVITY	Combination			19.6672	-8.8835	499.0115	17.29	1.3157	-3.1658
Base	~110317		01-01 GRAVITY	Combination			15.5779	-8.8099	511.0338	5.4285	1.0365	-1.1886
Base	~110320		01-01 GRAVITY	Combination			11.2462	-8.6439	521.1947	13.074	0.7665	-0.9789
Base	~110323		01-01 GRAVITY	Combination			-120.2572	-4.4171	1201.8889	10.9445	-8.698	-17.5268
Base	~110328		01-01 GRAVITY	Combination			-147.1126	-5.2998	1097.9265	1.5901	-10.1596	-16.4755
Base	~110331		01-01 GRAVITY	Combination			-157.7056	-5.7484	1003.5574	17.8503	-11.0285	-12.6531
Base	~110334		01-01 GRAVITY	Combination			-159.8059	-5.6233	921.2788	9.4517	-11.1083	-2.8249
Base	~110337		01-01 GRAVITY	Combination			-167.664	-5.6695	840.4807	11.2405	-11.1993	1.3216
Base	~110340		01-01 GRAVITY	Combination			-177.6741	-5.4992	767.1076	5.876	-12.8881	5.0121
Base	~110345		01-01 GRAVITY	Combination			-28.1688	-3.9751	1331.0602	10.7349	-2.4435	-13.5298
Base	~110350		01-01 GRAVITY	Combination			-39.4008	-4.7091	1313.0606	2.957	-2.985	-11.3421

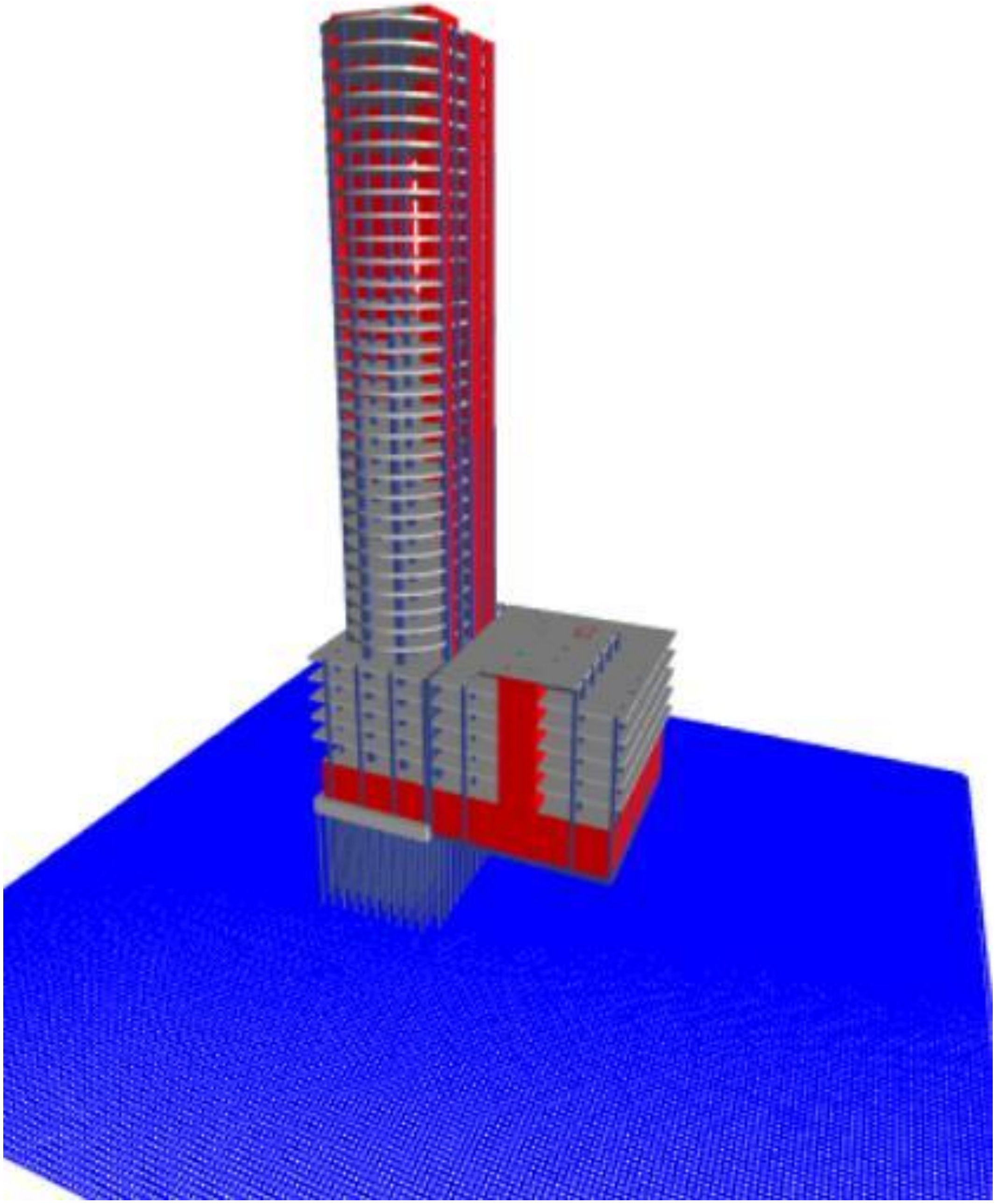
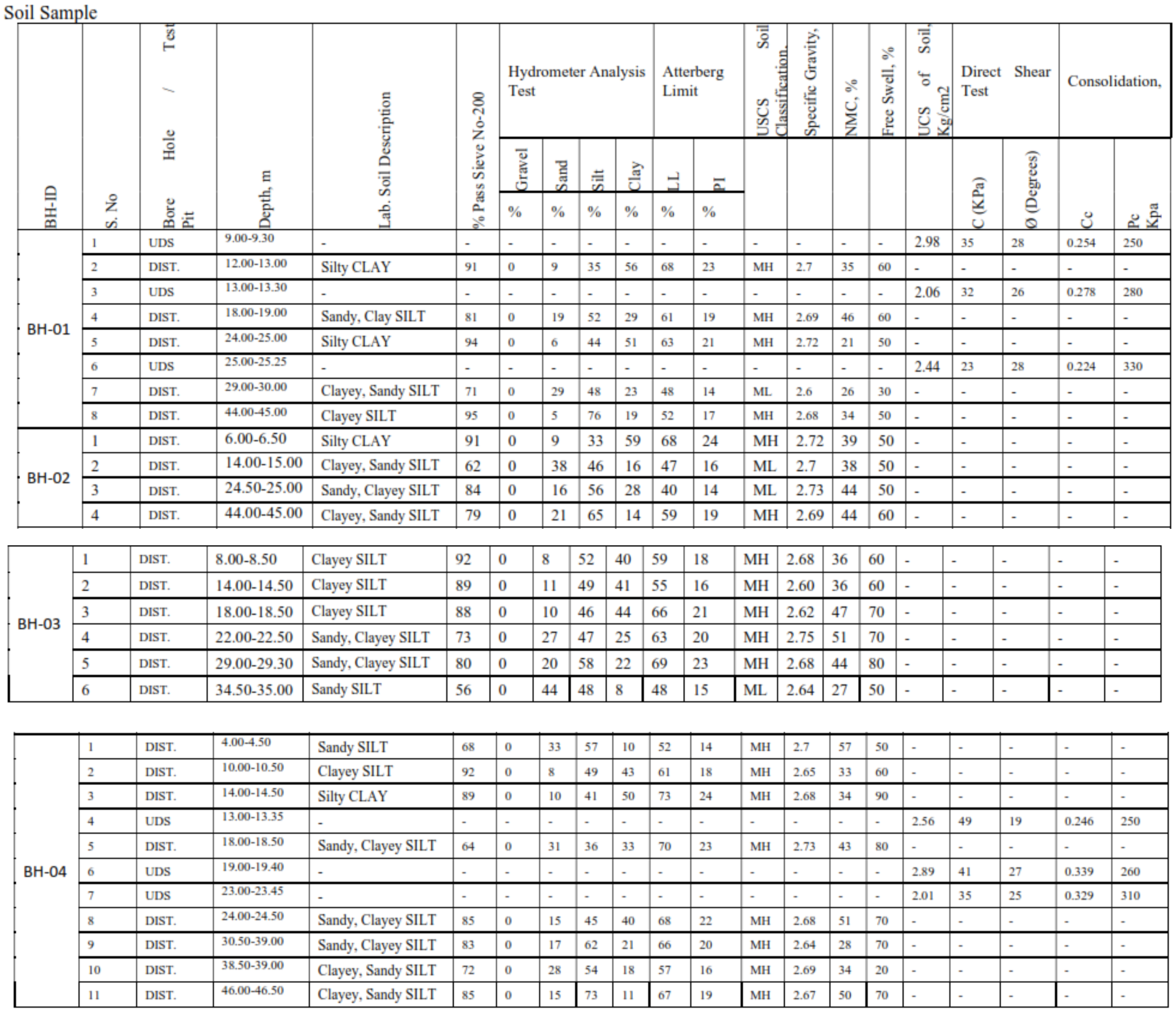


Figure: Modelling the ECX 3B+G+35 office building using ETABS

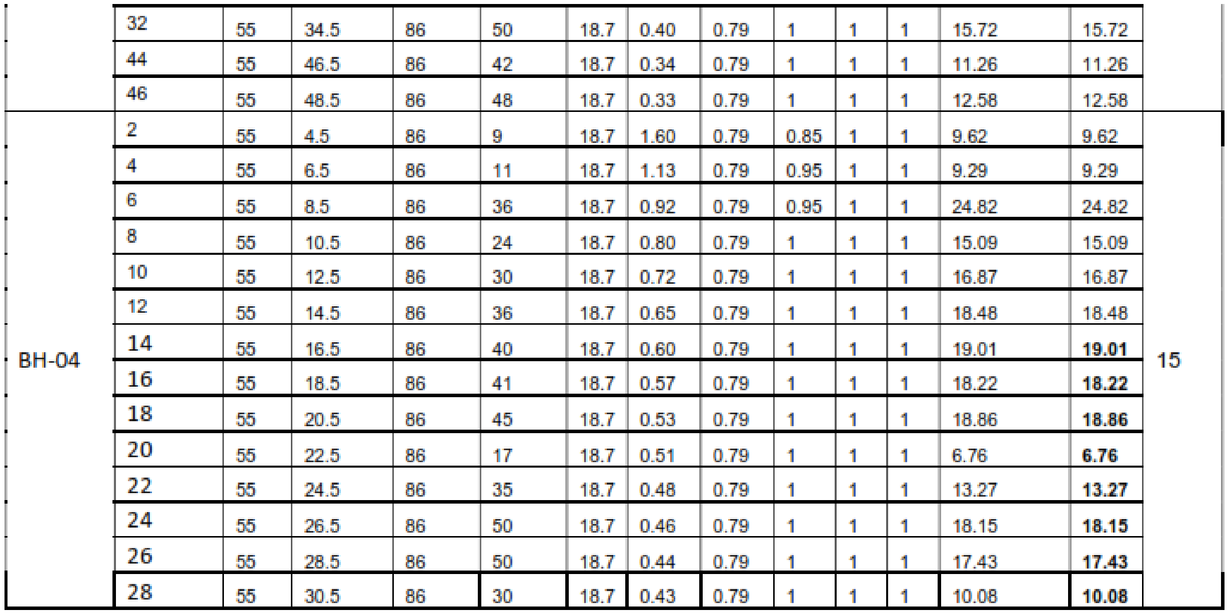
Appendix-2: Geotechnical Investigation Report



Soil Sample

BH-ID	S. No	Bore Hole / Test Pit	Depth, m	Lab. Soil Description	% Pass Sieve No-200	Hydrometer Analysis Test				Atterberg Limit		USCS Soil Classification	Specific Gravity,	NMC, %	Free Swell, %	UCS of Soil, Kg/cm2	Direct Shear Test		Consolidation,	
						Gravel %	Sand %	Silt %	Clay %	LL %	PI %						C (KPa)	Ø (Degrees)	Cc	Pc Kpa
BH-01	1	UDS	9.00-9.30	-	-	-	-	-	-	-	-	-	-	-	-	2.98	35	28	0.254	250
	2	DIST.	12.00-13.00	Silty CLAY	91	0	9	35	56	68	23	MH	2.7	35	60	-	-	-	-	-
	3	UDS	13.00-13.30	-	-	-	-	-	-	-	-	-	-	-	-	2.06	32	26	0.278	280
	4	DIST.	18.00-19.00	Sandy, Clay SILT	81	0	19	52	29	61	19	MH	2.69	46	60	-	-	-	-	-
	5	DIST.	24.00-25.00	Silty CLAY	94	0	6	44	51	63	21	MH	2.72	21	50	-	-	-	-	-
	6	UDS	25.00-25.25	-	-	-	-	-	-	-	-	-	-	-	-	2.44	23	28	0.224	330
	7	DIST.	29.00-30.00	Clayey, Sandy SILT	71	0	29	48	23	48	14	ML	2.6	26	30	-	-	-	-	-
	8	DIST.	44.00-45.00	Clayey SILT	95	0	5	76	19	52	17	MH	2.68	34	50	-	-	-	-	-
BH-02	1	DIST.	6.00-6.50	Silty CLAY	91	0	9	33	59	68	24	MH	2.72	39	50	-	-	-	-	-
	2	DIST.	14.00-15.00	Clayey, Sandy SILT	62	0	38	46	16	47	16	ML	2.7	38	50	-	-	-	-	-
	3	DIST.	24.50-25.00	Sandy, Clayey SILT	84	0	16	56	28	40	14	ML	2.73	44	50	-	-	-	-	-
	4	DIST.	44.00-45.00	Clayey, Sandy SILT	79	0	21	65	14	59	19	MH	2.69	44	60	-	-	-	-	-
BH-03	1	DIST.	8.00-8.50	Clayey SILT	92	0	8	52	40	59	18	MH	2.68	36	60	-	-	-	-	-
	2	DIST.	14.00-14.50	Clayey SILT	89	0	11	49	41	55	16	MH	2.60	36	60	-	-	-	-	-
	3	DIST.	18.00-18.50	Clayey SILT	88	0	10	46	44	66	21	MH	2.62	47	70	-	-	-	-	-
	4	DIST.	22.00-22.50	Sandy, Clayey SILT	73	0	27	47	25	63	20	MH	2.75	51	70	-	-	-	-	-
	5	DIST.	29.00-29.30	Sandy, Clayey SILT	80	0	20	58	22	69	23	MH	2.68	44	80	-	-	-	-	-
	6	DIST.	34.50-35.00	Sandy SILT	56	0	44	48	8	48	15	ML	2.64	27	50	-	-	-	-	-
BH-04	1	DIST.	4.00-4.50	Sandy SILT	68	0	33	57	10	52	14	MH	2.7	57	50	-	-	-	-	-
	2	DIST.	10.00-10.50	Clayey SILT	92	0	8	49	43	61	18	MH	2.65	33	60	-	-	-	-	-
	3	DIST.	14.00-14.50	Silty CLAY	89	0	10	41	50	73	24	MH	2.68	34	90	-	-	-	-	-
	4	UDS	13.00-13.35	-	-	-	-	-	-	-	-	-	-	-	-	2.56	49	19	0.246	250
	5	DIST.	18.00-18.50	Sandy, Clayey SILT	64	0	31	36	33	70	23	MH	2.73	43	80	-	-	-	-	-
	6	UDS	19.00-19.40	-	-	-	-	-	-	-	-	-	-	-	-	2.89	41	27	0.339	260
	7	UDS	23.00-23.45	-	-	-	-	-	-	-	-	-	-	-	-	2.01	35	25	0.329	310
	8	DIST.	24.00-24.50	Sandy, Clayey SILT	85	0	15	45	40	68	22	MH	2.68	51	70	-	-	-	-	-
	9	DIST.	30.50-39.00	Sandy, Clayey SILT	83	0	17	62	21	66	20	MH	2.64	28	70	-	-	-	-	-
	10	DIST.	38.50-39.00	Clayey, Sandy SILT	72	0	28	54	18	57	16	MH	2.69	34	20	-	-	-	-	-
	11	DIST.	46.00-46.50	Clayey, Sandy SILT	85	0	15	73	11	67	19	MH	2.67	50	70	-	-	-	-	-

BH ID	Depth of N count (m)	Er	Rod Length (m)	Hole Diam. (mm)	N count	γ	C_n	E_M	C_R	C_S	C_B	Adjusted-N	N_{55}	N_{55} ava.
BH-01	2	55	4.5	86	7	18.7	1.60	0.79	0.85	1	1	7.48	7.48	19
	4	55	6.5	86	10	18.7	1.13	0.79	0.95	1	1	8.45	8.45	
	6	55	8.5	86	26	18.7	0.92	0.79	0.95	1	1	17.93	17.93	
	8	55	10.5	86	42	18.7	0.80	0.79	1	1	1	26.40	26.40	
	10	55	12.5	86	42	18.7	0.72	0.79	1	1	1	23.61	23.61	
	12	55	14.5	86	52	18.7	0.65	0.79	1	1	1	26.69	26.69	
	14	55	16.5	86	55	18.7	0.60	0.79	1	1	1	26.14	26.14	
	16	55	18.5	86	48	18.7	0.57	0.79	1	1	1	21.34	21.34	
	18	55	20.5	86	50	18.7	0.53	0.79	1	1	1	20.95	20.95	
	20	55	22.5	86	48	18.7	0.51	0.79	1	1	1	19.08	19.08	
	22	55	24.5	86	50	18.7	0.48	0.79	1	1	1	18.95	18.95	
	26	55	28.5	86	53	18.7	0.44	0.79	1	1	1	18.48	18.48	
	28	55	30.5	86	31	18.7	0.43	0.79	1	1	1	10.42	10.42	
BH-02	2	55	4.5	86	7	18.7	1.60	0.79	0.85	1	1	7.48	7.48	14
	4	55	6.5	86	17	18.7	1.13	0.79	0.95	1	1	14.36	14.36	
	6	55	8.5	86	15	18.7	0.92	0.79	0.95	1	1	10.34	10.34	
	8	55	10.5	86	22	18.7	0.80	0.79	1	1	1	13.83	13.83	
	10	55	12.5	86	18	18.7	0.72	0.79	1	1	1	10.12	10.12	
	12	55	14.5	86	50	18.7	0.65	0.79	1	1	1	25.66	25.66	
	20	55	22.5	86	33	18.7	0.51	0.79	1	1	1	13.12	13.12	
	22	55	24.5	86	50	18.7	0.48	0.79	1	1	1	18.95	18.95	
	42	55	44.5	86	37	18.7	0.35	0.79	1	1	1	10.15	10.15	
BH-03	2	55	4.5	86	11	18.7	1.60	0.79	0.85	1	1	11.76	11.76	14
	4	55	6.5	86	16	18.7	1.13	0.79	0.95	1	1	13.51	13.51	
	6	55	8.5	86	16	18.7	0.92	0.79	0.95	1	1	11.03	11.03	
	8	55	10.5	86	23	18.7	0.80	0.79	1	1	1	14.46	14.46	
	10	55	12.5	86	30	18.7	0.72	0.79	1	1	1	16.87	16.87	
	12	55	14.5	86	26	18.7	0.65	0.79	1	1	1	13.35	13.35	
	14	55	16.5	86	31	18.7	0.60	0.79	1	1	1	14.73	14.73	
	16	55	18.5	86	37	18.7	0.57	0.79	1	1	1	16.45	16.45	
	18	55	20.5	86	37	18.7	0.53	0.79	1	1	1	15.51	15.51	
	20	55	22.5	86	32	18.7	0.51	0.79	1	1	1	12.72	12.72	
	22	55	24.5	86	39	18.7	0.48	0.79	1	1	1	14.78	14.78	



	32	55	34.5	86	50	18.7	0.40	0.79	1	1	1	15.72	15.72	
	44	55	46.5	86	42	18.7	0.34	0.79	1	1	1	11.26	11.26	
	46	55	48.5	86	48	18.7	0.33	0.79	1	1	1	12.58	12.58	
BH-04	2	55	4.5	86	9	18.7	1.60	0.79	0.85	1	1	9.62	9.62	15
	4	55	6.5	86	11	18.7	1.13	0.79	0.95	1	1	9.29	9.29	
	6	55	8.5	86	36	18.7	0.92	0.79	0.95	1	1	24.82	24.82	
	8	55	10.5	86	24	18.7	0.80	0.79	1	1	1	15.09	15.09	
	10	55	12.5	86	30	18.7	0.72	0.79	1	1	1	16.87	16.87	
	12	55	14.5	86	36	18.7	0.65	0.79	1	1	1	18.48	18.48	
	14	55	16.5	86	40	18.7	0.60	0.79	1	1	1	19.01	**19.01**	
	16	55	18.5	86	41	18.7	0.57	0.79	1	1	1	18.22	**18.22**	
	18	55	20.5	86	45	18.7	0.53	0.79	1	1	1	18.86	**18.86**	
	20	55	22.5	86	17	18.7	0.51	0.79	1	1	1	6.76	**6.76**	
	22	55	24.5	86	35	18.7	0.48	0.79	1	1	1	13.27	**13.27**	
	24	55	26.5	86	50	18.7	0.46	0.79	1	1	1	18.15	**18.15**	
	26	55	28.5	86	50	18.7	0.44	0.79	1	1	1	17.43	**17.43**	
	28	55	30.5	86	30	18.7	0.43	0.79	1	1	1	10.08	**10.08**	

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

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

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

$f = 7N$ for N<=4

$f = 27.12 + 0.2857N$ for N=4 to 50

$\nu = 0.2 + 0.01N$ N= 0 - 20 loose granular soil
$\nu = 0.2 + 0.005N$ N= 20 - 50 dense granular soil
$\nu = 0.15 + 0.0167N$ N= 0 - 6 Soft Clay
$\nu = 0.125 + 0.0125N$ N= 6 - 30 stiff clay

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

Skin Resistance and Base Resistance

Janbu's Method of Determining Q_b

$$Q_b = (cN^*_c + q''_o N^*_q)A_b$$

Where: -

c = unit cohesion

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

N^*_c and N^*_q = bearing capacity factors

A_b = base area of the pile

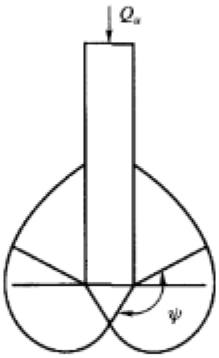


Figure A.1: The shapes of failure surfaces at the tips of piles as assumed by Meyerhof

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

ψ=	75⁰		90⁰		105⁰	
φ	N^*_q	N^*_c	N^*_q	N^*_c	N^*_q	N^*_c
0	1	5.74	1	5.74	1	5.74
5	1.5	6.25	1.57	6.49	1.64	7.33
10	2.25	7.11	2.47	8.34	2.71	9.7
20	5.29	11.78	6.4	14.83	7.74	18.53
30	13.6	21.82	18.4	30.14	24.9	41.39

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

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

Skin Resistance Q_f by Coyle and Castello (1981)

$$Q_f = A_s q'_o K_s \tan \boldsymbol{\delta}$$

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

$$f_s = K_s \tan \boldsymbol{\delta} q'_o = \beta q'_o$$

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

$$Q_f - f_s * p$$

Where: -

f_s = unit skin friction

β = the skin factor

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

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

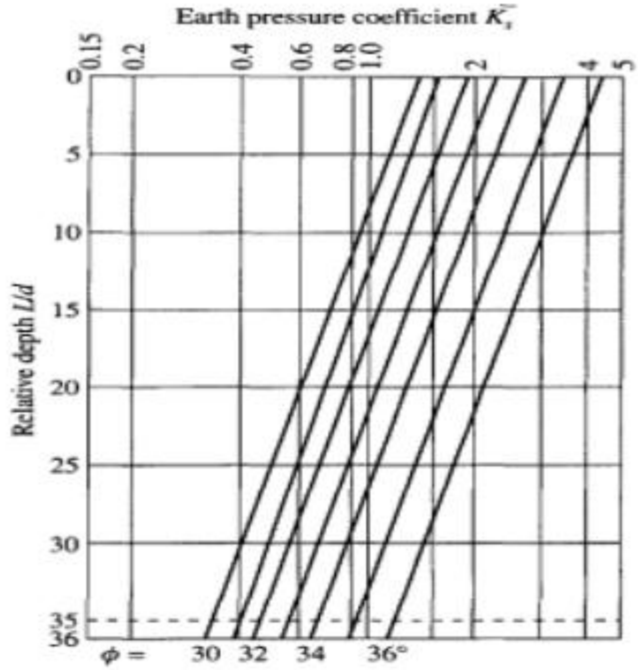
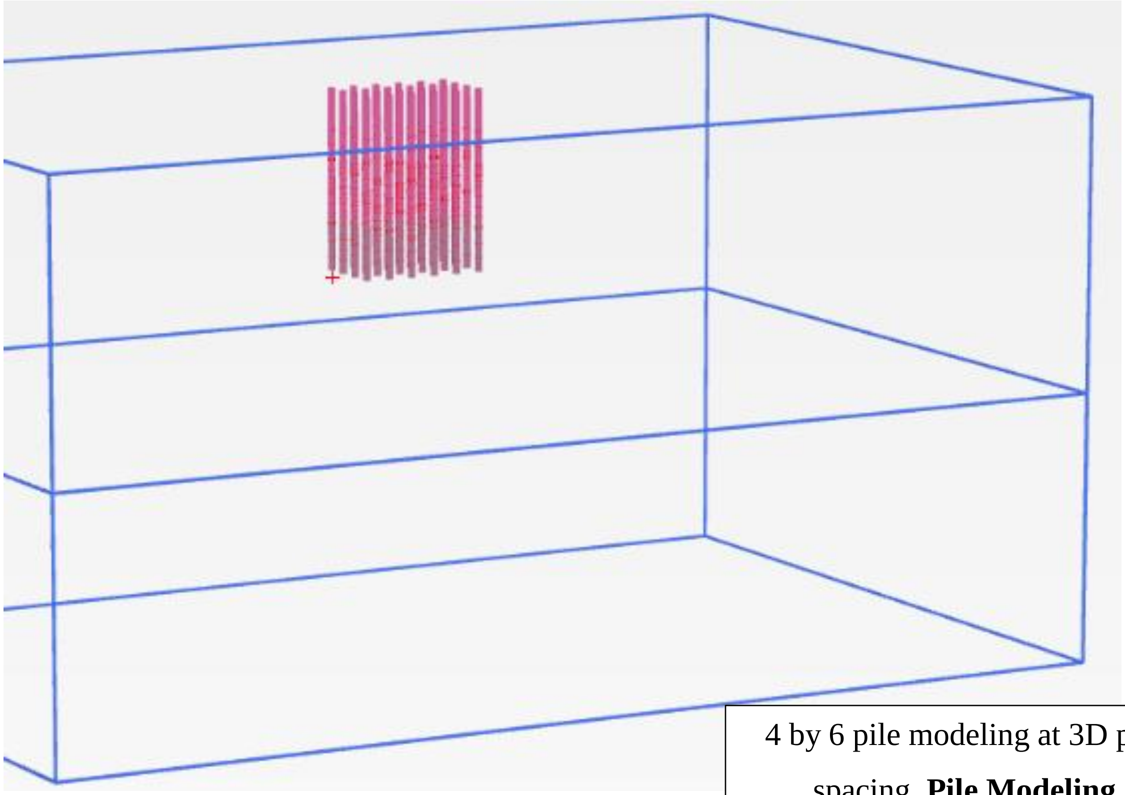


Figure: Coefficient K versus L/d, **δ** = 0.8 *φ* (Coyle & Castello, 1981)

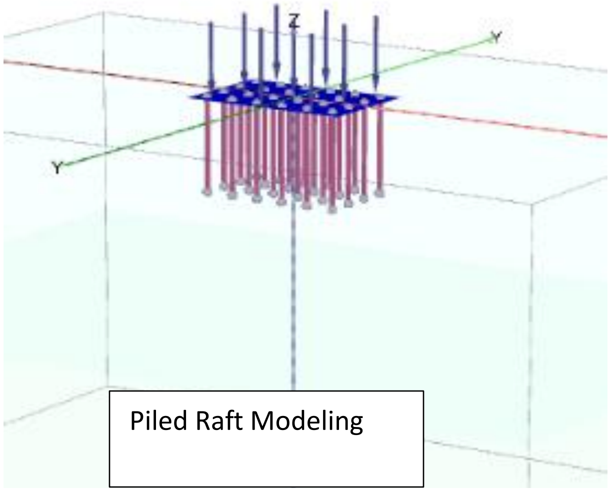
Table: Base resistance and skin resistance value for this study

L	D	L/D	C	$	#	@	NC	NQ	Ab	P	TAN@	KS	Q'	Q"	Qb	Qf
18	1	18	41.7	23.7	90	18.96	10.95	20.495	0.785	3.14	0.343359349	0.65	306.837	163.182	5295.012862	114.3573633
14.4	1	14.4	41.7	23.7	90	18.96	10.95	20.495	0.785	3.14	0.343359349	0.7	240.957	130.242	4235.097541	98.29413876
10.8	1	10.8	41.7	23.7	90	18.96	10.95	20.495	0.785	3.14	0.343359349	0.8	175.077	97.302	3175.18222	83.9247931

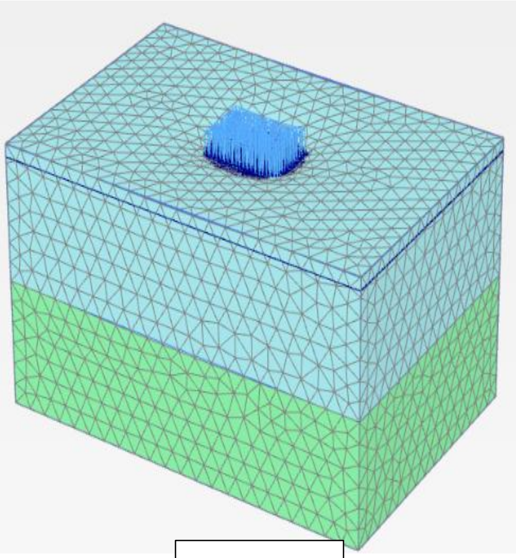
Appendix -3: Plaxis 3D Modeilng and Results



4 by 6 pile modeling at 3D pile spacing, **Pile Modeling**

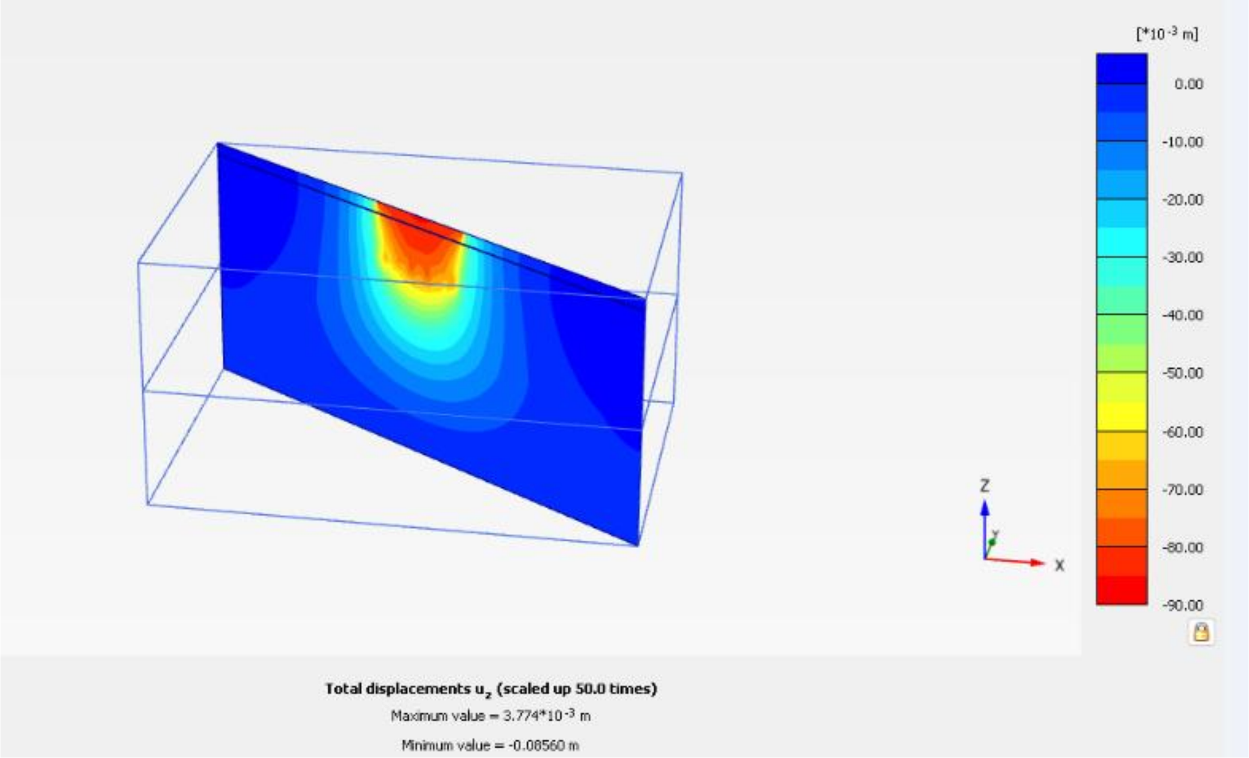


Piled Raft Modeling



Meshing

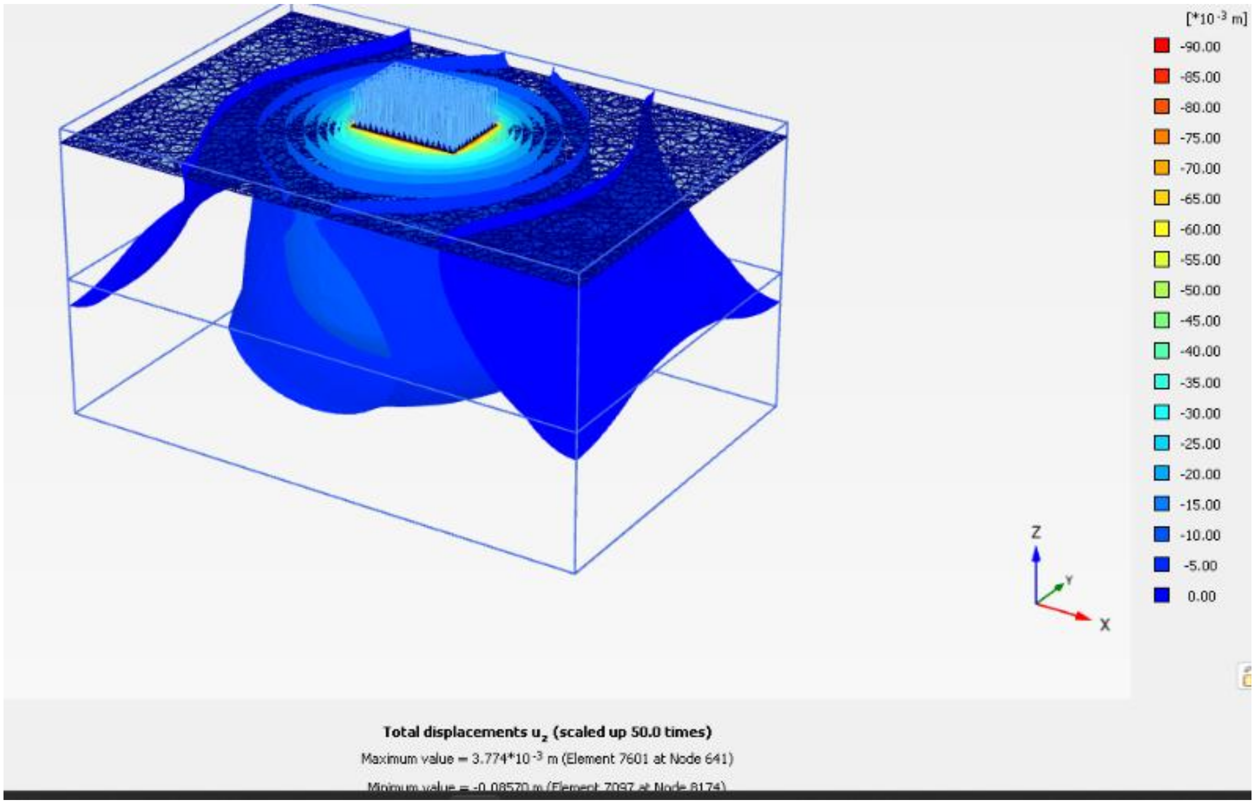
Deformations



Total displacements u_z (scaled up 50.0 times)

Maximum value = $3.774 \cdot 10^{-3}$ m

Minimum value = -0.08560 m



Total displacements u_z (scaled up 50.0 times)

Maximum value = $3.774 \cdot 10^{-3}$ m (Element 7601 at Node 641)

Minimum value = -0.08570 m (Element 7097 at Node 8174)

Deformations