TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

THESIS NO. PUL079MSGtE010

"Comparative Settlement Analysis of Transmission Tower Foundations Using PLAXIS 3D with a Proposed Settlement Evaluation Guideline"

by

Janak Kumar Thapa

A THESIS
SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE
DEGREE OF
MASTER OF SCIENCE IN GEOTECHNICAL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING
LALITPUR, NEPAL

APRIL , 2026

TRIBHUVAN UNIVERSITY

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

THESIS NO. PUL079MSGtE010

"Comparative Settlement Analysis of Transmission Tower Foundations Using PLAXIS 3D with a Proposed Settlement Evaluation Guideline"

by

Janak Kumar Thapa

A THESIS

SUBMITTED TO THE DEPARTMENT OF CIVIL ENGINEERING

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER IN GEOTECHNICAL ENGINEERING

DEPARTMENT OF CIVIL ENGINEERING

LALITPUR, NEPAL

APRIL , 2026

COPYRIGHT

The author has agreed that the library, Department of Civil Engineering, Pulchowk Campus, Institute of Engineering may make this thesis freely available for inspection. Moreover, the author has agreed that permission for extensive copying of this thesis for scholarly purpose may be granted by the professor(s) who supervised the work recorded herein or, in their absence, by the Head of the Department wherein the thesis was done. It is understood that the recognition will be given to the author of this thesis and to the Department of Civil Engineering, Pulchowk Campus, Institute of Engineering in any use of the material of this thesis. Copying or publication or the other use of this thesis for financial gain without approval of the Department of Civil Engineering, Pulchowk Campus, Institute of Engineering and author's written permission is prohibited. Request for permission to copy or to make any other use of the material in this thesis in whole or in part should be addressed to:

Head of Department

Department of Civil Engineering,

Pulchowk Campus, Institute of Engineering

Lalitpur

Nepal

INSTITUTE OF ENGINEERING

PULCHOWK CAMPUS

DEPARTMENT OF CIVIL ENGINEERING

The thesis titled **"Comparative Settlement Analysis of Transmission Tower Foundations Using PLAXIS 3D with a Proposed Settlement Evaluation Guideline"** prepared and submitted by Janak Kumar Thapa, (PUL/079MSGtE/010) in partial fulfilment of the requirements for the degree of Master of Science (M. Sc.) in Master's in Geotechnical Engineering has been examined by us and is accepted for the award of M. Sc. In Geotechnical Engineering by Tribhuvan University.

The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis report entitled **"Comparative Settlement Analysis of Transmission Tower Foundations Using PLAXIS 3D with a Proposed Settlement Evaluation Guideline"** submitted by (PUL/079MSGtE/010) in partial fulfillment of the requirements for the degree of Master in Geotechnical Engineering.

Supervisor:
Dr Ram Chandra Tiwari
Department of Civil Engineering
Pulchowk Campus, Lalitpur Nepal

External Examiner:
Dr Mohan Parsad Acharaya
NEA Engineering Company Ltd
Pulchowk, Lalitpur Nepal

Dahal.

Program Coordinator:
Dr Bhim Kumar Dahal
Department Of Civil Engineering
Pulchowk Campus, Lalitpur Nepal

Date: April, 2026

DECLARATION

I hereby declare that this study titled titled **"Comparative Settlement Analysis of Transmission Tower Foundations Using PLAXIS 3D with a Proposed Settlement Evaluation Guideline"**is based on my original research work. Related works on the topic by other researchers have been duly acknowledged. I owe all the liabilities relating to the accuracy and authenticity of the data and any other information included hereunder.

……………………………..

Janak Kumar Thapa
(PUL/079MSGtE/010)
MSc in Geotechinical Engineering
April 2026

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor “Dr. Ram Chandra Tiwari” for his continuous support, guidance and encouragement throughout my thesis journey. His valuable constructive suggestions, insights, and expert advice played a vital role in shaping this study and helping me to refine the work to a higher value. I am sincerely thankful for the time, patience, and motivation he provided during every stage of this study.

I am also grateful to Mrs Chattra Jora and Mrs Reymond Khadka for their generous help in the modeling processes. Their technical inputs and willingness to help whenever needed greatly contributed to the successful completion of this thesis. Without their support, several essential components of the research would not have been possible.

Sincere appreciation goes to the Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, for providing the necessary resources, facilities, and a supportive academic environment. The availability of software tools, laboratory data, and departmental cooperation enhanced the quality of the study.

Finally, I express my special thanks to my family, friends, and colleagues who helped me throughout this thesis journey. Their motivation, support and understanding have been a constant source of strength, enabling me to complete this study successfully.

Name: Janak Kumar Thapa
Roll No: (PUL/079MSGtE/010)

ABSTRACT

The serviceability and stability of transmission tower foundations are critically influenced by their settlement criteria under various subsurface conditions and loading. This research presents a comprehensive comparative settlement analysis of different types of transmission tower foundations using advanced three-dimensional finite element modeling in PLAXIS 3D, along with the development of a practical settlement evaluation criteria. The research focuses on commonly used transmission tower foundation types, such as isolated pad foundations, raft foundations, and pile foundations, subjected to vertical loading condition. Representative soil profiles, including homogeneous and layered soil conditions, are considered to simulate realistic field scenarios. Soil parameters are derived from standard geotechnical investigations and various literature. Numerical models are developed in PLAXIS 3D to analyze settlement behavior, stress distribution, and deformation characteristics of each foundation type. The influence of key parameters such as soil stiffness, foundation geometry is evaluated.

The results demonstrate significant variation in settlement performance among different foundation systems, with pile foundations generally showing improved settlement control in weak and layered soils, while shallow foundations perform adequately in competent ground conditions. Based on the numerical findings, a settlement evaluation guidelines are proposed to assist engineers in selecting appropriate foundation types and assessing allowable settlement limit for transmission tower structures.

This study contribute to improved design and analysis practices for transmission tower foundations by combining advanced numerical modeling with practical guideline development. The outcomes are expected to support safer, more economical, and performance-based foundation design, particularly in region with complex geotechnical conditions such as Nepal.

Keywords:

Settlement Analysis; Transmission Tower Foundations; Finite Element Method (FEM); Soil–Structure Interaction; Differential Settlement; Layered Soil; Numerical Modeling; Design Guideline; Load–Settlement Behavior; Eccentric Loading; Foundation Performance.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

PLAXIS 3D – Finite Element Software for Geotechnical Analysis

FEA – Finite Element Analysis

TTF – Transmission Tower Foundation

SF – Spread Footing

RF – Raft Foundation

PF – Pile Foundation

SPT – Standard Penetration Test

CPT – Cone Penetration Test

USCS – Unified Soil Classification System

Mohr–Coulomb (MC) – Linear Elastic–Perfectly Plastic Soil Model

Hardening Soil (HS) – Nonlinear Soil Model in PLAXIS

HSsmall – Hardening Soil Model with Small-Strain Stiffness

γ – Unit Weight of Soil

σ' – Effective Stress

$\sigma'v$ – Vertical Effective Stress

Pa – Atmospheric Pressure

E50 – Secant Stiffness in Triaxial Loading

Eoed – Tangent Stiffness for Primary Oedometer Loading

Eur – Unloading/Reloading Stiffness

Dr – Relative Density

OCR – Overconsolidation Ratio

GWT – Groundwater Table

PGA – Peak Ground Acceleration

g – Acceleration due to Gravity

SCF – Stress Concentration Factor

FOS – Factor of Safety

SSR – Strength Reduction Method (for stability in PLAXIS)

EL – Elastic Limit

FSI – Foundation–Soil Interaction

SET – Total Settlement

DSET – Differential Settlement

ULS – Ultimate Limit State

SLS – Serviceability Limit State

NBC – Nepal National Building Code

NEA – Nepal Electricity Authority

CSRS – Consolidation Settlement Response Surface

K0 – Coefficient of Earth Pressure at Rest

$\Delta\sigma$ – Stress Increment due to Foundation Loading

qnet – Net Bearing Pressure

Qult – Ultimate Bearing Capacity

1. INTRODUCTION

1.1 Background

The rapid growth of electrical energy demand and the expansion of hydropower generation in Nepal have necessitated the development of an efficient and reliable transmission network. Transmission lines play a vital role in transporting electrical energy from generation stations to load centers, and their performance largely depends on the stability and safety of transmission tower foundations (NEA, 2020). Among various performance factors, settlement behavior of foundation is one of the most crucial aspect affecting the serviceability and structural integrity of transmission towers (Das, 2010).

Complex loading conditions, including vertical loads, lateral forces due to wind, and uplift forces caused by conductor tension are acting on transmission towers. These loads are transferred to the ground through foundations, which may experience settlement which depends on soil properties and loading conditions. Differential settlement may lead to misalignment of conductors, tower tilting, failure of the transmission system and increased structural stress (IS 1904, 1986). So, accurate evaluation and prediction of settlement are essential for the safe design and long-term performance of transmission tower foundations (Arora, 2004).

In geotechnical engineering at present, numerical modeling techniques based on the finite element method (FEM) have gained significant importance. Advanced software such as PLAXIS 3D allows engineer to model appopriate soil–structure interaction and analyze complex foundation behavior under different loading and soil conditions (B.S 2023). Compared to conventional analytical methods, numerical modeling provides more accurate and detailed insight into settlement characteristics, stress distribution and deformation patterns of foundations (Murthy, 2002).

Despite the availability of advanced tools, there is still a lack of standardized settlement evaluation criteria especifically for transmission tower foundations, particularly in developing countries like Nepal where geological conditions are varied highly. The eastern region in Nepal, specially the areas extending from Ilam to Jhapa, presents diverse geotechnical conditions, ranging from soft alluvial soils in the Terai region to hilly and residual soils along the mid-hills (DMG, 2019). These non uniform soil profile significantly influence the settlement behavior of foundations and demand careful design and analysis.

The present study which is focused on transmission line project such as the Godak–Soyak 132 kV and Godak–Anarmani 132 kV transmission lines, which are part of the broader Kabeli corridor transmission network. This corridor plays a crucial role in evacuating electricity generated from hydropower projects in eastern Nepal and transmitting it to major substations (NEA, 2020). The transmission line network extends through multiple districts, including Panchthar, Ilam, and Jhapa, connecting substations as like Godak and Lakhanpur, and facilitating efficient power distribution across these region.

The Kabeli corridor transmission line is strategically important as it connects hydropower production area with load centers and strengthens the national grid. The alignment passes through varing terrain, including river valley, steep slope, and plain area, which introduce challenge in foundation design and construction. In particular, section between Godak (Ilam) and Damak (Jhapa) has experienced issue such as flood-induced damage to transmission tower, highlighting the importance of foundation design and proper settlement analysis (NEA, 2021).

Through these challenges, it becomes important to conduct a comparative study of different type of transmission tower foundation under real site conditions. Various foundation types, such as isolated pad foundations, raft foundations, and pile foundations, exhibit different settlement behaviors depending on loading characteristics and soil conditions (Poulos, 2001). A comparison of these foundation system can help to identify the most suitable foundation type for specific geotechnical condition.

This research aims to perform a detailed settlement analysis of transmission tower foundations using PLAXIS 3D. The study considers various soil profile and loading scenario with respect to the Godak–Soyak and Godak–Anarmani transmission line sections. The numerical analysis focus on evaluating total settlement, differential settlement, and load–settlement relationships of different foundation types.

Further, with respect to analytical results, this research proposes a practical settlement evaluation criteria for transmission tower foundations. These criteria is expected to help engineers in selecting appropriate foundation type and assessing allowable settlement limit under various soil and loading conditions (IS 8009,1976).

This is particularly important in the context of Nepal, where site-specific variable and limited design criteria often pose challenge in foundation engineering.

This research integrates advanced numerical modeling with real life engineering application to address critical gap in transmission tower foundation design. By focusing on real project site in eastern Nepal and incorporating site specific soil condition the study aims to contribute to safer, practical and more economical transmission infrastructure development.

Statement of the Problem:

The efficient and safe run of electrical transmission systems mainly depends on the stability of transmission tower foundation. In the context of Nepal, rapid expansion of hydropower project has led to the development of several high voltage transmission lines including both the Godak Soyak 132 kV and Godak Anarmani 132 kV lines that extend from Ilam to Jhapa. These projects posses diverse geological and topographical conditions, ranging from hilly terrain in Ilam to alluvial plains in Jhapa. Such variable in subsurface conditions poses high challenges in the design and performance of transmission tower foundation, particularly with respect to settlement behavior.

Settlement of foundation is a critical geotechnical concern that directly affects serviceability and structural safety of transmission tower. The total settlement or uneven settlement can lead to tilting of towers, dis-alignment of conductors of additional stress in structural member and in extreme cases, structural failure. In transmission line system, even minor deviations in tower alignment can disrupt power transmission efficiency and increase maintenance requirements. So, accurate prediction and control of settlement are essential for ensuring the long-term performance and long run of transmission infrastructure.

In real life the foundation design for transmission tower in Nepal often depends on simplified analytical methods and empirical correlations derived from standard soil test. While these approach provide a basic understanding of soil behavior they cannot sufficiently capture the complex of soil structure interaction under varying loading conditions. Transmission towers are subjected to a combination of vertical loads, lateral forces, and uplift forces often acting regularly. Additionally, eccentric loading conditions are common due to conductor tension, uneven terrain and wind effects.

These factors contribute to complex stress distribution and deformation patterns in the soil which cannot be fully addressed by conventional design methods.

The eastern region of Nepal is particularly along the alignment from Ilam to Jhapa which show variation in soil types including residual soils in hilly areas, colluvial deposits along slopes, and soft alluvial soils in the Terai region. In hilly regions, foundations may be constructed on sloping ground with heterogeneous soil conditions, leading to differential settlement. In contrast, in the Terai region, soft and compressible soils may result in high settlement even under moderate load. The presence of potential flooding, groundwater and seasonal variations further complicate the behavior of foundation system.

Field observation and project report from transmission line construction in eastern Nepal have indicated issue such as foundation instability, excessive settlement, and damage to tower structure in various locations. In some cases flood event and weak soil condition have contributed to the failure or displacement of transmission tower. These challenges highlight the need for a highly reliable and comprehensive approach to settlement analysis and foundation design.

Although advanced numerical modeling tools such as PLAXIS 3D enables simulating realistic soil structure interaction, their application in transmission tower foundation design in Nepal remains limited. Many engineering practice still depend on conservative assumption or simplified calculation, which may either underestimate or overestimate settlement behavior. Underestimation can lead to unsafe design, while overestimation can result in unnecessarily expensive foundation system.

Also, there is a lack of specific and practical settlement evaluation criteria guided for transmission tower foundation under Nepal condition. Existing codes and standard primarily focus on building foundation and may not adequately address the unique loading conditions and performance requirements of transmission tower. As a result, engineers often face difficulties in selecting appropriate foundation type and determining allowable settlement limit for different site condition.

With these challenges, there is a clear need for a systematic and comparative research of settlement behavior of different transmission tower foundation types under practical soil and loading conditions. Such a study should incorporate advanced numerical modeling technique to provide accurate prediction of settlement and to better understand the influence of key parameter such as soil properties, foundation geometry, and loading condition.

1.2 Research Gap And Problem Statement

The main problem addressed in this research is the lack of a comprehensive and practical framework for evaluating and comparing the settlement behavior of transmission tower foundation in changing geotechnical conditions. Despite the settlement analysis, there is limited research focused specifically on transmission tower foundations in the context of Nepal's changing geology.

Present studies in geotechnical engineering are focused on building foundations, embankments, or other civil structures, with relatively less attention given to transmission tower foundation. Further, transmission towers differ significantly from conventional structure in terms of loading conditions, structural configuration, and performance requirement. For example, transmission towers are more vurnable to differential settlement and require strict on displacement to maintain proper alignment of conductor.

For the Godak Soyak and Godak Anarmani transmission line projects, the variation in terrain and soil conditions necessities the use of different type of foundations, such as pad foundations, raft foundations, and pile foundations. However, selection of these foundation types is often based on experience or general guidelines other than detailed analysis. This can lead to suboptimal design choice either compromising safety or increasing construction costs.

Another important gap is the absence of a standardized settlement evaluation guideline that integrates numerical analysis results with practical design consideration. Engineers need Simple yet reliable method to assess settlement and make informed decision during the design and construction stages Without such criteria, there is a risk of inconsistency in design practices and potential performance issues in the field.

Also, the use of advanced numerical tools like PLAXIS 3D provides a platform to simulate realistic site conditions and analyze complex soil structure interactions. still, the results obtained from such analysis are often not translated into practical design recommendation. There is a need to bridge the gap between advanced analysis and practical application by developing guidelines that can be easily used by trainee engineers.

1.3 Objectives

The objectives of this paper are to compare the settlement of transmission tower foundations in different soil conditions through PLAXIS 3D, compare performance of various types of foundations and come up with practical recommendations on the choice of foundation based on their settlement.

Table 1.1 : Settlement Analysis Of Soil

Soil Type (Including Similar Soils)	**Foundation Type**	**PLAXIS 3D Settlement (mm)**	**Permissible Limit (mm)**	**Criteria Check**	**Performance**	**Preferred Foundation**
Soft Clay *(marine clay, organic clay, silty clay, peat, highly compressible clay)*	Spread Footing		50–65 mm			
	Raft Foundation		50–75 mm			
	Raft + Pile		10–25 mm			
Stiff Clay *(overconsolidated clay,*	Spread Footing		50–65 mm			

Soil Type (Including Similar Soils)	Foundation Type	PLAXIS 3D Settlement (mm)	Permissible Limit (mm)	Criteria Check	Performance	Preferred Foundation
clayey silt, hard clay, partially weathered clay)						
	Raft Foundation		50–75 mm			
	Raft + Pile		10–25 mm			
Sand *(silty sand, gravelly sand, dense sand, alluvial sand)*	Spread Footing		25–40 mm			
	Raft Foundation		25–40 mm			
	Raft + Pile		10–25 mm			

Main Objective

To perform a comparative settlement analysis of transmission tower foundations with sophisticated 3D finite element modeling in PLAXIS 3D, and to create useful settlement evaluation guidelines to practical transmission line projects.

Specific Objectives

- To conduct in-depth settlement analysis of the foundation of transmission towers in different soil types with the advanced 3D finite element modeling in the PLAXIS 3D, to encapsulate the practical simulation and credible outcomes.
- To evaluate and compare the performance of different foundation types, and to identify key geotechnical and structural factors influencing settlement behavior.
- To develop a practical settlement evaluation guideline and engineering recommendations for selecting safe, economical, and efficient foundation systems in real transmission line projects.

1.4 Scope

This research relies on the assessment of the settlement Actions of transmission tower foundations in varying soil conditions by the use of numerical modeling in PLAXIS 3D. The study is restricted to vertical loading situations and Concentrates on the interaction of the soil structure in order to determine settlement performance.

The research will involve:

- Numerical simulation of foundations of transmission towers with the aid of finite element software PLAXIS 3D.
- Settlement Action analysis under the different types of soil e.g. stiff clay, soft clay, sandy soil, etc.
- Comparison study of three foundations: spread footing, raft foundation and piled raft foundation.
- Evaluation of settlement results and allowable limits and standard design.
- Formulation of a workable guidelines on how to choose the right type of foundation depending on the settlement performance.

The research will not deal with:

- Field testing or validation of full-scale experimental results
- Full-scale experimental results field testing or validation.
- Dynamic loading provisions like during earthquake, vibration caused by wind, or cyclic loading.
- Structural transmission towers (only foundation behavior is taken into

account) detailed design.

- Economic analysis or Cost comparison of various classes of foundation systems.
- Construction methods, material requirements, or operation related matters.
- Impacts of variation in ground water other than modeling conditions.
- Time dependent soil behavior, e.g., creep or consolidation not in the scope of the simulation (unless assumption of model)

1.5 Limitations

- The research is mainly founded on numerical modeling with the PLAXIS 3D and the accuracy in the results are based on assumptions in terms of the boundary conditions, the soil constitutive model and input parameters that might not necessarily reflect the realistic behavior of the field.

- The study relies on the existing geotechnical information of the projects of Godak-Soyak and Godak-Anarmani 132 kV transmission lines; and the inadequacy of the data in terms of quality, quantity and localization can impact the accuracy of the soil parameter employed.

- The profile of the representative soils are taken rather than modeling all the tower locations along the IlamJhapa profile, thus, localized soil differences like weak areas or heterogeneity cannot be taken into account completely. Avoids: The analysis is only restricted to the most popular type of foundation (pad, raft and pile) and does not cover the specialized or hybrid foundation system that might be needed due to specific site conditions.

- The research is founded on the conditions of static loading (vertical and eccentric loads) and it is unable to take into consideration dynamic effects like vibration, seismic loading, or cyclic loading that are relevant in earthquake prone areas such as Nepal.

- The long-term settlement behavior, creep and long-term consolidation, is simplified and might not fully depict the time-dependent soil response. The simplified manner of considering groundwater conditions does not take into account seasonal changes, changes in pore water pressure or the effect of flooding prevalent in the Terai region.

- The modeling is based on the ideal construction conditions and homogeneous material properties, but real-world construction practices and the variability of materials can affect the performance of the foundation.
- The experiment does not involve complete full field validation and load testing; hence, there is no direct validation of the results against real time field measurements.
- The suggested settlement evaluation criterion relies on numerical outcomes and a little information about the project and might need additional validation and calibration before they can be used on real large-scale.

2. LITERATURE REVIEW

2.1 General Overview of Settlement in Geotechnical Engineering

Settlement in geotechnical engineering is the downward movement of a foundation or structure vertically as a result of deformation of the soil beneath the foundation or structure under the influence of applied loads. It is an important aspect that affects the serviceability, stability and long term performance of structures. Settlement mostly takes the form of total settlement and differential settlement, in which case differential settlement is more serious because it may lead to structural stress, tilting, and malfunctioning.

The classical geotechnical literature has extensively investigated the behavior of settlement. Settlement as Terzaghi, et al. (1996) state must be managed within acceptable tolerances so that the structure is safe. Components of classical settlements are as follows:

- Immediate (Elastic) Settlement - takes place right away when load is applied.
- Primary Consolidation Settlement – because of the expulsion of pore water that takes place in saturated soils.
- Secondary Compression (Creep) - constant stress deformation with time.

These classical theories give a basic understanding, but in most cases cannot be used in complex interaction of soil-structure problems (Das, 2010). In the past, it has been stressed that differential settlement is more important than total settlement and more specifically, when it comes to transmission towers, small tilting can cause alignment (Arora, 2004). Tiwari (2025) emphasized that the foundation of transmission towers needs stringent settlement check to the conventional buildings because of eccentric loading and sensitivity to conductor geometry.

2.2 Settlement Behavior of Transmission Tower Foundations

Combined loading conditions in transmission tower includes:

- Vertical loads (self-weight and conductor load)
- Lateral loads (wind forces)
- Uplift forces (because of tension in conductors)

These loads lead to non-uniform settlement patterns and complicated stress distribution.

Pad footings (Shallow foundations) is commonly applied in competent soils because of simplicity and cost-effectiveness (Murthy, 2002), but it is overly affected by weak soil resulting in excessive settlement. Raft foundations alleviate contact pressure with the loads distributed over a large area whereas pile foundations impose the loads to deeper and stronger strata and results in improved settlement control (Poulos, 2001). According to Tiwari et al. (2025), to uneven settlement is due to eccentric loading, design is complex and critical to transmission towers.

2.3 Settlement Theories in Geotechnical Engineering

Prediction of settlement is grounded on classical and sophisticated theories:

2.3.1 Elastic Theory

Settlement is computed based on the ideas of elasticity on the assumption that soil is an elastic substance. It is primarily applied to cohesionless soils and estimation of instant settlement.

2.3.2 Consolidation Theory

This theory was developed by Karl Terzaghi and it explains on the settlement in saturated cohesive soils, where the reduction of volume was experienced due to the expelled pore water pressure over time.

2.3.3 Secondary Compression Theory

Creep deformation of accounts after primary consolidation has occurred, especially in soft clay and organic soils.

2.3.4 Numerical Methods (FEM)

In modern methods, finite element techniques (FEM) are employed and these techniques are defined to simulate an interaction between soil and structure. The software such as PLAXIS 3D enables realistic modelling of nonlinear soil behaviour, staged building and loading condition with complicated behaviour.

2.4 Application of PLAXIS 3D in Settlement Analysis

PLAXIS 3D, a finite element software, is widely used for settlement analysis. It allows:

- Simulation of real soil behavior
- Modeling of complex geometries and loading
- Consideration of staged construction

Constitutive models which are used in general includes:

- Mohr–Coulomb Model – simple and widely used
- Hardening Soil Model – more accurate for nonlinear behavior

Bentley Systems emphasized that accurate settlement analysis depend on suitable selection of parameter. Tiwari (2025) explains that application of PLAXIS 3D in transmission tower analysis in Nepal is still limited, which shows a research gap.

2.5 Influence of Soil Types on Settlement

Soil properties can cause a vital role in settlement analysis:

- Soft Clay – high compressibility → large settlement
- Silt – moderate compressibility, sensitive to water
- Sand (Loose/Dense) – low settlement, mostly immediate
- Gravel – very low settlement due to high stiffness

In layered soils, settlement becomes more complicated due to change in stiffness, which can cause differential settlement.

Tiwari et al. (2025) described type of soil along the Ilam–Jhapa corridor as lik:

- Residual soils
- Colluvial deposits
- Alluvial deposits

Each exhibits various settlement characteristics. Groundwater level and seasonal variation further influences behaviour of settlement.

2.6 Settlement Methods for Transmission Tower Footings

Settlement analysis of tower foundation can be done by using:

2.6.1 Analytical Methods

- Elastic theory equations
- Consolidation equations
- Empirical correlations

2.6.2 Field Methods

- Plate load test
- Standard penetration test (SPT)-based correlations
- Cone penetration test (CPT)-based methods

2.6.3 Numerical Methods

- Finite Element Method (FEM) using PLAXIS 3D
- Provides detailed insight into stress–strain behavior

Among them, FEM is most applicable for transmission towers due to complex loading and soil condition**.**

2.7 Comparative Studies of Foundation Types

Comparative studies show:

- Spread footing → economical but suitable only for strong soils
- Raft foundation → reduces settlement by load distribution
- Pile foundation → effective in weak soils

Tiwari et al. (2025) identified that piled raft foundation perform better in highly compressible soil.

2.8 Settlement Criteria and Evaluation Guidelines

Codes such as IS 1904 (BIS, 1986) provide permissible settlement for buildings, but are not fully applicable to transmission towers due to their sensitivity to alignment.

Tiwari et al. (2025) emphasized the need for strict differential settlement control and development of practical evaluation guidelines in Nepal.

2.9 Research Gap and Relevance to Study Area

Regardless excessive global research, limited studies focus on transmission tower foundation in Nepal**,** particularly along the Ilam–Jhapa corridor.

Key research gaps that occur in transmission tower include:

- Advance numerical tools with limited application
- Localized settlement guidelines are rare.
- Gap that exists between theoretical analysis and field practice

This study aims to address these gaps by providing a practical evaluation guideline and comparative settlement analysis**.**

3. STUDY AREA AND DATA

3.1 STUDY AREA

The region of study in this study is that of the Godak-Soyak 132 kV and Godak-Anarmani 132 kV transmission line corridors, which is found in the hilly district of Ilam to the Terai district of Jhapa in the eastern part of Nepal. This corridor is a geographically heterogeneous and geotechnically complicated area that can be extremely useful in studying the settlement characteristics of transmission tower foundation.

The alignment compares the extensive variety of topography, such as steep and undulating hills along Ilam, transitional foothill areas, and flat alluvial plains along Jhapa. Every type of terrain presents its own difficulties concerning the design of the foundation, the possibility of its construction, and the settlement performances.

The Ilam section has mostly residual soils which were formed due to weathering of rocks. These soils are heterogeneous, changeable in strength and responsive to changes in moisture levels and therefore, prediction of settlement is more challenging and there is uncertainty.

The intermediate zones in between Ilam and Jhapa mainly consists of colluvial and mixed soil deposit. These soils are basically loose, poorly graded, and highly variable, which increases the risk of differential settlement and uneven foundation performance under loading.

In the Jhapa region, located in the Terai belt of Nepal, subsurface conditions are mainly dominated by alluvial deposits basically consisting of clay, silt, and sand layers. These soils are typically more compressible and prone to higher settlement, especially under sustained loads and varying groundwater conditions.

Seasonal climatic conditions, due to heavy monsoon rainfall, heavily influence the geotechnical behavior of the area. Increased soil moisture and varying groundwater levels during the monsoon season effect soil strength, compressibility, and settlement characteristics. Additionally, the presence of rivers, drainage channels, and flood-prone areas along certain sections of the alignment makes complicated foundation design by increasing the erosion risk, lowering bearing capacity, and increasing settlement.

The selected transmission line projects are important for power transmission in eastern Nepal, connecting hydropower generation sources to load centers and contributing to stability of national grid.

Due to the varing terrain and soil conditions along the alignment, different types of foundations are required at various locations. This makes the study area highly appropriate for conducting a comparative settlement analysis of various types of foundation systems under practical field conditions.

3.2 Geological and Seismic Characteristics

The study area lies in a geologically complex region influenced by both hilly and alluvial formations. The Ilam region is characterized by weathered rock and residual soil deposit, while Jhapa is dominated by recent alluvial soil formation.

The geological variability result in layered soil profile with highly differences in compressibility, stiffness and strength. Such variations are critical factors influencing behavior of differential settlement.

The region also falls within a seismically active zone of Nepal. Seismic zone factors must be considered in foundation design, as earthquake-induced ground motion can influence soil behavior and long-term settlement performance.

A geological map, seismic zoning map, and satellite imagery of study area are shown in Figure 3.1. & Figure 3.2.

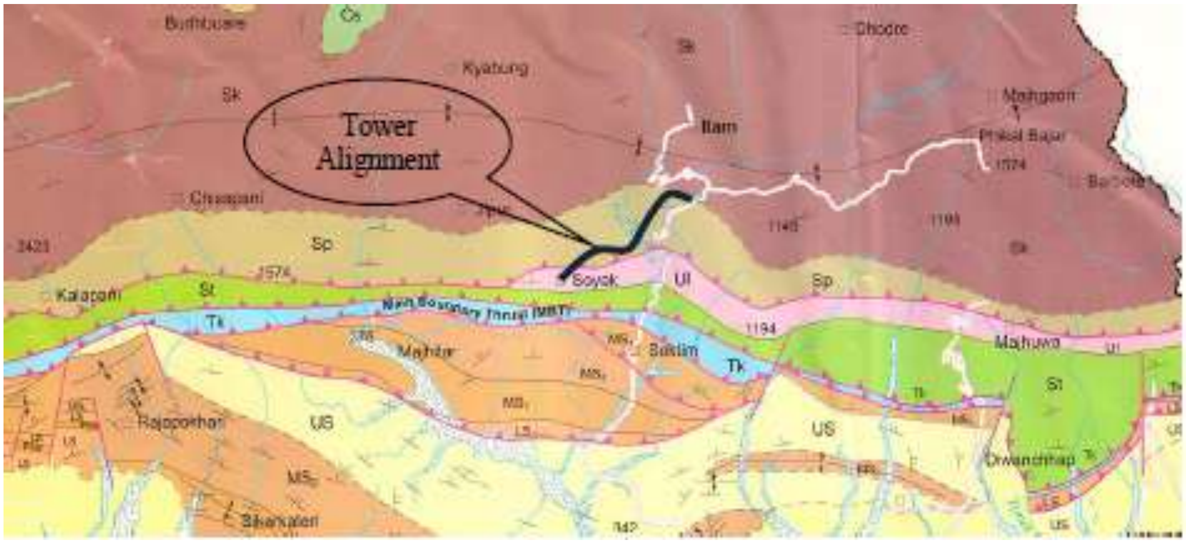


Figure 3.1: Geological Map of Study Area

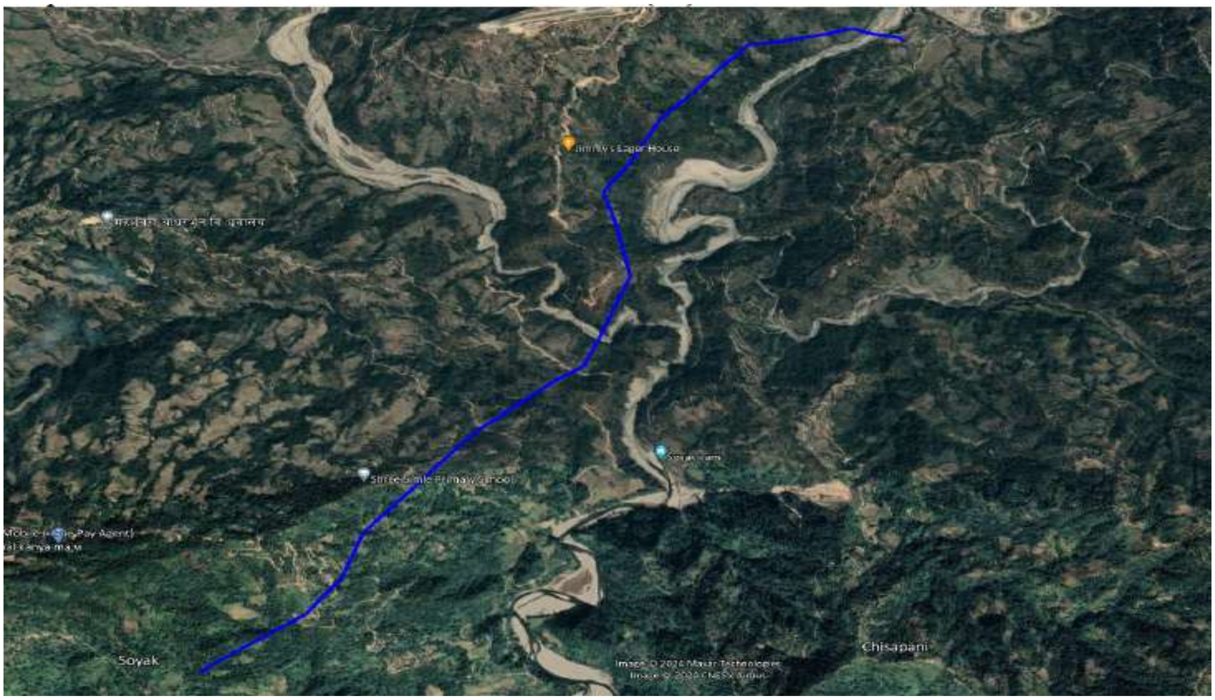


Figure 3.2: Google Map of Study Area

3.3 Data Collection

The data collection process involves systematic collection of geotechnical, topographical and structural data required for numerical modeling and settlement analysis of transmission tower foundations.

The primary objective was to obtain site based soil parameters, site characteristics, and loading conditions corresponding to tower location in Ilam Municipality (Ward 9, Ward 10 – Godak, and Ward 11 – Soyak).

3.3.1 Collection of Geotechnical Investigation Data

Geotechnical data were obtained through borehole logs, field investigation report, and laboratory test result were conducted during the transmission line project.

The borehole data includes:

- Stratification of soil and thickness of layer
- Groundwater table depth
- Standard Penetration Test (SPT-N) values
- Visual soil classification

- Soil types identification (clay, silt, sand, gravel, mixed soils)

Laboratory test data were analyzed to determine key engineering properties, which includes:

- Unit weight
- Atterberg limits
- Specific gravity
- Grain size distribution
- Cohesion (c)
- Angle of internal friction (φ)
- Compressibility parameters

These parameters are essential for selecting appropriate constitutive models such as the Mohr–Coulomb model and Hardening Soil model in finite element software PLAXIS 3D. The borehole locations used in this study are presented in Figure 3.3**.**

Figure 3.3: Location of Borehole

3.3.2 Collection of Topographical and Site Condition Data

Topographical and site condition data are extracted from project design documents and field survey. These included:

- Elevation of ground at tower locations
- Surface slope conditions, especially in hilly regions (Godak and Soyak)
- Transmission line alignment and accessibility
- Existing ground cover, vegetation, and drainage patterns

These data were used to establish realistic ground profiles and boundary conditions in the numerical models.

3.3.3 Collection of Tower Loading Data

Foundation loading data are extracted from structural drawings and loading schedule of transmission line project.

The loading data collected are as follows:

- Horizontal loads (wind forces and line tension)
- Vertical loads (conductor loads and tower self-weight)
- Design codes factored load combinations
- Torsional forces that act on the foundation

These loads were applied to all foundation types to ensure a fair comparison of behavior of settlement.

3.3.4 Data Validation and Screening

Collected data were carefully analyzed and validated so that completeness, accuracy and consistency can be maintained.

Methods used for validation are as follows:

- Field and laboratory data cross-checking
- standard empirical correlations use (e.g., SPT–φ relationships)
- Established geotechnical charts and guidelines reference
- Nepal-specific geotechnical data comparision

Along with validation, final soil parameters were prepared for PLAXIS 3D numerical model input.

4. Methodology:

This paper compares a numerical model based research design to compare and assess the settlement behaviour of transmission tower foundations in layered soil and loading conditions along the Godak-Soyak 132 kV and Godak-Anarmani 132 kV transmission line corridors between Ilam and Jhapa in eastern Nepal. The investigation starts with the problem statement, which involves the necessity of comparison of foundation performance in various geotechnical conditions, and then the selection of a viable study area with a variable topography and soil.

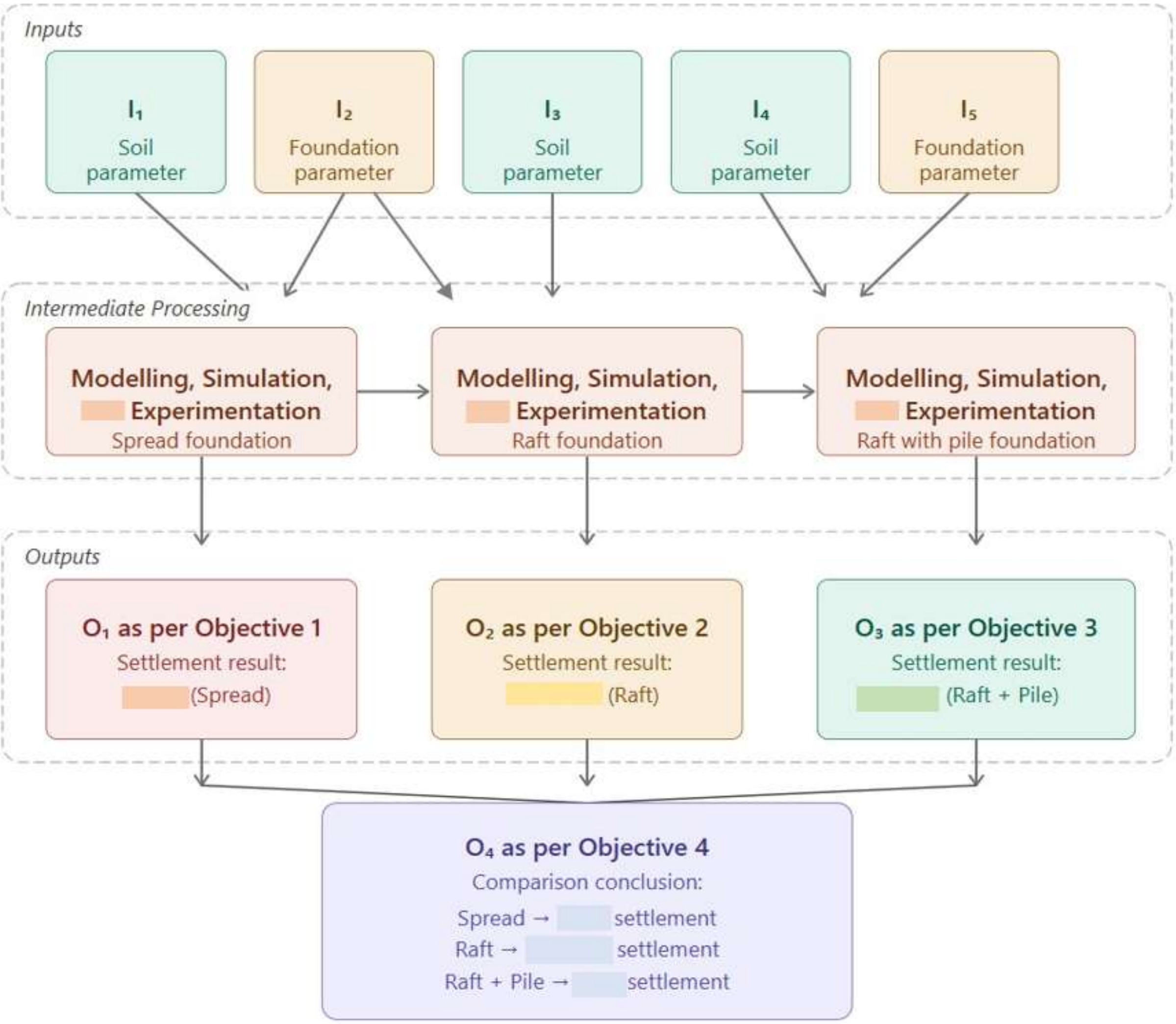
The research methodology entailed organized gathering and examination of data of geotechnical investigation reports, such as soil classification reports, borehole logs and laboratory test outcome. These data are incorporated to create realistic conditions of subsurface and also to find out the required engineering parameters that are analyzed. Representative soil profiles are prepared based on the information gathered, and this is meant to depict the ground situation that is usually experienced along the alignment such as residual soils in the hilly areas of Ilam, colluvial deposits in the transitional area and alluvial soil in the Terai plain of Jhapa. Laboratory results are then used to analyze soil parameters, empirical correlations, and standard geotechnical practice and suitable constitutive model like Mohr-Coulomb model and Hardening Soil model are chosen to model behavior of soil.

After designing a soil profile, the commonly used transmission tower foundation types, i.e. raft foundations, spread (pad) foundations and pile or piled raft foundations are chosen to be analyzed. These foundations have geometric dimensions and material properties that are specified consistently to allow making a fair and reliable comparison of the performances. PLAXIS 3D is then used to develop three-dimensional numerical model of the chosen foundation system with realistic stratification of soils, proper boundary conditions, and fine mesh generation to provide a realistic picture of the condition of field.

The interaction of soil-structure is included in the analysis in the form of modeling the interface between the foundation and the surrounding soil, enabling realistic simulation of the mechanism of load transfer and deformation behavior. The foundation is loaded under different conditions based on project design data, such as vertical load as a result of tower self-weight, horizontal loads as a result of wind and conductor forces, eccentric loading. conditions, and uplift forces whereever necessary.

These loading scenarios are applied in stage to simulate actual construction sequence and operational conditio.

The numerical simulations is performed step-by-step, beginning with the generation of initial stress condition, followed by activation of soil layer, foundation elements installation, and gradual load application. The staged analysis ensure that the development of settlement, stress distribution, and deformation pattern is captured practically. Key output from the simulation, including total settlement, differential settlement, load–settlement relationship, stress distribution, and deformation characteristics are obtained and analyzed for each foundation type under various soil condition.



Flow Chart

4.1 Settlement Analysis

Settlement analysis is an important element of assessing the stability and performance of transmission tower foundations, since even small vertical movements can have a significant impact on tower geometry, total structural safety and conductor tension. Settlement is a downward movement of a foundation under loads of applied loads, and it varies according to the type of foundation, compressibility of the soil, the nature of loads and interaction of soil-structure. In the case of transmission towers where vertical, eccentric and lateral loads are generally encountered, the behavior of settlement is necessary to provide serviceability and long-term service.

Settlement usually take place in three ways, including immediate (elastic) settlement, primary consolidation settlement, and secondary compression (creep). Elastic deformation during loading causes immediate settlement of the soil and this occurrence is usually seen in cohesionless soil like sand and gravel. Consolidation settlement takes place in fine-grain soils like clay which is saturated and the pore water pressures are removed causing gradual settlement in the long run. Settlement of secondary settlement can take place in organic soils or extremely soft clay as a result of long-term viscous deformation. Transmission tower in soft or layered soil profile can have a combination of above settlement mechanism. The magnitude and distribution of settlement is extremely dependent on the geometry and type of the foundation.

Spread footing (commonly found in transmission towers) is load-bearing contact with shallow layers of soil, but can experience considerable settlement in loose or soft soil and result in the individual legs of transmission towers moving differently. Raft foundations spread the load across a better area and they also tend to minimise overall settlement hence are applicable in moderately compressible soil. Pile foundation places transfers to deeper and stiffer soil layer using end bearing and skin friction and this causes minimal settlement when the top layers are weak. Nonetheless, pile foundation is more expensive to construct, and more technical.

Numerical modeling has played a critical role in forecasting settlement behavior in a better way compared to the traditional empirical method. PLAXIS 3D is a finite element software that enables the interaction of soil structure in detail, using a nonlinear relationship of soil behavior, stratified soil profile, realistic tower loading, and foundation complex geometry. By the method of numerical simulation, engineers are able to study the immediate and long-term settlement, stress distribution underneath the foundation and compare the performance of various types of foundations under the same soil condition. The method increases the accuracy of foundation design by detecting the possible issues like uneven settlement, stress concentration, and insufficient stiffness of the underlying soil.

Settlement analysis is of great essence in the context of the transmission tower design in Nepal, whereby, depending on the soil conditions, the soil is either soft alluvial deposits, silty sands or layered soil layers. According to many Nepal Electricity Authority (NEA) projects, extensive settlement or tilting of tower legs have been noted, and systematic and quantitative assessment of foundation options is required. Engineers can also evaluate the settlement behavior using PLAXIS 3D to see which type of foundation is appropriate to be used either the shallow or deep foundation type to guarantee an acceptable performance.

Consequently, settlement analysis furnish a definite ground on which one can compare the spread footings, raft foundations, and pile foundations in deformation properties and bearing capacity. The information gained through numerical settlement assessment is directly valuable to more economical, safer, and more robust transmission tower foundation design.

4.2 Plaxis 3D

Plaxis 3D They use an advanced finite element program, PLAXIS 3D, which is commonly applied in geotechnical and foundation engineering, to simulate the settlement of transmission tower foundation under varying soil and additional loading. The software allows realistic simulation of soil structure interaction through the summation of three-dimensional stress state, layered soil profile, non-linear soil constitutive model and complex foundation geometry. In this study, a comparative analysis of the various foundation types: spread footing, raft foundation and pile foundation under the same tower load and soil parameter is to be done using PLAXIS 3D. The numerical analyze enable closer observation of vertical settlement, differential displacement, and redistribution of stresses beneath every type of foundation. PLAXIS 3D were also used to enable the study of the mechanism of load transfer, which is made of end-bearing, skin friction and bearing pressure distribution at foundation-soil interface. The software can help us understand the overall tower performance by simulating three-dimensional response of the soil mass to determine how changes in foundation geometry and stiffness will impact the overall performance of the tower. This method allows high accurate assessment in comparison to the traditional analytical or empirical methods of analysis, especially when it comes to transmission towers; loading is often non-uniform and eccentric. The numerical modeling that will be conducted in PLAXIS 3D is a significant aspect of this research, as it will enable a direct comparison of settlement behavior in different foundation systems under the controlled and consistent loading conditions. Finally, the use of PLAXIS 3D improves the capacity to determine the most effective and stable type of foundations used in transmission tower structure, which leads to the safer, cost-effective and resilient in the long term design practice in the geotechnical engineering field.

4.3 Model Geometry and Soil Profile

The model geometry is defined as three-dimensional domain of 24 m × 24 m plan area with depth of 20 m, developed in PLAXIS 3D to ensure consistent and accurate numerical modelling. The soil profile consists of a two-layer system with an upper layer of 15 m and a lower layer of 5 m, representing non uniform geotechnical conditions for settlement evaluation.

4.4 Model Geometry

This study is numerically modeled with the three-dimensional finite element scheme of PLAXIS 3D in which the symmetric and consistent geometry is represented relative to a central origin point. Consideration of the coordinate system (0,0,0) origin is made at the center of the model which represents the position of the transmission tower foundation, enabling the even distribution of the model domain in all horizontal direction. This model is drawn on the X-axis between -12 m and +12 m to make the overall width of the model 24m, an amount that has been selected to reduce the effect of the boundaries as well as to ensure that the zone of influence of the foundation is completely covered by the model. Equally, the model is extended along the Y-axis between -12 m and +12 m, which also gives a total width of 24 m, forming a square plan area to facilitate the distribution of the stress uniformly and at a practical simulation of soil behavior surrounding the foundation. The model is extended vertically in the Z-direction to a maximum depth of 20 m (considered adequate to capture the influence zone of stress bulb and settlement under the foundation). The reference level is the top surface (ground level) and the depth is considered as downwards along the Z-direction to indicate subsurface condition. The model dimensions are also chosen wisely to make sure that the boundary conditions do not play a significant role in establishing the settlement results, something that is imperative when it comes to finite element modeling.

4.5 Soil Profile

The soils profile that was applied in this study is a two-layer system, which represents the common conditions in the subsurface along the Ilam to Jhapa transmission corridor. The upper 15 m of soil layer is the layer between the ground surface and 15 m in depth, which is reflective of relatively weaker or compressible soil conditions like residual soil, colluvial deposits or alluvial soil depending on the location. The bottom layer of soil is 5 m in thickness with a depth of 15 m to 20 m depth. This is a relatively stronger and stiffer layer of soil that has good load bearing capacity and minimizes settlement. Depending on the geotechnical information and the representative field conditions, each layer of soil is given appropriate engineering properties such as unit weight, cohesion, angle of internal friction, modulus of elasticity, and the Poisson ratio. The behaviour of soil is modeled with the aid of the appropriate constitutive models in PLAXIS 3D like Mohr Coulomb which is the simple model to represent the soil behaviour or Hardening Soil Model which are advanced models to analyse the behaviour of stress and strain. The interface between the two layers of soil is outlined in such a way that stress and deformation are shared between the soil layers as well as the soil layers are realistically simulated. The two-layer soil system is selected to reflect the variation of soil stiffness with depth due to which the settlement and stress distribution beneath the foundations of transmission towers is greatly affected.

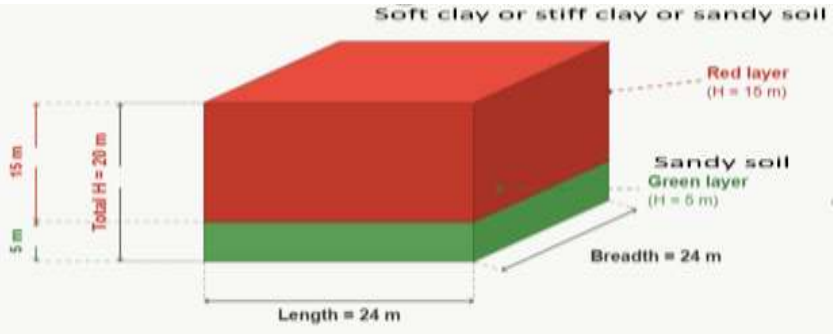


Figure 4.1 : Geometry of the Soil model

4.6 Material Properties and Soil Model Selection

The material properties of soils and structural elements are chosen over standard geotechnical ranges and entered in PLAXIS 3D to provide realistic simulation of behavior. Mohr-Coulomb soil model is used to describe the behavior of soft clay, stiff clay and sand when subjected to loading forces.

4.6.1 General Modeling Framework

This study performs the numerical analysis by three-dimensional finite element modeling in PLAXIS 3D, in which a unified model domain of 24 m length × 24 m breadth × 20 m depth is used in all the simulations to provide uniformity and comparability of results. There are three distinct soil models to represent typical ground conditions along the Ilam-Jhapa transmission corridor, which are lacustrine/soft clay (with similar weak soils), stiff clay (with similar cohesive soils) and sand (with granular soils). The soil profile is established as a two-layer system (15 m upper layer, and 5 m lower layer), with the property becoming different depending on the type of soil but the geometry is maintained in all the models.

4.6.2 Soil Modeling Approach

The MohrCoulomb constitutive model is used to simulate the soil behavior where linear elastic perfectly plastic behavior is assumed and can be used to compare settlements. The model parameters are:

- Unit weight (γ)
- Cohesion (c)

- Angle of internal friction (φ)
- Young's modulus (E)
- Poisson's ratio (ν)
- Dilatancy angle (ψ, for granular soils)

Simulation of soil-foundation interaction is done with interface elements, which makes stress and deformations transfer realistic.

4.6.3 Soil Material Properties

Soil The properties of the soil materials are defined in relation to common ranges of geotechnical parameters of soft clay, stiff clay and sand to reflect realistic ground conditions. The following properties are included in the PLAXIS 3D to enable settlement analysis; unit weight, cohesion, angle of friction and stiffness. Soft Clay (including similar soils) (e.g., Lacustrine clay,marine clay, organic clay, silty clay, peat, high compressible clay)

- Unit weight (γ): 14 – 17 kN/m^3
- Cohesion (c): 10 – 25 kPa
- Angle of internal friction (φ): 10° – 20°
- Young's modulus (E): 2,000 – 8,000 kN/m^2
- Poisson's ratio (ν): 0.35 – 0.45
- Dilatancy angle (ψ): 0°

These soils are characterized by high compressibility, low shear strength, and significant settlement, making them critical for foundation design.

Stiff Clay (Including Similar Soils)

(e.g., overconsolidated clay, clayey silt, hard clay, partially weathered clay***)***

- Unit weight (γ): 17 – 20 kN/m^3
- Cohesion (c): 30 – 80 kPa
- Angle of internal friction (φ): 18° – 28°
- Young's modulus (E): 10,000 – 40,000 kN/m^2
- Poisson's ratio (ν): 0.30 – 0.38
- Dilatancy angle (ψ): 0°

These soils exhibit moderate stiffness and strength, resulting in controlled and relatively smaller settlement compared to soft clay.

c Sand (Including Similar Soils)

(e.g., silty sand, gravelly sand, dense sand, alluvial sand)

- Unit weight (γ): 18 – 21 kN/m^3
- Cohesion (c): 0 – 5 kPa
- Angle of internal friction (φ): 28° – 38°
- Young's modulus (E): 20,000 – 80,000 kN/m^2
- Poisson's ratio (ν): 0.25 – 0.35
- Dilatancy angle (ψ): 0° – 10°

Sand soils are generally less compressible and provide higher bearing capacity, resulting in relatively low settlement.

4.6.4 StructuralMaterialProperties /Foundation/Basemet

In addition to soil modeling, structural components such as beams, columns, walls, and slabs are modeled using linear elastic material properties in PLAXIS 3D. Basement Beam (Plate Element / Beam Element)

- Unit weight (γ): 24 – 25 kN/m^3
- Young's modulus (E): 25×10^6 – 35×10^6 kN/m^2
- Poisson's ratio (ν): 0.15 – 0.25
- Thickness (t): 0.3 – 0.8 m (equivalent plate thickness)
- Bending stiffness (EI): Defined based on section size
- Basement beams act as load transfer elements, distributing loads from columns to foundation.

Basement Column (Embedded Beam Row / Volume Element)

- Unit weight (γ): 24 – 25 kN/m^3
- Young's modulus (E): 25×10^6 – 35×10^6 kN/m^2
- Poisson's ratio (ν): 0.15 – 0.25
- Cross-section: 0.3 m × 0.3 m to 1.0 m × 1.0 m

- Axial stiffness (EA): Based on section area
- Columns are modeled as vertical load-carrying members, transferring loads to the foundation.

Basement Wall (Plate Element)

- Unit weight (γ): 24 – 25 kN/m^3
- Young's modulus (E): 25 × 10^6 – 35 × 10^6 kN/m^2
- Poisson's ratio (ν): 0.15 – 0.25
- Thickness (t): 0.25 – 0.5 m

Basement walls act as retaining and structural elements, resisting lateral earth pressure.

Basement Floor / Slab (Plate Element)

- Unit weight (γ): 24 – 25 kN/m^3
- Young's modulus (E): 25 × 10^6 – 35 × 10^6 kN/m^2
- Poisson's ratio (ν): 0.15 – 0.25
- Thickness (t): 0.2 – 0.4 m

The floor slab distributes loads and provides uniform contact with the soil, influencing settlement behavior.

4.7 Settlement Assessment Criteria

Settlement determination in this paper is conducted in line with applicable provisions of Indian Standard codes like IS 8009 (Part 1): 1976 - Code of Practice of Calculation of Settlement of Foundations, IS 1904: 1986 - Design and Construction Foundations and IS 6403: 1981 - Bearing Capacity of Shallow Foundations, which also offer.

4.7.1 General Settlement Criteria

In the IS codes, the design of foundations shall meet ultimate limit state (failure safety) and serviceability limit state (acceptable settlement limits) with the later being critical in the case of the transmission tower foundations since it is sensitive to deformation and alignment. Numerical modeling in PLAXIS 3D is used to compare the total and differential settlements to determine the applicability of various types of foundations using permissible values stipulated in the IS standards.

4.7.2 Permissible Total Settlement (As per IS 8009 / IS 1904)

- For isolated (pad) foundations on clayey soils:
- Permissible total settlement: 50 mm – 65 mm
- For foundations on sandy soils:
- Permissible total settlement: 25 mm – 40 mm

4.8 Effect of Foundation Type on Settlement Behavior

The nature of the adopted foundation has great bearing on the settlement behavior of transmission tower foundations because each system has a different way of transferring the structural loads to the supporting soil hence impacting on the distribution of stress, the nature of deformation, and the overall performance. This paper discusses the different types of foundations, which include isolated (pad) foundations, raft (mat) foundations, pile foundations, and combined or hybrid systems, and defines their impact on settlement in a wide range of soil conditions, with the help of PLAXIS 3D.

Isolated (pad) foundations load the soil directly by a relatively low contact area leading to increased contact pressure and hence larger settlements, particularly in weak materials like a soft clay soil or lacustrine deposits. The foundations are usually appropriate in dense or stiff soils with high bearing capacity and low compressibility but tend to experience greater differential settlement when the soils are non-uniform or in layers.

Raft (mat) foundations instead spread the loads over a bigger area and this limits the contact pressure and assists in minimizing total and differential settlement. This foundation is especially useful in moderately compressible soils, where the stress concentration is minimized by distributing the load and enhances the overall stability. The even distribution of load also contributes to the control of angular distortion, which is very crucial in the alignment of transmission towers.

Pile foundations are different as they pass on the loads to the deeper and stronger soil layers through the mechanisms of end bearing and skin friction. Consequently, they have a great impact in minimizing settlement in soft and highly compressible soils hence are the best choice when settlement in weak ground conditions are involved. Their performance however relies on their pile length, diameter, spacing and soil stratification and even with improper design, they can still result in settlement or group effects.

Combined foundations (e.g. piled raft systems) combine the benefits of raft and piled foundations, distributing loads between the raft and piles, and thus providing better settlement control and lowering the cost of construction, than fully piled foundations. These systems are especially applicable in stratified soils where shallow and deep load transfer processes are needed. The PLAXIS 3D numerical findings show that settlement reduces as the load transfer mechanism changes towards deep foundations.

4.9 Foundation Modeling

In this study, the modeling of different transmission tower foundation systems is carried out to evaluate their influence on settlement behavior under a consistent loading condition using three-dimensional finite element analysis in PLAXIS 3D. A uniform soil model domain of 24 m × 24 m × 20 m depth is adopted, and the tower is assumed to be located at the center. The total applied load of 1200 kN from a single transmission tower is considered and is equally distributed among four corner supports**,** resulting in 300 kN load per foundation unit**,** which reflects realistic load transfer through tower legs.

4.9.1 Spread (Isolated Pad) Foundations

The initial model comprises of four single spread (pad) foundations which reflect on the four legs of the transmission tower. Footings are 4 m plan x 4 m and 3 m deep and the footing is symmetrical with regard to the center of the model. Each footing carries a vertical load of 300 kN which is equivalent to the load borne by the tower structure. The footings are represented as hard concrete volume elements and interface elements are employed to model the soil-foundation interaction. These bases cause increased contact pressure because of the relatively small contact area, resulting in increased total settlement and increased of differential settlement, especially in soft soils like lacustrine clay. The model can be used to assess the behavior of shallow foundations when there is localized loading. Figure 4.2

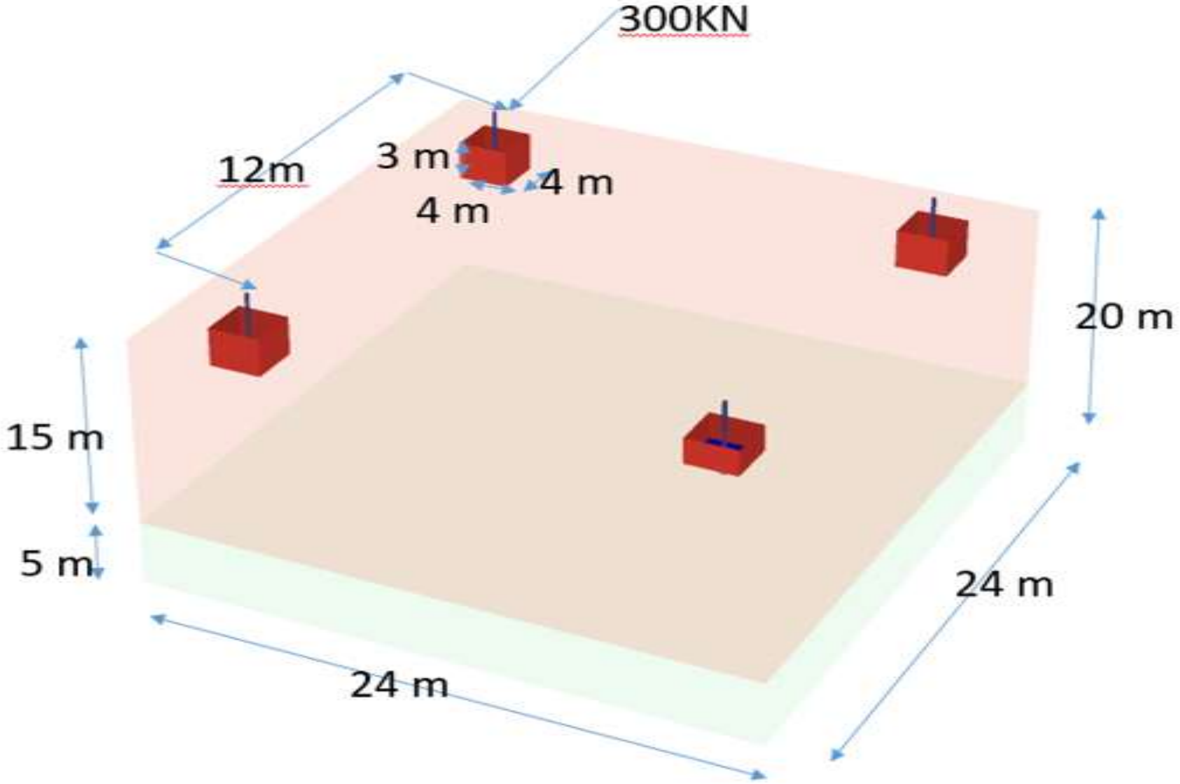


Figure 4.2 Geometry of model spread foundation

4.9.2 Raft (Mat) Foundation

The second model comprises a single raft base that encompasses the whole base of the tower. The raft size is 16 m x 16 m of thickness (depth) 3 m which gives a much larger contact area than isolated footings. The overall weight of 1200 kN is evenly distributed on the raft surface and the pressure of contact is minimized. The raft is defined as a plate or solid element with linear elastic concrete characteristics, which guarantee realistic stiffness behaviour. The raft spreads load more evenly due to the large area, resulting in lower overall settlement and small differential settlement, particularly with moderately large areas.

compressible soils model is shown to have better settlement control and structural stability over isolated footings. Figure 4.3

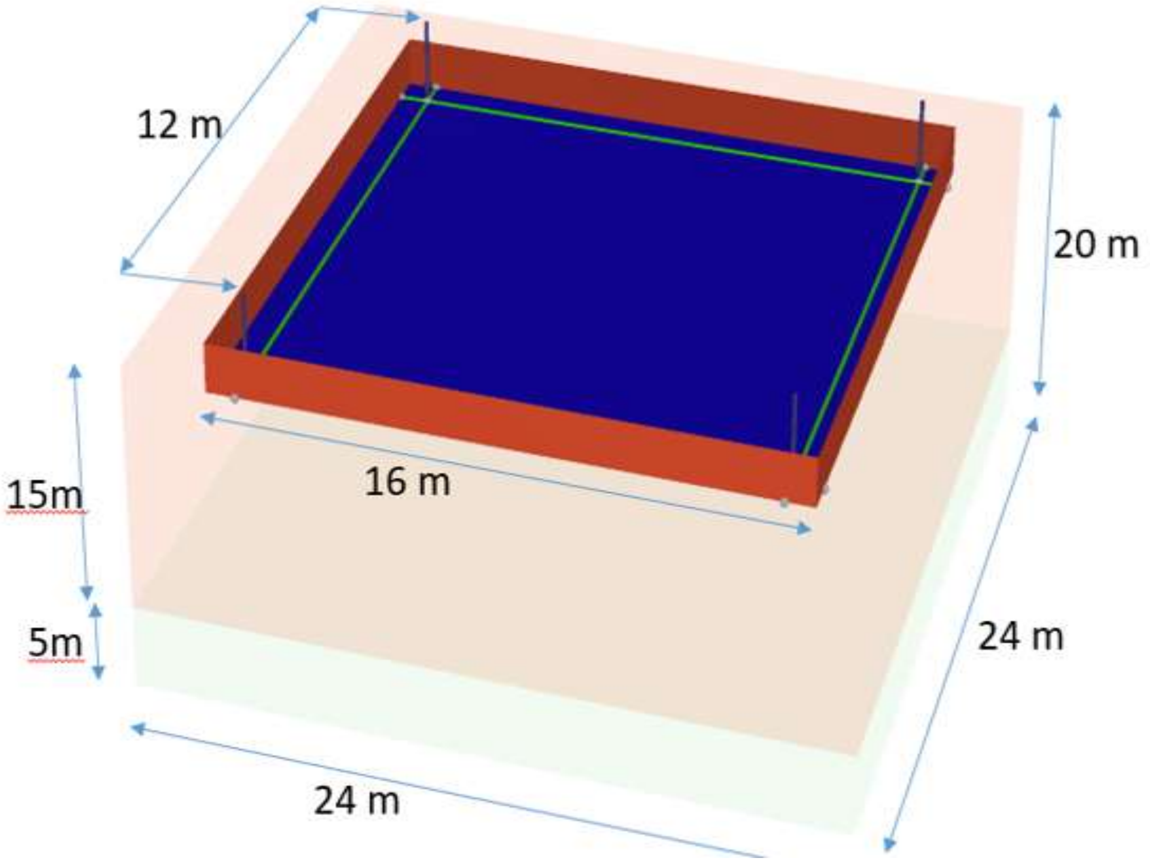


Figure 4.3 Geometry of model raft foundation

4.9.3 Raft with Group Pile Foundation (Piled Raft System)

The piled raft foundation system has been proven to be more effective in settling than any other type of foundation. The shallow foundation and deep foundation are integrated to enable efficient distribution of loads. The raft distributes the implemented load to a huge surface, minimizing the pressure of contact with the soil. The foundation zone is made up of 1 unit and 4 piles and there are 4 foundation zones to give a total of 16 piles. This system guarantees a consistent support under all tower legs. The piles move a large percentage of the weight to the deeper and more robust soil layers. Penetration and load-carrying capacity are sufficient as the pile diameter of 0.6 m and length of 15 m give the needed penetration and load-carrying capacity. The cap of the 1 m thick pile provides correct transfer of loads between the raft and the piles. PLAXIS 3D modeling method properly captures interaction between soil and piles. The incorporated beam elements are used to simulate effectively axial and skin resistance behavior of piles. The system minimizes the overall settlement in comparison with shallow foundations. Also, the differential settlement is reduced which enhances structural alignment and solidity. foundations are poor. In sum, piled raft system is the most efficient and reliable solution to the foundation design of transmission towers. Figure 4.5

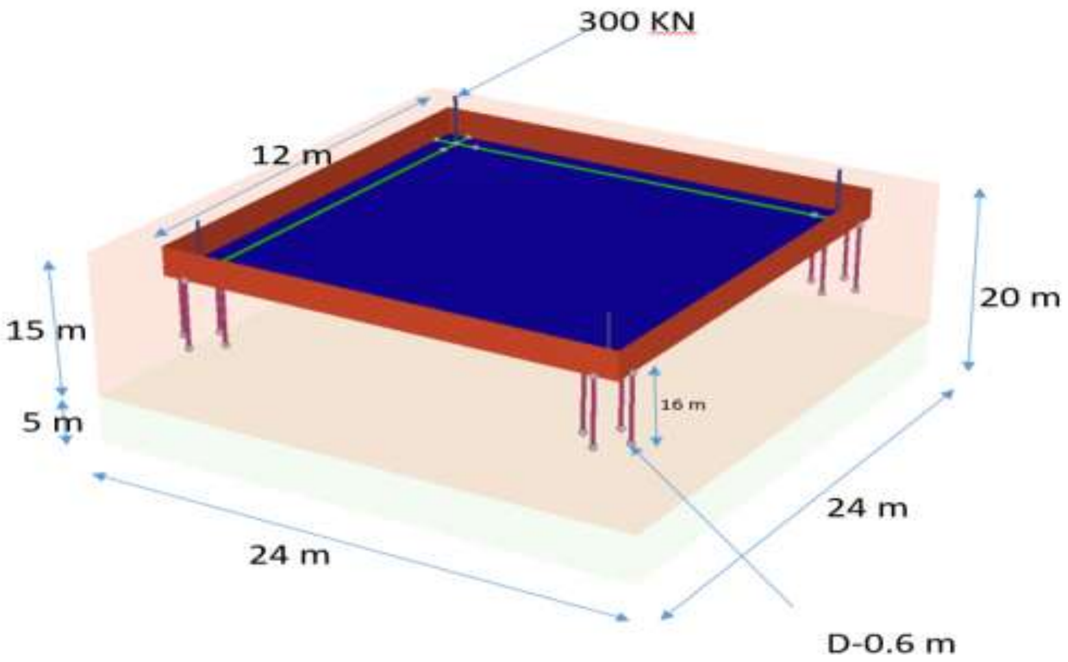


Figure 4.4 Geometry model of pile foundation

5. RESULTS AND DISCUSSION

The outcomes of the settlements are clear evidence that soil type and foundation system have a great impact on settlement behavior. The spread footing exhibits excessive settlement (approximately 95 mm) in soft clay conditions, such as marine clay, organic clay, peat and highly compressible soils, which is not within acceptable limits and this means poor performance. Settlement of the raft foundation is about 58 mm in the acceptable range but still near the upper limit and therefore hardly acceptable. Piled raft system on the other hand minimizes settlement to approximately 22 mm, within the acceptable limits, making it the best type of foundation to be used in such weak soils.

When there are hard clay conditions, such as over consolidated clay, and clayey silt, the settlement of the spread footing is about 48 mm, which is within the allowable limit and can be regarded as acceptable. Raft foundation works well with settlement of approximately 28 mm which offers better safety and consistency. Piled raft system demonstrates the minimal settlement (approximately 15 mm), which reflects the high performance; nevertheless, the system is not necessarily cost-effective unless it is necessary to provide extra safety.

All those types of foundations meet the settlement criteria in sandy soils (silty sand, gravelly sand, dense alluvial sand). Spread footings exhibit settlement of about 22 mm and falls within the allowable limits and thus makes it a cost-effective alternative. The raft foundations also minimise settlement to approximately 14 mm and are more effective and evenly balanced. The piled raft system has the least settlement (approximately 8 mm) though its application might not be warranted because the more economical shallow foundations are already effective.

All in all the findings validate the fact that settlement reduces in the following order, Spread Footing, Raft Foundation, Raft with Pile and the choice of foundation type must be made depending on the condition of soil and the allowable settlement standards. The analysis offers a good guideline on the selection of suitable foundation systems of transmission tower structures in various geotechnical settings.

5.1 Settlement Analysis of soil using plaxis 3D

The values of settlements calculated by numerical analysis in PLAXIS 3D are summarized below when using various soil types and foundation systems. The performance is analyzed at a total applied load of 1200 kN and the performance is compared with the permissible settlement limits (according to the IS guidelines: 25-40 mm on sand, 50-65 mm on clay, and 10-25 mm on pile-supported systems). The table also reflects the suitability of each type of foundation according to the performance of settlement.

Table 5.1Settlement Analysis of soil using plaxis 3d

Soil Type (Including Similar Soils)	**Foundation Type**	**PLAXIS 3D Settlement (mm)**	**Permissible Limit (mm)**	**Criteria Check**	**Performance**	**Preferred Foundation**
Soft Clay *(marine clay, organic clay, silty clay, peat, highly compressible clay)*	Spread Footing	95 mm	50–65 mm	✕ Exceeds	Poor	Not Recommended
	Raft Foundation	58 mm	50–75 mm	✓ Borderline	Moderate	Limited Use
	Raft + Pile	22 mm	10–25 mm	✓ Safe	Good	Highly Recommended
Stiff Clay *(overconsolidated clay, clayey silt,*	Spread Footing	48 mm	50–65 mm	✓ Safe	Moderate	Acceptable

Soil Type (Including Similar Soils)	**Foundation Type**	**PLAXIS 3D Settlement (mm)**	**Permissible Limit (mm)**	**Criteria Check**	**Performance**	**Preferred Foundation**
hard clay, partially weathered clay)						
	Raft Foundation	28 mm	50–75 mm	✓ Safe	Good	Recommended
	Raft + Pile	15 mm	10–25 mm	✓ Safe	Excellent	Best but costly
Sand *(silty sand, gravelly sand, dense sand, alluvial sand)*	Spread Footing	22 mm	25–40 mm	✓ Safe	Good	Recommended
	Raft Foundation	14 mm	25–40 mm	✓ Safe	Excellent	Highly Recommended
	Raft + Pile	8 mm	10–25 mm	✓ Safe	Excellent	Not Economical

The data given in Table 5.1 is a clear showing of the difference in the behavior of foundation settlement at various soil conditions and foundation types based on numerical calculation using the PLAXIS 3D. The analysis indicates that settlement response is highly dependent on the soil stiffness and foundation system with the highest settlement values being recorded in soft clay and the lowest settlement values being recorded in sand with all the foundation types. It is in line with the geotechnical principles, in which soft clay is extremely compressible, whereas sandy soils are stiffer and more prone to draining.

The settlement of the spread footing in the soft clay condition such as marine clay, organic clay, silty clay, peat and highly compressible clay is 95 mm, which is much higher than the allowable settlement of 50-65 mm. This means that such weak soils cannot be used with shallow foundations because of excessive deformation and poor distribution of loads. The raft foundation minimizes settlement to 58 mm that is in a borderline condition that indicates moderate performance, but not quite reliable in long-term safety. Nonetheless, the raft with pile foundation considerably decreases the settlement to 22 mm, which is in the safe range, and it is possible to conclude that piles-assisted systems are the most effective to control settlement in extremely soft soils. All types of foundation work better than soft clay in the case of stiff clay including overconsolidated clay, clayey silt, hard clay and partially weathered clay because they are more powerful and stiffer.The spread footing causes a settlement of 48 mm, which lies within the acceptable range but shows a moderate performance. The raft foundation also decreases the settlement to 28 mm with improved load distribution and structural behavior. The raft with pile foundation has the best performance and only 15 mm settlement and it has shown to be under good control but this might not always be economically viable under such soil conditions.

In the case of sand soils (such as silty sand, gravelly sand, dense sand and alluvial sand), the settlement values are lowest of all soil types because of high stiffness and good drainage characteristics. The spread footing notes 22 mm settlement that is quite within the allowable range, meaning that shallow foundations are appropriate in those circumstances. The raft foundation also minimizes settlement to 14 mm with good performance and enhancement of load distribution. The raft with pile system exhibits minimum settlement of 8 mm, however, its application is not usually cost-effective in thick sandy soils, since the performance gains are not even sufficient to cover the extra construction costs.

All in all, the findings suggest that the most prevalent factor that governs settlement behavior is soil type, and secondly, foundation type. Spread footings can only be used on strong soils like sand and dense clay, whereas raft foundations can give balanced performance in the moderate conditions. Pile-assisted raft foundations can be very useful when the soil is soft but can prove to be economical where the soil is stronger. Thus, it is clear in the study that optimum foundation selection should be founded on geotechnical conditions and performance of settlement in terms of safety, serviceability, and economic viability in the design of transmission towers foundations.

5.2 Plaxis Analysis

The numerical analysis carried out in this study using PLAXIS 3D provides a quantitative evaluation of the settlement behavior of different transmission tower foundation systems under varying soil conditions. The analysis is based on a three-dimensional finite element model with dimensions of 24 m × 24 m in plan and 20 m depth**,** incorporating a two-layer soil profile and realistic boundary conditions. A total load of 1200 kN is applied to a single transmission tower, which is equally distributed into four foundation (300 kN each) in the case of spread footings, while uniformly applied in raft and piled raft systems.

The quantitative findings have shown that settlement is considerably different with soil type and system of foundation. The settlement values of the analysis are relatively high in conditions of lacustrine or soft clay including marine and peat clay and highly compressible soils since they are of low stiffness and great compressibility. The spread footing system demonstrates a maximum settlement of about 95 mm which is definitely more than the allowable limit (5065 mm) and as such, unsafe operation. The settlement of approximately 58 mm is acceptable within the range of tolerances, but it is very near the upper limit indicating that it might be just acceptable. Nevertheless, piled raft system is much more effective and settles to around 22 mm, which is well inside the allowable limit (1025 mm), thus showing that it is effective in soft soil environment.

Numerical results indicate moderate settlement behavior in the case of stiff clay soils, such as overconsolidated clay, clayey silt, and partly weathered clay. The settlement is approximately 48 mm and it is in the acceptable range and can be deemed acceptable in the spread footing system. The raft foundation also provides a further reduction in settlement to around 28 mm, which gives the foundation a better performance and better distribution of loads. Piled raft system registers the lowest settlement of about 15 mm which is a good performance but the same system may not necessarily be economical to use when there are simpler systems that are already designed to the required standards.

In the case of sandy soils such as silty sand, gravelly sand, dense sand and alluvial sands, the numerical analysis indicates relatively low settlement values because the soil is more stiff and has high shear strength. The settlement of the spread footing system is about 22 mm which is within the acceptable limit (25-40 mm) and signifies good performance. The raft foundation saves additional settlement to approximately 14 mm, providing uniform deformation and better serviceability. The piled raft system has the lowest settlement of approximately 8 mm, which is the best technical performance but a piled raft system might not be necessary in sandy soils because they will have foundations that are deep enough already.Patterns of stress distributions calculated as a result of the analysis show that spread footings create very concentrated stress zones, in contrast to raft foundations, which spread stress more uniformly, and piled raft systems that shift much of the load to deeper strata, decreasing the intensity of stresses in the upper soil layers.In general, the numerical analysis confirms that the settlement reduces in the sequence: spread footing, raft foundation, piled raft foundation and the outcome is largely dependent on the stiffness and compressibility of soil.

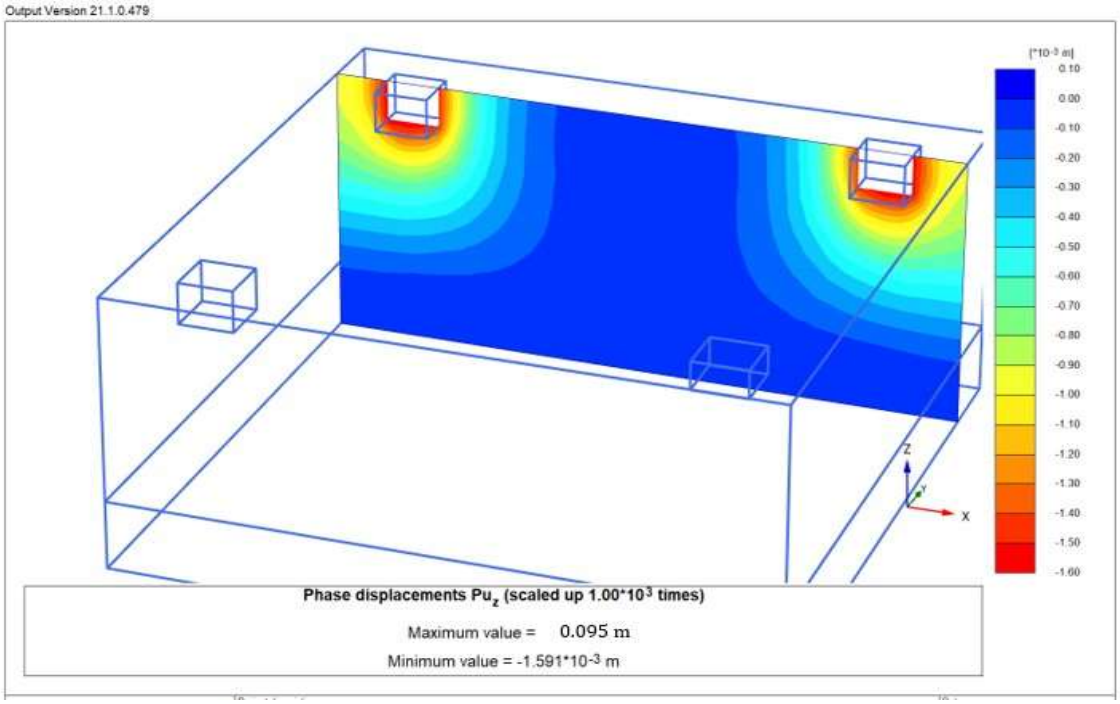


Figure 5.1 : Total displacement of spread foundation on soft clay

In soft clay soil conditions, the spread footing presents a settlement of 95 mm that was obtained using PLAXIS 3D. This is more than the required limit of 5065 mm, which implies that the foundation does not abide by the serviceability requirements. The resultant contour lines depict extremely concentrated settlement below the footing with deformation being severe in the underlying soft clay layer. The arrows show that it strongly moves downwards, which verifies the fact that the soil experiences a large compressive movement under the force. A big area of high settlement intensity is noted in the shading pattern and indicates poor distribution of loads and low soil stiffness.

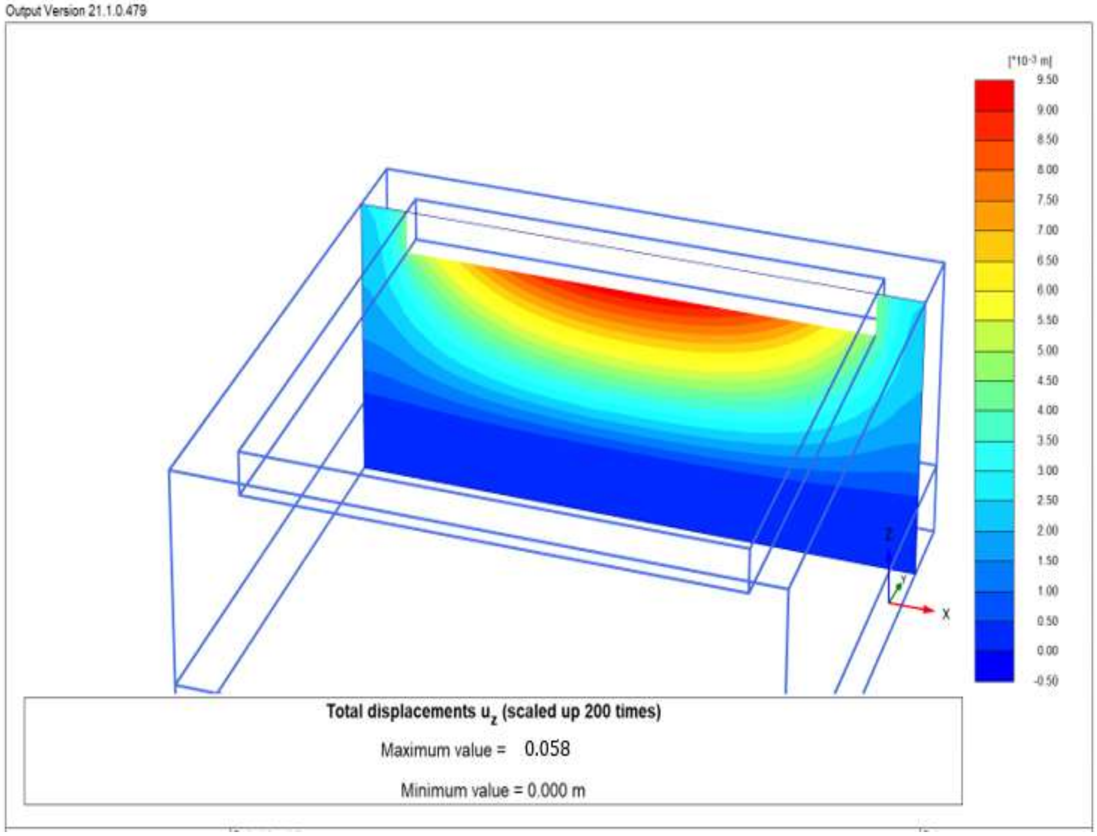


Figure 5.2 : Total displacement of raft foundation on soft clay

In the case of soft clay, the raft foundation states a settlement of 58 mm as the result of the analysis in PLAXIS 3D. This value is in the acceptable range of 50 75 mm, meaning that the foundation is acceptable, but not very efficient to work in the long term. The contour lines in the output are the distribution of vertical displacement indicating smooth settlement variation around the raft foundation. The arrows in the model indicate the direction of deformation, confirming downward movement due to applied loading on the soft clay layer. The shaded contour pattern illustrates moderate settlement zones, showing that the load is spread more evenly compared to isolated footing systems. Therefore, the performance is classified as moderate and borderline, meaning the raft foundation is suitable only for limited use in soft clay conditions where pile foundations are not feasible.

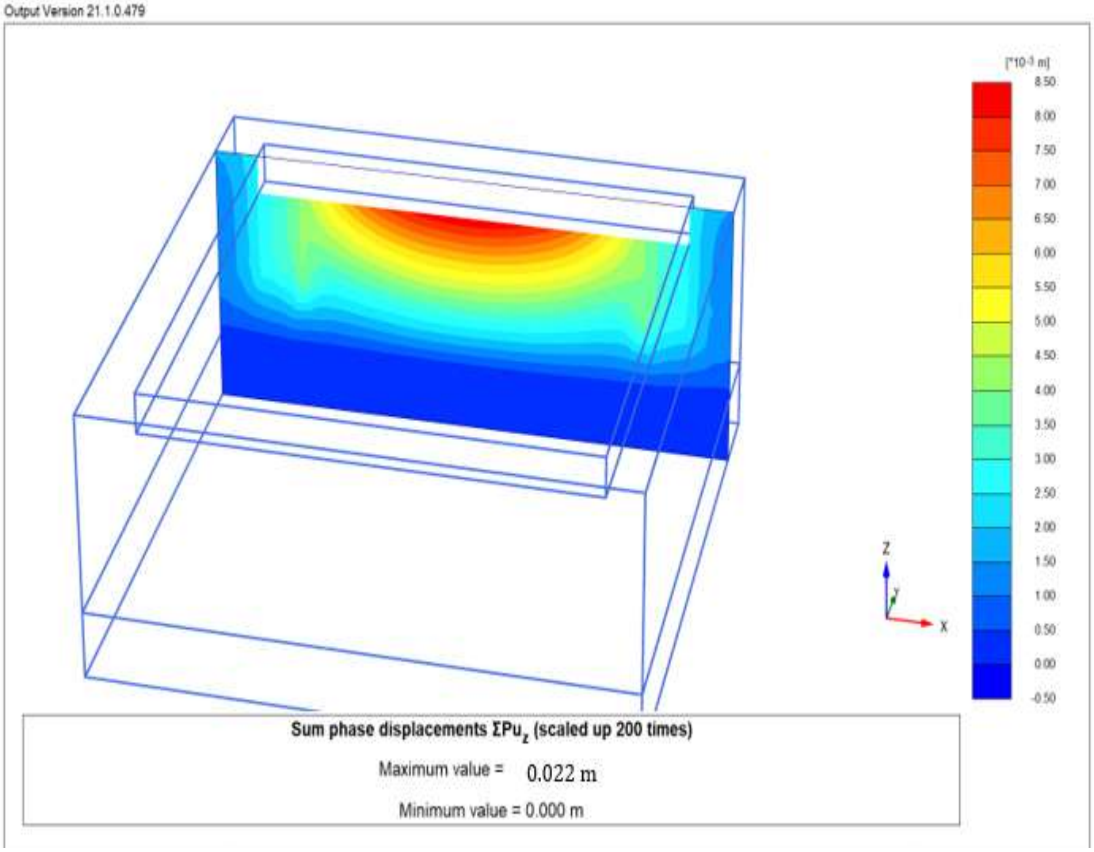


Figure 5.3 : Total displacement of pile foundation on soft clay

For soft clay conditions, the raft with pile foundation shows a settlement of 22 mm obtained from PLAXIS 3D analysis. This value lies within the permissible limit of 10–25 mm, indicating that the foundation system performs safely under the applied loading conditions.. The shading pattern shows limited high-stress zones, which means that stress concentration in the soft clay layer is greatly reduced. This behavior occurs because the pile system bypasses the weak upper soil and mobilizes end-bearing and skin friction resistance in deeper strata. As a result, the raft works together with the piles to share the load, improving overall stability. Therefore, the performance is classified as good, and the raft–pile foundation is highly recommended for soft clay conditions due to its excellent settlement control and structural reliability.

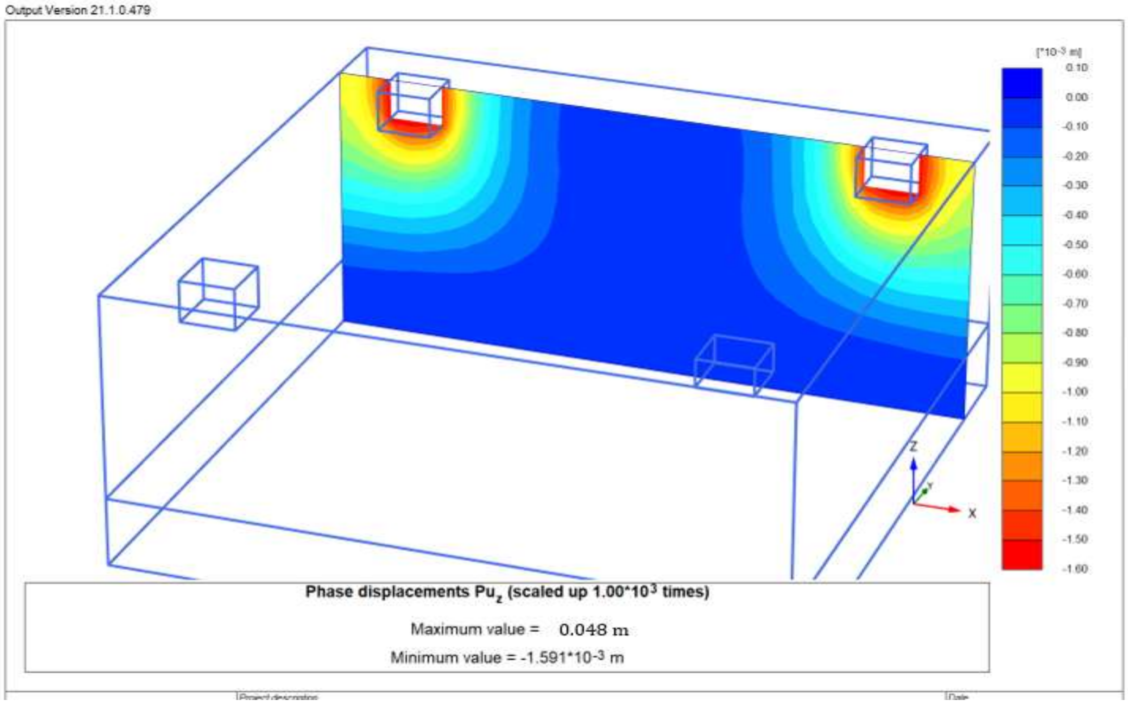
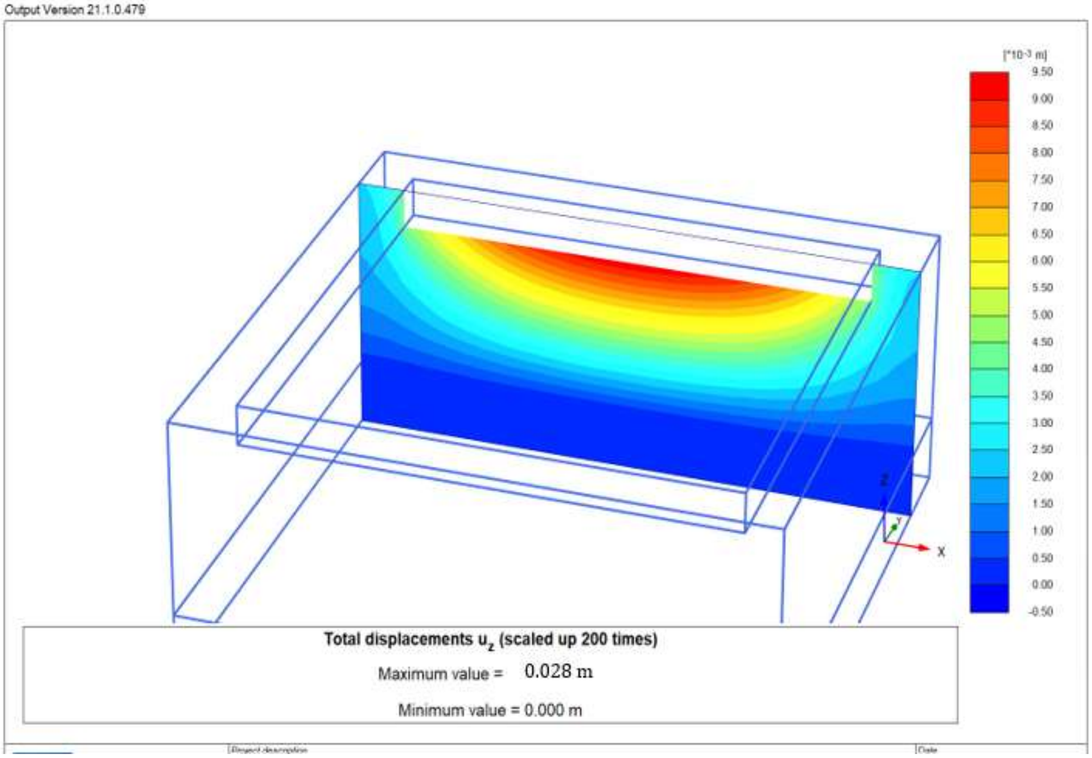


Figure 5.4: Total displacement of spread foundation on stiff clay

In the case of stiff clay conditions, the settlement of the spread footing is 48 mm according to the PLAXIS 3D results of the analysis. This is below the allowable range of 50-65 mm meaning that the foundation is safe under the loading. The result contour lines indicate a fairly homogeneous settlement pattern indicating higher soil stiffness and deformation than that of soft clay. The arrow vectors show moderate downward movements, which proves that the soil can withstand a substantial part of the load exerted on it. The shading pattern identifies few areas of deformation, indicating that the stress is more balanced under the footing. Hence, the spread footing can be regarded as moderating and acceptable in the conditions of stiff clay since it can be characterized by a stable settlement behavior and sufficiently high load-bearing capacity.



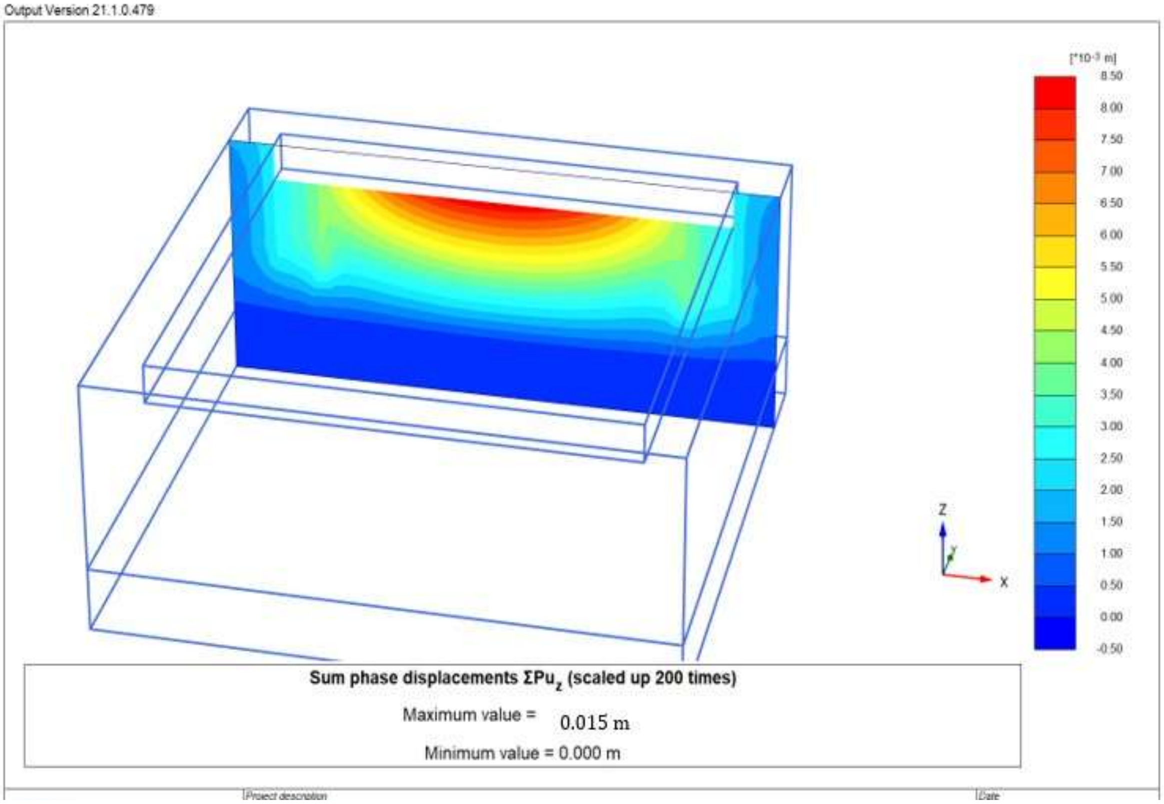
Total displacements u_z (scaled up 200 times)

Maximum value = 0.028 m

Minimum value = 0.000 m

Figure 5.5: Total displacement of raft foundation on stiff clay

For In case of stiff clay, the raft foundation presents a settlement of 28 mm according to the results of the PLAXIS 3D analysis. This is much within the acceptable range of 50-75 mm which means that the foundation is safe and efficient when loaded. The output lines of contour show smooth and diffusive pattern of settlement and this is a demonstration of the capacity of the raft to distribute loads over a greater area. The arrow vectors depict comparatively low downward displacements, which proves the resistance and stiffness of stiff clay are higher than soft clay. The shading pattern indicates the areas of low-intensity deformations, i.e., the stress concentration is minimized a lot. All in all, raft foundation is effective in stiff clay soils because of better distribution of the load and minimal settlement. It is thus a good and recommended type of foundation in such soils.



Output Version 21.1.0.479

Sum phase displacements ΣPu_z (scaled up 200 times)

Maximum value = 0.015 m

Minimum value = 0.000 m

Figure 5.6 : Total displacement of raft foundation on stiff clay

In the case of stiff clay, the raft on pile foundation has a settlement of 15 mm as per the analysis of PLAXIS 3D. This is a very acceptable value of 10-25 mm meaning that the foundation system is safe and efficient within the applied loads. The contour lines of the result indicate an extremely homogeneous and small settlement distribution, which is indicative of a good load transfer behavior. The arrow vectors are much smaller downward movements, which proves that the bulk of the load is actually being supported by the pile system and deeper layers of soil. The shading pattern depicts extremely low deformation intensity indicating that stress concentration in the soil is greatly minimized. The reason behind this behavior is that the piles increase the stiffness and decrease the load requirement by the upper stiff clay layer. Consequently, the raft and pile system has an excellent settlement control and a high degree of stability.

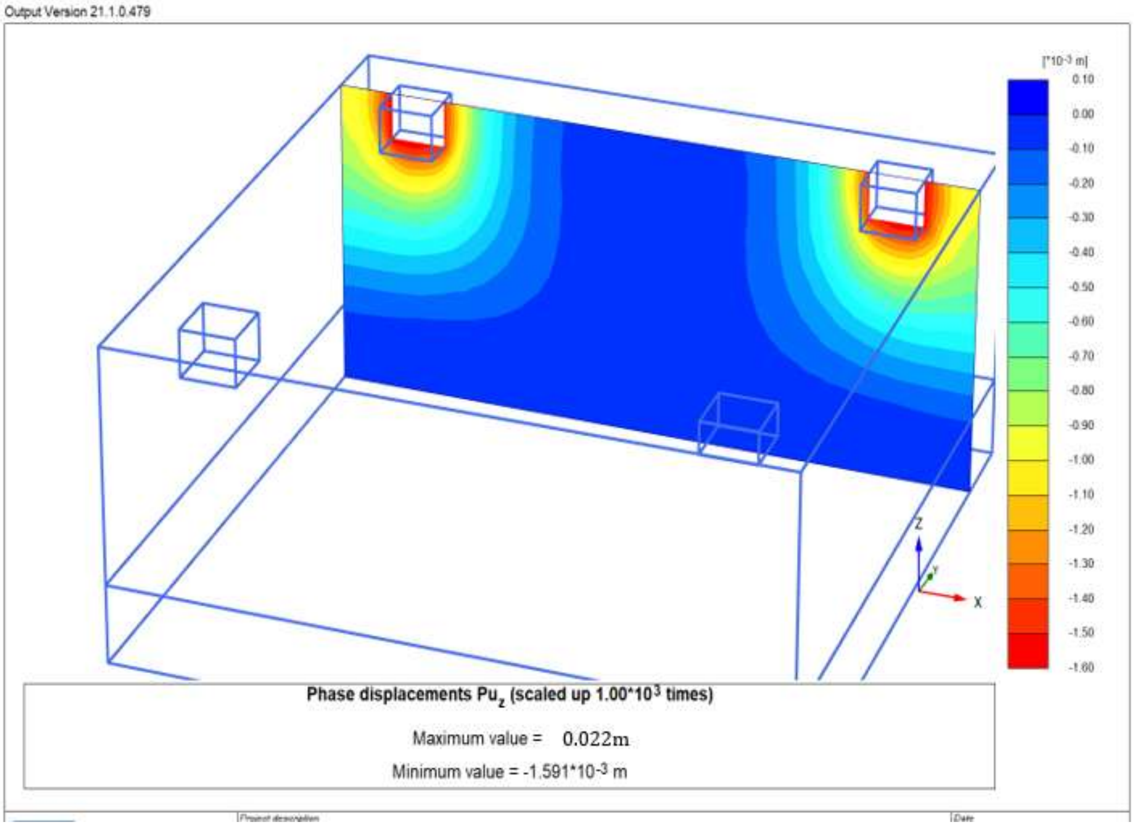


Figure 5.7: Total displacement of spread foundation on sandy clay

In the sand conditions such as silty sand, gravelly sand, dense sand and alluvial sand, the spread footing records a settlement of 22 mm, as per the PLAXIS 3D analysis results. This is within the acceptable range of 2540 mm which is a sign that the foundation is safe when the load is applied. The resultant contour lines indicate a rather homogeneous, shallow settlement pattern, which is indicative of high stiffness and good load-bearing capacity of sandy soils. The arrow vectors show minor downward movements, which proves that there is limited deformation through superior drainage and frictional resistance in sand. The pattern of shading indicates low intensity settlement areas, i.e., the stress is uniformly distributed below the footing. In general, the spread footing can be used in sand environment because it is stable and has an effective load transfer mechanism. Thus, it is good and recommended type of foundation to use in the sandy soil profiles.

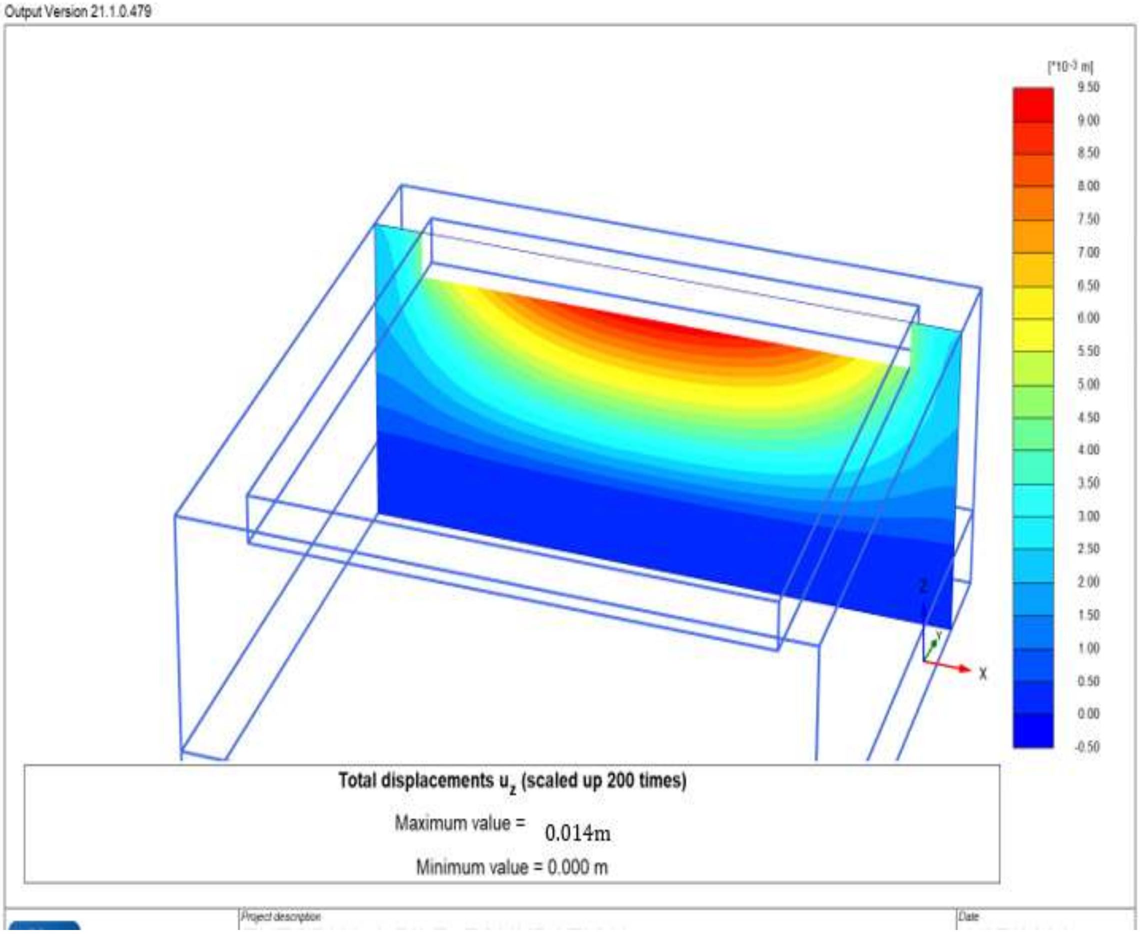
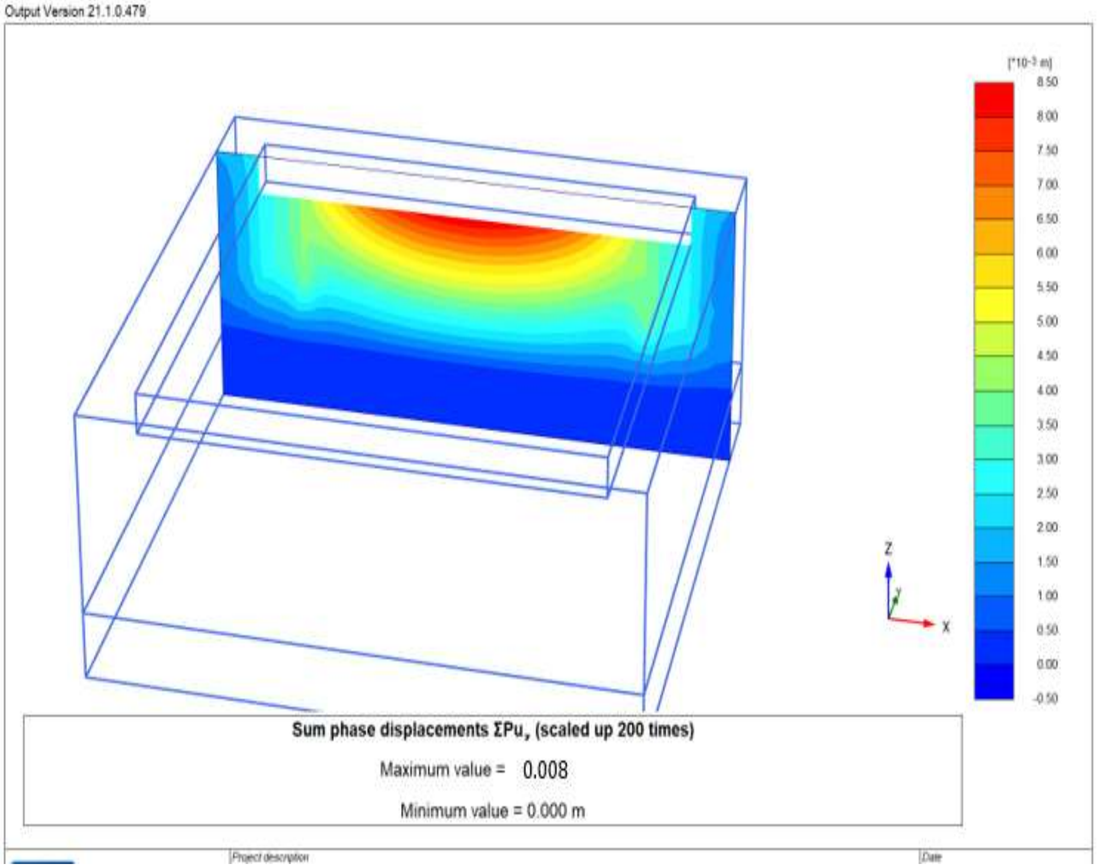


Figure 5.8 : Total displacement of raft foundation on sandy soil

In the case of sand conditions, such as silty sand, gravelly sand, dense sand, and alluvial sand, the raft foundation will have a settlement of 14 mm as represented by the results of the PLAXIS 3D analysis. It is actually much less than the allowable 25-40 mm with a very safe and efficient foundation response. This indicates that the raft is doing well to distribute the load to a wide area as the contour lines in the output show a wide and smooth settlement pattern. The vectors of the arrows show extremely small negative displacements which validate that sandy soils are very stiff and resistant to deformation. The shading pattern shows that there are few settlement areas indicating low stress concentration under the foundation. The overall performance is good because of the combined effect of good soil properties and distribution of load of raft. Hence, raft foundation is one of the best foundations to apply to sandy soil as it is more stable and does not show much settlement.



Sum phase displacements ΣPu$_y$ (scaled up 200 times)

Maximum value = 0.008

Minimum value = 0.000 m

Figure 5.9 : Total displacement of pile foundation on sandy soil

When using sand conditions, which comprise of silty sand, gravelly sand, dense sand and alluvial sand, the raft with pile foundation exhibits a settlement of 8 mm, as per PLAXIS 3D analysis results. This is quite close to the allowable range of 10-25 mm which means that it is very safe in operation with low deformation. The result display contour lines of a very uniform and shallow settlement pattern with the piles and the raft distributing loads efficiently. The arrow vectors show very minute downward movements and this is affirmation that the piles and the sandy soil are resistant to the load applied. The shading pattern indicates extremely low settlement intensity, i.e. the concentration of stress is low across the soil mass. Even though the performance is classified as excellent, it is understood that sandy soils already have high bearing capacity and low settlement with shallow foundation. It is thus not cost effective to use a piled raft system in this kind of condition since the extra expense is not of much practical value over more basic types of foundation.

5.3 Bar Chart Visualization

Figure 5.10 : Settlement vs permissible limits soft clay

The chart is a visualization of settlement behaviour of three types of foundations on soft clay soil, using the results of PLAXIS 3D simulation.

Spread Footing records the poorest with a settlement of 95 mm which is far beyond the acceptable mark of 50 65 mm. This implies that the soil becomes excessively deformed with the weight, and thus not stable enough to use in soft clay soil.

Raft Foundation lowers settlement considerably to 58 mm, which is within or slightly beyond allowable range of 50-75 mm. It is considered borderline technically passable in a few cases though not reliably safe, so only restricted use is recommended.

Raft + Pile Foundation is the definite winner and its settlement of only 22 mm is well within the safe range of 10-25 mm. The piles redistribute the structural load to more competent soil strata, and surface settlement is significantly decreased. This is a

"Good" performance rating that is highly recommended to soft clay such as marine clay, organic clay, silty clay, peat and highly compressible clay.

The most important point is that the more complex is the foundation (spread footing to raft to raft and pile), the less settlement and the better structural performance this is an important factor when the foundation is constructed on weak and compressible soils.

Figure 5.11 : Settlement vs permissible limit stiff clay

On stiff clay, that contains over consolidated clay, clayey silt, hard clay and partially weathered clay, all three types of foundation foundations do not exceed the acceptable boundaries of settlement, and so provide the engineer with more viable options than soft clay.

Spread footing settles at 48 mm, only a bit below the lower limit of 50 mm. It meets the criteria check technically and is considered safe, however, it is only acceptable and not the best in terms of performance. It is the most economical and the least safe, yet the simplest.

Raft foundation decreases the settlement even more to 28 mm, which is sufficiently within the safe range. It performs well and is the best option to use in stiff clay that strikes the right balance in terms of cost-effectiveness and structural reliability. The load is distributed but it covers a bigger area and this distributes stress evenly and restricts to differential settlement.

Raft + pile foundation has the least settlement of only 15 mm which gives it an outstanding performance rating. Nevertheless, it is marked as best, but very expensive in the sense that the extra engineering and material cost might not always be worth it on stiff clay, as the soil is already stiff enough to sustain more basic foundations.

The general impression is that stiff clay is a far more forgving base material. This is not a decision about failure avoidance, but the optimal cost/performance trade off with the raft foundation being a practical location in the tradeoff space that works well on most projects.

Figure 5.12 : Settlement vs permissible limit sandy soil

On sand that also contains silty sand, gravelly sand, dense sand, and alluvial sand all three types of foundations are easily settled within safe limits, indicating the favourable nature of the granular structure of sand and its drainage properties that make the material one of the most favourable soils to use in construction.

Spread footing is registered at a settlement of 22 mm, which is only 25 mm below the lower limit. It is considered as safe with good performance and is merely recommended as an affordable and reliable option that can perform well without the use of more elaborate foundation systems.

The Raft foundation also minimizes the settlement to 14 mm, which is well within the allowable range, and is graded excellent. It is strongly suggested to be used with sand, and has excellent performance at an affordable cost increase over spread footing. Rafts have a wide load spread that functions effectively on grains soils.

Although it has the lowest settlement of only 8 mm and is rated excellent, Raft + pile is marked as not economical. On sand, the natural bearing capacity of the soil is already high, and any further driving of piles will have little or no further effect to merit the additional expense. It would only be thought of in extraordinary cases when the structure is subjected to extremely heavy loads or when the settlement tolerance is extremely low.

Figure 5.13 : Settlement by foundation type in all types of soil

The chart is a comparison of settlement (mm) of three types of foundation Spread footing, Raft foundation and Raft + Pile in soft clay, stiff clay and sand. The vertical axis indicates settlement up to approximately 115 mm; two of the dashed lines indicate approximate settlement bands to be used in assessing safety. The three bars of each type of foundation (one of each soil) allow you to immediately compare the influence of soil stiffness and foundation options on settlement.

The largest settlements are made of soft clay. Spread footing = 95mm (exceeds acceptable limits and unsafe), Raft = 58mm (borderline/conditional) and Raft + Pile = 22mm (well within limits and a rated excellent). Judgment of engineering: shallow foundations are not suitable in soft clay; load-bearing piles to deep strata are the sure answer, although more expensive.

The largest settlements are made of soft clay. Spread footing = 95mm (exceeds acceptable limits and unsafe), Raft = 58mm (borderline/conditional) and Raft + Pile = 22mm (well within limits and a rated excellent). Judgment of engineering: shallow foundations are not suitable in soft clay; load-bearing piles to deep strata are the sure answer, although more expensive.

Hard clay experiences moderate settlements and acceptable performance. Spread footing = 48mm (almost to the lower limit and good with lighter constructions), Raft = 28mm (good but not as expensive), and Raft + Pile = 15mm (good but very costly). Judging: raft foundations provide a decent balance of cost and performance; piles are only required when very strict settlement control or heavy loads are desired.

Sand produces the least settlements due to its grains and drainage. Spread footing = 22mm (immediately below the lower allowable and safe limit and safe), Raft = 14mm (excellent) and Raft + Pile = 8mm (lowest settlement but tend to be uneconomical). Judgment engineering: spread or raft foundations are the logical, economical decisions in most circumstances; piles are used in unusual situations.

The settlement of soils is less on the soils with a higher stiffness (soft clay to stiff clay to sand) and on the stronger foundation systems (Spread to Raft to Raft + Pile). Select Raft + Pile where settlement control is most important (soft clay or extreme loads). A Raft is frequently the most advantageous compromise with stiff clay. In the case of sand, Spread footing or Raft would normally be the best in terms of cost performance tradeoff.

6. CONCLUSIONS AND RECOMMENDATIONS

The subject of the current study is that the choice of foundation type is significant to regulate the settlement behavior of transmission tower foundations in various soil conditions. These findings indicate that settlement reduction enhances significantly when advanced foundation systems are used especially in weak soils. The raft-pile foundation is the best performing foundation among the analyzed ones, with settlement reductions of approximately 64 to 77 percent lower than conventional spread footing. In the meantime, raft foundations offer a good compromise of performance and cost in moderately stable soils, but spread footing can only be used in highly competent soils with settlement within acceptable limits.

6.1 Conclusions

This research demonstrates a comparative analysis of settlement of various transmission tower foundation systems including spread footing, raft foundation, and raft combined with pile- under different soil conditions using PLAXIS 3D. The findings indicate clearly that soil type is a contributing factor in controlling the settlement behavior and foundation system performance is significantly different based on soil stiffness and compressibility.

In soft clay soils, which include highly compressible materials such as organic clay, , peat marine and clay, the spread footing shows a maximum settlement of 95 mm, exceed the permissible limit by a significant margin. When raft foundations were used settlement is found 58 mm, there is a reduction of approximately 39% in settlement, indicating moderate improvement. However, the most effective solution is the combined pile raft foundation system, which reduces settlement to 22 mm, representing a reduction of about 77% compared to spread footing and 62% compared to raft foundation. This clearly shows that combined pile raft systems provide superior performance in weak soils and are highly recommended despite higher cost.

In stiff clay soils, including overconsolidated and partially weathered clays, all foundation types satisfy permissible limits. The spread footing shows 48 mm settlement, while raft foundation reduces it to 28 mm, achieving a reduction of approximately 42%. The raft + pile system further reduces settlement to 15 mm, resulting in a reduction of nearly 69% compared to spread footing and 46%

compared to raft foundation. Although all options are safe, the raft foundation provides a balanced solution between performance and economy, while pile-supported systems offer the best performance where higher safety is required.

In sand and granular soils, including dense and alluvial sands, settlement values are relatively low for all foundation types due to high soil stiffness. Spread footing results in 22 mm settlement, while raft foundation reduces it to 14 mm, showing a reduction of about 36%. The raft + pile system achieves the lowest settlement of 8 mm, corresponding to a reduction of approximately 64% compared to spread footing. However, since all values are well within permissible limits, the additional reduction achieved by pile foundations is not economically justified. Therefore, raft and spread footing are more practical and cost-effective solutions in sandy soils.

Overall, the study concludes that:

- Settlement reduction increases significantly with the use of advanced foundation systems, particularly in weak soils.
- Combined pile raft foundation provides the highest performance across all soil types, with settlement reductions ranging from 64% to 77% compared to spread footing.
- Raft foundation presents an optimum of cost and performance particularly in average soil conditions.
- Spread footing can only be applied to highly competent soils, whereby settlement does not exceed permissible limits.

The findings narrow that there is no universal foundation type that is appropriate and that the choice should be made according to the conditions of the soil, the settlement allowable, and economics. This research provided a pragmatic foundation selection basis and aids in developing a settlement assessment guideline of transmission tower foundation in Nepal.

6.2 Recommendations

- The comparative settlement analysis approach used in this study should be used in future projects to select the optimal foundation type rather than relying on conventional assumptions.

- In this research representative soil profiles were used which can be applied for preliminary design; however, detailed analysis should be carried out for critical tower locations.
- A zone-wise foundation selection method is recommended for transmission lines passing through different geological regions (hill, foothill, and Terai), as demonstrated in this study.
- The paper has elaborated that combined pile raft foundation drastically minimizes the settlement (down to approximately 70%-75%), hence it ought to be taken into account in the weak soil setting where settlement control is of utmost concern.
- It should be noted that: This settlement evaluation guideline developed in this study should be applied as a practical instrument to enable engineers to make a rapid evaluation of the correct types of foundation under different soil conditions.
- In Plaxis 3D numerical modeling procedure such as soil parameter selection and boundary condition setup, should be followed as a standard methodology for similar studies.
- It is recommended to calibrate numerical models with field data wherever possible to improve prediction accuracy.
- The study approach can be extended to include more advanced constitutive models (e.g., Hardening Soil Model) for better simulation of nonlinear soil behavior.
- Differential settlement analysis, as emphasized in this study, should be prioritized in design guidelines for transmission towers.
- The methodology used in this research can be expanded to develop a national-level design guideline for transmission tower foundations in Nepal.
- Future studies should incorporate economic comparison (cost vs performance) of different foundation types to support practical decision-making.

REFERENCES

Bentley Systems (2023). *PLAXIS 3D Reference Manual*. Bentley Systems, Netherlands.

Braja M. Das (2010). *Principles of Foundation Engineering*. Cengage Learning.

Bureau of Indian Standards (1976). IS 8009 (Part 1): *Code of Practice for Calculation of Settlement of Foundations*. New Delhi, India.

Bureau of Indian Standards (1986). IS 1904: *Code of Practice for Design and Construction of Foundations in Soils*. New Delhi, India.

Bureau of Indian Standards (1987). IS 456: *Plain and Reinforced Concrete – Code of Practice*. New Delhi, India.

Department of Mines and Geology Nepal (2019). *Engineering Geological Map and Geotechnical Report of Eastern Nepal*. Kathmandu, Nepal: Government of Nepal.

H.G. Poulos (2001). *Piled Raft Foundations: Design and Applications*. Géotechnique Journal.

Hugh Bolton Seed and Kenji Ishihara (1982). *Soil Behavior and Critical State Soil Mechanics*.

Indian Roads Congress (2010). *Guidelines for Design of Foundations*. New Delhi.

International Society for Soil Mechanics and Geotechnical Engineering (2012). *Foundation Engineering Guidelines*.

J. B. Burland (1973). *Shaft Friction of Piles in Clay*. Ground Engineering Journal.

K. R. Arora (2004). *Soil Mechanics and Foundation Engineering*. Standard Publishers Distributors, New Delhi.

Karl Terzaghi, Ralph B. Peck, and Gholamreza Mesri (1996). *Soil Mechanics in Engineering Practice*. Wiley.

M.F. Randolph (1994). *Design Methods for Pile Groups and Piled Rafts*. Proceedings of the 13th International Conference on Soil Mechanics and Foundation Engineering.

Nepal Electricity Authority (2020). *Transmission Line Design and Foundation Guidelines*. Kathmandu, Nepal.

R. Katzenbach (2005). *Combined Pile-Raft Foundations*. International Journal of Geomechanics.

T. Matsumoto et al. (2004). *Performance of Piled Raft Foundations under Vertical Load*. Soils and Foundations Journal.

Tiwari, R. C. (2024). *Geotechnical Analysis of Foundation Systems under Variable Soil Conditions*. Kathmandu: Engineering Publications.

Tiwari, R. C. (2024). *Settlement Behavior of Transmission Tower Foundations Using Numerical Modeling*. Journal of Civil Engineering Research, 12(2), pp. 45–58.

Tiwari, R. C. (2025). *Advanced Foundation Design for Power Transmission Structures*. Kathmandu: Technical Press Nepal.

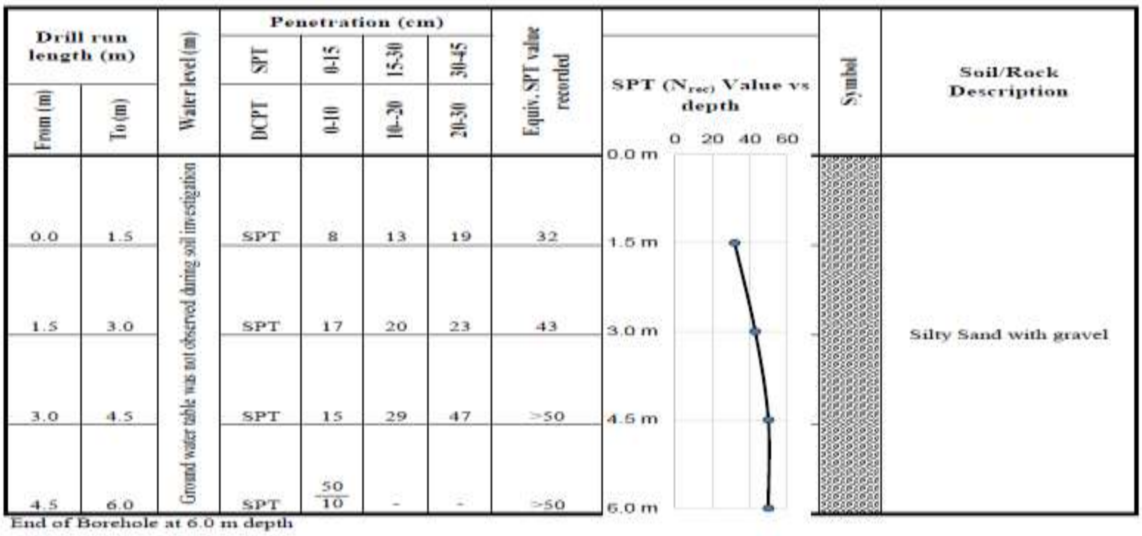
Tiwari, R. C. (2025). *Comparative Study of Shallow and Deep Foundations in Soft Soils*. International Journal of Geotechnical Engineering, 15(1), pp. 23–37.

V. N. S. Murthy (2002). *Geotechnical Engineering: Principles and Practices of Soil Mechanics and Foundation Engineering*. CRC Press.

ANNEX-A : BOREHOLE LOG

Table A.0.1: Borehole log

Tower no: AP-A

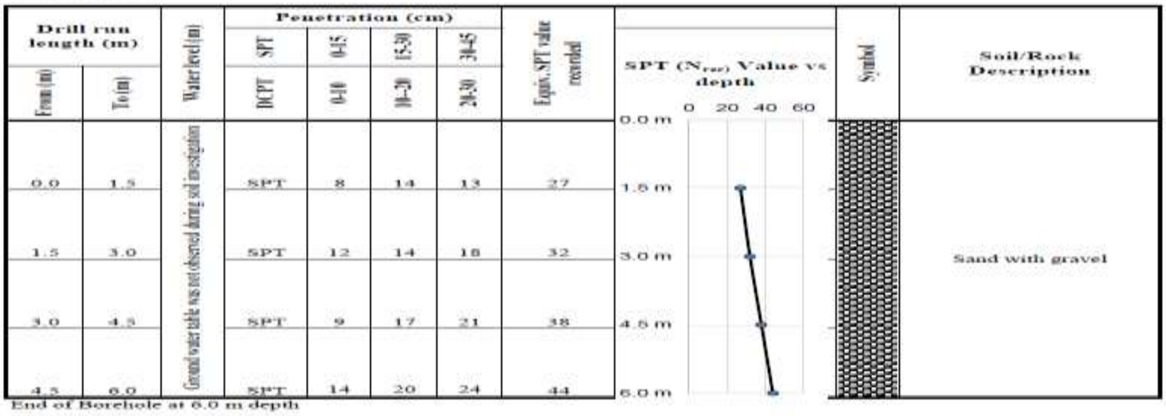


Drill run length (m)		Water level (m)	Penetration (cm)				Equiv. SPT value recorded	SPT (N_{rec}) Value vs depth	Symbol	Soil/Rock Description
			SPT	0-15	15-30	30-45				
From (m)	To (m)		DCPT	0-10	10--20	20-30		0.0 m		
0.0	1.5	Ground water table was not observed during soil investigation	SPT	8	13	19	32	1.5 m		Silty Sand with gravel
1.5	3.0		SPT	17	20	23	43	3.0 m		
3.0	4.5		SPT	15	29	47	>50	4.5 m		
4.5	6.0		SPT	50 10	-	-	>50	6.0 m		

End of Borehole at 6.0 m depth

Table A.2: Borehole log

Tower no: AP-1

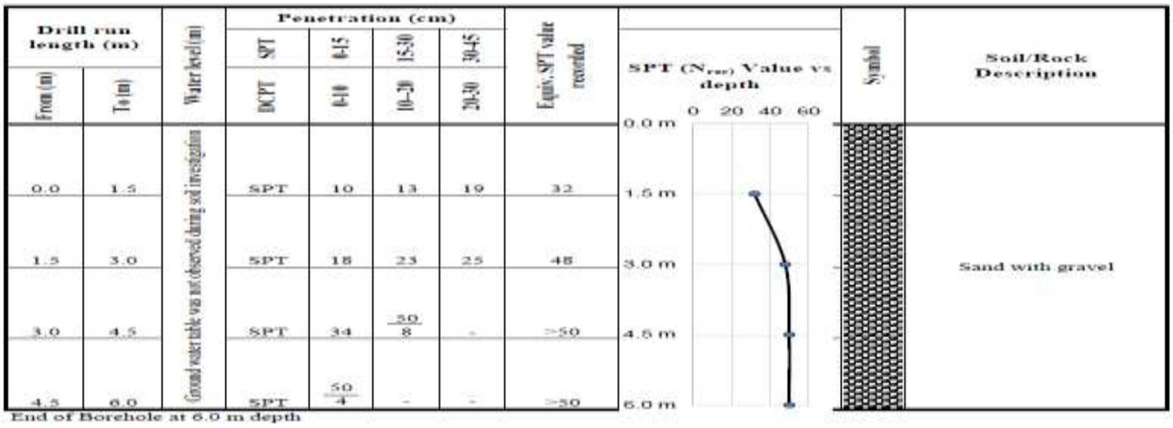


Drill run length (m)		Water level (m)	Penetration (cm)				Equiv. SPT value recorded	SPT (N_{rec}) Value vs depth	Symbol	Soil/Rock Description
			SPT	0-15	15-30	30-45				
From (m)	To (m)		DCPT	0-10	10--20	20-30		0.0 m		
0.0	1.5	Ground water table was not observed during soil investigation	SPT	8	14	13	27	1.5 m		Sand with gravel
1.5	3.0		SPT	12	14	18	32	3.0 m		
3.0	4.5		SPT	9	17	21	38	4.5 m		
4.5	6.0		SPT	14	20	24	44	6.0 m		

End of Borehole at 6.0 m depth

Table A.3: Borehole log

Tower no: AP-B

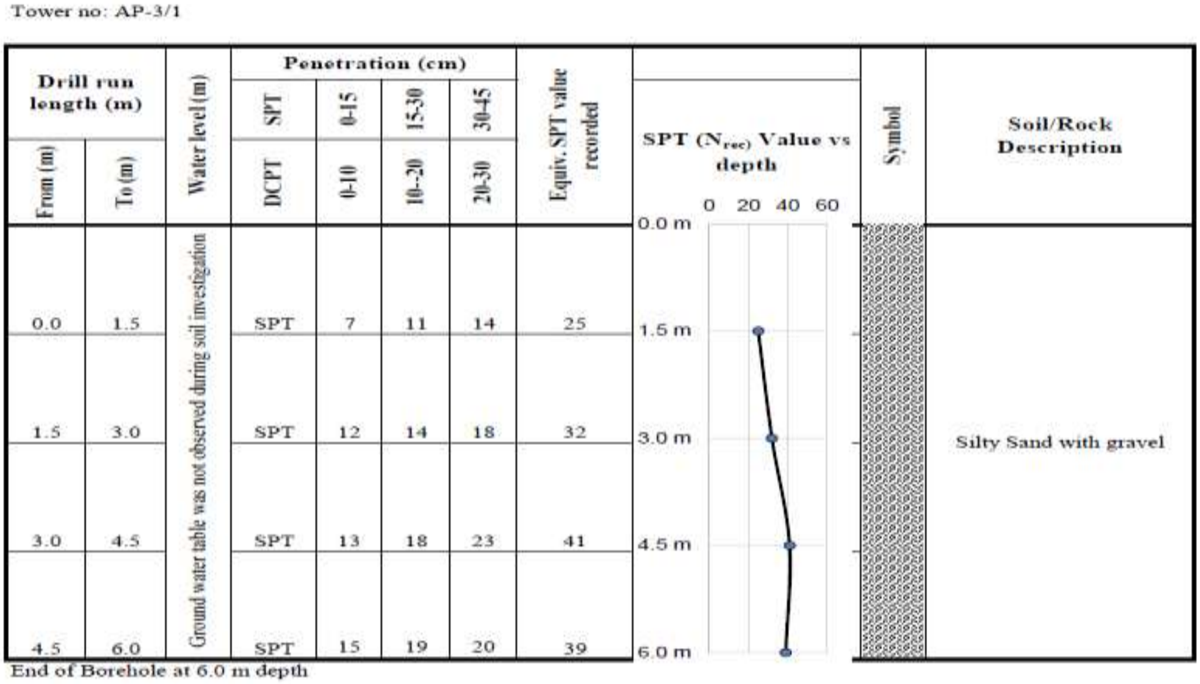


Drill run length (m)		Water level (m)	Penetration (cm)				Equiv. SPT value recorded	SPT (N_{rec}) Value vs depth	Symbol	Soil/Rock Description
			SPT	0-15	15-30	30-45				
From (m)	To (m)		DCPT	0-10	10--20	20-30		0.0 m		
0.0	1.5	Ground water table was not observed during soil investigation	SPT	10	13	19	32	1.5 m		Sand with gravel
1.5	3.0		SPT	18	23	25	48	3.0 m		
3.0	4.5		SPT	34	50 8	-	>50	4.5 m		
4.5	6.0		SPT	50 4	-	-	>50	6.0 m		

End of Borehole at 6.0 m depth

Table A.4: Borehole log

Tower no: AP-3/1

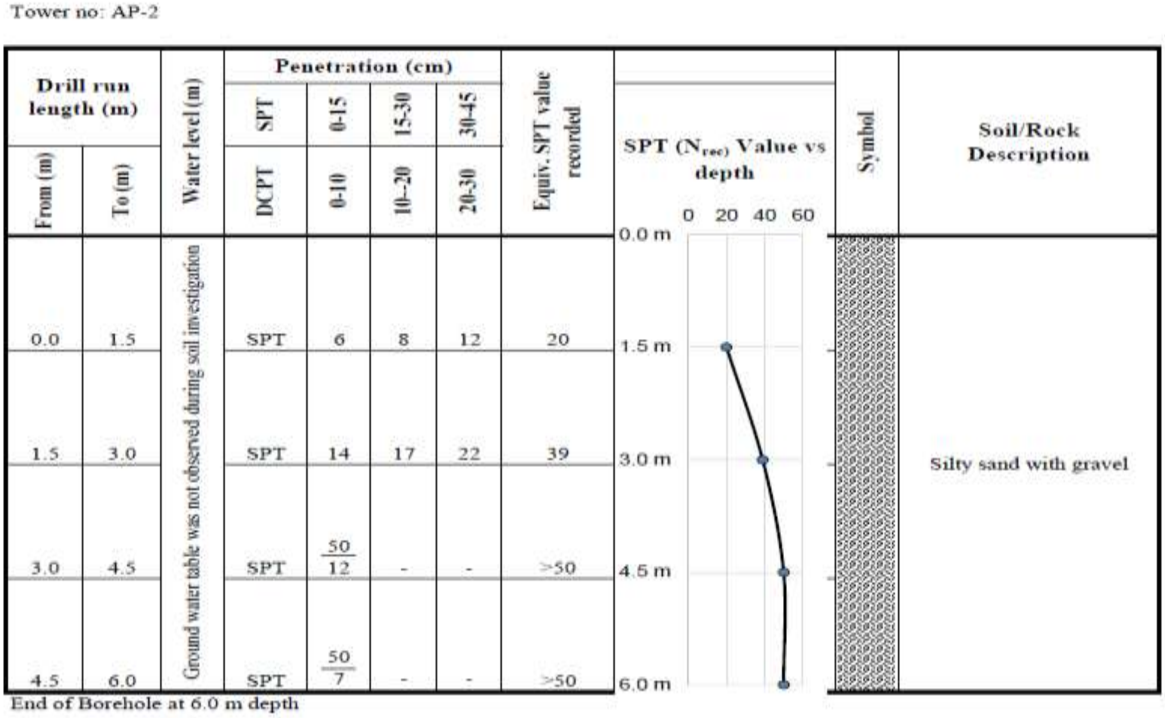


Drill run length (m)		Water level (m)	Penetration (cm)				Equiv. SPT value recorded	SPT (Nrec) Value vs depth	Symbol	Soil/Rock Description
From (m)	To (m)		SPT DCPT	0-15 0-10	15-30 10–20	30-45 20-30		0.0 m		
0.0	1.5	Ground water table was not observed during soil investigation	SPT	7	11	14	25	1.5 m	▩	Silty Sand with gravel
1.5	3.0		SPT	12	14	18	32	3.0 m		
3.0	4.5		SPT	13	18	23	41	4.5 m		
4.5	6.0		SPT	15	19	20	39	6.0 m		

End of Borehole at 6.0 m depth

Table A.5: Borehole log

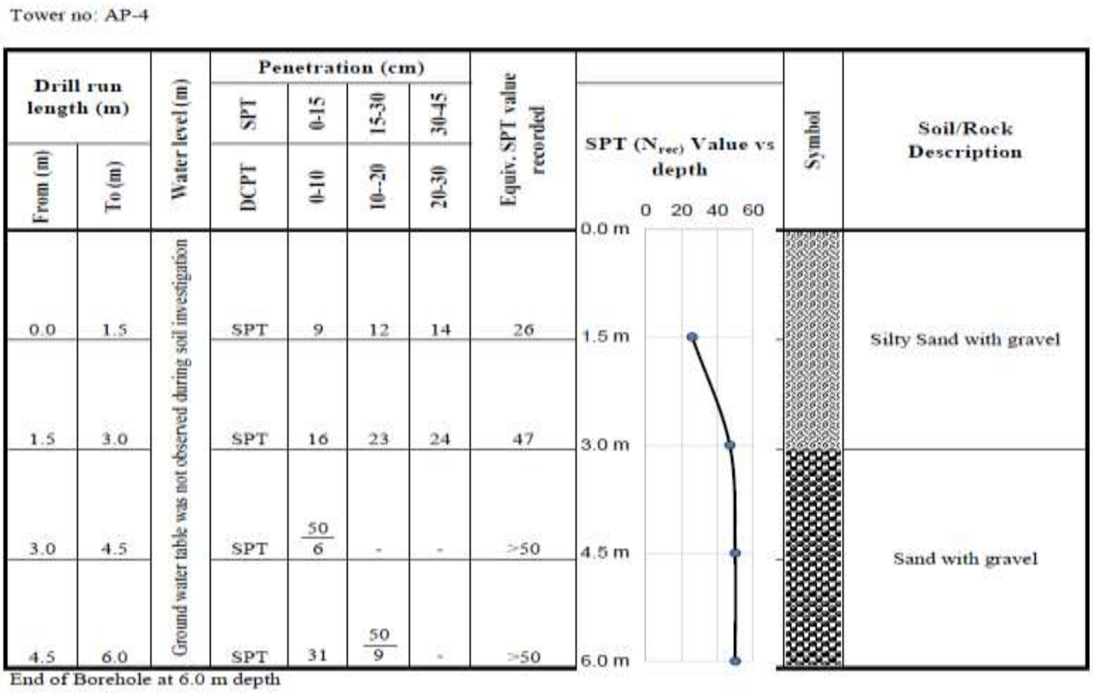
Tower no: AP-2



Drill run length (m)		Water level (m)	Penetration (cm)				Equiv. SPT value recorded	SPT (N_{rec}) Value vs depth	Symbol	Soil/Rock Description
From (m)	To (m)		SPT DCPT	0-15 0-10	15-30 10–20	30-45 20-30		0.0 m		
0.0	1.5	Ground water table was not observed during soil investigation	SPT	6	8	12	20	1.5 m	▩	Silty sand with gravel
1.5	3.0		SPT	14	17	22	39	3.0 m		
3.0	4.5		SPT	$\frac{50}{12}$	-	-	>50	4.5 m		
4.5	6.0		SPT	$\frac{50}{7}$	-	-	>50	6.0 m		

End of Borehole at 6.0 m depth

Table A.6: Borehole log



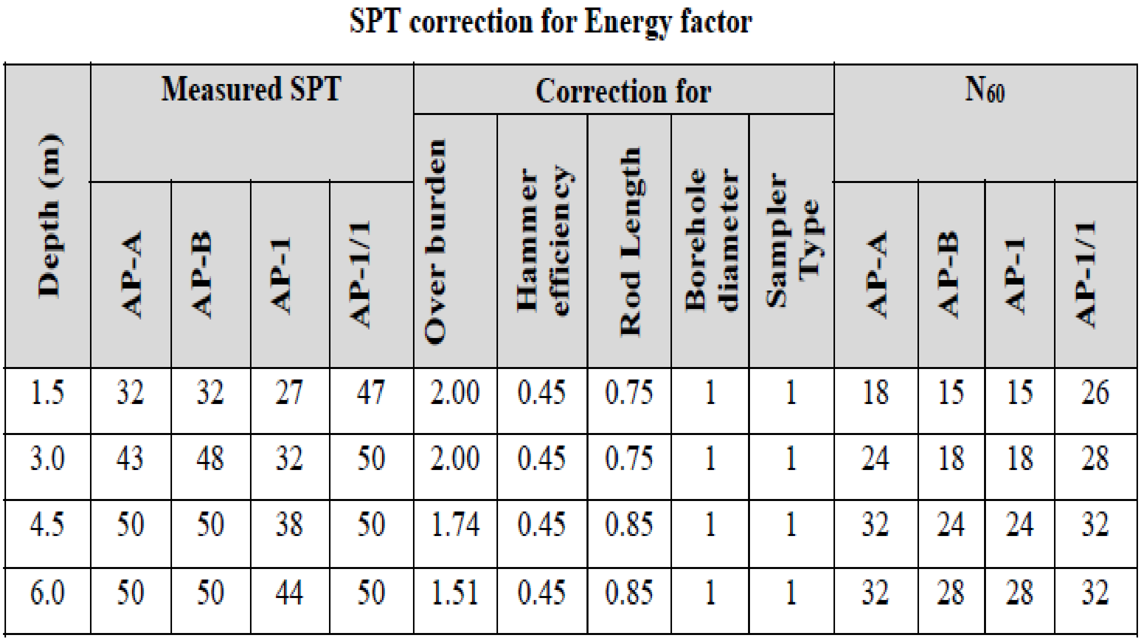
Tower no: AP-4

Drill run length (m)		Water level (m)	Penetration (cm)				Equiv. SPT value recorded	Symbol	Soil/Rock Description
From (m)	To (m)		SPT DCPT	0-15 0-10	15-30 10–20	30-45 20-30			
0.0	1.5	Ground water table was not observed during soil investigation	SPT	9	12	14	26		Silty Sand with gravel
1.5	3.0		SPT	16	23	24	47		
3.0	4.5		SPT	50/6	-	-	>50		Sand with gravel
4.5	6.0		SPT	31	50/9	-	>50		

End of Borehole at 6.0 m depth

ANNEX-B : SPT CORRECTION

Table B.1: Spt correction



SPT correction for Energy factor

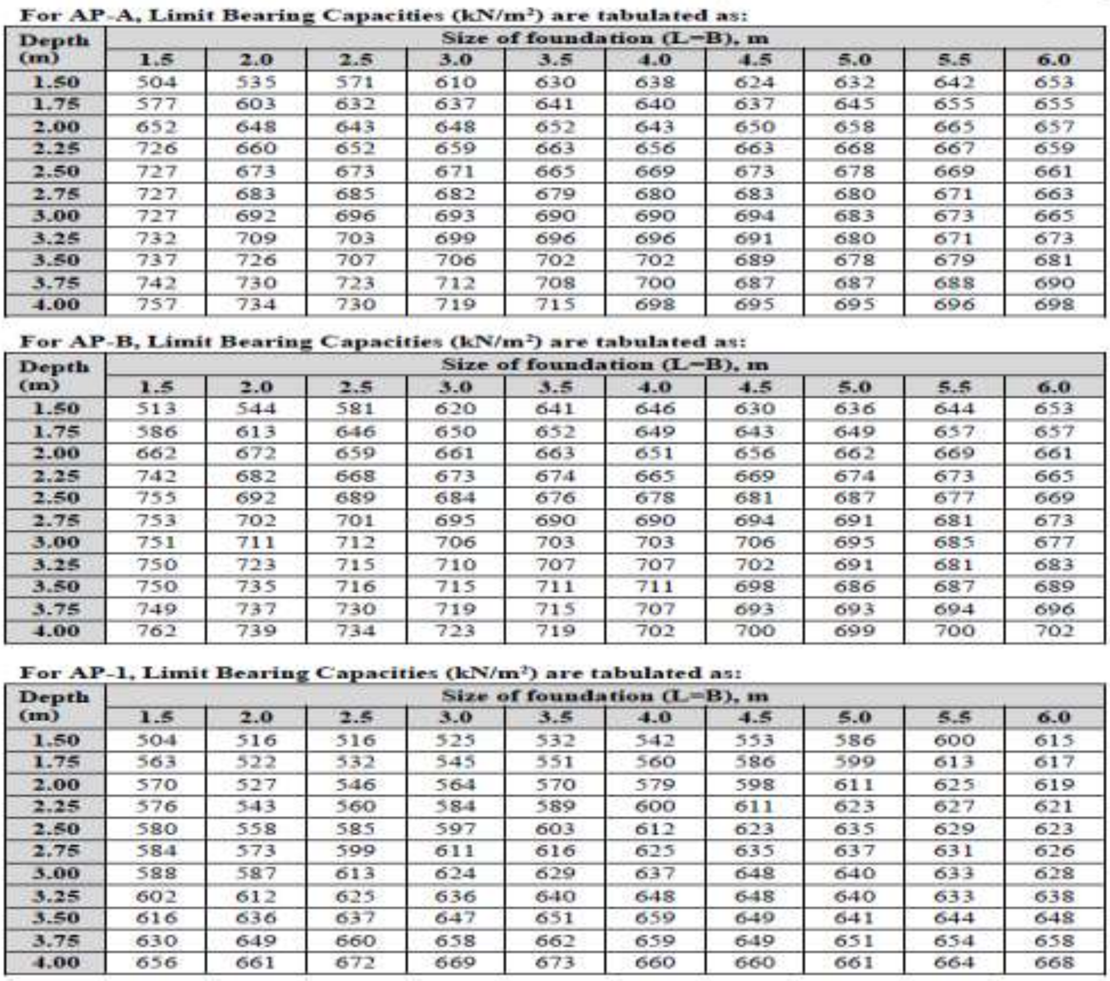
Depth (m)	Measured SPT				Correction for					N60			
	AP-A	AP-B	AP-1	AP-1/1	Over burden	Hammer efficiency	Rod Length	Borehole diameter	Sampler Type	AP-A	AP-B	AP-1	AP-1/1
1.5	32	32	27	47	2.00	0.45	0.75	1	1	18	15	15	26
3.0	43	48	32	50	2.00	0.45	0.75	1	1	24	18	18	28
4.5	50	50	38	50	1.74	0.45	0.85	1	1	32	24	24	32
6.0	50	50	44	50	1.51	0.45	0.85	1	1	32	28	28	32

Table B.2: Spt correction

Depth (m)	Measured SPT				Correction for					N60			
	AP-2	AP-3	AP-3/1	AP-4	Over burden	Hammer efficiency	Rod Length	Borehole diameter	Sampler Type	AP-2	AP-3	AP-3/1	AP-4
1.5	20	20	25	26	2.00	0.45	0.75	1	1	11	11	14	15
3.0	39	29	36	47	2.00	0.45	0.75	1	1	22	16	20	26
4.5	50	43	41	50	1.74	0.45	0.85	1	1	32	27	26	32
6.0	50	38	39	50	1.51	0.45	0.85	1	1	32	24	25	32

ANNEX-C : BEARING CAPACITIES

Table C.1: Bearing capacity



For AP-A, Limit Bearing Capacities (kN/m²) are tabulated as:

Depth (m)	Size of foundation (L=B), m									
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1.50	504	535	571	610	630	638	624	632	642	653
1.75	577	603	632	637	641	640	637	645	655	655
2.00	652	648	643	648	652	643	650	658	665	657
2.25	726	660	652	659	663	656	663	668	667	659
2.50	727	673	673	671	665	669	673	678	669	661
2.75	727	683	685	682	679	680	683	680	671	663
3.00	727	692	696	693	690	690	694	683	673	665
3.25	732	709	703	699	696	696	691	680	671	673
3.50	737	726	707	706	702	702	689	678	679	681
3.75	742	730	723	712	708	700	687	687	688	690
4.00	757	734	730	719	715	698	695	695	696	698

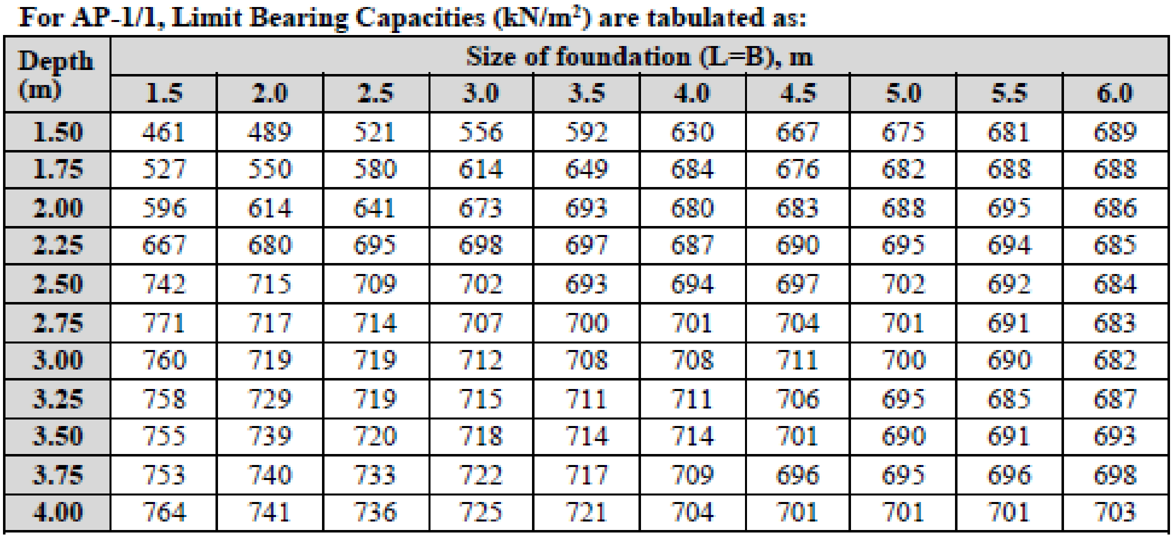
For AP-B, Limit Bearing Capacities (kN/m²) are tabulated as:

Depth (m)	Size of foundation (L=B), m									
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1.50	513	544	581	620	641	646	630	636	644	653
1.75	586	613	646	650	652	649	643	649	657	657
2.00	662	672	659	661	663	651	656	662	669	661
2.25	742	682	668	673	674	665	669	674	673	665
2.50	755	692	689	684	676	678	681	687	677	669
2.75	753	702	701	695	690	690	694	691	681	673
3.00	751	711	712	706	703	703	706	695	685	677
3.25	750	723	715	710	707	707	702	691	681	683
3.50	750	735	716	715	711	711	698	686	687	689
3.75	749	737	730	719	715	707	693	693	694	696
4.00	762	739	734	723	719	702	700	699	700	702

For AP-1, Limit Bearing Capacities (kN/m²) are tabulated as:

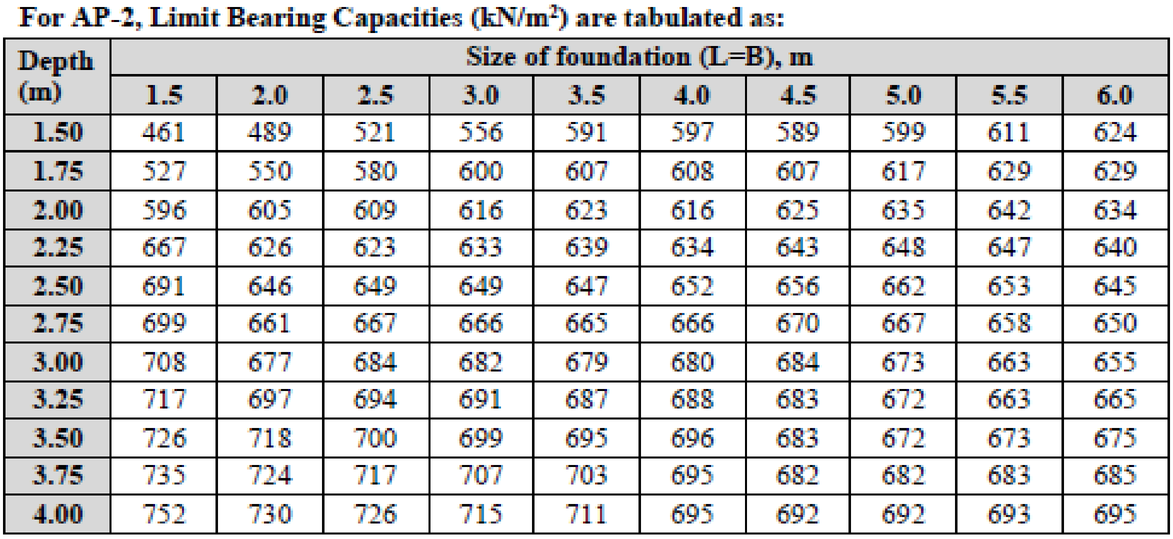
Depth (m)	Size of foundation (L=B), m									
	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
1.50	504	516	516	525	532	542	553	586	600	615
1.75	563	522	532	545	551	560	586	599	613	617
2.00	570	527	546	564	570	579	598	611	625	619
2.25	576	543	560	584	589	600	611	623	627	621
2.50	580	558	585	597	603	612	623	635	629	623
2.75	584	573	599	611	616	625	635	637	631	626
3.00	588	587	613	624	629	637	648	640	633	628
3.25	602	612	625	636	640	648	648	640	633	638
3.50	616	636	637	647	651	659	649	641	644	648
3.75	630	649	660	658	662	659	649	651	654	658
4.00	656	661	672	669	673	660	660	661	664	668

Table C.2: Bearing capacity



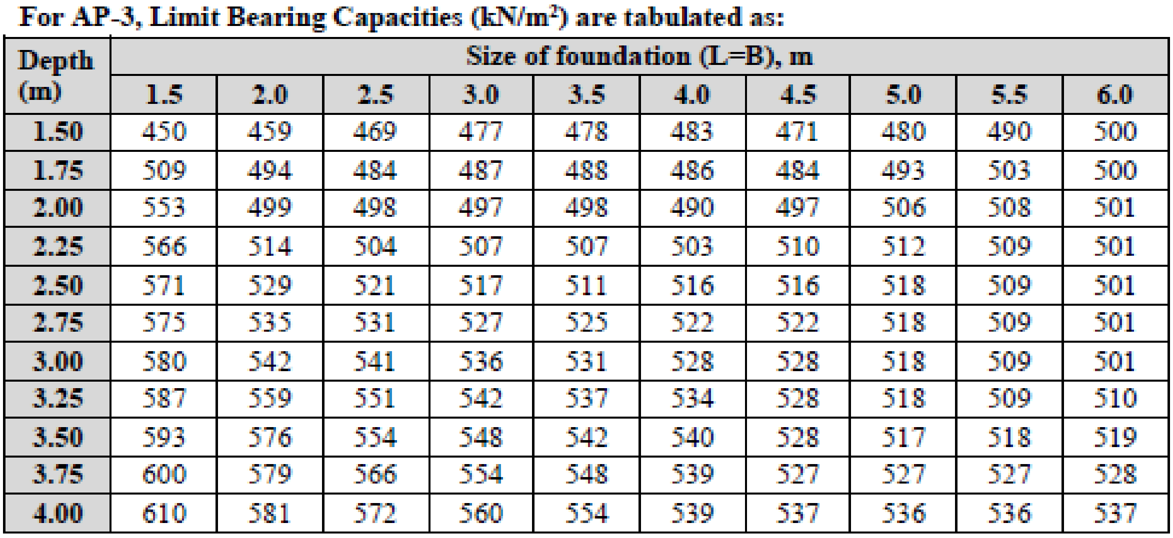
For AP-1/1, Limit Bearing Capacities (kN/m^2) are tabulated as:

Depth (m)	Size of foundation (L=B), m									
	1.5	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
1.50	461	489	521	556	592	630	667	675	681	689
1.75	527	550	580	614	649	684	676	682	688	688
2.00	596	614	641	673	693	680	683	688	695	686
2.25	667	680	695	698	697	687	690	695	694	685
2.50	742	715	709	702	693	694	697	702	692	684
2.75	771	717	714	707	700	701	704	701	691	683
3.00	760	719	719	712	708	708	711	700	690	682
3.25	758	729	719	715	711	711	706	695	685	687
3.50	755	739	720	718	714	714	701	690	691	693
3.75	753	740	733	722	717	709	696	695	696	698
4.00	764	741	736	725	721	704	701	701	701	703



For AP-2, Limit Bearing Capacities (kN/m^2) are tabulated as:

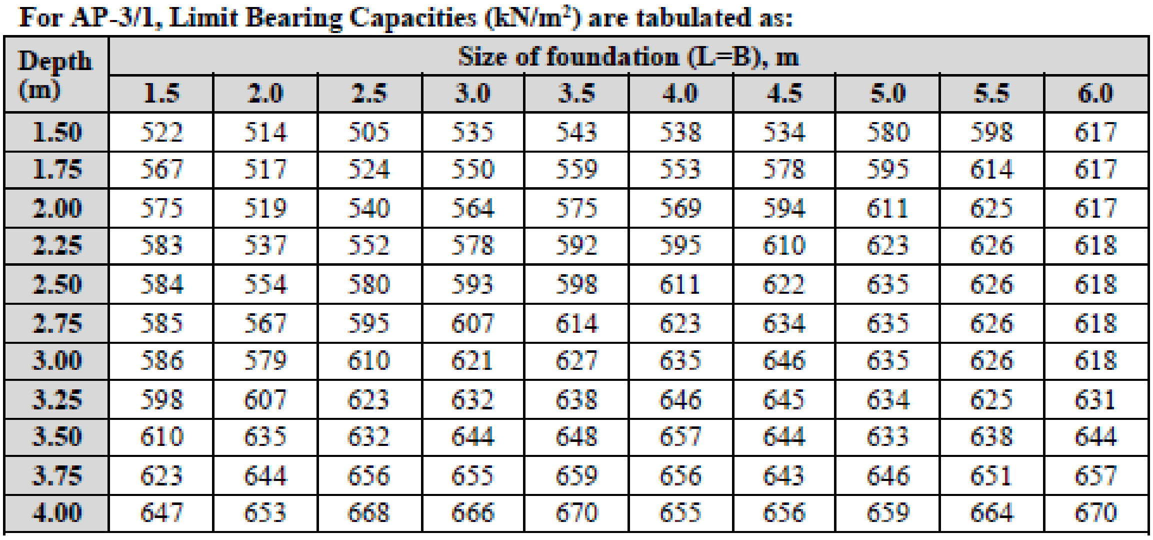
Depth (m)	Size of foundation (L=B), m									
	1.5	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
1.50	461	489	521	556	591	597	589	599	611	624
1.75	527	550	580	600	607	608	607	617	629	629
2.00	596	605	609	616	623	616	625	635	642	634
2.25	667	626	623	633	639	634	643	648	647	640
2.50	691	646	649	649	647	652	656	662	653	645
2.75	699	661	667	666	665	666	670	667	658	650
3.00	708	677	684	682	679	680	684	673	663	655
3.25	717	697	694	691	687	688	683	672	663	665
3.50	726	718	700	699	695	696	683	672	673	675
3.75	735	724	717	707	703	695	682	682	683	685
4.00	752	730	726	715	711	695	692	692	693	695



For AP-3, Limit Bearing Capacities (kN/m^2) are tabulated as:

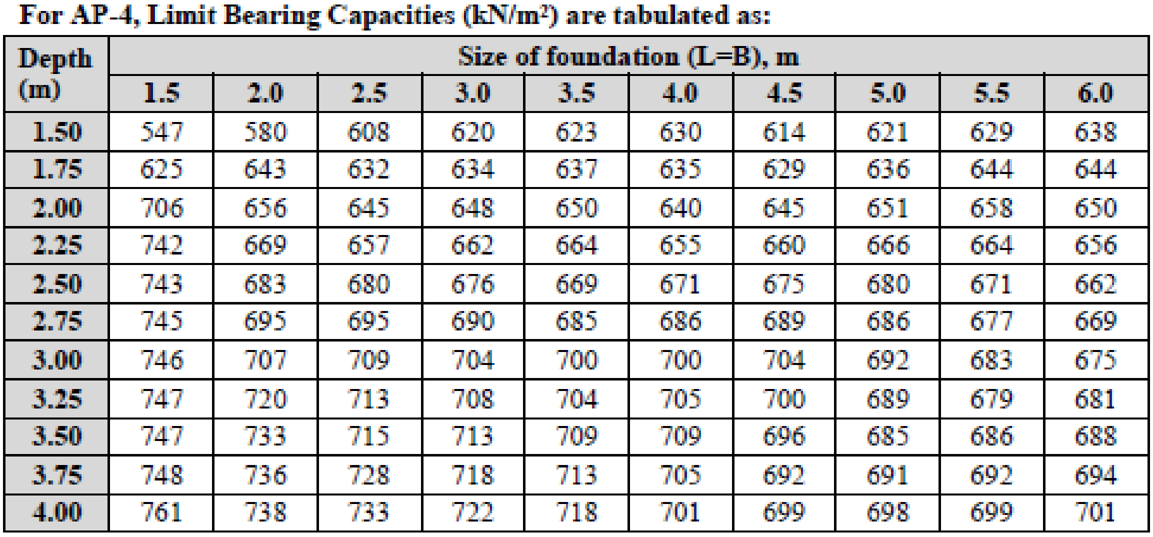
Depth (m)	Size of foundation (L=B), m									
	1.5	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
1.50	450	459	469	477	478	483	471	480	490	500
1.75	509	494	484	487	488	486	484	493	503	500
2.00	553	499	498	497	498	490	497	506	508	501
2.25	566	514	504	507	507	503	510	512	509	501
2.50	571	529	521	517	511	516	516	518	509	501
2.75	575	535	531	527	525	522	522	518	509	501
3.00	580	542	541	536	531	528	528	518	509	501
3.25	587	559	551	542	537	534	528	518	509	510
3.50	593	576	554	548	542	540	528	517	518	519
3.75	600	579	566	554	548	539	527	527	527	528
4.00	610	581	572	560	554	539	537	536	536	537

Table C.3: Bearing capacity



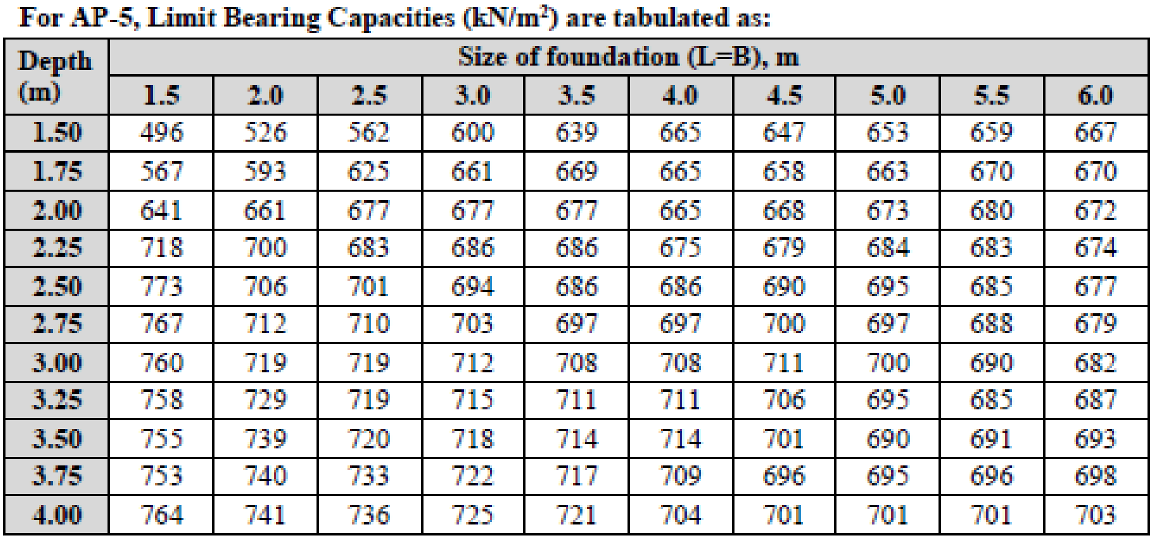
For AP-3/1, Limit Bearing Capacities (kN/m²) are tabulated as:

Depth (m)	Size of foundation (L=B), m									
	1.5	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
1.50	522	514	505	535	543	538	534	580	598	617
1.75	567	517	524	550	559	553	578	595	614	617
2.00	575	519	540	564	575	569	594	611	625	617
2.25	583	537	552	578	592	595	610	623	626	618
2.50	584	554	580	593	598	611	622	635	626	618
2.75	585	567	595	607	614	623	634	635	626	618
3.00	586	579	610	621	627	635	646	635	626	618
3.25	598	607	623	632	638	646	645	634	625	631
3.50	610	635	632	644	648	657	644	633	638	644
3.75	623	644	656	655	659	656	643	646	651	657
4.00	647	653	668	666	670	655	656	659	664	670



For AP-4, Limit Bearing Capacities (kN/m²) are tabulated as:

Depth (m)	Size of foundation (L=B), m									
	1.5	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
1.50	547	580	608	620	623	630	614	621	629	638
1.75	625	643	632	634	637	635	629	636	644	644
2.00	706	656	645	648	650	640	645	651	658	650
2.25	742	669	657	662	664	655	660	666	664	656
2.50	743	683	680	676	669	671	675	680	671	662
2.75	745	695	695	690	685	686	689	686	677	669
3.00	746	707	709	704	700	700	704	692	683	675
3.25	747	720	713	708	704	705	700	689	679	681
3.50	747	733	715	713	709	709	696	685	686	688
3.75	748	736	728	718	713	705	692	691	692	694
4.00	761	738	733	722	718	701	699	698	699	701

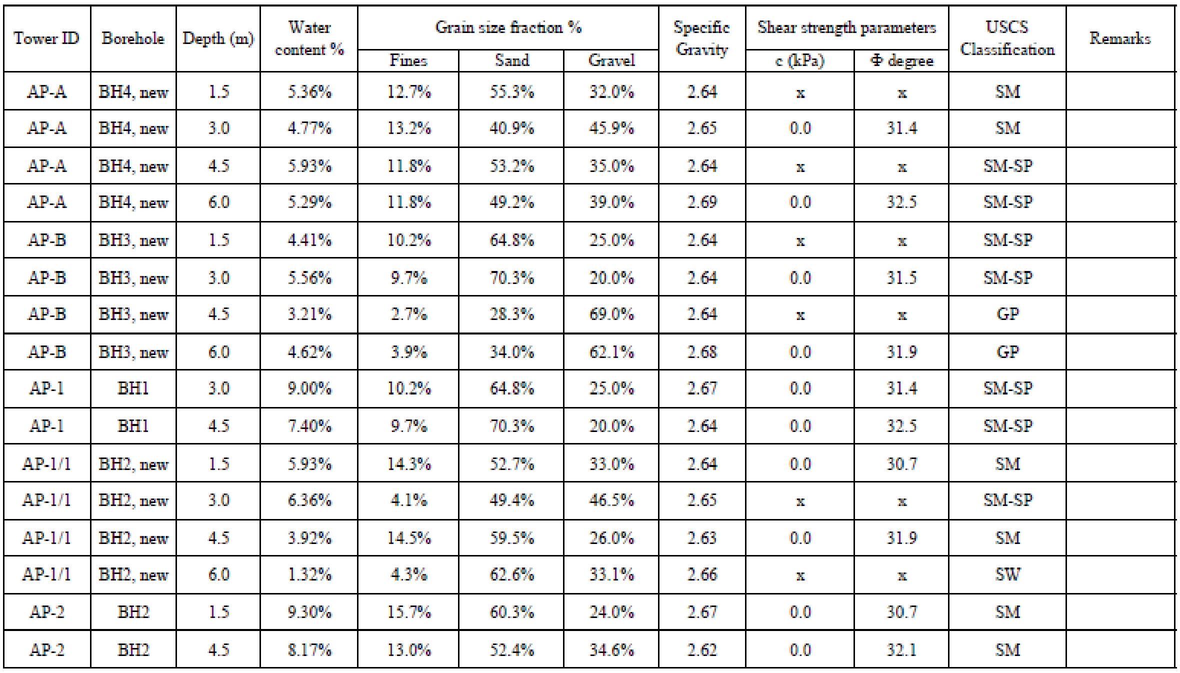


For AP-5, Limit Bearing Capacities (kN/m²) are tabulated as:

Depth (m)	Size of foundation (L=B), m									
	1.5	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**	**5.5**	**6.0**
1.50	496	526	562	600	639	665	647	653	659	667
1.75	567	593	625	661	669	665	658	663	670	670
2.00	641	661	677	677	677	665	668	673	680	672
2.25	718	700	683	686	686	675	679	684	683	674
2.50	773	706	701	694	686	686	690	695	685	677
2.75	767	712	710	703	697	697	700	697	688	679
3.00	760	719	719	712	708	708	711	700	690	682
3.25	758	729	719	715	711	711	706	695	685	687
3.50	755	739	720	718	714	714	701	690	691	693
3.75	753	740	733	722	717	709	696	695	696	698
4.00	764	741	736	725	721	704	701	701	701	703

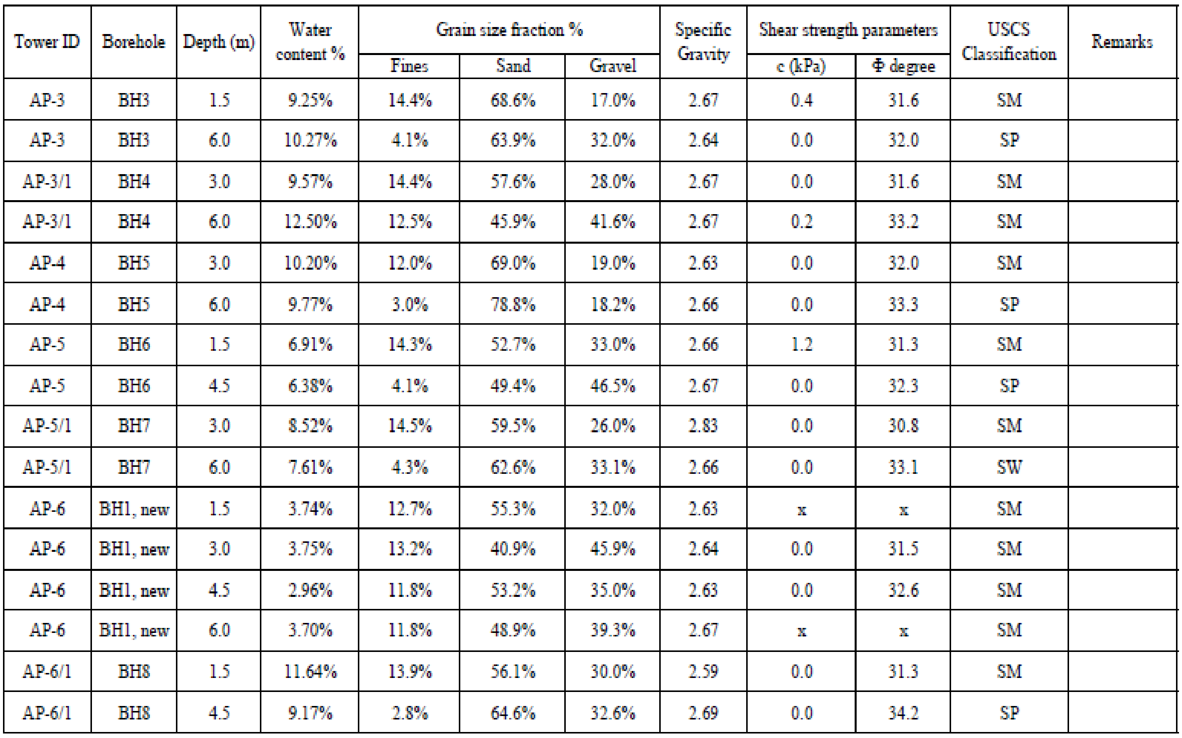
ANNEX-D : SUMMARY OF LAB TES

Table D.1: Summary Of lab Test



Tower ID	Borehole	Depth (m)	Water content %	Grain size fraction %			Specific Gravity	Shear strength parameters		USCS Classification	Remarks
				Fines	Sand	Gravel		c (kPa)	Φ degree		
AP-A	BH4, new	1.5	5.36%	12.7%	55.3%	32.0%	2.64	x	x	SM	
AP-A	BH4, new	3.0	4.77%	13.2%	40.9%	45.9%	2.65	0.0	31.4	SM	
AP-A	BH4, new	4.5	5.93%	11.8%	53.2%	35.0%	2.64	x	x	SM-SP	
AP-A	BH4, new	6.0	5.29%	11.8%	49.2%	39.0%	2.69	0.0	32.5	SM-SP	
AP-B	BH3, new	1.5	4.41%	10.2%	64.8%	25.0%	2.64	x	x	SM-SP	
AP-B	BH3, new	3.0	5.56%	9.7%	70.3%	20.0%	2.64	0.0	31.5	SM-SP	
AP-B	BH3, new	4.5	3.21%	2.7%	28.3%	69.0%	2.64	x	x	GP	
AP-B	BH3, new	6.0	4.62%	3.9%	34.0%	62.1%	2.68	0.0	31.9	GP	
AP-1	BH1	3.0	9.00%	10.2%	64.8%	25.0%	2.67	0.0	31.4	SM-SP	
AP-1	BH1	4.5	7.40%	9.7%	70.3%	20.0%	2.64	0.0	32.5	SM-SP	
AP-1/1	BH2, new	1.5	5.93%	14.3%	52.7%	33.0%	2.64	0.0	30.7	SM	
AP-1/1	BH2, new	3.0	6.36%	4.1%	49.4%	46.5%	2.65	x	x	SM-SP	
AP-1/1	BH2, new	4.5	3.92%	14.5%	59.5%	26.0%	2.63	0.0	31.9	SM	
AP-1/1	BH2, new	6.0	1.32%	4.3%	62.6%	33.1%	2.66	x	x	SW	
AP-2	BH2	1.5	9.30%	15.7%	60.3%	24.0%	2.67	0.0	30.7	SM	
AP-2	BH2	4.5	8.17%	13.0%	52.4%	34.6%	2.62	0.0	32.1	SM	

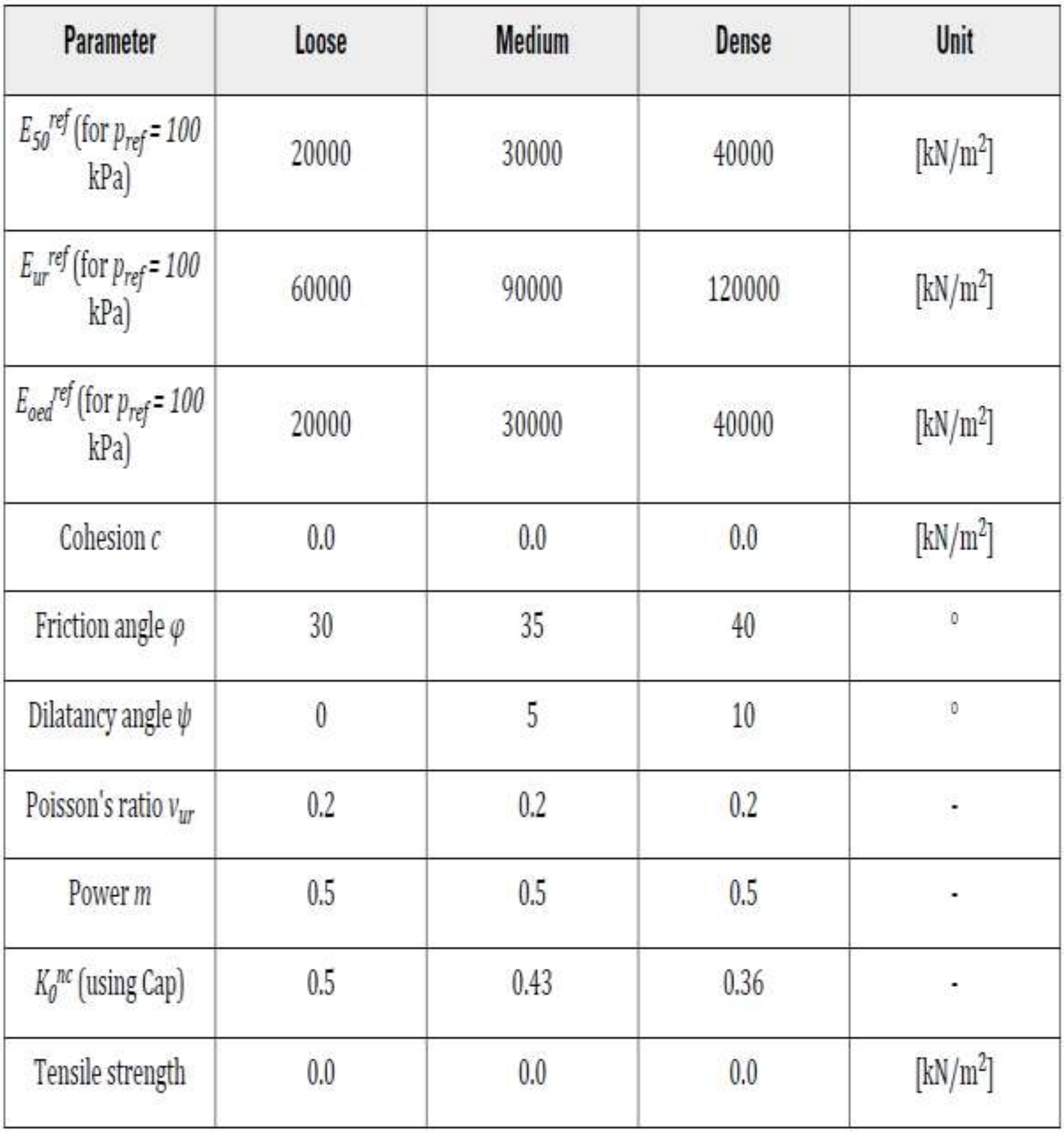
Table D.2: Summary Of lab Test



Tower ID	Borehole	Depth (m)	Water content %	Grain size fraction %			Specific Gravity	Shear strength parameters		USCS Classification	Remarks
				Fines	Sand	Gravel		c (kPa)	Φ degree		
AP-3	BH3	1.5	9.25%	14.4%	68.6%	17.0%	2.67	0.4	31.6	SM	
AP-3	BH3	6.0	10.27%	4.1%	63.9%	32.0%	2.64	0.0	32.0	SP	
AP-3/1	BH4	3.0	9.57%	14.4%	57.6%	28.0%	2.67	0.0	31.6	SM	
AP-3/1	BH4	6.0	12.50%	12.5%	45.9%	41.6%	2.67	0.2	33.2	SM	
AP-4	BH5	3.0	10.20%	12.0%	69.0%	19.0%	2.63	0.0	32.0	SM	
AP-4	BH5	6.0	9.77%	3.0%	78.8%	18.2%	2.66	0.0	33.3	SP	
AP-5	BH6	1.5	6.91%	14.3%	52.7%	33.0%	2.66	1.2	31.3	SM	
AP-5	BH6	4.5	6.38%	4.1%	49.4%	46.5%	2.67	0.0	32.3	SP	
AP-5/1	BH7	3.0	8.52%	14.5%	59.5%	26.0%	2.83	0.0	30.8	SM	
AP-5/1	BH7	6.0	7.61%	4.3%	62.6%	33.1%	2.66	0.0	33.1	SW	
AP-6	BH1, new	1.5	3.74%	12.7%	55.3%	32.0%	2.63	x	x	SM	
AP-6	BH1, new	3.0	3.75%	13.2%	40.9%	45.9%	2.64	0.0	31.5	SM	
AP-6	BH1, new	4.5	2.96%	11.8%	53.2%	35.0%	2.63	0.0	32.6	SM	
AP-6	BH1, new	6.0	3.70%	11.8%	48.9%	39.3%	2.67	x	x	SM	
AP-6/1	BH8	1.5	11.64%	13.9%	56.1%	30.0%	2.59	0.0	31.3	SM	
AP-6/1	BH8	4.5	9.17%	2.8%	64.6%	32.6%	2.69	0.0	34.2	SP	

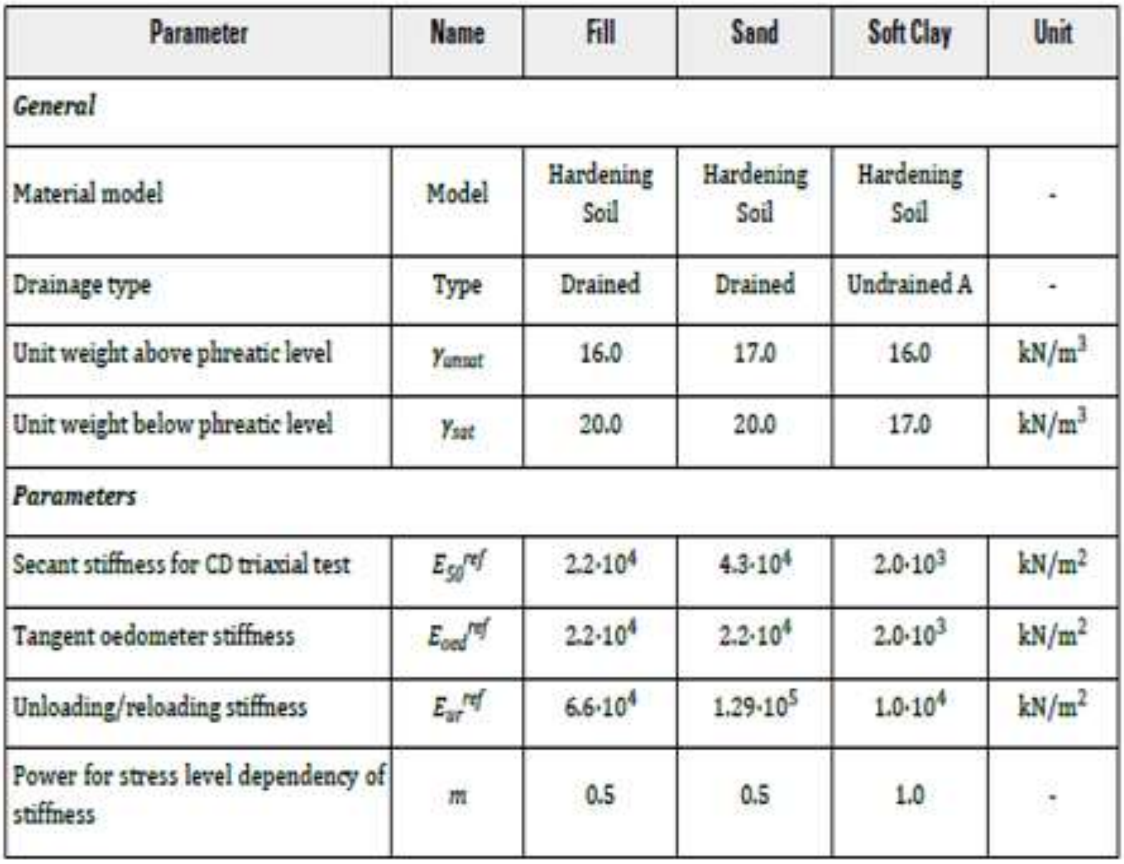
ANNEX-E : PARAMETER SHEET

Table E.1:Soil Parameter Sheet



Parameter	Loose	Medium	Dense	Unit
E_{50}^{ref} (for p_{ref} = 100 kPa)	20000	30000	40000	[kN/m^2]
E_{ur}^{ref} (for p_{ref} = 100 kPa)	60000	90000	120000	[kN/m^2]
E_{oed}^{ref} (for p_{ref} = 100 kPa)	20000	30000	40000	[kN/m^2]
Cohesion c	0.0	0.0	0.0	[kN/m^2]
Friction angle φ	30	35	40	°
Dilatancy angle ψ	0	5	10	°
Poisson's ratio v_{ur}	0.2	0.2	0.2	-
Power m	0.5	0.5	0.5	-
K_0^{nc} (using Cap)	0.5	0.43	0.36	-
Tensile strength	0.0	0.0	0.0	[kN/m^2]

Table E.2: Soil Parameter sheet



Parameter	Name	Fill	Sand	Soft Clay	Unit
General					
Material model	Model	Hardening Soil	Hardening Soil	Hardening Soil	-
Drainage type	Type	Drained	Drained	Undrained A	-
Unit weight above phreatic level	γ_{unsat}	16.0	17.0	16.0	kN/m^3
Unit weight below phreatic level	γ_{sat}	20.0	20.0	17.0	kN/m^3
Parameters					
Secant stiffness for CD triaxial test	E_{50}^{ref}	$2.2\cdot10^4$	$4.3\cdot10^4$	$2.0\cdot10^3$	kN/m^2
Tangent oedometer stiffness	E_{oed}^{ref}	$2.2\cdot10^4$	$2.2\cdot10^4$	$2.0\cdot10^3$	kN/m^2
Unloading/reloading stiffness	E_{ur}^{ref}	$6.6\cdot10^4$	$1.29\cdot10^5$	$1.0\cdot10^4$	kN/m^2
Power for stress level dependency of stiffness	m	0.5	0.5	1.0	-

Parameter	Name	Fill	Sand	Soft Clay	Unit
Cohesion	c'_{ref}	1	1	5	kN/m^2
Friction angle	φ'	30.0	34.0	25	°
Dilatancy angle	ψ	0.0	4.0	0.0	°
Poisson's ratio	ν'_{ur}	0.2	0.2	0.2	-
Drainage type					
Interface strength	-	Manual	Manual	Manual	-
Interface reduction factor	R_{inter}	0.65	0.7	0.5	-
Initial					
K_0 determination	-	Automatic	Automatic	Automatic	-
Lateral earth pressure coefficient	K_0	0.5000	0.4408	0.7411	-
Over-consolidation ratio	*OCR*	1.0	1.0	1.5	-
Pre-overburden pressure	*POP*	0.0	0.0	0.0	-

Table E.3: Concrete Pile Parameter sheet

Parameter	Name	Pile foundation	Unit
Young's modulus	E	$3{\cdot}10^7$	kN/m^2
Unit weight	γ	6.0	kN/m^3
Beam type	-	Predefined	-
Predefined beam type	-	Massive circular beam	-
Diameter	-	1.5	m
Axial skin resistance	Type	Linear	-
Skin resistance at the top of the embedded beam	$T_{skin,start,max}$	200	kN/m
Skin resistance at the bottom of the embedded beam	$T_{skin,end,max}$	500	kN/m
Base resistance	F_{max}	$1{\cdot}10^4$	kN

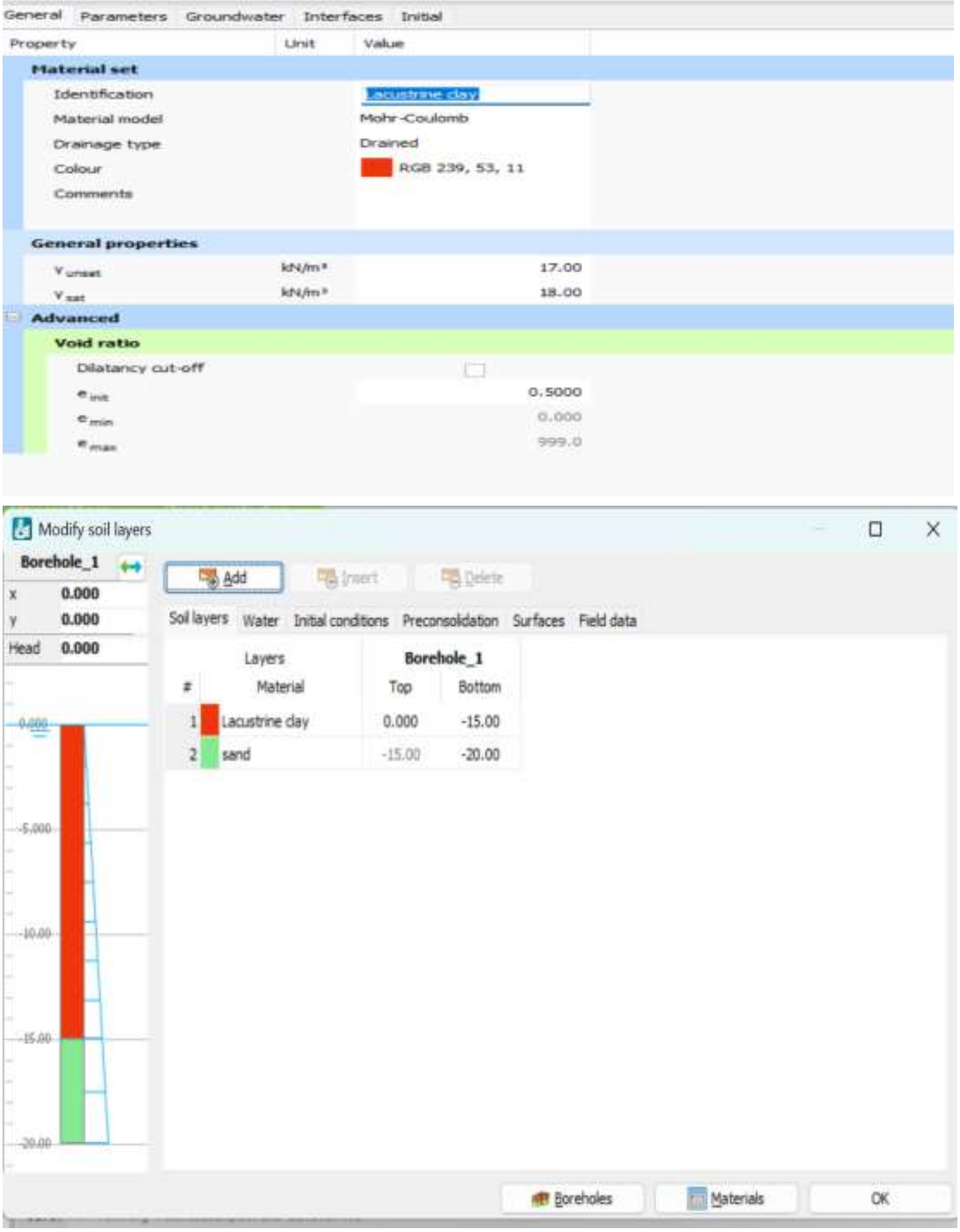
Table E.4: Concrete Parameter sheet

Parameter	Name	Basement floor	Basement wall	Unit
Isotropic	-	Yes	Yes	-
Thickness	d	0.5	0.3	m
Weight	γ	15	15.5	kN/m^3
Young's modulus	E_1	$3{\cdot}10^7$	$3{\cdot}10^7$	kN/m^2
Poisson's ratio	ν_{12}	0.15	0.15	-

Table E.5: Concrete Parameter sheet

Parameter	Name	Basement column	Basement beam	Unit
Material type	Type	Elastic	Elastic	-
Young's modulus	E	$3{\cdot}10^7$	$3{\cdot}10^7$	kN/m^2
Volumetric weight	γ	24.0	6.0	kN/m^3
Cross section area	A	0.49	0.7	m^2
Moment of Inertia	I_2	0.020	0.029	m^4
	I_3	0.020	0.058	m^4

ANNEX-F : FINITE ELEMENT MODELING



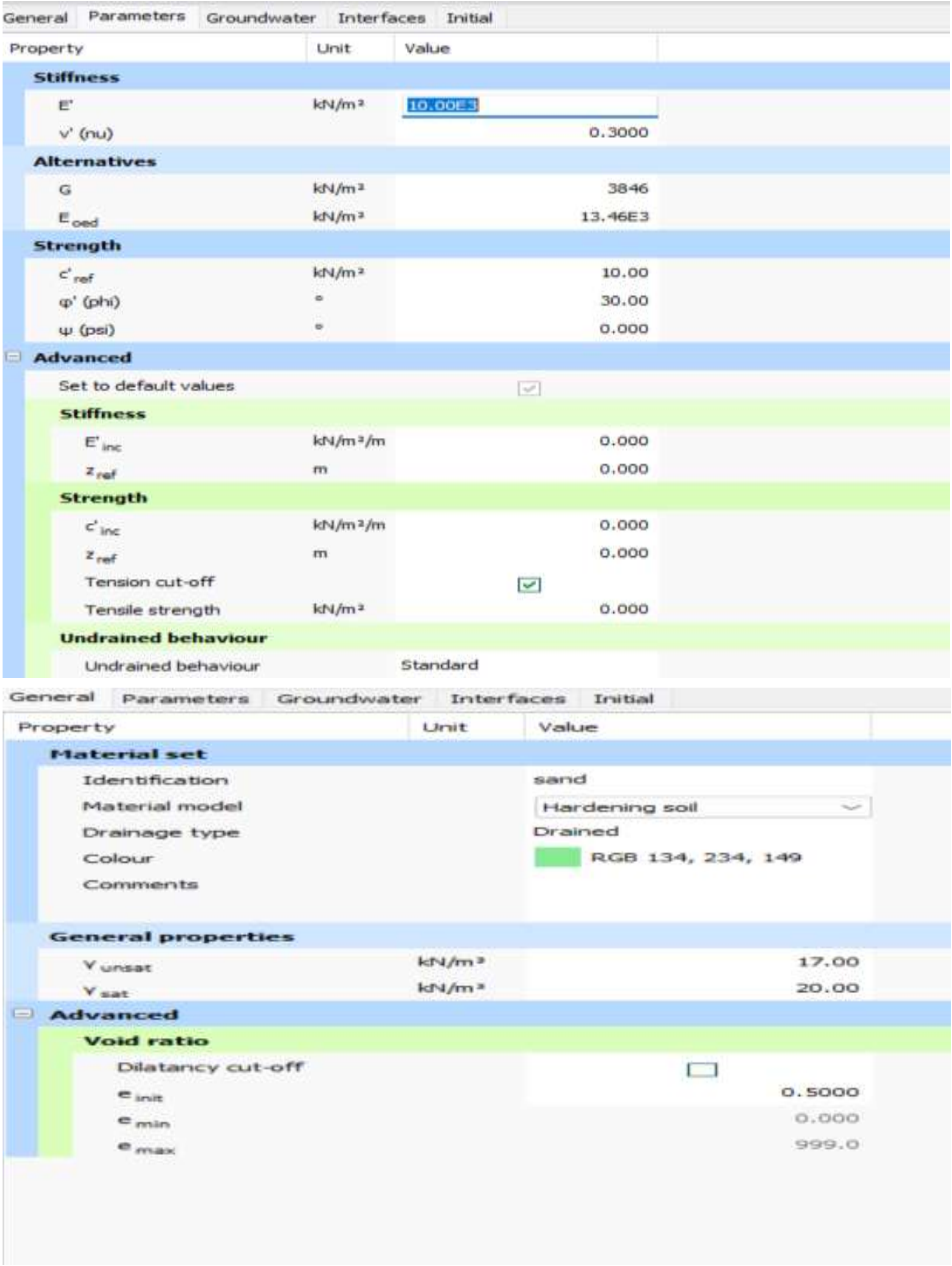
Property	Unit	Value
Material set		
Identification		Lacustrine clay
Material model		Mohr-Coulomb
Drainage type		Drained
Colour		🟥 RGB 239, 53, 11
Comments		
General properties		
γ_{unsat}	kN/m³	17.00
γ_{sat}	kN/m³	18.00
Advanced		
Void ratio		
Dilatancy cut-off		☐
e_{init}		0.5000
e_{min}		0.000
e_{max}		999.0

Borehole_1

x	0.000
y	0.000
Head	0.000

#	Layers Material	Borehole_1 Top	 Bottom
1	🟥 Lacustrine clay	0.000	-15.00
2	🟩 sand	-15.00	-20.00

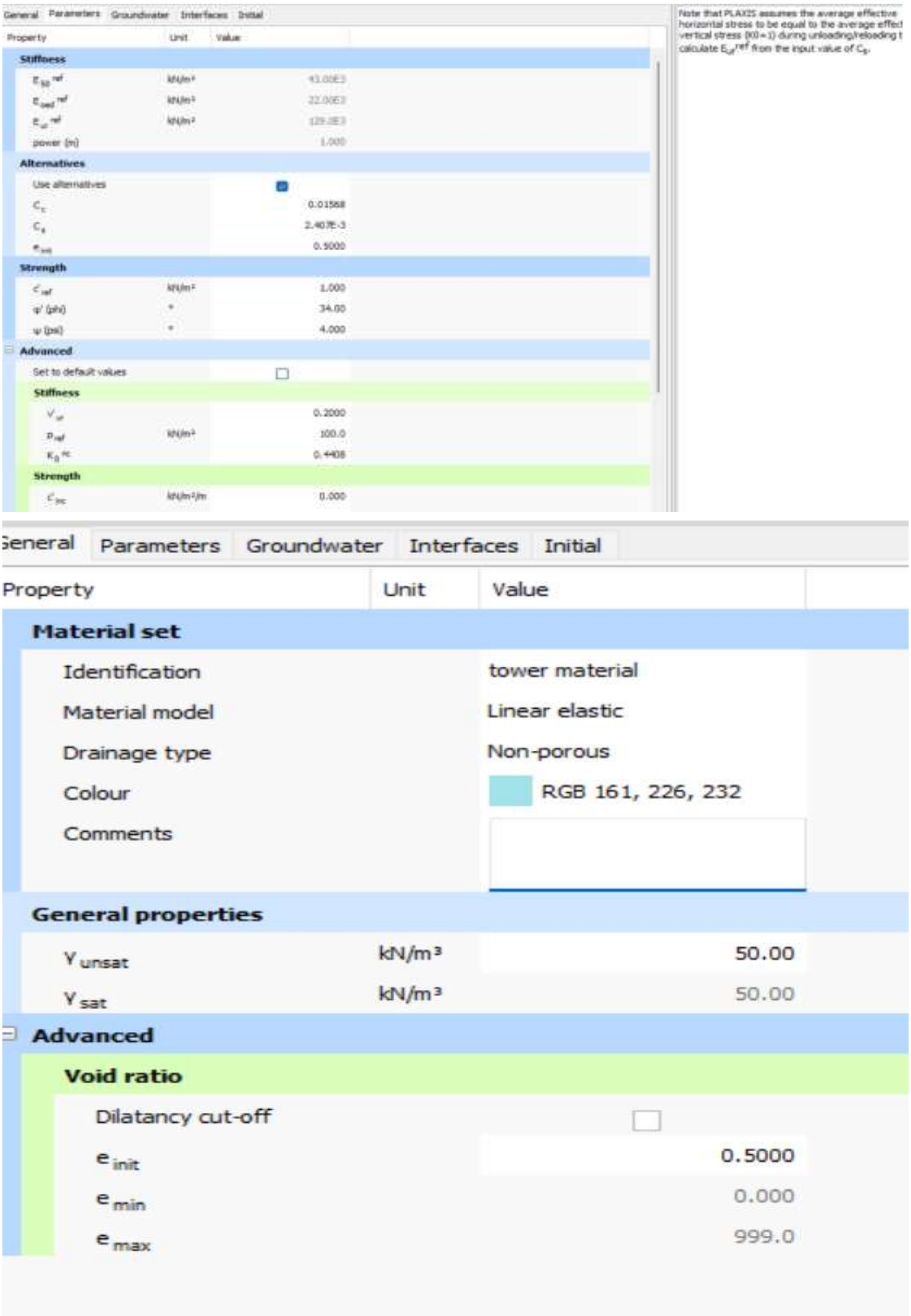
Figure F.1 : Bore hole defination for lacustrine clay and sandy soil



Property	Unit	Value
Stiffness		
E'	kN/m²	10.00E3
ν' (nu)		0.3000
Alternatives		
G	kN/m²	3846
E_{oed}	kN/m²	13.46E3
Strength		
c'_{ref}	kN/m²	10.00
φ' (phi)	°	30.00
ψ (psi)	°	0.000
Advanced		
Set to default values		☑
Stiffness		
E'_{inc}	kN/m²/m	0.000
z_{ref}	m	0.000
Strength		
c'_{inc}	kN/m²/m	0.000
z_{ref}	m	0.000
Tension cut-off		☑
Tensile strength	kN/m²	0.000
Undrained behaviour		
Undrained behaviour		Standard

Property	Unit	Value
Material set		
Identification		sand
Material model		Hardening soil
Drainage type		Drained
Colour		🟩 RGB 134, 234, 149
Comments		
General properties		
γ_{unsat}	kN/m³	17.00
γ_{sat}	kN/m³	20.00
Advanced		
Void ratio		
Dilatancy cut-off		☐
e_{init}		0.5000
e_{min}		0.000
e_{max}		999.0

Figure F.2 : Material proporties defination for lacustrine clay and sandy soil

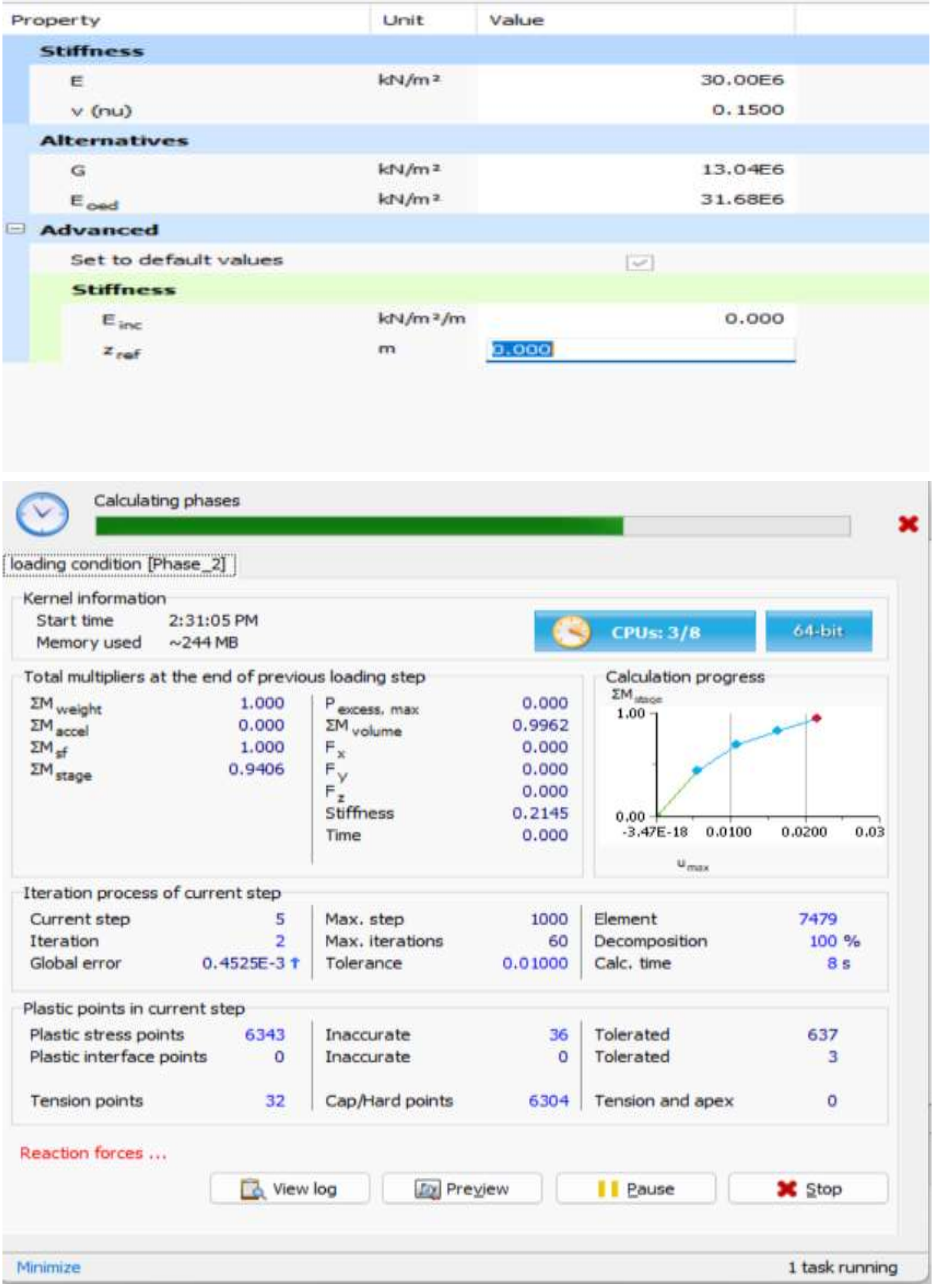


Property	Unit	Value
Stiffness		
E_{50}^{ref}	kN/m²	43.00E3
E_{oed}^{ref}	kN/m²	22.00E3
E_{ur}^{ref}	kN/m²	129.2E3
power (m)		1.000
Alternatives		
Use alternatives		☑
C_c		0.01568
C_s		2.407E-3
e_{init}		0.5000
Strength		
c'_{ref}	kN/m²	1.000
φ' (phi)	°	34.00
ψ (psi)	°	4.000
Advanced		
Set to default values		☐
Stiffness		
ν'_{ur}		0.2000
p_{ref}	kN/m²	100.0
K_0^{nc}		0.4408
Strength		
c'_{inc}	kN/m²/m	0.000

Note that PLAXIS assumes the average effective horizontal stress to be equal to the average effec vertical stress (K0 = 1) during unloading/reloading t calculate E_{ur}^{ref} from the input value of C_s.

Property	Unit	Value
Material set		
Identification		tower material
Material model		Linear elastic
Drainage type		Non-porous
Colour		RGB 161, 226, 232
Comments		
General properties		
γ_{unsat}	kN/m³	50.00
γ_{sat}	kN/m³	50.00
Advanced		
Void ratio		
Dilatancy cut-off		☐
e_{init}		0.5000
e_{min}		0.000
e_{max}		999.0

Figure F.3 : Material proporties defination for tower element



Property	Unit	Value
Stiffness		
E	kN/m²	30.00E6
ν (nu)		0.1500
Alternatives		
G	kN/m²	13.04E6
E_{oed}	kN/m²	31.68E6
Advanced		
Set to default values		☑
Stiffness		
E_{inc}	kN/m²/m	0.000
z_{ref}	m	0.000

Calculating phases

loading condition [Phase_2]

Kernel information

Start time 2:31:05 PM

Memory used ~244 MB

Total multipliers at the end of previous loading step

ΣM_{weight}	1.000	$P_{excess, max}$	0.000
ΣM_{accel}	0.000	ΣM_{volume}	0.9962
ΣM_{sf}	1.000	F_x	0.000
ΣM_{stage}	0.9406	F_y	0.000
		F_z	0.000
		Stiffness	0.2145
		Time	0.000

Calculation progress

Iteration process of current step

Current step	5	Max. step	1000	Element	7479
Iteration	2	Max. iterations	60	Decomposition	100 %
Global error	0.4525E-3 ↑	Tolerance	0.01000	Calc. time	8 s

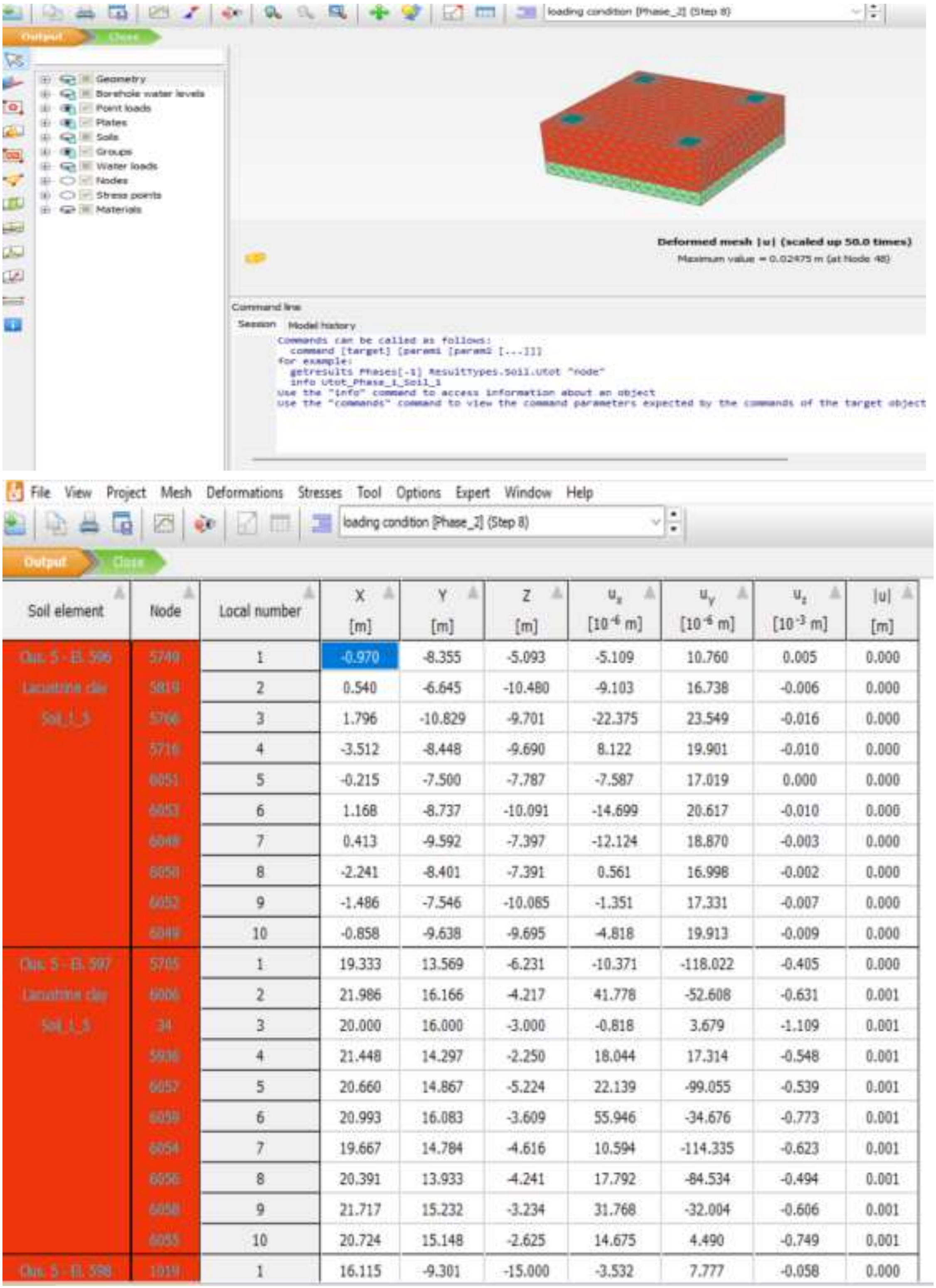
Plastic points in current step

Plastic stress points	6343	Inaccurate	36	Tolerated	637
Plastic interface points	0	Inaccurate	0	Tolerated	3
Tension points	32	Cap/Hard points	6304	Tension and apex	0

Reaction forces ...

1 task running

Figure F.4 : Analysis running



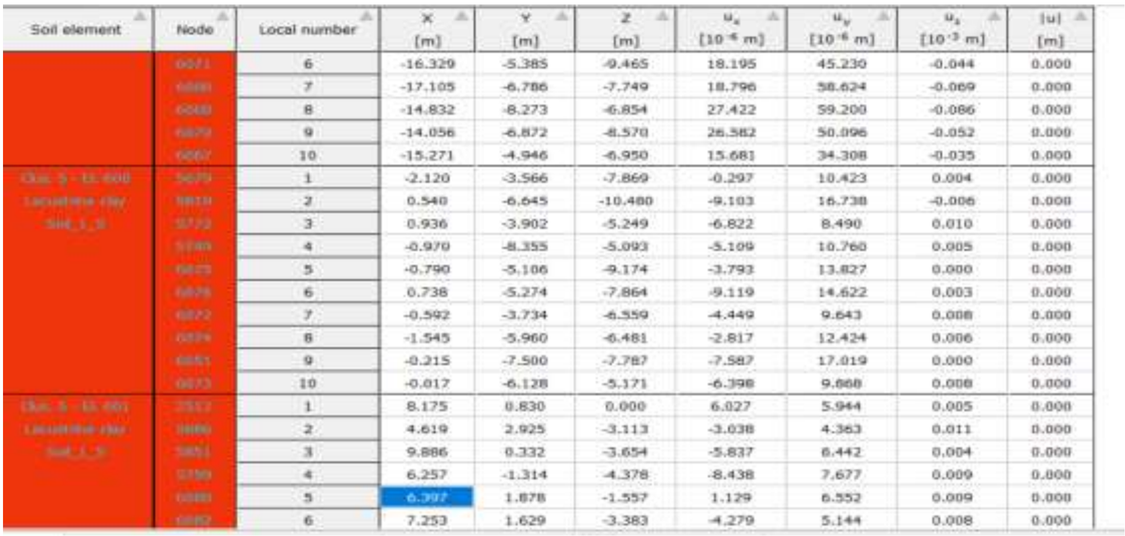
Deformed mesh |u| (scaled up 50.0 times)

Maximum value = 0.02475 m (at Node 48)

```
Commands can be called as follows:
  command [target] [param1 [param2 [...]]]
For example:
  getresults Phases[-1] ResultTypes.Soil.Utot "node"
  info Utot_Phase_1_Soil_1
Use the "info" command to access information about an object
Use the "commands" command to view the command parameters expected by the commands of the target object
```

Soil element	Node	Local number	X [m]	Y [m]	Z [m]	u_x [10^{-6} m]	u_y [10^{-6} m]	u_z [10^{-3} m]	|u| [m]
Clus. 5 - El. 596 Lacustrine clay Soil_1_5	5749	1	-0.970	-8.355	-5.093	-5.109	10.760	0.005	0.000
	5819	2	0.540	-6.645	-10.480	-9.103	16.738	-0.006	0.000
	5766	3	1.796	-10.829	-9.701	-22.375	23.549	-0.016	0.000
	5716	4	-3.512	-8.448	-9.690	8.122	19.901	-0.010	0.000
	6051	5	-0.215	-7.500	-7.787	-7.587	17.019	0.000	0.000
	6053	6	1.168	-8.737	-10.091	-14.699	20.617	-0.010	0.000
	6049	7	0.413	-9.592	-7.397	-12.124	18.870	-0.003	0.000
	6050	8	-2.241	-8.401	-7.391	0.561	16.998	-0.002	0.000
	6052	9	-1.486	-7.546	-10.085	-1.351	17.331	-0.007	0.000
	6048	10	-0.858	-9.638	-9.695	-4.818	19.913	-0.009	0.000
Clus. 5 - El. 597 Lacustrine clay Soil_1_5	5705	1	19.333	13.569	-6.231	-10.371	-118.022	-0.405	0.000
	6006	2	21.986	16.166	-4.217	41.778	-52.608	-0.631	0.001
	34	3	20.000	16.000	-3.000	-0.818	3.679	-1.109	0.001
	5936	4	21.448	14.297	-2.250	18.044	17.314	-0.548	0.001
	6057	5	20.660	14.867	-5.224	22.139	-99.055	-0.539	0.001
	6059	6	20.993	16.083	-3.609	55.946	-34.676	-0.773	0.001
	6054	7	19.667	14.784	-4.616	10.594	-114.335	-0.623	0.001
	6056	8	20.391	13.933	-4.241	17.792	-84.534	-0.494	0.001
	6058	9	21.717	15.232	-3.234	31.768	-32.004	-0.606	0.001
	6055	10	20.724	15.148	-2.625	14.675	4.490	-0.749	0.001
Clus. 5 - El. 598	1019	1	16.115	-9.301	-15.000	-3.532	7.777	-0.058	0.000

Figure F.5 : Calculation result



Soil element	Node	Local number	X [m]	Y [m]	Z [m]	u_x [10^{-6} m]	u_y [10^{-6} m]	u_z [10^{-3} m]	|u| [m]
	6071	6	-16.329	-5.385	-9.465	18.195	45.230	-0.044	0.000
	[illegible]	7	-17.105	-6.786	-7.749	18.796	58.624	-0.069	0.000
	[illegible]	8	-14.832	-8.273	-6.854	27.422	59.200	-0.086	0.000
	[illegible]	9	-14.056	-6.872	-8.570	26.582	50.096	-0.052	0.000
	6067	10	-15.271	-4.946	-6.950	15.681	34.308	-0.035	0.000
Clus. 5 - El. 600 Lacustrine clay Soil_1_5	[illegible]	1	-2.120	-3.566	-7.869	-0.297	10.423	0.004	0.000
	[illegible]	2	0.540	-6.645	-10.480	-9.103	16.738	-0.006	0.000
	[illegible]	3	0.936	-3.902	-5.249	-6.822	8.490	0.010	0.000
	[illegible]	4	-0.970	-8.355	-5.093	-5.109	10.760	0.005	0.000
	[illegible]	5	-0.790	-5.106	-9.174	-3.793	13.827	0.000	0.000
	[illegible]	6	0.738	-5.274	-7.864	-9.119	14.622	0.003	0.000
	6872	7	-0.592	-3.734	-6.559	-4.449	9.643	0.008	0.000
	[illegible]	8	-1.545	-5.960	-6.481	-2.817	12.424	0.006	0.000
	[illegible]	9	-0.215	-7.500	-7.787	-7.587	17.019	0.000	0.000
	6873	10	-0.017	-6.128	-5.171	-6.398	9.868	0.008	0.000
Clus. 5 - El. 601 Lacustrine clay Soil_1_5	[illegible]	1	8.175	0.830	0.000	6.027	5.944	0.005	0.000
	[illegible]	2	4.619	2.925	-3.113	-3.038	4.363	0.011	0.000
	5851	3	9.886	0.332	-3.654	-5.837	6.442	0.004	0.000
	[illegible]	4	6.257	-1.314	-4.378	-8.438	7.677	0.009	0.000
	[illegible]	5	6.397	1.878	-1.557	1.129	6.552	0.009	0.000
	[illegible]	6	7.253	1.629	-3.383	-4.279	5.144	0.008	0.000

Figure F.6 : Calculation result

ANNEX-G : LIST OF PUBLICATION , PLAGIARISM

17th IOE Graduate Conference

Certificate Of Participation

This certificate is awarded to

Janak Kumar Thapa

in recognition of an invaluable contribution as

Paper Presenter

at the 17th IOE Graduate Conference
Organized by
Tribhuvan University, IOE, Dean's Office and Purwanchal Campus
held from Jan 2 – 3, 2026 at Purwanchal Campus, Dharan, Nepal.

Asst. Prof. Kaji Ram Karki
Campus Chief , Purwanchal Campus

Asso. Prof. Anu Shrestha
Conference Converner

Prof. Dr. Sushil Bahadur Bajracharya
Dean, Institute of Engineering

IOE Graduate Conference
[Placeholder for Publication Information]

Comparative Analysis of Settlement Behavior of Transmission Tower Foundations Using PLAXIS 3D

Janak Kumar Thapa, Dr.Ram Chandra Tiwari

Department of Civil Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal
✉

Abstract

Transmission tower foundations play a crucial role in maintaining the stability and long-term performance of power transmission systems. Their behavior under vertical and lateral loads greatly depends on soil conditions and the type of foundation provided. In this study, a comparative finite element analysis is carried out to evaluate the settlement behavior of transmission tower foundations using PLAXIS 3D. The research focuses on two commonly used foundation systems: shallow foundations (spread footing/raft) and deep foundations (pile foundation). The purpose of this comparison is to understand how each foundation type performs under similar soil conditions and loading scenarios, and to determine the most suitable foundation type for minimizing settlement.

A detailed 3D numerical model was developed in PLAXIS 3D, incorporating realistic soil parameters obtained from laboratory test data and relevant geotechnical investigations. The tower loads were applied according to standard design recommendations, and both foundation types were analyzed under identical conditions. The simulations were conducted using advanced soil models to better represent actual soil behavior, especially under varying stress levels.

The results of the analysis show clear differences in how spread foundations and pile foundations respond to applied loads. While shallow foundations exhibit higher settlement due to the direct load transfer to softer upper soil layers, pile foundations demonstrate significantly reduced settlement as loads are distributed to deeper and stiffer strata. The comparative study highlights the advantages and limitations of each foundation type and provides useful guidelines for selecting suitable foundations for transmission tower projects. This research contributes to improving design decisions in transmission tower foundation engineering by providing a reliable comparison of settlement behavior obtained through numerical simulation.

Keywords

PLAXIS 3D, Transmission Tower Foundation, Settlement Behavior, Shallow Foundation, Pile Foundation.

1. Introduction

This study presents a comparative investigation of settlement behavior for transmission tower foundation using PLAXIS 3D, focusing on spread footings, raft foundations, and pile foundations under identical soil and loading conditions. Transmission towers play a critical role in maintaining the reliability of electrical power systems, and their performance is strongly governed by the settlement response of their foundations. In Nepal, where transmission line corridors frequently traverse soft, compressible, and heterogeneous soils—including silty clay, sandy silt, and loose to medium-dense sands—excessive or differential settlement has been observed in various 132 kV and 220 kV projects such as the Godak–Soyak, Amarpur–Dunge Sanghu, and Ghorahi–Madichaur transmission lines. These conditions highlight the need for rigorous foundation analysis beyond empirical design practices. (Christina Khalil, 2020)

The research problem addressed arises from the absence of a systematic comparative numerical study evaluating how different foundation types behave under identical geotechnical conditions . Shallow foundations, although economical, may undergo excessive settlement in weak soils, whereas deep foundations such as piles provide better performance but at higher cost and implementation difficulty. Existing NEA reports and available research rarely provide detailed 3D numerical comparisons, resulting in uncertainties in foundation selection. This study responds to this gap by applying PLAXIS 3D finite element modeling to realistically simulate soil–structure interaction, stress distribution, and settlement mechanisms using site-specific soil parameters from Nepal.

The research objectives include modeling each foundation type in PLAXIS 3D, analyzing total and differential settlement, assessing stress redistribution patterns, evaluating soil property influence, and providing evidence-based recommendations for optimal foundation selection. Numerical results from such analysis strengthen understanding of how foundation geometry, soil stiffness, and load transfer mechanisms influence settlement performance, thus guiding engineers toward safer and more economical designs.[7]

The scope of the study is limited to three foundation types, static loading, and typical soil profiles encountered in Nepal, emphasizing settlement behavior rather than seismic or long-term consolidation effects. While the PLAXIS 3D numerical approach provides valuable insights, the results remain dependent on the accuracy of soil parameters and do not include field validation. Tower loads, geometry, and boundary conditions are standardized for modeling, which may restrict applicability to towers with significantly different configurations.[2, 7]

Despite these limitations, the study contributes meaningful comparative data and enhances the use of 3D numerical simulation tools in geotechnical design for transmission towers. The conclusions support more informed decision-making regarding foundation selection, potentially reducing construction costs, minimizing settlement-induced maintenance issues, and improving the long-term resilience of Nepal's power transmission infrastructure. Transmission tower foundations play a critical role in ensuring the stability and serviceability of power transmission systems, and their performance is strongly governed by settlement behavior. Excessive settlement can cause tower tilting, uneven conductor tension, and structural instability, issues frequently noted in NEA transmission line projects such as the Godak–Soyak and Ghorahi–Madichaur corridors. Settlement behavior depends on soil compressibility, loading conditions, and foundation geometry. Shallow foundations—such as spread footings and raft foundations—are cost-effective but often susceptible to excessive settlement in soft or loose soils, whereas deep foundations such as piles transfer loads to stiffer strata and reduce settlement significantly.[3]

Several studies highlight the importance of evaluating both total and differential settlement. Gupta (2023) and Prasad (2022) used finite element modeling to demonstrate how soil type and foundation depth influence settlement patterns, showing that numerical tools can accurately predict field behavior. Comparative analyses across foundation types indicate that raft foundations perform better than spread footings in moderately compressible soils, while pile foundations offer superior settlement control in highly compressible deposits, despite higher installation costs. NEA reports also emphasize the variability of Nepalese soil profiles and the need for site-specific foundation solutions.[3, 7]

Numerical modeling using PLAXIS 3D has become an essential tool for studying soil–structure interaction, enabling detailed simulation of layered soils, stress redistribution, and settlement mechanisms. Studies such as Gupta and Dahal (2023) confirm that PLAXIS 3D reliably predicts settlement and stress distribution for both shallow and deep foundations, supporting its suitability for transmission tower analysis.[1]

Overall, the literature demonstrates that foundation selection for transmission towers must be guided by detailed geotechnical characterization and advanced numerical modeling, while also revealing a research gap in comparative 3D numerical studies under identical soil and loading conditions—an area addressed by the present study. [2]

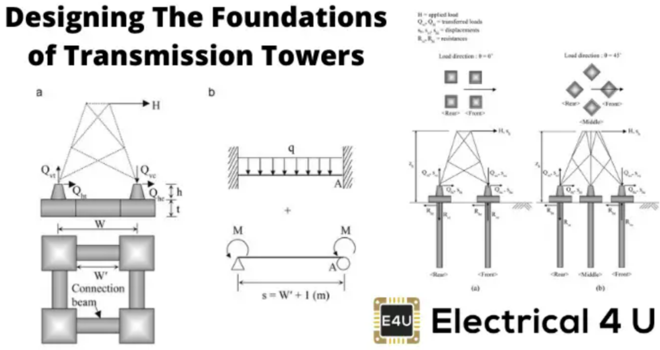


Figure 1: Soil Model

2. Methodology

2.1 Study Area

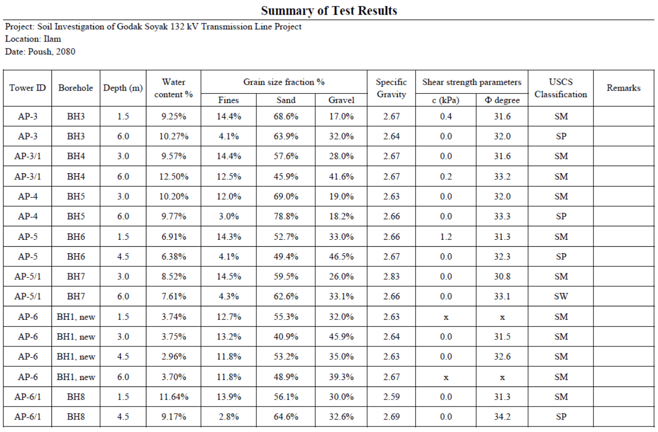
The study area is located in Ilam District, Nepal, situated along the alignment of a 132 kV transmission line corridor. The region exhibits diverse topographic features, ranging from gently rolling slopes to moderately steep terrains. Geologically, the area is characterized by a complex arrangement of alluvial deposits, residual soils, and weathered rock, which significantly influence the geotechnical behavior of transmission tower foundations. Field evidence suggests that soils often consist of silty sand, sandy silt, clayey silt, and moderately dense granular layers, with variable stiffness and compressibility. Field observations indicate that the moisture content of the soil changes with the seasons. During the monsoon, the ground becomes wetter, softer, and more compressible. During the dry months, the soil becomes harder and more stable. These seasonal changes affect how transmission tower foundations behave, especially in terms of settlement and long-term stability.

2.2 Data Collection and Inputs

The numerical analysis for this study was based on geotechnical investigation data, including borehole logs, laboratory test results, index properties, and soil strength parameters. Standard field techniques such as the Standard Penetration Test (SPT) and laboratory evaluations including grain-size distribution, Atterberg limits, specific gravity, and moisture content analysis provided essential inputs for soil characterization. The collected data facilitated the determination of:

- Soil classification and layer stratification.
- Stiffness and shear strength parameters.
- Compressibility and settlement-related properties.
- Groundwater table depth.
- Bulk and dry unit weights.
- Cohesion (c) and friction angle (ϕ).

These parameters formed the basis for developing an accurate soil model within the PLAXIS 3D environment.[2]

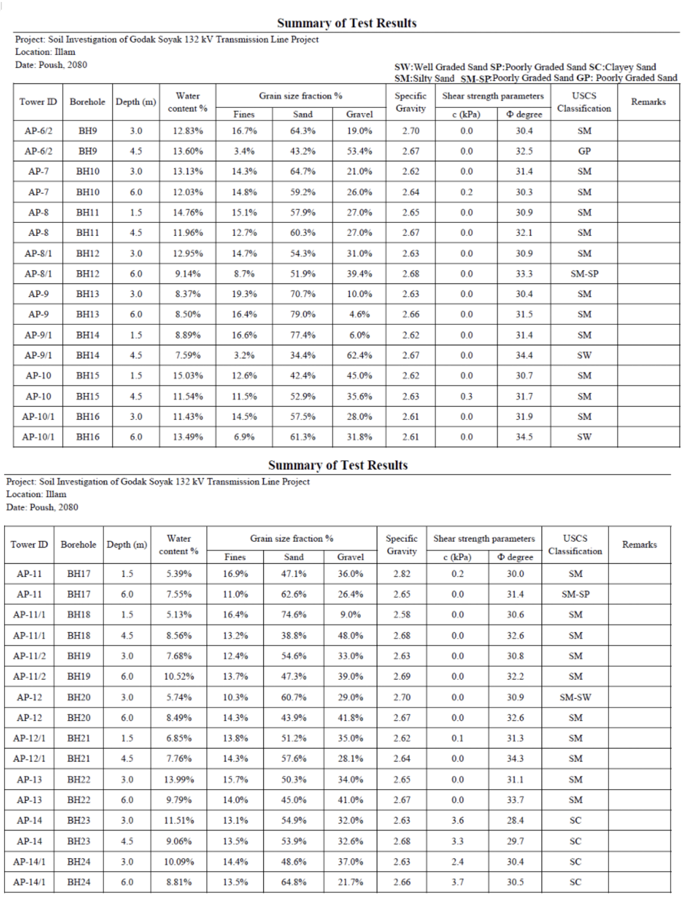


Summary of Test Results

Project: Soil Investigation of Godak Soyak 132 kV Transmission Line Project
Location: Ilam
Date: Poush, 2080

Tower ID	Borehole	Depth (m)	Water content %	Grain size fraction %			Specific Gravity	Shear strength parameters		USCS Classification	Remarks
				Fines	Sand	Gravel		c (kPa)	Φ degree		
AP-3	BH3	1.5	9.25%	14.4%	68.6%	17.0%	2.67	0.4	31.6	SM	
AP-3	BH3	6.0	10.27%	4.1%	63.9%	32.0%	2.64	0.0	32.0	SP	
AP-3/1	BH4	3.0	9.57%	14.4%	57.6%	28.0%	2.67	0.0	31.6	SM	
AP-3/1	BH4	6.0	12.50%	12.5%	45.9%	41.6%	2.67	0.2	33.2	SM	
AP-4	BH5	3.0	10.20%	12.0%	69.0%	19.0%	2.63	0.0	32.0	SM	
AP-4	BH5	6.0	9.77%	3.0%	78.8%	18.2%	2.66	0.0	33.3	SP	
AP-5	BH6	1.5	6.91%	14.3%	52.7%	33.0%	2.66	1.2	31.3	SM	
AP-5	BH6	4.5	6.38%	4.1%	49.4%	46.5%	2.67	0.0	32.3	SP	
AP-5/1	BH7	3.0	8.52%	14.5%	59.5%	26.0%	2.83	0.0	30.8	SM	
AP-5/1	BH7	6.0	7.61%	4.3%	62.6%	33.1%	2.66	0.0	33.1	SW	
AP-6	BH1, new	1.5	3.74%	12.7%	55.3%	32.0%	2.63	x	x	SM	
AP-6	BH1, new	3.0	3.75%	13.2%	40.9%	45.9%	2.64	0.0	31.5	SM	
AP-6	BH1, new	4.5	2.96%	11.8%	53.2%	35.0%	2.63	0.0	32.6	SM	
AP-6	BH1, new	6.0	3.70%	11.8%	48.9%	39.3%	2.67	x	x	SM	
AP-6/1	BH8	1.5	11.64%	13.9%	56.1%	30.0%	2.59	0.0	31.3	SM	
AP-6/1	BH8	4.5	9.17%	2.8%	64.6%	32.6%	2.69	0.0	34.2	SP	

Figure 2: Summary Of Test Result



Summary of Test Results

Project: Soil Investigation of Godak Soyak 132 kV Transmission Line Project
Location: Illam
Date: Poush, 2080

SW:Well Graded Sand SP:Poorly Graded Sand SC:Clayey Sand
SM:Silty Sand SM-SP:Poorly Graded Sand GP: Poorly Graded Sand

Tower ID	Borehole	Depth (m)	Water content %	Grain size fraction %			Specific Gravity	Shear strength parameters		USCS Classification	Remarks
				Fines	Sand	Gravel		c (kPa)	Φ degree		
AP-6/2	BH9	3.0	12.83%	16.7%	64.3%	19.0%	2.70	0.0	30.4	SM	
AP-6/2	BH9	4.5	13.60%	3.4%	43.2%	53.4%	2.67	0.0	32.5	GP	
AP-7	BH10	3.0	13.13%	14.3%	64.7%	21.0%	2.62	0.0	31.4	SM	
AP-7	BH10	6.0	12.03%	14.8%	59.2%	26.0%	2.64	0.2	30.3	SM	
AP-8	BH11	1.5	14.76%	15.1%	57.9%	27.0%	2.65	0.0	30.9	SM	
AP-8	BH11	4.5	11.96%	12.7%	60.3%	27.0%	2.67	0.0	32.1	SM	
AP-8/1	BH12	3.0	12.95%	14.7%	54.3%	31.0%	2.63	0.0	30.9	SM	
AP-8/1	BH12	6.0	9.14%	8.7%	51.9%	39.4%	2.68	0.0	33.3	SM-SP	
AP-9	BH13	3.0	8.37%	19.3%	70.7%	10.0%	2.63	0.0	30.4	SM	
AP-9	BH13	6.0	8.50%	16.4%	79.0%	4.6%	2.66	0.0	31.5	SM	
AP-9/1	BH14	1.5	8.89%	16.6%	77.4%	6.0%	2.62	0.0	31.4	SM	
AP-9/1	BH14	4.5	7.59%	3.2%	34.4%	62.4%	2.67	0.0	34.4	SW	
AP-10	BH15	1.5	15.03%	12.6%	42.4%	45.0%	2.62	0.0	30.7	SM	
AP-10	BH15	4.5	11.54%	11.5%	52.9%	35.6%	2.63	0.3	31.7	SM	
AP-10/1	BH16	3.0	11.43%	14.5%	57.5%	28.0%	2.61	0.0	31.9	SM	
AP-10/1	BH16	6.0	13.49%	6.9%	61.3%	31.8%	2.61	0.0	34.5	SW	

Summary of Test Results

Project: Soil Investigation of Godak Soyak 132 kV Transmission Line Project
Location: Illam
Date: Poush, 2080

Tower ID	Borehole	Depth (m)	Water content %	Grain size fraction %			Specific Gravity	Shear strength parameters		USCS Classification	Remarks
				Fines	Sand	Gravel		c (kPa)	Φ degree		
AP-11	BH17	1.5	5.39%	16.9%	47.1%	36.0%	2.82	0.2	30.0	SM	
AP-11	BH17	6.0	7.55%	11.0%	62.6%	26.4%	2.65	0.0	31.4	SM-SP	
AP-11/1	BH18	1.5	5.13%	16.4%	74.6%	9.0%	2.58	0.0	30.6	SM	
AP-11/1	BH18	4.5	8.56%	13.2%	38.8%	48.0%	2.68	0.0	32.6	SM	
AP-11/2	BH19	3.0	7.68%	12.4%	54.6%	33.0%	2.63	0.0	30.8	SM	
AP-11/2	BH19	6.0	10.52%	13.7%	47.3%	39.0%	2.69	0.0	32.2	SM	
AP-12	BH20	3.0	5.74%	10.3%	60.7%	29.0%	2.70	0.0	30.9	SM-SW	
AP-12	BH20	6.0	8.49%	14.3%	43.9%	41.8%	2.67	0.0	32.6	SM	
AP-12/1	BH21	1.5	6.85%	13.8%	51.2%	35.0%	2.62	0.1	31.3	SM	
AP-12/1	BH21	4.5	7.76%	14.3%	57.6%	28.1%	2.64	0.0	34.3	SM	
AP-13	BH22	3.0	13.99%	15.7%	50.3%	34.0%	2.65	0.0	31.1	SM	
AP-13	BH22	6.0	9.79%	14.0%	45.0%	41.0%	2.67	0.0	33.7	SM	
AP-14	BH23	3.0	11.51%	13.1%	54.9%	32.0%	2.63	3.6	28.4	SC	
AP-14	BH23	4.5	9.06%	13.5%	53.9%	32.6%	2.68	3.3	29.7	SC	
AP-14/1	BH24	3.0	10.09%	14.4%	48.6%	37.0%	2.63	2.4	30.4	SC	
AP-14/1	BH24	6.0	8.81%	13.5%	64.8%	21.7%	2.66	3.7	30.5	SC	

Figure 3: Summary Of Test Result

2.3 Numerical Modelling Using PLAXIS 3D

PLAXIS 3D, a finite element software widely applied in geotechnical engineering, was used to simulate the settlement behavior of different transmission tower foundations. Numerical modelling enabled the detailed representation of soil–structure interaction, stress redistribution mechanisms, and incremental settlement under applied loads.

2.3.1 Model Geometry

A symmetric soil domain was developed to optimize computational efficiency while maintaining accuracy. The model boundaries were defined as:

- X-direction: 30 m
- SY-direction: 30 m
- Z-direction (depth): 15 m

The tower foundation structure was modeled with dimensions:

- 2 m × 2 m in plan
- 3 m height, representing the foundation block or raft thickness as applicable.

Boundary conditions were assigned to prevent unrealistic movements:

- Bottom boundary: fully fixed
- Lateral boundaries: restrained horizontally but free vertically, preventing lateral displacement while allowing settlement.

2.3.2 Soil Model Selection

Based on the nature of the available soil data, the Mohr–Coulomb constitutive model was used. This model provides a reasonable first-order approximation of soil stiffness, strength, and deformation behavior and is widely accepted for preliminary settlement analysis.[2]

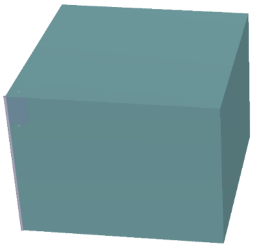


Figure 4: Soil Model

2.3.3 Meshing

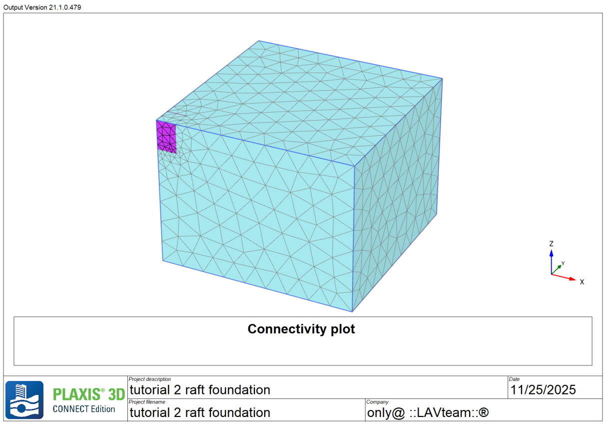
A refined tetrahedral element mesh was developed for all three foundation models—raft foundation, rigid foundation, and raft pile foundation—to ensure accurate simulation of the soil–structure interaction behavior. The meshing strategy followed a consistent approach: applying fine mesh zones around structural elements where high stress gradients and deformation concentrations occur, while using coarser elements away from the load-affected areas to improve computation speed without reducing accuracy.

For the raft foundation, a moderately refined mesh was applied around the raft–soil interface. The smaller elements in this region allow the model to capture settlement patterns, stress distribution, and deformation beneath the raft with high accuracy. The mesh gradually transitions into coarser elements toward the model boundaries, ensuring stability while reducing the number of elements and computational effort.

In the case of the rigid foundation, a higher level of refinement was necessary around the contact zone due to the stiffer nature of the rigid body. Stress concentrations near the edges of the rigid foundation lead to steep deformation gradients, making fine meshing essential to maintain numerical precision. The mesh becomes progressively coarser away from the rigid block, providing an optimal balance between accuracy and computational efficiency.

For the raft pile foundation, the mesh required even more specialized refinement. Dense tetrahedral elements were used around the pile heads, pile shafts, and the raft contact area, where load transfer between the raft, piles, and soil occurs. This refined mesh enables the model to capture complex interactions such as load-sharing between piles and raft, localized settlement, and variations in stress distribution around the pile group. Away from the pile zone, the mesh transitions to a coarser configuration to reduce the computational demand while preserving accuracy where it matters most.

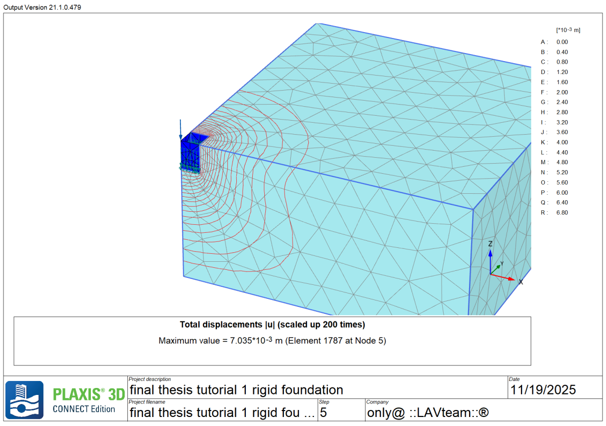
Overall, the meshing approach for all three models ensures that critical zones with high stress and deformation are modeled with fine detail, while less critical regions use coarser elements. This systematic meshing strategy provides both numerical accuracy and computational efficiency, making the simulations effective and reliable.[2, 7, 3]



Connectivity plot

Project description: tutorial 2 raft foundation
Date: 11/25/2025
Project filename: tutorial 2 raft foundation
Company: only@ ::LAVteam::®

Figure 5: Meshing Of Raft Foundation

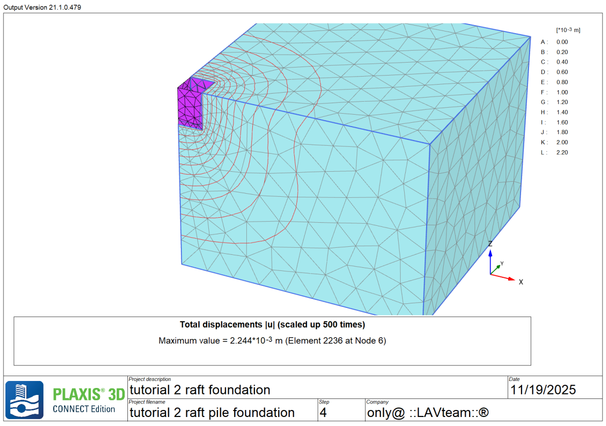


Total displacements |u| (scaled up 200 times)

Maximum value = $7.035*10^{-3}$ m (Element 1787 at Node 5)

Project description: final thesis tutorial 1 rigid foundation
Date: 11/19/2025
Project filename: final thesis tutorial 1 rigid fou ...
Step: 5
Company: only@ ::LAVteam::®

Figure 6: Meshing Of Rigid Foundation



Total displacements |u| (scaled up 500 times)

Maximum value = $2.244*10^{-3}$ m (Element 2236 at Node 6)

Project description: tutorial 2 raft foundation
Date: 11/19/2025
Project filename: tutorial 2 raft pile foundation
Step: 4
Company: only@ ::LAVteam::®

Figure 7: Meshing of Raft Pile Foundation

2.4 Modelling of Tower Foundations

Transmission towers (such as 132 kV towers) require strong foundations capable of resisting vertical, horizontal, and overturning forces caused by electrical components, wind pressure, and unbalanced conductor tensions.
To evaluate the performance of commonly used foundation types, three different foundation configurations were modeled:

- Spread (Isolated) Foundation.
- Raft (Mat) Foundation.
- Pile Foundation.

The comparative study helps identify which foundation type provides better settlement control, stability, and load distribution under the same loading and soil conditions.

2.4.1 Spread Foundation

A shallow square footing placed at the ground surface or slight embedment depth. This model simulates direct load transfer to upper soil layers, making it sensitive to soil compressibility. A spread foundation is a shallow, isolated footing typically constructed as a square or rectangular concrete block placed at or slightly below the ground surface. It transfers the load of the transmission tower directly to the upper soil layers. Because it relies on the strength of near-surface soil, its performance is strongly influenced by soil compressibility, moisture variation, and surface conditions. Spread foundations are economical, simple to construct, and suitable for locations where the soil has adequate bearing capacity and the water table is low. However, they are more prone to differential settlement and offer limited resistance to uplift and lateral forces, making them less effective for towers subjected to strong winds, unbalanced conductor loads, or soft ground conditions.[1, 2]

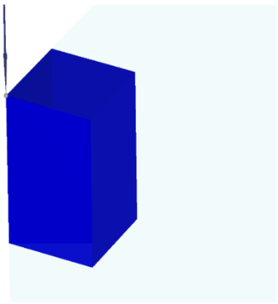


Figure 8: Spread Foundation

2.4.2 Raft Foundation

A larger continuous footing providing wider load distribution. This foundation reduces stress intensity but may still experience settlement in soft or moderately compressible soils. A raft foundation, also known as a mat foundation, consists of a large continuous concrete slab that covers a broad area beneath the tower base. This type of foundation spreads the structural load over a much wider soil contact area, thereby reducing bearing pressure and improving overall stability. Raft foundations are particularly beneficial in moderately weak or variable soils where individual footings might experience uneven settlement. They provide good resistance to overturning moments caused by wind and conductor tensions because the wide base helps stabilize the tower. Although raft foundations require more excavation and consume more concrete than spread footings, they offer improved settlement control and better load distribution, making them a reliable option for medium-strength soil profiles.[7, 3]

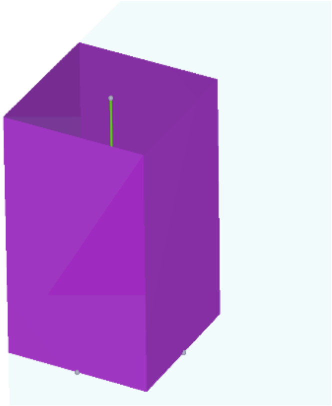


Figure 9: Raft Foundation

2.4.3 Pile Foundation

A group of piles transferring load to deeper and stiffer strata. Both skin friction and end-bearing resistance were incorporated, enabling realistic prediction of pile–soil interaction. A pile foundation is a deep foundation system composed of long, slender structural elements driven or cast deep into the ground to reach dense soil layers or bedrock. Pile foundations carry loads through a combination of skin friction along the pile shaft and end-bearing resistance at the pile tip, allowing them to bypass weak or compressible surface soils. They are highly effective for transmission towers located in areas with poor soil conditions, high groundwater levels, or where substantial uplift, lateral, or seismic forces are expected. Pile foundations provide excellent control of settlement and significantly enhance structural stability under extreme loads, though they are more costly and require specialized equipment to install. Despite the higher cost, their superior performance in challenging ground conditions makes them the preferred solution for critical tower structures.[4, 2, 3, 5, 6, 7]

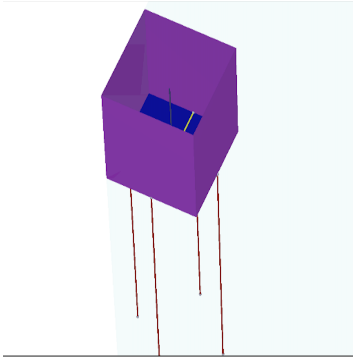


Figure 10: Pile Foundation

2.5 Loading Conditions

The loading conditions used in the analysis represent the complete range of forces that a 132 kV transmission tower foundation must safely resist throughout its operational lifespan. The most fundamental load acting on the structure is the self-weight of the tower, which includes the steel lattice members, joints, and bracing systems, all contributing to the primary vertical loading on the foundation. In addition to this, the system must support the weight of conductors, insulators, and ground wires, which impose continuous downward forces and contribute to the bending and shear effects at the foundation level. These loads vary depending on span length, conductor type, and loading configuration of the transmission line. Beyond static vertical forces, the foundation is subjected to significant environmental and dynamic loads, particularly wind pressure, which plays a dominant role in tower design. High-intensity wind forces generate large lateral loads and overturning moments, causing one side of the foundation to experience uplift while the opposite side undergoes increased compression. Seasonal wind variations, storm events, and terrain exposure (such as open plains or hilltops) can greatly amplify these effects. Furthermore, unbalanced loading conditions, such as conductor breakage, unequal span tensions, or maintenance-related detensions, create extreme uplift forces that attempt to pull the foundation out of the ground. Temperature variations also influence loading through thermal expansion and contraction of the conductors, altering tension forces applied to the tower. Additional operational factors, such as ice or snow accretion, can significantly increase the effective weight of conductors and modify aerodynamic behavior under wind. For towers located in seismically active regions, earthquake-induced ground motions introduce dynamic lateral and vertical forces that further challenge the stability of the foundation.[5, 1]

2.6 Settlement Analysis

Settlement predictions were obtained from the fully solved finite element model. Outputs included:

- Total vertical settlement beneath the foundation center.
- Differential settlement between foundation edges or tower legs.
- Stress contours and deformation patterns.
- Subsurface stress paths and load transfer characteristics Comparisons among the spread, raft, and pile foundations were carried out to evaluate their relative performance under identical soil and loading.[4, 7, 6, 3]

2.7 Field Verification

The numerical modeling approach adopted in this study was validated through comparison with published experimental, analytical, and numerical studies reported in the literature. Settlement trends obtained from PLAXIS 3D simulations were evaluated against findings from previous studies on shallow and pile-supported transmission tower foundations, which consistently indicate reduced settlement with increasing foundation depth and more effective load transfer to stiffer soil strata.

Standard geotechnical design principles were applied to assess the plausibility of the numerical results, including expected stress distribution patterns, deformation shapes, and relative settlement magnitudes among different foundation types. The observed settlement hierarchy—spread footing > raft foundation > pile foundation—shows strong agreement with established theoretical understanding and previously reported numerical investigations.

To support the numerical analysis with field-based verification, ground and foundation levels at the transmission tower foundation site were initialized and finalized using a leveling instrument both before construction and after completion of construction. These measurements provided a qualitative assessment of level changes and helped confirm that construction activities were carried out in accordance with the design levels.

Although direct long-term field monitoring data were not available for this study, the use of site-specific soil parameters obtained from detailed geotechnical investigations, widely accepted constitutive models in PLAXIS 3D, and supporting field-level observations provide a reasonable level of confidence in the reliability and engineering relevance of the numerical predictions.

3. Results and Discussion

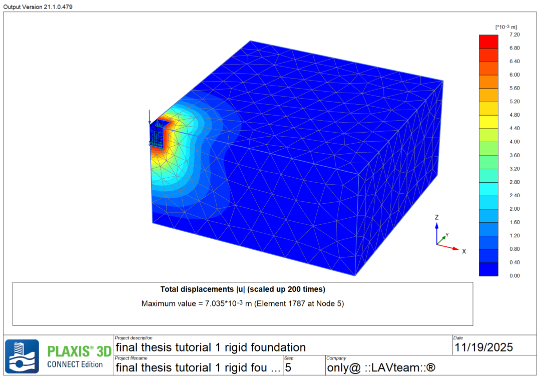
The numerical analyses conducted in PLAXIS 3D provide a comparative evaluation of the settlement behavior of transmission tower foundations with three different foundation types: spread footing, raft foundation, and pile foundation. The results clearly indicate that foundation type plays a significant role in controlling total and differential settlement under vertical tower loads.[7, 5]

The spread footing exhibited the highest settlement due to its shallow embedment and larger stress concentration near the ground surface. The deformation contours show a wider influence zone with notable soil compression directly beneath the footing. In contrast, the raft foundation demonstrated a more uniform settlement pattern, with reduced stress intensity and improved load distribution across a larger contact area. This behavior highlights the advantage of raft foundations in minimizing differential settlement, which is critical for the stability of lattice tower structures.[1]

The pile foundation performed best among all systems, showing the smallest settlement values. The load-transfer mechanism observed through axial force diagrams confirms that a substantial portion of the applied load is carried by skin friction and end-bearing resistance, effectively bypassing weaker near-surface soil layers. This results in a narrower settlement trough and minimal horizontal deformation.[7, 1, 2]

Comparative plots of vertical displacement and stress distribution reveal that while shallow foundations may be suitable in competent soil deposits, deep foundations provide superior performance in controlling long-term settlement and ensuring structural integrity. Overall, the analysis confirms that pile foundations offer the most reliable settlement response for transmission tower applications, especially in sites with variable or compressible soil conditions.[1, 2, 7]

Although pile foundations demonstrate superior settlement performance, their application to all transmission towers may not always be economically justified. Pile foundations involve higher construction costs due to material consumption, specialized equipment, and installation complexity. For sites with competent soil profiles and moderate loading conditions, shallow or raft foundations may provide adequate performance at a significantly lower cost. Therefore, the selection of pile foundations should be limited to locations with soft, compressible, or highly variable soils, critical tower positions, or areas where strict settlement control is required. A balanced foundation selection approach considering both geotechnical performance and economic feasibility is essential for large-scale transmission projects.

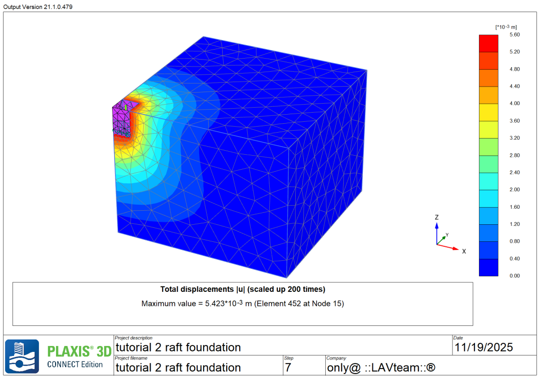


Total displacements |u| (scaled up 200 times)

Maximum value = $7.035*10^{-3}$ m (Element 1787 at Node 5)

Project description: final thesis tutorial 1 rigid foundation
Date: 11/19/2025
Project filename: final thesis tutorial 1 rigid fou ...
Step: 5
Company: only@ ::LAVteam::®

Figure 11: Rigid Foundation

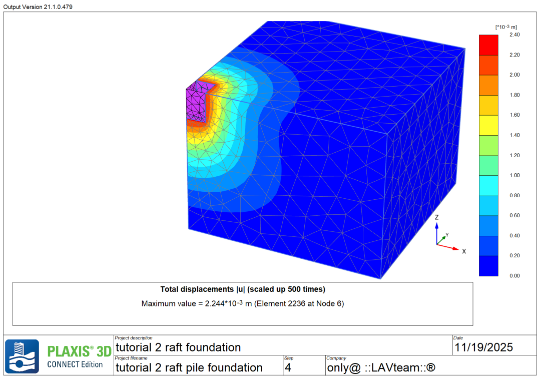


Total displacements |u| (scaled up 200 times)

Maximum value = $5.423*10^{-3}$ m (Element 452 at Node 15)

Project description: tutorial 2 raft foundation
Date: 11/19/2025
Project filename: tutorial 2 raft foundation
Step: 7
Company: only@ ::LAVteam::®

Figure 12: Raft Foundation



Total displacements |u| (scaled up 500 times)

Maximum value = $2.244*10^{-3}$ m (Element 2236 at Node 6)

Project description: tutorial 2 raft foundation
Date: 11/19/2025
Project filename: tutorial 2 raft pile foundation
Step: 4
Company: only@ ::LAVteam::®

Figure 13: Raft Pile Foundation

3.1 Numerical Analysis

PLAXIS 3D finite element software was used to simulate the settlement behavior of transmission tower foundations subjected to vertical loading. A symmetric 3D soil domain was modeled with a width and length of 30 m and a depth of 15 m, representing typical foundation conditions for transmission tower installations. Three foundation types—spread footing, raft foundation, and pile foundation—were analyzed under identical loading conditions to allow direct comparison of settlement performance. A vertical load of 150 kN was applied at the tower base for all foundation systems. The results indicate that the spread footing experienced the largest total displacement, with a maximum settlement of 7.03×10^{-3} m, demonstrating higher compressibility of the soil beneath shallow footings. The raft foundation showed improved behavior, with a reduced settlement of 5.00×10^{-3} m, attributed to its larger contact area and superior distribution of stresses over the supporting soil. The pile foundation exhibited the best performance among the three systems. With a maximum settlement of only 2.44×10^{-3} m, the load was effectively transferred to deeper and stiffer soil layers through shaft friction and end-bearing resistance. This reduced both total and differential settlement, confirming the efficiency of deep foundations in variable or softer soil conditions.[4, 6]

Displacement contours generated in PLAXIS 3D further illustrate that spread footings cause wider deformation zones, whereas raft foundations reduce stress concentration, and pile foundations confine settlement to a much smaller influence area. These findings highlight the direct influence of foundation type on settlement magnitude and deformation patterns, reinforcing the importance of selecting an appropriate foundation system for transmission tower stability.[3, 2]

4. Conclusions

This study presented a comparative numerical investigation of the settlement behavior of transmission tower foundations using PLAXIS 3D. Three commonly adopted foundation systems—spread footing, raft foundation, and pile foundation—were analyzed under identical soil conditions and a vertical load of 150 kN to evaluate their relative performance in controlling settlement.

The numerical results indicate that foundation type has a significant influence on both total and differential settlement. The spread footing exhibited the highest settlement (7.03×10^{-3}m, due to direct load transfer to compressible near-surface soil layers. The raft foundation showed improved performance, with a reduced settlement of 5.00×10^{-3} m, as the larger contact area facilitated better stress distribution and reduced deformation. The pile foundation demonstrated the most effective settlement control, recording the minimum settlement of 2.44×10^{-3} m, as the applied load was transferred to deeper and stiffer soil strata through shaft friction and end-bearing mechanisms.

The findings confirm that while shallow foundations may be suitable for sites with competent soil conditions and low settlement sensitivity, pile foundations provide superior performance in soft or heterogeneous soils commonly encountered along transmission corridors in Nepal. Although pile foundations involve higher initial construction costs, their enhanced settlement control and long-term stability make them a reliable option for critical transmission tower installations.

Overall, this study highlights the importance of site-specific foundation selection supported by advanced three-dimensional numerical modeling. The results provide practical guidance for engineers to balance settlement performance, constructability, and economic considerations in the design of transmission tower foundations. Future research may extend this work by incorporating field monitoring data, dynamic loading conditions, and parametric optimization of pile geometry.

The results of this study are based on numerical simulations and are dependent on the accuracy of soil parameters; therefore, field monitoring is recommended for future validation.

References

[1] Meshel Alkahtani and M Hesham El Naggar. "bearing capacity of power transmission tower footings near cohesionless slopes". *Innovative Infrastructure Solutions*, 6(4):187, 2021.

[2] Sayed" Hemeda. "geotechnical modelling and subsurface analysis of complex underground structures using plaxis 3d. *International Journal of Geo-Engineering*, 13(1):9, 2022.

[3] Volkan Kaltakcı. "a comparison of two–dimensional and three–dimensional finite element analysis for settlement behavior of piled raft foundations". Master's thesis, Middle East Technical University (Turkey), 2009.

[4] Christina Khalil, Ioanna Rapti, and Fernando Lopez-Caballero. "numerical evaluation of fragility curves for earthquake-liquefaction-induced settlements of an embankment". In *Geo-Risk 2017*, pages 21–30. 2017.

[5] Serhii Lozovyi and Evhen Zahoruiko. "plaxis simulation of static pile tests and determination of reaction piles influence". *arXiv preprint arXiv:1411.0929*, 2014.

[6] Pinky Merin Philip. "numerical analysis of transmission tower on pile foundation". *International Journal of Engineering Research & Technology (IJERT),*, 9, 2021.

[7] Atakan Yildirim and AC Aydin. "plaxis 3d study on the effect of soil conditions and material models on structural settlement and bending moments". *Journal of Civil Engineering Beyond Limits (CEBEL)*, 6(1):1–11, 2025.

Janak Kumar Thapa

Comparative Settlement Analysis of Transmission Tower Foundations Using PLAXIS 3D with a Proposed Settlement Eva…

Tribhuvan University

Document Details

Submission ID

trn:oid:::3117:585618497

Submission Date

May 3, 2026, 3:32 PM GMT+5:45

Download Date

May 3, 2026, 6:15 PM GMT+5:45

File Name

final thesis 20.pdf

File Size

2.6 MB

89 Pages

16,817 Words

100,665 Characters

8% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography
- Quoted Text
- Cited Text
- Small Matches (less than 8 words)

Custom Section Exclusions

{titlesCount} Section Titles, {keywordsCount} Keywords

Section title	No. of Section Starters	Section Starters			
"Acknowledgements"	4	Acknowledgements	Acknowledgement	Acknowledgment	Acknowledgments

Match Groups

- **100** Not Cited or Quoted 8%
  Matches with neither in-text citation nor quotation marks
- **0** Missing Quotations 0%
  Matches that are still very similar to source material
- **0** Missing Citation 0%
  Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
  Matches with in-text citation present, but no quotation marks

Top Sources

6%	Internet sources
5%	Publications
0%	Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Tribhuvan University
Institute of Engineerin
Department of Civil Engin