Numerical Modeling and Investigation of Laterally Loaded Pile Group Embedded in Layered Soil

Walabuma Debele Tekla

A Thesis Submitted to the Department of Civil Engineering

College of Civil Engineering and Architecture

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

Office of Graduate Studies

Adama Science and Technology University

June, 2025

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled **“Numerical Modeling and Investigation of Laterally Loaded Pile Group Embedded in Layered Soil”** is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation

Walabuma Debele Tekla	______________	__________________
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I/we, the advisor(s) of this thesis, hereby certify that I/we have read the revised version of the thesis entitled "**Numerical Modeling and Investigation of Laterally Loaded Pile Group Embedded in Layered Soil**" prepared under my/our guidance by **Walabuma Debele Tekla** submitted in partial fulfillment of the requirements for the degree of Masters of Science in **Geotechnical Engineering.**

Therefore, I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

Argaw Asha (PhD	____________________	____________________
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APPROVAL PAGE

I/we, the advisors of the thesis entitled "**Numerical Modeling and Investigation of Laterally Loaded Pile Group Embedded in Layered Soil**" and developed by Walabuma Debele Tekla, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

<u>Argaw Asha (PhD)</u> __________________ _________________

Advisor Signature Date

____________________________ _________________ _________________

Co-advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by Walabuma Debele Tekla have read and evaluated the thesis entitled "**Numerical Modeling and Investigation of Laterally Loaded Pile Group Embedded in Layered Soil**" 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 Geotechnical Engineering.

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ACKNOLEDGEMENT

Above all, I would like to thank my God for giving me the courage and health to start and finish this research paper. Also, I am deeply grateful to my advisor, Dr. Argaw Asha, for providing me with scientific advice, experience sharing, and constructive criticism during my research work. Finally, I would like to give thanks to my beloved family and friends for their endless moral and economic support, as well as to all those who have contributed to the success of this study. And also it is impossible to jumping without gratitude all of my classmate for their brotherly communicated and helped with each other kindly.

ABSTRACT

The central purpose of this research is to determine numerical modeling and investigation of group of pile in layered soil when laterally loaded. Deformation and load-bearing capacity of pile groups in relation to the impact of spacing, length, diameter, number of pile were discussed. Since the complex soil-structure interaction in pile group foundations and the absence of field data, numerical approaches are frequently needed. In this study, the load-settlement behavior of pile group from previous numerical works was analytically simulated to validate the 3D finite element model. The performance of a rectangular combination pile cap system is evaluated in layered soil subjected to uniform lateral loading. The analysis is conducted using the powerful finite element-based program Plaxis 3D to examine the effects of various parameters. The analysis conducted using the powerful FE-based Plaxis 3D to examine the effects of various parameters. A finite element of three-dimensional was used to evaluate the lateral pile group response subjected to pure lateral load. The study properly focused to assessed (2x2, 3x3 and 4x4)pile group configuration with three values of pile spacing (3D, 4D, 5D), three pile diameter (0.5m, 0.75m and 1m) and three pile length (10m, 15m and 20m) . The impact of group configuration, pile diameter, pile length and pile spacing were discussed in terms of response of load vs. lateral displacement, load vs. soil resistance. In this study and the field test full-scale result obtained from literature were used PLAXIS 3D FOUNDATION FEM for the validation. The pile diameter has a significant effect on the lateral capacity of pile and pile length. Pile spacing has no significant change on lateral resistance of pile. By increasing pile diameter from 0.5m to 0.75m and from 0.75m to 1m, the ultimate lateral load increased by 55% and 59.88 respectively. It is recommended the researchers as they properly and widely to do the influence of axially and laterally subjected loads simultaneously.

Keywords; *Pile group, Finite Element, Pile & soil parameters, pile configuration, Plaxis 3D*

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ABBRIVATIONS

ϕ	Angle of Internal friction
c	Cohesion
v	Poisson's ratio
ψ	Dilatancy
FEM	Finite Element Method
FEA	Finite Element Analysis
D	Pile diameter
P_L	Pile Length
S	Pile spacing
3D	Three-dimensional
2D	Two-dimensional
Q_s	Skin friction
Q_p	Load carrying capacity of the pile
γ	Unit weight
STP	Standard Penetration Test
EBCS	Ethiopian Building Code Standards
E	Modulus of Elasticity
σ_f	Failure Normal stress
τ_f	Failure shear stress
A_g	Area of Pile group

P_B	Pile Group width
γ_{unsat}	***Unsaturated unit weight***
γ_{sat}	Saturated unit weight
BEM	Boundary Element Method
n	Number of pile
P_g	Lateral load of pile group
P_s	Lateral load of single pile

CHAPTER ONE

INTRODUCTION

In civil engineering, Piles are widely utilized to supporting framework subjected to various loads, including lateral forces, wind, earthquakes, waves, or vehicular traffic. Among these, laterally loaded pile groups play a critical role in insuring the stability of structures such as bridges, offshore platforms, and multi-story buildings. Understanding the characteristics of these foundation affected by side loads is essential for safe and cost-effective design. However, the behavior of pile groups becomes significantly more complex when embedded in layered soil, where variations in spoil properties influence the pile-soil interaction mechanisms. This complexity is addressed in the study by Salgado et al., (2024).

As it conducted by Journal of Geotechnical and Geo environmental Engineering (2004), layered soils, characterized by distinct strata with varying stiffness, strength, and density, are commonly encountered in geotechnical practice. These soil conditions lead to non-uniform stress distributions and complex deformation patterns in the pile-soil method, making it challenging to predict the structural response of pile groups. Traditional design methods often rely on empirical or analytical approaches that may oversimplify the interaction between piles and layered soils, leading to conservative in accurate designs.

Numerical modeling has emerged in recent years as a powerful tool to address these challenges by providing detailed insights into the behavior of pile foundations under complex soil conditions and loading. Numerically advanced techniques (FEM and FDM) allow for simulation of pile-soil interaction while accounting for the effects of soil layering, pile geometry, group configuration, and loading conditions. The vital objective of this study is to develop and apply numerical modeling techniques to investigate group of pile’s response embedded in layered soil when laterally loaded. The present research aims to express the influence of critical parameters, including soil stratification, pile spacing, pile length and lateral load intensity, on the performance of the pile group. By doing so, this research seeks to provide a more accurate understanding of the pile-soil interaction mechanism and contributes to the advancing enhanced design guidelines for pile foundations in layered soil scenarios.

The findings of current research are predicted to have relevant real world application for geotechnical engineering. A better understanding conduct of horizontally forced group of pile in multi deposited soil was led to more reliable and economical foundation designs, reducing construction costs while maintaining safety and performance. Furthermore, the research advanced the state of knowledge in soil-structure interaction and numerical modeling, serving as a valuable resource for engineers and researchers in the field.

1.1 Background of the Study

Constructing pile groups is a practical and efficient solution for creating high-capacity foundations in areas with limited space. However, when piles are placed uniformly and closely together, the inner piles often contribute minimally to the overall performance of the group. In such scenarios, the group's capacity is more influenced by the outer boundary shape than by the strength of individual piles. Therefore, the most effective design may involve placing piles only around the perimeter of the group area, leaving out the central piles entirely. (Zhang, et al., 2024).

Engineers must navigate the complexities introduced by layered soil profiles, which significantly impact load distribution and structural performance. This investigation employs numerical modeling techniques to simulate the interactions between pile groups and their surrounding soil, providing valuable insights into load response and displacement behaviors. Incorporating advanced modeling software, I aim to replicate real-world scenarios that account for soil stratification and inherent material properties. Through this exploration, I aspire to contribute to the body of knowledge that supports engineers in optimizing the performance and reliability of pile foundations under lateral loading.

This research investigates perimeter-type pile groups clusters in which piles are installed only around the boundary, leaving unpiled soil core. Designers favor such layouts when large loads must be carried in confined plans, yet few data exist on their performance. In particular, it has been suggested that interior piles in conventional grids contribute little to ultimate capacity. The main challenges involve calculating the loads transferred to each pile within the group and assessing the efficiency of closely spaced pile groups. These issues are key aspects of soil structure interaction. When piles are spaced far apart several times their diameter the interaction between pile, soil, and adjacent piles is minimal. However, as the spacing decreases, the stresses in the soil caused by axial or lateral loads begin to influence neighboring piles. A straightforward way to account for this stress interaction is to recognize that the efficiency of closely spaced piles drops below unity.

1.2 Statement of the Problem

A number of previous studies that investigate the characteristic of group of pile subjected to lateral loads with factors like spacing, pile-soil interaction and load distribution. The behavior of laterally loaded pile groups is crucial for the stability of structures such as offshore platforms and bridges. The review highlights how understanding the lateral load behavior is vital for Geotechnical design (Randolph and Wlotn, 1979). Pile groups are complex under lateral loads compared to single piles due to pile interactions and soil heterogeneity.

In layered soil, which consists of distinct strata with varying stiffness, strength, and density, complicates the prediction of pile-soil interaction. Variations in soil properties across layers lead to non-uniform stress distribution, differential displacement, and complex deformation patterns. Traditional empirical or analytical methods used to analyze laterally loaded pile groups often fail to account for the effects of soil layering accurately, resulting in either conservative or unsafe designs.

1.3 Objective

1.3.1 General

The central goal of this research is to investigate the behavior of load on lateral pile groups installed in multi layered strata using advanced numerically modeling techniques.

1.3.2 Specific Objective

- To develop numerical model validation for simulating the behavior of pile groups under the horizontal forces
- To evaluate the influence of layered soil on the horizontal response of groups of pile
- To analyze the influence of pile groups’ parameters (pile number, pile length, pile spacing and pile diameter) on head deflection and lateral resistance.

1.5 Research Questions

- How develop the accuracy and validation of numerical modeling to simulate the behavior of pile groups supported to lateral load?
- How layered soils impact the lateral response of pile groups?
- How pile length, pile spacing, group configuration and pile diameter affect lateral resistance?

1.6 Significance of the Study

Some significant key points are:

- Enhanced design accuracy
- Improved safety and reliability
- Cost-effective solutions
- Understanding soil structure interaction
- Adaptation to site diverse condition
- Contribution to research and practice

1.7 Delimitation

This study limited due to lateral loads for laterally loaded group of pile. This study was excluded or not considered the application of vertical loads or loads that come from supper structure. To evaluate the impacts of pile parameters on lateral displacement and ultimate lateral resistance when pile is subjected to lateral, loads this study limited. The effect of water table, the stress changes, the effect of heave and vertical settlements are not in the scope of this thesis. This study was limited only the parametric study of laterally loaded pile group under constant distributed load along pile length. Here the effect of vertical loads which is transferred to the pile from the super structure is ignore, the cap or raft was modeled as a thin plate and for this study only linear displacement were considered.

1.8 Scope of the study

The research focuses only on laterally loaded pile groups, excluding axially loaded piles. The study is confined to specific layered soil profiles, not considering highly irregular stratifications. This study assumed concrete pile groups and non-uniform pile diameters and lengths. The loading condition of the research considered only laterally loaded, neglecting seismic, cyclic, or dynamic load unless explicitly included. Environmental effects (ground water table fluctuations, temperature changes, other environmental influences) and pile cap not included.

1.9 Limitation

The investigation is bounded to studying characteristic of pile group for laterally loaded due to lateral loads. This study excluded not only the application of vertical loads (load that comes from supper structure of the building) but also the effect of water table. The effect of stress changes, heave and vertical settlements were not part of this thesis. Pile groups' configuration, diameter, length, horizontal displacement, and ultimate lateral resistance when pile is responded to horizontal force is limitation of current investigation. Here theimpact of vertical loads which is transferred to the pile from the super structure is ignore, the cap or raft was modeled as a thin plate and only linear displacement were considered for this study. Why this study was limited is because of time constraints, limited access to data and budget. In this case the factors or variables were out of control.

This study rely on linear elastic soil and the results depends on the numerical simulation software PLAXIS 3D FOUNDATION 21V. Numerical model of Finite element method required to identify how stresses and displacements propagated. Because of the unavailability of experimental or field test data, results rely solely on theoretical and numerical interpretations.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

It is crucial knowing behavior of pile groups subjected to lateral loads, especially in layered soils systems, due to their relevance in Geotechnical Engineering (foundations for structures like bridges, buildings, and offshore platforms). The complexity introduced by layered soils, which can vary in properties (such as stiffness, strength, and density) across different layers.

A number of previous studies that investigate the characteristic of group of pile subjected to lateral loads with factors like spacing, pile-soil interaction and load distribution. The behavior of laterally loaded pile groups is crucial for the stability of structures such as offshore platforms and bridges. The review highlights how understanding the lateral load behavior is vital for Geotechnical design (Randolph and Wlotn, 1979). Pile groups are complex under lateral loads compared to single piles due to pile interactions and soil heterogeneity.

Review of models such as; boundary element models and finite element methods, with other numerical systems were used to simulate the interaction between soil and pile. Soil-pile interaction plays a critical role in the behavior of pile groups. Various studies (Poulos and Davis, 1980) (Gazetas, 1991) have explored the way piles transmit load to surrounding soils and how the interaction changes with the lateral displacement. Numerical models are needed to capture this interaction accurately, as traditional method may not fully represent complex soil responses.

Discussion of how layered soil profile are modeled, with a focus on how the variation in soil stiffness affects pile group performance, and how different soil models (elastic, Mohr-Coulomb, or models non-linear) were utilized to present soil characteristic. The review emphasizes the challenges in modeling layered soil profiles, where soil stiffness varies across layers. Many studies (Wei and Hunan, 2009) have shown that layered soils can significantly influence the lateral load capacity of pile groups. Proper representation of soil stratigraphy, including the stiffness and strength of each layer, is crucial for accurate simulations. Methods such as Finite Element Analysis (FEA) are commonly used for this purpose (Miao and Zhang, 2016).

The numerical methods like the Finite Difference Method (FDM) and Finite Element Method (FEM) are extensively used to simulate the pile-soil interaction under lateral loads (Andrianopoulos et al., 2011). The review compares these methods, noting that FEM is particularly useful for complex soil profiles due to its ability to model nonlinear behavior and varying boundary conditions. Recent advancements in 3D FEM simulations (Souri, Ahmed, 2017) have improved the understanding of pile behavior in layered soils.

(Prakash, 1962) found from model tests in sand that piles behave as individual units if the center-to-center spacing is more than three pile widths in a direction normal to the line of the loading and where they are spaced at more than six to eight pile widths measured along the loading direction. These findings are supported by results of finite element analyses reported by (Yigian and Wright, 1973) who showed that, for a given pile spacing, the group efficiency factor of a row of piles is smaller (i.e. greater interaction) when the horizontal loading is applied along the line joining the piles, compared to that when the loading is perpendicular to the line joining the piles.

Results of instrumented full-scale tests on a pile group in sand reported by (Brown el at, 1988) indicate that the lateral load of piles in the leading row is around 90% of a single pile; even though, the measured load of the piles in the trailing row is near to 40% of a single pile. It is characterized to the influence of obscuring, which means impact of interplay of stress fields in the way of the load.

As noted from the recent studies, understanding the influence of depth's scour and slope on horizontal pile capacity is essential. The results indicate that scour depth significantly impacts pile performance, while the width and angle of the scour can also alter reaction forces (Lee et al, 2022). A considerable number of model tests have been carried out to determine group efficiency factors in homogeneous clay-for example, (Whitaker, 1957), (Saffery and Tate, 1961) and (Sowers, 1961). A summary of some of these tests has been presented by de (Mello, 1969). From de Mello's in summary, higher efficiency factors are observed in a pile groups with smaller length –to diameter ratios, wider spacing, and fewer piles.

The experimental study, which observed a single piles behavior in multi-layered soil, demonstrated that variations in soil composition directly influence the lateral capacity of the pile, particularly highlighting the contribution of sand layers in increasing stability. Such empirical evidence solidifies the necessity of incorporating soil stratification in numerical modeling to enhance the accuracy of predictions and design methodologies in geotechnical Engineering. Consequently, the conclusion drawn from this research not only advance theoretical understanding but also underscore practical implications for future constructions involving lateral loads on pile foundations.

Advances in computational power and modeling technique have allowed for more detailed simulations of pile group behavior in layered soils. Recent works (Goh, W.et al., 2019) have integrated advanced soil models in to FEM frameworks to better represent the non-linear behavior of soils under large lateral displacements.

A preliminary investigation of lateral behavior of pile under lateral loads in sand carried out using nonlinear FE methods. The finite element model was verified against a full-scale pile load test in sand in terms of pile deflection, bending moment, and p-y curves along the length of the pile (C.C. Fan et al. 2005).

Contextually, the properties' of horizontally loaded piles reliance has led to the distinction between rigid & flexible piles. These classifications reflect an intuitive understanding of pile characteristic where a very rigid and relatively stiff pile (such as a fence strainer post) is expected to exhibit rigid deflection under lateral loading. Whereas very long pile in the same situation would be predicted to exhibit a different type of behavior due to the increased embedment and accompanying fixity that implies. (C. Reese, 1986) discussed this dependence of lateral behavior on pile length, noting that short piles can deflect a large amount at the ground line given movement of the pile tip, but with increasing depth of penetration the soil resistance at the pile tip increases until a point is reached at which ground line deflection reaches a limiting value.

(Broms, 1965) developed a simplified solution based on the assumption of shear failure in soil, which is the case for short piles and bending of the pile, governed by the plastic yield resistance of the pile section, which is applicable to long piles for laterally loaded piles. Soil properties and Pile Group parameters are directly influence Numerical Modeling results (Lateral displacement, stress/strain, and lateral ultimate resistance). Numerical modeling validates the impact of parameter variations on dependent variables.

The importance of understanding these interactions cannot be overstated, as it reveals how factors such as pile spacing and arrangement can exacerbate or mitigate load effects, which is particularly crucial for safety and durability (Yang et al.). By investigating these dynamics, engineers can optimize design practices ensuring structures can withstand these lateral forces effectively. The horizontal tendency of the pile group with both cohesion less and soils with cohesive properties has been extensively studied, with various modeling approaches developed to predict their behavior under lateral loads. A significant contribution in this field is the work as stated in the research conducted by Al- Sharma et al. (2018), who employed a three-dimensional finite element method for evaluating the lateral behavior of piles under purely lateral loading. Their study evaluated different pile group configurations and spacing, providing insights into load-displacement behavior and soil resistance, which are crucial for the design of laterally loaded piles.

Another notable study is by Reese and Van Impe (2001), who presented methods for calculating deflections, ultimate resistance, and moment distribution for laterally loaded single piles and pile groups in cohesion less soils.

Present studies (S.Karthigeyan et al.,, 2007) and (Wong et al.,, 2018) have shown that the fundamental nature of the laterally loaded pile problem is three-dimensional, demanding the use of three-dimensional numerical models to properly assess behavior. Previous numerical investigations have shown that finite element modeling offers a reliable means of evaluating pile-soil interaction, supporting a more rational understanding of the underlying mechanics. This study conducts a three-dimensional finite element analysis based on a well-documented benchmark case and proposes a deformation-based approach for design. It also simulates instrumented lateral load tests, facilitating the evaluation of p-y curve behavior in comparison with empirical models.

The behavior of laterally loaded cluster of piles embedded in layered soils has been extensively studied through both experimental and numerical methods. Numerical modeling, in particular, has become a pivotal tool for understanding the rections complexity between piles and soil strata.

A significant study by Mohammad Reza Ghasemi, Mohammad Saleh Ghasemi, and Mohammad Reza Ghanberi (2020) utilized a 3D finite element framework was developed to model the response of pile groups subjected to lateral loads. The research established a benchmark database to systematically analyze group reduction factors and various behaviors of horizontally impacted pile groups. The numerical accuracy model was against small-scale laboratory tests, demonstrating its capability to predict pile groups behavior accurately. The analysis also explored the influence of lateral load angle changes on group efficiency, highlighting the importance of considering load direction variations in design.

In another investigation, Yohannes Tadesse (2019) conducted a three-dimensional finite element analysis to assess the influence of pile diameter, pile length, and site conditions on the behavior of laterally loaded single piles embedded in layered soils. The study found that pile head deflection decreased with increasing pile diameter due to enhanced stiffness, while variations in pile length beyond a critical point had negligible effects on deflection. Additionally, the position and depth of hard soil layers close to the surface significantly impacted the pile's response, emphasizing the need for careful site characterization in design.

These studies collectively underscore the critical role of numerical modeling in understanding the complex interactions in pile group subjected to lateral loads installed within stratified soil. They highlight the influence of factors such as pile geometry, soil stratification, and loading conditions on pile performance, providing valuable insights for the design and analysis on the foundation of pile in layered strata environments.

Researchers S.T Kok and Bujang B.K. Huat (2008) focused on the design of horizontally exerted piles responsible to soil motion, employing both theoretical and numerically approached. It highlighted the importance of considering soil-structure interaction in the design process and provided insights into pile behavior under lateral loading conditions.

Authors, (2019) utilized two-dimensional finite element analysis with soil works 2D software to examine the lateral performance of pile groups in sandy soils. The study considered various pile group configurations and soil densities, finding that factors such as soil layering, pile slenderness ratios (L/D), lateral loads, and soil density significantly influence the lateral response of pile groups.

According to P.E. Kavitha, K.S. Beena, and K.P. Narayanan (2016) comprehensive review delves into the relevance of structural reaction of soil in the behavior of structures under various loading conditions. The authors emphasized the non-linear nature of the soil-pile system and discuss factors influencing this interaction, such as soil properties, pile material, and loading types. The study underscores the importance of advanced simulation tools, like finite element analysis, in accurately predicting structural behavior.

As Researcher Fenta Nebiyou (2019) studied on behavior of laterally loaded pile embedded in layered soil, the investigation aimed to identify the influence of pile diameter, pile length, and site conditions on the response of single piles subjected to lateral loads.

The characteristic of horizontal force for individual piles was examined in Addis Ababa at three different sites using piles of varying diameters and lengths. The analysis was performed on free-headed variable piles, and field test of full-scale results from the published materials were utilized to validate the PLAXIS 3D foundation finite element model. Horizontal displacement, bending moment and shear force were estimated for variable pile configurations at different sites mentioned above, and the outcomes were presented accordingly.

The investigation illustrated deflection of pile's head, lateral displacement, distribution of bending moment, distribution of shear force through the pile shaft, and horizontal soil's resistivity were affected by both pile's diameter and site scenarios. It was observed that pile's top displacement decreased with increasing pile diameter due to enhanced stiffness, while it remained nearly constant with increasing pile length-since the embedded length exceeded the critical length. An increase in pile diameter also led to higher maximum horizontal load tendency, bending moment and shear force, whereas increasing length of pile had a little effect on these parameters. Additionally, the location and the thickness of the hard strata near the ground surface played a significant role in the response of laterally loaded piles (Nebiyou, 2019).

2.2 Pile Group Parameters

2.2.1 Pile Group Geometric

2.2.1.1 Number of Pile (n)

Ultimate load tendency increases with number of piles. Under the same lateral load, a number of piles reduce group deflection. Even if more number of piles reduces group deflection, piles in different rows (leading against trailing) indicate different deflection patterns and bending moment.

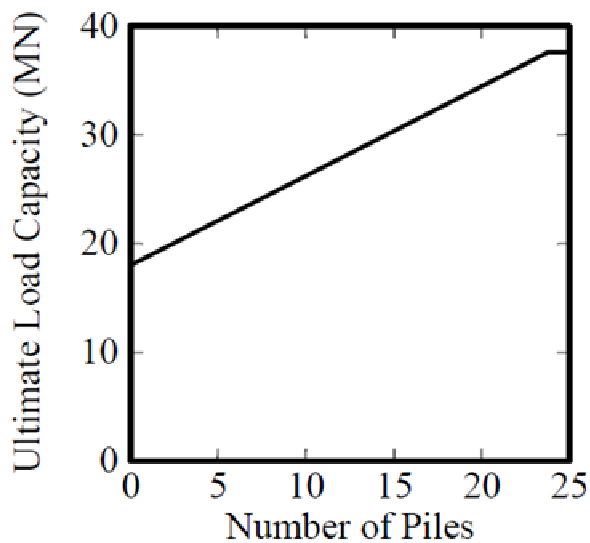


Figure2.1: Effect of the number of piles on the ultimate load capacity (Poulos, 2001)

2.2.1.2 Pile Spacing (s)

Lee et al. (2015) demonstrated that the load-carrying capacities of individual piles foundation increase with increased center-to-center pile spacing. In addition, with increasing pile spacing , the load-carrying capacity of the pile foundation decreases, which indicates a higher proportion of load taken by the piles.

As the center-to-center distance of piles reduces, the stress fields around the piles start to overlap more, which direct to a reduction in the piles' ability to carry loads. In a study conducted by Samee (2018), both experimental and theoretical analyses were used to investigate the effect of pile spacing on the ultimate capacity and load shearing of non-rested and directly rested pile foundations on the soil. When the pile cap is directly contact with the soil, increasing the spacing between piles enhances the ultimate load-bearing capacity. However, for pile caps that are elevated and not resting on the ground surface, the ultimate capacity begins to decrease once the spacing exceeds four times the pile diameter.

Additionally, for pile caps not in contact with the soil, the frictional load transferred to the surrounding soil increases as the pile spacing increases. In contrast, when the pile cap rests directly on the soil, the frictional resistance transmitted to the soil also maximizes with spacing up to four times the pile's diameter, after which it begins to decline as spacing continues to grow.

2.2.1.3 Pile Arrangement

Pile arrangement based on different factors (load type; either vertical or lateral or both, types of soil; either cohesive or cohesion less and soil layering impact.) The pile arrangement plays a critical role in lateral load resistance, group efficiency, and interaction effects. For lateral load resistance the pile arrangement, be linear (1row), rectangular or square group (2x2, 3x3, 4x4, etc.)

2.2.1.4 Pile Cap Size & Thickness

The pile cap size for a laterally loaded pile group embedded in layered soil depends on different conditions such as pile group geometry, soil stratigraphy, etc. For heavy loads or high lateral demands the pile cap thickness rough estimation may be 1.5m – 2.0m.

2.2.2 Pile Properties

2.2.2.1 Pile Diameter (D)

As the pile groups' diameter increases, the lateral deflection of the group reduces. In most cases, the top displacement of a horizontally loaded pile primarily based on the stiffness and tendency characteristics of the soil layers located near the ground surface.

2.2.2.2 Pile Length (L)

As pile length increase embedded depth also increase and hence greater lateral stiffness leading to reduced lateral deflection.

2.2.2.3 Pile Type

Pile type may be categorized based on **material** (Concrete, steel, timber) in this research, the pile type I used is concrete pile, based on **installation method** (driven piles, bored piles), based on **function** (friction pile, end bearing pile).

2.2.2.4 Pile Materials

Concrete piles may be precast concrete piles (made in a factory and transported to the site), cast-in-situ concrete piles (poured into a drilled hole at the construction site) and pre-stressed concrete piles (reinforced with pre-stressed tendons for higher strength).

2.2.3 Soil Parameters

2.2.3.1 Soil Type and Stratification

Soils generally classified based on their grain size, composition and engineering behavior as **course-grained soils** (gravel & sand), **fine-grained soil** (silt & clay), etc.

Soil stratification describes how these soil types are arranged in layers beneath the surface, which affects bearing capacity, settlement, and lateral resistance

2.2.3.2 Soil Strength (Cohesion (c), angle of internal friction)

It refers to a soil's capability to resist deformation and failure under applied loads. It is a key factor in Geotechnical engineering and foundation design. There are two primary types of soil strength (shear strength & tensile and compressive strength). **Shear strength** is the most critical for stability and is defined by the Mohr-coulomb failure criterion (T = c + σ'+ tan ϕ).

2.2.3.3 Bearing Capacity (ultimate and allowable)

Lateral capacity is not typically defined in terms of a traditional bearing capacity (as in axial cases) but rather the Ultimate lateral resistance (maximum load before failure or excessive deflection), and/or the Allowable load based on a lateral deflection limit (25mm or as per code).

2.2.3.4 Pile-Soil Interaction (Negative skin friction, group effect, etc.)

Pile soil interaction refers to the complex behavior that occurs between a pile (deep foundation element) and the surrounding soil under various loading conditions. Understanding this interaction is essential for designing safe and efficient pile foundations, especially under vertical, lateral, and combined loading.

Lateral interaction (the pile resists horizontal forces through bending and mobilizing soil resistance along its embedded length). This is modeled using **p-y curves** or p-multiplier for group effects (p= soil resistance per unit length, y= lateral deflection of the pile).

As Reese & Wang (1998) proposed, an empirical method to account for pile-soil-pile interaction in laterally loaded pile groups, by introducing the concept of a p-multiplier (p_m). The p-multiplier reduces the lateral soil resistance (p-value in p-y curves) for piles with in a group to account for (shadowing effects, overlapping failure zone, reduced soil mobilization due to nearby piles).

Soil reactions are modified from p-y curves as:

$$P_{group} = p_m * p_{single} \qquad (2.1)$$

Where:

P_{group} = modified lateral soil resistance for a pile in a group

P_{single} - resistance for an isolated pile

p_m – p-multiplier (p_m <= 1)

Reese & Wang (1998) provided p_m values for sand based on pile spacing (s), pile diameter (D) and pile position in the group. These values primarily for sandy soils, under static lateral loading. The following table indicated that the modification of p-y curve of single pile to pile group. This p-multiplier is a key factor used to adjust lateral soil defense for single piles in a group, to reflect the reduced efficiency due to pile-soil-pile interaction. It accounts for the shadowing effect, where soil resistance is reduced due to overlapping zones of influence between adjacent piles. It ranges from 0.3 to 1.0 depending on the pile position, pile diameter and spacing.

P-multiplier is especially important when s/d<6 where group effects are significant. In the following table, Reese and Wang (1998) proposed p_m only for spacing (s/d) 3, 5 and >=6 for all pile position. For spacing (s/d =4) I used interpolation.

Table2.1: Typical p-multiplier values for sand (Reese & Wang, 1998)

Pile position	**Spacing (s/d)**	**p-multiplier (p_m)**
Leading row	3	0.7
	4	0.75
	5	0.8
	>=6	1.0
Middle row	3	0.5
	4	0.575
	5	0.65
	>=6	0.9
Trailing row	3	0.4
	4	0.5
	5	0.6
	>=6	0.8 – 1.0

The same load magnitude is carried with the piles in the leading row when compared with single isolated pile. This is attributed to the reduced group interaction effect on the leading pile compared to the other piles. Similarly, the piles in the first and second trailing rows tend to carry similar amounts of load. It appears that pile spacing in the range of 3D to 5D result in lower p-multiplier values. When comparing closely spaced piles with widely spaced ones, the group interaction effect is more significant in the case of smaller spacing. This suggests that, for pile groups with wider spacing, each pile behaves more independently and can be designed using the response of a single isolated pile.

2.2.4 Load Parameters

When analyzing a pile group embedded in layered soil, the load parameters and their distribution based on several factors, inclusive the characteristics of the soil layers, the pile group configuration and type of lateral loading.

2.2.4.1 Lateral Load

Applied lateral load on pile group, transmitted to the surrounding soil through lateral resistance. Both lateral stiffness of each pile and the reaction of piles with surrounding soil govern the distribution of lateral load. The lateral resistances in different soil layers differ depending on their properties (stiffness, friction angle, cohesion). The depth of the pile in each layer and the soil's shear strength plays a significant role in how the pile group responds to lateral loading.

2.2.4.2 Moment and Shear force

The bending moment develops along the pile length due to the application of lateral load. The soil's lateral stiffness (which varies with depth and layer type) influences how the moments are distributed along the length of each pile. The shear force in a laterally loaded pile group refers to the internal forces that develop in the piles due to lateral loading. In laterally loaded pile groups, shear forces are important for evaluating the structural integrity of the pile and understanding how theside load is distributed.

2.2.5 Group Efficiency Parameter

Due to pile-to-pile interaction, increasing the number of piles in a group tends to reduce the side resistance per individual pile and the efficiency of load distribution. This effect is influenced by the spacing between the piles, with closer pile spacing resulting in greater interference.

2.2.5.1 Efficiency Failure

Efficiency failure indicates a situation where the pile group fails to effectively share the load, leading to a reduction in the overall load-carrying tendency of the group. This often happens when the piles are too closely spaced or if there is an imbalance in the distribution of lateral forces.

2.2.5.2 Lateral Static Load Transfer Mechanism of Piles

By using lateral resistance of soil, piles transfer lateral load to the surrounding soil mass. (Fleming et al., 2009) and (Basu et al., 2008) stated that, when a pile is loaded laterally, a part or whole of the pile tries to shift horizontally in the direction of the applied load (causing bending, rotation, or translation of the pile). The external horizontal forces are balanced by the total soil resistance along the entire pile shaft.

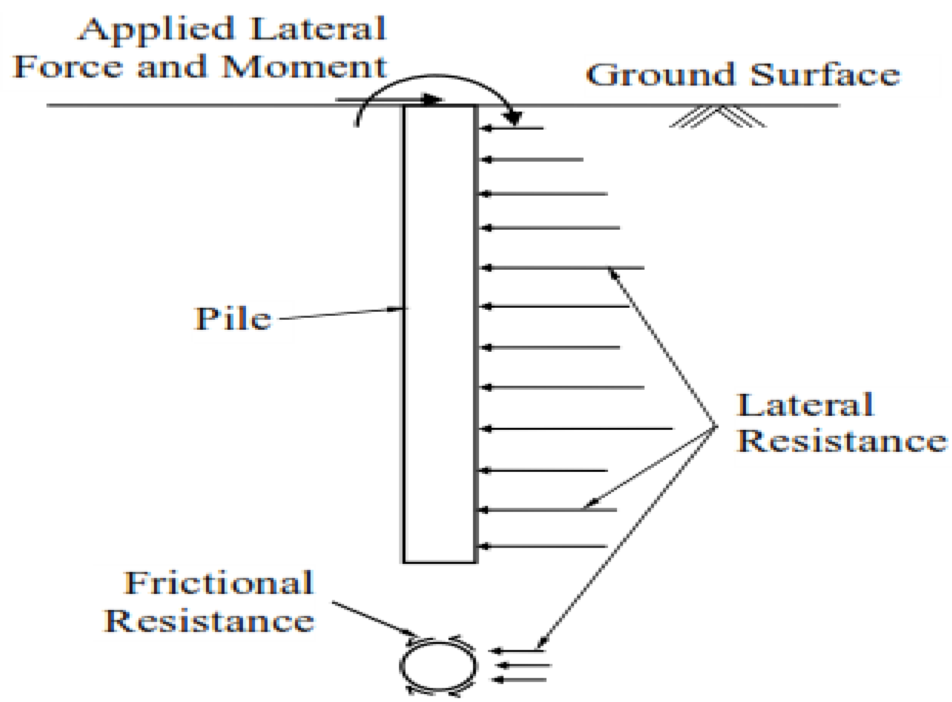


Figure2.2: Load Transfer Mechanism of Laterally Loaded Piles (Basu et al., 2008)

As usual, the load acting on a superstructure is larger than the capacity of a single pile.

2.2.5.3 Kinematics & Failure Modes of Laterally Loaded Piles

The kinematics and failure behavior of laterally loaded piles are complex and depend significantly on the type of pile involved. Since these piles are subjected to transverse loading, they may undergo bending, rotation, or translation (Basu et al., 2008; Fleming et al., 2009). As the pile displaces in the location of the exerted lateral load, a gap may form behind the pile near the surface, typically within the upper few meters of soil. If the pile is relatively short and thick, it tends to experience minimal bending and instead rotates or translates-this type is referred to as a rigid pile (see Figure 2.3). Conversely, when the pile is long and slender, it deforms primarily through bending under lateral loads, this type is known as a flexible pile (see Figure 2.4).

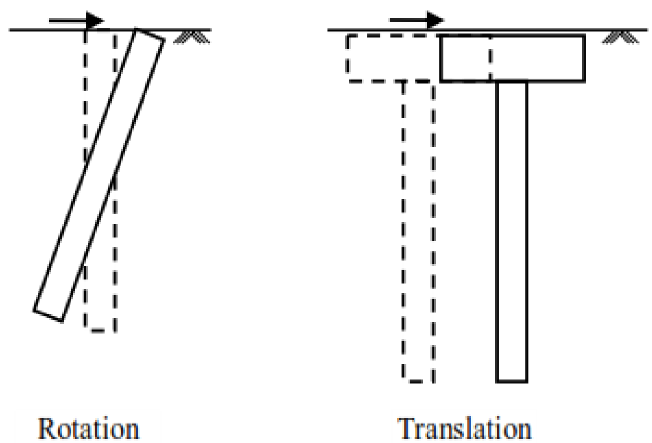


Figure2.3: Motion Characteristics of rigid piles

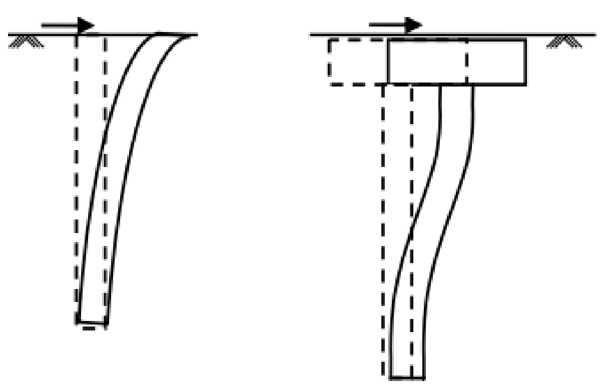


Figure2.4: Motion Characteristics of flexible piles

Engineers often define "failure" based on practical design criteria established for structural stability and equilibrium. For any structure or foundation system, certain predefined conditions must be met to ensure acceptable performance. If one or more of these conditions are violated, the structure or foundation is considered to have failed. Generally, failures are categorized in to two main types: (1) ultimate limit states and (2) serviceability limit states (Basu et al., 2008).

In structural and geotechnical design, all potential ultimate and serviceability limit states associated with a given element must be identified, and the design must ensure that none of these states exceeded. The ultimate limit state may result in collapse of the superstructure. In the case of flexible piles, failure mechanisms often involve the formation of the plastic wedge in the surrounding soil, leading to excessive lateral deflection and bending. However, before reaching this pile-centered ultimate limit state, other limit states-particularly serviceability limits such as excessive pile head deflection-may be reduced and cause failure in terms of usability or performance.

2.3 Analysis Method

A laterally loaded pile group analyze involves a multi-step approach that combines theoretical understanding, numerical modeling and empirical data to predict the behavior of the pile group under lateral loading.

2.3.1 Brom's Method

Brom's method is a simplified approach for analyzing laterally loaded single piles**.** For cohesive soils (typically soft to stiff clays), Broms provided a closed-form solution that assumes plastic behavior of the soil. Is also broadly used approach to approximate the lateral tendency of load and deflection of laterally loaded piles, particularly for cohesive soil.

2.3.1.1 Brom's Method for Cohesive Soils

Soil parameters such as **undrained shear strength** (Su) define the soil's resistance to lateral load and **soil modulus** (E) the modulus of elasticity can vary with depth and type of cohesive material.

2.3.1.2 Brom's Method for Cohesionless Soils

Broms' method provides a simplified approach to determining the lateral load capacity and deflection of piles, particularly in cohesion less soils. The maximum soil resistance assumed three times the Rankine passive pressure. The method considers both free-headed and restrained-head conditions and is often presented graphically through it can be adapted for computer applications. It consider both free-head and fixed-head piles, which influence the deformation pattern and bending moment distribution.

2.3.2 Subgrade Reaction Approach

The subgrade reaction approach (also known as the spring-based method) is widely used for analyzing laterally loaded pile groups, particularly for the evaluation of lateral displacement and deflection of piles under lateral loading. It assumes that soil resistance can be modeled as representative function or idealized response as a set of springs, each corresponding to the lateral resistance of the soil at various depths along the pile. This approach simplifies the complex interaction between the pile and surrounding soil, making it easier to analyze and model

2.3.3 Continuum Approach

The soil is commonly modeled as an infinite, linear elastic medium where its response is characterized by the deflection profile along the vertical direction (Kavitha et al., 2016). However, applying this theoretical approach in practical engineering is often challenging due to its mathematical complexity. Research in this area is generally divided into two main computational systems: both Boundary Element Method (BEM) and Finite Element Method (FEM).

2.3.3.1 Boundary Element Method

The technique that analyzes the mutual response and influence between the supporting soil and the structural elements by considering the impact functions of both soil and foundation plate is known as boundary element method. With this method, it is sufficient to define just the limits of the foundation system need to be divided into elements which reduce computation time and computer storage compared to the finite element method. Kuwabara (1989) used this method to study the behavior of group piles in a homogeneous elastic soil.

For laterally loaded piles, the early work on BEM goes back to (D.Douglas and E.Davis, 1964) who introduced a simple theory for a laterally applied load and a moment. Similarly, (W.R.Spillers and R.D.Stoll, 1964) proposed a simplified theoretical solution based on BEM by introducing a limiting lateral pressure value for the soil-pile interaction to account for the soil nonlinearity for a pile in both elastic half-space and plastic half space.

H.G.Poulos (1971a, 1971b) built up on earlier research and made significant contributions to the field of pile-soil interaction. He introduced a method for analyzing stress distribution in single piles and pile groups using the Boundary Element Method (BEM), incorporating various boundary conditions at both the top and bottom of the pile. The soil-pile interaction response was evaluated by applying a uniformly distributed normal load along each pile segment, while shear stress along the pile-soil interface was neglected. Additionally, horizontal displacements at each segment were determined by equating the displacements of the pile and surrounding soil at the segment's center. In this process, the soil horizontal displacement was calculated through the (R.D.Mindlin, 1936) equation, while the pile deflection was calculated by the differential equation, which is expressed as a finite difference expression for bending of a thin beam. (H.G.Poulos, 1973), had improved his model by considering the soil yielding and nonlinearity, i.e. the elastic-perfectly plastic soil behavior.

Moreover, (P.K.Banerjee and T.G Davis, 1978) used the BEM to analyze the laterally loaded piles in a two-layered elastic half space system with soil modulus that is linearly increasing with depth. Thereafter, (T.Davies and M.Budhu, 1986), (M.Budhu and T.G.Davies, 1987,1988) extended the linear algorithm of (P.K.Banerjee and T.G Davis, 1978) to account for the nonlinear behavior of laterally loaded piles embedded in over consolidated clays, cohesionless soils and soft clays.

2.3.3.2 Finite Element Method

Kuhlemeyer (1979b) employed a cantilever response solution proposed by Timoshenko and Gere (1972) as an analytical benchmark for validating his finite element model. This solution offers a more accurate representation than basic bending theory by accounting for shear deformations. When evaluating predicted tip deflection of a stocky cantilever subjected to tip loading, it is evident that simple bending theory yield errors of at least five percent for beams with a ratio of L/D of less than three.

This finding implies that piles embedded in soil with an workable length of less than three times their diameters may exhibit behavior that deviates from predictions based on simple bending theory. Although this conclusion is derived from tip loading conditions, it serves as an indicator of the more complex behavior that can arise due to the distributed loading typically experienced during pile-soil interaction. Consequently, a minimum pile length of three diameters is recommended when employing simple bending theory in lateral pile analysis.

An expression fitted by Kuhlemeyer to the results of Poulos (1972) appears to contain an error, as it fails to reproduce Poulos' original findings. Specifically, the impact coefficient for top displacement due to top shear, instead of increasing with the ratio of L/D as expected, shows a decreasing trend. This contradicts not only Poulos' results but also the finite element-based equations developed by Kuhlemeyer himself, which—when reformulated for direct comparison demonstrate dependence on the length-to-diameter ratio.

According to Randolph (1977, 1981) developed a semi-analytical finite element approach to analyze the response of laterally loaded piles embedded in an elastic soil mass. The resulting equations for flexible pile behavior are comparable in form to those proposed by Kuhlemeyer and show general agreement. Randolph demonstrated that the behavior of flexible piles in elastic soils is influenced by the relative stiffness of the pile and soil, as well as the degree of inhomogeneity in the soil profile.

Through dimensional analysis, Randolph derived general expressions for head load–deformation behavior. By examining two boundary conditions constant Young's modulus and a modulus varying proportionally with depth he established appropriate power-law relationships. While his expressions for uniform soils closely resemble those of Kuhlemeyer, different formulations were required to account for non-uniform soil profiles. Randolph introduced a non-homogeneity parameter in his models and validated the proposed expressions against finite element results.

In his 1981 study, Randolph presented the finite element analysis outcomes as simplified equations suitable for use in design with basic programmable calculators. His design charts enable the estimation of bending moments and deflected shapes for flexible piles in various Young's modulus soil profiles. Central to his approach is the concept of a "critical length" of the pile, which he used to non-dimensionalize the expressions. This significantly simplified the equations describing pile head response to lateral loading.

The study conducted by Bransby and Springman (1995) in order to evaluate the short-term behavior of piles when subjected to lateral loading occurred by deformation of a clay layer under an adjacent surcharge load, using 3D FEA.

Different study was performed by Kahyaoglu et al. (2009) using 3D finite element analysis to investigate the behavior of single piles and a group of free-head piles subjected lateral soil movement. Several numerical analyses were conducted to determine the forces acting on passive piles with varying pile spacing.

Kahyaoglu et al. (2009) concluded that results of the analysis performed using Plaxis 3D Foundation and the experiments were in close agreement. As the spacing between piles increases, the load carried by individual piles also increases. However, when the pile spacing exceeds eight times the pile diameter (8D), each pile tends to behave as an isolated single pile, with minimal arching effects between adjacent piles. Numerical analysis results further indicate that the residual load transferred to the soil mass between piles increases with greater pile spacing.

In addition to spacing, the influence of pile cross-sectional shape circular versus square was also examined, along with the slenderness ratio, to assess their effects on the lateral behavior of piles.

Despite the valuable insights that can be gained from advanced numerical modeling, several challenges persist. These include the high cost of validated software, the significant time required for nonlinear analysis and model development, difficulties in interpreting results using conventional pile (as embedded beam) variables, and uncertainties conserned with three-dimensional non-linear soil modeling.

Poulos et al. (1996) presented a two-stage analysis involving finite element method and boundary element method.

Yang and Jeremić (2002) investigated the lateral response of piles in layered elastic-plastic soils using a three-dimensional finite element model that incorporated interface separation and slippage. Their study considered two different soil profiles: one with an average compact cohesion less soil layer embedded with a cohesive cumulative, and another with a cohesive soil layer embedded with an average compact sand cumulative. In both scenarios, the contrasting soil layer began at a depth equivalent to four times the pile diameter and extended an additional four pile diameters in thickness.

The results showed that although the distribution of soil pressures along the pile length varied significantly between the two cases, the overall pile deflection profiles and pile top deflections were remarkably similar under lateral loading.

The effect on the initial stiffness from diameter was investigated by Sorensen et al. (2010), Lesny and Wiemann (2006) by using of numerical modelling. Sorensen et al. (2010) model piles with diameters of 1 to 7 m with an embedment length of 20 m. The shear force was applied to the pile at some height above the soil surface and the relative density (Id) of the soil was varied between 0.13 and 0.8.

Lesny and Wiemann (2006) analyzed piles with a diameter of 1 to 6 m and embedment lengths of 10.6 m to 38.9 m. The pile length had been chosen to fulfill a critical embedment length criterion to ensure a rigid fixation in the soil. The goal was to correct the modulus of subgrade reaction to ensure a consistent stiffness with the critical embedment length criteria and the numerical model for large piles' diameter. The analyses showed that a parabolic function fits the numerical model, and that the function is inversely proportional to the diameter.

The numerical analyses presented by Fan and Long (2005) showed that the influence from the pile stiffness on the soil response was insignificant whereas the ultimate capacity had a non-linear dependency with pile diameter. Additionally, the increasing of fundamental lateral stress increased vital stiffness and an apparent increase of lateral maximum tendency. The soil's dilatancy had a significant impact on the soil tendency, with increasing capacity with increasing dilatancy.

Zania and Hededal (2011) conducted a numerical study on a 2.0 m pile with the primary objective of evaluating how pile stiffness and pile-soil interface friction affect pile performance. Their findings indicated that pile stiffness had a negligible influence on both the ultimate lateral capacity and the shape of p-y curves, provided the conditions for treating the pile as rigid such as those outlined by Poulos and Davis (1980) were met. As anticipated, an increase in interface shear strength led to a greater length from pile's toe to the ground surface at point of zero lateral desplacement.

Recognizing the Finite Element Method (FEM) is a robust tool for rigorously analyzing interaction of soil and pile. Several modeling approaches exist, ranging from fully nonlinear three-dimensional analyses (e.g., Faruque & Desai, 1982) to simplified elastic quasi-3D models (Desai, 1977; Kuhlemeyer, 1979; Baguelin et al., 1979; Randolph, 1981). In quasi-3D FEM, the symmetry of the problem is exploited using Fourier series expansion of the displacement field. The interaction of soil and pile is discretized to finite element, each of which can represent different material properties, allowing the modeling of complex, non-homogeneous, and non-linear soil behavior. Advanced constitutive models are used for the soil-pile interface, while structural elements simulate the pile itself.

Randolph (1981) developed algebraic equations derived from his elastic quasi-3D finite element analysis, which were validated by comparison with elastic continuum solutions. The close agreement between the methods is expected, given that both treat the soil as a linear elastic material (Poulos & Randolph, 1982; Poulos, 1982). A key benefit of the elastic FEM is its ability to accommodate varying soil properties with depth and spatial non-homogeneity.

Fan and Long (2005) employed a 3D finite element approach to study the behavior of laterally loaded piles in sandy soils. Their research explored the effects of pile properties such as stiffness and diameter, initial horizontal stress levels, and soil dilatancy. They found that pile stiffness had minimal effect on soil response, whereas ultimate lateral capacity exhibited a nonlinear relationship with pile diameter. Additionally, greater vital lateral stresses extended both fundamental strength and apparent maximum tendency. Soil dilatancy also played a critical role, with higher dilatancy leading to greater lateral resistance.

2.3.4 Pile Group Design Philosophy

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

2.3.4.1 Conventional Approach

The conventional approach for foundation design involves uniformly distributing piles over the foundation area to form a pile group that carries the majority of the load. This technique is appropriate for Small Piled Rafts that require pile support from a capacity standpoint (Kambala, 2010).

2.4 Ultimate Lateral Resistance

Pile foundations often experience lateral loads and displacements due to various external forces, such as wave action and ship impacts in offshore and harbor structures, earth pressure in retaining walls, high wind forces acting on transmission towers, and seismic-induced lateral accelerations in earthquake-prone areas. Consequently, a critical aspect of designing pile foundations is the accurate estimation of their ultimate lateral resistance. Various methods have been proposed to estimate the ultimate lateral load capacity Hu (Hansen, 1961; Broms,1964; Petrasovits and Award, 1972; Prasad and Chari, 1999 and Zhang et a1., 2005).
The most popular method for estimating Hu is Broms' method (Lee et al., 2010).

It can be determined based on the excessive lateral displacement of the pile head or the rotation of the pile (Hu, et al. 2006). According to Sawwaf (2006), the ultimate lateral capacities can be defined as the loads corresponding to the lateral displacements at the pile head equal to around 10% of the diameter of the pile. As stated by Dickin and Nazir (1999), it can also be obtained from the p-y curve as the point where the curve turns into linear or considerably linear. The ultimate lateral resistance of a pile can be defined as the maximum load observed on a p–y curve, beyond which additional lateral deflection does not result in a significant increase in resistance. In Helmer's field test conducted in Virginia, the loading process was intentionally stopped once the desired deflections were achieved to prevent further deformation.

A horizontal load test was performed by installing two piles at a certain distance apart and applying force to either pull them together or push away. The outcome load deflection response for single pile was recorded, showing the relationship between the applied horizontal load (Ho) and the corresponding lateral deflection (yo) (see Figure 2.5). From this curve, an ultimate load H_{ou} can be defined as the horizontal load Ho corresponding to a displacement equal to one-tenth of the pile diameter (B/10) (Briaud, 1997).

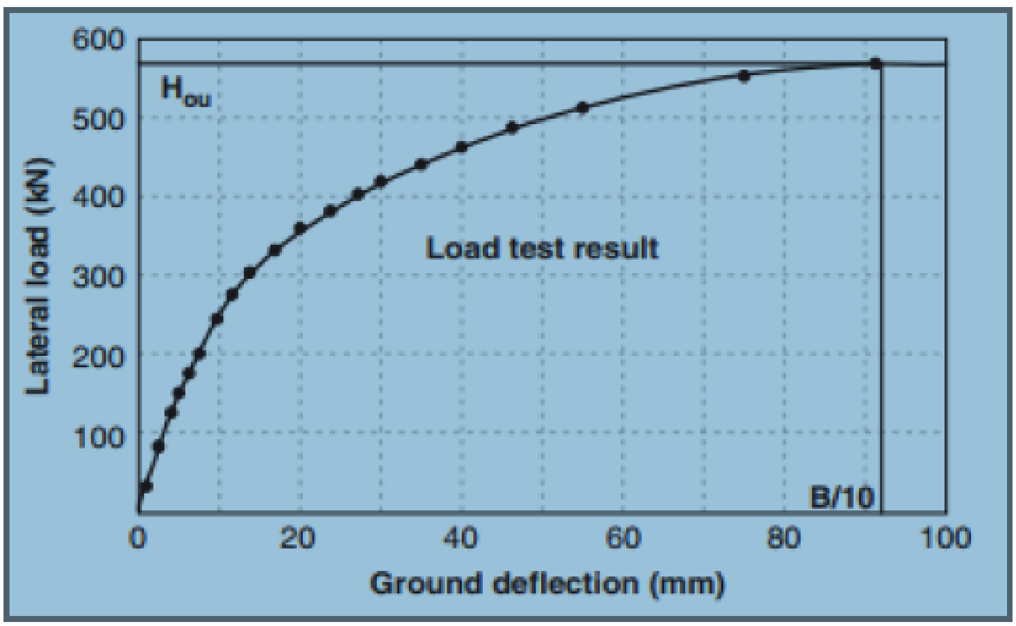


Figure2.5: Load Test Result (Briaud 1997)

According to (ASTM STP-835, 1983 and USACE, 1998), the FEM control factor in evaluating the ultimate lateral load capacity of the piles is the yield of the maximum allowed lateral displacement at the pile head which is taken to be *10%* of the pile diameter as it is more compliant with the design criterion

According to British Standard as recommended in BS EN 1997-1:2004+A1:2013, 7.6.1.1(3), the ultimate horizontal load measured at deflection equal to *10%* of the pile’s diameter when it is difficult to define the ultimate limit state from the loading deflection curve.

2.5 Constitutive Models

Soil is a complex material due to its inherently **nonlinear**, anisotropic, and time-dependent behavior under stress. It undergoes plastic deformation, exhibits varying dilatancy, and displays small-strain stiffness at very low strain levels, particularly during stress reversal. Moreover, soil failure under a three-dimensional state of stress is highly intricate. To address this complexity, various failure criteria have been developed to define the conditions under which soil fails under such stress states. The model incorporates a broad interval of soil's characteristics and time-dependent effects. The selection of a constitutive model for a geotechnical application depends on the mechanical properties of the soil. (i.e. permeability, stiffness and strength), previous history on the mechanical properties of the soil and the stress changes that will occur in feature (Wood, D., Muir., 1990).

In finite element analysis (FEA), accurate predictions depend heavily on selecting an appropriate constitutive model that reflects the specific geotechnical conditions being analyzed. The evaluation criteria for choosing a soil model should strike a balance between capturing essential aspects of soil behavior from a continuum mechanics perspective, aligning with data obtained from laboratory testing, allowing for practical parameter determination, and maintaining computational efficiency. This study briefly discusses the implementation of selected constitutive models within the PLAXIS finite element framework.

2.5.1 Linear Elastic Model

The use of the linear elastic model is quite common to model massive structures in the soil or bedrock layers that include piles and so on (Brinkgreve, R.B.J. & Broere, W., 2006). This model is based on law of Hooke for isotropic linear elasticity and is typically utilized to represent the stress strain behavior of materials like piles. The linearly elasticity constitutive model is among the all widely used to estimate material behavior under stress. It is defined by two primary stiffness parameters: Young's modulus (E) and Poisson's ratio (ν). While this model is not suitable for simulating soil due to its behavior of irreversible & highly non-linear also it is suitable for modeling stiffness, elastic materials such as concrete components embedded in soil.

2.5.2 Mohr-Coulomb model

The Mohr-Coulomb model is a simplified representation that combines linear elasticity with perfectly plastic behavior. It incorporates both elastic parameters (such as Young's modulus and Poisson's ratio) and plasticity parameters, including cohesion (c), angle of internal friction (ϕ), and angle of dilatancy (Ψ). Under this model, the material response below the failure envelope is considered linear elastic, as per Hooke's law. However, the model does not accurately capture pre-failure deformation behavior, particularly when stress paths vary or stress levels change significantly. Additionally, it does not simulate post-peak softening behavior.

Soft soils like normally consolidated clays, generally show a decreasing mean effective stress during undrained shearing, whereas the Mohr-Coulomb's model would predict a constant mean effective stress in this case, which results in an over prediction of the shear strength (Plaxis 3D Foundation Manual, 2004). Nevertheless, the model doesn't exhibit any softening behavior following the peak strength. Soft soils like normally consolidated clays, generally show a decreasing mean effective stress during undrained shearing, whereas the Mohr-Coulomb's model would predict a constant mean effective stress in this case, which results in an over prediction of the shear strength (Plaxis 3D Foundation Manual, 2004).

The model doesn't exhibit softening behavior after reaching the peak strength. Soft soils like normally consolidated clays, generally show a decreasing mean effective stress during undrained shearing, whereas the Mohr-Coulomb's model would predict a constant mean effective stress in this case, which results in an over prediction of the shear strength (Plaxis 3D Foundation Manual, 2004).

The matter addressed in current investigation is, the soil mode as an elasto-plastic strata. According to the fundamental concept of elasto-plasticity, strain rates are divided in to elastic and plastic components, as illustrated in Figure 2.6. According to (Plaxis 3D Foundation Manual, 2004), Mohr-Coulomb type yield functions the theory of associated plasticity overestimates dilatancy.

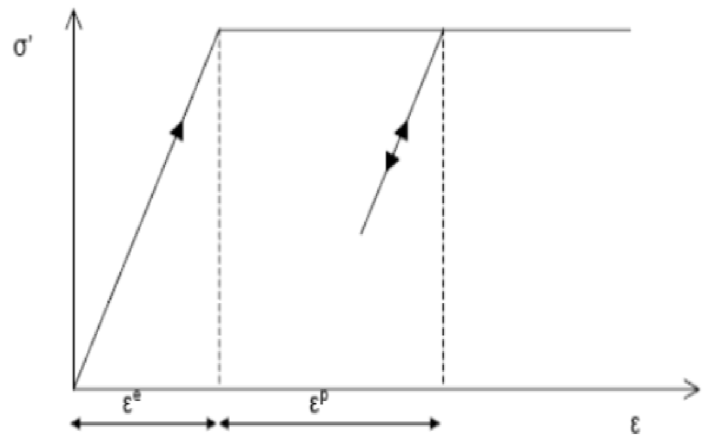


Figure2.6: Fundamental Concept of the elastic-perfectly plastic (R.B.J. Brinkgreve and W.Broere, 2006)

The yield of Mohr-Coulomb criterion generalizes friction law of Coulomb to account for arbitrary stress conditions. The full Mohr-Coulomb yield condition consists of six yield functions when formulated in terms of principal stresses and six plastic potential functions (Plaxis 3D Foundation Manual, 2004). The $f_i = 0$ for all functions yield (f_i denotes individual yield function) defines a hexagonal cone in principal stress space, as illustrated in Figure 2.7.

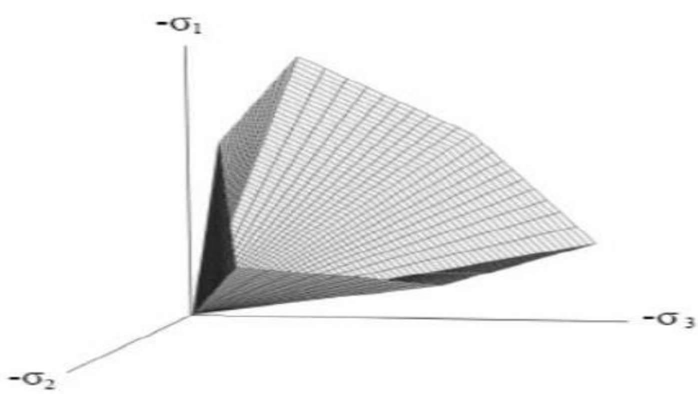


Figure2.7: Mohr-Coulomb yield surface principal stress space (assuming cohesion = 0) (R.B.J. Brinkgreve and W.Broere, 2006)

Summary of Research Gap

Laterally loaded pile groups embedded in layered soil investigation has yielded significant insights that deepen our understanding of their behavior under various loading conditions. Findings indicate that soil layering markedly influences the load distribution among piles, demonstrating that variations in soil stiffness can lead to disparate lateral capacities. This underscores the necessity for engineers to incorporate detailed soil profile evaluations in their design processes. Additionally, the analysis revealed that group arrangement and pile spacing play critical roles in optimizing performance, suggesting that strategic configurations can enhance stability and reduce lateral displacement. The implications of these findings extend to future research avenues, particularly the need for advanced numerical modeling that captures complex soil-pile interactions more accurately. Investigating the effects of time-dependent soil behavior and pile-soil interface mechanics could lead to improved design methodologies, ultimately contributing to the resilience and efficiency of foundation systems in varying environmental contexts. Many researchers have been tried to examine the impact of pile soil characteristics and input variables concerning the single pile's efficiency and few pile groups'. Most investigation conducted on single pile with some limited parameters. The present research analysis examines how the impact of pile number concerning the horizontal behavior of pile groups' laterally loaded in addition to pile's diameter, length and spacing. This is the gap I identified from different literatures.

CHAPTER THREE

MATERIALS AND METHODS

This topic describes the area of study and the process undertaken to obtain general and specific objectives of the study. To accomplish these objectives, several steps were followed. First, a detailed published review was conducted to gain a deep understanding of pile group foundations, including relevant parameters, methods, and the impact of these characteristics on the deformation of the structure. Next, representative data were gathered from geotechnical design offices, companies specializing in geotechnical investigations, and government agencies concerned with these matters. Considering the number of boreholes and the extent of the area covered, the research area where weak soil could be found was determined based on the collected data. Parameters used as input for numerical modeling of the foundation system using Plaxis 3D were identified. Subsequently, numerical modeling of pile group foundations for different parameters was conducted. Results and discussions were made based on the output of the model. Finally, conclusions and recommendations were drawn.

3.1. Sampling Technique

In this study, the sampling process involved employing non-probabilistic methods, specifically purposive sampling techniques. The researchers selected samples that were readily accessible and able to address the research objectives. Additionally, purposive sampling was used to target objects that represented the study area and research issues. The goal of this sampling approach was to guarantee that the chosen samples were representative of the objective and gap of the study, allowing the study's findings to be applicable to similar contexts. By selecting participants according to these criteria, the study aimed to gain a comprehensive understanding of the research issue and offer relevant suggestions for the local building industry in Addis Ababa, Ethiopia.

3.2. Data Collection

In the current research, the data collection method utilized secondary data sources. Secondary data consisted of a comprehensive review and analysis of resources such as publications, literature, journals, books, and case studies focused on pile group foundation analysis and design. Furthermore, a desk study of data from design offices was conducted to gather relevant information on the subject. Utilizing secondary data sources offers a cost-effective and time-efficient approach to obtaining information on the research topic while ensuring that the study's objectives are met.

3.3. Analysis Method

A comprehensive analyze and parametric test of pile group foundations were conducted using the powerful finite element-based software Plaxis 3D connect Edition V20/V21 with current investigation. The selection was made on various parameters from the components of the pile Group system; some were kept constant, while others were varied based on their effects on performance of group of pile system. The material characteristics of both soil and structural elements were kept constant throughout the study.

The goal of this study is to evaluate the influence of lateral load on the horizontal displacement features of a pile Group. Various factors contribute to the pile group layout, such as the piles' diameter, their embedded depths, the numbers and configuration of piles, as well as spacing of piles. These displacements often serve as the governing factors for the type of structure considered in this study. Data analysis was conducted using suitable statistical tools on the data collected from the Plaxis software, and the findings were displayed in tables and graphs.

3.4. Numerical Modeling Approach

Current investigation on numerical modeling was employed to analyze the behavior of horizontally loaded pile groups installed in multi soils typically in Addis Ababa. To ensure the reliability of the numerical results, the model was utilized against full-scale lateral load test data available in the literature. All analyses were performed using **Plaxis 3D**, a three-dimensional geotechnical finite element software.

3.5 Model Setup and Simulation in PLAXIS 3D

PLAXIS 3D Foundation is an advanced finite element tool designed for the analyze of deformation and stability in a variety of geotechnical applications, including foundations, anchors, and retaining structures. It features an intuitive graphical user interface that facilitates the efficient creation of geometric models and generation of finite element meshes.

The software employs an implicit solver that enforces equilibrium between forces and displacements at each point in the model. The 3D finite element model is constructed using geometric entities such as; volume, surface, line, and point. To define the soil's strata, users can input multiple bore holes, which represent directions within the model domain where soil layer information and groundwater table levels are specified. The software then interpolates the soil layer boundaries between boreholes. Plaxis 3D follows sign convention depends on the Cartesian co-ordinate system, as illustrated in the following figure.

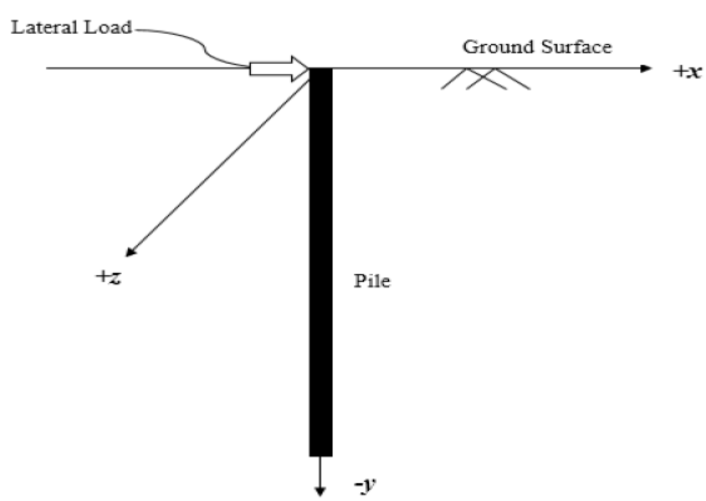


Figure3:1: 3D co-ordinate system associated in sign convention used in model

Development process of numerical model in Plaxis 3D consists of two main stages: the **model generation** and the **calculation phase**. The geometric model incorporates boreholes and work planes. Due to the unavailability of detailed site-specific soil stratigraphy, only a single borehole was used in the model, with the assumption that the soil stratigraphy is horizontal and homogeneous. Working plane was utilized to apply loads and define structural elements at various elevations.

Material and soil properties are assigned using the material library available in Plaxis 3D, which includes standard values for various construction materials.

PLAXIS 3D contains of 2 main modules: the **data** and the **outcomes** programs. For model definition and setting analysis parameters up the data module is used. The data module is used for model definition and setting up analysis parameters. At the beginning of the input process, the user must define project properties, including boundaries of model in the lateral locations (x, z) and the international unit system for the analysis.

The Input environment comprises five key components:

- **Soil Mode**: Allows the definition of soil stratigraphy through borehole creation, including groundwater levels at specific points.
- **Structures Mode**: Used to define all geometric and structural elements, including boundary conditions and imposed loads or displacements.
- **Mesh Mode**: Provides options for mesh generation, including fine, very fine, coarse, very coarse and medium. Local refinement factor can be applied to increase accuracy in selected regions.
- **Water Levels Mode**: Enables the definition of external water pressures or phreatic surfaces, useful for simulating partially saturated soil conditions (if needed).
- **Staged Construction Mode**: Facilitates simulation of construction sequences, where model members can be sensitive or non-sensitive at each step depending on the analyze requirements.

The Output module of Plaxis 3D offers a comprehensive platform for result visualization and interpretation. It presents results in various formats including diagrams, graphs, and tables. Structural forces and displacements can be directly viewed, enabling detailed assessment of performance.

3.6 Model generation

3.6.1 Geometry's model

In the current investigation, laterally loaded groups of pile with finite element modeling in layered strata was carried out using **Plaxis 3D**. Piles were modeled as volumetric elements utilizing the in-built pile volume feature. The model geometry was primarily governed by pile's diameter and pile's length. The strata profile stratified based on the site-specific layering, and the soil's block cross-section of pre-configured in the project settings.

Horizontal boundaries of the model were defined using $\mathbf{x_{min}}$, $\mathbf{x_{max}}$, $\mathbf{z_{min}}$, and $\mathbf{z_{max}}$ based on the pile dimensions. The depth (y-direction) was set using the "create borehole" function, which also allows specification of the groundwater table. The top boundary was fixed at y = 0, while the bottom was determined based on the pile's diameter and pile's length function.

After defining the soil's block, relevant material properties were assigned. Based on the recommendations of **Karthigeyan et al. (2006, 2007)**, the dimensions of the soil domain were selected to minimize impacts of boundary under lateral loading. The **width** of the soil mass was set to **60 times the pile diameter (60D)**, beyond which the influence on pile response becomes negligible. The depth of the strata domain considered as **L + 30D**, where **L** represents the pile's length, as illustrated in the figure below.

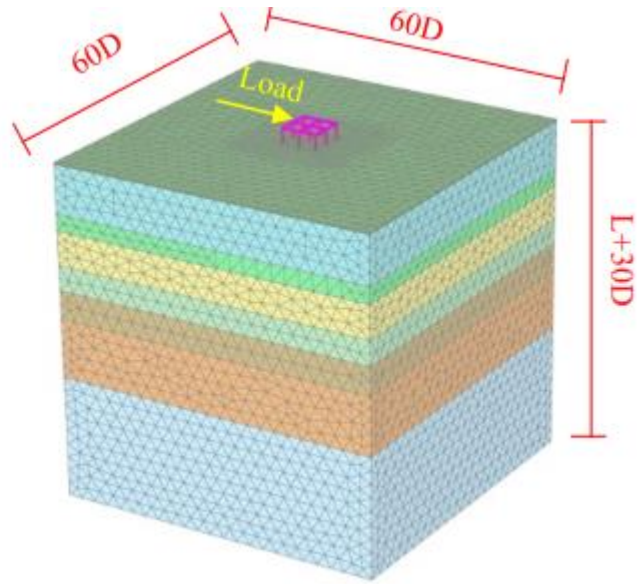


Figure3:2: Model geometry, Karthigeyan et al. (2006 and 2007)

3.6.2 Numerical Modeling Approach Using Plaxis 3D

The PLAXIS 3D foundation Finite Element was utilized to analyze the behavior of horizontally loaded piles. In conducting a parametric study, it is crucial to maintain all other variables constant while varying a single parameter to isolate its effects. However, interpreting the results of such studies can be challenging, as interactions between multiple parameters may complicate the outcome. Additionally, creating full-scale 3D models with all external boundaries increases the number of finite elements required, leading to significantly longer computation times.

To represent the vertical piles in the analysis, the **installed pile feature** in PLAXIS 3D was employed. This feature allows piles to be modeled as structural elements with defined stiffness and mechanical properties, providing a more realistic representation of pile behavior within the soil matrix.

Prior to conducting a detailed investigation of the parameters influencing pile-soil interaction, preliminary analyses were conducted to determine appropriate **boundary dimensions**,

boundary conditions, and **mesh configurations**. This step ensured that the model geometry and setup were suitable for accurate simulation results.

3.6.3 Model boundary Condition

In the numerically modeled, it is essential to apply constraints at the soil boundaries to prevent unrealistic displacements, particularly in response to lateral loading. Boundaries must be sufficiently distant from the pile to avoid influencing stress and deformation patterns near the pile shaft. Several studies, including those by **Karthigeyan et al. (2006, 2007)**, recommend a horizontal extent of **60D** (where *D* is pile's Diameter) & the **L + 30D** (*L* being the pile length) a vertical extent beyond which boundary effects become negligible.

In line with these recommendations, boundary locations were carefully selected to minimize their impact on the simulation results. Three types of boundary fixities were applied in the model:

- **Lateral boundaries** were fixed in the horizontal directions ($u_x = u_z = 0$) but allowed vertical movement.
- **Bottom boundary nodes** were fully fixed ($u_x = u_y = u_z = 0$) to simulate rigid support.
- **Head boundary** remained to free displace along all directions, accommodating the deformation of the ground surface.

It is generally desirable to design the model geometry such that boundaries are positioned far from the area of interest to ensure that stress and strain distributions are not influenced by proximity to artificial constraints. However, larger model sizes significantly increase computational effort in 3D analyses, making the simulation process less efficient.

Therefore, a balance was sought between model accuracy and computational efficiency. The selected geometry and boundary conditions were verified through sensitivity analyses to confirm that soil deflections induced by pile resistance were not constrained or influenced by the model boundaries.

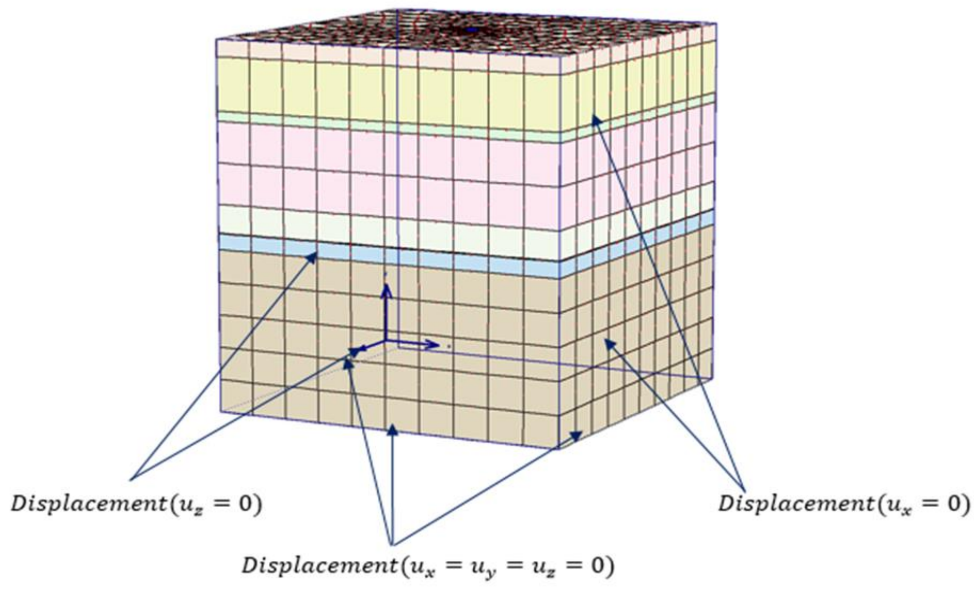


Figure3:3: Boundary Conditions

3.6.4. Mesh Generation

To conduct finite element analysis (FEA), the model geometry must be discretized into smaller subdomains known as finite elements, collectively forming the finite element mesh. In Plaxis 3D, the soil domain is typically discretized using 15-node wedge elements, which provide accurate representation of three-dimensional stress and deformation states. These wedge elements are derived from 6-node triangular elements, with a combination of node of 6 in the horizontal triangular plane and node of 8 quadrilateral in the vertical plane**.**

For this study, the mesh was generated automatically PLAXIS 3D foundation used **mesh generation tool**. The elements used support **second-order interpolation of displacements**, ensuring better accuracy in capturing non-linear behavior. Plaxis 3D applies **local coordinate systems (ξ, η, ζ)** to define shape functions. These shape functions are formulated such that the equal function value at the corresponding zero node at all different nodes, satisfying the interpolation condition. Each node of the 15-node wedge element is defined with **three translational degrees of freedom**, allowing realistic simulation of soil deformation. The mesh structure is particularly suited for modeling complex geotechnical problems in three dimensions, where capturing interaction effects and stress distributions accurately is critical.

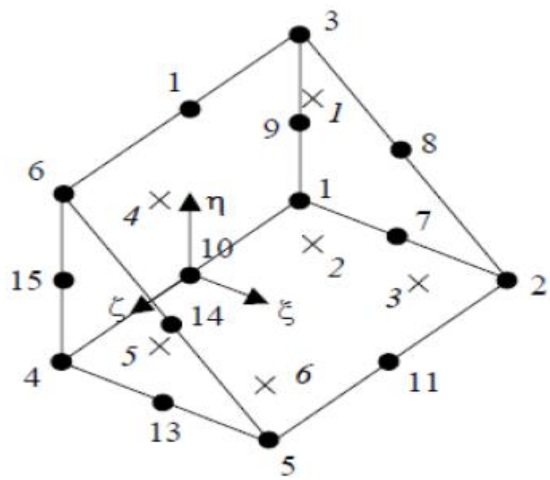


Figure3:4: Local numbering and positioning of nodes (•) and integration points (x) of a 10-node wedge element in Plaxis 3D Foundation (Plaxis 3D Foundation Manual, 2006)

The mesh element size can be adjusted by using a general mesh size varying from very coarse to very fine and by using line, cluster and point refinements. To minimize memory usage and reduce computational time, **excessively fine meshing should be avoided**, as it significantly extends the number of finite elements in the model. Once the mesh is generated, the software does not permit the addition of new soil clusters or structural elements. Therefore, if any changes are made to the geometry such as adding new components the mesh must be regenerated to incorporate the updated input.

The **3D Finite Element Mesh** in Plaxis 3D consists of nodes, elements, and stress points. During mesh generation, the model geometry is discretized to **15-node wedge elements**, which is constructed using **6-node triangular faces** in the horizontal (x, z) plane derived from two-D mesh generation and **8-node quadrilateral faces** in the vertical (y) direction. These higher-order elements enhance the accuracy of the analysis by allowing for more precise interpolation of displacement and stress fields.

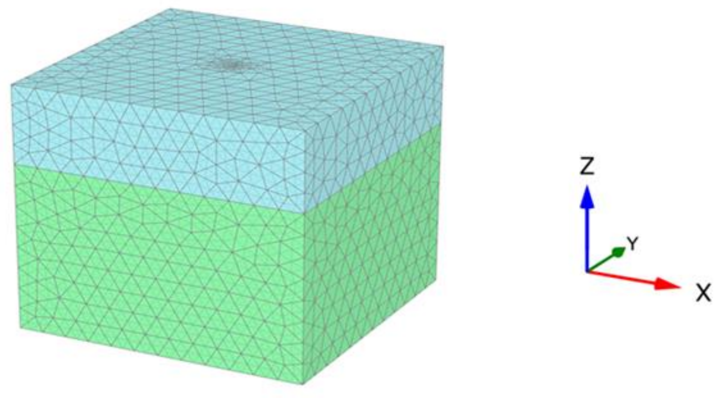


Figure3:5: 3D Finite Element mesh generation model

3.6.5 Analysis of Sensitivity

As analysis of finite element previously noted, model must be discretized to smaller units known as finite elements, which collectively form the mesh. The accuracy of simulation results can be significantly influenced by the mesh size. To evaluate how laterally loaded pile group foundation behavior affected by mesh density. A sensitivity analysis was conducted using five different mesh configurations. These variations were achieved by adjusting the size and number of elements, while keeping all other model parameters such as material properties and boundary conditions unchanged.

The resulting of pile top deflections was recorded to assess the effect of mesh coarseness. The findings of the study were summarized in Table 3.1.

Table3.1: Impact of Size of mesh Size on pile's head Displacement

Model	Mesh coarseness	Number of elements	Head displacement (mm)
1	Very Coarse	6,062	53.2
2	Coarse	7,121	52.2
3	Medium	12,146	50.11
4	Fine	25,071	49.31
5	Very Fine	59,832	48.22

The table illustrates the mesh density's effect of on the pile top displacement. As shown, the head deflection decreases as the number of elements increases, up to a point. Specifically, once the element count reaches approximately 7,121, further refinement of the mesh does not result in a significant change in deflection. This indicates that mesh convergence is achieved at this level, as increasing the element count to 59,832 yields only minimal variation in results. Consequently, Model 2, which uses a coarse mesh with 7,121 elements, was selected for further analysis on the general lateral response of the pile foundation.

3.6.6. Interface Creation and Calculation Process

To ensure accurate pile-soil interaction, interface elements were introduced in the model. These interfaces were added along the surfaces where structural elements connect with the soil, facilitating proper simulation of mutual response of soil and structural system. Specifically, interface elements were implemented to represent the contact between the plate of the pile and the adjacent soil layers. In this model, contact elements were applied adjacent to the pile surfaces.

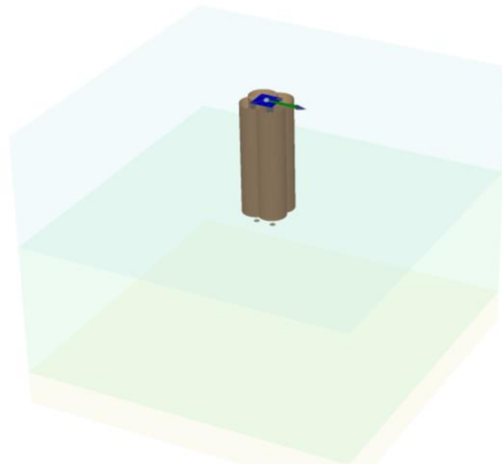
The interface elements have zero thickness, meaning the node pairs share identical spatial locations. Each interface made up of 16-node quadrilateral elements and is evaluated using numerical integration. Figure 3.4 illustrates the configuration of the nodes and integration points used.

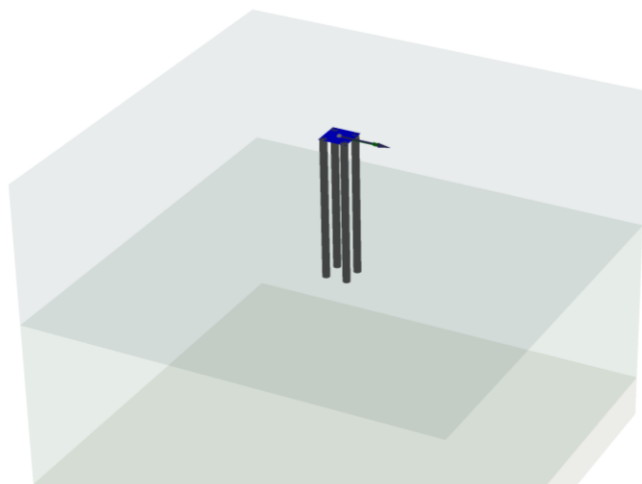
For the loading process, the pile head was represented with a surface where a lateral load was exerted in the form of a **prescribed displacement**. This method allows for direct extraction of both force and displacement values from Plaxis 3D output. The calculation process was divided into distinct phases using **Plastic analysis with staged construction**. Force and displacement data were collected from a node at the center of the pile head.

In Plaxis 3D, model development is organized into calculation phases. The following phases were used in this study:

- **Phase 0**: Initial stress state calculation using the K_0 procedure.
- **Phase 1**: Activation of the pile and associated interface elements.
- **Phase 3**: Resetting of displacements.

- **Phase 4**: Application of horizontal force via prescribed displacement at the pile head.





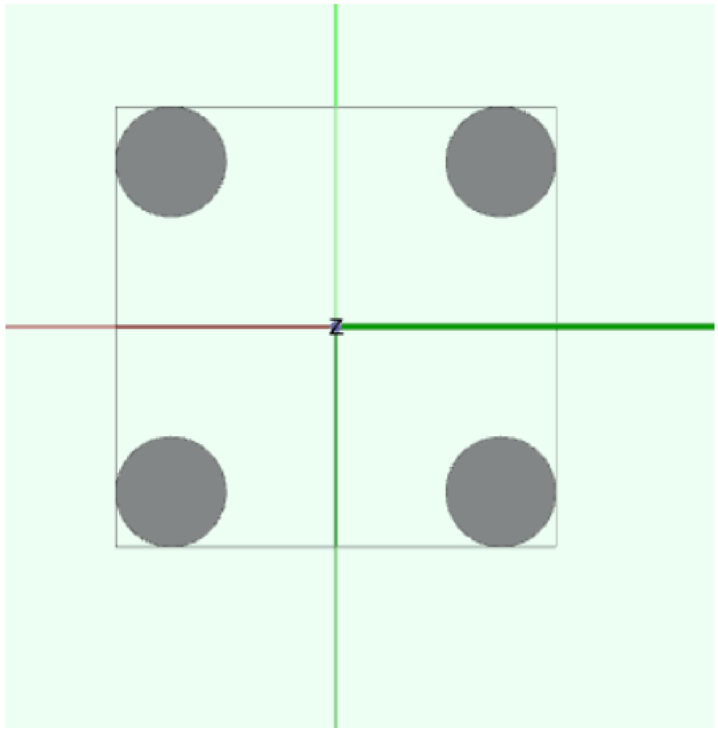


Figure3:6: Creation of Pile structure and Loads.

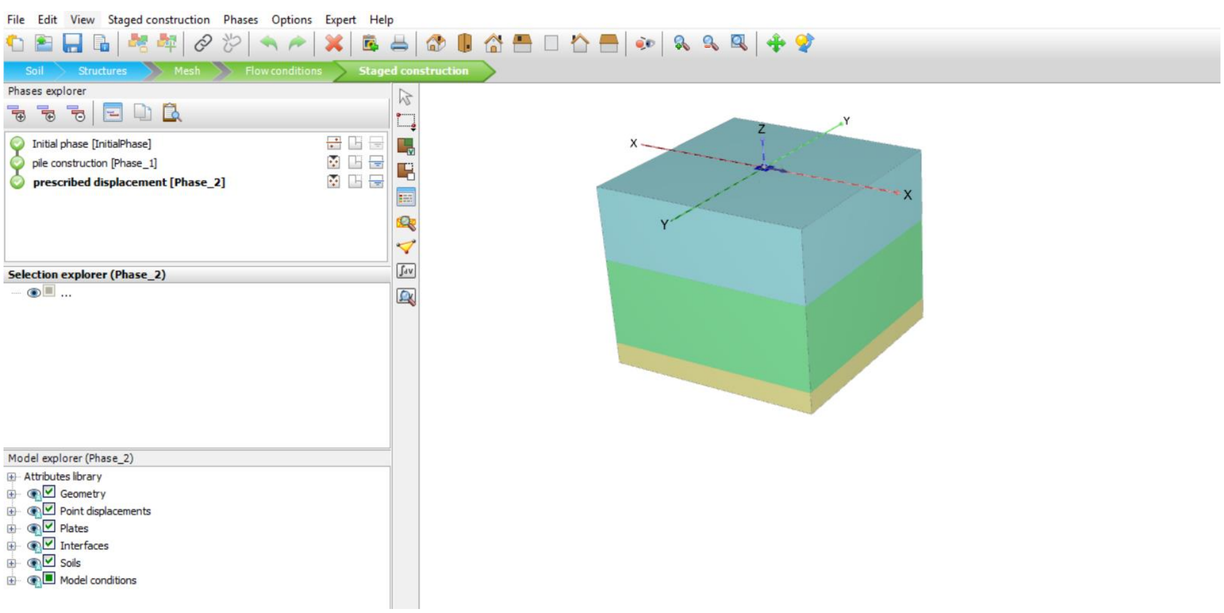


Figure3:7: Application of load on Pile in different stages

3.7 Selection of a realistic material model and its calibration properties

3.7.1 Geotechnical material model

Based on site investigation input of Abyssinia Bank Headquarter building in Addis Ababa, the soil exhibited inelastic behavior under static loading conditions. This behavior was appropriately captured using an **elasto-plastic constitutive model**. The **Mohr-Coulomb model** selected for static investigation because the model available in PLAXIS 3D.

Even if more advanced models (e.g., Hardening Soil or HS Small) can better represent the nonlinear and stress-dependent nature of soils, they require a larger number of input parameters and detailed laboratory data. Considering the scope of this study, the Mohr-Coulomb model provided a reasonable balance between accuracy and practicality. By using a **linear elastic** material model, the R.C pile was modeled as it behaves elastically under the loading conditions considered.

3.7.2. Geotechnical Properties and Construction Materials

Abyssinia Bank new head quarter building is in the vicinity of Kirkos Sub-city, Addis Ababa, near the national theatre.

3.7.2.1. Identification of Fundamental Geotechnical parameters for simulation

Part of the soil properties available in the foundation investigation obtained from existing engineering investigation data. Nevertheless, all valuable input not inclusive in these reports. As a result, parameters that were not directly available from laboratory testing were estimated using empirical correlations derived from various scholarly sources.

The following categories are data used in this investigation:

1. **Stiffness**:
   - Elastic modulus (Es)
   - Lateral strain ratio (v)
2. **Shear Strength**:
   - Internal angle of friction (ϕ)
   - Shear strength due to bonding/cohesion(c)
3. **Unit Weight of Soil**:

- Saturated unit weight (γ_{sat})
- Unsaturated (dry) unit weight (γ_{dry})

These values were essential for defining the soil behavior in the numerical model, particularly in simulating realistic stress-strain responses under load.

a) Stiffness Properties

a.1 Modulus of Elasticity (Es)

It is a fundamental characteristic that characterizes the stress-strain relationship of soils and is critical for predicting deformation behavior in geotechnical engineering. According to Bowles (1996), Es can be estimated through various laboratory and in-situ tests, such as unconfined compression tests, triaxial compression tests, and standard penetration tests (SPT).

While some values for Es were provided in the geotechnical investigation reports for different soil layers, others were missing. For layers where test results were unavailable, the modulus of elasticity was estimated based on literature values. For instance, the Es of completely weathered rock was adopted from values recommended by Gu (2008). These derived values were then used as input parameters in the PLAXIS 3D.

Additional guidance for estimating Es based on SPT results and soil classification systems is provided in Appendix B. Standard data of stiffness constants for both granular and cohesive soils, according to the Unified Soil Classification System (USCS), are listed in Tables B.2 and B.3 of Appendix B.

a.2 Lateral strain ratio (ν)

It is a material's characteristics that express the ratio of lateral strain to axial strain under uniaxial loading. It reflects how much a material deforms in the perpendicular direction when compressed or stretched. Accurate estimation of this parameter is important for understanding volume change behavior during loading and was included for each soil type in the analysis.

It is defined as the ratio of the lateral expansion to the axial compression of soils. (Bowles 1996) recommend a range of values of Poison's ratio between 0.4 and 0.5 for most clay and 0.2 to 0.4 for medium to dense cohesion less soil. In current study, each soil layer's Poisson's ratio the poison's ratio was determined based on standard data obtained from reported in various published sources. And the typical values of Poisson's ratio for soils and other materials according to Bowls are given in Table A.4, in the Appendix-A.

b. Shear Strength

Shear strength parameters, namely, angle of internal friction (ϕ) and cohesion (c) are taken from literature recommendation given by (Braiud 2013). According to Bowls (1977), PI and SPT-N can be used to estimate the angle of internal friction (ϕ) and unconfined compressive strength of cohesive soils (q_u) respectively.

c. Unit weight of soil

Soil density is a crucial parameter required as data for the finite element analysis software. Accordingly, the γ_{sat} and γ_{unsat} of the various soil layers were obtained from the geotechnical evaluation summary, supplemented with average measurements found from relevant published sources where necessary.

The engineering characteristics of the materials of rock & soil are used as input for the finite element model was summarized in Table 3.2. In addition, material properties derived from empirical correlations and standard reference values were employed to estimate the composite behavior of the materials, particularly through the combination of Poisson's ratio young's modulus and Poisson's ratio. Table 3.2 also presents the geotechnical characteristics of the piles used in the analysis.

Table3.2: Soil Parameters for Base Model.

Depth (m)	Descriptions	E (MPa)	poison's ratio (v)	Unit weight (bulk, KN/m3)	c (MPa)	Friction angle (ϕ)

0-10	Medium to Stiff, highly plastic SILT	13	0.3	17	0.005	28
10-22	Stiff to Very Stiff, highly plastic SILT	30	0.3	17	0.0115	30
22-60	Highly to moderately weathered fractured BASALT	270	0.27	27	8.316	48.59

3.7.2.2 Pile parameters

Actual length and diameter of the piles used for parametric study were obtained from foundation recommendation report and the engineering properties of reinforced concrete were taken from Ethiopian Building Code of Standard (EBCS).

Table3.3: Pile parameters as input data.

Parameter	R.C Pile
Modulus of elasticity ($E_{s,}$ GPa)	31
Poisson's ratio, (v)	0.15
Concrete unit weight (γ, KN/m^3)	25
Pile Length (L, m)	10, 15, 20
Pile Diameter (D, m)	0.5, 0.75, 1.0
Pile spacing (s, m)	3D, 4D, 5D

3.8 Plaxis 3-D V21 validation with the field test result

The validation is used to confirm the ability of Plaxis 3D V21 finite element software to predict the load–displacement relationships for pile groups with various configurations. It is the procedure of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (Oberkampf et al., 2002, Roy et al., 2015). Quantifying the confidence in the capability of the model in predicting the response by comparison with experimental data is the goal of validation.

3.8.1. Validation case-1

Pile load test on laterally loaded pile**:** A pile load test conducted by Ismael et al. (1998) has been modeled and studied. The pile was 0.3 m in diameter and had a length of 5 m situated in Kuwait. The surface soil was found to a depth of 5 m and was characterized as having both component of shear strength, c and ϕ. The soil profile consisted of a medium dense cemented silty sand layer to a depth 3 m. This was underlain by medium dense to very dense silty sand with cemented lumps to the bottom of the borehole. All properties of soil are listed in Table Below.

Table3.4: Geotechnical Properties of the Soil Layers and the pile Ismael et al. (1998)

Properties	Silty Sand medium dense-Cemented layer	Silty sand medium dense to very dense layer	Pile
Dry Soil Weight, γ_{unsat} (KN/m^3)	18	19	25
Saturated unit Weight, γ_{sat} (KN/m^3)	18	19	-
Young's modulus, E (MPa)	13	13	35
Poisson's ratio, v	0.3	0.3	0.15
Cohesion, c (KPa)	20	1	-
Internal angle of friction, ϕ (°)	35	45	-

The following 3D-block diagram indicates that the output of the validation result of 80kN load result. Generally, over all the load used by Ismael at the field test is starting from

20kN up to 180kN. In this research too, to validate with the test result the same stepping load is used and the output is shown below graphically as well as by tabular form.

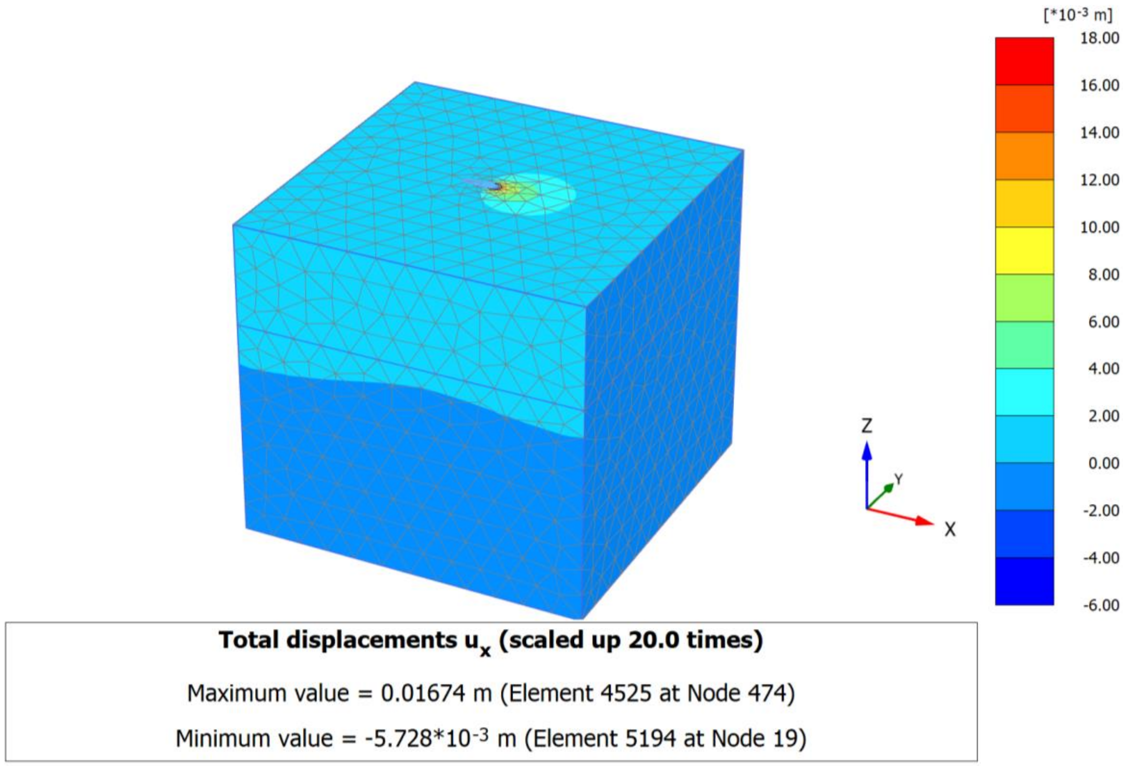


Figure3:8: 3D Finite Element mesh generation model

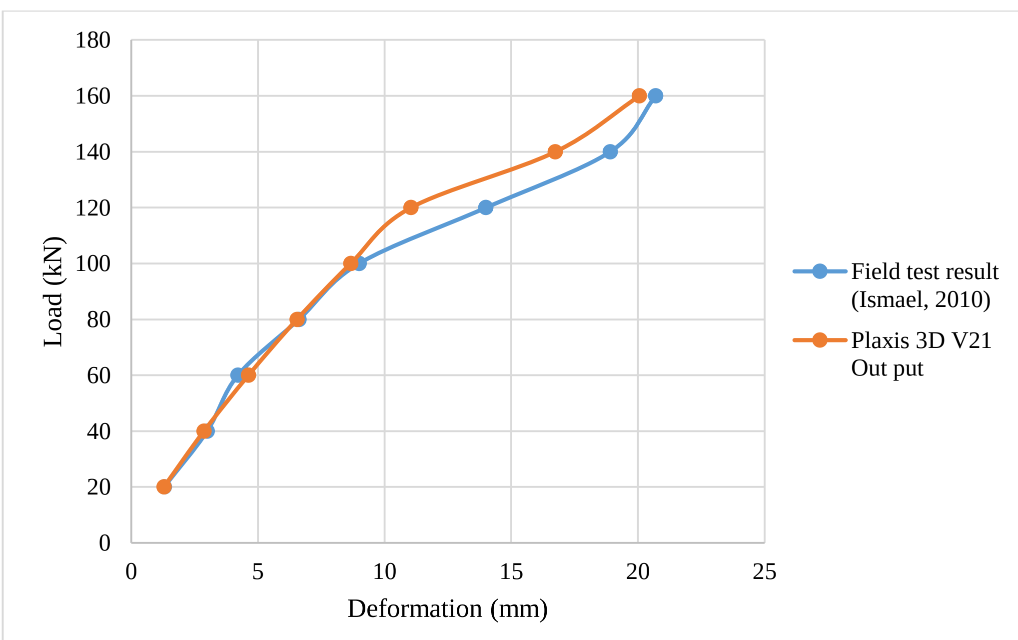


Figure3.9: Validation result of the full -scale field test graphically (P-y) curve with Plaxis 3D

The above p-y curve and the table shows that both results are very close to each other therefore Plaxis 3-D V21 FEM is validated correctly**.**

3.8.2. Validation case-2 Field test of laterally loaded pile

The bored cast-in situ pile considered in this study is a diameter (D) of 1000 mm, length 17m and of C35 grade concrete. The site soil is composed of layers of sandy clay and soft-weathered rock. Table 3.8 lists the parameters of the soil stratums at the test site and Table 3.9 lists the parameters of the concrete pile. The same parameters have been used for the numerical simulations. A hydraulic jack, fixed horizontally between an immovable wall and the top of the pile, was used to apply lateral loads (Hu), in stages, up to 120kN (B.P. Naveen et.al, 2014) Therefore, the validated result is as follows. The soil layer is partially removed to indicate the pile deformation.

Table3:5: Field soil data parameters (B.P. Naveen, 2014.et.al)

		Layer 1	Layer 2
Material Model		Sandy clay Mohr-coulomb	Soft weathered rock Mohr- coulomb
Unit weight, ɤ	kN/m^3	18.00	21
Young's Modulus, E_{ref}	kN/m^2	55000	65000
Poisons ratio, v		0.330	0.330
Cohesion, $c_{ref,}$	kN/m^2	15.00	42.00
Friction angle, ϕ	°	42.00	65.00

Table3:6: Pile data set parameters

Material	Normal stiffness, EA [kN/m]	Flexural rigidity, EI [kN/m^2
Pile	2.11E07	1.32E06

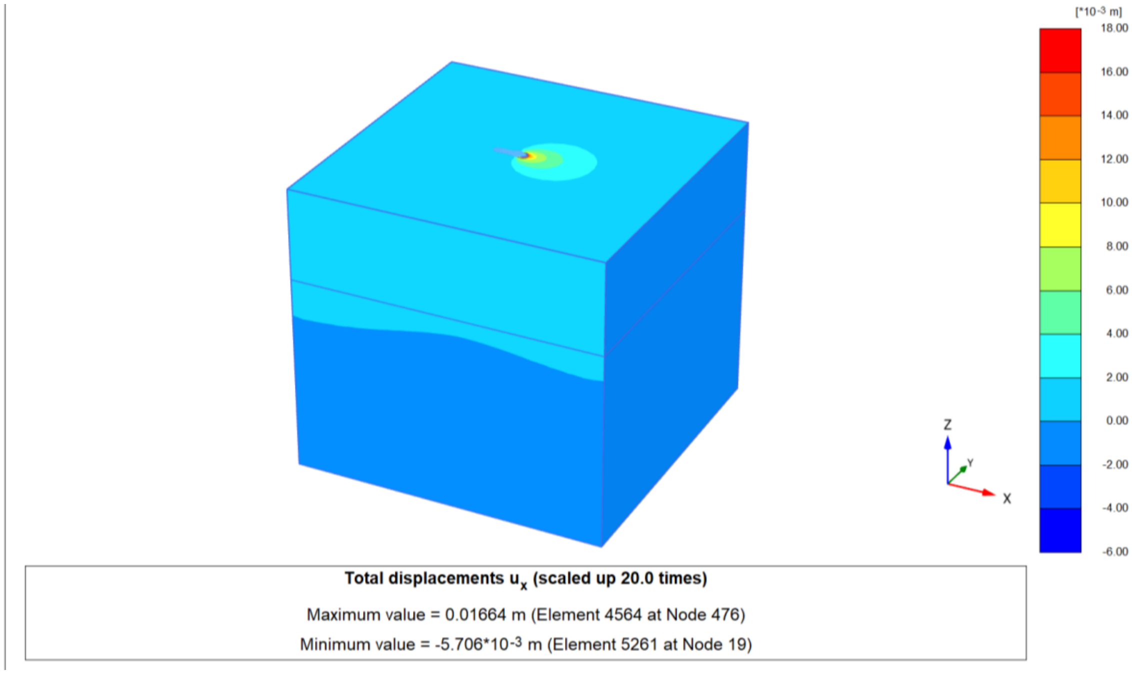


Figure3:10: Plaxis 3d validation of meshed pile case 2

The above figure clearly shows that the deformation of the field test and the Plaxis is very small due to small amount of applied load. Generally, by this applied load test the ultimate capacity of the pile was not satisfied, because of to reach the maximum ultimate

CHAPTER FOUR

RESULT AND DISCUSSION

Under this chapter, study of characteristics was conducted on a laterally loaded pile group inserted in layered soil strata conditions using PLAXIS 3D V21. The most purpose of the study was to evaluate the lateral behavior of the laterally loaded group of pile by using variation of different pile parameters (diameter, length, spacing and pile number) under static lateral loading. The analysis was performed on the model with not the same pile length, pile diameter, and number of piles and spacing. To carried out current study, other properties constant while the influence of the change on a certain property is being investigated. In this investigation, parameters such as pile length, pile diameter, pile spacing and loading were analyzed. By setting constant diameter, and varying length, spacing, and number of piles the study conducted. Again, by setting constant length, and varying diameter, spacing and number of piles the study conducted. The same is true for spacing and number of piles.

Table4.1: Material properties used in parametric Analysis

Parameters	Soil Property			Concrete Property	
	Soil 1	Soil 2	Soil 3	Pile	Pile cap
FE Model	Elasto-plastic	Elasto-Plastic	Elasto-Plastic	Elastic	Elastic
E (Mpa)	13	30	270	31000	31000
v	0.3	0.3	0.27	0.15	0.15
C (Kpa)	5	11.5	8316	-	-
γ (KN/m^3)	17	17	27	25	25
Φ (°)	28	30	48.59	-	-

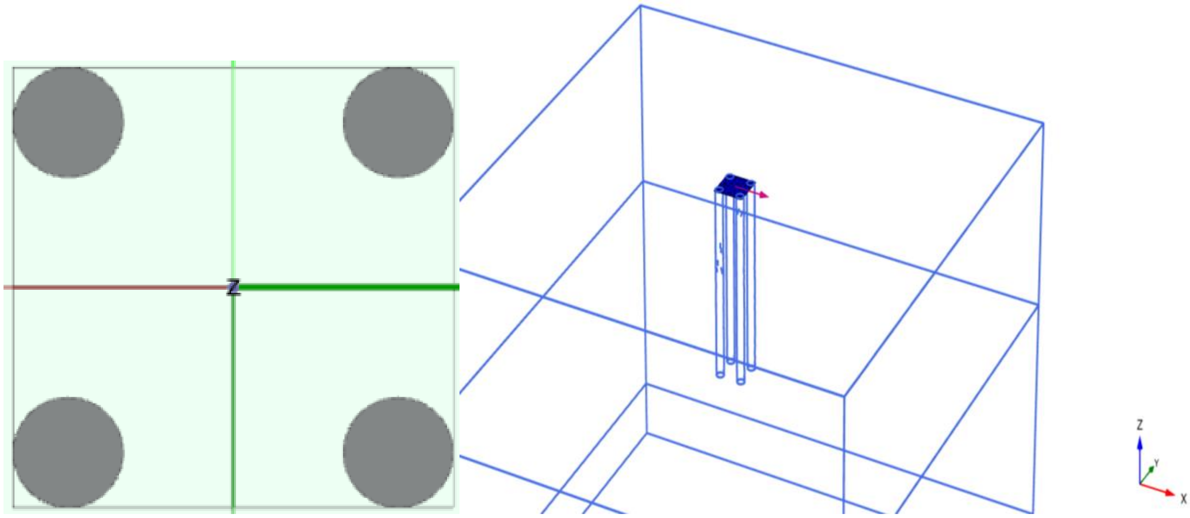


Figure4.1: Structural Configuration of pile number 2x2 (4)

4.1. Influence of Pile Diameter on Lateral Load

In this study, the impact of pile diameter on the performance of group pile was investigated by modeling three different pile diameters (0.5m, 0.75m, and 1.0m). The pile spacing of 3D, Pile number 2x2 (4) and pile length of 10m was used.

Figure 4.2 illustrates horizontal deflection corresponding to change of lateral load in *x* direction or *p*-*y* curves at the end of finite element method (FEM) analysis. Also, it is observed in the relationship of lateral load with lateral deflection (*p*-*y curve)* as the diameter of the pile increase head deflection decreased and the reverse is true. Additionally, the pile flexural rigidity (EI) increases with the pile moment of inertia (I), which directly proportional with pile diameter. Increasing the pile diameter from 0.5m to 0.75 and from 0.75m to 1m, increased the ultimate lateral load by 55% and 59.88% respectively.

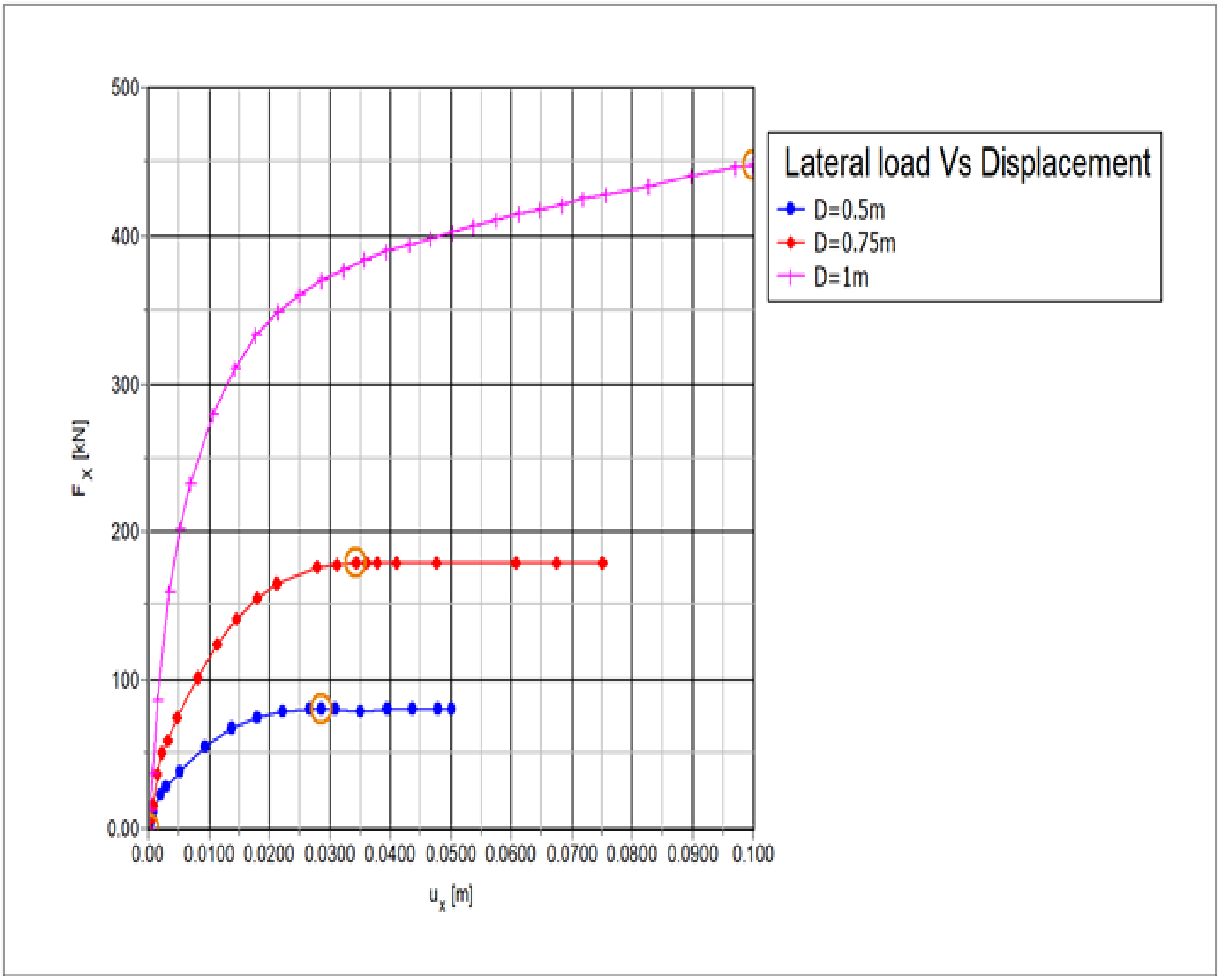


Figure4:2: Lateral load versus head deflection of 10m pile length

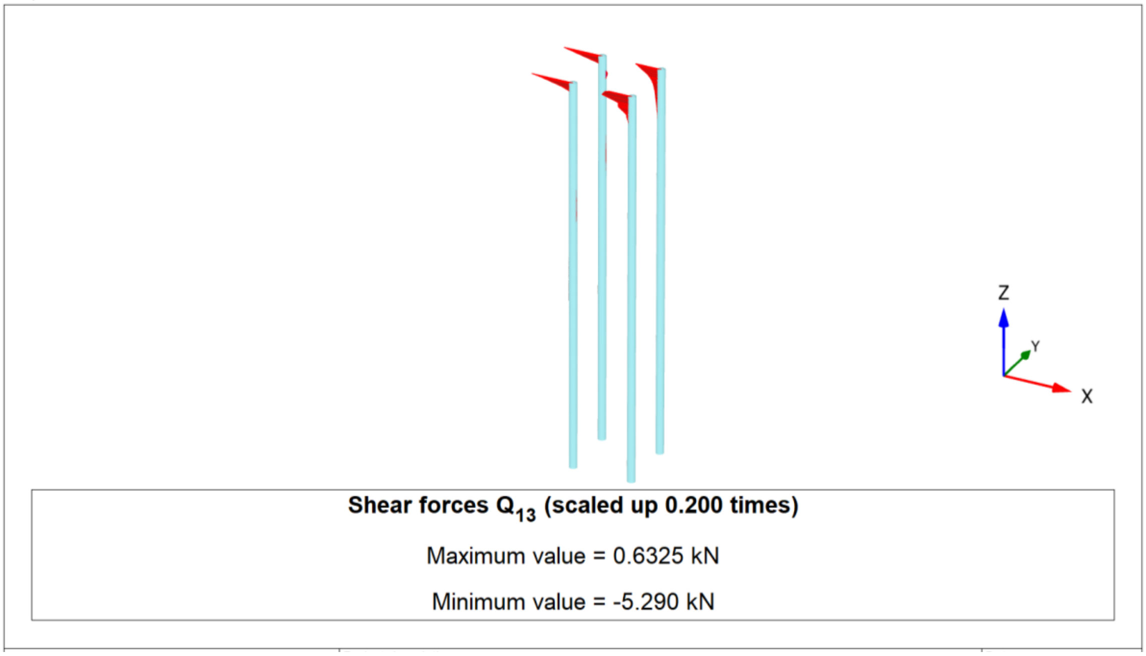


Figure4:3: Variation of pile shear force (kN) with pile depth (m) for pile length 10 with diameter of 0.5m

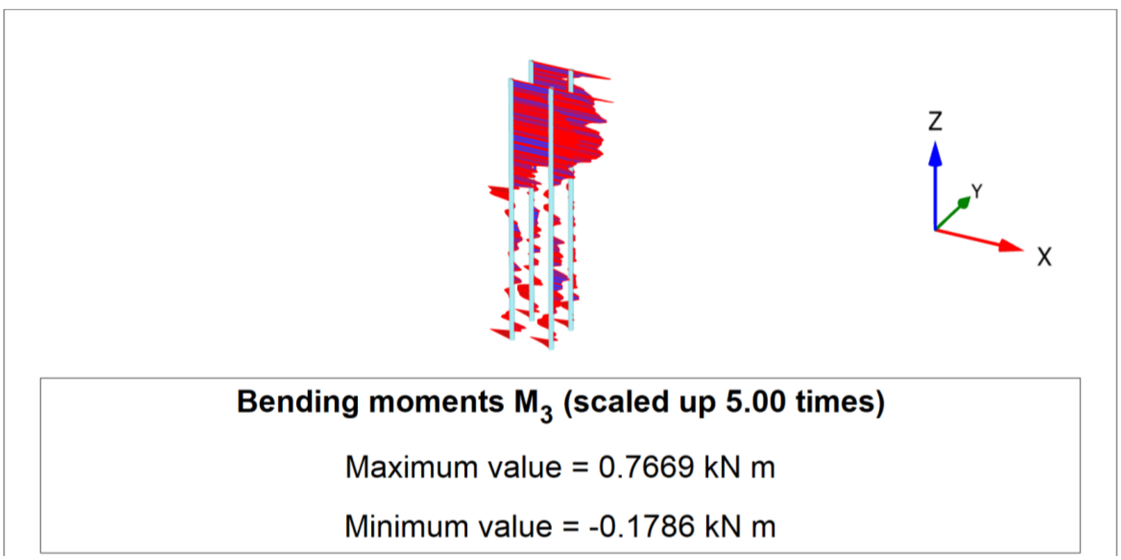


Figure4:4: Variation of pile bending moment (kNm) with pile depth (m) for pile length 10 with diameter of 0.5m

4.2 Effects of spacing in group pile

The primary target of this study was to analyze how the spacing of piles affects the performance of pile groups. The models employed three different piles spacing of 3D, 4D, and 5D with a pile diameter of 0.5 meters and pile length of 10 meters was subjected to a prescribed displacement 0.05m. The effect of pile spacing was examined for configurations comprising number of piles (4).

The results from Figure 4.5 indicate no substantial variation in lateral load capacity is observed as spacing increases, because the pile is short pile and as well the soil is stiff.

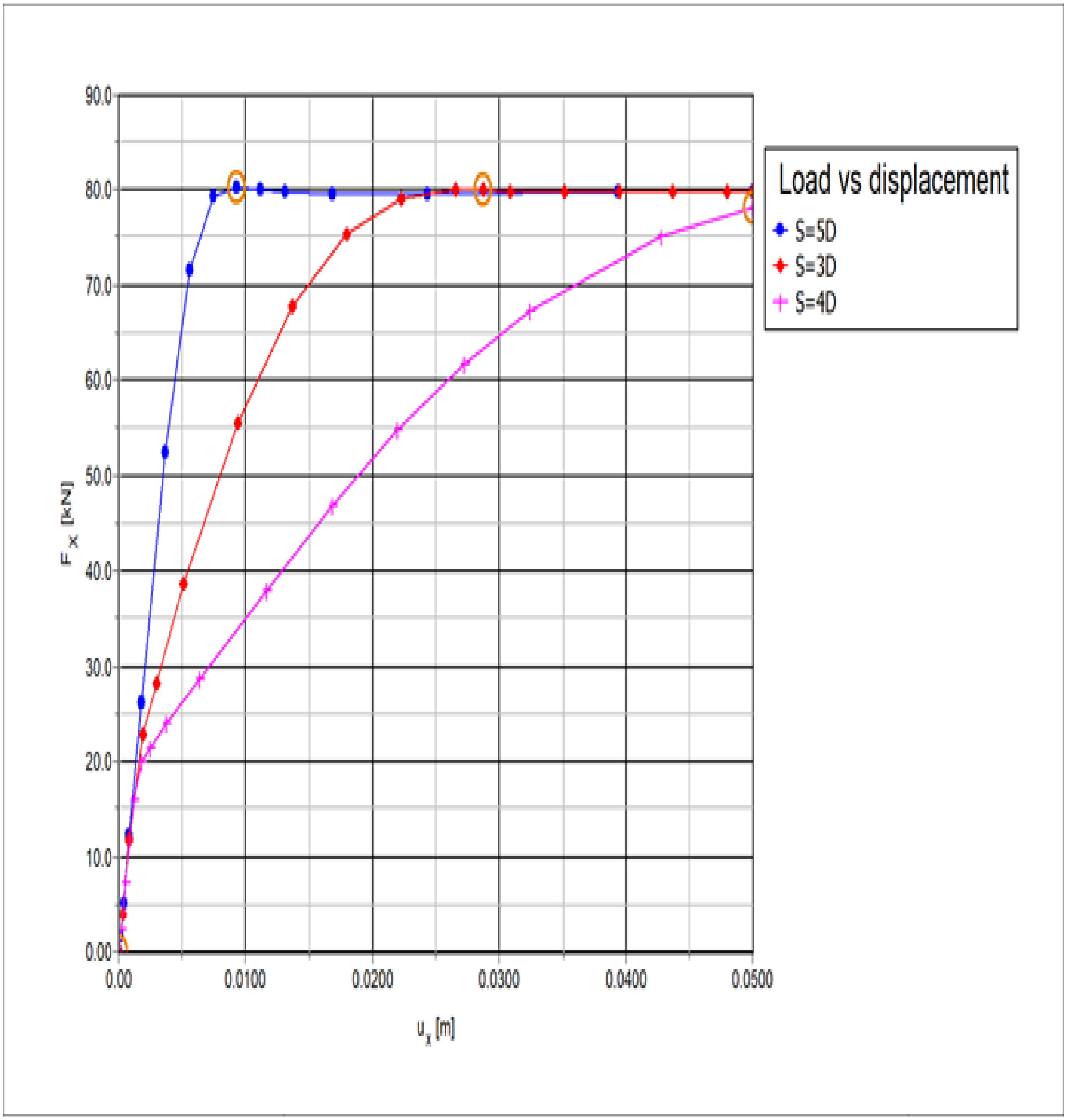


Figure4.5: Effect of Pile Spacing on horizontal capacity

4.3 Effect of Pile Length on lateral response of pile

The study focused to examine the impact of pile length on the behavior of pile foundations. To evaluate the impact of pile length on load carrying capacity, a basic model consisting of 4 piles with lengths of 10m, 15m, and 20m and a spacing of three times the pile. The model had a pile diameter of 0.5 meters and was subjected to a prescribed displacement 0.05m.

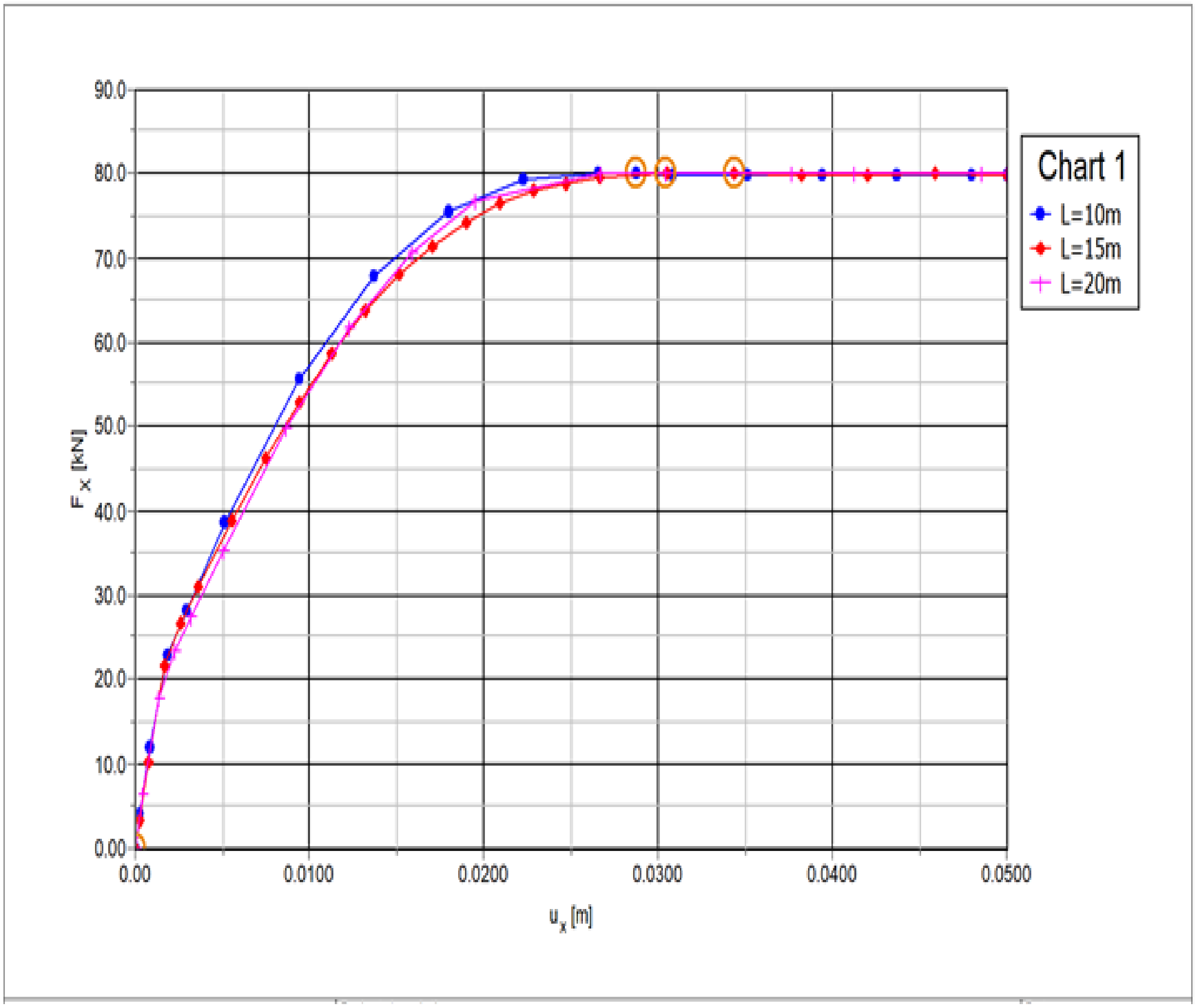


Figure4.6: Effect of pile length on lateral capacity of load

4.4 Effect of Pile Group on Lateral response of Pile

The study focused to examine the impact of pile group on the behavior of pile foundations. To evaluate the impact of pile group on load carrying capacity, a basic model consisting of 0.5m of pile diameter with lengths of 10m, and and a spacing of three times the pile. The model had a pile diameter of 0.5 meters and was subjected to a prescribed displacement 0.05m.

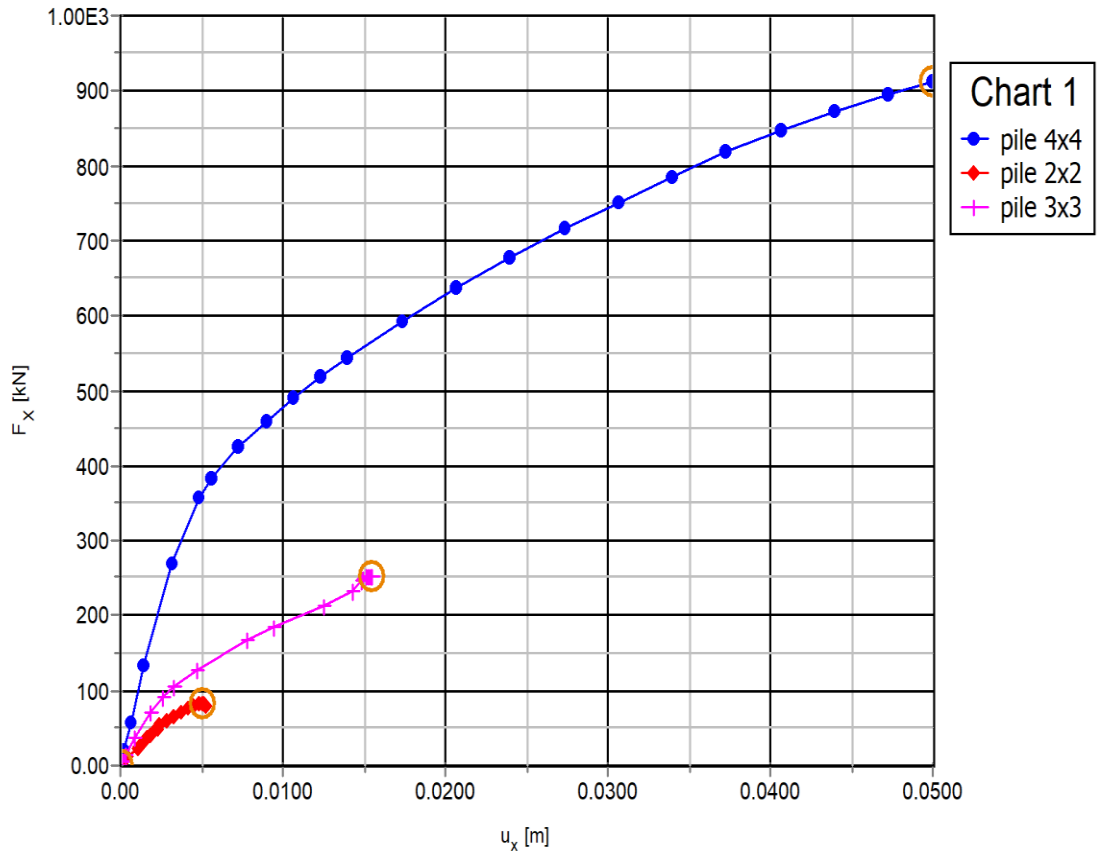


Figure4.7: Impact of Pile number on lateral capacity of Load

The ability of a pile group to resist lateral loads is a significant design issue. The deflection of a pile group under a lateral load is typically 2 to 3 times larger than the deflection of a single pile loaded to the same intensity. Many researchers, starting early on (e.g. Holloway et al. (1981) and Brown et al. (1988)) reported that piles in trailing rows of pile groups have significantly less resistance to a lateral load than piles in the lead row, and therefore exhibit greater deflections. Piles in closely spaced groups behave differently than single isolated piles because of pile-soil-pile interactions that take place in the group. It is generally recognized that deflections of a pile in a closely spaced group are greater than the deflections of an individual pile at the same load because of these interaction effects. The maximum bending moment in a group will also be larger than that for a single pile, because the soil behaves as if it has less resistance, allowing the group to deflect more for the same load per pile.

CONCLUSION AND RECOMMENDATION

5.1. Conclusions

The primary aim of this thesis was to investigate the lateral behavior of a pile group subjected to lateral loads and embedded in layered soil strata, with attention to the influence of pile diameter, pile length, pile spacing and pile numbers using PLAXIS 3D.

The three-dimensional numerical model was developed using PLAXIS 3D V21 software to analyze laterally loaded piles. The validation of model result was compared with the field test results available in the literature. The numerical model results were found in reasonable agreement with the field test results available in the literature.

As understood from the results, pile diameters significantly affect the response of laterally loaded piles. However, when the pile length and pile spacing changed, the outcomes from the finite element method (FEM) indicate that the response remains constant for the laterally loaded pile; the extension in pile length has minimal effects. The following points were concluded from the results:

- Increasing pile diameter from 0.5m to 0.75m and then from 0.75m to 1m, increased the ultimate lateral load by 55% and 59.88% respectively. Increasing diameter of pile reduces top deflection of the pile due to strength of structural stiffness.
- The maximum lateral capacity of laterally loaded pile remains constant with constant pile diameter while increase in length of pile since the critical length is less than embedment length of pile.
- From results of the investigation, the impact of pile length and spacing on the maximum lateral resistance was negligible.
- The maximum lateral capacity of laterally loaded pile unchanged with increasing in pile length since the critical length is less than embedment length of pile.
- The maximum lateral load was calculated in the stage of Plaxis 3D software and one can identify from the relationship of lateral deflection versus lateral load from the graph of 4.2 as (Max. 80KN) laterally.

5.2. Recommendations

In this study, the soil parameters utilized for numerical analysis were primarily derived from correlations of geotechnical properties and typical values reported in the literature. Only a limited number of parameters were directly obtained from laboratory or field tests. This reliance on estimated values stems from the insufficient availability of comprehensive laboratory and in-situ test data across various soil layers and depths. Validate determination of soil parameters through direct testing is crucial for reliable numerical modeling. Laboratory testing is integral to geotechnical analysis, providing essential data on soil properties such as strength, compressibility, and permeability, which are vital for evaluating foundation design criteria and ensuring a project's resiliency. Therefore, to enhance the fidelity of finite element method (FEM) simulations, it is recommended that future studies prioritize the acquisition of soil parameters through comprehensive laboratory and field investigations

My recommendation to future researchers is;

- Laboratory experiments and validate the numerical results obtained from Plaxis 3D using different soil types and loading conditions should performed.
- In this study, a static force was exerted at the top of the pile. It is recommended to investigate the lateral performance of pile when dynamic is applied on the pile and compare the effects with static load.
- The current investigation does not address the dynamic response of piles subjected to lateral loading. Hence, future research should explore the impact of dynamic forces on the lateral strength and performance of laterally loaded pile.
- In our country, no more research has been conducted on pile group, so the researchers should conduct on pile group with combined loading.

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APPENDIX

Appendix A: Soil profile from Geotechnical Investigation

Table A-1: Description of strata and corrected SPT blow count for BH1

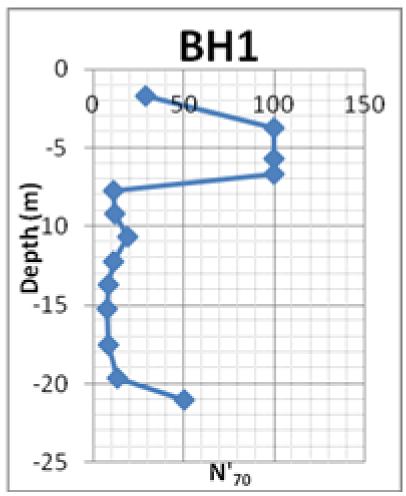
BH No.	Depth of test	N	Description of stratum based on visual inspection and lab index property test results	N’55 (corrected)
1	1.50 – 1.95	26	Medium stiff, black, highly plastic silty CLAY(CH)mixed with some gravel.	28.5
	2.00 – 7.00	-	Ignimbrite	-
	7.50 – 7.95	17	Very stiff to hard, reddish brown, highly plastic clayey SILT (MH) with traces of sand 	11.1
	9.00 – 9.45	20		11.9
	10.50 – 10.95	33		19.2
	12.00 – 12.45	21		11.5
	13.50 – 13.95	16	Stiff, variegated color, highly plastic SILT(MH) with weak core stones (weathering product of vesicular/Scoriaceous BASALT).	8.2
	15.00-15.45	16		7.8
	17.25 – 17.70	18		8.2
	19.40 – 19.85	30		12.9
	21.00	R		50
	22.40 -59.85	-	BASALTIC layer with a wide range of degree of fracturing and intensity of weathering (gravely soil of varying thickness is intercalated with this rock layer at varying depths)	

Table A-2: Description of strata and corrected SPT blow count for BH2

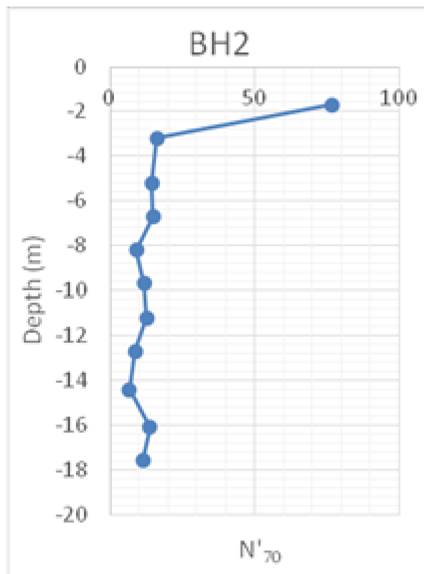
<table>
<tr><th>BH No.</th><th>Depth of test</th><th>N</th><th>Description of stratum based on visual inspection and lab index property test results</th><th>N’55 (corrected)</th></tr>
<tr><td rowspan="14">2</td><td>1.50 – 1.95</td><td>22/R</td><td>Contact between medium stiff soil and decomposed IGNIMBRITE</td><td>76.7</td></tr>
<tr><td>3.00 – 3.45</td><td>21</td><td rowspan="8">Stiff to v. stiff red to yellowish, highly plastic SILT(MH) with traces of sand

</td><td>16.3</td></tr>
<tr><td>5.00 – 5.45</td><td>21</td><td>14.5</td></tr>
<tr><td>6.50 – 6.95</td><td>22</td><td>15.0</td></tr>
<tr><td>8.00 – 8.45</td><td>15</td><td>9.2</td></tr>
<tr><td>9.50 – 9.95</td><td>21</td><td>11.9</td></tr>
<tr><td>11.00 – 11.45</td><td>23</td><td>12.7</td></tr>
<tr><td>12.50 – 12.95</td><td>17</td><td>8.8</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>14.2 – 14.65</td><td>14</td><td rowspan="3">Stiff to hard, variegated color, highly plastic SILT(MH) with weak core stones (weathering product of vesicular scorious basalt)</td><td>6.8</td></tr>
<tr><td>15.90 - 16.35</td><td>30</td><td>13.8</td></tr>
<tr><td>17.40 – 17.85</td><td>26</td><td>11.5</td></tr>
<tr><td>22.40 – 65.00</td><td>-</td><td>BASALTIC layer with a wide range of degree of fracturing and intensity of weathering (gravely soil of varying thickness is intercalated with this rock layer at varying depths)</td><td>-</td></tr>
</table>

Table A-3: Description of strata and corrected SPT blow count for BH3

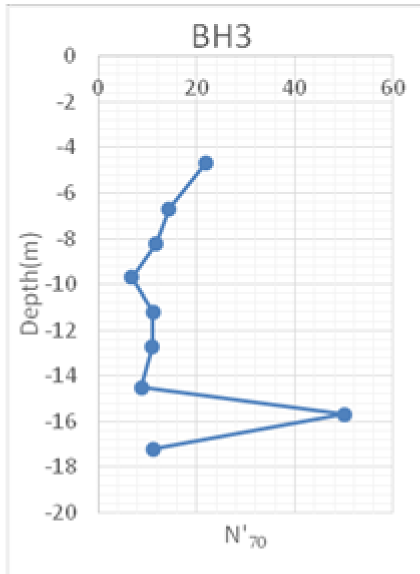
BH No.	Depth of test	N	Description of stratum based on visual inspection and lab index property test results	N'55 (corrected)
3	4.50 – 4.95	30	Very stiff to hard, red, highly plastic SILT(MH) 	21.8
	6.50 – 6.95	21		14.3
	8.00 – 8.45	19		11.7
	9.50 – 9.95	12		6.8
	11.00 – 11.45	20		11.1
	12.50 – 12.95	21		10.9
	14.00 -14.95	18		8.8
	15.50 – 15.95	R		50
	17.00 – 17.45	25		11.2
	20.00 – 80.00	-	BASALTIC layer with a wide range of degree of fracturing and intensity of weathering (gravely soil of varying thickness is intercalated with this rock layer at varying depths)	

Table A-4: Description of strata and corrected SPT blow count for BH4

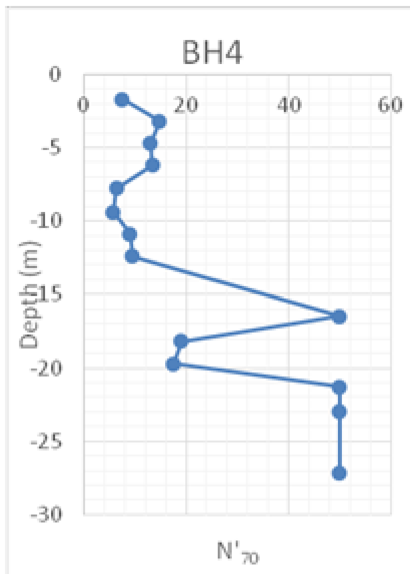
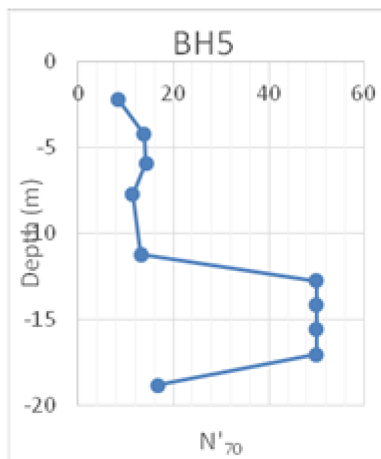
BH No.	Depth of test	N	Description of stratum based on visual inspection and lab index property test results	N’55 (corrected)
4	1.50 – 1.95	7	Medium stiff, dark to light gray, highly plastic CLAY to SILT (CH-MH)	7.5
	3.00 -3.45	19	Very stiff, reddish brown, highly plastic silty Clay (MH)	14.8
	4.50 – 4.95	18		13.1
	6.00 – 6.45	19		13.4
	7.65 – 8.10	10	Stiff to hard, variegated color (predominantly brown), highly plastic SILT with clay (MH)	6.3
	9.15 – 9.60	10		5.7
	10.65 – 11.10	16		9.0
	12.15 – 12.60	18		9.5
	16.50	R		50
	18.00 – 18.45	44		19.1
	19.50 – 19.95	42		17.5
	21.30	R		50
	23.00	R		50
	27.15	R	V. dense, reddish brown silty Sand (SM) with gravel and weak core stones	50
	23.15 – 70.00		BASALTIC layer with a wide range of degree of fracturing and intensity of weathering (gravely soil of varying thickness is intercalated with this rock layer at varying depths)	

Table A-5: Description of strata and corrected SPT blow count for BH5

BH No.	Depth of test	N	Description of stratum based on visual inspection and lab index property test results	N’55 (corrected)
5	2.00 – 2.45	9	Stiff, dark brown, highly plastic SILT (MH)	8.4
	4.00 – 4.45	18	Stiff to v. stiff, reddish brown, highly plastic SILT(MH) (weathering product of ignimbrite)	13.8
	5.70 – 6.15	22		14.3
	7.50 – 7.95	18		11.4
	11.00 – 11.45	25	V. stiff, variegated color (dark brown), highly plastic SILT (MH) with intermittent weak core stone	13.1
	12.50 – 12.95	R	Hard, variegated color, non to low plastic sandy SILT (MS) with weak core stones (weathering product of vesicular/scoracious BASALT); Below 19.25m: rockier 	50
	14.05	R		50
	15.50	R		50
	17.00	R		50
	18.80	39		16.7
	20.00 – 85.00		BASALTIC layer with a wide range of degree of fracturing and intensity of weathering (gravely soil of varying thickness is intercalated with this rock layer at varying depths)	

APPENDIX B: Geotechnical Properties of Soil

Table B.1: Typical values of Poisson's ratio for soils and other material, Bowels (1977)

Types of soil and materials	Poisson's ratio (v)
Saturated clay	0.4 – 0.5
Unsaturated clay	0.1 – 0.3
Sandy clay	0.2 – 0.3
Silt	0.3 – 0.35
Sand - Dense	0.2 – 0.4
Sand –Coarse (void ratio = 0.4 – 0.7)	0.15
Sand-Fine (void ratio = 0.4 – 0.7)	0.25
Rock (depending on type)	0.1 – 0.4
Loess	0.1 – 0.3
Ice	0.36
Concrete	0.15

Table B.2: Typical values of Young's modulus (Mpa) for granular and cohesive materials (Kezdi and Rethati, 1974 and Prat el., 1995)

	USCS	Description	Loose	Medium	Dense
Granular materials	GW, SW	Gravels/Well graded sand	30 - 80	80 - 160	160 - 320
	SP	Sand, uniform	10 - 30	30 - 50	50 - 80
	GM, SM	Sand/Gravel silty	7 - 12	12 - 20	20 - 30
	Cohesive materials				
USCS	Description	Very soft to soft	Medium	Soft to very stiff	Hard
ML	Silts with slight plasticity	2.5 - 8	10 - 15	15 - 40	40 - 80
ML, CL	Silts with low plasticity	1.5 - 6	6 - 10	10 - 30	30 - 60
CL	Clays with low-medium plasticity	0.5 - 5	5 - 8	8 - 30	30 – 70

CH	Clays with high plasticity	0.35 - 4	4 - 7	7 - 20	20 - 32
OL	Organic silts	-	0.5 - 5	-	-
OH	Organic clays	-	0.5 - 4	-	-

Table B.3: SPT values- based on soil and rock classification systems (Skempton, 1986)

Sand	**N_{60}**	
	0 - 3	Very loose
	3- 8	Loose
	8 - 25	Medium
	25 - 42	Dense
	42 - 58	Very Dense
Clays	**N_{60}**	
	0 - 4	Very soft
	4 - 8	Soft
	8 - 15	Firm
	15 - 30	Stiff
	30 - 60	Very Stiff
	>60	Hard
Weak Rock	**N_{60}**	
	0 - 80	Very weak
	80 - 200	Weak
	>200	Moderately weak to very strong