Evaluating the Performance of Piled Raft Foundations on Soft Soil Using PLAXIS 2D

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ABSTRACT

A large number of building projects have been built on soft soil in recent years. Differential settlements can occur in structures built on soft soil because of its properties. The raft foundation is one way to lessen differential settling. It may result in excessive settling even when it has a sufficient bearing capacity. A piled raft foundation system is one that uses piles in conjunction with a raft foundation. The analysis of piled raft foundations in soft soil conditions presents a critical challenge in geotechnical engineering due to the complexities associated with soil-structure interactions and settlement behavior. This study employs PLAXIS 2D, a finite element analysis software, to investigate the performance of piled raft foundations subjected to varying load conditions on soft soil. The research aims to optimize the design by examining the contribution of piles to load sharing and settlement reduction. Key parameters such as pile length, pile spacing, and raft thickness are analyzed to evaluate their impact on the overall foundation behavior. Results from numerical simulations highlight the significant influence of pile arrangement and soil properties on the settlement response and load distribution efficiency. The findings provide a comprehensive understanding of the piled raft system, offering insights for the effective design of foundations in challenging soft soil environments, enhancing stability and reducing excessive settlement. Based on the permitted settlements, the ideal amount of piles for a piled raft foundation system must be taken into account for an economical design.

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CHAPTER 1
INTRODUCTION

1.1 General

Building projects on soft soil have been built on a large scale in recent years. Structures constructed on soft soil are susceptible to differential settling because of these features. One way to lessen differential settling is with a raft foundation. Despite having a sufficient bearing capacity, it could lead to excessive settling. A raft foundation and piles can be combined to create a piled raft foundation system. The purpose of adding heaps is to bring the settlements down to a manageable level (Poulos, 2001). In the discipline of geotechnical engineering, finite element studies are widely used. Numerous studies have examined the performance of stacked rafts by utilizing the finite element approach to analyze the structures. This approach can produce good findings for stacked raft analyses (Prakoso, 2001). A structure's foundation is the structural component that supports the edifice. The "foundation bed's" load-bearing capability is maintained by the transmission and distribution of both the foundation's own weight and external loads to the soil. Deep foundations are needed to transfer weights to deeper strata when the soil at a shallow depth is insufficient to sustain a structure. The deep foundation will be used if a firm stratum is so deep that open excavation is not feasible to reach it. The piles can be used as raft foundations or as part of a raft pile system, which helps to reduce settling by sharing the super building weight between the raft and the pile. The raft passes through pointless settlements yet has a sufficient rolling limit and lessens differential settlement. Consequently, in order to address the aforementioned issue, the pile-side raft is utilized as a piled raft to provide sufficient dropping below the bearing limit at large, sensible, and secure cut-off locations. Even with a rolling limit that is high enough, it can lead to unreasonable liquidation. In geotechnical engineering, limited component examinations are typical. piled high Utilizing the component approach to exploit exposure and lower settlement support capability, foundation studies have been finished by several scholars. Excellent findings for pile foundation studies may be obtained with this approach. This investigation aims to investigate the settlements of the raft foundation installation and add piles beneath a comparable piling like the pile pontoon establishment. A restricted study of components using PLAXIS 2D was the focus of this test.

The objective of this research is to examine the raft foundation's settlements and the effects of adding piles under identical loading conditions to create a pile raft foundation. This study used PLAXIS 2D to do a finite element analysis.

1.2 Background of the Study

A structure's foundation is a crucial part in contemporary geotechnical engineering as it offers stability and guarantees that the building can bear applied loads throughout time without suffering from damaging settlement or failure. Dealing with soft soils, which are common in riverbeds, coastal regions, and other places with high moisture content and fragile soil structure, makes foundation design especially difficult. These soils are not suited for standard shallow foundations because they usually have poor shear strength, considerable compressibility, and a propensity for severe settlement under load. Soft soils provide a number of issues that need to be taken into consideration when designing a foundation. Both differential and complete excessive settlement can cause structural damage, from minor problems like cracking that are aesthetically pleasing to more serious problems like tilting and collapse. In particular, differential settlement can lead to structural distortions that compromise the building's structural integrity by causing an uneven distribution of stress. Innovative foundation systems that may reduce settlement and effectively transmit structural loads to deeper, more capable soil layers are required to meet these problems.

The stacked raft foundation is a viable option for building on soft soils. With the raft serving as a load-distributing platform and the piles serving as load-bearing components that carry loads to deeper, stiffer soil or bedrock, this system combines the benefits of both shallow and deep foundations. Effective load distribution made possible by the interplay of the raft and piles lowers total settling while maintaining the viability of the foundation system economically. Piled raft foundations use less piles than fully piled systems, which lowers construction costs without sacrificing performance.

1.3 Problem Statement

The intricate relationships between the raft, piles, and surrounding soil provide special difficulties for the design and operation of stacked raft foundations in soft soils. In soft soil circumstances, traditional design methods which frequently regard the raft and piles as separate elements might not accurately depict the system's true behavior. Soft soils behave nonlinearly, especially when loaded, therefore it's important to take time-dependent settling, consolidation, and creep into consideration. Furthermore, while a piled raft foundation's piles lessen settling by shifting some of the weight to deeper, stronger strata, the precise load-sharing process between the piles and raft is not always obvious. A number of factors, such as the soil's characteristics, the rigidity of the raft, and the length and spacing of the piles, affect how efficient the technique is. A detailed understanding of how these characteristics interact to affect system performance is necessary to design an ideal foundation.

In order to solve these issues, using finite element analysis (FEA) technologies like PLAXIS 2D has become crucial. Engineers may model intricate soil-structure interaction issues with PLAXIS 2D, which offers a robust framework for simulating the behavior of stacked raft foundations in soft soils under varied loading scenarios. Compared to conventional analytical approaches, the program provides a more realistic picture of the foundation's performance by taking into account non-linear soil behavior, consolidation effects, and time-dependent settlement.

1.4 Scope and Objectives

This study focuses on the utilization of PLAXIS 2D for the analysis of piled raft foundations on soft soils. Conducting a series of numerical simulations using PLAXIS 2D to model piled raft foundations with varying pile lengths, pile spacing, and raft thickness.

The objectives of the study are as follows:

1. To investigate the performance of raft foundations on soft soils using PLAXIS 2D.
2. To evaluate the effects of raft thickness, pile length, and spacing on load distribution and settling.

CHAPTER 2
LITERATURE REVIEW

2.1 General

There have been a lot of construction projects on soft ground in recent years. Differential settlements can occur in structures built on soft soil due to its properties. One way to lessen differential settling is to use a raft foundation. Despite having a sufficient load capacity, it may lead to excessive settling. A raft foundation and piles can be combined to create a piled raft foundation system. The purpose of adding heaps is to bring settlements down to a manageable level. The aim of this research is to examine the settlements caused by the installation of piles under the same weight as the raft foundation. Using PLAXIS 2D and the finite element approach, numerical analysis was carried out while taking into account the various pile counts. Therefore, adding piles might lessen settlement; but, adding piles beyond a certain point indicated that settlement tended to remain constant. Based on the permitted settlements, the ideal amount of piles in the piled raft foundation system must be taken into account for an inexpensive project (Besseling, 2013). When insulated footings enclose more than 70% of the building space beneath a superstructure, raft foundations are employed. A piled raft foundation combines raft foundation construction with the use of piles. In the case of tall clay structures, pile raft foundations have shown to be more economical and can offer safe load-carrying capability and maintenance needs.

By strategically placing piles, the raft's load capacity is increased and differential settling is decreased. This study sheds light on the behavior of the piled raft immersed in sand as well as the rationale behind employing piles as settling reducers for raft foundations. Tests on small-scale models are conducted. Experimental research is done to determine how the alignment and length of the pile affect the last load achieved. Based on the conducted tests, it was determined that the weight borne by the raft increases as the number and length of piles decrease (Prakoso, 2001).

2.2 Piled Raft Foundations

A piled raft foundation is a type of hybrid foundation system that combines the deep load-bearing capability of piles with the load distribution characteristics of a shallow foundation (raft). This technology makes it possible to solve problems with difficult soil conditions more effectively and economically, especially in places with soft soils or where heavy weights must be sustained. The idea is that the raft functions as a broad platform that is stretched out across the soil, and the piles, which offer additional load-bearing support by penetrating deeper into bedrock or more competent soil layers, interact with one another. A load-sharing mechanism underpins the piled raft foundation system, wherein the structural load is shared by the piles and the raft. When compared to standard pile foundations, the foundation offers considerable economic and performance advantages by spreading loads more efficiently over the piles and the underlying soil, hence reducing total settling.

2.2.1 Evolution and Importance of Piled Raft Foundations

Pinned raft foundations originated from attempts to minimize settlement and retain adequate structural stability in deep foundation systems by cutting down on the number of piles. Historically, pile foundations especially in regions with soft soil were intended to support the whole structural load, which led to high material and construction costs. The concept of enabling the raft to contribute to its load-bearing capability resulted in the development of piled rafts, which are currently seen to be a cost-effective substitute for completely piled systems. When a completely piled foundation would be too expensive to use or when employing a shallow raft foundation alone would cause excessive settling, the piled raft foundation is particularly advantageous. By making use of the raft's capacity to distribute the weight, the system optimizes the load distribution between the raft and the piles, enabling a decrease in the number of piles needed. The resulting reductions in costs can be significant, particularly in large-scale projects in areas where the usage of vast pile networks would otherwise be required due to soft soil conditions.

2.2.2 Load Sharing in Piled Raft Foundations

The load-sharing mechanism between the piles and the raft is one of the basic ideas of piled raft foundations. Under this arrangement, the piles transport the remaining structural load to stronger, deeper soil layers or bedrock, while the raft itself directly bears a portion of the weight through contact with the soil. The precise percentage of the weight supported by the piles and the raft depends on a number of variables, such as:

- **Raft Stiffness**: A stiffer raft will distribute loads more evenly across the piles and soil. The stiffness of the raft is typically increased by thickening the raft or by reinforcing it with steel or concrete.
- **Pile Length and Stiffness**: Longer or stiffer piles tend to carry a greater proportion of the load as they penetrate into more competent soil layers or bedrock. This reduces the amount of load borne by the raft and helps in controlling settlement.

- **Pile Spacing**: The spacing between piles influences the distribution of load between the raft and the piles. Closer pile spacing increases the load on the piles, while wider spacing allows the raft to carry more of the load.
- **Soil Stiffness**: The properties of the underlying soil, particularly its stiffness and compressibility, play a key role in determining the distribution of load. Softer soils tend to result in a higher proportion of the load being transferred to the piles, as the raft alone may not provide sufficient support without undergoing excessive settlement.

Optimizing the balance between the loads carried by the raft and the piles is a crucial design goal for piled raft foundations in order to reduce total settling while preserving cost-effectiveness. Compared to fully piled structures, the technique delivers significant material and construction cost reductions by lowering the number of piles needed.

2.2.3 Behavior of Piled Raft Foundations in Soft Soils

Since mild soils, such as clays, have high compressibility and poor shear strength, using a shallow raft foundation alone may result in significant settlements, stacked raft foundations are especially useful in soft soil situations. In a setting with soft soil, the use of piles aids in distributing the weight to bedrock or deeper, tougher soil layers, minimizing both differential and total settlement.

Soft soils provide a number of difficulties that affect stacked raft foundation performance and design, including:

- **Excessive Settlement**: Soft soils are prone to large settlements, particularly under sustained loads. In piled raft systems, piles help mitigate this by transferring a portion of the load to more stable soil layers, reducing the total settlement experienced by the structure.
- **Differential Settlement**: In structures supported by piled raft foundations, differential settlement (where different parts of the structure settle at different rates) can lead to structural damage. Piled rafts help reduce this by distributing the loads more uniformly across the foundation.
- **Non-linear Soil Behavior**: Soft soils often exhibit non-linear stress-strain relationships under load. Piles within the raft foundation system interact with this non-linear behavior, helping to stabilize the foundation by reducing stress concentrations in the soil and improving overall load distribution.

As long as the pile length, spacing, and raft stiffness are carefully taken into account during the foundation's construction, several studies have shown that piled raft foundations function effectively in soft soils. Because the raft and piles share the weight, there is less stress on the earth, which prevents excessive settlement and maintains the integrity of the structure.

2.2.4 Design Considerations for Piled Raft Foundations

To guarantee that the system operates well under the specified soil conditions and structural loads, a number of crucial factors must be taken into account when designing a stacked raft foundation. Among these factors are:

- **Raft Thickness and Stiffness**: The raft must be designed to distribute the structural load effectively over the piles and the surrounding soil. A thicker and stiffer raft improves load distribution, reduces differential settlement, and ensures that the foundation remains stable under load.
- **Pile Length and Spacing**: The length of the piles should be sufficient to reach deeper, more competent soil layers or bedrock. The optimal pile length is determined by the depth of the weak soil layer and the strength of the underlying material. Pile spacing is also crucial, as too close a spacing can lead to excessive interaction between piles, while too wide spacing may result in the raft carrying more load than intended.
- **Pile-Soil Interaction**: The interaction between piles and soil, particularly in soft soils, is complex and requires careful analysis. The behavior of the piles under load, including the possibility of soil displacement or pile settlement, must be taken into account during the design process.
- **Settlement Control**: One of the primary objectives in designing piled raft foundations is controlling settlement. In soft soils, both total and differential settlement must be minimized. This requires careful selection of the raft thickness, pile length, and pile spacing to ensure that the foundation provides adequate support without excessive deformation.
- **Load Sharing Mechanism**: Understanding the load-sharing behavior between the raft and the piles is crucial for optimizing the foundation design. Numerical modeling tools such as PLAXIS 2D can be used to simulate the interaction between the raft, piles, and soil, providing insights into how loads are distributed and helping to refine the design.
- **Cost Efficiency**: One of the key advantages of piled raft foundations is the potential for cost savings. By reducing the number of piles required to support the structure, the overall cost of materials and construction can be significantly reduced. However, this must be balanced against the need to control settlement and ensure structural stability.

2.2.5 Advantages of Piled Raft Foundations

There are several benefits to piling raft foundations, especially when dealing with difficult soil conditions such soft soils:

- **Reduction in Pile Count**: Compared to fully piled foundations, piled raft systems require fewer piles, leading to substantial cost savings in material and installation.
- **Improved Load Distribution**: The combination of the raft and piles allows for better load distribution across the foundation, reducing stress concentrations and minimizing differential settlement.
- **Flexibility in Design**: Piled raft foundations can be adapted to suit a variety of soil conditions and structural requirements. By adjusting the raft thickness, pile length, and pile spacing, the foundation can be optimized for different geotechnical scenarios.
- **Suitability for Large Structures**: Piled raft foundations are particularly well-suited for large buildings, bridges, and other infrastructure projects that require a foundation capable of supporting heavy loads in soft soil conditions.

2.2.6 Disadvantages and Limitations

Although stacked raft foundations have several advantages, it's important to be aware of their limits as well:

- **Complex Design and Analysis**: Designing a piled raft foundation requires a thorough understanding of soil-structure interaction, as well as the use of advanced numerical tools to model the behavior of the foundation under load. This complexity can make the design process more time-consuming and costly.
- **Settlement Control**: Although piled raft foundations are designed to reduce settlement, controlling differential settlement can be challenging, particularly in soft soils where the behavior of the soil under load is non-linear and time-dependent.
- **Pile Installation**: In some cases, installing piles in soft soils can be difficult due to issues such as pile driving resistance or soil displacement during installation. These challenges must be addressed during the construction phase to ensure the foundation performs as intended.

2.3 Application of PLAXIS 2D in Piled Raft Foundation Design

The design and study of stacked raft foundations, especially in soft soils, heavily relies on numerical modeling techniques such as PLAXIS 2D. By considering variables like soil stiffness, pile spacing, and the load-sharing mechanism, engineers may simulate the intricate relationships that exist between the raft, piles, and soil using PLAXIS 2D. Engineers may improve their designs and make sure the foundation functions as needed in practical situations by using the software, which offers comprehensive insights into the settlement behavior, stress distribution, and load transmission within the foundation system.

2.4 FEA Method Analysis

Finite Element Analysis (FEA) is the computational process of understanding and forecasting an object's potential behavior under different physical situations. It is carried out by models, simulations, and calculations. Engineers utilize finite element analysis (FEA) as a method to find flaws in their design prototypes. To gain a better understanding of the patterns in soil mass deformation, a series of two-dimensional Finite Element Analyses (FEA) were performed on a prototype dry excavation system. The PLAXIS software package, a finite element tool, was utilized to do the analysis (Brinkgreve, 2002). Numerous geotechnical issues, including deep excavations, tunnels, and earth constructions like retaining walls and slopes, can be handled by PLAXIS. Three or five- node beam elements and six or fifteen-node triangular plane strain elements for the soil, as well as three or five-node elastic elements for the geotextile components, can be automatically generated by the software. Creating the model's geometry is the first step in the analysis process. The dimensions of the excavation, including its breadth and height.

2.5 Finite Element Modeling

The hardening soil model, an Elastoplast hyperbolic stress-strain model based on friction and hardening plasticity, was used to study the non-linear behavior of sand. Using Mindlin's beam theory, the foundation was represented as elastic beam components with considerable flexural rigidity (EI) and normal stiffness (EA). Soil stiffness is determined by stress in the hyperbolic model. Because the geogrid-soil interaction is represented by interface components, wall friction is smaller than soil friction. The limiting state of stress is described by secant Young's modulus, tangent stiffness modulus for primary compression, Poisson's ratio, effective cohesion, angle of internal friction, angle of dilatancy, failure ratio, and interface reduction factor. The modeled boundary conditions assume free vertical and confined horizontal bounds, with a fixed bottom horizontal boundary. The software automatically generates six node triangular plane strain elements for soil and three node beam elements for geogrid. Reinforced tests use 250 elements, while unreinforced tests include 160. FEM is widely used in various fields, including structural analysis, heat transfer, fluid dynamics, electromagnetics, and more (Brinkgreve, 2002).

2.6 The Mohr-Coulomb (MC) Model

A mathematical model known as the Mohr-Coulomb theory describes how brittle materials, such as concrete or heaps of rubble, react to both shear and normal stress. This is the general norm that most traditional engineering materials adhere to in at least part of their shear failure envelope. The theory is generally applicable to materials whose compressive strength is significantly higher than their tensile strength (Juvinal, 1991). It is used to specify the shear strength of rocks and soils at various effective stresses in geotechnical engineering. Józsa explained how it serves as the initial approximation method (Józsal, 2011). Its continuous rigidity makes the calculation extremely quick. The displacements and forces found are not real, even though the model is ideal for the stability test. The parameters of (the MC) model are given below:

a. (E) Young's modulus [kN/m^2]
b. (ν) Poisson's ratio
c. (φ) Friction angle [°]
d. (c) Cohesion [kN/m^2]
e. (ψ) Dilatancy angle [°]

2.6.1 The Mohr-Coulomb Failure

Joseph F. Labuz additionally outlined the failing criteria. To comprehend the connections and differences between deformation, stress, and modifications to other parameters. I used this relationship to predict the soil behavior (Zang, 2012).

1. Principal Stresses Explained and Shear Stress and Normal Stress Introduced.
    a. Three major primary vectors, σ_1, σ_2, and σ_3, at right angles to one another, are identified as the sources of stress, with $\sigma_1 \geq \sigma_2 \geq \sigma_3$.
    b. The smallest primary stress is denoted by σ_3, the intermediate principal stress by σ_2, and the largest principal stress by σ_1.
    c. Stress for any plane that is parallel to σ_2 can be broken down into two parts: Shear stress (σ_s), which is in the plane's direction, and Normal stress (σ_n), which is perpendicular to the plane.
    d. The specified stress components are connected as follows:

$$\sigma_s = \tfrac{1}{2}(\sigma_1 - \sigma_3)\sin(2\theta) \qquad \text{eq. (1)}$$

$$\sigma_n = \tfrac{1}{2}(\sigma_1 + \sigma_3) - \tfrac{1}{2}(\sigma_1 - \sigma_3)\cos(2\theta) \qquad \text{eq. (2)}$$

2.6.2 Coulomb Failure Criterion

a. Every homogeneous material has a distinct characteristic failure envelope for the fracture of brittle shear on a Mohr-Coulomb diagram.
b. Fractures will arise from combinations of 'σ_s' and 'σ_n' that plot outside of the envelope. The plots within the envelope exhibit stability.
c. Failure envelopes should take the form of compressive stress for straight lines and tensile stress for parabolic behavior.
d. The Coulomb law of failure defines the failure envelope under compressive load at any particular position.

   $\sigma_c = \sigma_0 + \tan(\varphi)\sigma_n$ eq. (3)

   Where: σ_c = critical shear stress, σ_0 = cohesive strength, or σ_s value of the given failure envelope where $\sigma_n = 0$ (where failure envelope intersects the y-axis), φ = angle of internal friction. $\varphi = 90\text{-}2\theta$. Tan ($\varphi$) is known as the coefficient of internal friction.
e. Approximately 30° is the internal friction angle for most rocks and soil. Therefore, even though σ_s reaches its maximum at $\theta = 45°$, θ at failure is likewise $\approx 30°$.
f. The Mohr circle is moved slightly to the right, or closer to the failure boundary, by an increase in pore fluid pressure.

2.7 Numerical Modeling with PLAXIS 2D

Numerical modeling is a crucial tool in geotechnical engineering that allows engineers to simulate complex interactions between soil layers and structures. PLAXIS 2D is a popular and extensively used software tool for accurately and precisely representing geotechnical concerns in two dimensions. This chapter's goal is to go over how PLAXIS 2D is used to model embankment stability and geogrid reinforcement. Particular attention is paid to the sophisticated soil constitutive models, the capability to simulate complicated loading circumstances, and the modeling tools for soil-reinforcement interchanges. In addition to this, it examines examples of research projects and case studies in which PLAXIS 2D was utilized to model geogrid-reinforced embankments. These examples demonstrate how numerical modeling may be utilized to anticipate performance, optimize design parameters, and evaluate probable failure risks. In order to emphasize the benefits and drawbacks of numerical modeling in this context, the chapter performs a comparison between the outputs of PLAXIS 2D simulations and the experimental data and real-world outcomes (Pamuk, 2015).

2.8 Piled Raft Foundations in Soft Soils

Given the difficulties these types of soils provide, the usage of stacked raft foundations in soft soils has become increasingly popular. Raft components by themselves would not be adequate to stop excessive settling in soft soil conditions. To reduce the danger of settlement and increase overall stability, the foundation system can transmit loads to deeper and more stable soil layers by adding piles. Large constructions may be especially vulnerable to differential settling in soft soils, which is why the load-sharing mechanism between the raft and piles is so important. Research has demonstrated that piled raft foundations in soft soils not only improve the overall stiffness of the foundation system but also decrease settlement. To prevent issues like pile-soil displacement, pile bending, and excessive settlement in specific areas, the interaction between the raft, piles, and soft soil must be carefully considered in the design.

2.9 Challenges of Foundation Design in Soft Soil

Soft soils pose substantial issues for foundation construction since they are very compressible and have poor shear strength, such as clays, silts, and organic deposits. When exposed to external stresses, especially if the load is sustained over time, these soils usually experience significant settlements. Among the main geotechnical problems related to soft soils are:

- **Low Bearing Capacity**: Soft soils often lack the necessary strength to support heavy structures, leading to excessive settlements or even bearing capacity failures.
- **High Compressibility**: Soft soils undergo considerable compression under loads, resulting in long-term settlements. This characteristic is particularly problematic in clayey soils, where consolidation can lead to prolonged settlement periods.
- **Differential Settlement**: Structures built on soft soils are prone to non-uniform settlement, where different parts of the foundation settle at different rates. This can lead to structural distortions, cracking, or even failure.
- **Time-Dependent Behavior**: Soft soils, particularly clays, exhibit time-dependent consolidation behavior. After the initial settlement caused by load application, there is often a continued, slower settlement due to water expulsion from the soil pores.

Typically, radial shallow foundations like strip or pad footings are inappropriate for soft soils because they depend on the soil layers that are close or on the surface to support the weight. When the structure is huge or the weight is distributed unevenly, this might lead to excessive settlements and instability. To overcome these difficulties, engineers typically resort to deep foundations, such as piles. Alternative options, such as stacked raft foundations, are being investigated since deep foundation systems can be too costly and complicated.

2.10 Previous Studies on Piled Raft Foundations

PLAXIS 2D has been used by several studies to examine stacked raft foundations on soft soils. Their research has improved our knowledge of how stacked raft foundations behave in different scenarios and offered insightful information on how to optimize foundation design.

- **Poulos and Davis** (1980) conducted early studies on piled raft foundations, focusing on the load-sharing mechanism between the raft and piles. Their work laid the foundation for future research on the design of piled rafts in soft soils.
- **Randolph** (1994) developed analytical methods to estimate the settlement and load distribution in piled raft foundations. His work highlighted the importance of considering both the stiffness of the raft and piles, as well as the properties of the surrounding soil.
- **Katzenbach et al.** (2024) conducted extensive field studies and numerical analyses of piled raft foundations in soft soils. Their research demonstrated that piled raft foundations could effectively reduce settlement in soft soil conditions while minimizing the number of piles required.
- **Chow et al.** (2005) used PLAXIS 2D to model the performance of piled raft foundations in soft clay. Their study revealed that the optimal pile length and spacing depend on the soil's stiffness and compressibility, with longer piles and closer spacing resulting in reduced settlement.

CHAPTER 3
METHODOLOGY

3.1 General

A well-known finite element analysis (FEA) tool called PLAXIS 2D was utilized to simulate the behavior of embankments reinforced with geogrid. Commercial software currently uses finite element techniques. The structural components that need excavation processes have been analyzed using PLAXIS. Nevertheless, earlier missteps indicated that selecting the constitutive model to describe soil behavior and the related soil parameters was essential for a productive study that made use of the codes. A variety of element types, including the anchors that support the retaining wall, pile foundation, slope stability, different kinds of loads behind the wall, and elements that serve as an interface between the soil and the anchored retaining wall, can all be modeled using PLAXIS (Chehade, 2008). The analysis was conducted using the 15-noded triangular elements of the PLAXIS 2D finite element program. To understand how different parameters affect the behavior of the wall as mentioned above, all of the modeled and studied cases had their total displacement, wall bending moments, stresses, and wall shear forces examined (PLAXIS2D, 2002).

3.2 Model Details

A large number of 2D simulations have been employed for research and during the design process because of the limitations of the available software and processing resources. I will be looking at PLAXIS's constitutive soil models because it was chosen for this particular project. the more thorough information. With the engineering soil simulation tool PLAXIS, soil properties are quantitatively characterized using parameters, and the qualitative behaviors of the soil are reflected through numerical soil models. With just one integrated application, PLAXIS 2D is an easy-to-use finite-element tool that allows modeling of various geotechnical issues. Examine how projects including tunneling, mining, geomechanics, embankments, foundations, and excavations deform and stabilize. All of the necessary features to do routine deformation and safety analyses for rock and soil without taking into account creep, steady-state thermal or groundwater flow, consolidation analysis, or any time-dependent effects are included in PLAXIS 2D (PLAXIS2D, 2002). PLAXIS 2D, a finite element software tool for geotechnical engineering and rock mechanics, examines two-dimensional deformation and stability. Geotechnical structures, such as excavations, dams, embankments, and tunnels, can be represented using the software. The software can calculate 2D plane strain, axisymmetric deformations, soil stresses, water flow, pressures, and structural, and thermal forces. Various soil models are used to account for the behavior of different soil types, including clay, sand, and rock, as well as loading, unloading, and reloading. In addition, PLAXIS 2D offers a CAD-like environment for quick and efficient model creation, allowing users to focus on analyzing results.

3.3 Soil Parameters

The soil profile was analyzed using feasibility study results from past mega-projects. However, due to the unavailability of some attributes, empirical correlations have been utilized (Wulandari, 2015). Soil parameters used in the model have been shown in Table 3.1.

Table 3.1: Properties of materials used in modeling

Parameter Name		Soft Clay	Stiff Clay	Loose Sand	Medium Dense Sand	**Units**
Material model		MC	MC	MC	MC	
Soil unit weight above phreatic level	γ	15	15	17	17.5	kN/m^3
Soil unit weight below phreatic level	**γ(sat)**	17	18	20	18	kN/m^3
Young's modulus	**Eref**	4	50	30	37	Mpa
Poisson's ratio	**ν(ur)**	0.25	0.3	0.3	0.35	
Cohesion	**c(ref)**	5	120	7	5	kN/m^2
Friction angle	**Φ**	0	5	30	41	°
Dilatancy angle	**Ψ**	0	0	0	14	°

3.4 Model Geometry

In this investigation, a 21 m × 21 m raft with varying numbers of piles was subjected to a uniformly distributed load of 60 kN/m^2. It was a model of an industrial structure constructed on loose dirt. The raft and the piles were modeled as plate components in the finite element analysis. The ability to describe the pile-soil interaction, a highly three-dimensional phenomenon (Sluis, 2013), is limited when using 2D finite element modeling of piles as plates. To obtain realistic load-displacement behavior when modeling piles with plate elements, it is necessary to modify both the interface behavior and the stiffness parameters of these parts, as shown in Figure 3.1.

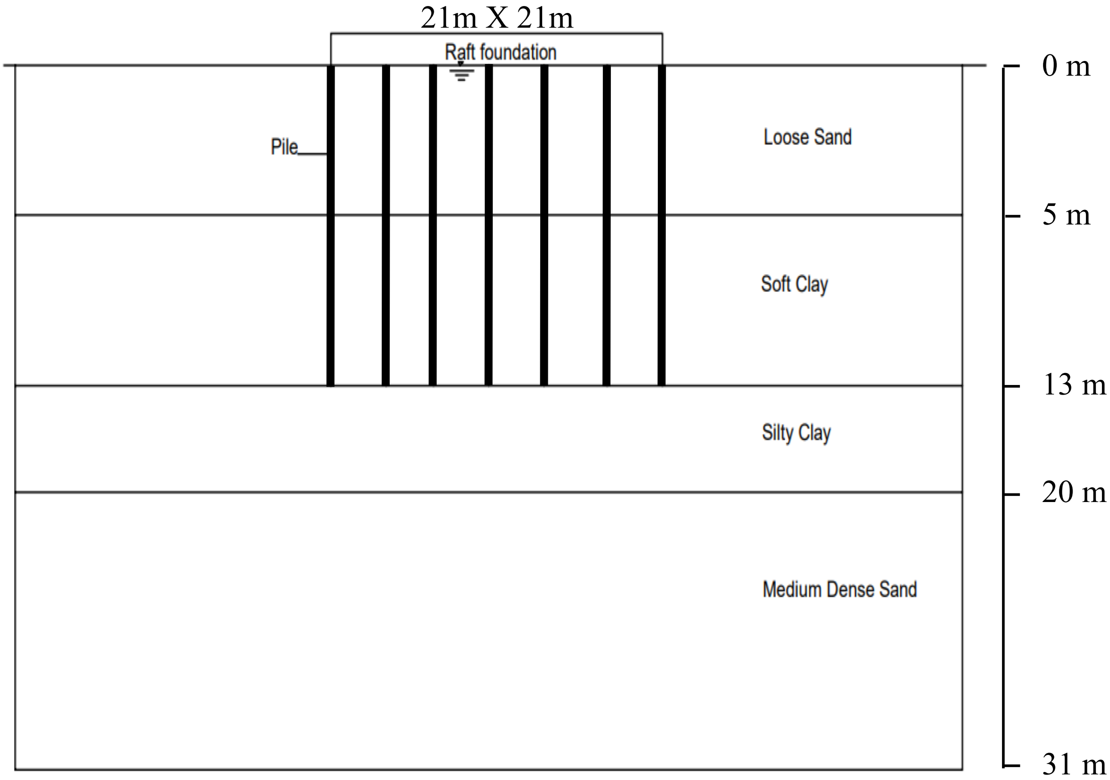

Figure 3.1: Geometry model

The purpose of the Soft Soil model is to simulate the behavior of clays and other soft soils that are highly compressible typically consolidated, or slightly over-consolidated. These soils usually show substantial settlement and deformation under loading. All details are shown in Table 3.2.

Table 3.2: Geometry details

Uniform Load	60	kN/m^2
Raft foundation area	21× 21	m
Raft foundation thickness	0.4	m
Pile thickness	0.5	m
Number of piles	7	-
Pile length	13	m

3.5 Soil Layers

The diagram depicts several distinct soil strata, each with varying properties that influence the behavior and design of the foundation system:

- **Loose Sand:** The topmost layer beneath the raft. Loose sand is relatively weak and can be highly compressible or prone to settlement under heavy loads. It may also have low shear strength, making it necessary for the piled raft system to mitigate potential issues with settlement or instability.
- **Soft Clay:** Below the Loose Sand layer is Soft Clay, which is known for high compressibility and significant settlement potential. Soft clay poses a risk for structures due to its tendency to undergo long-term consolidation under sustained loads. This is another reason why piles are needed to transfer the load to deeper, more stable soil layers.
- **Silty Clay:** This layer is below the Soft Clay and may exhibit better strength and lower compressibility compared to Soft Clay. However, it can still experience considerable settlement and deformation under load. Silty clay has mixed properties between fine clay and granular silt, requiring careful evaluation in foundation design.
- **Medium Dense Sand:** The deepest layer shown in the diagram, Medium Dense Sand is much stronger and has a higher load-bearing capacity compared to the upper layers. It is more compact and provides good resistance against shear deformation. The piles are typically designed to transfer the structural loads to this layer, ensuring a stable foundation with minimal settlement.

This piled raft foundation system is specifically designed to handle the challenges posed by weak, compressible upper soil layers like Loose Sand and Soft Clay. The raft distributes the structural loads over the surface, while the piles penetrate these weaker layers to reach the more competent Medium Dense Sand layer. By doing so, the foundation effectively reduces the risk of excessive settlement and increases the overall stability of the structure. The load distribution between the raft and the piles depends on the stiffness and properties of the soil layers, ensuring that both elements work together to support the structure.

CHAPTER 4
RESULTS ANALYSIS

4.1 Introduction

The investigation used the Mohr-Columb (MC) models to simulate soil behavior. This section is crucial in interpreting the findings from the numerical simulations of the piled raft foundation using PLAXIS 2D. This section discusses the outcomes from the analysis, highlights the significance of key parameters, and draws comparisons to understand the behavior of the piled raft foundation under different loading and soil conditions. The findings are explained with reference to settlement patterns, load distribution, and the effectiveness of the foundation system in reducing settlement and improving load-bearing capacity.

4.2 Total Deformed Mesh

The raft foundation's settlement is a primary area of focus in the deformed mesh. The visualization allows engineers to identify whether the raft settles uniformly or experiences differential settlement. Typically, in piled raft foundations, the raft shows reduced deformation compared to a raft foundation without piles. The piles help mitigate excessive deformation, leading to a more even displacement across the raft. The deformed mesh also illustrates how loads are transferred from the raft to the piles and eventually to the deeper soil layers. Piles embedded in the soft soil layers often exhibit vertical displacements, but the deformation reduces significantly in the stiffer, deeper strata. The mesh helps assess the efficiency of the load transfer mechanism, indicating whether the piles are effectively transferring loads to the more competent soil layers. Each soil layer shows varying degrees of deformation, depending on its strength and compressibility. Soft soils, such as loose sand or soft clay, exhibit larger deformations than denser or stiffer soils, such as medium-dense sand. The deformed mesh highlights these differences, enabling a better understanding of how soil properties influence the overall performance of the foundation. The total deformed mesh analysis in PLAXIS 2D serves as a powerful tool for understanding the deformation behavior of piled raft foundations on soft soils. It provides a visual representation of settlement, load transfer, and soil-pile interaction, offering insights that are critical for foundation design and optimization. In the MC model, the total deformed mesh is $0.2183*10^{-3}$ m which is shown in Figure 4.1.

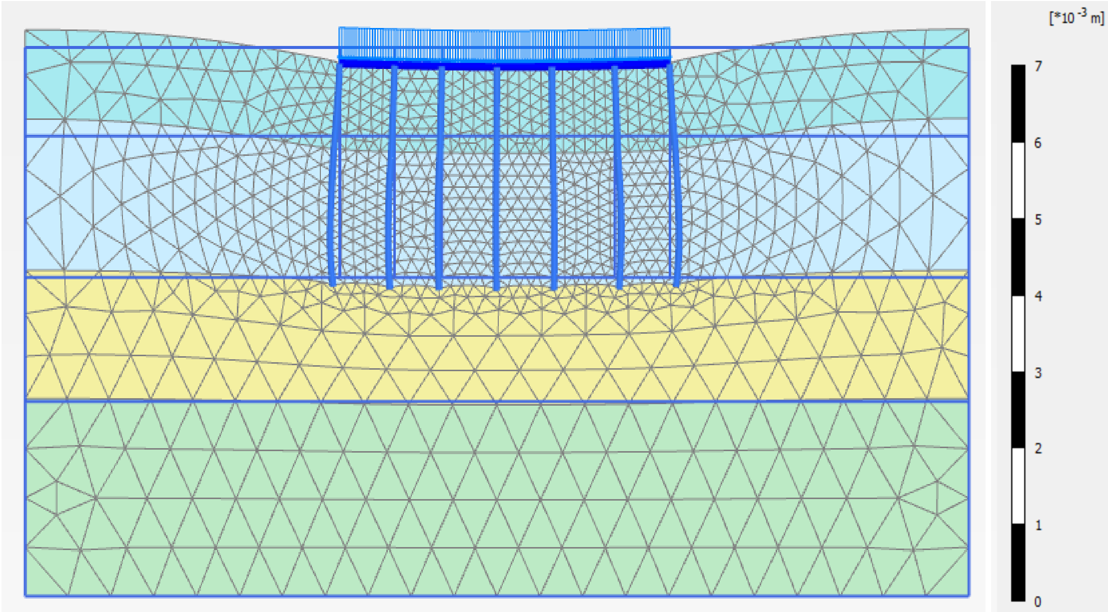

Figure 4.1: Total deformed Mesh

4.3 Total Displacements

The "Total Displacements" analysis focuses on evaluating the magnitude and distribution of displacements throughout the piled raft foundation system and the surrounding soil under applied loading conditions. Understanding the total displacements is critical in assessing the performance and serviceability of the foundation system, particularly when dealing with soft soil layers known for their susceptibility to settlement and deformation. Total displacement refers to the cumulative movement experienced by the soil and foundation system, combining both vertical and horizontal components. The total displacement field provides a comprehensive overview of how the foundation system deforms as a whole, allowing engineers to assess whether the structure remains within acceptable serviceability limits. Excessive displacements can lead to structural damage, serviceability issues, and even failure of the superstructure. Therefore, analyzing total displacements is a crucial step in evaluating the safety and effectiveness of the piled raft foundation. Load-settlement curves are generated to illustrate the relationship between the applied load and the resulting vertical displacement. These curves provide valuable insights into the load-bearing behavior of the piled raft foundation. The analysis typically shows that the piled raft foundation has a higher load-bearing capacity and experiences smaller settlements compared to a conventional raft foundation, particularly in soft soil conditions. In the MC model, the total displacement is $0.2183*10^{-3}$ m which is shown in Figure 4.2.

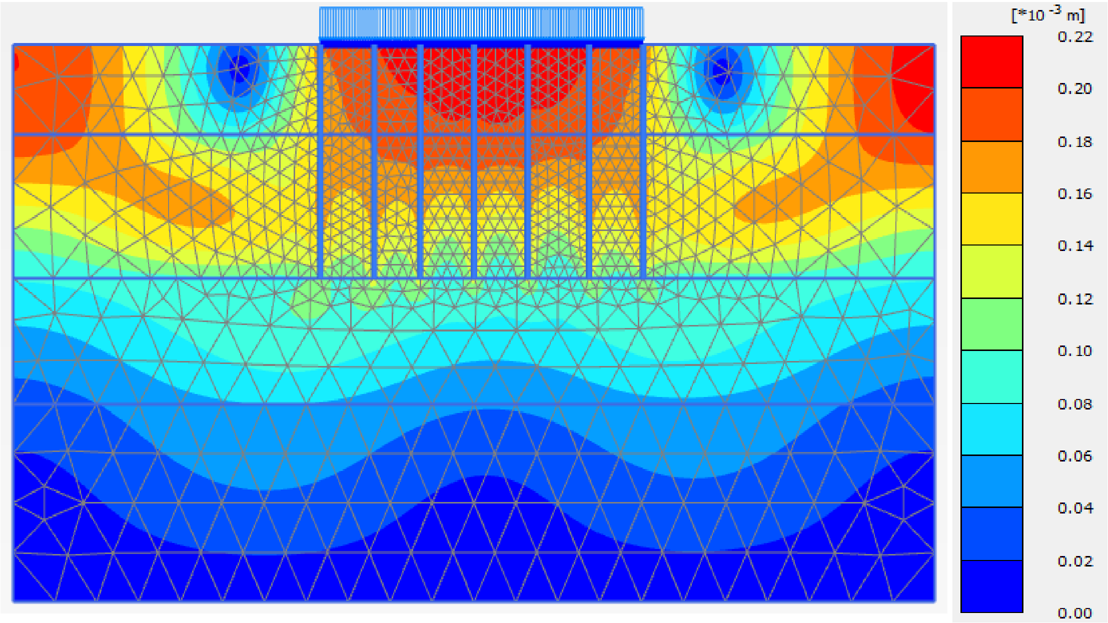

Figure 4.2: Total displacement for 50 kN/m^2

When 60 kN/m^2 load is applied the displacement increases significantly. In the MC model, the total displacement is 0.01706 m which is shown in Figure 4.3.

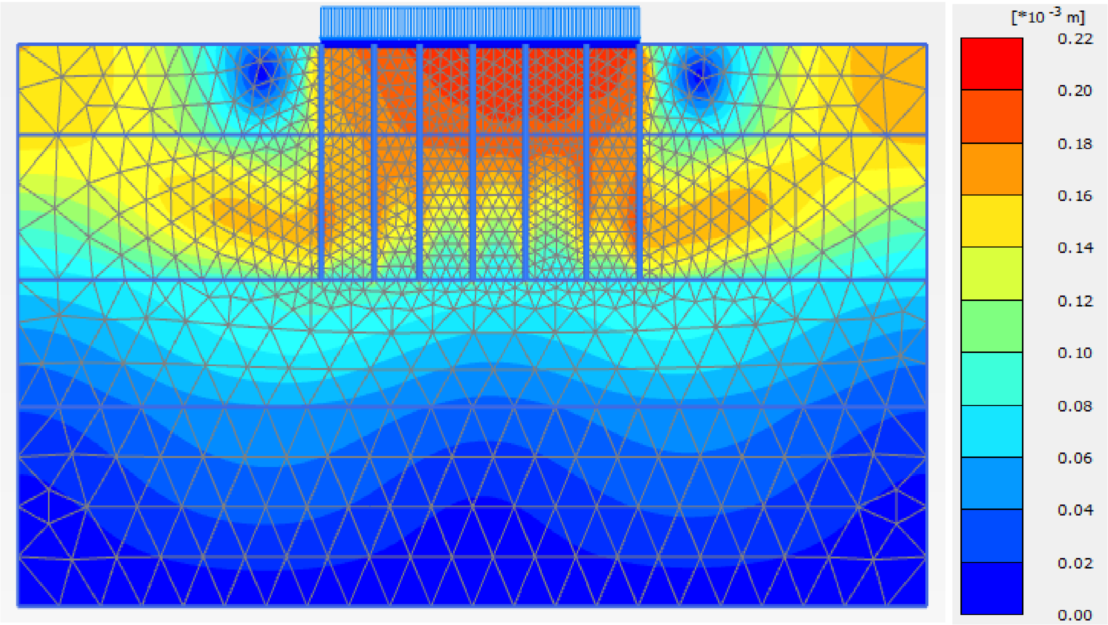

Figure 4.3: Total displacement for 60 kN/m^2

4.4 Horizontal Displacement

Horizontal displacements, though often considered secondary to vertical settlement, are crucial in the overall stability analysis of a piled raft foundation, especially when it is constructed on soft or weak soil layers. In the context of a comprehensive foundation analysis using PLAXIS 2D, understanding the behavior and magnitude of horizontal displacements is essential for ensuring the structural integrity and long-term performance of the foundation system. Analyzing these displacements helps determine the foundation's ability to withstand earthquake-induced forces. When loads are not evenly distributed, such as when there are eccentric loads or uneven soil pressure, horizontal displacements may become a governing factor in the design. The analysis helps ensure the foundation can handle such scenarios. In the MC model, the horizontal displacement is $0.1503*10^{-3}$ m which is shown in Figure 4.4.

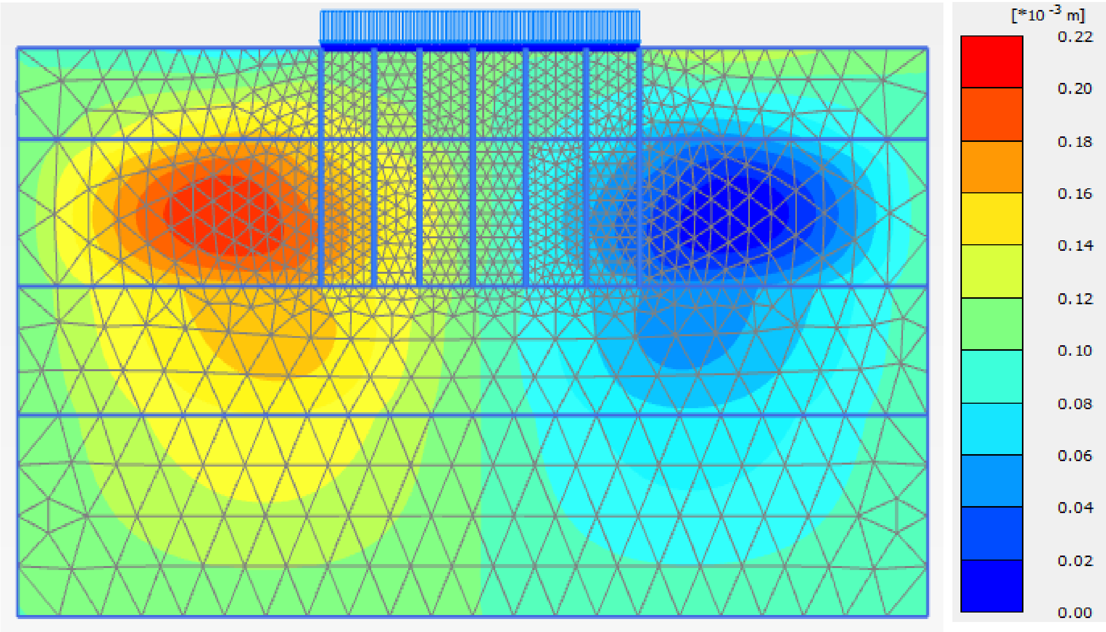

Figure 4.4: Horizontal displacements for 50 kN/m^2

Significant increases in horizontal displacements occur when a load of 60 kN/m^2 is applied. In the MC model, the horizontal displacement is 0.01359 m which is shown in Figure 4.5.

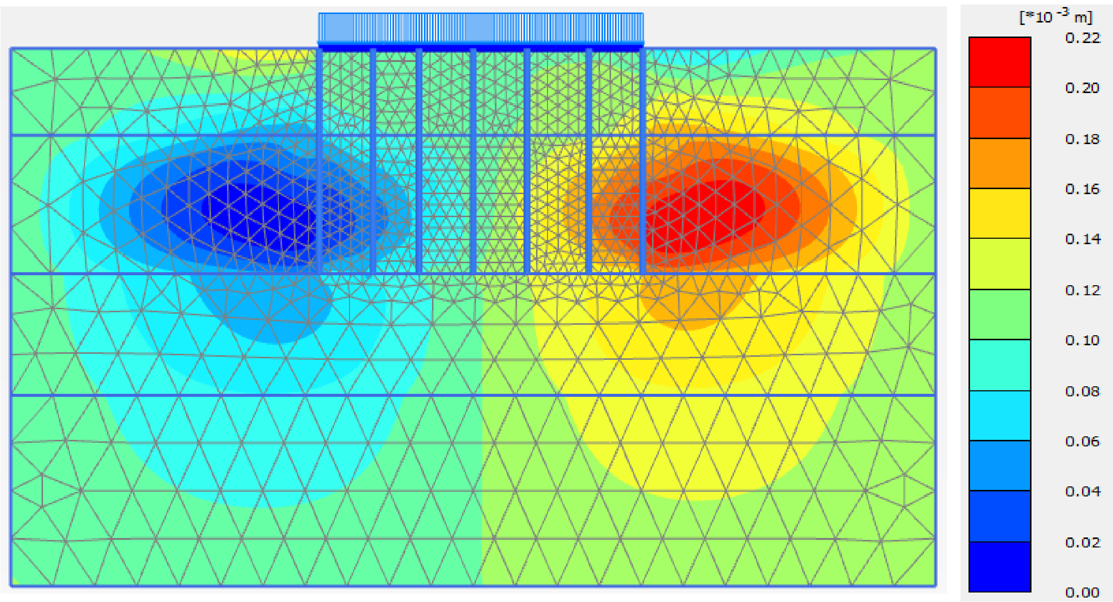

Figure 4.5: Horizontal displacements for 60 kN/m^2

4.5 Vertical Displacement

Vertical displacement, or settlement, is a key parameter in the analysis of piled raft foundations, particularly when these foundations are constructed on soft soil. The distribution and magnitude of vertical displacement provide crucial information about the load-carrying behavior of the foundation system and the potential for differential settlement, which can affect the overall structural integrity. In this section, the analysis of vertical displacement using PLAXIS 2D is presented, detailing the behavior of the soil and foundation elements under applied loads. Excessive vertical displacement can lead to significant settlement, which may cause structural damage, such as cracking in walls, tilting of structures, or even complete structural failure in extreme cases. It is important to ensure that the foundation system can distribute the loads efficiently to prevent such outcomes. The compressibility of the soil layers, especially soft clay or loose sand, directly affects the amount of vertical displacement. Highly compressible soils are prone to greater settlement compared to stiff soils. In the MC model, the vertical displacement is $0.2076*10^{-3}$ m which is shown in Figure 4.6.

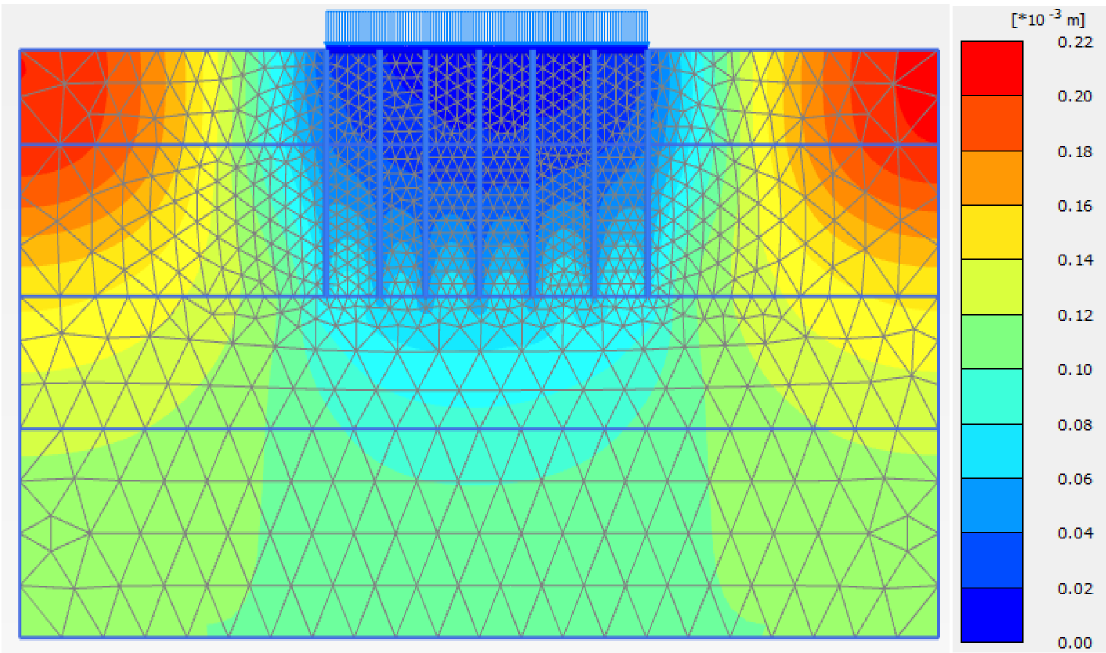

Figure 4.6: Vertical displacement for 50 kN/m^2

When a load of 60 kN/m² is applied to the piled raft foundation, there is a substantial increase in vertical displacement. This increase is critical in evaluating the foundation's performance and the potential for settlement, especially when the foundation is situated on soft soil. Understanding the behavior of vertical displacement under this load is essential for ensuring the safety, serviceability, and longevity of the structure. In the MC model, the vertical displacement is 0.01388 m which is shown in Figure 4.7.

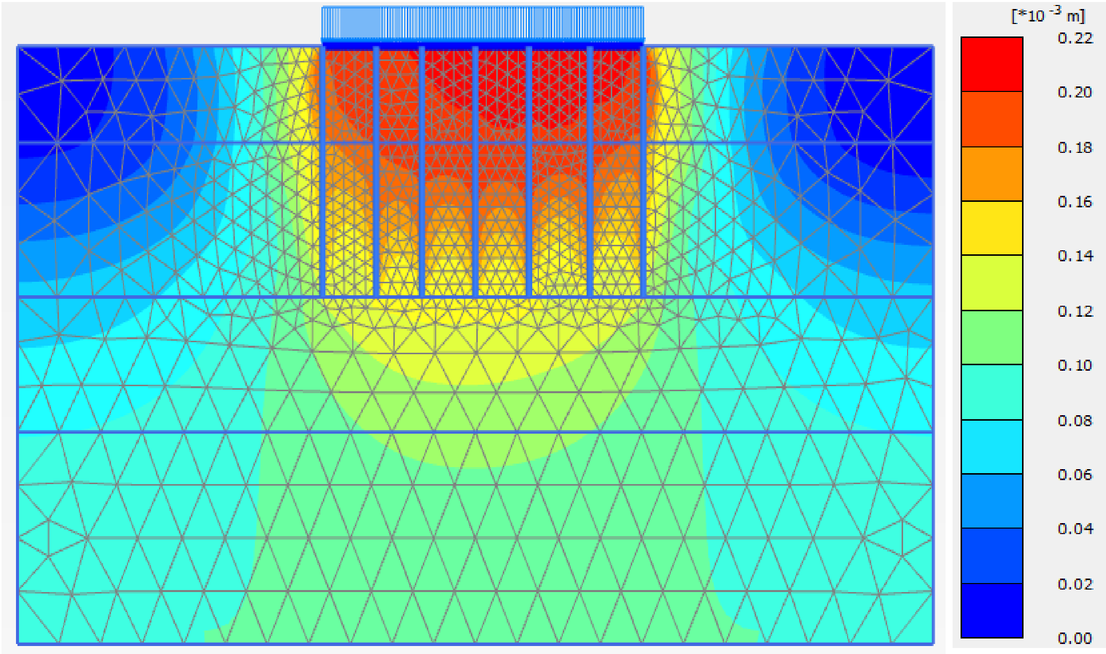

Figure 4.7: Vertical displacement for 60 kN/m^2

4.6 Effective Stresses

Effective stress is a critical concept in geotechnical engineering, especially when analyzing the behavior of piled raft foundations on soft soil. It refers to the portion of the total stress in the soil that is carried by the soil skeleton, as opposed to being borne by the pore water. The effective stress concept is fundamental in understanding how soil compresses, consolidates, and ultimately supports the load from a structure. In the MC model, the effective stress is 0.01388 kN/m^2 which is shown in Figure 4.8.

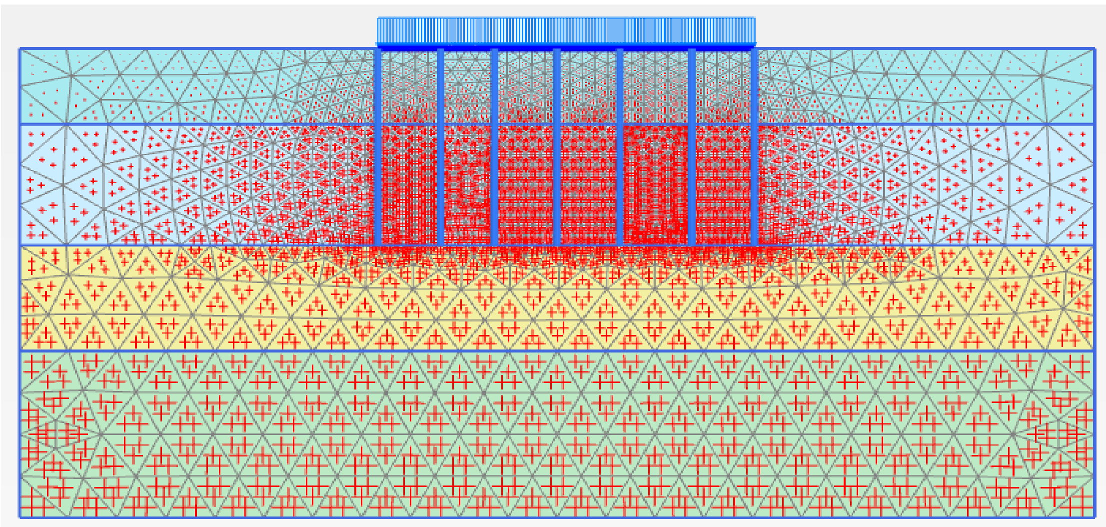

Figure 4.8: Effective stress for 50 kN/m^2

The application of a 60 kN/m² load on the piled raft foundation system leads to a notable and significant increase in effective stress within the underlying soil layers. This phenomenon is crucial to understand as it directly affects the foundation's stability, settlement behavior, and the overall geotechnical performance of the soil-structure interaction. The effective stress is 0.3824 kN/m^2 which is shown in Figure 4.9.

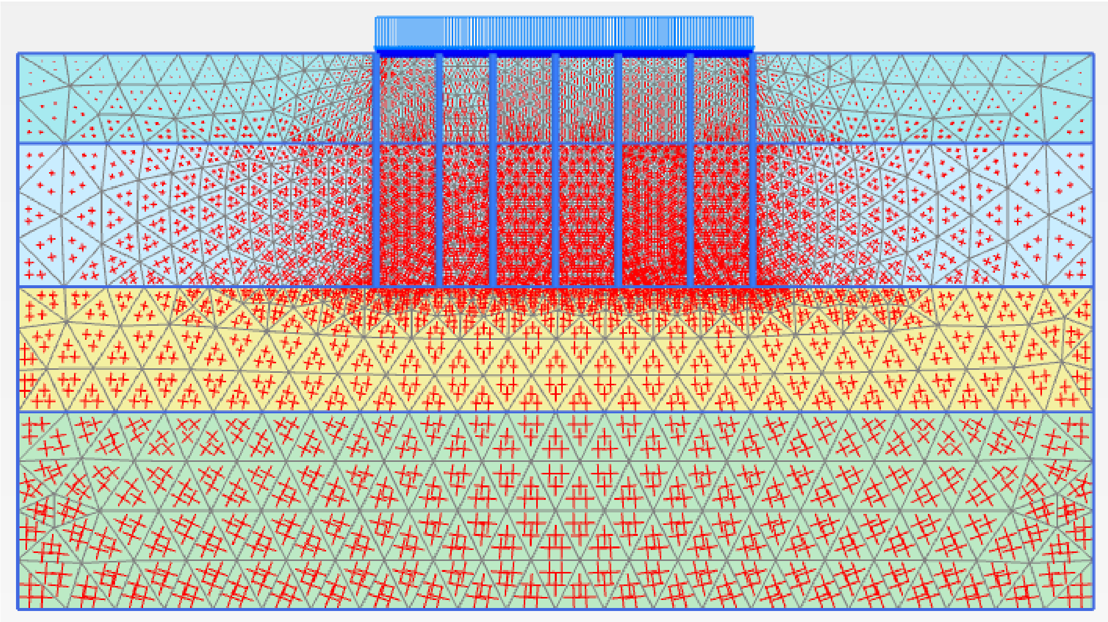

Figure 4.9: Effective stress for 60 kN/m²

4.7 Axial Forces for Pile and Raft Foundation

Axial force refers to a force that is applied along the longitudinal axis of a structural element, such as a column, beam, or pile. It acts in the direction parallel to the axis of the member, either compressing or stretching it. Axial forces are typically generated by loads applied directly on the structure or by reactions transmitted through connected elements. Axial forces in pile foundations are a critical aspect of geotechnical engineering. Proper understanding and analysis of these forces ensure the stability and safety of structures built on piles, especially in challenging soil conditions or environments with dynamic loads. Using tools like PLAXIS 2D, engineers can simulate and evaluate the behavior of axial forces to optimize pile design and ensure effective load transfer to the ground. The axial forces for the pile are -0.7183 kN/m which is shown in Figure 4.10, and the axial force for the raft is -0.8024 kN/m which is shown in Figure 4.11.

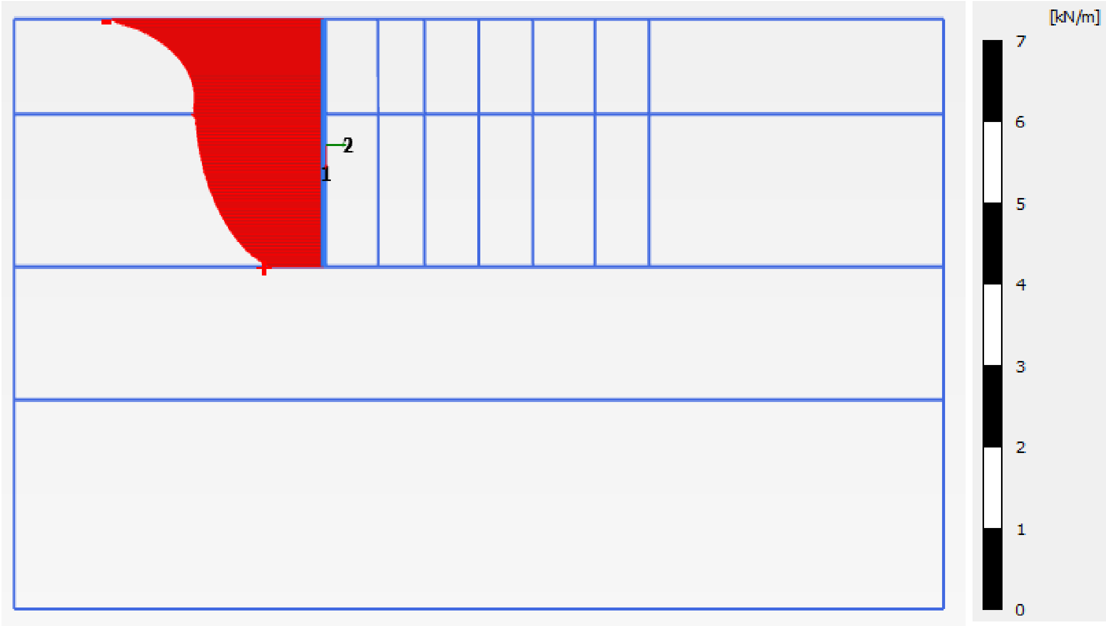

Figure 4.10: Axial force (pile)

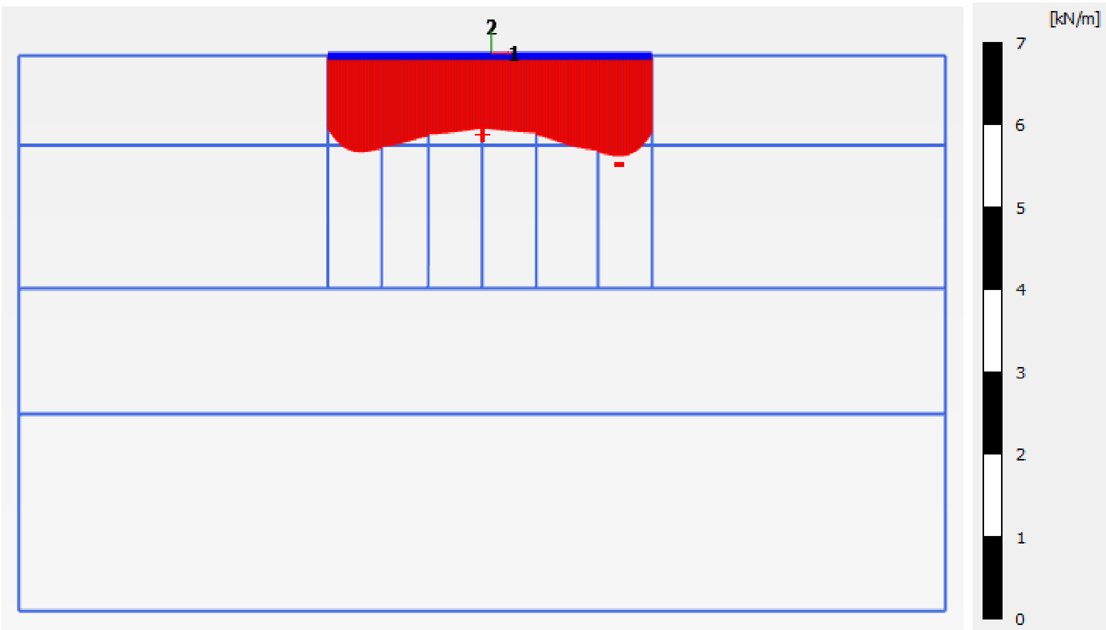

Figure 4.11: Axial force (raft foundation)

4.8 Shear Forces for Pile and Raft Foundation

Shear forces are critical in the design and analysis of pile and raft foundations. They refer to forces that act parallel to the cross-section of a structural element, causing it to slide or deform. In the context of pile and raft foundations, understanding shear forces is essential for ensuring that the foundation can safely support and transfer loads from the structure to the underlying soil. Structures like bridges or tall buildings may be subjected to wind or seismic forces, generating shear forces in the supporting piles. Lateral soil movements, such as from slope instability or soil settlement, can impose shear forces on piles. When loads are applied off-center or at an angle, they can create shear forces in addition to axial forces. Shear forces can cause the pile to bend and experience lateral deflection. The pile must be designed to withstand these forces without experiencing excessive deformation or failure. Shear stress varies along the length of the pile, typically being higher near the top where the lateral loads are applied. The interaction between the pile and the surrounding soil also influences the distribution of shear stress. The shear forces for the pile are 0.6003 kN/m which is shown in Figure 4.12.

In a raft foundation, shear forces occur when lateral loads or uneven vertical loads act on the raft, causing it to experience internal shear stress. These forces are critical in determining the thickness and reinforcement of the raft slab. Variations in loading from the structure, such as heavy machinery or concentrated loads, can create shear forces within the raft. External forces, like wind or seismic activity, can generate shear forces across the raft foundation, particularly at the edges or corners. Differential pressure from the underlying soil can induce shear forces in the raft, especially in areas with varying soil stiffness or settlement patterns. The shear forces for the pile are 3.156 kN/m which is shown in Figure 4.13.

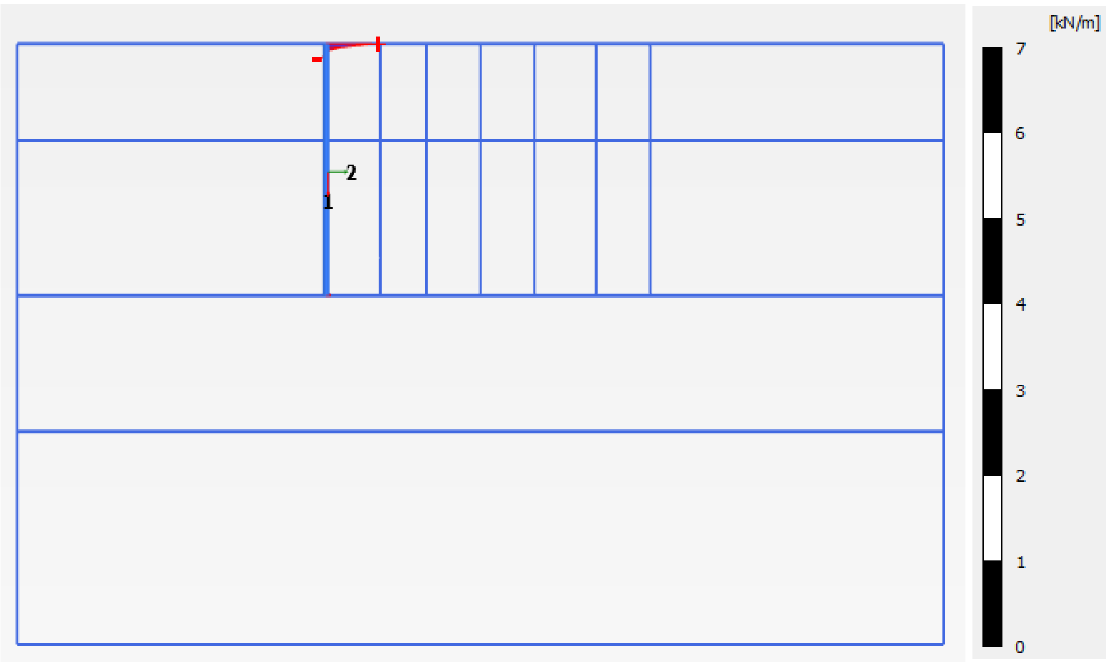

Figure 4.12: Shear force (pile)

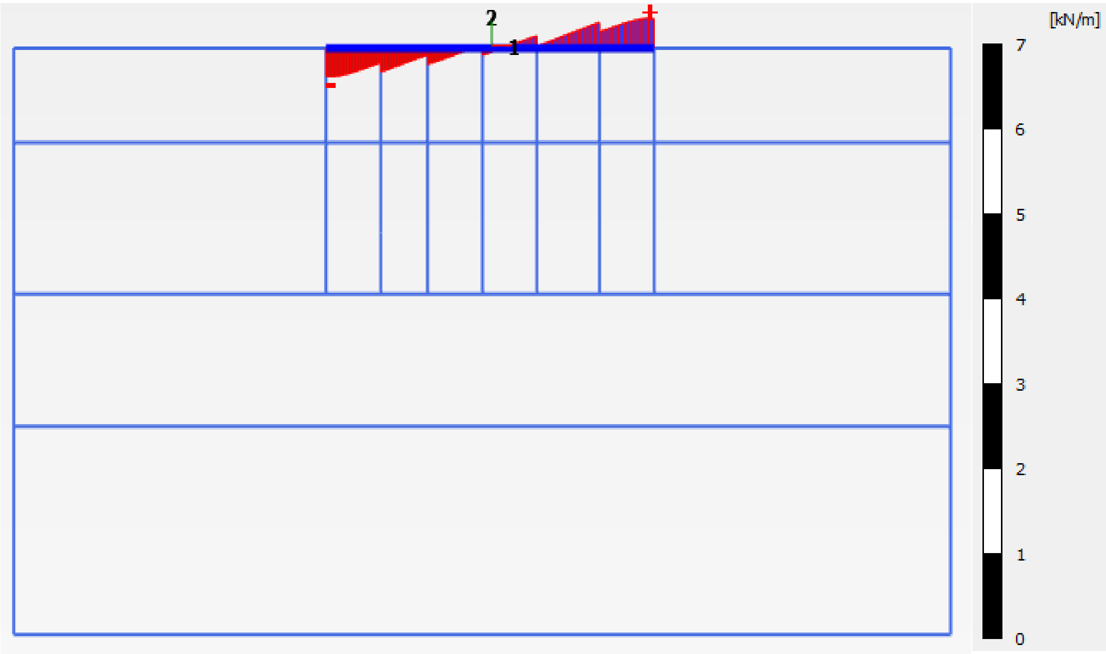

Figure 4.13: Shear force (raft foundation)

4.9 Settlement of raft foundation

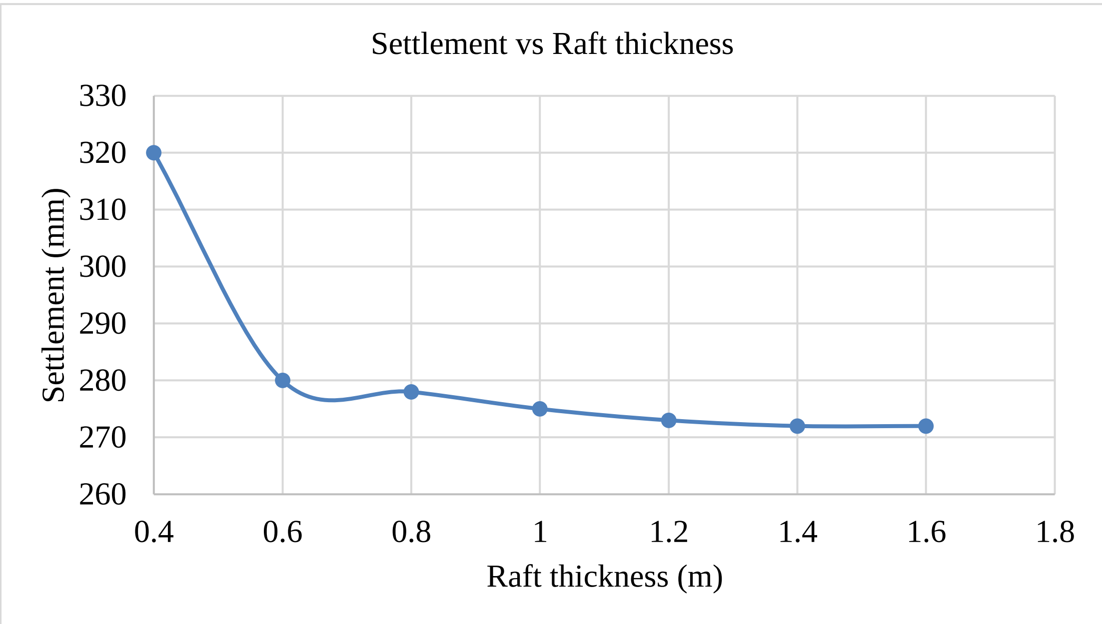

Figure 4.14: Settlement and raft thickness

Raft foundation thickness and the related settlement of the structure are shown in the settlement vs. raft Thickness graph. From a raft thickness of 0.4 m to approximately 0.6 m, there is a sharp decline in settlement from around 320 mm to 280 mm. This indicates that increasing the raft thickness significantly reduces settlement in this range. A thinner raft foundation has less stiffness, which allows more compression and deformation of the soil beneath. As the thickness increases, the raft becomes stiffer, distributing the load more effectively and reducing soil compression, thus lowering settlement. In this range, the additional thickness does not significantly enhance the stiffness of the raft or the load distribution. The soil may have already been compacted optimally by the initial increase in thickness, and the soil behavior becomes less sensitive to further increases.

The most significant reduction in settlement occurs with the initial increase in thickness. Beyond a certain point (around 0.6 to 1.2 m), further increases in thickness yield diminishing returns in reducing settlement. The graph suggests that there may be an optimal range of raft thickness, beyond which increasing the thickness has limited practical benefit in reducing settlement. This is crucial for cost-effective design because thicker rafts are more expensive and may not offer proportional benefits in reducing settlement. Engineers must balance the cost of constructing a thicker raft foundation with the need to minimize settlement to acceptable levels. The graph can be used as a reference for determining an economical and efficient raft thickness based on the required performance criteria.

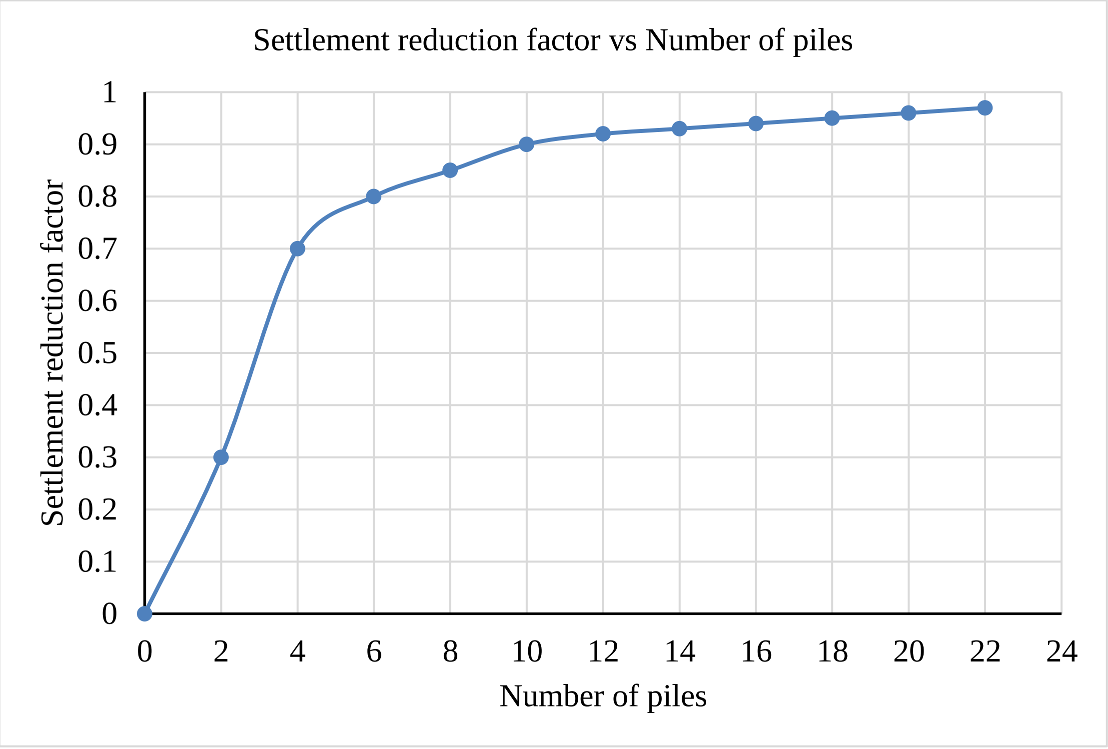

Figure 4.15: Settlement reduction factor and number of piles

The graph titled "Settlement Reduction Factor vs Number of Piles" illustrates how the settlement reduction factor of a foundation system changes as the number of piles supporting the foundation increases. This factor is a measure of the reduction in settlement achieved when piles are added to a foundation system, compared to a raft foundation without piles. It ranges from 0 to 1:

- **0** indicates no reduction in settlement (equivalent to a raft foundation with no piles).
- **1** indicates maximum reduction, meaning the settlement has been significantly minimized.

This is the number of piles incorporated into the foundation system. The graph ranges from 0 (no piles) to 24 piles.

The graph shows that adding a few piles is highly effective in reducing settlement initially. However, as more piles are added, their efficiency in reducing settlement diminishes. There is an optimal range of the number of piles (around 6 to 12) where the settlement reduction factor increases significantly. Beyond this range, the benefits of adding more piles are marginal. Engineers must balance the cost and effort of installing additional piles with the benefits of settlement reduction. The graph suggests that after a certain number of piles, it may not be cost-effective to add more, as the settlement improvement becomes minimal. The graph demonstrates the effectiveness of pile inclusion in reducing settlement in a foundation system. It highlights that while the initial addition of piles is highly beneficial, the advantages decrease as more piles are added. Engineers can use this information to optimize foundation design, ensuring both structural performance and economic efficiency.

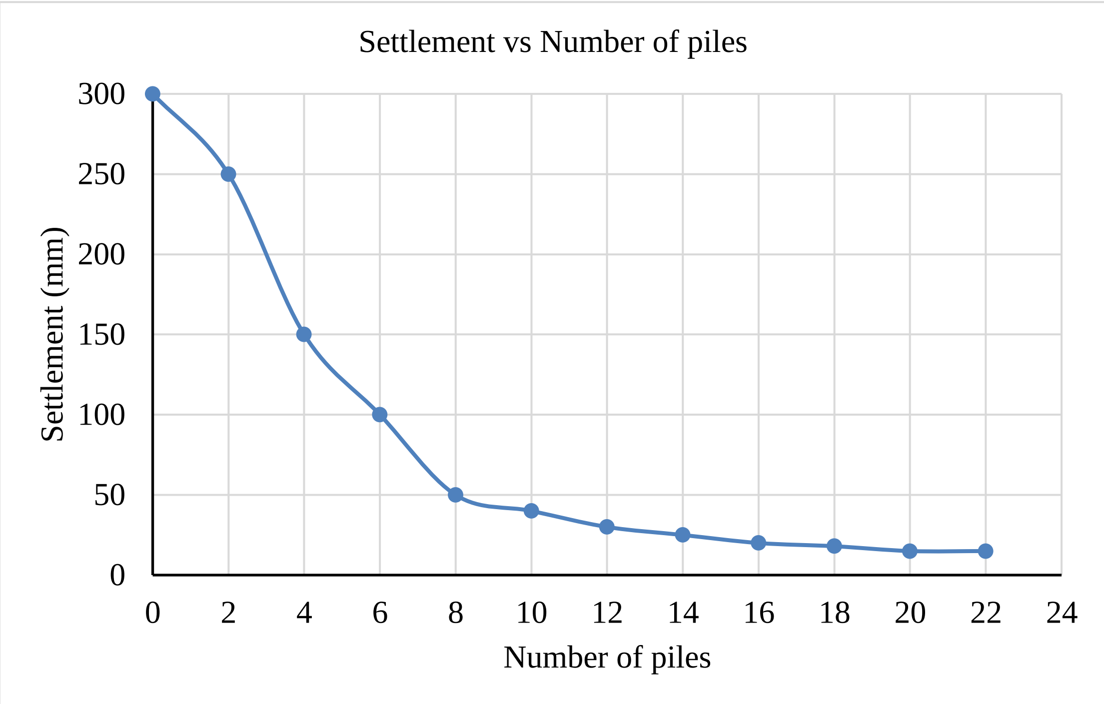

Figure 4.16: Settlement and number of piles

The graph you've shared shows the relationship between "Settlement" (measured in millimeters) and the "Number of piles" used. Here's a breakdown of what the graph represents:

1. **Settlement**: This refers to the downward movement or subsidence of the ground or structure, often due to loading or foundation issues. Higher settlement values indicate more movement or sinking of the structure.

2. **Number of Piles**: This refers to the number of piles (deep foundation elements) used in construction. Piles are driven into the ground to transfer the load to deeper, more stable layers of soil or rock, thereby reducing settlement.

Interpretation

- The graph shows that as the number of piles increases, the settlement of the structure decreases significantly.

- Initially, with a low number of piles, the settlement is very high (close to 300 mm).

- Adding more piles causes a sharp decrease in settlement, with a steep drop up to around 8-10 piles.

- After around 10 piles, the rate of reduction in settlement slows, and the curve begins to level off.

- Beyond about 12 piles, the settlement becomes almost constant and very low, indicating that further increases in pile numbers have little to no additional effect on reducing settlement.

This graph suggests diminishing returns: initially, adding piles greatly reduces settlement, but beyond a certain number, the additional piles contribute minimally to further settlement reduction.

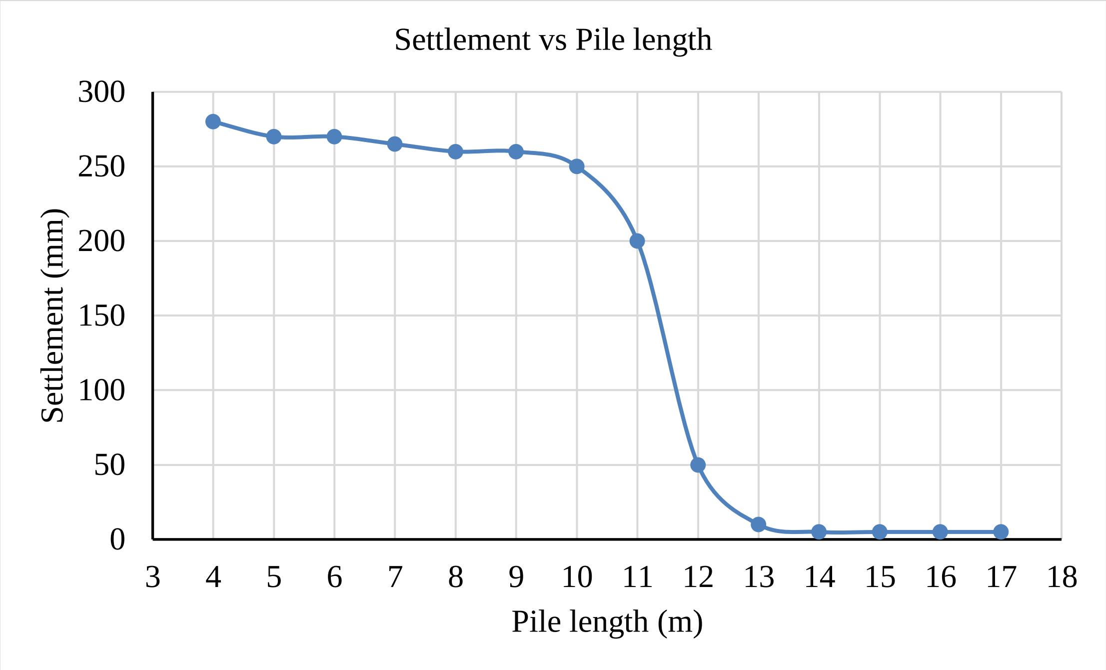

Figure 4.17: Settlement and pile length

The graph illustrates the relationship between "Settlement" (measured in millimeters) and "Pile length" (in meters).

Interpretation

1. **Settlement**: This is the vertical subsidence or downward movement of the structure or ground.
2. **Pile Length**: This indicates the depth to which piles are driven into the ground.
3. For pile lengths between 3 and 10 meters, the settlement remains high, around 250-280 mm, with only minor variations. This indicates that shorter piles do not significantly reduce settlement.
4. At around 11 meters, there is a sharp decrease in settlement. The curve drops steeply, showing that increasing pile length beyond this point substantially reduces settlement.
5. Beyond a pile length of about 13 meters, the settlement reaches very low values and levels off, meaning that further increases in pile length have minimal additional impact on settlement reduction.

The graph demonstrates that settlement reduction becomes effective when the pile length reaches around 11-13 meters, suggesting that the piles need to reach a certain depth to anchor in more stable soil or rock layers. Beyond this optimal depth, further increases in pile length provide diminishing returns in reducing settlement.

For more in-depth observation, 4 parameters are increased by 5% and decreased by 5% Those parameters are: cohesion, young's modulus, poisson's ratio and unit weight. Shown in Table 4.1. By summarizing the results of carefully varying input parameters, the table is a geotechnical or structural engineering simulation element that offers vital information on the stability and deformation behavior of a system.

Table 4.1: Analysis of the results

		Total Displacement	Horizontal Displace	Vertical Displacement	Stress Distribution	Deformed Mesh
Poisson's ratio	decreased by 5%	$0.2174*10^{-3}$	$0.1552*10^{-3}$	$0.2039*10^{-3}$	0.06708	0.000217
	increased by 5%	$0.2188*10^{-3}$	$0.1605*10^{-3}$	$0.2115*10^{-3}$	0.06772	0.000218
soil unit weight	decreased by 5%	$0.2184*10^{-3}$	$0.1580*10^{-3}$	$0.2074*10^{-3}$	0.06742	0.000218
	increased by 5%	$0.2183*10^{-3}$	$0.1579*10^{-3}$	$0.2076*10^{-3}$	0.2598	0.000218
Young's modulus	decreased by 5%	$0.2260*10^{-3}$	$0.1691*10^{-3}$	$0.2157*10^{-3}$	0.0748	0.000226
	increased by 5%	$0.2117*10^{-3}$	$0.1486*10^{-3}$	$0.2007*10^{-3}$	0.06016	0.000211
Cohesion	decreased by 5%	$0.2179*10^{-3}$	$0.1575*10^{-3}$	$0.2072*10^{-3}$	0.06749	0.000217
	increased by 5%	$0.2183*10^{-3}$	$0.1579*10^{-3}$	$0.2076*10^{-3}$	0.06768	0.000218
	units	m	m	m	kN/m^2	m

CHAPTER 5
CONCLUSION

5.1 Introduction

The analysis of piled raft foundations on soft soil using PLAXIS 2D provides a comprehensive understanding of the interaction between foundation components and the underlying soil. The study highlights the effectiveness of utilizing a combined piled raft system to optimize load distribution and minimize settlement in challenging soil conditions. Key findings indicate that the incorporation of piles into a raft foundation significantly enhances the overall performance of the foundation by reducing both total and differential settlements. The simulation results show that increasing the raft thickness and the number of piles initially yields considerable improvements in settlement reduction, but there are diminishing returns as the system approaches a stabilized state.

5.2 Conclusion

The behavior of soft soils under loading conditions is complex and requires careful modeling using appropriate soil constitutive models, such as the Soft Soil and Mohr-Coulomb models employed in this study. These models effectively capture the non-linear, compressible nature of soft soils, providing realistic predictions of soil behavior under various loading scenarios. Additionally, the analysis of parameters such as horizontal and vertical displacements, effective stresses, and axial and shear forces demonstrates the importance of understanding the complex interactions between foundation elements and soil.

- The settlement of a piled raft foundation decreases with the addition of piles, but after reaching a certain number, the settlement remains constant.

- Piled raft foundations effectively reduce settlement and improve load-sharing in soft soil conditions, optimizing material usage and structural stability, making them a cost-effective alternative to conventional pile-only foundations.

the study underscores the importance of careful design and analysis of piled raft foundations in soft soil environments. By optimizing foundation design parameters, engineers can ensure the structural integrity and longevity of buildings and infrastructure on soft, compressible ground.

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