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Numerical Analysis of Load Settlement Behavior in Sand Deposits for Axially Loaded Pile

by

Sunil Kumar Gupta

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APPROVAL PAGE

The undersigned certify that they have read and recommended to the Institute of Engineering for acceptance, a thesis entitled "**Numerical Analysis of Load Settlement Behavior in Sand Deposits for Axially Loaded Pile** " submitted by Mr. Sunil Kumar Gupta (078/MSGtE/018) in partial fulfillment of the requirement for the degree of Master of Science in Geotechnical Engineering.

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ABSTRACT

This study presents a comprehensive numerical analysis of the load settlement behavior in sand deposits surrounding axially loaded piles, aiming to enhance the understanding of pile-soil interaction in geotechnical engineering. The research employs advanced finite element modeling techniques to simulate the intricate mechanical response of piles subjected to axial loads within sand deposit.

The numerical simulations incorporate crucial parameters such as soil-pile interface characteristics, and loading conditions to investigate their impact on the load settlement behavior. The study reveals insights into the mobilization of skin friction and end-bearing resistance within the sand matrix, shedding light on the complex mechanisms governing pile performance in different geological contexts

The findings of this numerical analysis contribute to the advancement of geotechnical engineering practices, offering a deeper understanding of the factors influencing the load settlement behavior of axially loaded piles in sand deposits.

A load-settlement curve was generated, extrapolated, and simulated using Plaxis 3D using various stiffness correlation with SPT value. Papadopoulos (1982) established a correlation that shows a close prediction about 2.1% more with field settlement values. Bowles and Tromienkov's correlations underestimate settlement values by 16 %, while Chaplin and Webb's correlations overestimate settlement by 34% and 29% respectively.

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Sunil Kumar Gupta

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ABBREVIATION AND SYMBOLS

2D	Two Dimensional
3D	Three Dimensional
CIS	Cast-in-situ
DOR	Department of Roads
FEA	Finite Element Analysis
FEM	Finite Element Method
HS	Hardening Soil
IRC	Indian Road Congress
IS	Indian Standard
KN	Kilo Newton
LE	Linear Elastic
MC	Mohr-Coulomb
MM	Millimeter
SPT	Standard Penetration Test

1. INTRODUCTION

Pile load testing is an important component in the design and evaluation of deep foundations, especially in sandy soils. Sandy soils present a particular challenge due to their loose and granular nature, which can significantly affect the bearing capacity and behavior of piles. Therefore, accurate analysis and understanding of the behavior of piles in sandy soils is critical to ensuring the structural stability and safety of various construction projects, such as high-rise buildings, bridges, and offshore structures. Additionally, sandy soil possesses different characteristics at the time of in situ piling as it constantly collapses at a larger depth due to its non-cohesive nature. However, it becomes more crucial if even the silty component is less in quantity.

1.1 Background

Sandy soil is a common soil type in many regions of the world. It is characterized by high permeability, low cohesion, and low shear strength. These characteristics make sandy soils susceptible to settlement, liquefaction, and lateral spreading under load. When designing pile foundations in sandy soils, engineers must carefully consider the unique properties of the soil to ensure that the piles can effectively transfer loads to the underlying strata. In order to evaluate the load-carrying capability, deformation characteristics, and general performance of piles in sandy soil, pile load testing is crucial. It entails applying incremental or maximum loads to a pile while observing how the pile reacts. However, there are two basic tests, namely static or dynamic load tests, to predict the settlement behavior of piles and the capacity assessment of piles in soil strata. Although capacity cannot be assessed directly, settlement may be directly evaluated with the help of field tests. To assess bearing capacity, different geotechnical explorations are employed, such as the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT), which are frequently used for the assessment of stratigraphy. A type of test depends on the geological status of the project locations. A SPT is generally used in loose, granular soils, whereas a CPT is employed in hard strata like boulder-mixed gravel.

When the soil near the ground surface and up to the zone of substantial stress has enough bearing strength to support the weight of the superstructure without giving the superstructure any suffering from settling, shallow foundations are typically used.

However, the weight from the structure must be shifted to deeper, firmer strata where the top soil is either loose, soft, or of a swelling nature.

Through the use of piles, the structural loads can be moved to deeper, firmer strata. Long, thin columns known as piles can be driven, drilled, or cast-in-situ (CIS). Cast-in-situ piles are built of concrete, whereas driven piles can be formed of a range of materials, including concrete, steel, wood, etc. Buildings, bridges, railway tracks, power plants, dams, landslides, etc. are all supported by their foundations. Where liquefaction of the soil is likely, pile foundations are frequently employed to control soil settlement. They could experience lateral, vertical, or a mixture of lateral, vertical, and lateral loads.

The analysis of pile load tests in sandy soil involves the interpretation of field data obtained during the test. Traditionally, empirical methods have been used to estimate the ultimate bearing capacity and load-settlement behavior of piles. However, these methods often have limitations in accurately capturing the complex interactions between the pile, soil, and loading conditions. To overcome these limitations, numerical analysis techniques have emerged as powerful tools for simulating and predicting the behavior of piles in sandy soil.

Numerical analysis techniques, such as the finite element method (FEM) and the finite difference method (FDM), provide a more comprehensive understanding of the soil-pile interaction and offer a means to simulate the behavior of piles under different loading scenarios. These techniques consider various factors, including soil properties, pile geometry, load distribution, and boundary conditions, to predict the response of piles with greater accuracy. By conducting numerical analyses of pile load tests in sandy soil, engineers and researchers can gain insights into the behavior of piles under different soil and loading conditions. This information is invaluable for optimizing pile designs, improving construction techniques, and ensuring the safety and reliability of deep foundation systems in sandy soil.

In Nepal, the use of pile foundations for deep foundations is growing in popularity. In bridge foundations, where deep foundations are needed, bored cast-in-situ piles are frequently used. Bored cast-in-situ piles are currently taking on the role of traditional well foundations. The use of piling foundations for bridges in Nepal has been mandated by a number of issues, including wells that are tilting, sinking, or require lengthy construction. Numerous bridge projects that were planned for well foundations by the Department of Roads (DOR), including the Sunkoshi Bridge (Ghurmi, Udayapur), Sunkoshi Bridge (Khurkot, Sindhuli), Kaligandaki Bridge (Ridi, Gulmi), and Arun Bridge (Leguwaghat, Sankhuwasabha), were delayed due to various issues in well foundations(Shiva Saran Timalsina A, 2022). The CIS bored pile, when carefully planned and built with quality workmanship, proves to be an effective and affordable deep foundation. While inadequate geological analysis and shoddy pile construction techniques result in disasters, as was the case with the Department of Roads-built Babai Bridge (Jabdighat, Bardiya), Kamala Bridge (Kamala-Balan, Dhanusha-Siraha), etc. (Timilsina , 2022)

1.2 Problem Statement

Nepal is situated in a complex geological region that includes complete plain regions in the southern part and, in contrast to the southern part, the highest mountain regions, including Mount Everest, in the northern part. Therefore, the proper choice of foundations for structures invariably depends on the geography of a region. In Nepal, most of the foundations for structures like bridges in hilly areas are shallow, and deep foundations are designed in plain areas. However, this practice is not standard to follow but rather to explore geological status to conform a type of soil below the surface. Mostly, two types of deep foundations are constructed in Nepal, viz., pile and well foundations, but recently, well foundations are rarely found in practice nowadays. Additionally, well foundations are much more suitable than piles due to boring issues, but piles are preferable for many designers in Nepal, and hence pile foundations are crucial to study deeply to understand their characteristics.

Despite significant advances in the design and analysis of deep foundation systems, the behavior of piles in sandy soils remains a complex and difficult issue. Sandy soils, characterized by their loose and granular nature, present a particular challenge to the engineer due to their low cohesion, low shear strength, and susceptibility to settlement and liquefaction. Accurately evaluating the performance of piles in sandy soils is critical to the stability, serviceability, and safety of various structures, such as high-rise buildings, bridges, and offshore installations. In spite of numerous problems in the realm of pile foundations, in this study only the numerical settlement of piles is studied since it causes the number of piles to fail worldwide, including Nepal.

Conventional empirical methods for estimating the bearing capacity and settlement behavior of piles in sandy soils are often limited in their ability to capture the complex interactions between pile, soil, and loading conditions. These limitations can lead to conservative designs, increased costs, and potential safety risks. In addition, empirical methods cannot adequately account for the variability of soil properties and site-specific conditions, resulting in unreliable predictions of pile behavior.

In order to get beyond these restrictions, numerical analysis techniques have become effective resources for modeling and forecasting the behavior of piles in sandy soil. However, more study and investigation are still required to enhance the comprehension and precision of numerical assessments of pile load tests in sandy soil circumstances. The issue is that there aren't enough thorough studies that take into account the pertinent soil properties, simulate realistic loading circumstances, and validate the numerical models using measurements from the field. To better understand the interaction between piles and soil and to effectively forecast the load-settlement behavior of piles under various loading situations, a thorough numerical analysis of pile load experiments in sandy soil is the problem statement for this thesis.

The results of field observations, laboratory testing, and empirical and semi-empirical approaches are used to estimate pile load capacity and settlement under a load. Field pile load testing should subsequently be used to verify these estimated values. Because there are so many unknowns when analyzing pile foundations, it has become common, and often essential, to conduct a predetermined number of full-scale pile load tests at the location of larger projects. The primary objective of these tests is to verify experimentally that the actual response of the pile to load, as indicated by its load displacement relationships, matches the assumed response of the designer and that the actual ultimate load of the pile is equal to or greater than the computed ultimate load that served as the foundation design's basis.

One way to find out how much weight a pile can support is to put it through a static load test. A driven pile or a cast-in-situ pile, a working pile or a test pile, a single pile or a collection of piles can all be used for the experiment. The initial test and the routine test are the two forms of static load tests that are performed on piles (IS Code, 1985). The routine test, which is carried out in at least one test pile in each foundation, helps to verify the safety, while the initial test, which is carried out in cases of significant and/or major projects, helps to verify the ultimate capacities of piles and is relatively small in number. piles' capacities for load. In accordance with IS Code 2911, a test pile is loaded to either its ultimate load or twice the estimated safe load in order to assess the pile's capacity to support loads.

In contrast to Nepal, where initial pile load testing of CIS-drilled piles is rarely or never done to confirm the intended ultimate loads, predicted settlements for bridges are regarded as major projects. As part of the design process to conform the expected properties of bearing strata and pile capacity, an initial load test is required, according to the popular foundation design code among Nepalese designers (Indian Road Congress, 2014). However, the preliminary load tests do not adequately support the pile designs. This means that it is still unclear what the pile's maximum capacity is. To ascertain whether a pile is strong enough to support the service loads, only standard tests on the axial load capacity of piles are carried out during the construction phase.

The most accurate way to assess pile capacity is to conduct full-scale load tests that faithfully capture the true behavior of the pile, which is usually expressed in terms of a load-deformation relationship. Nevertheless, this direct method has some disadvantages, such as the high cost and duration of conducting these experiments. Furthermore, it would not be feasible to conduct pile load testing while the project was still in the planning stages. They usually occur on production piles that cannot be loaded past failure during the building phase. This may demand any other appropriate methods to uncover the ultimate capacity of the pile and settlement that can occur due to loadings for life.

1.3 The objective of the Study

The main aim of this study is to carry out a numerical analysis of pile load tests in sandy soil to establish behavior of soil-pile interaction under different loading circumstances. Specific objectives or this study are:

1. Using the appropriate software, developing a numerical model to replicate pile load testing in sandy soil (such as Plaxis 3D).
2. Analyzing the impact of significant variables on the response of piles in sandy soil to load-settlement, including soil properties, water level effects, mesh dependency, and interface strength variations.
3. Estimating ultimate settlement by applying validated model to a large extends of vertical loads of any intensity.

1.4 Scope and Limitation of Study

The scope of the thesis is to conduct a comprehensive numerical analysis of the load settlement behavior in sand deposits when subjected to axial loading on piles. The study will focus on investigating the various factors influencing the pile response in sandy soil, water level variations, pile arrangement and stiffness of sandy soil. The numerical analysis will be carried out using advanced computational methods, such as finite element analysis, to simulate the complex interactions between the pile and the surrounding soil.

- The research is limited to a borehole data and load settlement data from single source of bridge site
- The numerical model is validated by HS model and using field data available from a bridge site from SASEC project East-West Highway.
- In addition to these, the study is limited to sand deposits only, which may not be accounted for real field scenario.

2. LITERATURE REVIEW

2.1. Introduction to Piles

A pile is a slender, structural component that is buried in the ground to transfer structural loads to soils that are located a considerable distance below the structure's base. Pile foundations are a very good way to transfer the structural loads into the underlying ground, especially in weaker soils. Nowadays, pile design processes are primarily semi-empirical and are derived from data from pile load tests and elastic theories. Some classifications on distinct bases are enunciated below:

- Materials: Steel; timber; concrete (plain, reinforced, or pre-stressed); or a mix of these.
- Methods of transferring load to the soil or rock: Principally in end-bearing, principally in skin friction, or in some combination of the two methods.
- Methods of installation: Impact hammers, vibratory hammers, drilling an open hole; or by use of some special method.
- Impact of installation on soil or rock: displacement piles, like a closed-ended steel pile pipe, which move a lot of soil when they are driven; non-displacement piles, like an H-pile or open-ended steel pile, which move a lot less soil when they are driven; or bored piles, which move almost no soil or rock at all.

However, according to Muni Budhu (2010), pile foundations, sometimes also called deep foundations, can be classified as mentioned below:

- Non-displacement piles only move about 10% as much dirt as their exterior volume suggests they should. Non-displacement piles include steel H-piles and open-ended pipe piles.
- An end bearing is a type of bearing where the majority of the structural load is transferred to the soil at the bottom of the pile.
- A friction pile is one that, over a significant portion of its length, skin frictionally transfers almost all of the structural load to the soil.
- A floating pile is a type of friction pile where the resistance at the end is not taken into account.
- A concrete pile that is cast into a hole made by a spiral auger is called a bored pile or drilled shaft. In most cases, these piles are cylindrical.

- A barrettes pile is a drilled shaft made by using a grab instead of an auger to excavate. Barrette piles' cross sections are either square or rectangular.

Recently, competitions to build high-rise buildings and multi-span bridges with multi-lane facilities have been everywhere, including Nepal. To carry heavy loads, foundations need to be installed deeper, and wells and piles are the two major options. Due to advancements in pile construction technology, well foundations are almost phased off in many places, including Nepal, and piles are taken over instead. Moreover, they are almost bored piles. Bored piles involve making pile holes in the site needing piles by mechanical drilling methods and other methods, then placing a reinforcing cage in the bored hole and pouring concrete inside the holes (Zhu, 2015). If required, a steel cage for reinforcement might be built in the excavation before the concrete is poured in order to keep the bored hole stable; otherwise, it may create a cavity inward anytime due to low cohesions in sandy soils. Other names for bored piles include caissons, drilled shafts, and drilled piers worldwide, including in the United States. Bored piles use a combination of shaft and base resistances to predominantly support axial stresses (Timilsina, 2022). As shown in Figure 1 below, a conceptualized bored pile with minor details

Applications of Pile Foundations as per (Budhu, 2010):

1. Buildings and High-Rise Structures: Pile foundations are commonly used for tall buildings and structures where shallow foundations would not provide adequate support. They ensure stability and prevent excessive settlement.

2. Bridges and Flyovers: Pile foundations are employed for bridge piers and abutments, especially in areas with weak soil near the surface or high-water tables.

3. Offshore Structures: Pile foundations are extensively used in the construction of offshore platforms, jetties, and coastal structures due to their ability to withstand dynamic loads and harsh marine environments.

4. Wharves and Docks: Pile foundations provide stability for marine structures, such as wharves and docks, where the structure needs to be elevated above the water level.

5. Retaining Walls: In some cases, pile foundations are used to support retaining walls to prevent soil erosion and sliding.

6. Transmission Towers: Pile foundations are used to support transmission towers for power lines in various terrains.

7. Infrastructure Projects: Pile foundations are utilized in various infrastructure projects, such as highways, railways, and airports, where weak or expansive soils pose a challenge.

A strong bearing layer is most effectively used when bored piles are present, which can be erected in a range of soil and rock profiles. It is possible to produce extraordinarily high axial resistance with a tiny footprint when the pile toe is built within or on rock. In situations where driving piles could be impractical or impossible because of hard, scour-resistant soil and rock formations beneath scour-able soil, bored piles can prove extremely useful. Due to the flexural strength of a wide diameter column of reinforcing concrete, bored piles are increasingly used for highway bridges in seismically active areas. Additionally, bored piles can serve as the foundation for various structures, including jetties, tall buildings, retaining walls, etc.

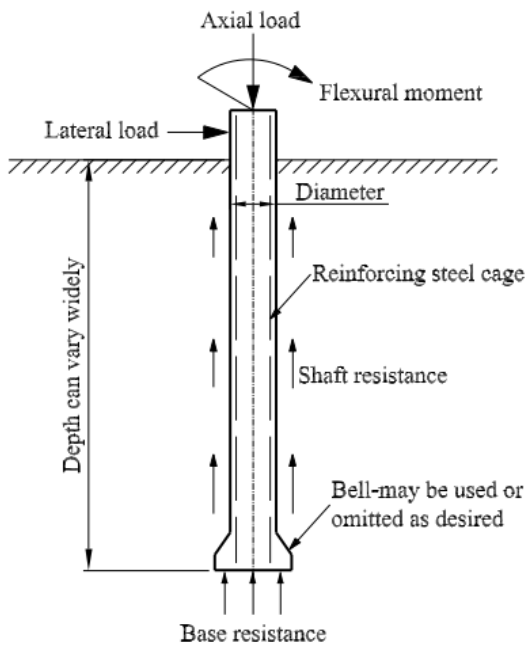

Figure 1: Concept of bored pile subjected to load

2.2. Load Test on Pile

A pile load test is a direct method of determining the ultimate geotechnical capacity of the pile. It is a comparatively fast and reliable way to evaluate the bearing capacity of the pile with respect to the soil in which it is installed. Static load tests measure the response of a pile under an applied load, especially a vertical load, and are the most accurate method for determining pile capacities and settlement behavior. Because it is an in-situ test as opposed to capacities computed by other methods, like static formulas, dynamic formulas, and penetration test data, it is thought to be more reliable, but it takes a long time to start. Since there are so many variables to consider, it is especially difficult to establish a valid standard for determining the ultimate and safe bearing capacity of piles and predicting the behavior of pile groups from test data obtained from individual load tests on single piles (Timilsina, 2022) IS 2911 (Part 4)-1985 is a code that provides a guideline to follow the standard procedure that is typically used in Nepal for load tests on piles. According to IS 2911 (Part 4)-1985, there are two different types of tests initial and routine tests for each type of loading (viz., vertical, lateral, and pullout).

2.2.1. Initial Test

One or more of the following reasons require this test: This is carried out in instances involving significant and/or large-scale projects, and the number of tests could be one or more depending on how many piles are needed.

1. Using the safety factor to arrive at a safe load and determine ultimate load capacities
2. To offer instructions for establishing the acceptance limits for standard tests,
3. To determine the appropriate type of piles to be used and to investigate the impact of pilings on nearby existing structures,
4. To get an idea of suitability of piling system, and
5. To have a check on calculated load by dynamic or static approaches

2.2.2. Routine Test

One or more of the following reasons require this test: Typically, 5% of the total number of piles needed can be used for testing. In a given case, the number of tests may be increased by up to 2 percent based on the type, nature, and condition of the strata.

1. One of the factors used to calculate the pile's safe load;
2. Verifying the safe load and safety margin for the particular functional need of the pile at operating load; and

3. If the test is done, identifying any unusual performance that deviates from the results.

2.2.3. Vertical Load Test (Compression)

This kind of test applies a compression load to the pile top using a hydraulic jack against a suitable load frame or rolled steel joist that can react, and it records the settlement using dial gauges that are positioned appropriately. The test should be carried out by applying a series of vertical downward incremental loads, each of which is about 20 percent of the safe load is on the pile. Settlement must be documented using a minimum of two dial gauges for individual piles and four dial gauges with a sensitivity of 0·01 mm for groups. These gauges should be placed equally around the piles and are typically held by datum bars that are resting on immovable supports at a minimum of 1.5 meters from the edge of the piles. The diameter of D represents the pile stem diameter for circular piles or the diameter of the circumscribing circle for square or non-circular piles.

The safe load on single pile for the initial test should be least of the following:

1. Unless otherwise specified in a particular scenario based on the nature and type of structure, in which case the safe load should correspond to the specified total displacement allowable. Alternatively, two-thirds of the final load at which the total displacement reaches a value of 12 mm.
2. Half of the final load, or 7·5 percent of the bulb diameter in the case of under-reamed piles, at which the total displacement equals 10% of the pile diameter in the case of uniform diameter piles.

Nonetheless, routine testing must be done with a test load that is at least 1.5 times that of the working load, with a maximum settlement of 12 mm for the test loading in place.

The safe load on groups of piles for initial test shall be least of the following:

1. The final load, unless otherwise necessary in a particular situation based on the nature and type of structure, at which the total displacement reaches a value of 25 mm, and
2. Two-thirds of the final load at which the total displacement attains a value of 40 mm.

However routine test shall be carried for a test load of at least one and half times the working load; the maximum settlement not exceeding 25 mm.

2.2.4. Maintained Load Method

This holds true for both preliminary and ongoing examinations. This method involves applying a test load increment and measuring or recording displacement at each loading stage until the pile top displacement rate reaches a value of 0·1 mm within the first 30 minutes, 0·2 mm within the first hour, or 2 hours, whichever comes first. For a full day, the test load must be maintained.

2.3. CRP Method

Although the load and deflection characteristics of this method—which is used for the initial test—are very different from those of the maintained load test, it is generally accepted that this method is more appropriate for determining ultimate bearing capacity than the latter. Consequently, it is not possible to predict the pile's settlement under working load conditions. Regular tests shouldn't use this technique. The typical setup for pile load tests using anchor piles is shown in Figure 2: Typical Setup for Pile Load Tests in Compression Using Anchor Piles (Sharma et al., 1984) while the typical setup for pile load testing using timber cribbing and a weighted box is shown in Figure-2

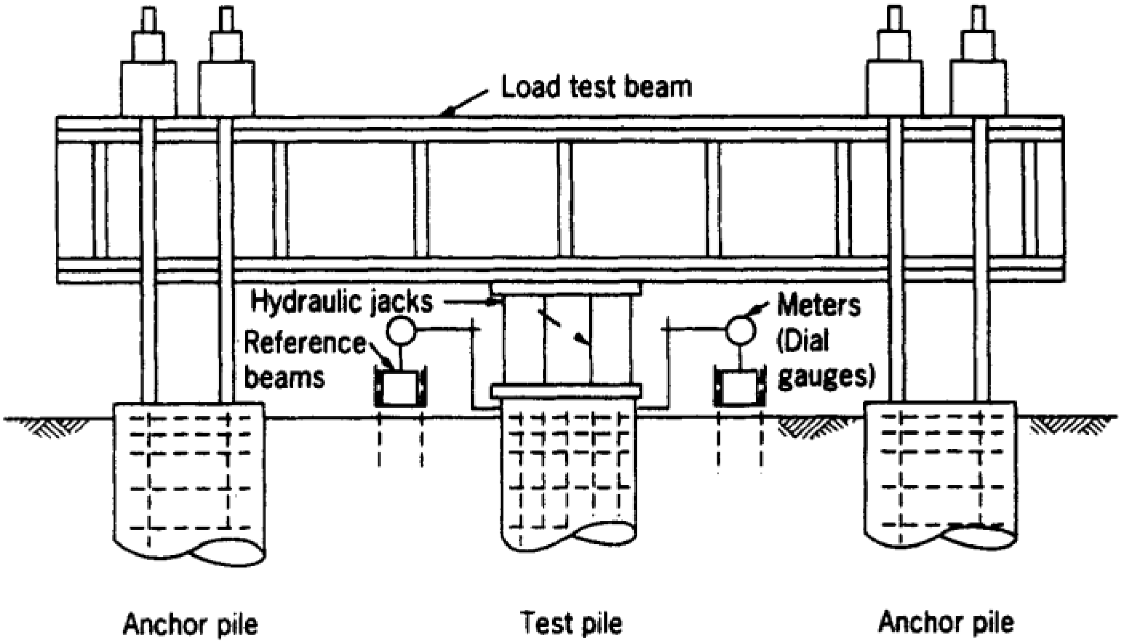

Figure 2: Typical setup for Pile Load Test in Compression using Anchor Piles. (Sharma et al., 1984)

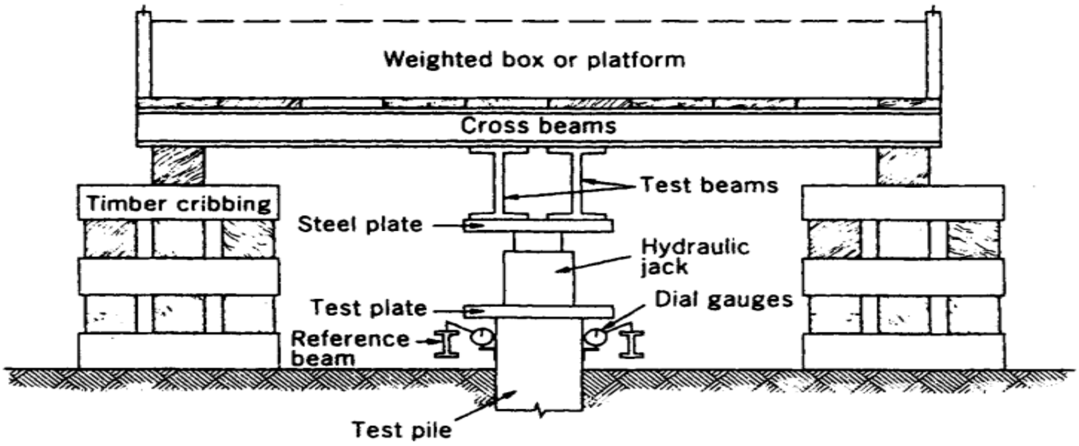

Figure 3: Typical setup for Pile Load Test in compression using Timber Cribbing and the weighted box (ASTM, 1986)

2.4. Load Displacement Relationship

It is possible to derive three distinct load-displacement relationship curve shapes from the results of pile load tests, as illustrated in Figure 4 (Kulhawy & Mayne, 1990a). The peak value of curve A and the asymptote value of curve B in this figure indicate the test pile's maximum resistance. It will be extremely challenging to assess the ultimate resistance or capacity of the tested pile if the load-displacement relationship resembles the shape of curve C, as is frequently the case with bored piles.

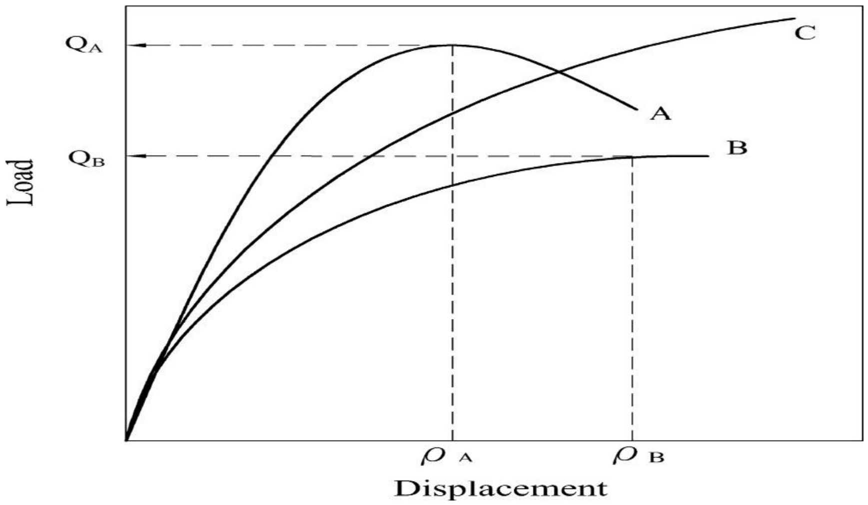

Figure 4: Typical Load-Displacement curves of Pile Load Tests (Hirany A. and Kulhawy F. H. (1988))

2.5. Finite Element Overview

Many studies have been carried out in the last few decades to investigate the properties of sands and clays (Dahal et al., 2018). Numerous academics have studied this topic and made contributions to the field by offering tables, charts, and formulas as useful tools to help with the design of geotechnical structures (Dahal et al., 2019; Paudyal et al., 2023). The parameters that are frequently examined in this context include sand's mechanical properties, such as φ, E, v, and ψ (Degago et al., 2010). Conversely, parameters related to clayey soil depend on various constitutive models, which include φ, c, E, v, and compression properties (λ, κ, etc.) (Nguyen, 2016). Additionally, soil stiffness parameters specifically, E and v have a significant impact on pile settlement, especially in sandy soil. The literature currently in publication offers a broad range of E values that are derived from FHWA-IF-02-034 for sand (Jones, 2020), leading to noteworthy disparities. while ν, like E, is non-linear and dependent on stress The exact determination of v is usually given less importance because its range is generally narrower than that of E (Kulhawy and Mayne, 1990).

FEM has become more and more popular lately for geoengineering project design and analysis. The finite element method (FEM) is a valuable tool in modeling the load-deformation characteristics of piles subjected to axial loading (Johnson et al., 2001). Constitutive models simulate the mechanical behavior of soils in the field of FEM. (Devkota & Dahal, 2022; Puri & Dahal, 2022; Regmi et al., 2021). Constitutive models, however, come in a variety of complexity levels. In the last few years, the finite element method of analysis has been used to tackle a wide range of issues in the field of soil and rock mechanics. The study examines the advancements that are especially relevant to soil engineers and is published in several technical journals across multiple fields. (Radhakrishnan and Reese, 1970) .

Numerical analysis methods, particularly the Finite Element Method (FEM), have revolutionized geotechnical engineering by providing a powerful tool to analyze complex soil-structure interaction problems. FEM is a widely used numerical technique for solving partial differential equations, making it applicable to a wide range of geotechnical problems such as slope stability analysis, foundation design, soil-structure interaction analysis, retaining wall design, tunneling and excavation analysis, pile behavior and design, and underground excavation. The FEM divides the problem domain into smaller elements, allowing for more accurate modeling of the behavior of soil and structures under different loading conditions. Additionally, FEM can consider non-linear material behavior and account for the heterogeneity of soil properties, enhancing the accuracy of geotechnical analyses.

The phrase "Finite-Element (FE) modeling" is widely used in geotechnical engineering to describe a numerical technique in which engineering structures and the soil around them are discretized into particular numerical elements that adhere to particular constitutive laws. However, it is necessary to employ complicated constitutive models for all materials, particularly for characterizing the behavior of the soil, in order to achieve findings that are close to the true behavior of the investigated structures (Popa and Batali, 2010). Due to the intricate and nonlinear behavior of soil, all modeling techniques must be numerical, and geotechnical engineers frequently employ techniques based on FE theory. A numerical FE model of a geotechnical issue must replicate the problem's real-world circumstances. To accurately predict deformations, settlements, and straining actions and give engineers a unique viewpoint for making assessments and decisions, the model must reflect the complex behavior of the soil (Elgamal, 2022).

Large movements or rotations are a common feature of geotechnical engineering problems; examples include man-made pile penetration and earthmoving techniques as well as natural processes like landslides. Although numerical modeling—more specifically, the finite element method (FEM) is now widely used in geotechnical design and analysis, modeling large deformation problems quickly exposes the shortcomings of traditional FEM. Numerous examples of problems where significant deformations are likely can be found in geotechnics. Examples include large structural movements, like installing piled foundations, and dealing with extremely soft geomaterials, like footings on soft ground.

There are two types of numerical techniques: continuum approaches and dis-continuum approaches. In the first, we make the assumption that the unique characteristics of geomaterials can be represented as a continuous material without making a distinction between individual particles, and that constitutive models connecting stresses to strains at different points in the material can be used to handle variations in properties. Dis-continuum approaches use a completely different framework and model the geomaterial as a set of explicit particles that may or may not correspond to a real particle arrangement. The standard finite element method (FEM), the most widely used continuum method in geotechnics, is based on the assumption that strains are a linear function of displacement. This assumption is invalid or inaccurate once deformation or rotation becomes significant with respect to the problem's starting geometry (Augarde et al., 2021).

A literature review of the numerical analysis of pile load tests in sandy soil using Plaxis 3D reveals that this field has been extensively studied over the past few decades. The numerical analysis of pile load tests in sandy soil using Plaxis 3D is a heavily researched topic. Numerical simulations have become increasingly popular due to their ability to accurately predict a variety of factors, such as displacements, shear strength, and stresses associated with piles and other types of foundation systems in different soils. There have been numerous studies conducted to analyze the behavior and performance of piles loaded with different types of sand, including coarse-grained soils such as silty and gravelly sands, fine-grained uniform or non-uniform sands, layered sand deposits consisting of multiple layers with varying gradations, etc. Recent studies have shown that Plaxis 3D can be used for a variety of engineering applications, including settlement and bearing capacity calculations.

Naveen (2011) utilized PLAXIS 3D to simulate field vertical load tests on large-diameter piles embedded in residual soils using a finite element method (FEM) model. In order to assess the settling of the pile in residual soils, the simulation is run for a single pile with a vertical load at the pile top. With an elastic-plastic Mohr Coulomb model, 15 noded triangular elements idealize the soil stratum, and linear-elastic pile behavior is assumed. The interface between the soil and pile models has been modeled using interface elements. Field tests yielded vertical load versus settlement plots on a single pile, which were compared using PLAXIS 3D to the finite element simulation results. There was a fair amount of agreement.

Hamed et al. (2020) performed FEM based on Plaxis 3D software to investigated well numerical analysis can forecast the load capacity of a pipe pile. The results of the numerical analysis and experiment have been understood to be in good agreement. Long and thin elements, such as piles, are used to transfer weight from shallow soil layers with poor bearing capacity to deeper soil or rock layers with less compressibility and higher load capacities. To simulate the load-settlement performance of a single pipe pile, numerical analyses with Plaxis 3D were utilized to simulate the vertical pile under an axial loading case, which is dependent on the finite element approach. The pipe piles were examined using the volume pile model while assessing the results. For various pile kinds, the volume model has been used, and it has been reflected as a round, non-porous substance. The Mohr-Coulomb material model is commonly used to study soil behavior in the analysis of geotechnical engineering problems for the reasons mentioned here. The failure criteria, for example, can be established using simple physical properties such as cohesion and internal friction angle; only a limited number of model parameters are needed; geotechnical engineers are familiar with the required model parameters; and these parameters (c, ϕ, ψ, v, and E) can be readily obtained by conducting simple laboratory experiments on soil samples.

Bak (2013) conducted Cone penetration test to prepare diagrams and load-displacement curves are used as input data for the numerical calculations in order to determine the limits of pile resistances and the mechanical properties of the soil. The software packages AXIS 8 VM and PLAXIS 3D are used to investigate the modeling of single pile behavior. This work aims to assess the accuracy of the load-settlement curve determination using the current interface and sub-grade reaction models in relation to the field load test results. Here, the contemporary material models of the code might be used to directly input the soil characteristics. For this investigation, the hardening soil material model, specifically the undrained A type for granular soils and the undrained B type for cohesive soils, was utilized. The so-called embedded pile elements served as the model's representation of the piles. Pile load test modeling can produce accurate results when combined with the mathematical techniques employed by AXIS and PLAXIS. As may be observed, it is challenging for civil engineers to accurately model static pile load tests. It would be difficult to identify true pile behavior without adequate load-test curves.

Gowthaman and Nasvi (2018) demonstrated that the settlement of the pile foundation is a determining factor in its construction because its primary goal is to prevent the structure it supports from deforming. Researchers have used a variety of methodologies to forecast the actual settlement behavior of pile foundations, including experimental techniques, analytical techniques, and numerical techniques. The associated formulas, however, have not been able to accurately fit and forecast the complete process of settlement load curves. One of the most common methods used in geotechnical and structural analysis today is the numerical simulation of structures. Consolidated

Drained (CD) triaxial tests as well as Standard Penetration Tests (SPTs) have been carried out on the layers. They have established a correlation between Old Alluvium strength parameters (c and ϕ) and SPT values (N) based on the findings of their tests. In this research investigation, the suggested correlations were used to calculate Old Alluvium's c and ϕ values from the SPT values.

Drusa and Vlcek (2014) investigated that the static pile load test is the best method of verifying the bearing capacity of a pile. The in-situ pile load test serves as the basis for calibrating the numerical model. It explained how a variety of soil properties working in contact with a pile and numerical techniques can produce results that agree with tested outcomes. More requirements are placed on the quality and quantity of input data in numerical modeling. The objectives of the numerical modeling are an accurate model of soil-pile interaction and adequate soil parameters. Despite the numerous design strategies, the pile foundation design still needs to be validated by in-situ load tests to make sure the design stage assumptions are correct. Modulus value changes have an impact on the settlement, but only when a large range of values are considered.

Lozovyi and Zahoruiko (2014) analyzed finite element simulation of four pile static test using Plaxis 3D software. The load-displacement curves from the plaxis and the in-situ measurements showed good correlation. Utilizing the computer program Plaxis 3D Foundation to simulate pile foundation testing speeds up the calculation of pile settlement. Load-displacement maps produced by pile foundation testing simulations using the computer application Plaxis 3D Foundation are compared to the outcomes of actual full-scale pile static tests. Soil parameters were determined in the laboratory.

S.G and Nasvi (2017) pointed out that one of the main design criteria for piles is settlement of the pile foundation, and numerical simulation is a common method for predicting the settlement behavior of piles. This study used the finite element (FE) method, which is based on the static pile load test, to examine the settling behavior of a pile group located in silty-sand deposits. This study was based on the three constitutive models for soil linear elastic model, Mohr-Column model, HS model and combined of them as well the elastic modulus (E) and Poisson's ratio (vs) for soil elasticity, the friction angle (φ) and cohesion (c) for soil plasticity, and the dilatancy angle (ψ) were based on laboratory and empirical relations, which are themselves time-consuming to analyze. Pile is modeled as an embedded beam element in plaxis 3D. This finite element analysis of the settling behavior of an axially loaded group pile situated in deep silty-sand deposits made use of the PLAXIS 3D numerical tool. With the help of 15-node wedge elements, the soil was modeled. These elements consist of 8-node quadrilateral faces in the y-direction and 6-node triangular faces in the work planes created using 2D mesh creation. The computing domain's lateral sides were sufficiently separated from the pile to prevent the boundary effect. Ground surface level, pore pressure distribution, and soil stratigraphy were defined using PLAXIS 3D's borehole option. When necessary, geometry lines were employed to divide or isolate different soil types from one another. To distinguish between distinct soil types and distinguishing characteristics, different boreholes were employed. To increase the convergent outcome, fine mesh analysis was performed throughout the numerical examination of the settlement behavior.

The purpose of this literature review is to analyze the numerical analysis of pile load tests in sandy soil using Plaxis 3D. However, there has been limited research examining how it performs on piles in sandy soils specifically. The findings from these studies suggest that Plaxis 3D is capable of providing accurate results for most common cases; however, more research is needed before its use can be widely accepted within geotechnical engineering practice.

From the above literature review, it can be concluded that the static pile load test is the most widely used technique to evaluate the pile ultimate capacity and load settlement assessment in a field application. The traditional method to evaluate pile characteristics in the field is time-consuming, as a pile load test takes time depending on the type of test, such as an initial pile load test or a routine pile load test. For faster and more accurate prediction of pile characteristics in terms of settlement, a modern approach to numerical analysis can be employed, and this number of FEM software is available in the market for educational and professional purposes. In this study, PLAXIS 3D has been utilized for finite element analysis. The accuracy of result prediction through software largely depends on the input parameters required for different constitutive models for soil. There are generally three constitutive models that have been applied in this research, such as the linear elastic (LE), Mohr-Column (MC), and hardening soil (HS) models. The LE model requires fewer input parameters, whereas the HS model requires a greater number of input parameters compared to the other two, but the focus of this research is on the MC model, which requires five input parameters for finite analysis. This research work is concerned with sandy soils only. The engineering properties of the sandy soil are obtained from laboratory works like cohesion and friction angle of soils, and the physical properties of the sandy soil like unit weight, saturated unit weight, and other parameters are taken from literature. Stiffness parameters like the elastic modulus, Poisson's ratio, and angle of dilation are estimated by the correlations provided by the distinct scholars. Many studies suggest that the modulus of elasticity majorly describes the settlement behavior of the pile numerical analysis. In all the literature reviewed above, there is no clear indication of finding the modulus of elasticity; perhaps they could have obtained it from the laboratory, which is time-consuming and costly. So, to reduce time and cost, different correlations between the standard penetration test value and modulus of elasticity have been deployed to embrace the value of E and present a pile load settlement trend. The scope of my research is to find a way to present the settlement behavior of a bored in situ pile, the effect of the water table, and the dilation effect on settlement.

2.6. Site Description

The bridge project is located across the Mahuli River in the Saptari region of Province 2 of East-West Highway at (Ch. 160+700). Along Nepal's East-West Highway, there are a large number of rivers flowing from north to south. The site has a flat topography. The project's location is in Nepal's eastern Terai region. It is the northern extension of the Indo-Gangetic Plain, 100 to 200 m above sea level, with a subtropical climate. It stretches northward from the foot of the Siwalik Hills to the Nepal-India border in the south, varying between 10 and 50 kilometers in width. There are three further Terai regions: the northern (Bhabar), central, and southern zones. In the north, close to the foot of the mountains, the Terai Zone consists of coarse gravels, which gradually become finer in the south. The approximate coordinates of the site are 26.644797° E and 86.816281° N (Engineering, 2021), as shown in Figure 5.

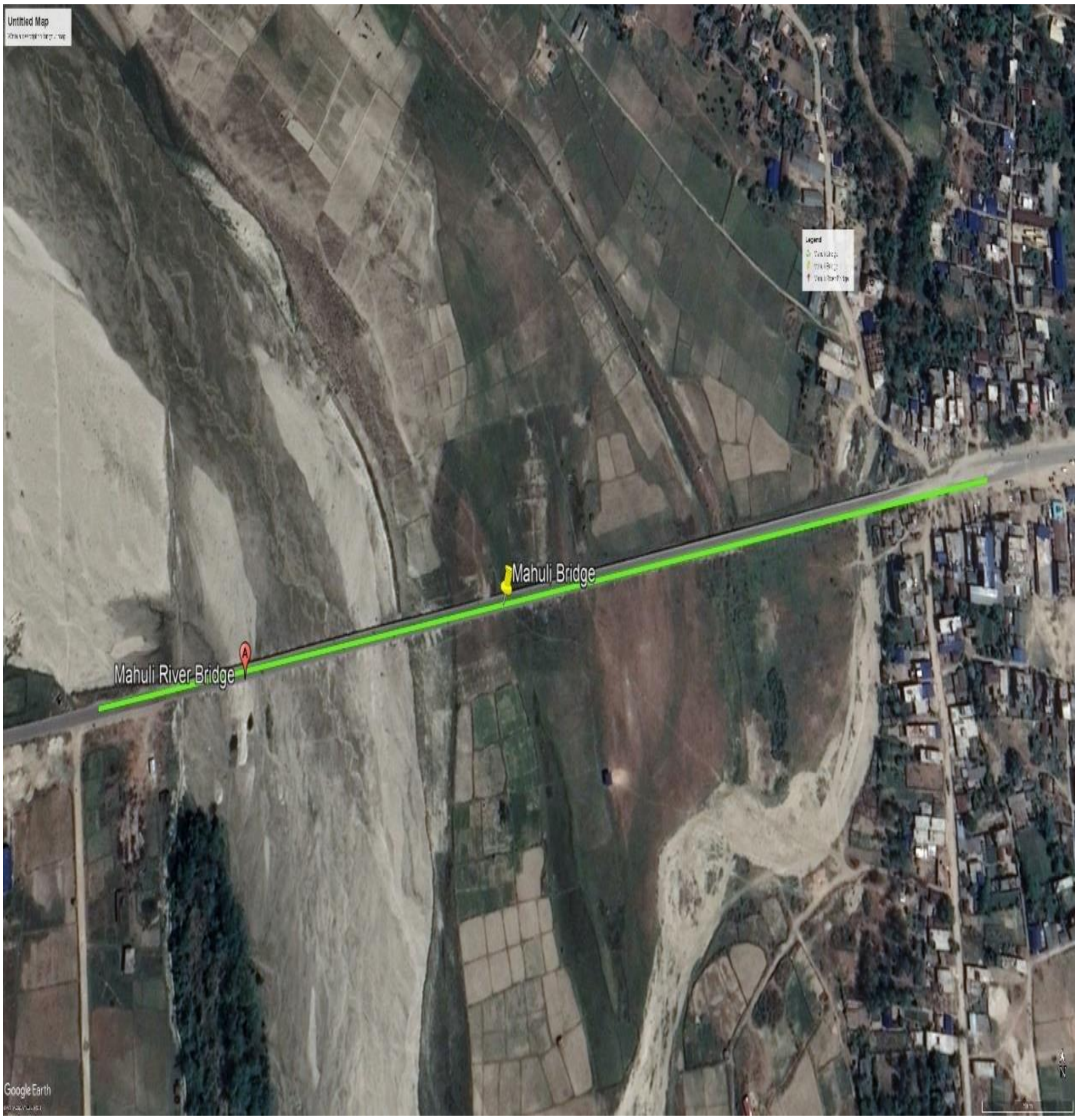

Figure 5: Google map of site location

3. RESEARCH METHODOLOGY

The methodical and theoretical examination of approaches used in a field of study is known as research methodology. It consists of the theoretical examination of the collection of practices and ideas related to a field of study. The methodology is the overarching research strategy that specifies how the study is to be conducted and, among other things, what methods are to be employed. **Figure 6** provides an overview of the research's general methodology. It entails a number of steps, such as reading through the body of literature already in existence, investigating in the field and in the lab to determine geo-mechanical parameters, developing numerical models, and utilizing pile load test data to validate these models. Detailed instructions on each step, along with information on the tools, materials, and techniques used, are provided in the following section. A thesis or dissertation's methodology chapter describes what you did and how you did it, enabling readers to assess the validity and dependability of your research and the topic of your dissertation. It ought to contain:

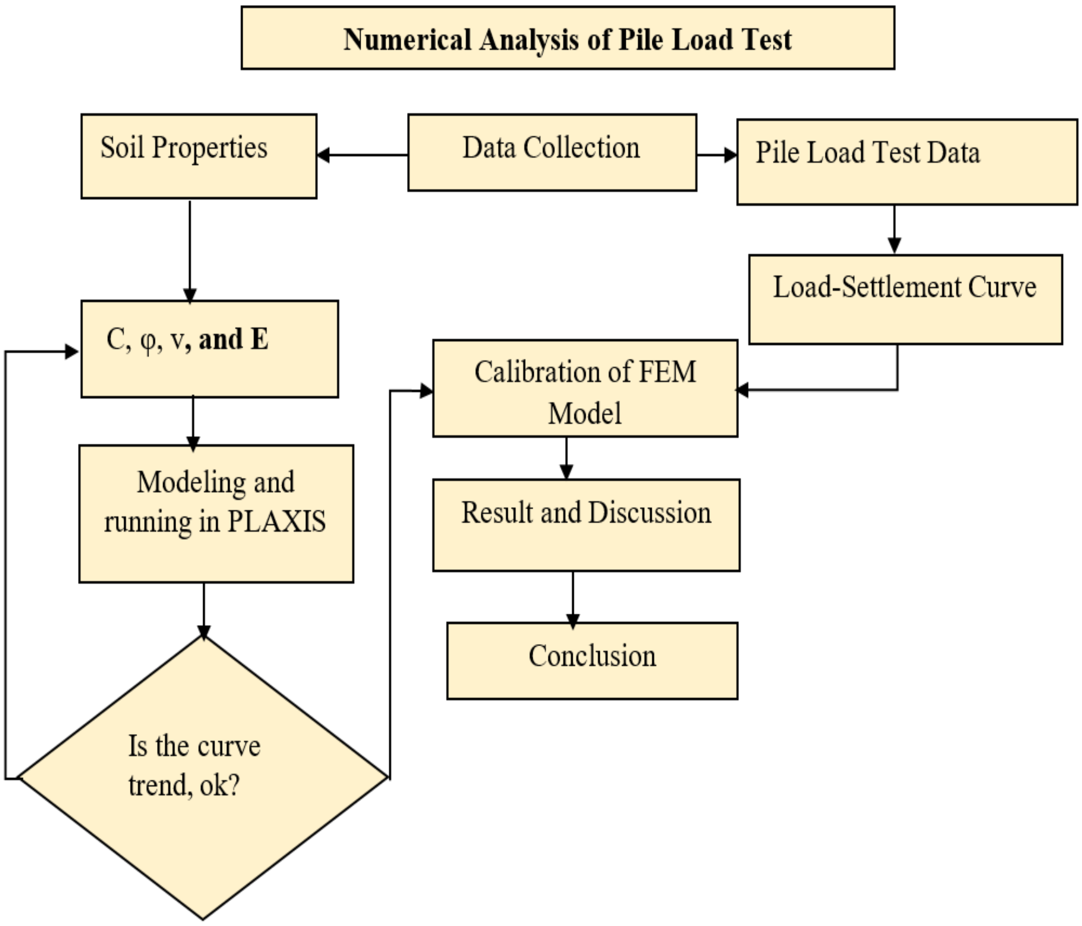

Figure 6: Conceptual framework of the study

3.1. Geometry

The model's dimensions and elemental composition have a significant impact on the processing time for numerical analysis (Garcia and De Albuquerque, 2018). Additionally, depending on the model's dimensions and element count, the computational time needed for numerical analysis varies greatly (Nasasira Derrick, 2020). In light of this, choosing appropriate boundary conditions is an important factor that has been mentioned in a number of academic works. As a result, the bottom edge of the model was fixed in all directions, while side edges were limited in horizontal movement (Liyanapathirana et al., 2005). With its axisymmetric mesh of 10-node triangular elements, the actual model size could be fully calculated. Additionally, as shown in **Figure-7**, the mesh size was changed to improve model analysis from coarse, far from the pile, to very fine, close to the pile. The geotechnical model is built up by defining layers of different soils, each with its own properties such as unit weight, strength parameters, and stiffness. These layers can be continuous or discontinuous, representing different soil strata. The soil stratigraphy has been divided into five different layers with varying thickness.

The dimensions of the model were selected such that there would be less strain close to the boundary. The longer the calculation will take, the larger the geometry of the model. Therefore, the overall dimension of the model was decided to be 20 m in length, 20 m in breadth, and 30 m in depth in order to maximize the geometry of the model and computational time, as shown in Figure -7.

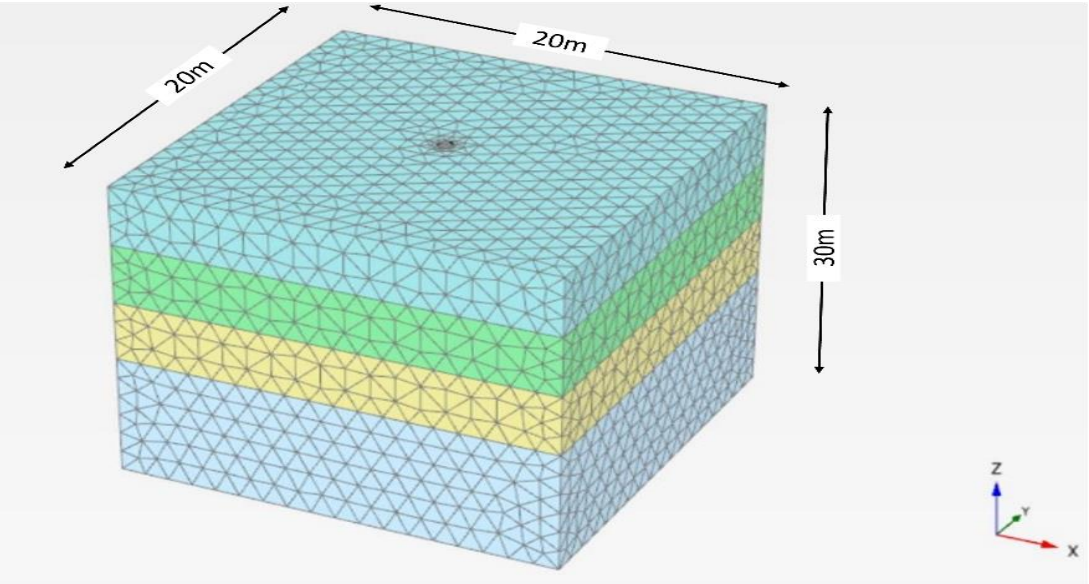

Figure 7: Plaxis 3D model with mesh

Generally speaking, the model's dimensions were assumed to be 20 m x 20 m x 30 m, or 20xB along the x and y axes and (D+9B) along the z axis, where D and B represent the sectional dimensions and D is the pile's diameter(Gupta and Dahal, 2023).

3.2 Boundary Condition

In every piece of Finite Element Method (FEM) software, an iterative analysis is carried out while computing the stresses and strains within the model. This process aims to converge towards a solution that satisfies the imposed boundary conditions. Hence, the selection of appropriate boundary conditions is crucial, ensuring that displacements or strains at the model's boundaries in all three dimensions align with the real on-site conditions. A boundary condition is a location on a structure where, at the beginning of the analysis, either the displacement or the external force is known. Boundary conditions can be defined as the situations in which the structure interacts with its surroundings, either by means of an external force acting upon it or by means of a constraint imposing a displacement. Boundary conditions are the restrictions that limit the flow in a certain space or area. For boundary conditions where closed-form (analytical) solutions are not feasible, numerical methods (finite difference, finite element, and boundary element) offer approximations for solving differential and integral equations. Testing soil samples with loading and boundary conditions similar to what would probably happen in the field is preferable. This is frequently challenging to achieve due to the uncertainty surrounding the loading and boundary conditions in the field. Most "real" structures have complicated boundary conditions, making it impossible to find an analytical or closed-form solution for them. We are forced to use approximations, which we can get by applying numerical techniques like boundary element, finite difference, and finite element (Budhu, 2010). In geotechnical engineering, boundary conditions are important because they can affect the movements or response spectrum at any point within the analyzed domain. The actual behavior of the soil is time-dependent, and the pore pressures are influenced by the rate of loading, the permeability of the soil, and the hydraulic boundary conditions (Oblak, 2010).

To accurately represent the actual conditions on-site, the displacements or strains at locations situated more than a few meters away from the point where the load is applied are set to zero for the purpose of this study. In the context of deformation boundary conditions, the term "normally fixed" indicates that the displacement perpendicular to the plane being analyzed is restricted, while movement in the other orthogonal direction is allowed. Conversely, under the "fully fixed" condition, the displacement of the analyzed plane in all three dimensions is completely restricted to zero. In contrast, the "free" boundary condition implies the opposite of "fully fixed." In essence, the free boundary condition permits displacement of the examined plane in any of its three dimensions.

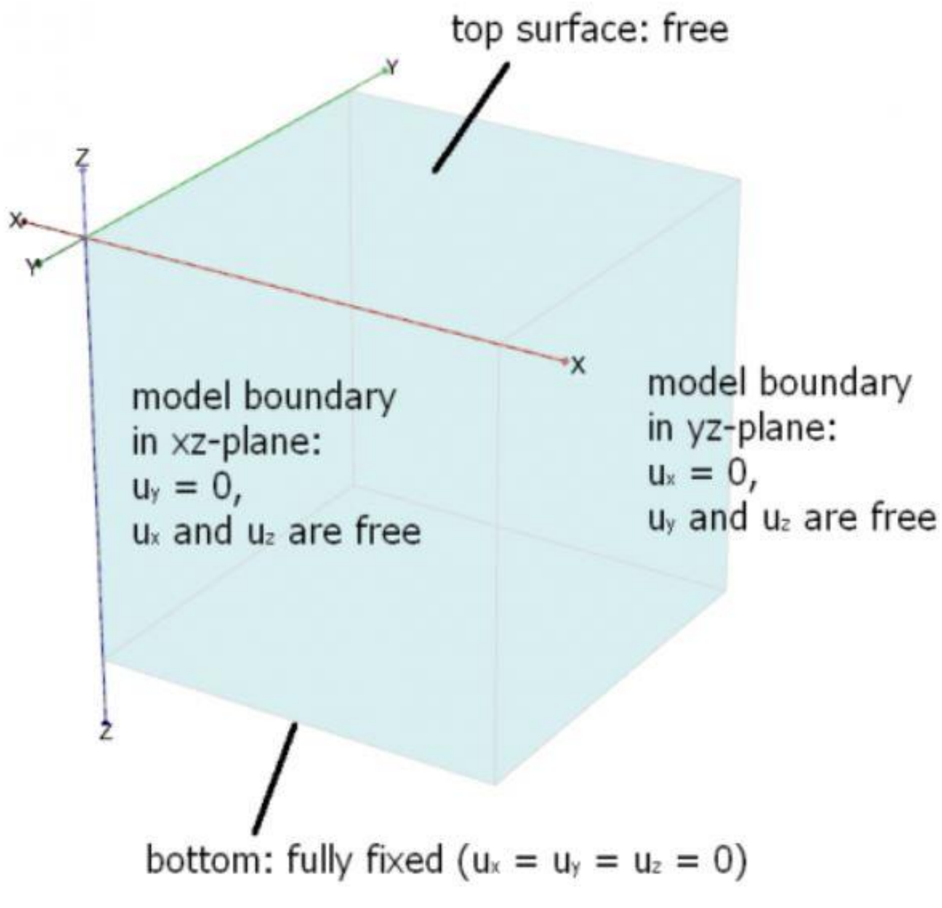

Figure 8: Boundary Conditions

3.2.1 Pile as volume element

The volume pile is made up of volume elements with interface elements modeling the interaction with the surrounding soil. In PLAXIS 3D, there are two ways to generate the volume pile. The first one has to do with utilizing the "Insert Solid" feature, which enables setting up the placement and shape of the volume element **(Figure-8).** The second one is about using the "command box," where the length, radius, and variety of shaft segments determine the volume pile.

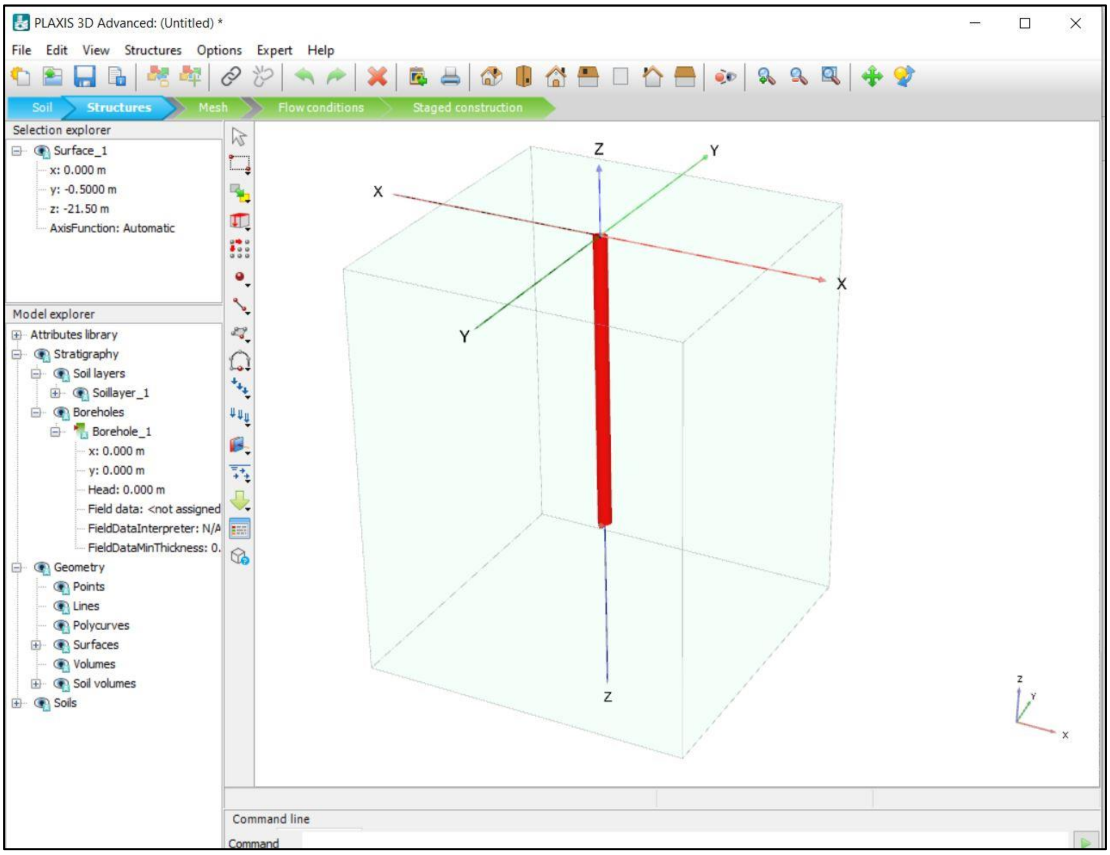

Figure 9: Pile as Volume element

A material data set for soil was used to assign the volume pile's properties, but the properties were concrete instead. Additionally, concrete was used of M35 strength, and its modulus of elasticity can be evaluated as shown in Equation (1)

$$E = 5000 * (fck)0.5 \; in \; Gpa \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Table 1: Material Data Set of the PLAXIS volume pile

Parameter	Name	Value	Unit
Material model	-	Linear -elastic	-
Drainage type	-	Non-porous	-
Unit weight	γ	25	KN/m^3
Young’s modulus	E	30	Gpa

Diameter	D	1	M
Length	L	22.77	M
Poisson's ratio	$\boldsymbol{v}$	0.15	-

3.3 Geo-mechanical Parameters

3.3.1. Data Collection

Data collection includes the collection of secondary data and primary data. Secondary data refers to second-hand data collected from relevant literature, articles, and relevant offices or agencies. Primary data, on the other hand, refers to the collection of data from field visits, material samples, and their laboratory tests.

The soil stratification and groundwater conditions were obtained from the borehole logs of Mahuli Khola Bridge. The soil properties were also taken from the detailed design report of the bridge of the SASEC Highway Improvement Project, Kamala-Kanchanpur Road. For the properties that were not taken from the corresponding reports, various correlations with SPT were used. Routine pile load tests were conducted on the test piles of each bridge foundation for 24 hours. In this study, one pile foundation is considered. A site visit was also conducted during the routine pile load tests.

3.3.2. Soil Exploration and Properties

The Mahuli Khola Bridge in Saptari, Nepal, served as the site of the soil investigation program. Most parameters were determined through laboratory and field investigations, with some relying on correlations (Kulhawy and Mayne, 1990). Standard penetration test (SPT) results are recorded at varying depths and are shown starting with Table-2.

3.3.2.1 Sub-soil properties

The basic soil properties, such as bulk density and saturation density, were taken from the corresponding geotechnical report of Mahuli Khola Bridge, and the engineering properties of the subsoil and soil stratification were derived using various correlations with the SPT (N) values. Bowels and Tromienkov takes hammer efficiency 55 % and 60 % energy respectively. Similarly, other correlation applicable to field value of SPT. Angle of Internal Friction for sand was taken from geotechnical report layer wise. The dilatancy angle determined by the equation (2). The following correlations were used as shown in table:

$\psi = \emptyset'_{peak} - \mathbf{30}$.................................... *(2)*

Where ψ = 0 for $\emptyset'_{peak}$ < 30°

Table 2: Young's Modulus of Elasticity for Sand

S. No	Correlation	Equation
1	Bowels (1997)	E=7000*√(N_{60}*60/55) Kpa
2	Denver (1982)	E=7*(√N) Mpa
3	Webb (1969)	E=5(N+15) in tons/ft2
4	(Modified after AASHTO, 996)	E=700*N (1)60 Kpa
5	Chaplin (1963)	E=(44N)3/4 tsf
6	Papadopoulos (1982)	E=(7.5+.8*N), Mpa
7	Tromienkov (1974)	$E_s = (3.5\ to\ 5.0) * 10^4\ log\ N_{60}$
8	(Kulhawy and Mayne, 1990)	ν'=0.1+0.3*(Φ'-25)/20

3.3.3. Mohr-Coulomb Parameters

The right choice of material model is essential when performing numerical simulations for precise settlement predictions. Soil characteristics and structural loading conditions both have an impact on the material model selection (S.G. and Nasvi, 2017). A linear elastic (LE) model was used to simulate the piles, and an elastoplastic MC model was used to simulate the soil and capture non-linear stress-strain behavior (Yapage and Liyanapathirana, 2019). Measurements required to determine design parameters can be direct or indirect. Indirect measurements require a transformation to obtain an estimate of the actual design parameters (Caltran, 2022). For various depths, the standard depth of penetration values (SPT) was noted and recorded as given in the tables. γ, c, φ, E, and v are the soil properties that were assigned to different layers according to presumptive failure criteria, as shown in Tables. While E and v are computed using various correlations, parameters such as c, φ, and γ are found through laboratory testing.

The nonlinear behavior of the soil under stress and strain was simulated using the fully elastoplastic Mohr-Coulomb model. Furthermore, the significance of initial stress conditions in soil deformation issues cannot be overstated. Appropriate K_0 values should be selected in order to generate initial horizontal soil stresses (Brinkgreve, 2021).

The perfectly plastic, linear-elastic The Mohr-Coulomb soil model takes five input parameters: the dilatancy angle (ψ), the internal friction angle (φ) and cohesion (c) for soil plasticity, and the elastic modulus (E) and Poisson's ratio (v) for soil elasticity (Katuwal et al., 2015). An approximate representation of the first-order behavior of rock or soil can be found in the Mohr-Coulomb model. It is advised that the problem in question be first analyzed using this model. For every layer, a constant average stiffness is assumed. This constant stiffness allows for relatively quick calculations and the acquisition of an initial impression of the deformations. For the majority of soil deformation issues, initial conditions are just as important as the model parameters previously mentioned. Selecting suitable K_0 values is necessary to generate the initial horizontal soil stresses (Brinkgreve, 2021).

Table 3: Properties of surrounding soil in PLAXIS 3D for Layer 1

Parameter	Name	Value	Unit
Material Type	Type	Sand	-
Drainage Type	Type	Drained	-
Depth of Layer (m)	Depth	3	m
Unit Weight	γ_{unsat}	18	kN/m^3
	γ_{sat}	19.34	
Young's Modulus	Bowels (1997)	24220	Mpa
	Tromienkov (1974)	42114	
	Webb (1969)	16620	
	Chaplin (1963)	14620	
	Papadopoulos (1982)	20300	

	Kulhawy and Mayne (1990)	11000	
Poisson's ratio	ν'	0.28	-
cohesion	c'	0	kN/m^2
Friction Angle	Φ'	30	Degree
Strength Reduction Factor of interface	R_{inter}	0.5-0.8	

Table 4: Properties of surrounding soil in PLAXIS 3D for Layer 2

Parameter	Name	Value	Unit
Material Type	Type	Sand	-
Drainage Type	Type	Drained	-
Depth of Layer (m)	Depth	9	M
Unit Weight	γ_{unsat}	18	kN/m^3
	γ_{sat}	18.08	
Young's Modulus	Bowels (1997)	33541	Mpa
	Tromienkov (1974)	48121	
	Webb (1969)	20824	
	Chaplin (1963)	19740	
	Papadopoulos (1982)	26565	
	Kulhawy and Mayne (1990)	21166	
Poisson's ratio	ν'	0.27	-
cohesion	c'	0	kN/m^2
Friction Angle	Φ'	30	Degree

Strength Reduction Factor of interface	R_{inter}	0.5-0.8	

Table 5: Properties of surrounding soil in PLAXIS 3D for Layer 3

Parameter	Name	Value	Unit
Material Type	Type	Sand	-
Drainage Type	Type	Drained	-
Depth of Layer (m)	Depth	7.5	M
Unit Weight	γ_{unsat}	18	kN/m^3
	γ_{sat}	19.56	
Young's Modulus	Bowels (1997)	40927	Mpa
	Tromienkov (1974)	53627	
	Webb (1969)	26383	
	Chaplin (1963)	25890	
	Papadopoulos (1982)	34860	
	Kulhawy and Mayne (1990)	31400	
Poisson's ratio	ν'	0.29	-
cohesion	c'	0	kN/m^2
Friction Angle	Φ'	31	Degree
Strength Reduction Factor of interface	R_{inter}	0.5-0.8	

Table 6: Properties of surrounding soil in PLAXIS 3D for Layer 4

Parameter	Name	Value	Unit

Material Type	Type	Sand	-
Drainage Type	Type	Drained	-
Depth of Layer (m)	Depth	4.5	M
Unit Weight	γ_{unsat}	18	kN/m^3
	γ_{sat}	19.80	
Young's Modulus	Bowels (1997)	34756	Mpa
	Tromienkov (1974)	48647	
	Webb (1969)	21270	
	Chaplin (1963)	20260	
	Papadopoulos (1982)	27230	
	Kulhawy and Mayne (1990)	22666	
Poisson's ratio	ν'	0.28	-
cohesion	c'	0	kN/m^2
Friction Angle	Φ'	32	Degree
Strength Reduction Factor of interface	R_{inter}	0.5-0.8	

Table 7: Properties of surrounding soil in PLAXIS 3D for Layer 5

Parameter	Name	Value	Unit
Material Type	Type	Sand	-
Drainage Type	Type	Drained	-
Depth of Layer (m)	Depth	6	m
	γ_{unsat}	18	

Unit Weight	γ_{sat}	19.60	kN/m^3
Young's Modulus	Bowels (1997)	47940	Mpa
	Tromienkov (1974)	58523	
	Webb (1969)	33247	
	Chaplin (1963)	32885	
	Papadopoulos (1982)	45100	
	Kulhawy and Mayne (1990)	43000	
Poisson's ratio	ν'	0.30	-
cohesion	c'	0	kN/m^2
Friction Angle	Φ'	32	degree
Strength Reduction Factor of interface	R_{inter}	0.5-0.8	

3.3.4. Hardening Soil Parameters

Several constitutive models, such as the hardening soil model, the HS small strain model, the cam clay model, the modified cam clay model, and some other models for rocky strata, are used to accurately represent soil behavior. The Hardening Soil model is an advanced model for simulating soil behavior in granular and soft soil. The limiting states of stress in the MC model are explained by the friction angle, cohesion, c, and dilatancy angle. However, a much more accurate description of soil stiffness is possible when three distinct input stiffnesses are used: the oedometer loading stiffness, E_{oed}; the triaxial loading stiffness, E_{50}; and the triaxial unloading stiffness, E_{ur}. For different types of soil, the average values of E_{ur}, E_{50}, and E_{oed} can be used to account for the effects of each layer. Nonetheless, very soft and very stiff soils typically produce different E_{oed}/E_{50} ratios.

Unlike the Mohr-Coulomb model, the Hardening Soil model considers the stress-dependency of stiffness moduli. This suggests that all stiffness increases in response to pressure. Consequently, each of the three input stiffnesses has a relationship to a reference stress, which is typically 100 kN/m^2 (100 kPa, 1 bar) (Schanz et al., 1999). In addition to the aforementioned model parameters, the early soil conditions, such as pre-consolidation, are crucial to the majority of soil deformation issues. These can be considered when creating the initial stress for choosing the coefficient of earth pressure at rest (K_0) (Brinkgreve, 2008).

Table 8: Input Parameters for HS

Layer	Depth (m)	Average (N)	E_{50}^{ref}	E_{oed}^{ref}	E_{ur}^{ref}	Φ'	ν_{ur}'	m	R_{inter}	R_f	K_0^{nc}
L-1	3	16	11667	11667	35000		.20	.50	.67	.90	.515
L-2	9	24	15180	15180	45543		.20	.50	.67	.90	.500
L-3	7.5	32	19806	19806	59420		.20	.50	.67	.90	.485
L-4	4.5	30	15300	15300	45900		.20	.50	.67	.90	.470
L-5	6	47	25237	25237	76011		.20	.50	.67	.90	.470

3.4 Pile and Pile load test

A pile is a long, slender structural element made of concrete, steel, or timber that is driven or installed into the ground to transfer structural loads from a building or structure to deeper, more competent soil or rock layers. Transferring vertical loads from weak, surface soils to solid soil layers or rock at a predefined depth is the main goal of a pile foundation. A deep foundation known as a bored pile is created by filling an open-drilled hole with fluid concrete (Saran and Kumar, 2022). On foundation piles, static load tests are typically performed to quantify the load-related pile head displacement. Usually, this kind of test yields sufficient information for common (basic) engineering techniques. However, it can be very beneficial to understand how force is distributed along the pile core, how it is divided into friction along the shaft and resistance under the base, and how these forces are combined. Static pile load tests are frequently performed to measure the pile head displacement caused by the load in order to confirm the integrity of the design. It can be very helpful to understand how force is distributed along the core of the pile, how it is shared between resistance at the base and friction on the shaft, and how these effects work together. Using strain gauge pile instrumentation, this data is obtainable (Naveen, 2011; Zhang et al., 2013). The analysis of a single pile under axial compression serves as the foundation for the pertinent theoretical analysis of static pile load tests. One direct way to ascertain the pile's ultimate geotechnical capacity is through pile load testing. Preliminary pile tests and working pile tests are the two basic types of pile load tests. A working pile test is usually performed during piling or after significant piling work is finished, whereas a preliminary pile test is usually performed prior to the start of piling operations. The analysis of a single pile under axial compression serves as the foundation for the pertinent theoretical analysis of static pile load tests. With the invention of computers, more advanced analytical techniques have been created to forecast the settlement and load distribution in a single pile (Potts and Zdravković, 2001). The test pile was a circular piece of reinforced concrete that had been cast in position. The characteristics and dimensions of the test pile are summarized in Table 8.

Table 9: Test pile properties

Materials	Concrete
Length (m)	22.77
Outer Diameter (m)	1
Young’s Modulus (GPa)	30
Poisson’s ratio	0.15

3.4.1 Pile Load test data

Traditionally, load and settlement test results are plotted graphically, with load represented on the horizontal axis and settlement on the vertical axis. However, this arrangement can be reversed as per the requirements of an engineer's inclination. The settlement shown on the graph could pertain to either gross settlement, signifying the overall displacement of the pile's bottom during the complete test load application, or net settlement, denoting the pile's lasting shift after rebounding once the test load is removed. These plotted datasets serve as the basis for approximating the failure load, which, in turn, facilitates the computation of the permissible pile capacity.

The ultimate failure load of a pile is established as the point at which the pile experiences either a sudden collapse or rapid settlement under a continuous load. However, achieving this plunging effect might necessitate considerable movements that could exceed the acceptable range of the soil-pile system. Alternatively, other definitions of failure involve the consideration of predetermined settlement thresholds. For instance, a pile might be classified as failed if its head displaces by 10 percent of the pile end diameter or if a gross settlement of 1.5 inches (38 mm) and a net settlement of 0.75 inches (19 mm) transpire under a load equivalent to twice the design load. A common approach involves defining the failure load at the point where the initial tangent to the load-displacement curve intersects with the tangent to, or extension of, the final segment of the curve (Saran and Kumar, 2022).

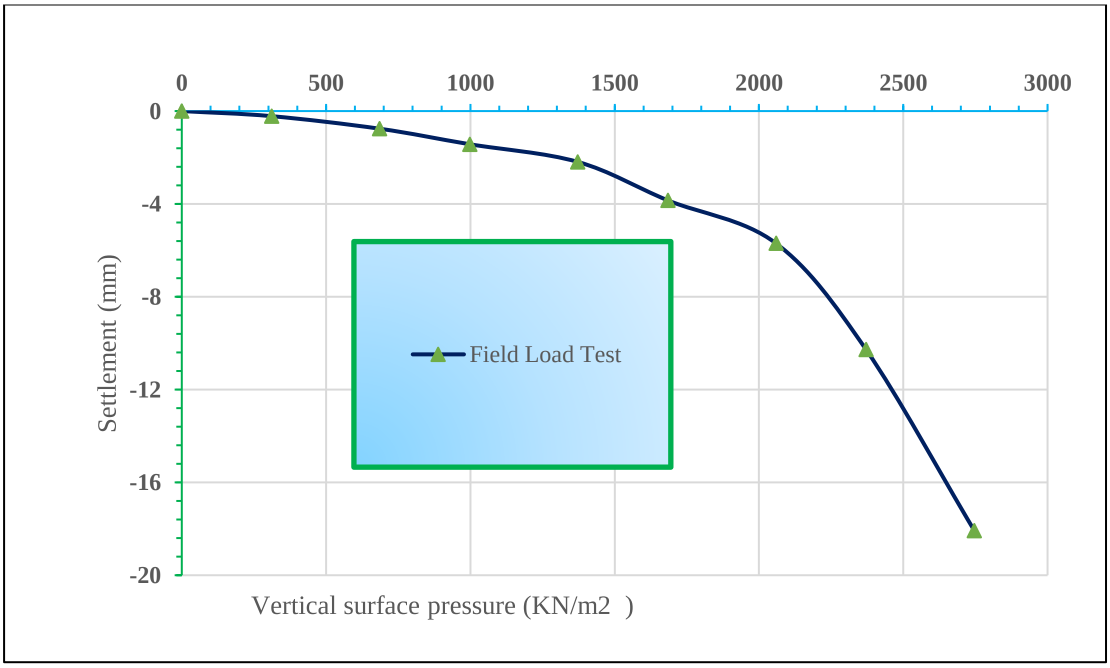

Figure 10: Pile Load Test Curve at Field (Source: SASEC Highway Improvement Project, Kamala-Kanchanpur Road)

3.5 Pile settlement and Soil stiffness

In geotechnical problems, stress-related deformations must be investigated and/or modeled using soil stiffness and constitutive model parameters (Cox and Mayne, 2015). The most important parameter for estimating pile subsidence is the modulus of elasticity of the soil (Al-Khazaali and Vanapalli, 2015). For geotechnical engineers, having a solid understanding of the stiffness properties of soil is essential. Many geotechnical computations involving settlement or horizontal deformations require stiffness parameters. The available calculation techniques have advanced significantly over the past few decades. Since finite element methods are now widely available to both specialized engineers and general practitioners, they are commonly used through software like PLAXIS and other programs. Consequently, there is a growing need for sound knowledge and techniques to assess soil parameters. Both in-situ and laboratory testing can be used to determine the parameters related to soil stiffness. There are many different tests available globally, particularly for in-situ testing (Sture, 2004). The settlement of the pile is determined by the ratio between the modulus of elasticity of the pile profile (EP) and the modulus of elasticity of the soil (ES), the ratio between the modulus of elasticity of the base layer (Eb) and the modulus of elasticity of the soil (ES), and the ratio between pile length and diameter L/d. Since the stiffness of the pile is very high (i.e., the compressibility of the pile is low compared to the compressibility of the soil), in a homogeneous soil layer, the modulus of elasticity of the soil would be the main factor controlling the elastic settlement (Poulos, 1989).

3.6 Finite Element Method

A numerical analysis method for approximating solutions to a range of engineering problems is the finite element method (FEM). The governing equations of a problem can be approximated piecewise using a finite element model. The fundamental tenet of FEM is that a solution domain can be discretized—that is, replaced with a set of discrete elements—in order to model or approximate it analytically. These components can be combined in many different ways to represent very large domains (Jagota et al., 2013). The numerical analysis is based on the finite element method (FEM), an advanced method that can take into account most of the factors involved (Sert, 2003). In finite element analysis, this means that only two degrees of freedom of displacement need to be considered at each node, but more importantly, the analysis can be performed over a representative two-dimensional section of the problem. In reality, however, most geotechnical problems are three-dimensional, and although in many cases, plane deformations or axisymmetric approximations are not inappropriate, some must be treated as three-dimensional. This means that three displacement components must be considered and all three-dimensional geometry must be considered (Potts and Zdravković, 2001).

3.6.1 Numerical Analysis

Examining algorithms that use numerical approximations to solve mathematical analysis problems is known as numerical analysis. The analysis for this study uses the previously mentioned soil constitutive parameters for the MC model; the drainage condition is assumed to be drained because of the soil's notable high permeability, and the pile is modeled using linear elastic material (Gupta and Dahal, 2023).

According to the PLAXIS CONNECT Edition V21.01 Material Models Manual, PLAXIS 3D is used in this study for both modeling and analysis (Brinkgreve, 2021). In order to evaluate the impact on the outcomes, this numerical analysis looks at a number of parameters, including the relationship between load and settlement, the impact of meshing on the model, and the interactions between the soil and piles. In order to validate the model, the outcomes of the numerical analysis are then compared with those of field pile load tests.

The study of algorithms that employ numerical approximations to solve mathematical analysis problems is known as numerical analysis. It is used to obtain numerical solutions to problems involving continuous variables. The value SPT can be used to evaluate the modulus of elasticity (E) based on correlations provided by various scientists for sandy soils. Other parameters, such as the friction angle and Poisson's ratio (v), are evaluated using correlations provided by F.H. Kulhawy and Mayne (1990). A system of mathematical formulas that establish the relationship between stress and strain characterizes a material model (Brinkgreve, 2008). When exposed to stress or load variations, soils typically exhibit nonlinear behavior. In actuality, the load, the stress profile, and the stress magnitude all have an impact on how stiff the soil is. A portion of these characteristics are present in PLAXIS's sophisticated soil models. Nonetheless, a straightforward and well-known linear-elastic, fully plastic model that can be utilized as a preliminary approximation of soil behavior is the Mohr-Coulomb model. Hooke's law of isotropic elasticity—which describes linear-elastic-plastic behavior—forms the foundation of the Mohr-Coulomb model's linear-elastic section. The Mohr-Coulomb failure criterion, developed in the context of non-associated plasticity, is the foundation for the perfectly plastic portion (Brinkgreve, 2021). The soil parameters obtained from various correlations are used in finite element analysis software such as PLAXIS.

3.6.2 Meshing

Although finer meshes require more time and a better computer, the settlement prediction of the pile load test varies from very coarse to very fine meshes, depending on the refinement of the meshes. The effects of changes in mesh size on the model results were analyzed. For elements with 15 nodes, the distribution of nodes is better, and the results are more accurate than for elements with six nodes or 10 nodes(Gupta and Dahal, 2023). Mesh size affects the bearing pressure at a given settlement and vice versa (Nasasira Derrick, 2020). Therefore, the analysis is performed with 10 node elements. However, elements with 15 nodes result in better results, but educational Plaxis has only elements with 10 nodes. The finer the mesh, the more accurate the settlement trend and prediction.

The geometric model has been established, as has the subsequent step involved in meshing. The objective was to achieve a refined, accurate, and numerically stable calculation. To attain this, a substantial number of soil elements were generated, characterized by regular shapes to avoid excessive elongation and thinness. The mesh's quality was of utmost importance; elements were designed to be regular in shape without being overly elongated or thin. This was essential to ensuring the numerical stability of the calculation. The mesh granularity was chosen to strike a balance between accuracy and computational efficiency, avoiding the extreme of employing a full mesh composed of tiny elements, which could significantly prolong calculation times.

In order to maintain mesh quality, meticulous attention was paid to attain the optimal equilibrium between precision and computational duration. The soil material employed element with 10-nodes tetrahedral elements, as depicted in Figure 11, while for simulating the behavior of the embedded beam, three-node line elements were used. To enhance calculation accuracy, meshing was executed with a "Fine" element distribution coupled with refined mesh refinement. The post-mesh generation geometric model can be observed in Figure 12.

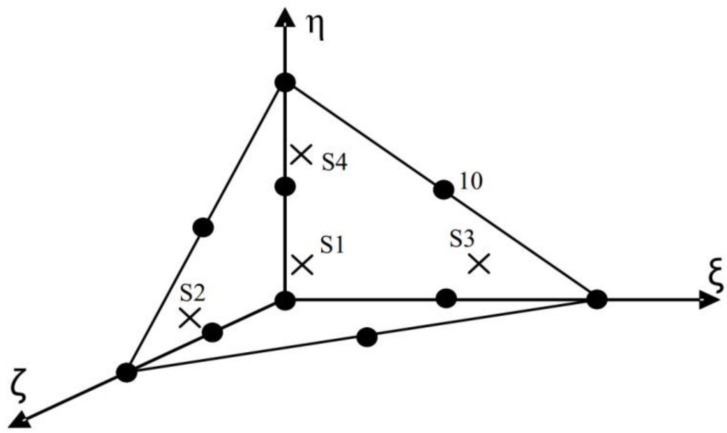

Figure 11: 3D soil elements (10-node tetrahedron) (Source: PLAXIS)

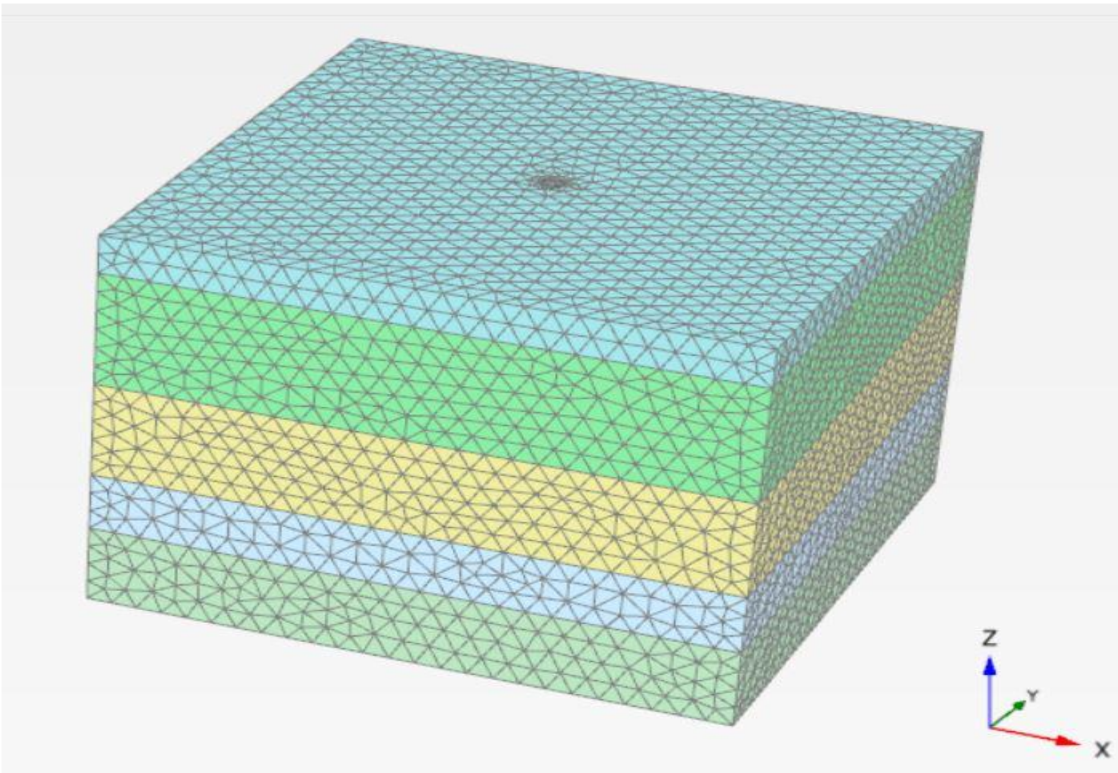

Figure 12: FEM model after meshing

3.7 Routine Pile Load Test

Situated in the Mahuli Bazaar neighborhood of Saptari District, just below the Chure region of Nepal's foothills, is the Mahuli Khola Bridge. The soil sampled during the exploration program contains a small amount of silt, and the stratigraphy of the bridge location is composed of poorly graded sand. A bored cast in situ pile with a diameter of 1000 mm, a length of 20 meters, and a concrete grade of M35 makes up the bridge foundation. 2160 kN was the maximum permitted pile capacity as designed. For every foundation, routine pile load tests were performed at 1.5 times the permissible load (3250 KN). A routine pile load test has been conducted in the test pile of the pier pile of Mahuli Khola Bridge as per load settlement report. Following load-settlement data were obtained during the test. The plot of the load-settlement data is shown in Figure-13

Table 10: Load-Settlement data of routine Pile Load Test

S.N.	Load (Ton)	Vertical Settlement (mm)
1	0	0
2	24.45	0.22
3	53.80	0.76
4	78.34	1.43
5	107.70	2.19
6	132.24	3.85
7	161.64	5.70
8	186.14	10.21
9	215.59	18.08
10	186.14	16.87
11	161.64	16.38
12	132.24	15.77
13	107.70	14.93
14	78.34	13.77
15	53.80	12.45
16	24.45	10.71
17	0	7.75

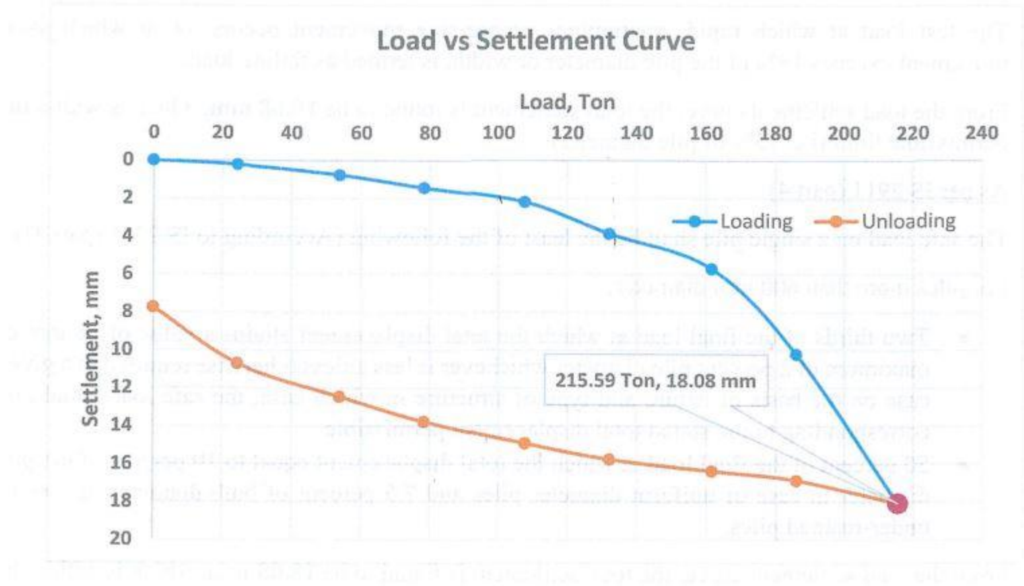

Figure 13: Field plot of load-settlement (Source: SASEC Highway Improvement Project, Kamala-Kanchanpur Road)

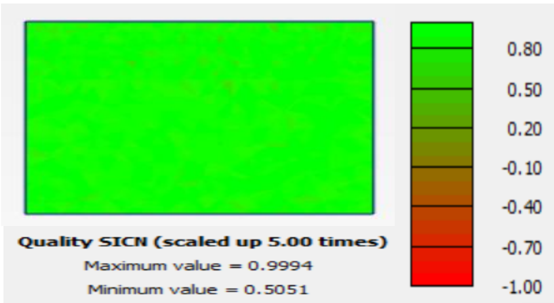

Figure 14: Quality of generated mesh

3.8 Numerical Calculation

After meshing, the geometric model is divided into several project phases in the construction stage tab of PLAXIS 3D. In each phase, the soil and structures were activated as per the requirements. The calculation of the initial stress field for the initial geometry configuration by the K_0 procedure always constitutes the first calculation phase (the initial phase), which was defined automatically. Subsequent phases of the calculation were defined manually by turning on the corresponding geometry and structure after the first phase. In each construction stage, the load on the pile was started at **24.45 Ton** and increased until it reaches to **215.59 Ton** with approximately 25 Ton increment in 1 hour interval as shown in **Table-10.** Node points and stress points were selected at the interested location for the visualization of displacement and stress-strain parameters during and after the numerical calculation.

4. RESULT AND DISCUSSION

In this study, a numerical analysis of a pile load test was conducted on sandy soil using the Plaxis 3D software. The aim was to simulate and understand the behavior of the pile and soil interaction under varying load conditions. The results obtained from this analysis provide valuable insights into the performance and capacity of the pile in sandy soil. After completing the analysis of the model FEM, the output data of the forces in the structures, such as the axial force and the vertical displacement of the pile for different loads, were extracted and recorded graphically. Various parameters, such as stiffness of soil (estimated by different correlations provided by different authors), interface strength between piles and soils (R_{inter}), and variation of water level fluctuations, were taken into consideration in this study. The results of the different conditions are described in the following headings below.

4.1. Load settlement Behavior

The load-settlement response of the pile under different loading scenarios was investigated. The numerical simulation showed that as the load increased, settlements occurred in the sandy soil. This behavior is consistent with the expected response of a pile-soil system, where the applied load induces downward displacement. The vertical load versus settlement behavior is dependent on various soil parameters, like soil stiffness. The majority of literature takes modulus of elasticity values from laboratory investigations. However, laboratory investigations have been a time-consuming process most of the time. Therefore, in this study, a correlation between elastic modulus and the standard penetration test value has been considered for soil stiffness. Other parameters, like frictional angle and cohesion, have been taken from the geotechnical report of the study site. The Poisson’s ration is the average of values that come from two different correlations. One correlation is based on the frictional angle, and another is based on the standard penetration test value. One of the interesting factors in numerical analysis is soil pile interface strength, which plays an important role in the settlement value and trend of curves obtained. Therefore, it is necessary to find the approximate value of R_{inter}, which resembles the curve as obtained in the field.

4.2. Effect of meshing on model

One technique used to improve the accuracy of finite element analysis is mesh refinement. To increase the number of elements in the model, this technique divides larger elements into smaller ones. When applied to situations with complex geometry or large stress gradients, it is advantageous. By lowering the errors associated with element dimensions, mesh refinement improves the accuracy of load settlement analysis (Derrick, 2020). Consequently, the analysis uses elements with ten nodes. Figure 15 illustrates how finer meshing improves predictive capabilities and settlement trend accuracy.

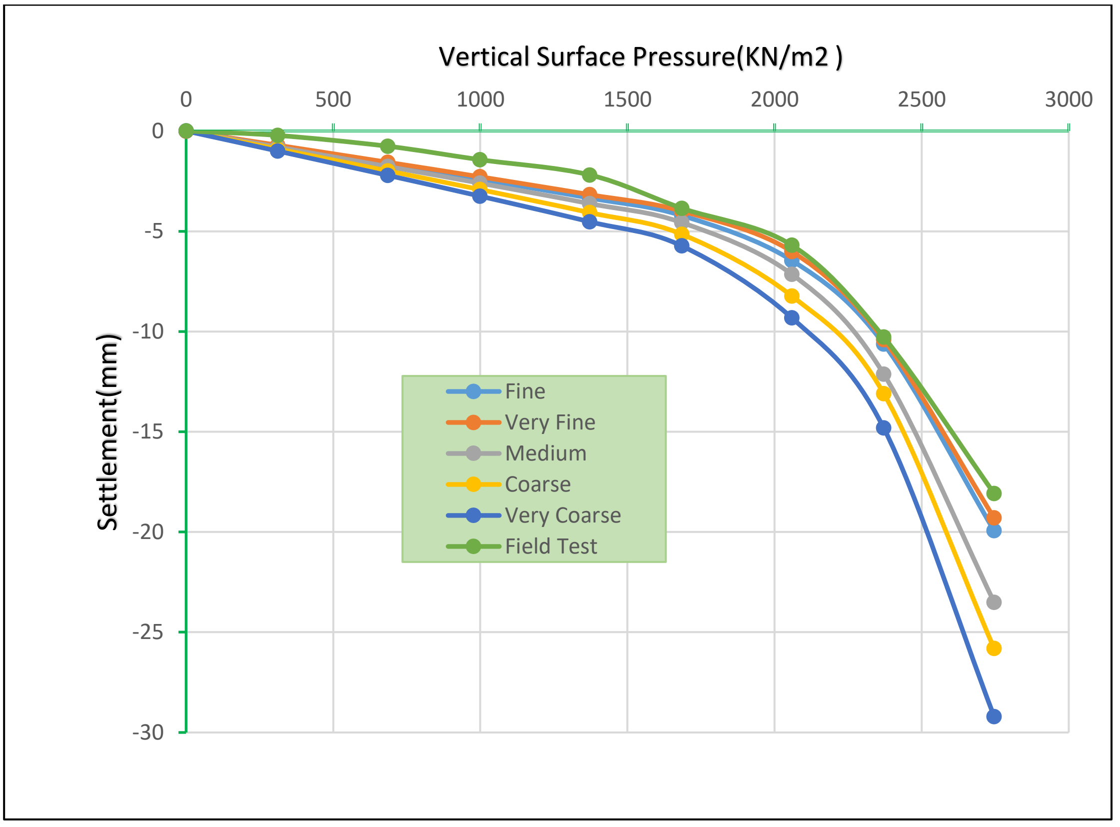

Figure 15: Effect of meshing on settlement

4.3. Load settlement for R_{inter} =1

The load settlement curve in this case seems to act like a linear behavior of soil against vertical loads. The vertical load versus settlement for interface strength equals one, as shown in Figure below. The curve plotted between vertical load and settlement for field realizations shows non-linear behavior, but the output obtained from the software is almost linear for the interface strength value at unity. Therefore, it doesn't represent the real soil behavior, as soil behaves in nonlinear ways when a load is applied. It implies that soil in numerical analysis acts like rigid soil-pile interaction for interface strength at unity.

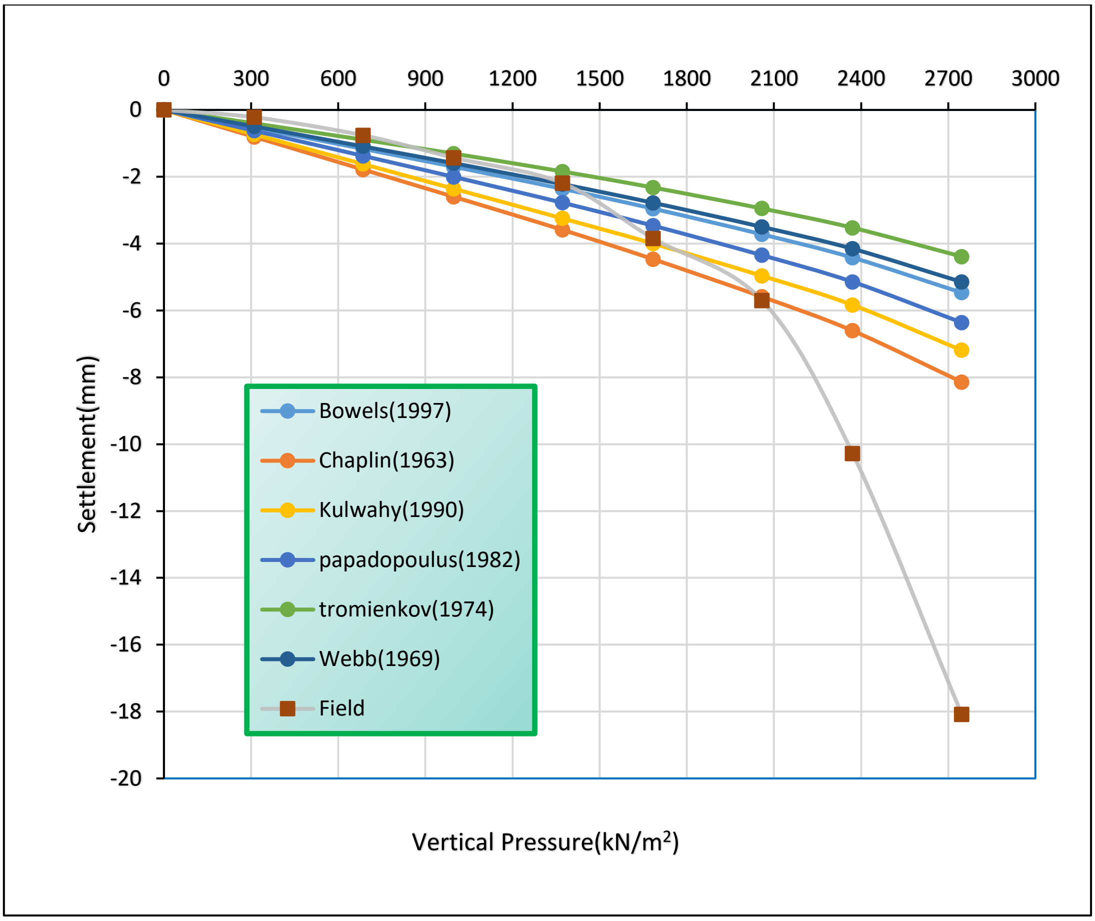

Figure 16: Load versus Settlement for Rinter=1

4.4. Load settlement for R_{inter} =.5

The load versus settlement curve appears to be highly flexible for the interface value equal to 0.5 when other parameters are not changed. The behavior of the soil pile-pile interaction is nonlinear in this case, but the settlement value is highly biased compared to the real field data, even though the curve resembles the field curve. The curve obtained in this case is similar to the previous one except for the interface strength value, which is half that of the previous one. It overestimates the ultimate settlement for the applied vertical load due to the assumption of weak soil around the pile periphery.

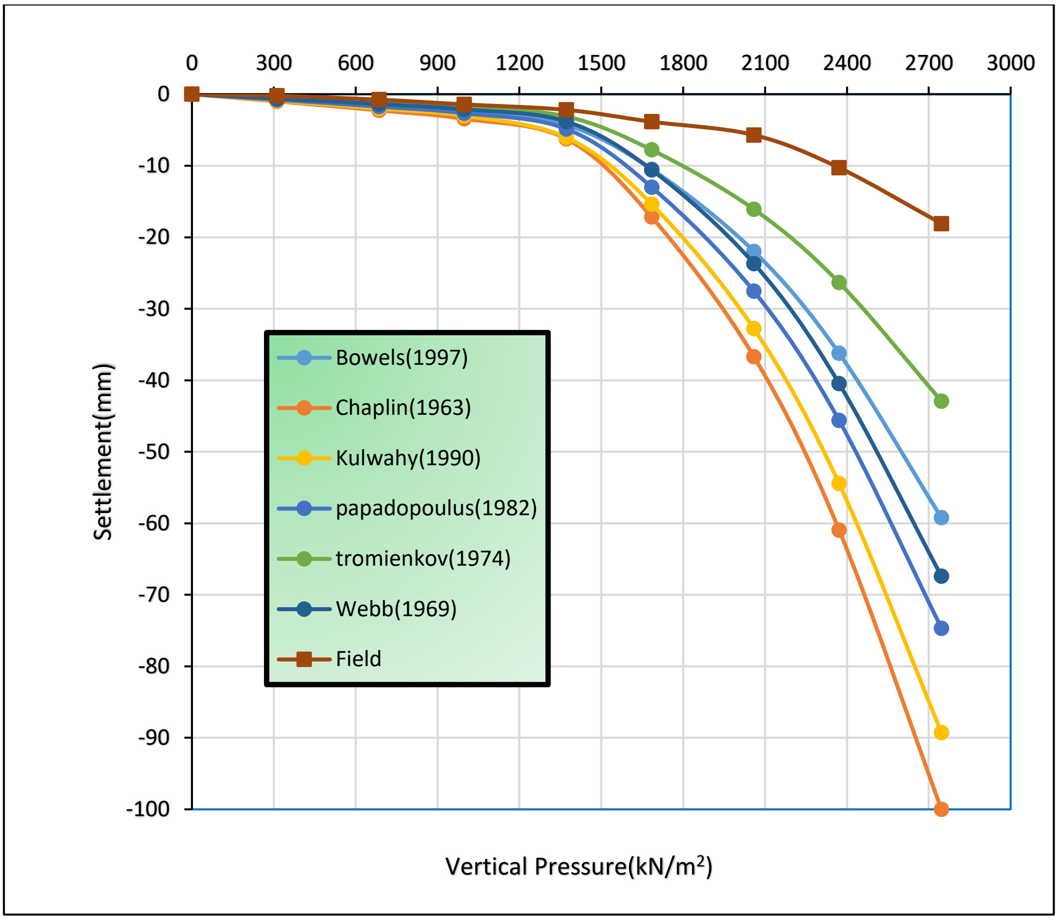

Figure 17: Load versus Settlement for Rinter=0.50

4.5. Load settlement for R_{inter} =0.80 or 0.67.

The load settlement curve is nonlinear when Rinter varies in the range of 0.67 to 0.80. However, no literature suggests a fixed value for it. Therefore, it is necessary to make trials for different values of interface strength and check for resemblance with the field value of settlement. Although settlement value is equally important, the curve trend should also be matched to the curve obtained when plotted between vertical load and settlement in field data. An approximation is obtained for R_{inter} = 0.67 when the modulus of elasticity obtained by the correlation given by Tromienkov (1974) is used in modeling, as shown in Figure. However, a value suggested by Brinkgreeve and Shen (2011) is in the range of 0.80 to 1 for sand and concrete interaction, as shown in Figure-18 (Liong, 2014).

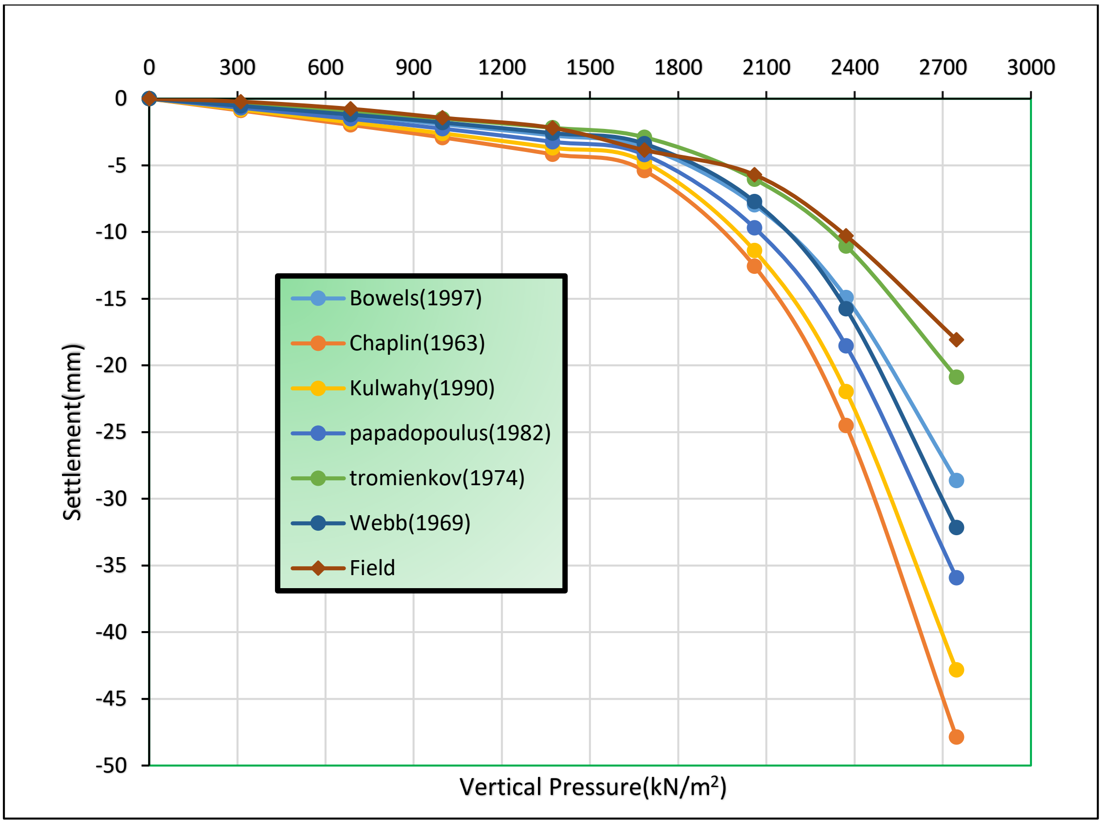

Figure 18: Load versus Settlement for Rinter=0.67

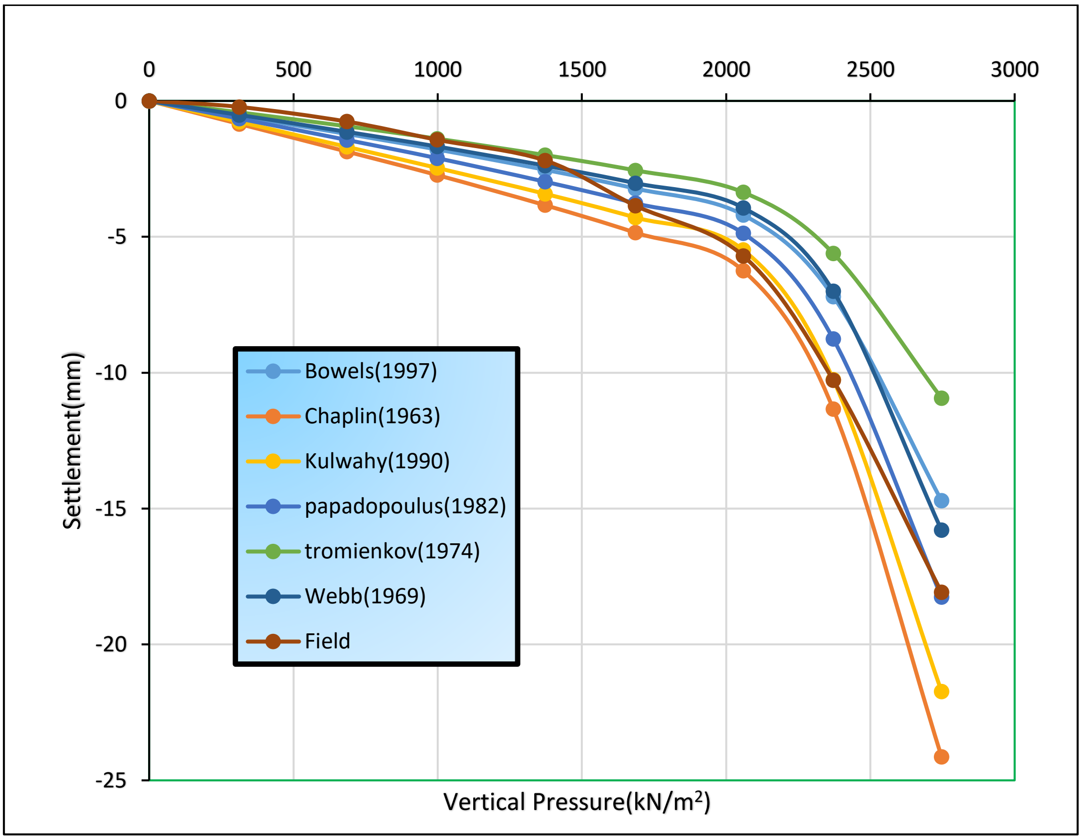

Figure 19: Load versus Settlement for Rinter=0.80

4.6. Comparison of settlement curves

A value of $R_{inter} = 0.80$ is taken to estimate settlement numerically instead of performing a pile load test in the field. The data obtained from the numerical simulations is compared to the data obtained from a field test graphically using Plaxis software. The curve obtained from the software is validated by comparing it with the field curve.

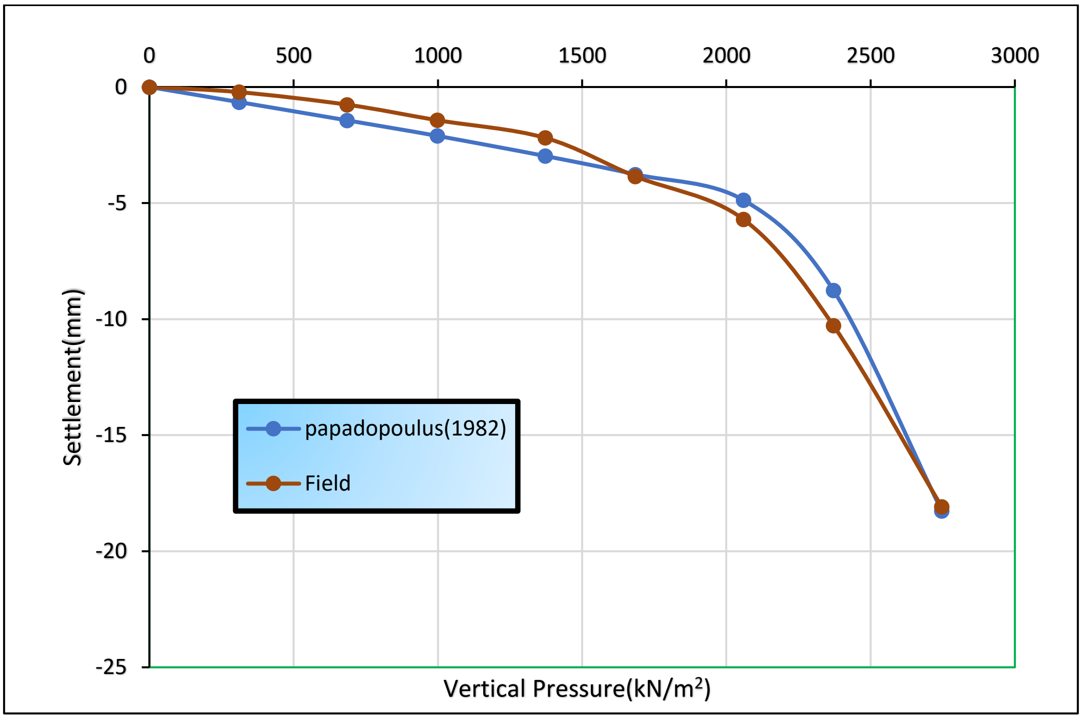

Figure 20: Comparison of Load versus Settlement for Rinter=0.67 against field

4.7. Water Level Variations

The water table can have a significant impact on the behavior of a pile during a load test. The presence of groundwater can influence the pile's load-bearing capacity, settlement characteristics, and overall behavior. If the water table is close to the ground surface, the pile might experience a buoyant force due to the upward pressure of groundwater. This buoyancy can reduce the effective load on the pile and consequently affect the load-displacement behavior observed during the test. Water can lubricate the interface between the pile and the surrounding soil, reducing the frictional resistance. Groundwater can influence the soil's effective stress and compressibility. If the water table rises during the test, it can increase pore water pressure and result in higher settlements in the surrounding soil. The water table depth and settlement behavior are shown in Figure-21.

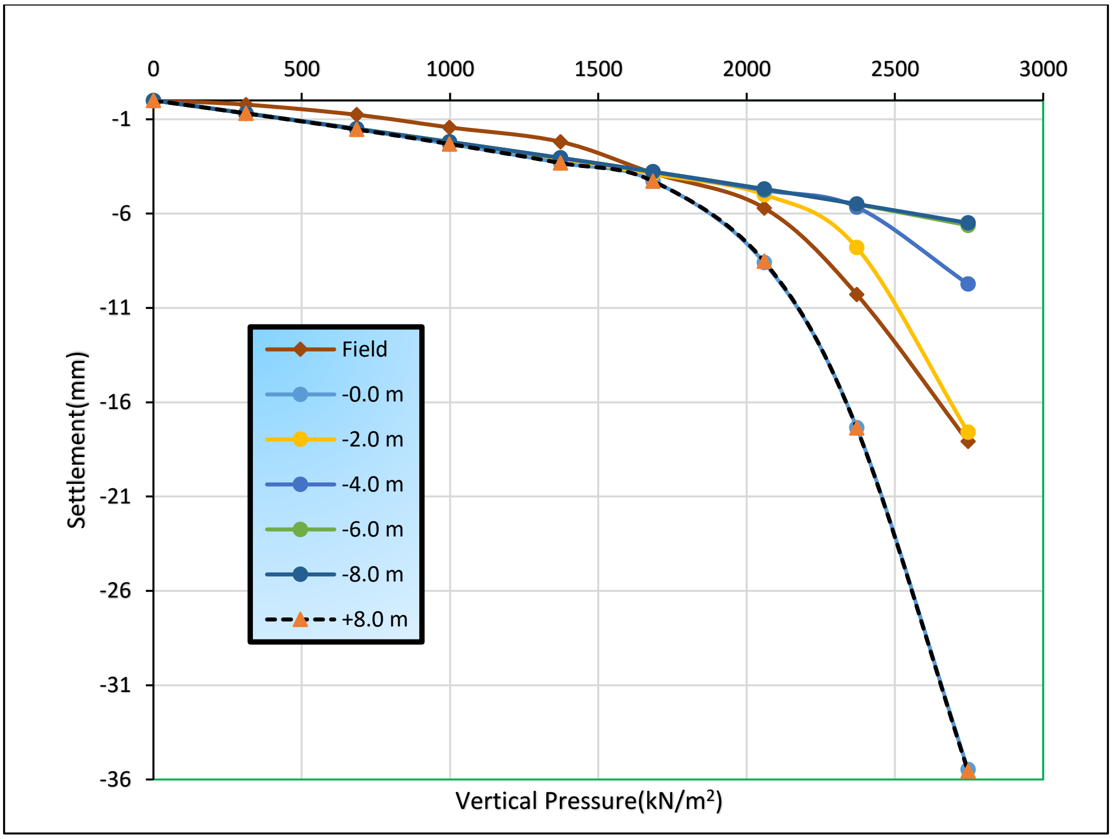

Figure 21: Variation of settlement versus water table

The water table greatly influenced the settlement characteristics of soil-pile interaction. Settlement is higher at the water table at the ground surface, remaining other parameters unchanged. However, the water table above the ground surface has a negligible effect on the pile settlement, as shown in Figure. Therefore, water levels should be noted carefully while conducting soil explorations.

4.8. Settlement Analysis by hardening Soil Model

A sophisticated constitutive model of soil, the hardening soil model is developed within the context of the traditional theory of plasticity. Virgin loading and unloading determine stress-dependent stiffness, which is used by the hardening model to compute total strains. Additionally, total stains can be calculated by introducing multi-surface yield criteria (Schanz et al., 1999). To describe the non-linearity behavior of soil besides the cam clay model, a pseudo-elastic model (hypo-elastic) has been developed. A stress-strain relationship is employed according to Hook's law, and non-linearity is achieved by varying Young's modulus. The best known model in this category is the Duncan and Change model, but due to inconsistency in distinguishing between loading and unloading, and therefore to overcome these restrictions, the hardening soil model has been utilized to tackle the nonlinear behavior of soils(Schanz et al., 1999). A number of finite element software packages are available nowadays. The hardening soil model, which is an expansion of the Duncan-Chang stress strain model in the finite element program Plaxis, can be used to investigate the nonlinear properties of granular soil (Ryull, 2007). The below table summarizes the hardening soil parameters that are used in soil modeling and analysis in Plaxis 3D. Other dimensions and parameters for piles are the same as those used in the Mohr-Column constitutive model. It only lists the input parameters regarding the Papadopoulos correlation, as shown in Table-(2-6).

Soil stiffness parameters for hardening soil model requires a greater number of input parameters than Mohr-Coulomb requires. Reference deviatoric hardening stiffness modulus at p^{ref}=100 Kpa, is taken from the plot between the ratio of E_s and Secant Modulus E_{50}^{ref}, cohesion and friction angle ϕ' as shown in Figure-22

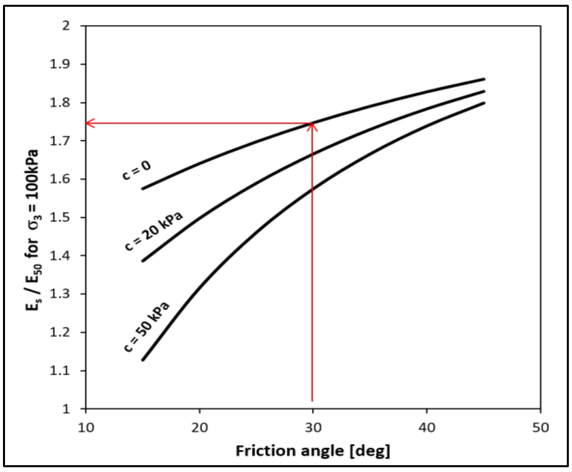

Figure 22: Estimating the ratio between the static modulus Es and secant modulus E50. (Z Soil. PC 100701 report)

Reference oedometer stiffness at p^{ref} = 100 Kpa

$$E_{oed}^{ref} = E_{50}^{ref} \text{..................................} \quad (3)$$

Reference un-/reloading stiffness at pref = 100 Kpa

$$E_{ur}^{ref} = 3E_{50}^{ref} \text{..................................} \quad (4)$$

Power index m =0.5

Poisson's ratio for unloading/reloading υ_{ur} = 0.2

According to ((Ryull, 2007; Schanz et al., 1999) these input parameters can be defined as follows.

Φ' Internal friction angle

R_f Failure Ratio (.9)

$E_{50}^{\ ref}$ Reference Secant Stiffness from drained triaxial test

$E_{oed}^{\ ref}$ Reference tangent stiffness from oedometer primary loading

$E_{ur}^{\ ref}$ Reference unloading/ Reloading stiffness

m Exponential power (.5)

ν_{ur}' Unloading and Reloading Poisson's ratio (.20)

K_0^{nc} Coefficient of earth pressure at rest (NC soil)

$E_{50}^{\ ref} = E_{oed}^{\ ref}$ and $(E_{ur}^{\ ref})/(E_{50}^{\ ref}) = 3$

The output of the Hardening soil model provides a relatively conservative result in a small amount compared to the Mohr-Coulomb soil model output. However, the output of the HS model is obtained by calculating input parameters from plots and correlations and is presented here for comparison with field data. Additionally, while modeling in plaxis, it is significantly influenced by the value chosen for interface strength, and therefore, the same interface value has been used for both models. The output clearly indicates that the HS model overestimates settlement for smaller depths and underestimates settlement for larger depths due to the fact that this model considers modulus of elasticity varying with depths, as shown in Figure-23.

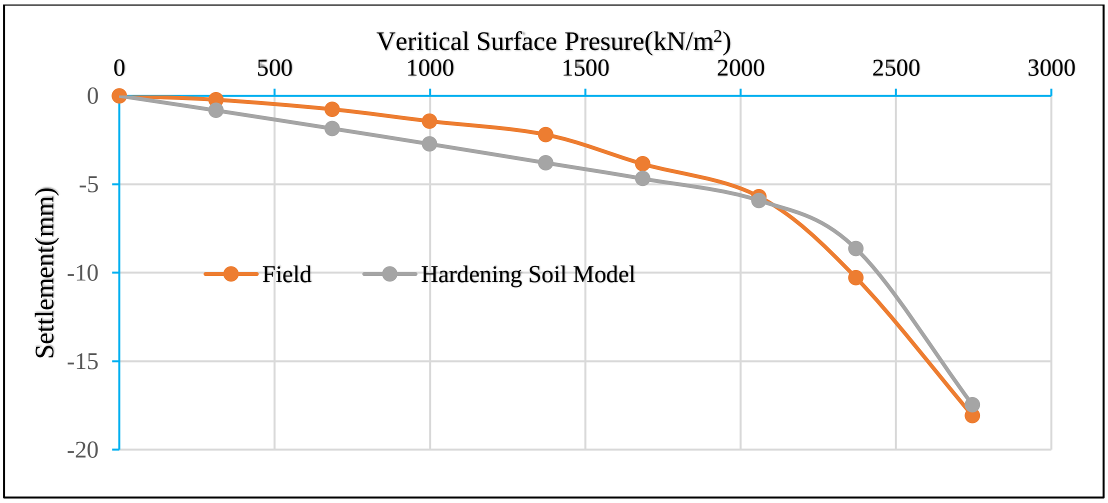

Figure 23: Comparison of Field and Hardening Soil Model

4.9. Model Validation

Model validation is the methodical process of determining whether a model accurately captures the dynamics of a particular system. A comparison of the model's outputs with data gathered from experiments or field testing constitutes this validation process (Feng et al., 2017). Validation is the process of determining how well a model represents reality (Brinkgreve et al., 2021).

The load settlement data obtained from field pile load tests is used in this study's validation. In order to evaluate the settlement variations with the various correlations taken into consideration, a number of model analyses have been carried out. Notably, the MC model is validated using both the hardening soil (HS) model and the field data as benchmarks. The results are shown graphically in Figure -24, which shows that the simulated field pile settlement and the MC model's predictions satisfactorily align.

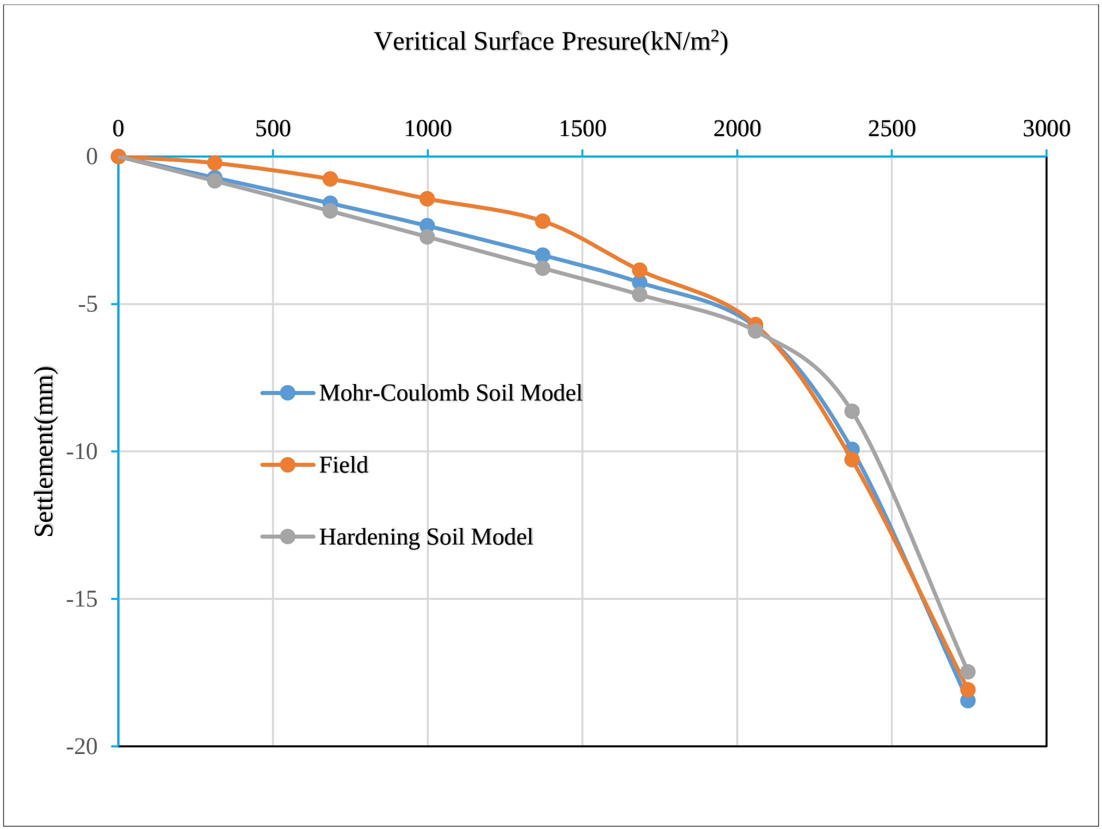

Figure 24: Model Validation

4.10. Application of Validated model

The traditional static load settlement method to calculate the ultimate and net settlement of a pile is still extensively used in the modern era in spite of a number of limitations.

It consumes a considerable amount of time while performing the test in the field for the routine test category. If it embraces an initial pile load test, it may require a significant time period for the test to be accomplished. Additionally, a static pile load test needs to gather massive arrangements to perform the test as per guidelines. Consequently, this increases costs invariably and delays the completion of further stages of construction. Due to the heavy arrangement in performing tests, it is difficult to test for emergence loadings because much testing is done by applying loads through hydraulic jacks. It requires a higher capacity if the load application is greater than the design loads, as many folds in emergency cases. The advancement in numerical simulation can foster a technique to predict settlements in a much easier way for any loads that need to be tackled. As the model in this study is validated by field data and hardening soil, it can be used to estimate the ultimate settlement occurring when any loads are applied. The below plot is a presentation of predictions of settlement at different larger loads in Figure-25.

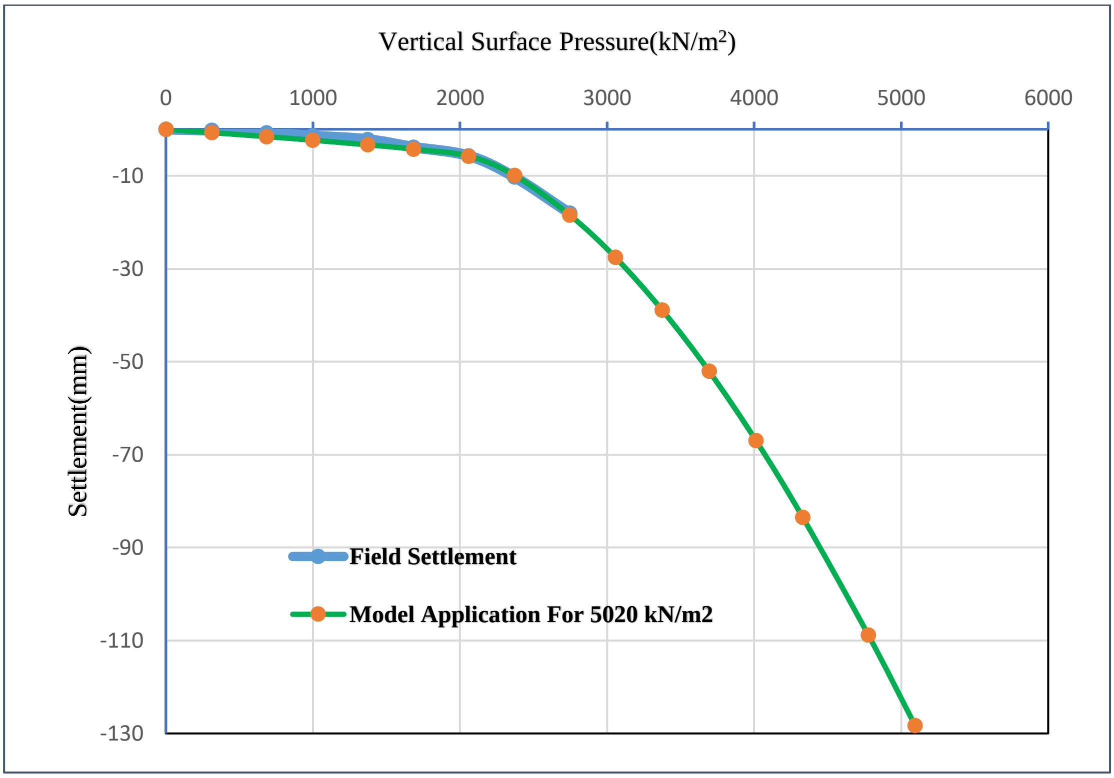

Figure 25: Application of Model to Find Settlement

4.11. Group Settlement

A pile is rarely used alone to transfer structural loads into a ground, but a number of piles are used to transfer loads from structures to soil strata. The pile arrangement may be any shape, such as a circular, rectangular, or square pattern. A pile needs a raft to integrate group pile arrangements in the field application of this kind of deep foundation. The raft thickness also affects the settlement of a group pile. Increasing the thickness of the raft, however, increases the cost of the project and reduces group settlement. Increasing the diameter of the pile obviously decreases settlement due to the larger skin surface area of the soil if it is designed as a frictional pile. The spacing of piles also plays a significant role in settlement behavior. Increasing pile spacing may decrease settlement, but raft volume has increased considerably. Therefore, different codes suggest accepting 3D spacing between piles from center to center.

4.11.1. Plate Raft Vs Concrete Raft

The assignment of pile cap materials in the numerical analysis plays a vital role in assessing the settlement. The settlement with plate raft exceeds that with concrete raft, and the reason may be frictional variations between soil and raft assignment in numerical software. However, more research needs to be done to reach a conclusion. The below Figure -26 shows a comparison between settlement between two cases: one when plate is assigned as a raft and the other when concrete material is assigned as a raft.

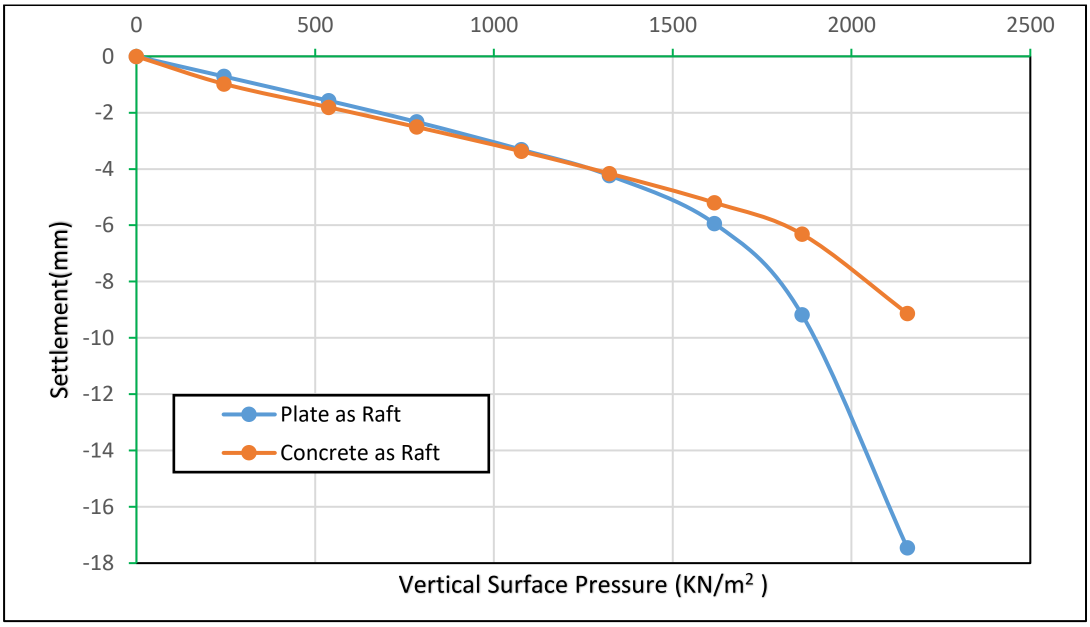

Figure 26: Plate Raft Vs Concrete Raft Result in Plaxis

4.11.2. Group Settlement Vs Raft Size

Generally, piles in field applications are in group arrangements and combined with a raft to behave as single blocks while transferring loads to the ground. The number of piles depends on the soil strength and diameter of the pile and the load to be carried and transferred to the soil safely. Whenever the number of piles increases, the size of the raft increases consequently to permit 3D spacing of piles from center to center. For a single pile, it is multiplied by the number of piles and then distributed to the raft according to the size of the raft. The numerical analysis showed that the settlement of piles increases whenever the raft volume or size increases. The pattern of pile arrangement is also important in evaluating pile group settlement. The result revealed that a rectangular pattern of pile arrangement indicates low settlement compared to a square pattern. However, raft area dictates overall settlement, and different arrangements with the same number of piles were evaluated, as shown in the figures below.

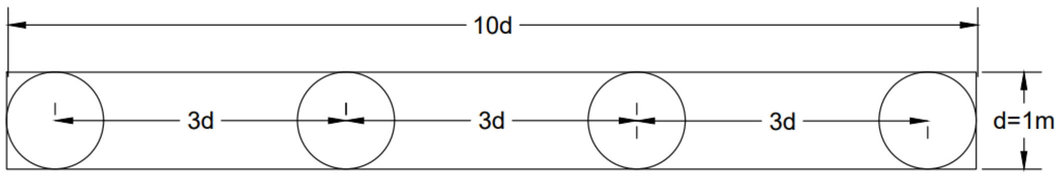

Figure 27: 4 pile arrangement with 10 sqm. Raft size

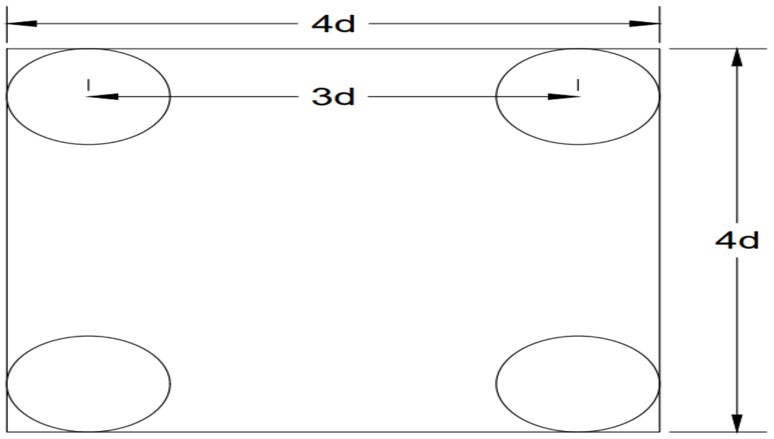

Figure 28: 4 pile arrangement with 16 sqm. Raft size

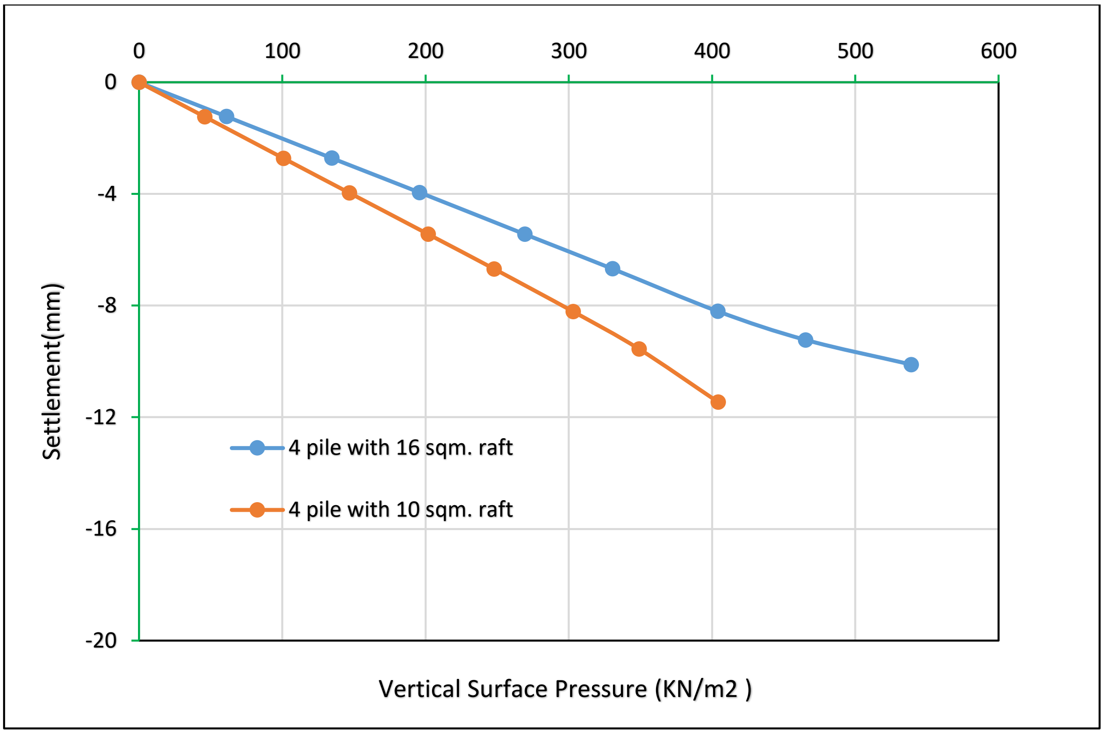

Figure 29: Settlement of 4 piles in group with two raft sizes

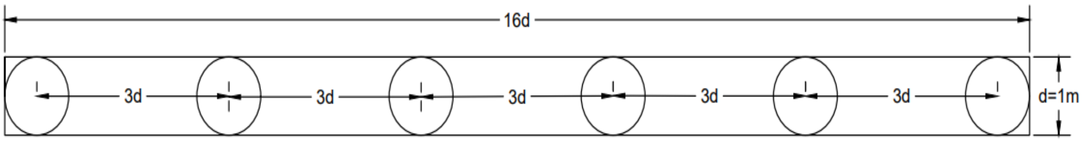

Figure 30: 6 pile arrangement with 16 sqm. Raft size

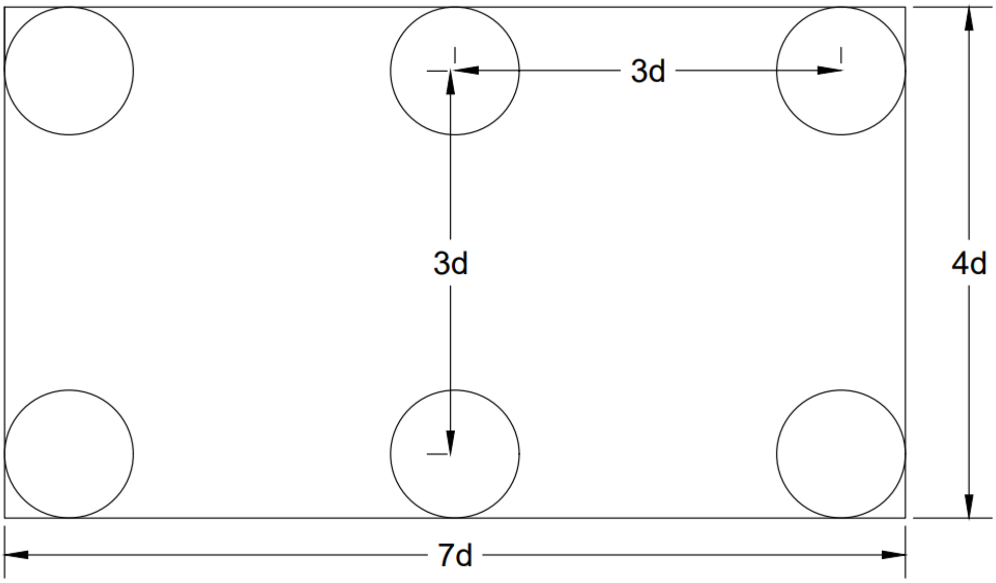

Figure 31: 6 pile arrangement with 28 sqm. Raft size

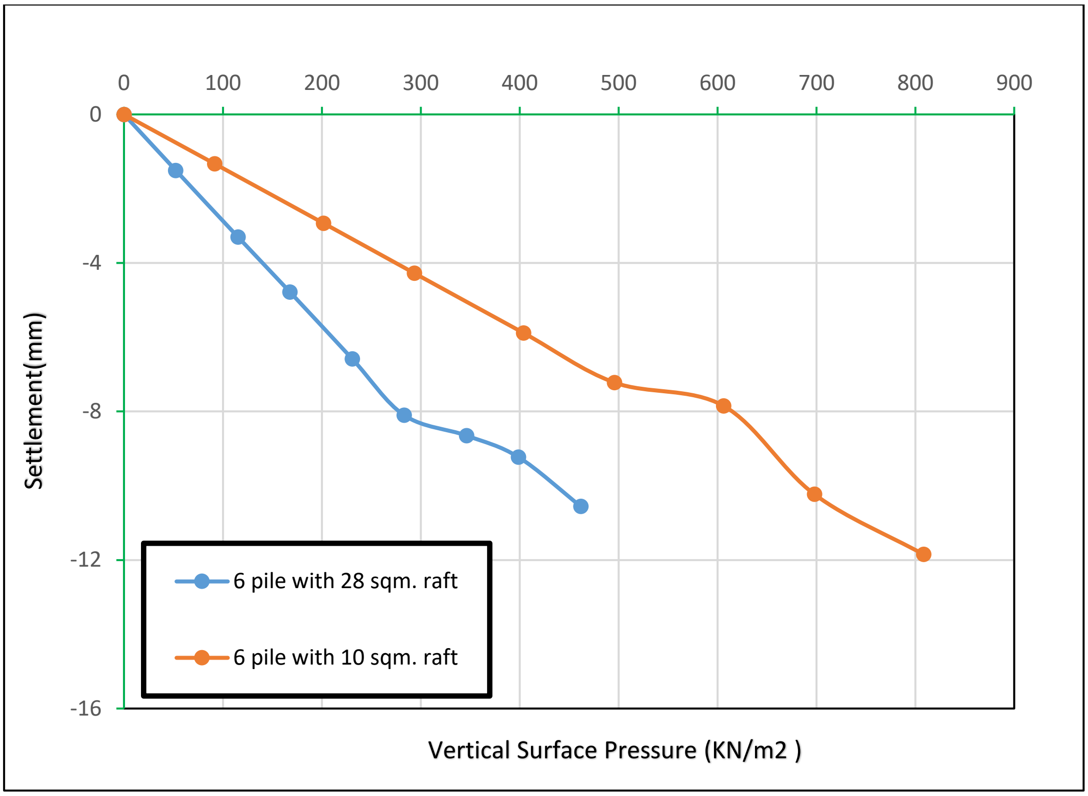

Figure 32: Settlement of 6 piles in group with two raft sizes

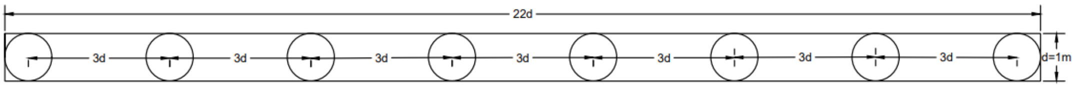

Figure 33:8 pile arrangement with 22 sqm. Raft size

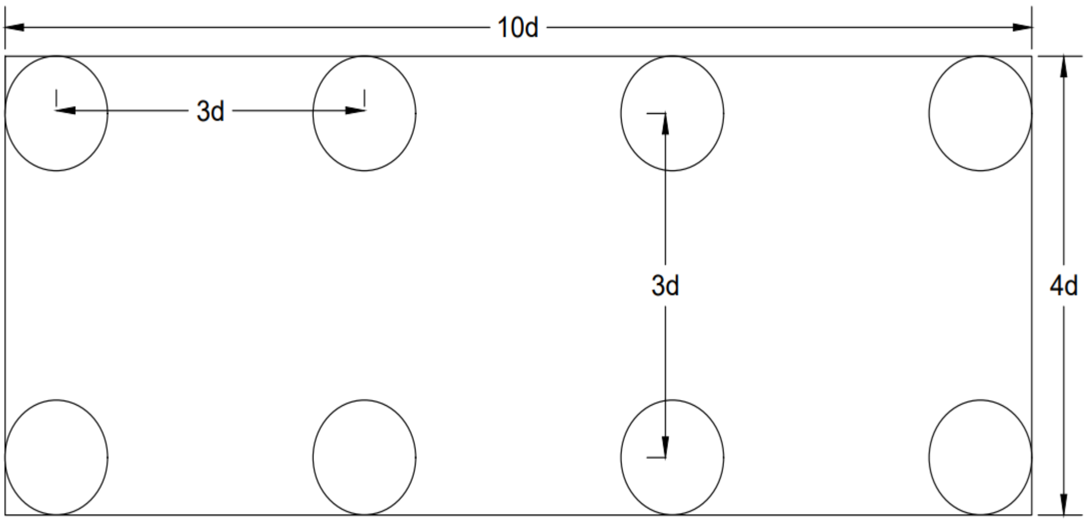

Figure 34: 8 pile arrangement with 40 sqm. Raft size

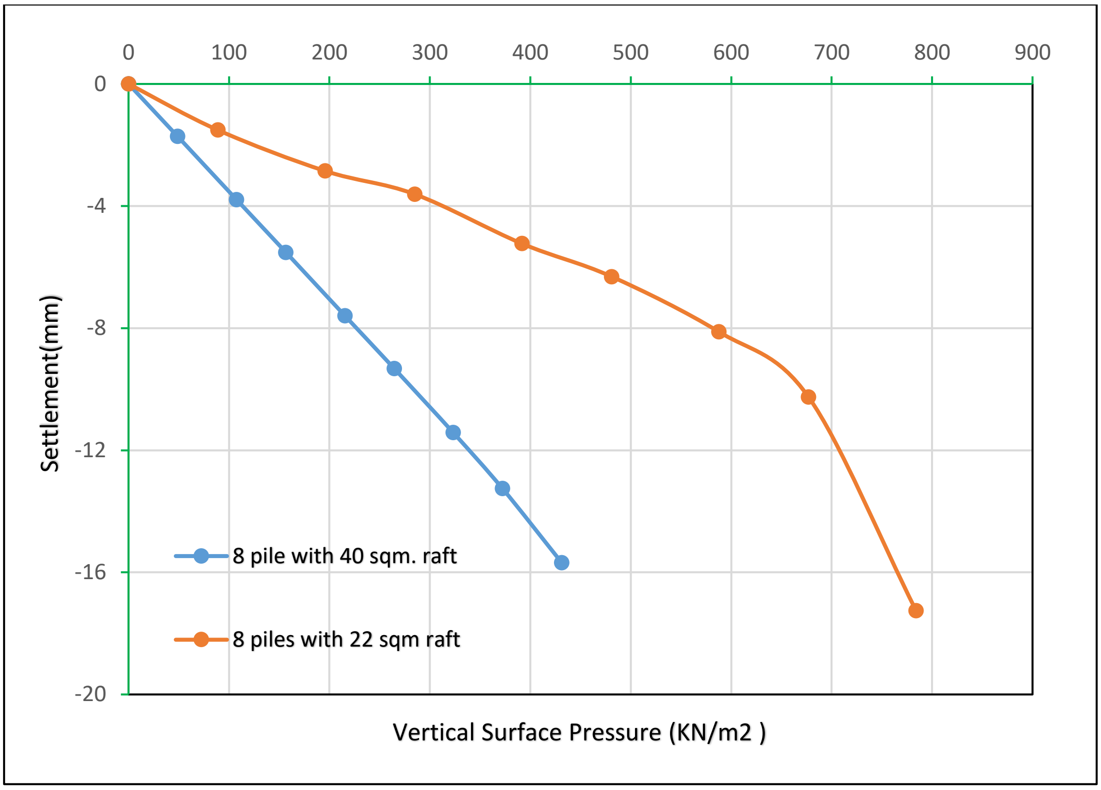

Figure 35: Settlement of 8 piles in group with two raft sizes

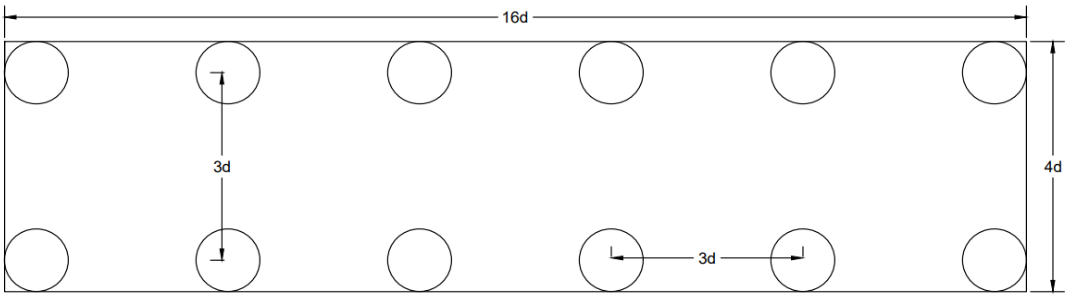

Figure 36: 12 pile arrangement with 64 sqm. Raft size

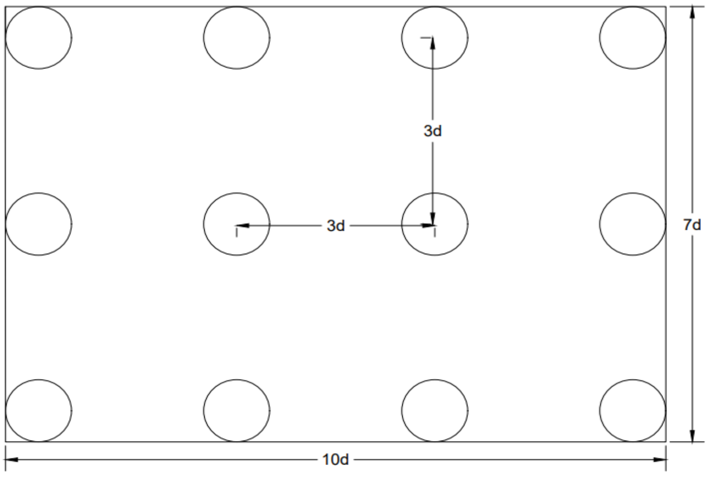

Figure 37: 12 pile arrangement with 70 sqm. Raft size

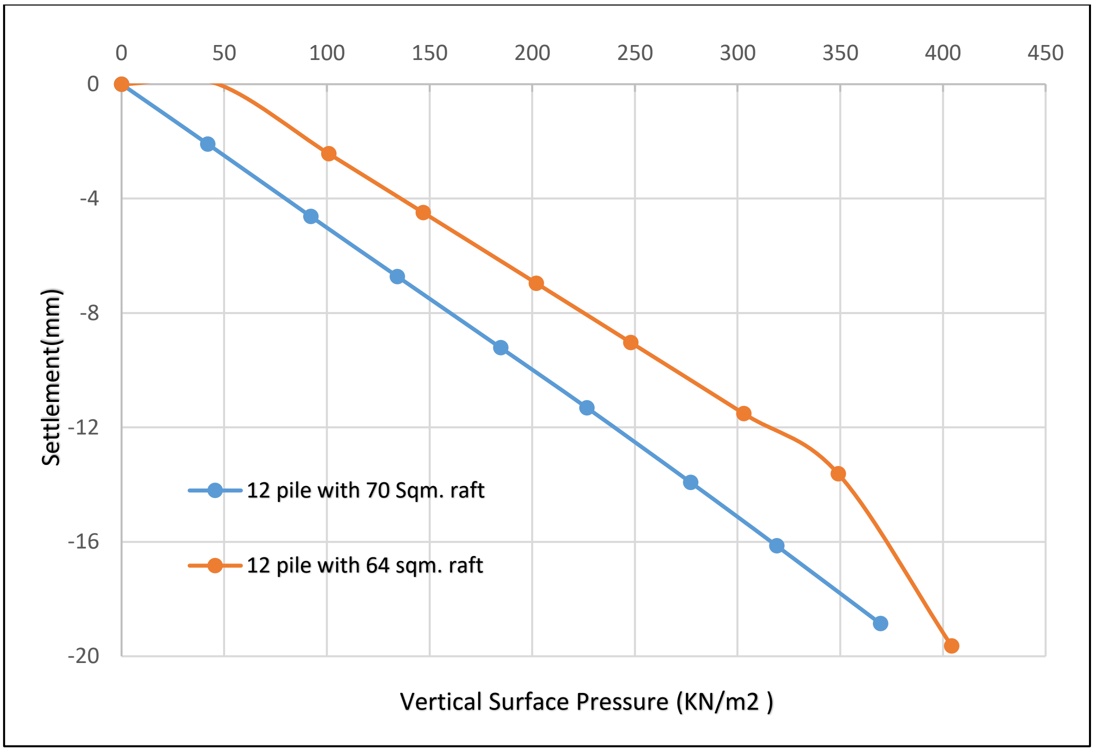

Figure 38: Settlement of 12 piles in group with two raft sizes

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

Using various correlations for the modulus of elasticity in the Finite Element Analysis Framework, the study examined the pile load settlements. The study considers the impact of soil-structure interaction and mesh size on the results. The settlement is also heavily influenced by changes in the water table. Additionally, settlement behaviors are impacted by sandy soil dilation. The following succinctly summarizes the study's main findings:

- It has been found that using a finer mesh size produces a more accurate outcome.
- Two correlations stand out for their propensity to greatly underestimate settlement values: Bowles (1996) and Tromienkov (1974) shows **16.63%** lesser than field value. On the other hand, the correlations put forth by Chaplin (1963) and Webb (1969) have a tendency to overestimate **34%** and **29%** field settlement values respectively.
- Papadopoulos (1982) established a correlation that shows a close prediction about 2.1% more with field settlement values. Furthermore, as the mesh size is fine-tuned, the accuracy of this correlation increases.
- The interface conditions have a significant impact on the traits and values of settlements. The load settlement behavior shows an approximately linear relationship and the predictions are underestimated when stiff soil-pile interfaces are taken into account. Settlement trends and final settlement are in close proximity to the field values when the reduced interface strength (as R_{inter} = 0.67) is taken into account.
- The load-settlement curve can be used in the analysis of pile behavior using numerical modeling. Additionally, the preliminary bearing capacity of pile foundations may be found by extracting curves after soil exploration, like SPT.
- The settlement value and trend are significantly influenced by the water table variations. Rising water levels increase settlement and resonate curve trends, and vice versa. The water level varied from +8 m to -8 m. It shows the settlement behavior is not affected by the water level rising above the ground surface.
- The validated model is applied to estimate settlement for larger loads that are not economically applicable at the field or to extend settlement against a load.

- The Mohr-Coulomb constitutive model numerical analysis yields reasonable pile settlement predictions within the sandy layer.
- It can be easy to predict settlement of a pile for a particular vertical axial load after validation of numerical model.
- When modeling the raft there are two possibilities in the plaxis, either a slab can be created or concrete can be used with the same material as the pile. The result shows that the settlement behavior is remarkable and the raft with slab shows larger settlements compared to the raft with concrete.
- The arrangement of the piles has a significant influence on the settlements. It was found that the same number of piles arranged to have a larger surface area or volume of the raft caused smaller settlement compared to a smaller surface area or volume of the raft.

5.2. Recommendation for further studies

In this study only attempt has been made in simulations of static pile load test from routine test performing on field for single bored pile. The pile is loaded vertically only. As initial load test is much reliable to take account of realistic behavior of piles but due to lack of reliable data, it is difficult to perform simulation of static pile load test obtained from initial load test. If data are available for initial load test or performed in field then a better result could be achieved. This could be helpful in quick estimation or judgement of the required loading arrangement during performing any full-scale loading tests of bored piles. The possible further study may be followings:

- A full-scale pile load test can be performed with advanced arrangement using stain gauges in single pile and or group piles.
- The lateral behavior of pile load test can be assessed and performed in numerically.
- Stress characteristics of pile may also be studied by validating in this manner.

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ANNEXES

Annex – I Soil Exploration Bored Hole Data

Fig: Hammering 37

Consulting Services for Soil Investigation of Mahuli Bridge

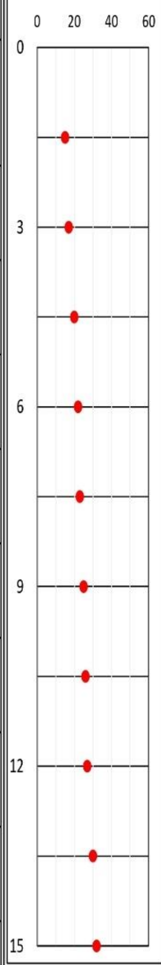
BORE HOLE LOG BH07

Contractor: S.R. Engineering & Exploration Pvt. Ltd.
Location: Siraha
Bore Hole No.: BH-7 (K 160+355.000)
Easting: 481840.03 m
Northing: 2947156.18 m
Diameter of BH: 100mm
Drilling Method: Rotary

GWT: 1.60 m
Drilling started: 2078/03/09
Drilling finished: 2078/03/10
Total Drilling depth: 25.00 m

Depth (m)	Layer Thick (M)	Soil Classification	Symbol	USCS	SPT / DCPT	Sample recovered	No. of SPT/DCPT Blows (Field Record) 0-15cm	15-30cm	30-45cm	SPT / DCPT N
1.50		Poorly Graded Sand with Silt		SP-SM	S.P.T	Wash	5	7	8	15
3.00						Wash	6	8	9	17
3.50	3.50									
4.50		Poorly Graded Sand		SP		Wash	8	9	11	20
6.00						Wash	8	10	12	22
7.50						Wash	9	11	12	23
9.00						Wash	9	12	13	25
10.50						Wash	10	11	15	26
11.00	7.50									
12.00		Poorly Graded Sand with Silt		SP-SM		Wash	9	12	15	27
13.50						Wash	10	13	17	30
15.00						Wash	10	16	16	32

SPT N Plot



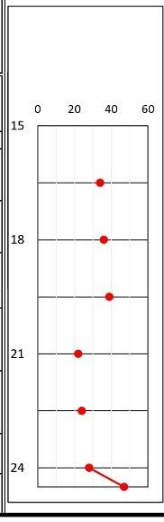
Consulting Services for Soil Investigation of Mahuli Bridge

BORE HOLE LOG BH07 *Contd…*

Contractor: S.R. Engineering & Exploration Pvt. Ltd.
Location: Siraha
Bore Hole No.: BH-7 (K 160+355.000)
Easting: 481840.03 m
Northing: 2947156.18 m
Diameter of BH: 100mm
Drilling Method: Rotary

GWT: 1.60 m
Drilling started: 2078/03/09
Drilling finished: 2078/03/10
Total Drilling depth: 25.00 m

Depth (m)	Layer Thick (M)	Soil Classification	Symbol	USCS	SPT / DCPT	Sample recovered	No. of SPT/DCPT Blows (Field Record) 0-15cm	15-30cm	30-45cm	SPT / DCPT N
15.50		Poorly Graded Sand with Silt		SP-SM	S.P.T					
16.50						Wash	12	17	17	34
18.00						Wash	12	17	19	36
19.50						Wash	13	18	21	39
20.00	11.00									
21.00		Silty Sand		SM		Wash	9	10	12	22
22.50						Wash	9	12	12	24
24.00	4.00					Wash	10	13	15	28
24.50		Well-Graded Sand with Sit		SW-SM		Wash	19	22	25	47
25.00	1.00									



Annex- II Static Pile Load Test of Mahuli Bridge

A
FINAL REPORT
ON
STATIC PILE LOAD TEST OF MAHULI BRIDGE
P6-PP3 WORKING PILE

Kathmandu, February 2022

SUBMITTED BY:	SUBMITTED TO:
N.S. ENGINEERING & GEO-TECHNICAL SERVICES PVT. LTD. JAWAGAL, LALITPUR, NEPAL (AN ISO 9001:2015 CERTIFIED COMPANY) TEL: -+977-1-5260121 E-MAIL: WE.NSENGINEERING@GMAIL.COM, INFO@NSENGINEERING.COM WEBSITE: WWW.NSENGINEERING.COM.NP	CHINA RAILWAY NO.2 ENGINEERING GROUP CO., LTD.

1.GENERAL

1.1 Introduction

Static pile load test is an in-situ test to observe the settlement behavior of a pile under an applied load and the most reliable method for determining pile capacities. This test is performed in cast in-situ pile under static axial compressive load testing for Mahuli Bridge P6-PP3 Working Pile.

1.2 Test Purpose

The purpose of the static pile load test is

- To determine the adequacy of pile capacity.
- To determine the load-settlement behavior of a pile, especially in the region of anticipated working load.

1.3 Related Specification

The test load is applied in the increments as specified or approved by the Engineer. These are generally be those recommended in

- Standard Specification of Roads and Bridges
- ASTMD1143_07

2. DETAILS OF TEST PILE

The test pile is cast in-situ piles. The location and test load are decided by the Consultant. The details of test piles are shown in the following table:

Table 1 Details of Test Pile

SN.	Bridge Name	Chainage	Pile ID	Design pile loads (KN)	Date of Casting	Date of Testing
				Pier		
1	Mahuli	K 160+ 355.012	P6-PP3 Working Pile	1056.83	16 Dec 2021	31 Jan 2022

<u>Additional Information</u>

RL of cutoff (Top) level of pile = 114.562 m

RL of testing level of pile = 117.56 m

3.TEST METHOD

The test was done by application of an axial static load to a single pile by compression method. In this type of test, compression load was applied to the pile top by means of a hydraulic jack acting directly opposite in reaction to the series of statically placed Kentledges loads. The loading and unloading process of these weights increments for increasing the loads and decrements for

N.S. Engineering & Geo-technical Services Pvt. Ltd.

KUNHWA BCL JV (PE) KATHMANDU, NEPAL 3/3/22

5. TEST PROCEDURE

5.1 Test preparation

The following preparations were done before commencing the test.

- Excavate or add fill to the ground surface around the test pile to the final design elevation.
- Cut off or build up the test pile as necessary to permit construction of the load-application apparatus, placement of the necessary testing and instrumentation equipment, and observation of the instrumentation.
- Remove any damaged or unsound material from the pile top and prepare the surface so that it is perpendicular to the pile axis with minimal irregularity to provide a good bearing surface for a test plate.
- Install a solid steel test plate at least 25 mm thick perpendicular to the long axis of the test pile that covers the complete pile top area. The test plate is spanned across and between any unbraced flanges on the test pile.

5.2 Loading Procedure

Based on the loading procedures, the load was applied in increment load. Each load increment and decrement were held for a specified interval of time. Readings of gross settlement, load, and time are taken and recorded immediately before and after the application of each load increment and decrement.

Following the application of each load increment and decrement, the load was maintained at the specified value for not less than the time shown on the lower portion of the table or until the rate of settlement is less than 0.25mm/60 min in every stage.

Table 2: Loading and Unloading procedure as per ASTM D 1143/D 1143 M-07

S. N	Designed load (%)	Minimum Holding time	Accumulated Time	Remarks
1	0	0		
2	25	60 minutes		≥ 60 minutes till the settlement rate is ≤ 0.25mm/hour
3	50	60 minutes	1 hour	"
4	75	60 minutes	2 hours	"
5	100	60 minutes	3 hours	"
6	125	60 minutes	4 hours	"
7	150	60 minutes	5 hours	"
8	175	60 minutes	6 hours	"

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9	200	5 hours	7 hours	till the settlement rate ≤ 0.25mm/hour and reaching at least 12 hours from the beginning of test
10	175	60 minutes	12 hours	≥ 60 minutes till the settlement rate is ≤ 0.25mm/hour
11	150	60 minutes	13 hours	"
12	125	60 minutes	14 hours	"
13	100	60 minutes	15 hours	"
14	75	60 minutes	16 hours	"
15	50	60 minutes	17 hours	"
16	25	60 minutes	18 hours	"
17	0		19 hours	

5.3 Measurement Procedure

During loading and unloading, the readings of time, load and settlement of pile head were taken and recorded for every increment and decrement at 0,1, 15, 30 and 60 minutes. Rate of loading and rate of unloading remains same.

5.4 Abandonment of load test

The test is discontinued if any of the following occurs:

- Pre-loading before the commencement of the test.
- Improper setting of datum.
- Faulty of pile cap or instability of the Kentledge.
- Faulty jack or gauge.
- Pile head crack or broken.
- Initial readings are incorrect.

5.5 Failure of test pile

If any of the following conditions is detected after the preliminary tests have been completed as stipulated above, the tested piles are judged to have failed or attained the ultimate load capacity.

- Pile material is broken.
- A settlement equal to 15% of the test pile diameter is recorded.
- The rate of settlement continues undiminished without further increment of load.

Table 3 Recorded Data of Static Pile Load Test

Elapsed Time	Read Time(min.)	Load (Tonnes)	Dial gauge Readings(mm)				Average Settlement (mm)	Rate of Settlement(mm/hr)	Remarks
			A	B	C	D			
8:00 AM	1	24.45	0.18	0.17	0.16	0.17	0.17		
	15		0.19	0.18	0.18	0.19	0.19		
	30		0.20	0.19	0.19	0.21	0.20		
	60		0.22	0.21	0.20	0.23	0.22	0.05	
9:00 AM	1	53.80	0.65	0.61	0.69	0.64	0.65		
	15		0.70	0.66	0.74	0.69	0.70		
	30		0.73	0.68	0.77	0.72	0.73		
	60		0.76	0.71	0.80	0.75	0.76	0.11	
10:00 AM	1	78.34	1.40	1.33	1.31	1.28	1.33		
	15		1.45	1.38	1.36	1.34	1.38		
	30		1.48	1.41	1.39	1.37	1.41		
	60		1.50	1.43	1.41	1.39	1.43	0.10	
11:00 AM	1	107.70	2.21	2.11	2.02	1.98	2.08		
	15		2.26	2.16	2.08	2.04	2.14		
	30		2.29	2.19	2.12	2.07	2.17		
	60		2.30	2.21	2.15	2.09	2.19	0.11	
12:00 PM	1	132.24	3.85	3.79	3.75	3.56	3.74		
	15		3.90	3.84	3.81	3.61	3.79		
	30		3.93	3.86	3.86	3.66	3.83		
	60		3.95	3.88	3.88	3.67	3.85	0.11	
1:00 PM	1	161.64	5.70	5.58	5.64	5.42	5.59		
	15		5.75	5.64	5.71	5.47	5.64		
	30		5.78	5.64	5.75	5.51	5.67		
	60		5.80	5.71	5.77	5.53	5.70	0.12	

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2:00 PM	1	186.14	9.20	9.16	9.26	8.78	9.10		Settlement rate >0.25mm/hr
	15		9.72	9.59	9.87	9.26	9.61		
	30		10.13	9.98	10.39	9.69	10.05		
	60		10.22	10.09	10.51	9.76	10.15	1.05	
	75		10.26	10.12	10.56	9.79	10.18	0.57	"
	90		10.29	10.14	10.60	9.81	10.21	0.16	
3:30 PM	1	215.59	15.41	14.99	15.35	15.26	15.25		Settlement rate >0.25mm/hr
	15		16.32	15.88	16.26	16.06	16.13		
	30		16.93	16.55	16.87	16.60	16.74		
	60		17.46	16.98	17.40	17.07	17.23	1.98	
	120		17.89	17.31	17.81	17.43	17.61	0.38	"
	180		18.24	17.52	18.13	17.68	17.89	0.28	"
	240		18.39	17.61	18.27	17.79	18.02	0.12	
	300		18.48	17.64	18.35	17.83	18.08	0.06	
8:30 PM	1	186.14	17.53	16.47	16.98	16.66	16.91		
	60		17.48	16.44	16.95	16.62	16.87	-0.04	
9:30 PM	1	161.64	16.91	16.07	16.51	16.19	16.42		
	60		16.84	16.05	16.46	16.15	16.38	-0.05	
10:30 PM	1	132.24	16.18	15.56	15.82	15.63	15.80		
	60		16.14	15.53	15.79	15.60	15.77	-0.03	
11:30 PM	1	107.70	15.28	14.79	14.95	14.83	14.96		
	60		15.23	14.77	14.92	14.81	14.93	-0.03	
12:30 AM	1	78.34	14.09	13.57	13.89	13.73	13.82		
	60		14.02	13.55	13.84	13.68	13.77	-0.05	
1:30 AM	1	53.80	12.67	12.34	12.51	12.47	12.50		
	60		12.59	12.31	12.45	12.43	12.45	-0.05	
2:30 AM	1	24.45	10.96	10.57	10.79	10.68	10.75		
	60		10.91	10.54	10.75	10.64	10.71	-0.04	

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8. Conclusions and Discussions

As per ASTMD 1143/D 1143M-07

The test load at which rapid, continuing, progressive movement occurs, or at which axial movement exceeds 15% of the pile diameter or width, is termed as failure load.

From the load settlement curve, the total settlement is found to be **18.08 mm,** which is within the permissible limit (i.e. 15% of pile diameter)

As per IS 2911 (part 4)

The safe load on a single pile shall be the least of the following (According to IS 2911 (part 4)):

For piles more than 600 mm diameter:

- Two-thirds of the final load at which the total displacement attains a value of 18 mm or maximum of 2 percent pile diameter whichever is less unless otherwise required in a given case on the basis of nature and type of structure in which case, the safe load should be corresponding to the stated total displacement permissible
- 50 percent of the final load at which the total displacement equal to 10 percent of the pile diameter in case of uniform diameter piles and 7.5 percent of bulb diameter in case of under-reamed piles.

From the load settlement curve, the total settlement is found to be **18.08 mm,** which is within the permissible limit. But as noted from the static load test of other bridge sites of the same project, the settlement of the piles were below 6mm. This pile has much higher settlement as compared to those piles. Besides, if we see at the rate of settlement data, it is observed that at 186.14 KN and 215.59 KN load, the rate of settlement is much higher (greater than 0.25mm/hr), which is questionable.

From the PIT test report, the pile do not haveany integrity defect. According to the geotechnical report, the Soil Investigation shows, the soil condition around this test pile mostly are poorly graded sand with silt. The reason for higher settlement of the pile may be due to the presence of some loose pocket of sandy soil along the shaft or toe of the pile thatwerenot detected during drilling. This may result in the actual friction are less than reported in geological reports.

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Annex – III Pile Integrity Test Report

1. GENERAL

1.1 Introduction

Integrity refers to the change in physical dimension, continuity of a pile, consistency of pile material. Pile integrity test is non-destructive test for evaluation of integrity in concrete piles. This procedure explains in detail the method statement conducting pile integrity test of cast in-situ pile of diameter 1000mm Mahuli Bridge.

1.2 Test Purpose

The purpose of pile integrity test is

- To determine the length of pile
- To evaluate the integrity of pile
- To check the consistency of pile material

1.3 Related Specification

The test shall generally be those recommended in ASTM C1740 Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations.

2. DETAILS OF TEST PILE

The location is decided by the Designer, Consultant or Employer. The details of test piles are shown in the following table:

Table 1 Pile Details

Location	Type	Code of Pile in Drawing	Pile Diameter mm	Pile length m	Date of Casting	Date of Testing
Pier	Cast in-situ	P6-PP3 Working Pile	1000	20	16 Dec 2021	17 Jan 2022

Additional Information

- The Test pile has 1.3m diameter up to a depth of 2.7m from the top followed by 1.0m diameter.
- The total estimated length of the pile during the test is 22.77m
- Required pile diameter = 1.0m
- RL of cutoff level of pile = 114.562m
- RL of Test level of pile = 117.26m

3. TEST METHOD

Pile Integrity Test can be applied to any concrete pile. The test is performed with a hand held hammer, an accelerometer or geophone and data acquisition and interpretation electronic instrument. Hammer is used to induce impact of low strain. An accelerometer of geophone measures the response of hammer impact. Data acquisition and interpretation electronic instrument display results.

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Table 2 Showing Beta Analysis

Design Diameter of Pile (m):	1.00
Constructed Pile head Dia (m):	1.30
Pile Depth of Critical Impulse Location (m)	2.73
Impact Impulse amplitude, Vi	0.52
Critical Impulse amplitude, V	0.18
Alpha	0.17
Beta	0.70
Beta increment due to large pile head	1.69
Modified Beta at Critical Location	1.19

7. CONCLUSIONS AND RECOMMENDATIONS

From the profile analysis of the Pile Integrity test data, following observations are made;

a) The prominent toe reflection at the depth of 22.77m from the pile top indicates the termination of pile. Hence the estimated pile length is 22.77m.

b) The critical necking is noted at the depth of 2.7m. This the point where the enlarged pile head ends. The beta value at the point is 1.19 (adopting beta=1 for pile of diameter = 1.0m).

c) The beta values in other portions are higher than 1.19. Hence the pile is under acceptable limit.

8. LIMITATIONS

- ✓ Data interpretation based on theoretical considerations is applicable only under ideal circumstances. On the other hand, if a large number of piles are tested on a single site, then a certain standard response may be observed which includes site dependent patterns caused by soil resistance effects. Unusual test results on any pile should be cause for concern and further investigations.
- ✓ It is possible to miss serious pile defects; it is possible to interpret defects as harmless cross sectional increases and it is possible that tensile reflections cause alarm even though a pile meets all requirements.
- ✓ The presence of a clear pile toe reflection does not necessarily confirm that the pile is of sound quality along the entire shaft.
- ✓ The Low Strain Method is limited when a high soil resistance masks the lower pile portion and when a wide impact pulse width is hiding deficiencies near the pile top.

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LIST OF PUBLICATION

- Gupta, S. K., & Dahal, B. K. (2023). “Finite Element Analysis on Load-Settlement Behavior of Axially Loaded Pile on Sand”. *Journal of Engineering Technology and Planning*, *4*(1), 72–81. https://doi.org/10.3126/joetp.v4i1.58443