NUMERICAL INVESTIGATION ON THE SETTLEMENT BEHAVIOR OF PILED RAFT FOUNDATION IN WEAK LAYERED SOIL

KIDIST, MUHABAW AGIDEW

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MSC THESIS ON
NUMERICAL INVESTIGATION ON THE SETTLEMENT
BEHAVIOR OF PILED RAFT FOUNDATION IN WEAK
LAYERED SOIL

BY
KIDIST MUHABAW AGIDEW

AUGUST, 2021
BAHIR DAR, ETHIOPIA
BAHIR DAR UNIVERSITY

BAHIR DAR INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND WATER RESOURCES ENGINEERING

NUMERICAL INVESTIGATION ON THE SETTLEMENT BEHAVIOR OF PILED RAFT FOUNDATION IN WEAK LAYERED SOIL

BY

KIDIST MUHABAW AGIDEW

A Thesis Submitted to the school of graduate studies of Bahir Dar Institute of Technology, BDU in partial fulfillment of the requirements for the Degree of

Master of Science in Geotechnical Engineering

Advisor: Addiszemen Teklay (Ph.D)

AUGUST, 2021

BAHIR DAR, ETHIOPIA
Declaration

This is to certify that the thesis entitled “Numerical Investigation on the Settlement Behavior of Piled Raft Foundation in Weak Layered Soil”, submitted in partial fulfillment of the requirements for the degree of Master of Science in Geotechnical Engineering under Faculty of Civil and Water Resource Engineering, Bahir Dar Institute of Technology, is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

Kidist Muhabaw Agidew

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To my parents for their everlasting love and support.
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<tbody>
<tr>
<td>E</td>
<td>Young’s modulus</td>
</tr>
<tr>
<td>G</td>
<td>Shear modulus</td>
</tr>
<tr>
<td>d&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Element of the cap area (Butterfield &amp; Banerjee, 2015)</td>
</tr>
<tr>
<td>d&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Pile shaft element (Butterfield &amp; Banerjee, 2015)</td>
</tr>
<tr>
<td>Q&lt;sub&gt;C&lt;/sub&gt;</td>
<td>Cap bearing capacity (Butterfield &amp; Banerjee, 2015).</td>
</tr>
<tr>
<td>Q&lt;sub&gt;S&lt;/sub&gt;</td>
<td>Shaft bearing capacity (Butterfield &amp; Banerjee, 2015).</td>
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<tr>
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<tr>
<td>p&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Uniform normal stress under cap element</td>
</tr>
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<td>σ</td>
<td>Normal stress</td>
</tr>
<tr>
<td>σ&lt;sub&gt;z&lt;/sub&gt;</td>
<td>Vertical stress</td>
</tr>
<tr>
<td>C</td>
<td>Cohesion of the soil</td>
</tr>
<tr>
<td>ν</td>
<td>Poisson’s ratio of the soil</td>
</tr>
<tr>
<td>δ</td>
<td>Soil pile frictional angle</td>
</tr>
<tr>
<td>K</td>
<td>Effective earth coefficient</td>
</tr>
<tr>
<td>f</td>
<td>Friction factor for pile soil interface</td>
</tr>
<tr>
<td>α</td>
<td>Empirical adhesion factor</td>
</tr>
<tr>
<td>ϕ</td>
<td>Friction angle of the soil</td>
</tr>
<tr>
<td>L</td>
<td>Length of the pile</td>
</tr>
<tr>
<td>D</td>
<td>Diameter of the pile</td>
</tr>
<tr>
<td>γ</td>
<td>Unit weight of the soil</td>
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P Total load (concentrated)

$I_{ij}$ Influence factor (Davis & Poulos, 2016).

$\xi_s$ Settlement reduction factor

CAE Complete Abaqus environment

SSI Soil structure interaction

FE Finite element
ABSTRACT

Combined –Piled –Raft-Foundation (CPRF) systems are often suitable for foundations of high-rise buildings to reduce the excessive settlement of foundations. The conventional design of the pile group foundation, loads are designed to be transferred via the piles to the soil neglecting the contribution of the raft.

In the last decades, geotechnical engineers have started to design the piled raft foundation more optimized by allowing a part of the pressure to transfer directly from the raft to the ground. Piled raft foundations have a complex soil-structure interaction particularly when weak layered soils are encountered. This often requires the use of advanced numerical methods.

In this research, the objective is to study the settlement characteristics of piled raft foundation on a weak layered soil in which detail literature study were undertaken, a 3D numerical FEM based model were developed, sensitivity/ convergence analysis of the different factors were studied and finally the parametric study of pile length, pile diameter, pile spacing and raft thickness factors were performed. The raft and piles were modeled with a linear elastic constitutive model whereas; the soil continuum was modeled with both elastic and Mohr-Coulomb plasticity constitutive models.

The results of the analyses show that the differential settlement does not change significantly after a raft thickness of 1.5 m; this thickness was taken as a good fit for this foundation in terms of cost. In order to develop a cost effective foundation with minimum total and differential settlement, an optimization among the pile length, diameter and spacing should be established. A parametric study was carried out by using geotechnical finite element software, ABAQUS to investigate the influence of various parameters on the relationship of settlement reduction factor ($\xi_s$) which is calculated as the ratio of settlement of combined piled raft foundation to that of unpiled raft for the midpoint of the raft and the normalized load. For pile spacing and raft thickness the application of combined piled raft foundation is more effective up to a certain load level (700 kPa) which is equivalent to a normalized value of 0.33. And for pile length and pile diameter the normalized optimal load level becomes 0.22 which is equivalent to 450 kPa. Another parametric study has been conducted to see the effect of weak layer located below the raft on the settlement reduction factor ($\xi_s$) relative to midpoint of the raft. Based on the results, it can be concluded that for all stiffness ratios (0.14 to 0.9) considered in this study, the piled raft
behavior is not affected if the weak stratum is located below 18 m and the effect is negligible for relative stiffness of the weak layer to the stiffness of the soil layer below the raft greater than 0.6.

**Key words:** Pile; raft; soil-structure interaction; finite element; settlement reduction factor
CHAPTER ONE

INTRODUCTION

1.1 Background

The last two decades have seen a remarkable increase in the rate of construction of ‘Super-Tall’ buildings in excess of 300m in height and ‘Mega-tall’ buildings in excess of 600m in height are presenting new challenges to engineers, particularly in relation to structural and geotechnical design when located on poor soil. Many of the traditional design methods cannot be applied with any confidence since they require extrapolation well beyond the realms of prior experience, and accordingly, structural and geotechnical designers are being forced to utilize more sophisticated methods of analysis and design. In particular, geotechnical engineers involved in the design of foundations for super-tall buildings are leaving behind empirical methods and are increasingly employing state-of-the-art methods. A foundation system is required to safely support the large lateral and vertical loads associated with high-rise buildings and to control total and differential movements of the foundation within tolerable limits (Poulos H., 2016).

Often the subsurface conditions at high-rise building sites are far from ideal, and geotechnical uncertainty is one of the greatest risks in the foundation design and construction process particularly when the weak layered foundation soil is loaded with a mega super-structural load. Establishing an accurate knowledge of the ground conditions is essential in the development of economical foundation systems that perform to expectations. The type of foundation system for a high-rise building is determined by the main design elements such as the building loads, the ground conditions and the required building performance as well as other important factors like local construction conditions, cost and project program requirements. Good foundation design, therefore, requires close collaboration between the structural and geotechnical engineers as the behavior of both the superstructure and the foundation system needs to be adequately captured in the structural design, which in turn needs to be based on the foundation response provided by the geotechnical engineer. The design should ideally be an iterative process in order to establish compatible structural loadings and foundation deformations (Wadhwa, Aamir, & Khan, 2017).
The main advantages of adopting a piled raft foundation are: as piles need not be designed to carry all the load, there is the potential for substantial savings in the cost of the foundations; piles may be located strategically beneath the raft so that differential settlements can be controlled; piles of different length and/or diameter can be used at different locations to optimize the foundation design; varying raft thicknesses can be used at different locations to optimize the foundation design; piles can be designed to carry a load approaching (or equal to) their ultimate geotechnical load, provided that the raft can develop an adequate proportion of the required ultimate load capacity (Poulos H., 2016).

Broad design guidelines for piled rafts foundation have been developed by (Choudhury, 2013). A more detailed discussion of the geotechnical design of piled rafts is given in different books (Poulos H., 2016). In recent years large numbers of mega projects are constructed using raft and/or the piled group foundation system in Ethiopia. Hence noticeable attention is drawn toward a better understanding of the performance of piled raft foundation systems subjected to vertical loading as an optimum alternative to rafts and pile group foundation. In the conventional design of the piled-raft foundation and the design practice in different countries, the contribution of load-carrying by the raft is usually ignored. However, recent studies on real case histories and full-scale pile group tests (Liang, 2003) demonstrated that the raft can carry 15% to 70% of the total load. Piled raft foundations, however, have a complex soil-structure interaction scheme including the pile-soil interaction, pile-pile interaction, raft-soil interaction, and finally the pile-raft interaction.

Consequently, there is a need for 3D numerical models that is capable of studying this complex soil structure interaction. The 3D FEM model can able to capture the behavior of the piled raft foundation system more accurately. In addition, an extended parametric study in which the effect of different parameters, such as load variation, pile spacing, pile diameter, pile length and raft thickness on the overall geotechnical and structural behavior of a piled raft foundation have been undertaken. Therefore, this research aims to study the behavior of piled raft foundation in weak layered soil (loose sand overlaying clay soil), undertake 3D numerical modeling and conducting parametric study of critical parameters, which are pile spacing, pile diameter, pile length and raft thickness based on the finite element method using ABAQUS CAE software. The present study, therefore, attempts to assess the piled-raft foundation settlement
behavior and to broaden the understanding of the complex interaction between the piles, raft, and soil via numerical simulations.

1.2 Problem statement

Significant contributions have been made to study the settlement behavior of piled raft foundation on weak layered soils. It is noted that, performing parametric studies on the effect of design parameters related to piles and raft dimensions on the relationship of settlement reduction factor and normalized applied load was seldom considered. It can be observed that settlement reduction factor increases till some load and decrease again or vice versa which implies that application of piled raft foundation is more effective up to a certain load level. Therefore, it is important to investigate the settlement behavior of piled raft foundation for governed parameters (pile spacing, pile length, pile diameter and raft thickness) to obtain the optimal load level normalized by a common capacity. This research finally suggests the optimal load level normalized by ultimate bearing capacity of the raft.

1.3 Objectives of the study

1.3.1 General objective

The general objective of this study is to investigate the deformation behavior of piled raft foundation in weak layered soil using numerical modeling, conducting parametric studies where load-settlement reduction factor relationship is considered and come up with a suggestion to the optimal load level normalized by the ultimate bearing capacity of the raft.

1.3.2 Specific objectives

These are the specific objectives of this research:

1. Performing parametric studies for various pile and raft configuration in order to capture the foundation settlement behavior.
2. Develop normalized load-settlement reduction factor relationship of piled raft foundation in weak layered soil by varying pile spacing, pile length, pile diameter and raft thickness.
3. Assessing the effect of weak stratum on the settlement behavior of piled raft foundation when this stratum is located below the raft.
4. Conducting model validation.

1.4 Scope of the study

This study is limited to investigate the settlement characteristics of piled raft foundation in two layered soil under static loading. This study is also limited to investigate the effect of pile spacing, pile length, pile diameter and raft thickness on the settlement behavior of piled raft foundation when uniformly distributed load (UDL) is applied at the raft top.

Elastic -perfectly plastic Mohr-Coulomb constitutive model was used for soil continuum and elastic constitutive models were considered for piles and raft. In this research, an undrained condition was assumed.

1.5 Organization of the Thesis

After the introduction on Chapter one which deals with the general background behind piled raft foundation, the works of different researchers related to this research are given a great emphasis. Available design considerations, favorable and unfavorable conditions, the design process of CPRF system, settlement of piled raft foundation, review of the available methods of analysis, parametric study on raft thickness and size, pile number and configuration, pile length and diameter, type of load and all other related works are presented in Chapter two. Chapter three consists of the numerical model development and numerical model validation. This is to investigate the adequacy of the piled raft, with regard to settlement requirements. The developed numerical model was then simulated for the parametric studies in order to capture the settlement behavior of the foundation. Parametric study results and discussion has been presented in terms of load settlement curves in chapter four. Lastly, the study is summarized and recommendations for further studies are given in the conclusion section of Chapter five.
CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

Piled raft foundation provides an economical foundation option for circumstances where the performance of the raft alone does not satisfy the design requirements. Under these situations, the addition of a limited number of piles may improve the ultimate load capacity, the settlement and differential settlement performance, and the required thickness of the raft (H. Poulos, 2001). The most effective application of piled rafts occurs when the raft can provide adequate load capacity, but the settlement and/or differential settlements of the raft alone exceed the allowable values. This generally occurs when the near-surface soil profile contains relatively stiff clays or relatively dense sands (H. Poulos, 2002).

Under this section the general features and the specific details of previous studies related to this research work are focused on. This includes the review of different design philosophies which includes the available design considerations, favorable and unfavorable conditions, the design process of CPRF system, review of the available methods of analysis and parametric study on raft thickness and size, pile number and configuration, pile length and diameter, type of load and other related works.

2.2 General design requirements of CPRF

2.2.1 General

The design of building foundations involves the consideration of several aspects that require input from both geotechnical and structural experts. The structural experts are usually responsible for the assessment of the loads applied to the foundation, while the geotechnical expert focuses on the foundation resistance and the movements arising from the applied loads. The CPRF design process is generally carried out in a number of stages and this part will summaries the key design issues that must be addressed, and then the stages of design which culminate in the final design. The foundation for any structure, but particularly a high-rise structure, must be designed to satisfy the following broad criteria: (a) design so that the structure–foundation system is stable, and safety is secured under all forms of loading, (b) design
for serviceability, so that settlements, differential settlements and lateral movements and strains do not impair the function of the structure, (c) design for human comfort, so that the vibrations of the building are sufficiently small that the building occupants are not inhibited from carrying out their intended activities (d) design for durability, so that the foundations remain durable and functional throughout the design life of the building and (e) design for sustainability.

The design criteria associated with the key design issues are dealt with mainly on how the foundation of a structure transmits the total structural load to the soil safely and satisfies the strength, serviceability, constructability and economic requirements. Foundations that make use of raft and piles to reduce differential settlements leading to a considerable economy are referred to as pile-enhanced raft or piled raft foundations (Sinha, 2017). In order to develop an effective CPRF system design approach, investigation on all the components related to these requirements is now in progress.

The development of various methods is mainly due to the inadequate perception of the complex pile-raft-soil interaction. Each method comes with its own sets of assumptions, boundary and limiting conditions; based on various geological conditions (soil strata and its nature, soil type and their properties, moisture level etc.), structural requirements and considerations (stiff or elastic raft, floating or end-bearing pile and their arrangement), and environmental condition. To reach the ultimate goal of utilizing the full capacity of pile and raft at the ultimate state, researchers are investigating the different aspects from various viewpoints. The advancement of computer technology and its high-speed processor provides greater computing facility for numerical methods in geotechnical engineering. This computational advancement helps the researchers to perceive the complex foundation behavior with more convenience (Reul & Randolph, 2013).

2.2.2 Design Philosophies

Researchers use their own design philosophy to formulate the design process for the piled raft foundation. The various design philosophy is categorized into three different design approaches (Poulos H. , 2001).
The conventional approach, in which, the foundation is designed as a pile group with regular spacing over the entire foundation area, to carry the major portion of the load (60 - 75% of the total structural load) and allowance is made for the raft to transmit some load directly to the ground. The conventional approach has the limitation that any design by this philosophy will remain inevitably in elastic regime, where the piles are loaded below their shaft capacity and the load is not defined in this approach, which they let it for engineering judgment.

Creep Piling approach, in which, piles are designed to operate at a working load, at which significant creep starts to occur (typically at about 70 – 80% of its ultimate load-bearing capacity). To reduce the net contact pressure between the raft and soil, adequate piles are added in order to reduce the pre-consolidation pressure of the clay. The creep piling approach again sets the limitation of operating the pile, below the creep load, which is, as mentioned above, as 70% to 80% of the ultimate load-bearing capacity. However, the ultimate capacity is based on conventional group theory, which is under investigation. Moreover, the reduction of net contact pressure between raft and soil by means of pile addition will refrain the raft from transmitting the load to its full capacity directly to the soil (Solanki & Sorte, 2016).

Differential settlement control approaches, in which, pile supports are designed tactfully in order to minimize differential settlement rather than reducing average settlement significantly. The differential settlement control approach could be the economical one, as piles are located strategically to reduce the differential settlement. It will require less number of piles, in comparison to the other two approaches. However, to cause the differential settlement to occur, the utilization of the ultimate bearing capacity of each of the single individual pile in the group is required, which has not established yet and cannot be captured by any so far developed analytical method. The goal, to use the ultimate bearing capacity according to the requirement of raft-pile-soil interaction, can be achieved by the numerical-geotechnical methods by simulating the complex nature of piled raft foundation.

Figure 2.1 illustrate, conceptually, the load-settlement behavior of piled rafts designed according to different strategies. Curve O shows the behavior of the raft alone. Curve 1
represents the conventional design philosophy, for which the behavior of the pile-raft system is governed by the pile group behavior. Curve 2 represents the case of creep piling where the piles operate at a lower factor of safety, but because there are fewer piles, the raft carries more load than for Curve 1. Curve 3 illustrates the strategy of using the piles as settlement reducers, and utilizing the full capacity of the piles at the design load. Therefore, the design depicted by Curve 3 is acceptable and is likely to be considerably more economical than the designs depicted by Curves 1 and 2.

Figure 2.1 Load settlement curves for piled rafts according to various design philosophies (Poulos H. G., 2001).

2.2.2.1 Design Considerations

The following design issues must be taken into consideration, in order to develop a successful pile raft foundation (Poulos H., 2001).

- Ultimate geotechnical capacity under vertical, lateral and moment loadings
- Maximum and total settlements
• Differential settlement and angular rotation
• Lateral movement and stiffness
• Load sharing between the piles and raft
• Raft moment and shear for the structural design of raft and its stiffness
• Pile loads and moments for the structural design of the piles and its stiffness

2.2.2.2 Favorable and Unfavorable Conditions

After examining a number of idealized soil profiles for piled raft foundation, the following situations may be favorable (Poulos H., 2001).

• A uniform soil layer of relatively stiff clay.
• A uniform soil profile of relatively dense sand.

Whereas Unfavorable conditions are:

• Presence of relatively soft clay in the soil profile near the surface.
• Presence of relatively loose sand in soil profile near the surface.
• Presence of soft compressive layer in a soil profile at relatively shallow depth.
• Soil profiles, which are likely to undergo consolidation settlement due to external causes.
• Soil profiles, which are likely to undergo swelling movement due to external causes.

2.2.3 Design Process

The design of a piled raft foundation involves a three-stage design process (Poulos H., 2001).

2.2.3.1 Approximate Preliminary Stage

It is just to assess the feasibility of the pile-raft foundation for the project and estimation of the required number of piles to satisfy design requirements; in this stage the
performance of raft without piles is assessed under uniformly distributed load over the raft to estimate vertical and lateral bearing capacity, settlement and differential settlement may be made via conventional techniques.

2.2.3.2 Second stage
This stage is to assess where piles are required and the general characteristics of the piles. If the raft alone adequate or nearly adequate capacity to carry the total load but does not satisfy the serviceability limit state from the Preliminary stage; the performance of raft without piles is evaluated in this stage under the actual load pattern to identify where pile is required. Piles may provide below a column up on the following conditions.

- If the maximum moment in the raft below the column exceeds the allowable value for the raft.
- If the maximum shear in the raft below the column exceeds the allowable value for the raft.
- If the maximum contact pressure below the raft exceeds the allowable design value for the soil.
- If the local settlement below the column exceeds the allowable value.

2.2.3.3 Complete Analysis Procedure
It is to obtain detailed design information such as:

- The spacing of the piles, Pile diameter and Pile location/arrangement of piles to compute the detailed distributions of settlement, bending moment and shear in the raft, and the pile loads and moments.

2.3 Settlement of piled raft foundation
The primary purpose of the piles in most CPRF designs is the reduction of settlements. In the case of large pile groups or CPRF supporting heavy structures, the optimization criteria of design are the reduction of differential settlements (Leung, 2010).

Settlement of piled raft foundation reviewed by (Gebregziabher, 2011) as follows:
The design of CPRF shall be in such a way that the settlements are in compliance with specifications of local and international building standards. While handling serviceability of a building, it would be necessary to consider the following settlement measures:

- Maximum settlement $s_{Max}$: usually occurs at the midpoint of the raft of a CPRF with piles of uniform dimensions acted upon by uniform loads. In that case, its magnitude will be equal to the midpoint settlement $s_M$
  \[ s_{Max} = s_M \]

- Minimum settlement $s_{Min}$: usually occurs at the corner of the raft of a CPRF with piles of uniform dimensions acted upon by uniform loads, in which case its magnitude will be equal to the corner settlement $s_C$
  \[ s_{Min} = s_C \]

- Differential settlement $\Delta S$ is defined as the difference between the maximum and minimum settlements
  \[ \Delta S = s_{Max} - s_{Min} \]

- Maximum angular distortion $\delta/L$ is defined as the differential settlement between two points divided by the distance between them.

For ease of comparison it is common to non-dimensionalize the settlements of a CPRF with respect to the unpiled rafts. Thus the settlement reduction factors or the normalized settlements are defined with respect to the maximum settlement $\xi_s$ and the differential settlement $\xi_\Delta$ as follows:

\[ \xi_s = \frac{s_{Max}}{s_{raft}} \]  \[ \xi_\Delta = \frac{\Delta S}{\Delta s_{raft}} \]

2.4 Methods of analysis

The various methods that have been developed for analyzing piled raft can be ranged from simplified calculation to more rigorous computer based method. All the analysis methods can be classified into three broad categories: Simplified methods, approximate methods and more rigorous methods.
The simplified analysis method involves the development of a mathematical model, based on established theory and principles, which can be performed by simple hand calculation without extensive use of a computer.

The approximate computer-based methods are based on elastic theory and mainly have two approaches (H. Poulos, 2001). Strip on Springs Approach (GASP) and Plate on Springs Approach (GARP). In the first approach, the raft is represented by a strip and the supporting piles by springs. The analysis is carried out by taking some allowance of interaction factors to obtain the settlements and moments due to the applied loading on that strip section. In the second approach, the raft is represented by an elastic plate, the soil is represented by an elastic continuum and the piles are modeled as interacting springs.

In more rigorous computer-based methods, the interactions of piled raft components are accounted by modeling the actual problem in computer program.

2.4.1 Simplified Analysis Method

a) Poulos-Devis –Randolph (PDR) method

PDR method is the combination of both Poulos-Devis and Randolph methods. This method is used for assessing the overall bearing capacity and load settlement behavior of piled raft in the preliminary design stage. There are two phases in the preliminary stage of piled raft foundation as described by (H. Poulos, 2002).

In the first phase of preliminary design stage the performance of raft foundation without piles is assessed in terms of its bearing capacity and average settlement using conventional approach. This process helps to identify a proper design philosophy and to estimate the number piles which satisfy the requirements.

In the second phase, the performance of raft under column loading is evaluated to decide where these piles should be located. For assessing vertical bearing capacity of a piled raft foundation using simple approaches, the ultimate load capacity can generally be taken as the lesser of the following two values (H. Poulos, 2002).

a) The sum of the ultimate capacities of the raft plus all the piles

b) The ultimate capacity of a block containing the piles and the raft, plus that of the portion of the raft outside the periphery of the piles
B) Burland’s approach

Burland has developed some simplified process of design when piles are designed to act as settlement reducer and to develop their full capacity at the design load (Burland, 1977).

1) Estimate the total long-term load-settlement relationship for the raft without piles (Figure 2.2 a). The design load \( P_0 \) gives a total settlement \( S_o \).

2) Assess an acceptable design settlement \( S_a \) which should include a margin of safety.

3) \( P_1 \) is the load carried by the raft corresponding to \( S_a \).

4) The load excess \( P_0 - P_1 \) is assumed to be carried by settlement reducing piles. The shaft resistance of these piles will be fully mobilized and therefore no factor of safety is applied. However, Burland suggests that a “mobilization factor” of about 0.9 be applied to the “conservative best estimate” of ultimate shaft capacity \( P_{su} \).

5) If the piles are located below columns which carry load in excess of \( P_{su} \) the piled raft may be analyzed as a raft (Figure 2.2 b) on which reduced column loads act. At such columns, the reduced load \( Q_r \) is \( Q_r = Q - 9 P_{su} \).

6) The bending moment in the raft can be obtained by analyzing the piled raft as a raft subjected to the reduced loads \( Q_r \).

Figure 2.2 a) Load settlement curve for raft b) Simplified representation of pile –raft unit (Burland, 1977).
2.4.2 More rigorous methods

In the preliminary design stage only bearing capacity and average settlement of rafts are considered. This helps to decide the number piles required and where these piles should be located, but other issues such as differential settlement, raft shear force and bending moment, distribution of load among the piles etc. are not considered. So it is necessary to carry out a more detailed design in order to assess the detailed distribution of settlement and decide upon the optimum locations and arrangement of the piles. The raft bending moments and shears, and the pile loads, should also be obtained for the structural design of the foundation.

The numerical methods employed to simulate the complex piled raft foundation are mainly the Finite Element Method (FEM), Boundary Element Method (BEM), Finite Difference Method (FDM) or a combination of two or more of these methods.
2.5 Parametric Study

The study of this complex three-dimensional foundation involves a number of geometrical, mechanical and their bi-product parameters. The geometrical parameters are related to pile geometry (e.g. pile length, diameter, areas, number & spacing) and raft geometry (raft length, breadth and thickness). Whereas, the mechanical properties include the soil properties (e.g. modulus of elasticity, Poisson’s ratio etc) and the byproduct parameters can include the various interaction factors (e.g. pile-raft, pile-soil, raft-soil and vice versa) and other derived parameters.

2.5.1 Raft Thickness and Size

Poulos (2001b) summarized his study of 2001a for the influence of raft thickness variation on maximum and differential settlement, raft moment, and load sharing for a particular load of 12 MN (Figure 2.3). The similar identical behavior can be found for larger number of piles (Clancy, Anagnostopoulos, & Rabiei, 1998). The study showed that the maximum settlement is not greatly affected by raft thickness except for thin rafts, whereas the differential settlement decreases significantly with increasing raft thickness. On the other hand, the maximum moment in the raft and percentage of the total load carried by the piles increases with increasing raft thickness. This study concluded that increasing raft thickness is effective in reducing the differential settlement. Moreover, increasing raft thickness is very effective in resisting the punching shear from both piles and column loadings.
2.5.2 Pile Number and Configuration

The pile number dictates the pile spacing, which has significant influence on the behavior of piled raft foundation. There is a study on the load settlement behavior for varying pile number and found a linear increment relationship between the ultimate load bearing capacity and number of pile. Conversely, a reverse relation (as expected) is observed between the settlement and increased number of piles but after a certain limit, the additional number of piles has less or no influence on settlement reduction. This phenomenon is termed as “law of diminishing returns” and obviously, it contributes to the concept of design optimization (Poulos H., 2001).

2.5.3 Influence of Pile Group Area

The conventional practice is to leave a half pile space outside of the exterior pile (Prakoso, Sacntis, Ataala, Badrawi, Essam, & Nabil, 2015). Fully piled raft is more effective in reducing average settlement. On the other hand, the ratio of the width of pile group to raft, in the range of 0.4 – 0.6, is very effective in reducing the differential settlement for most of the pile raft (Prakoso et al., 2015). However, a little variation is observed which may be due to the variations in methods, assumptions, conditions and considerations, but the curve pattern is same in both cases (Samctis, Xie, & Chi, 2019).
2.5.4 Pile Length and Diameter

Influence of varying pile length Poulos (2001b) studied the effect of varying pile length on maximum settlement, differential settlement between the centre and outer piles, maximum moment in the raft, and portion of load carried by the piles and raft. The analyses showed that the settlement, differential settlement and maximum moment decrease with increasing pile length, while the proportion of load carried by the piles increases (Balakumar, kalaiarasi, & Ilamparuthi, 2006).
Figure 2.4 Influence of pile length variation on load settlement behavior of piled raft foundation (0.5 m raft with 9 piles subjected to 12 MN load) (Balakumar, kalaiaarasi, & Ilamparuthi, 2006).

The pile diameter variation has important influence on frictional bearing capacity of free standing piles. The increasing pile diameter yields increasing pile shaft peripheral area that increases the pile bearing capacity. The insignificant influence of varying pile diameter on the average and differential settlement has been found and suggested for smaller pile diameter to reduce settlement of any type (Prakoso, et al. (2015). Obviously, a further investigation is required to solve this contradiction and to estimate the interaction influence on pile diameter, which may play key role in this respect.

2.5.5 Type of Load

Poulos (2001a) showed the influence of concentrated and uniformly distributed load with varying pile numbers on maximum and differential settlement, maximum moment and load portion carried by the pile group and raft. The maximum settlement for a small number of the pile is larger for concentrated loading than that of uniformly distributed loading. For a large number of piles, the loading type has no effect on settlement. The settlement pattern is identical in both cases. The loading type also has almost no effect on the load portion carried by the pile group, although, it influences the load distributions among the piles.
The following part of literature review is to present a brief review of different studies on piled raft foundation in sandy soil, clayey soil and layered soil. Their work consists of experimental and analytical studies on piled raft foundation system.

### 2.6 Experimental Studies

Horikoshi (1995) and Randolph (1996) carried out centrifuge test on model piled raft in clay and found that it reduces settlement and differential settlement of raft. Conte et al (2003) extended the work of Horikoshi (1995) and Horikoshi and Randolph (1996) and states that settlement reducing piles at centre of raft can be loaded to full capacity without affecting the foundation stability. Lee and Chung (2005) carried out model test on pile footing in dense sand and found that increase in skin friction is cause due to contact pressure between cap and soil; also found that lesser load is taken by raft at initial load stage. Fioravante et al (2008) carried out centrifuge test on circular raft in over consolidated clay and found that distribution of load between the piles underneath the raft is not uniform and load transfer mechanism differed from isolated pile. He also observed that as number of piles increase, raft settlement decreases and also postulates that displacement piles are more effective than non displacement piles in reducing raft settlement. He stated that when the piles reach the ultimate capacity, after that contribution of raft starts and also found that stiffness of foundation system increases as number of piles underneath the raft increases. Hakam (2004) performed model test on piled raft in soft clay and postulates that pile raft system increases the ultimate load of pile raft more than 100%.
V.A.Barvashov and G.G.Boldyrev (2009) carried out research experimental and theoretically on pile raft system postulates that the settlement of soil at a depth 2d under the pile tip is 1.5 to 2.0 times more than the inter pile-soil and it remain constant up to depth of 6d. It states that soil layer under tip of pile is divided in two layers: deformation depends on distinct effect of individual piles and lower layer, deformation depends on action of piles and inter piles soil as a distributed load. A 1g model test of circular piled raft system on sand and found that the stiffness of piled raft system is very closed to raft-soil stiffness, which implies that piles performs as settlement reducers rather than load sharing member (Balakumar, kalaiarasi, & Ilamparuthi, 2006).

Balakumar.V and Ilamparuth. K (2010) performed a 1g model test of square and circular shape piled raft foundation and proved that the nonlinearity of piled raft behavior is very near to hyperbolic relation and also proved that asymptotic load ratio and initial stiffness ratio remains same, irrespective the physical properties of piles and soil. EI Sawwaf (2010) carried an experimental work on short piles under a raft either connected or disconnected which was loaded eccentrically and found that it improves raft bearing pressure, reduces raft settlement and tilting, which leads to an economical design. Fioravante and Giretti (2010) performed a centrifuge test on piled raft foundation in sandy soil and found that piles transfers the load from raft to wider and deeper volume of soil, hence proves piles act as settlement reducer and also observed that sharing of load between pile and raft is related to stiffness of pile-soil system.

Matsumoto et al. (2010) performed an experimental study subjected to horizontal and vertical load on piled raft foundation model to study the effect of pile head connected on raft performance. They found that when the vertical load is applied, pile head connection condition has little effect on its behavior and when the connection is less rigid, the horizontal load taken by raft decreases. Singh.A.K and Singh.A.N (2011) performed experiment on piled raft foundation in sand and postulate that numbers and location of piles plays an important role in improving the capacity of piled raft system.

2.7 Theoretical Studies

The development of computer technology and high speed processor provides greater and quicker for computing numerical methods in structural and geotechnical engineering. It helps the researchers to solve the complex interaction taking place between soil and structure in more convenient way. Brown P.T (1969) introduces numerical method in geotechnical engineering of
circular raft on elastic layer of finite depth. Banarjee and Butterfield (1971) developed numerical analysis for pile cap interaction. Hooper (1973) was the first user of finite element method for understanding complex interaction of piled raft foundation.

Garcia et al (2005) used visco-hypoplastic constitutive law in three dimensional finite element analyses to study the piled raft foundation system on clay soil. Novac et al (2005) studied load settlement behavior of piled raft foundation system by performing three dimensional finite element analysis and found that results obtained from finite element analysis match with the measured value of two case studies (Westebd I if Frankfurt, Germany and Urawa, Japan) on over consolidated stiff clay. The piled raft was modeled as reinforced concrete was embedded in soil media. Vasquez et al (2006) studied the three dimensional non linear finite element analyses to understand the behavior of piled raft foundation system considering non linear behavior of soil and linear elastic behavior of raft and pile. Hassen G.et al (2006) developed 2D plane strain elasto-plastic multiphase model to simulate the behavior of piled raft foundation system subjected to combined loading. Six nodded triangular finite element were used to represents surrounded soil mass and pile reinforced zone. Vasquez et al (2006) replaced the linear elastic soil constitutive law by non linear soil constitutive equation of Mohr coulomb model.

Novac et al (2005) studied the same case and findings of both of them are settlement of central pile assuming a dish shape settlement of the raft. Ningombam Thoiba singh et al (2008) used finite element software ANSYS to study the interaction analysis for piled raft in cohesive soil. The pile and raft considered to be linearly elastic. He found that in reducing overall settlement of piled raft is not influence by thickness of raft. He also stated that in piled raft foundation piles reach their ultimate capacity earlier than raft. R.Ziae Moayed et al (2010) studied the effect with different pile diameter on behavior of piled raft foundation by 3D finite element method. If the bottom soil layer is dense than the piled raft foundation with different pile diameter proves to reduce total and differential settlement, but it is not so in case where bottom soil layer is soft. Sandeep rai et al (2010) studied to understand the effect of piles on response of raft foundation. He stated that by providing the piles in central portion of raft, settlement of pile raft reduce system reduces.

Sangseom Jeong (2012) carried out numerical analysis using FE package ABAQUS to study the behavior of square piled raft in weak clay soil. The pile soil slip interface model were performed to study the behavior of piled raft .He stated that variation of reduction ratio of stiff
clay was smaller than soft clay, whereas reduction ratio of stiff clay was greater than soft clay. He also stated that pile group area ratio for stiff clay was slightly lesser than soft clay. Henok F.Gebregziabher and Rolf Katzenbach (2012) carried out parametric studies on piled raft foundation on layered soil by three dimensional non linear finite element analyses. The pile and soil are modeled as 20 nodded second order solid element of brick shape and raft is modeled as 8 nodded second order shell element. They postulated that critical spacing between piles, pile length and their arrangement is important in reducing settlement and load sharing behavior of combine piled raft foundation. They also stated that load sharing of raft foundation increases, when the piles are widely space and applied load are higher. Dang Dinh Chung N Guyen (2013) carried out a centrifuge test on piled raft foundation and same is compared with PLAXIS 3D software results, to calculate central and differential settlement with different arrangement of piles. He found that model with concentrated pile arrangement reduces central and differential settlement than pile raft model with uniform arrangement.

2.8 Related Works

Piled-raft foundations for important high-rise buildings have proved to be a valuable alternative to conventional pile foundations or mat foundations. The concept of using a piled raft foundation is that the combined foundation is able to support the applied axial loading with an appropriate factor of safety and that the settlement of the combined foundation at the working load is tolerable. Piled raft foundation behavior was evaluated with many types of research and the effect of pile length; pile distance, pile arrangement, and cap thickness are determined under vertical or horizontal static and dynamic loading. In the present study, the influence of pile length configurations on the behavior of multi-storied was evaluated under vertical loading. In practice, the foundation loads from the structural analysis were obtained without allowance for soil settlements and the foundation settlements were estimated assuming a perfectly flexible structure. However, the stiffness of the structure can restrain the displacements of the foundations and even tiny differential settlements of the foundations will also alter forces of the structural members. Hence, the interaction among structures, their foundations and the soil medium below the foundations alter the actual behavior of the structure considerably than what is obtained from the consideration of the structure alone (Chaudhary & Kadam, 2014).
In this study, the settlement behavior of piled raft was examined by the use of a computer program MI DAS GTS based on the finite layer and finite element methods. The finite layer method was used for the analysis of the layered soil system. The finite element method was used for the analysis of the raft and piles. Full interaction between raft, piles, and soil which is of major importance in the behavior of piled rafts were considered in the analysis. Among the four different types of interaction present in the piled raft foundation, the interaction between piles plays an important role. For the un-piled raft, the normalized settlement parameter (IR) for the raft sizes of (8x8) m and (15x15) m ranged as 1.03 mm - 1.17 mm and 0.66 mm - 0.83 mm respectively. In the case of the piled raft with a raft thickness of 0.25 m, 0.40 m, 0.80 m and 1.50 m, the corresponding maximum settlements were 66 mm, 64 mm, 63.7 mm and 63 mm. The results of these analyses are summarized in a series of design charts, which can be used in engineering practice (Reul & Randolph, 2013).

This paper presented raft-pile-soil interaction for a vertically loaded flexible piled raft on layered subsoil using a two-dimensional finite difference numerical tool. The subsoil was modeled as a linear elastic material and the raft was modeled as a beam structure under plane strain. In addition, the piles were simulated by a series of pile elements considering the pile/soil interface behavior. In the simulations, the required input parameters of soil, pile and interface are determined by back analyses of pile loading tests. Settlement, bending moment, both in pile and raft, as well as effects of raft flexibility for vertical uniform loading in the subsoil were examined. It is found that even though for vertical uniform loading, a relatively high bending moment may be induced in the piles due to lateral displacement of the stressed subsoil. For the case of a piled raft placed over a soft clay layer at the ground surface, the contact pressure at the raft-soil interface is merely 4 ~ 6% of that developed in the unpiled raft. Nevertheless, the contact pressure may reach 15 ~ 25% of that of the unpiled raft if the piled raft is resting on a sand layer at the ground surface. This implies that the loading carried by the pile group could be reduced by almost 1/4 of the design load and it could eventually reduce the cost of pile group construction to a certain extent (Lin & Feng, 2014).

2.9 Summary

According to the present study it was concluded that considerable research on the performance of piled-raft foundations has been conducted. Significant contributions have been
made to study different aspects of piled-raft foundations. However, parametric studies on the effect of design parameters related to piles and raft dimensions on the relationship between settlement reduction factor and the normalized applied load was seldom considered.

The effect of various parameters related to pile and raft on the normalized settlement of piled raft adopting two dimensional plane strain model has studied by (Prakoso, 2001). The modulus of pile wall was computed from the term equivalent modulus which was a function of number of piles, width or diameter of the pile and soil modulus. The study concluded that the ratio between the width of the raft and the length of the pile played an important role on settlement behavior of piled raft. The piled raft with ratio equal to unity was very effective in reducing overall settlement, where as a ratio 0.5 was very effective in minimizing the differential settlement. Further it was concluded that a pile to raft area ratio of 5% to 6% was adequate to reduce the overall settlement. The results were mostly in the form of non-dimensional parameters. While the contribution was very useful as a parametric study, it has only a very limited application. The procedure would be ideal for a single group of large number of piles, in a row (Prakoso, 2001).
CHAPTER THREE

3D NUMERICAL MODELING FOR ANALYSIS OF PILED RAFT FOUNDATION

3.1 Introduction

The objective of this chapter is to develop a 3D finite element (numerical) model for the analysis of a piled raft foundation on weak layered continuum and perform a validation using secondary sources of data. The 3D numerical model to be developed mainly focuses on the following tasks. The first one is numerical modeling approaches and procedures and the second task is model validation. The first task generally describes research methods, materials and procedures. Under this sub-section model geometry and material properties; constitutive model of the continuum, pile and raft; selection of finite element; mesh discretization and sensitivity analysis; modeling of the contact zone; boundary condition of the 3D model and analysis step time increment are included. The second task deals with model validation, how validation is carried out and its result is compared with other methods available in the literature. In the last section of this chapter, the results obtained from the 3D numerical model are discussed and conclusions are given.

The key feature of the proposed finite element approach lies in its computational efficiency which makes the analysis economically viable not only for the design of piled rafts supporting high rise buildings (generally based on complex and expensive 3D FEM or FDM analyses) but also for that of bridges, viaducts and normal buildings. In times, when there no computers were available, simplified methods were used considering as low as possible computation effort to receive the results with acceptable accuracy. The computers whose programming and memory possibilities are developed increasingly caused a revolution of the calculation practice. Now the programming and extensive computation effort can expand considerably to achieve the results as perfect as possible to the reality. These methods are considered particularly for the analysis of mostly deformation- sensitive large structures. In this study, the finite element software ABAQUS was used to simulate the interaction between pile, raft and soil.
3.2 3D Numerical Modeling Approaches and Procedures

3.2.1 Objectives and Numerical model development steps

The main objective of this section is to show how this study goes through the different approaches and procedures in order to obtain the 3D numerical simulation. Figure 3.1 describes the numerical model development steps. It starts from selecting the appropriate soil properties for the numerical model and then performs finite element analysis. Not only soil properties but also material properties of piles and raft have taken from the available literature. This leads to select the appropriate elasto plastic constitutive model for the soil continuum and the structure. As described in the previous sections, the commercially available finite element software ABAQUS was used to carry out the three dimensional analyses. This can be done by first performing geometric modeling of the soil continuum, pile, raft and the contact zones. And finally the combination of all these steps provides a 3D piled raft foundation numerical model which need to be validated in order to represent the real world scenario.

After developing a converged 3D-numerical model, parametric studies were conducted. In this research pile length, pile diameter, pile spacing and raft thickness were among the varied factors whereas soil continuum model, boundary conditions, soil properties and concrete property for raft and piles are kept constant. The numerical analysis also considers different load levels mainly to obtain the optimal load level. There for effect of load variation was also considered. To study the effect of load variation on the settlement behavior of piled raft foundation, the chosen FEM (Finite Element Model) has been numerically analyzed by increasing the magnitude of uniformly distributed load (UDL) on top of the raft up to 1000 kPa. In this case four different load levels were considered (300 kPa, 450 kPa, 750 kPa and 1000 kPa). Varying the externally applied load in similar way as the CPRF doesn’t lead to a change of the shape of settlements of the corresponding unpiled raft (Gebregziabher, 2011).

Piled raft foundation is a three dimensional problem, which requires three dimensional modeling. ABAQUS is a multipurpose computer package that allows user to investigate mechanical, structural and geotechnical problems under static and dynamic loadings. The accuracy of the results from 3D-numerical model development depends on several factors such as the size of model geometry, element type and number of elements. Three-dimensional finite
element simulations of piled-raft foundations with an average number of elements in the range of 10,000 to 25,000 need about 18 hours of computational time on a Sun-Ultra 2 workstation. It is also expected that increasing the number of elements would lead to an enormous increase of computational time. In the 3D numerical model development, reducing the number of elements could save much time in the calculation process but have a significant effect on the accuracy of the results (Katzenbach et al, 2005). Therefore this chapter is devoted to develop an optimized 3D numerical model and perform a convergence analysis.

Figure 3.1 Steps in numerical model development
3.2.2 Model geometry and Material properties

3.2.2.1 Model geometry: soil block, piles and raft

This section of study focuses on the general geometry of the soil, piles and raft. On these study two layers of soil (loose sand overlying thick clay soil) has been investigated. Soil is assumed to be finite in the horizontal and vertical direction. Therefore, the distances from boundaries are chosen large enough to eliminate the boundary effect and the soil has been modeled by a 40 m x 25 m rectangle (Roshan & Shooshpasha, 2014) in which full scale (simulation of the whole) soil block were considered. Figure 3.2 and Table 3.1 describes soil profiles below the foundation level.

![Figure 3.2 Soil profile below the foundation level](image)

Table 3.1 Description of soil layers

<table>
<thead>
<tr>
<th>Soil layers</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>Loose sand</td>
</tr>
<tr>
<td>Layer 2</td>
<td>Soft Clay</td>
</tr>
</tbody>
</table>

It is also necessary to fix x, y and z dimensions for pile and raft. In this study two different raft sizes were chosen for different number of piles and pile spacing to the parametric study. The raft considered was a flat slab having uniform thickness resting on the ground surface. However, the volume occupied by the raft is much smaller as compared to that of the soil mass.
Whereas piles were modeled similar to that of raft, having higher Young’s modulus compared to the soil. The raft under each frame is assumed to be supported by a group of piles of circular cross-section having 0.2 m, 0.4 m and 0.5 m diameter. Piles are generally required to transfer load from a superstructure through weak or compressible strata, or through water, on to stiffer and less compressible soils and rock. Piles are also required to reduce both overall and differential settlements of the supported structure and may be required to enable construction processes such as top-down construction.

### 3.2.2.2 Material Properties

The material properties for soils pile and raft used in this research is depicted in Table 3.2 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>sand</th>
<th>clay</th>
<th>pile</th>
<th>Raft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young modulus, E</td>
<td>N/m²</td>
<td>30e6</td>
<td>5e6</td>
<td>25e9</td>
<td>34e9</td>
</tr>
<tr>
<td>Poisson’s ratio, ν</td>
<td></td>
<td>0.25</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Unit weight, γ</td>
<td>kg/m³</td>
<td>1554</td>
<td>1580</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle of internal friction, ϕ</td>
<td>degree</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cohesion</td>
<td>N/m²</td>
<td>0.3e3</td>
<td>12e3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 3.2.3 Constitutive Model of the Continuum (Material Modeling)

A soil model is a mathematical representation of the behavior of the soil under load. The model typically relates the stresses applied to the strains experienced by the soil as a result. The simplest of these relationships is the theory of elasticity that states that stresses and strains are linearly related. When load is applied to a linear elastic material, the stresses, strains and displacements occur instantaneously and remain constant with time. Viscoelasticity introduces the influence of time on the deformation process. Linear viscoelasticity further simplifies the phenomena by allowing superposition of the elastic deformation and the time – dependent deformation. The way to model a soil was considering that it behaves elastically at first, then reaches a yield point, and then continues to deform plastically until it reaches failure (Briaud, 2013).
In Abaqus a wide range of material models are available to model the elasto-plastic behavior of soil (Mohr-Coulomb, extended Drucker-Prager, modified Drucker-Prager, Cam-Clay etc.). As the Mohr-Coulomb model is generally considered to be adequate in most practical applications, the behavior of soil was simulated using Mohr-Coulomb model. It is a linear elastic perfectly plastic model and represents first order approximation of soil behavior. From Figure 3.3, it is clear that material behaves linearly in the elastic range, defined by two parameters like Young’s modulus and Poisson’s ratio and for defining the failure criteria, parameters are friction angle and cohesion intercept (Kate, 2005).

These two parameters are used to relate stresses as function of strain in the following manner.

\[
\sigma_x = \frac{E}{(1+\nu)+(1-2\nu)} \left( \epsilon_x(1-\nu) + \nu(\epsilon_y + \epsilon_z) \right) \tag{3-1}
\]

\[
\sigma_y = \frac{E}{(1+\nu)+(1-2\nu)} \left( \epsilon_y(1-\nu) + \nu(\epsilon_x + \epsilon_z) \right) \tag{3-2}
\]

\[
\sigma_z = \frac{E}{(1+\nu)+(1-2\nu)} \left( \epsilon_z(1-\nu) + \nu(\epsilon_y + \epsilon_x) \right) \tag{3-3}
\]

Where, \(\sigma_x, \sigma_y, \sigma_z\) are normal stresses in x, y and z directions respectively and

\(\epsilon_x, \epsilon_y, \epsilon_z\) are normal strains in x, y and z directions respectively

![Figure 3.3 Linear and non-linear relation of stress and strain curve (Kate, 2005).](image)

A linear elastic material model is valid for small elastic strains (normally less than 5 %), can be isotropic, orthotropic, or fully anisotropic; can have proper ties that depend on temperature and/or other field variables; and can be defined with a distribution for solid continuum elements in Abaqus. Both linear and non linear elastic materials will elastically return...
to an unloaded state after loading (without permanent deformations), but the relationship between stress and strain is different in them. The elastic material model and the Mohr-Coulomb plasticity model were used as a constitutive model for loose sand and clay soil whereas elastic constitutive models were considered for piles and raft having material properties mentioned in the previous section.

To predict the behavior of piled raft foundations at large settlements a non-linear analysis is required. Therefore, the behavior of the soil was considered as non-linear. The elastic perfectly-plastic Mohr-Coulomb model was used to simulate the non-linear stress-strain behavior of the soil. The Mohr-Coulomb model is a non-linear model which is based on soil parameters that are well-known in engineering practice. For this model, the modulus of elasticity of soil, $E_s$, and Poisson’s ratio, $\mu_s$, were used for the soil elasticity while the friction angle, $\varphi$, and the cohesion, $c$, were used for the soil plasticity and the dilatancy angle is needed to model the irreversible volume change due to the shearing (Abaqus User's Manual, 2013).

Figure 3.4 Mohr-Coulomb failure envelopes (K.R.Arra, 2003).
According to Mohr, the failure is caused by a critical combination of the normal and shear stresses. The functional relation between normal and shear stress on the failure plane can be given by:

\[ s = f(\sigma) \]  \hspace{1cm} [3-4]

Where, \( s \) is the shear stress at the failure and \( \sigma \) is the normal stress on the failure plane. The curve defined by Eq.3.4 is known as Mohr envelope (Figure 3.4 a). There is a unique failure envelope for each material. At the point of contact D of the failure envelope and the Mohr circle, the critical combination of shear and normal stress is reached and failure occurs. The plane indicated by the line PD is therefore the failure plane. Any Mohr’s circle which does not cross the failure envelope and lies below the envelope represents a (non-failure) stable condition. The shear strength (\( s \)) of a soil at a point on a particular plane was expressed by (Coulomb, 1776) as a linear function of the normal stress on that plane (Eq.3.5).

\[ s = c + \sigma \tan \varphi \]  \hspace{1cm} [3-5]

Where \( c \) is cohesion and \( \varphi \) is angle of friction of the soil.

Figure 3.4 b shows the Mohr envelope which is replaced by a straight line by Coulomb. As mentioned before, the failure occurs when the stresses are such that the Mohr circle just touches the failure envelope as shown by point B in Figure 3.4 c. If the stresses plot as point A below the failure envelope, it represents a stable, non-failure condition. On the other hand a state of stress represented by point C above the failure envelope is not possible. It may be noted that a material fails along a plane when the critical combination of the stress \( \sigma \) and \( \tau \) gives the resultant with a maximum obliquity (\( \beta_{max} \)), in which case the resultant just touches the Mohr circle.

3.2.4 Selection of Finite Element

Abaqus has an extensive element library to provide a powerful set of tools for solving many different problems. There are five aspects of an element in abacus that characterize its behavior; those are family, degrees of freedom (directly related to the element family), number of nodes, formulation and integration. Each element in Abaqus has a unique name and the element name identifies each of the five aspects of an element. Figure 3.5 shows the element families that are used most commonly in a stress analysis; in addition, continuum (fluid)
elements are used in a fluid analysis. One of the major distinctions between different element families is the geometry type that each family assumes.

![Element Families](image1.png)

**Figure 3.5 Commonly used element families (Abaqus User's Manual, 2013).**

The available elements for three dimensional analyses are the hexahedral, tetrahedral and the wedge as shown in Figure 3.6. For a same volume of continuum; hexahedral with its eight nodes rather than four nodal tetrahedral or six nodal wedges would be more accurate and involve least computing costs. Apart from the computational cost, the hexahedral element is more accurate than the other two. This is because the increased number of elements in wedge or tetrahedral for the same volume of continuum results in increased number of discretization error, because these elements cannot assume all the displacement fields, handled by the hexahedral element. Besides accuracy, meshes comprised of hexahedrons are easier to visualize than meshes comprised of tetrahedrons or wedges. In addition, the reaction of hexahedral elements to the applied loads, more precisely corresponds to loads under real world conditions (Hibbit, B.L, & Sorrensen, 2007). The eight-node hexahedral elements are, therefore, superior to other elements as it provides fast, less expensive and more accurate formulation for finite element analysis, which is more precise to the real world. Therefore hexahedral elements are applied for this study as the soil continuum and raft has consistent shape to accommodate this hexahedral element.
3.2.5 Mesh Discretization and Sensitivity Analysis

Discretization in finite element method is the process of dividing the body into equivalent number of finite elements associated with nodes. The total number of elements involved and their size variation within a given body are matters of engineering judgment. In order to generate the finite element mesh, the mesh module was used. In the module, one can choose the meshing technique that Abaqus/CAE uses to create the mesh, element shape and element type. The default meshing technique assigned to the model was indicated by the color of the model that was displayed when the mesh module is entered. If Abaqus/CAE displays the module in orange, it cannot be meshed without assistance from us.

Meshing is an integral part of the engineering simulation process where complex geometries are divided into simple elements that can be used as discrete local approximations of the larger domain. By meshing, the domain is broke up in to pieces, each piece representing an element. This element is needed to be able to apply finite element and stitching a bunch of local solutions together to build the global one. The mesh influences the accuracy, convergence and speed of the simulation. A mesh is considered to have higher quality if a more accurate solution is calculated more quickly. The choice of mesh element type affects both discretization and solution error. Accuracy depends on both the total number of elements, and the shape of individual elements.

Figure 3.6 Geometry of 3-D finite elements (Hibbit, B.L, & Sorrensen, 2007).
Abaqus/CAE offers a variety of meshing techniques to mesh models of different topologies. The different meshing techniques provide varying levels of automation and user control. The following three types of mesh generation techniques are available.

a) Structured meshing: applies preestablished mesh patterns to particular model topologies. Complex models, however, must generally be partitioned in to simpler regions to use this technique.

b) Swept meshing: extrudes an internally generated mesh along a sweep path or revolves it around an axis of revolution. Like structured meshing, swept meshing is limited to models with specific topologies and geometries.

c) Free meshing: is the most flexible meshing technique. It uses no pre established mesh patterns and can be applied to almost any model shape.

In Figure 3.7 some special partition techniques were used to make a smooth transition of element sizes from the finer to the larger one. The partition toolset were used to divide parts or instance in to smaller regions. There are mainly three reasons to create partitions in the mesh module. The first one is to divide a complex, three dimensional part or instance into simpler regions that Abaqus/CAE can mesh using primarily hexahedral elements with the structured or swept meshing techniques. (Almost all three–dimensional parts are mesh able using the free meshing technique, but three-dimensional free meshes can include only tetrahedral elements). The second is to gain more control over mesh generation and finally to obtain regions to which different element types can be assigned.
Sensitivity analysis

In the finite element calculations, the model has to be divided into elements which compose the “finite element mesh”. To investigate the influence of number of elements and their sizes on the bearing behavior of pile raft foundation, several finite element analyses were performed. These were done by varying their number and sizes keeping material properties and all other parameters constant.

It is important that using a sufficiently refined mesh to ensure that the results from Abacus simulation are adequate. Coarse meshes can yield inaccurate results in analyses using implicit or explicit methods. The numerical solution provided by this model was tending toward a unique value as the mesh density increased. The computer resources required to run the simulation also increase as the mesh is refined. The mesh is said to be converged when further mesh refinement produces a negligible change in the solution. In this study, it is learnt to judge what level of refinement produces a suitable mesh to give acceptable results for most simulations. However, it is always good practice to perform a mesh convergence study, where the same problem was simulated with a finer mesh and compare the results. Then confidence had developed that the model produced a mathematically accurate solution when the two meshes gave essentially the same result. All the results were normalized with respect to the values predicted by the coarse mesh.

To investigate the influence of number of elements or mesh coarseness on the bearing behavior of pile raft foundation, five different finite element meshes were performed. These were
done by varying their number and sizes keeping material properties and all other parameters constant. According to Mandolini et al (2005), the magnitude of the piled-raft settlement at failure is 10% of D, where D= pile diameter.

Table 3.3 Effect of mesh size on maximum settlement

<table>
<thead>
<tr>
<th>Model</th>
<th>Mesh Coarseness</th>
<th>Number of elements</th>
<th>Maximum settlement $u_z$ (mm)</th>
<th>Time required to complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>Very Coarse mesh</td>
<td>50312</td>
<td>84.82</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Model 2</td>
<td>Coarse mesh</td>
<td>61273</td>
<td>86.93</td>
<td>20 minutes</td>
</tr>
<tr>
<td>Model 3</td>
<td>Medium mesh</td>
<td>83410</td>
<td>89.41</td>
<td>35 minutes</td>
</tr>
<tr>
<td>Model 4</td>
<td>Fine mesh</td>
<td>103254</td>
<td>90.52</td>
<td>60 minutes</td>
</tr>
<tr>
<td>Model 5</td>
<td>Very fine mesh</td>
<td>163271</td>
<td>90.77</td>
<td>372 minutes</td>
</tr>
</tbody>
</table>

3.2.6 Modeling of the Contact Zone

Among varieties of contacts models available in ABAQUS, surface to surface interaction has been used for modeling the interface between soil and structure .Surface-to-surface contact interactions describe contact between two deformable surfaces or between a deformable surface and a rigid surface. The interaction between structure and soil surface consists of two force components. One is perpendicular to the interaction surface, which is the normal behavior, and the other one, tangent to the surface, which is the tangential behavior and consists of sliding between two surfaces and possibly frictional shear stresses. While modeling clay, the structure - soil interaction is assumed to be an adhesive friction and no sliding occurs before the shear stress on the surface reaches to its maximum shear stress. This is numerically achieved by assuming a large friction coefficient in Coulomb friction model in the soil- structure interface. In general, the maximum shear stress $\tau_{max}$ along the structure- soil interface can be assumed to be $1/2C_u$, where $C_u$ is the cohesion of the soil. In sand the friction coefficient between soil and structure has a small value. The skin friction angle between soil and structure is about 20-30 degrees, that will give a friction coefficient between 0.3 - 0.5. In this study sand- structure friction coefficient for the base model has assumed to be about 0.3 (Canadian foundation engineering manual, 2007).

Three contact zones are required to be modeled in piled raft foundation, the pile-soil, the raft-soil and the pile-raft. To model the contact behavior among the soil and pile/raft surface
material, it is essential to obtain the friction factor between these materials which is again a function of surface roughness, porosity, adhesion etc. Several procedures and methods are available in literature from which Das (2007) summarized three widely accepted methods (α, β and λ method) based on empirical formulas to calculate the friction factor for clay and pile material. Here only the formula in α method is described below.

According to α method, the friction factor, \( f = \alpha c_u \)

Where, \( \alpha \) = empirical adhesion factor can be estimated from Figure 3.8.

Several other semi-empirical equations to estimate \( \alpha \), are available in the literature (e.g., API, 1984; Semple and Ridgen, 1984; Fleming et al., 1985). Budhu (1999) summarized several of these equations to estimate \( \alpha \). The empirical equation by API (1984), as stated below, can be used along with the value from Figure 3.7 which describes variation of \( \alpha \) with undrained cohesion, \( c_u \).

\[
\alpha = 1 - \frac{c_u - 25}{90} \quad \text{For } 25 \text{kpa} < c_u < 70 \text{kpa} \quad \text{[3-6]} \\
\alpha = 1 \quad \text{For } c_u \leq 25 \text{kpa} \quad \text{[3-7]} \\
\alpha = 0.5 \quad \text{For } c_u \geq 70 \text{kpa} \quad \text{[3-8]}
\]

Similarly, for pile in sand, this friction factor can be given as stated in Das (2007)

\[
f = K \sigma_z \tan \delta \quad \text{For } z = 0 \text{ to } L \quad \text{[3-9]} \\
f = f z L \quad \text{For } z = L \text{ to } L \quad \text{[3-10]}
\]

Where,

\( L' \) = effective length=15D

\( K \) = effective earth coefficient = \( 1 - \sin \phi \) for bored pile

\( \sigma_z \) = Effective vertical stress at depth \( z \)

\( \delta \) = Soil pile frictional angle = \( 0.5\phi \sim 0.8\phi \)

Judgment is applied to choose the value of \( \delta \) and some correlations are available in the literature of Bhusan (1982), Meyerhof (1976) for low and high displacement driven pile. The empirical formula to predict \( K \) is also different for driven pile and available in Das (2007). Since piled raft foundation is erected on the bored pile, those formulas are not mentioned here.
To simulate the interaction or contact behavior, especially for the soil, pile and raft, the following concepts are available in the literature. From Figure 3.9, the material behavior of the soil was modeled with a Mohr-Coulomb model, and to simplify the analysis process, average values of material parameters were adopted for the soil layer. Since the piles have great Young’s modulus in comparison with the soil, they remain in elastic range. Due to the aforementioned reason, they were modeled with a non-porous linear elastic model. The modeling techniques used for the pile-soil interface were generally divided into two types: thin layer element and slip element. The former was used by Jeong et al. (2004) and Lee et al. (2010), in which the slip behavior between the adjacent surfaces could be considered. The latter was used by (Reul and Randolph, 2004) and a middle layer is used to model the interface using the behavior of the soil. In this case when a slide occurs, the shear stress ($\tau$) will be created in the interface and the relationship between shear force and normal pressure $P'$ is governed by a modified Coulomb’s friction theory.
The widely accepted master-slave concept has been used in this work, where the pile and raft has been treated as master surface and soil surface as slave surface. To choose between the ‘node to surface contact’ and ‘surface to surface’ contact option, the surface to surface contact is more accurate, as shown by Hibbitt et al. (2007) in Figure 3.10. This surface to surface discretization technique has been used in this work. Again to define the mechanical tangential behavior, the penalty type frictional constraint enforcement method rather than Lagrange method is justified in order to formulate the stiffness (penetration in other words) of the contact surfaces. Lagrange method requires the multiplier that increases the computational cost of the analysis by adding more degrees of freedom to the model and often by increasing the number of iterations required to obtain a converged solution. The Lagrange multiplier formulation may even prevent convergence of the solution (Hibbit, B.L, & Sorrensen, 2007).
Figure 3.10 Comparison of contact pressure accuracy for node to surface and surface to surface contact discretizations (Hibbit, B.L, & Sorrensen, 2007).

3.2.7 Boundary condition of the 3D-Model

The objective of this section is to make sure that the selected parameters for the parametric study didn’t affected by the boundary extent. And boundary size of the model need to be fixed as soil is assumed to be semi-infinite in the lateral and vertical direction. In all cases no x, y or z translations at the bottom nodes were allowed. Applied boundary conditions to the soil are fixed support at the bottom with no displacement in the horizontal and vertical direction (x=y=z=0), and there is no translational degree of freedom at the corner nodes (x=y=0). Figure 3.11 represents the boundary conditions applied for the 3D- model used in this research to idealize the numerical simulation for the full scale (simulation of the whole) soil block under consideration. In order to set the boundary extent of the continuum to reduce the analysis or computational cost (time, resources like RAM, processor speed etc.), a number of elastic, elasto -plastic simulations of the soil continuum have been performed. Both the stress and strain variation with the length, breadth and depth were investigated. It is concluded that the horizontal length extent of 80D (where, D is pile diameter) and vertical depth extent of L+1 (Where, L is length of pile) is sufficient after which no appreciable stress and strain variation effect was observed (Roshan & Shooshpasha, 2014).
The layout and the configuration of minimum required piles become very important to produce the desired settlement reduction and load sharing. Even though there are many shapes of pile, the circular pile is most commonly used in structural construction. On the other hand, the numerical simulation can be performed by considering the octagonal or square cross-sectional shape of the pile. As explained in the previous section, hexahedrons are the best choice for the three-dimensional analysis, so to accommodate these elements for a fast, less expensive and more accurate simulation, the consideration of circular pile is decisive. While creating constraints in Abaqus piles are considered as embedded regions for the boundary condition of the 3D numerical model in this study.

Figure 3.11 Boundary condition of a 3-D model.
3.2.8 Analysis Step Time Increment

Abaqus has two measures of time in a simulation. The total time increases throughout all general steps and is the accumulation of the total step time from each general step. Each step also has its own time scale (known as the step time), which begins at zero for each step. Time varying loads and boundary conditions can be specified in terms of either time scale. The time scales for an analysis whose history is divided into three steps, each 100 seconds long as shown in Figure 3.12.

In general steps the loads must be specified as total values, not incremental values. A pressure load had a value of 100 kPa in the first step and it increased to 300 kPa in the second general step, the magnitude given for the load in the two steps was 100 kPa and 300 kPa. By default, all previously defined loads were propagated to the current step. In the current step additional loads must be defined as well as any previously defined load must be modified (deactivated). Any previously defined load that was not specifically modified in the current step continued to follow its associated amplitude definition, provided that the amplitude curve was defined in terms of total time, otherwise, the load can be maintained at the magnitude it had at the end of the last general step.

![Figure 3.12 Step and total time for a simulation (Abaqus User's Manual).](image)

An analysis is defined in abacus by: dividing the problem history in to steps, specifying an analysis procedure for each step and prescribing loads, boundary conditions and output requests for each step. Abaqus distinguishes between general analysis steps and linear
perturbation steps, and also includes multiple steps in the analysis. It is possible to control how prescribed conditions are applied throughout each step and specify the incrementation scheme used for controlling the solution, the matrix storage and solution scheme in Abaqus and the precision level of the Abaqus/CAE executable.

There are many steps used for applying boundary conditions and different type of loading conditions. In this model, initial step, primary load step, pile installation step, raft installation step and loading step were included.

3.3 Model Validation (validation of the numerical model)

In this study, Model validation is conducted by considering the aspects and components and using material properties taken from literature, as it the procedure of evaluating the wellness of models performance against the real data and validation is essential before introducing the numerical model into the real world scenario. Table 3.4 describes the material properties used for validation purpose.

To conduct validation, the load was applied incrementally with a pattern similar to the applied load on the literature. The ultimate bearing capacity of the piled raft foundation from the numerical analysis is 1600 N which is obtained from the load-settlement curve using the tangent failure method. To check the validity of the results the model (ABAQUS), an example of piled-raft foundations was analysed. Figure 3.13 shows the layout of the piled-raft foundation considered in this analysis for model validation.
Figure 3.13 Layouts of piled-raft foundations (H. G. Poulos, 2001)

As shown in Figure 3.13 the raft dimension is 10 m by 6 m with 0.5 m thickness and the 9 piles are 10m in length and 0.5 m in diameter. The middle three piles in transverse direction were subjected to the concentrated load of 2 MN, while the edge piles were subjected to the concentrated load of 12 MN.
Table 3.4 Model geometry and material properties of ASCE TC 18 pile raft

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Soil</th>
<th>Pile</th>
<th>Raft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (m)</td>
<td>20x20x20</td>
<td>0.5(D)x10(L)</td>
<td>10x6x0.5</td>
</tr>
<tr>
<td>Unit weight, $\gamma \left( \frac{kg}{m^3} \right)$</td>
<td>1700</td>
<td>2500</td>
<td>2500</td>
</tr>
<tr>
<td>Elastic Modulus, E(MPa)</td>
<td>20</td>
<td>30,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Poisson’s Ratio, $\nu$</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Load (MN)</td>
<td>Self Weight</td>
<td>Self Weight</td>
<td>Self Weight + 2MN on middle row and 1MN on sides row of piles</td>
</tr>
</tbody>
</table>

3.4 Results and Discussion

3.4.1 Introduction

Prior to the detailed geotechnical design, a feasibility assessment is necessary by considering various foundation schemes. This is to investigate the adequacy of the raft alone, both in regard to ultimate bearing capacity and settlement. If the raft alone is not adequate, the number of piles required which satisfy the design requirements will be determined using simplified method.

Under this section a geotechnical assessment was carried out for the raft alone and piled raft with 4 number of piles considering raft sizes (6 m*6 m*0.5 m). The piles were assumed to be 0.4 m diameter with a length of about 13 m. After comparing the ABAQUS-CAE results with the analytical one, overall conclusion have been drawn based on the allowable settlement tolerated by the unpiled raft and piled raft foundation.

3.4.2 Unpiled raft analysis

The ultimate capacity of the raft alone can be determined using (EBCS-7).

\[ c N_c S_c + q'N_q S_q + 0.25 \gamma' N_\gamma S_\gamma r_\gamma \]  \[ 3.11 \]

Where, \( N_q = e^{\pi \tan \phi \tan^2 (45 + \frac{\phi}{2})} \)

\[ N_c = (N_q - 1) \cot \phi \]

\[ N_\gamma = (N_q - 1) \tan \phi \]
\[ S_c = 1 + 0.2 \left( \frac{B'}{L} \right) \]
\[ S_q = 1 + \left( \frac{B'}{L} \right) \sin \phi \]
\[ S_y = 1 - 0.3 \left( \frac{B'}{L} \right) \]
\[ r_y = 0.7B' \]

Taking the soil parameter from Table 3.2 and substituting in to (Eq. 3.1), the ultimate bearing capacity of the raft \( q_{ult} \) becomes: \( q_{ult} = 3.2 \) MPa.

Taking a factor of safety of 3 the allowable bearing capacity \( q_a \) is 1.06 MPa.

\[ q_a = \frac{q_{ult}}{FS} \]

Multiplying this stress \( q_a \) by the area of the raft gives 38.4 MN. The total load applied on the raft top including the raft weight is 36 MN. The capacity of the raft is greater than the total applied load. Therefore it can be concluded that bearing capacity failure may not occur.

Table 3.5 Settlement results for unpiled raft

<table>
<thead>
<tr>
<th>Raft size</th>
<th>Maximum settlement (mm)</th>
<th>Differential settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 m<em>6 m</em>0.5 m</td>
<td>240</td>
<td>24</td>
</tr>
</tbody>
</table>

The allowable maximum settlement depends up on the type of soil, type of foundation and structural framing system. The maximum settlement ranging from 20 m to 300 mm is generally permitted for various structures (K.R.Arora, 1987). However settlements exceeding 150 mm may cause trouble in utilities. Whereas the maximum differential settlement for raft foundation is 32 mm on sand soil and 45 mm on clay soil (Bowles, 1996).

Raft foundation has an advantage of providing the adequate bearing capacity and also reducing differential settlements of structure. Unfortunately, raft foundation may cause excessive settlement although it has an adequate bearing capacity. Considering that foundation building must have adequate bearing capacity but the total or differential settlements of the foundation should not exceed the allowable value, the combination of raft and pile foundation as named
piled raft foundation system may be considered as the good alternative solution for this problem. The contribution of a group of pile under raft could acts as a settlements reducer.

3.4.3 Piled raft analysis

For this case, the piles were assumed to be 0.4 m diameter extending to the overlaying clay layer with an average length of about 13 m.

Table 3.6 Settlement results for piled raft

<table>
<thead>
<tr>
<th>Raft size</th>
<th>Maximum settlement (mm)</th>
<th>Differential settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 m<em>6 m</em>0.5 m</td>
<td>80</td>
<td>8</td>
</tr>
</tbody>
</table>

Figure 3.14 shows the load settlement plot of the simulated ABAQUS output for a pressure load of 1 MPa with 6 m*6 m*0.5 m raft size. It deals with the comparison between settlements of piled raft over unpiled raft foundations. And as of different literatures, this thesis has proved unpiled raft foundations offer much settlement than piled raft foundations, therefore piled raft foundation has been selected for further analysis. At this loading condition, the maximum settlements of UPR and PR are obtained 240 mm and 80 mm respectively, which shows the settlement reduction. There for, based on the result, it can be concluded that inserting piles below the raft has significant contribution for settlement reduction.
3.4.4 Validation of the numerical model

Poulos (2001) predicted the load-settlement relationship of this piled-raft example using the simple method Poulos-Devis-Randolph (PDR)-method and numerical models developed using software such as FLAC 3D and FLAC 2D. The results of the developed model showed a good agreement with the results predicted by Poulos (2001) using different methods. Comparison between the results of the developed model and other models is summarized in Table 3.5. Load-settlement predictions using the developed ABAQUS 3D model were in good agreement with the predictions of other models.
Table 3.7 Comparison of the results of ABAQUS 3D model with other models for total of 12 MN

<table>
<thead>
<tr>
<th>Model</th>
<th>Central settlement (mm)</th>
<th>Corner pile settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDR(Poulos-Davis-Randolph) Method</td>
<td>36.8</td>
<td>-</td>
</tr>
<tr>
<td>PLAXIS 2D Predicted by Omeman (2013)</td>
<td>32</td>
<td>26</td>
</tr>
<tr>
<td>The developed ABAQUS 3D (in this thesis)</td>
<td>31</td>
<td>26.7</td>
</tr>
</tbody>
</table>

As mentioned in the previous section of this study, validation is conducted using material properties from the literature. The model reported in the American Society of Civil Engineers (ASCE) Technical Committee –18 (TC -18) report in (H. G. Poulos, 2001), has been used in this thesis for validation purpose. Figure 3.15 presents a comparison between load-settlement curves of piled-raft foundation that obtained from the literature model and numerical analysis using finite element method. From Figure 3.15, it can be seen that, the analysis by ABAQUS program revealed a very close result with the experimental model of load settlement relationships. This shows a good agreement of the results between the experimental model in the literature and model used in this study.

![Figure 3.15 Load-settlement curves for validation](image-url)
In the mesh discretization and sensitivity analysis section of this study, the effect of mesh density on maximum settlement has been conducted. Figure 3.16 describes direct relationship between the generated number of elements and the total maximum settlement in the foundation. It shows maximum settlement increases as the number of elements increases till the numbers of elements reach 103254, after that increasing number of elements has no significant effect on the maximum settlement. It can be concluded that mesh is converged with 103254 elements because there is no significant change in deformation when the number of elements increased to 163271. Therefore model 4 (fine mesh) was used to investigate the settlement behavior of piled raft foundation.

![Figure 3.16 Effect of mesh density on maximum settlement](image)

From the output of the numerical investigation, Figure 3.17 shows the contour plot of displacement components (lateral displacement component, U2 and vertical displacement, U3) for 7D pile spacing with 13 m pile length subjected to a load of 0.3 MPa. The location of maximum and minimum settlements of the raft occur at the centre and corner respectively. At
this load, the vertical settlement of the raft top centre element is observed as 113.9 mm (contoured by red color in Figure 3.17 b) while no influence is observed at the bottom.

![Displacement contour](image)

**Figure 3.17** Displacement contour for a) lateral component, U2 and for (b) vertical component, U3

**3.5 Conclusion**

The various components and the process of developing the numerical model in 3D finite element code have been detailed in this chapter. The optimum and careful technique is used in
selecting the element, setting the boundary limit, partitioning, mesh discretization, sensitivity analysis and model validation. While investigating the performance of piled raft foundation, there are plenty of parameters that can be considered for parametric study. In this study, there are four parameters which are not affected by the boundary extent. This chapter depicted that pile spacing, pile diameter, pile length and raft thicknesses are free from boundary effect. Therefore these parameters are investigated and results are drawn in the next chapter.
CHAPTER FOUR
PARAMETRIC STUDY RESULTS AND DISCUSSION

4.1 Introduction

The main objective of this study is to investigate the behavior of piled raft foundation in weak layered soil, 3D modeling and parametric study based on finite element method. In this study, the effect of some parameters on the load-settlement relationship was investigated. The aim of this study is to identify the most important parameters which affect the performance of piled-raft foundations and then to develop a model to predict the settlement. Therefore, the results obtained by the developed model are related with these parameters. Furthermore, discussions are made by considering comparisons to previous works related to the specific topic under consideration.

Identifying the important parameters which significantly affect the performance of piled-raft foundations can assist in optimizing the design of such foundations. Therefore, studying the effect of different design parameters on the behavior of piled-raft foundations were carried out. This study focused on the effect of pile spacing. Pile length, pile diameter and raft thickness parameters on the load-settlement relationship and of piled-raft foundations. The effects of the selected parameters on the load-settlement relationship were investigated at small and large settlements. In general the settlement consideration plays a main role in foundation design and the choice of appropriate factor of safety for the foundation depends to large extent on how much settlement, the supporting soil can tolerate. In this study, the effect of the weak stratum on the failure mechanism of the piled raft when this stratum is located below the raft has been also assessed.

4.2 Effect of pile spacing

Oh et al. (2008) observed that the pile spacing greatly affects the settlement of piled raft foundation. When the pile spacing is large, the stiffness of the pile group is large due to the reduction in the interaction between the piles as the pile spacing increases. In addition, good distribution of piles assists in reducing the differential settlement between the raft center and edge. However, when the pile spacing is small, all piles are located under the center of the raft. In this case, there will be a large difference between the settlement at the raft center and edge. The settlement at the raft edge will be large and hence the contact stress between the raft and the
soil will be large as well. Other studies have shown that when the piles are close to the edge of the raft they take more load than the piles at the center of the raft. Singh (2008) observed that the contact pressure at the edge of the raft is larger than that at the center of the raft.

The major question for the group pile is the spacing for the piles. It dictates not only the number of piles and thereby construction cost, but also provides the structural safety by means of stiffness of the structure. The conventional group pile theory implies that the group action is no more valid for pile spacing greater than 2.5D (Das 2007) but this theory does not take into account the bearing contribution of the raft. Investigation was therefore made to observe the influence of pile spacing on pile raft foundation behavior.

Using the soil continuum model, boundary conditions, soil properties, the concrete property for raft and piles and modeling technique mentioned in the previous section, six models for various pile spacing were developed and simulated for this purpose. A pressure load of 1 MPa was applied on raft top for each case where the pile length of 13 m with perimeter equivalent to a 0.4 m diameter of circular pile was used. The rest geometric properties of rafts and piles of various configurations are as described in Table 4.1 below.

Table 4.1 Geometric properties of pile raft models

<table>
<thead>
<tr>
<th>Pile Spacing</th>
<th>Raft Size (L<em>B</em>D)</th>
<th>No of Piles</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D,3D,4D,5D,7D &amp; 10D</td>
<td>6<em>6</em>0.5</td>
<td>4</td>
</tr>
</tbody>
</table>

In Figure 4.1, the numerical analysis output of ABAQUS for the pile spacing, ranging from 2D to 10D have been plotted in load settlement behavior of piled raft foundation.
It can be seen from Figure 4.1 that the spacing between the piles affects the load-settlement curve of piled-raft foundations in which the settlement increases with the increase in pile spacing and the load bearing capacity increases sharply for the spacing smaller than 7D. The settlement is even worse for the pile spacing of 10D than that of other spacing. Therefore, for pile spacing equal or greater than 7D, only the raft footing is sufficient to withstand the structural load. In order to decide the maximum spacing for the raft foundation, it is necessary to observe the raft top deflection at that spacing. There is also another settlement plot for various pile spacing, subjected to a load of 1 MPa as shown in Figure 4.2.
From the above plot, the slope of the curve is constant up to 7D, after which, it changes dramatically and seems to attain another constant slope again, just after the pile spacing of 10D. This slope changing pattern is identical for any other magnitudes of load, because the pattern of load settlement curves for different spacing are identical as shown in Figure 4.1 above. This phenomenon dictates that the pile spacing for pile raft foundation should not be greater than 7D.

Considering the constructional aspect and simplicity, both the raft centre and differential settlements have been plotted for the pile spacing of 2D, 7D and 10D, as shown in Figure 4.3 and 4.4 respectively. The raft centre settlements for the various spacing imply that the settlement increases with the increase in spacing. Figure 4.3 implies the relationship in between them is almost directly proportional. The differential settlement is in between the centre and the corner.
point of the raft. The differential settlement plot against spacing shows no significant changes for a pile spacing of up to 7D, after which it increases with the pile spacing.

Figure 4.3 Raft centre settlement for various pile spacing
The settlement reduction factor ($\xi_s$) calculated as the ratio of settlement of combined piled raft foundation to that of unpiled raft for the midpoint of the raft. The relationship between settlement reduction factor and the applied load which is normalized by the ultimate bearing capacity of the raft is shown in Figure 4.5. This is numerically analyzed by increasing the magnitude of a uniformly distributed load of certain magnitude on the top of the raft for 2D, 7D and 10D pile spacing. The lowest pile spacing has the lowest settlement reduction factor. It can be observed that, the settlement reduction factor ($\xi_s$) decreases at some load and increases again. In that case the application of combined piled raft foundation is more effective up to a certain load level which is approximately 700 kPa; beyond this load the settlement reduction factor ($\xi_s$) increases with the applied load.
Figure 4.5 Effect of pile spacing on $\xi_s$ relative to midpoint of the raft

4.3 Effect of pile diameter

Seo et al. (2003) observed that the pile diameter effect is minimal on the total settlement of piled-raft foundations on weak clay soil. It can be stated that the effect of pile diameter on load-settlement relationship of piled-raft foundations can be different from this observation at small or large settlement levels.

Nine models have been developed for the varying pile size of 0.2 m, 0.4 m and 0.5 m sides of circular cross-section. These three types of pile size categories have been simulated numerically for 2D, 7D and 10D pile spacing for which the soil continuum model, boundary conditions, soil properties, the concrete property for raft and piles and modeling technique mentioned in the previous section were used in the same fashion. And the same UDL of 1 MPa was applied on Raft top in each case.

In Figure 4.6, the raft top settlement from the numerical simulated analysis output by ABAQUS has been observed. The settlement pattern of the raft top is same for all the pile spacing and size variation. The settlement is observed greater for 0.2 m diameter and reduced gradually as the pile diameter increased. The settlement intensity varies with the pile spacing. For smaller pile spacing, the piled raft settles in a greater magnitude than that of the bigger size.
piles. And Figure 4.7 shows the uniform settlement for various pile sizes for the spacing of 7D in which the 0.5 m diameter pile settles much less than the other two whereas 0.2 m and 0.4 m diameter pile raft settlement were approaching each other. The curves on Figure 4.8 are steeper than the other two curves for the pile spacing of 10D.

![Raft top settlement for various pile diameter (S=2D)](image)

Figure 4.6 Raft top settlements along diagonal path for various pile diameter (s = 2D)
Figure 4.7 Raft top settlements along diagonal path for various pile diameter (s = 7D)

Figure 4.8 Raft top settlements along diagonal path for various pile diameter (s = 10D)

In Figure 4.9, the raft centre settlements for varying pile sizes have been investigated for each case of 2D, 7D and 10D pile spacing. In each case, the centre point settlement is decreased with the increased pile diameters. It shows that the settlement reduction rate is steeper for smaller
pile spacing and flatter for the larger pile spacing. It can be concluded, the larger spacing of the piles reduces the effectiveness of increased pile diameter.

This study also includes the influence of pile size variation on the differential settlement of piled raft foundation. The settlement difference between the raft centre and corner point has been taken into consideration. Figure 4.10 shows the differential settlement variation with varying pile diameters for the pile spacing of 2D, 7D and 10D. The differential settlement does not vary significantly with the pile size variation for 2D and 7D pile spacing with the same variation patterns. However, the differential settlement is observed in a huge amount for the pile spacing

Figure 4.9 Raft centre settlement for various pile spacing

![Raft center settlement for various pile diameter (S=2D,7D & 10D)](image)

Figure 4.10 Center settlement for various pile diameter (S=2D,7D & 10D)
of 10D having different pattern of the change in differential settlement as compared with the previous differential settlement curves.

Figure 4.10 Raft differential settlements for various pile spacing

Figure 4.11 shows the relationship between settlement reduction factor $\xi_s$ and the normalized load for 0.2 m, 0.4 m and 0.5 m pile diameter. It can be observed that $\xi_s$ remains constant up to a certain load level, but beyond that it increases with the applied load (in this case about 450 kPa). Therefore the equivalent optimal load level which is normalized by the ultimate bearing capacity of the raft is about 0.22 and as observed from the plot, the highest pile diameter has the lowest $\xi_s$ while increasing the load.
Figure 4.11 Effect of pile diameter on $\xi_s$ relative to midpoint of the raft

### 4.4 Effect of raft thickness

Oh et al (2008) reported that raft thickness has little effect on the maximum settlement of piled-raft foundations on sand soil. Singh (2008) reported that finite element analyses of piled-raft foundations showed that the raft thickness has little effect on maximum settlement in soft cohesive soils. It can be stated that the effect of raft thickness on load-settlement relationship of piled-raft foundations is the same at small or large settlement levels. And for the weak layered soils, increasing the raft thickness reduces the differential settlement but generally increases the maximum bending moment. For zero piles, that’s the raft only- the raft behavior is quite non-linear for small raft thicknesses and the development of plastic zones below the raft tends to reduce the differential settlement. Once again the raft with only few piles performs very well, and this clearly demonstrates the importance of locating the piles below the parts of the foundation that most require support. This is in accordance with the philosophy of designing piled rafts for differential settlement control. (Clancy, Anagnostopoulos, & Rabiei, 1998).

Different thicknesses have been investigated to the raft thickness influences on pile raft foundation behavior by applying 1 MPa UDL on square rafts of 6 m×6 m. The material property, modeling technique, boundary condition and analysis technique are as mentioned in the previous sections. The load settlement behavior of the piled raft foundation for varying raft thickness of 0.5 m, 1 m, 1.5 m, 2 m and 2.5 m was plotted in Figure 4.12. The raft top centre point settlement is plotted here for a typical pile spacing of 7D. The settlement profile of various thickness
indicate that raft thickness of 1m or less yield a load settlement behavior, which is inferior to that of raft only footing of identical condition. This observation can be viewed by another plotting of settlements profile for various raft thickness as shown in Figure 4.13. The plot implies that the settlements reduce sharply from a raft thickness of 1 m to 1.5m and increase again after a raft thickness of 2 m. The increased settlement after raft thickness of 2 m is due to the increased self weight of increased raft thickness.

Figure 4.12 Raft centre settlement for various raft thickness
A rafts relative stiffness (thickness) has an important effect on the differential settlement but has a negligible effect on the average settlement and load distribution between piles and the raft (EL-Garhy, Gaalil, Youssef, & Raia, 2013). The minimum differential settlement is related to the raft thickness. Upon comparing rafts at thickness of 0.5 m, 1 m and 1.5, the 1.5 m thick raft showed good performance. The differential settlement of 1.5 m thick raft was smaller than that of 1 m thick raft. Further increase in the raft thickness to 2 m is not recommended, due to the accompanying increase in cost. As shown in the Figure 4.14, the raft centre settlement increases with the increased raft thickness and the differential settlement does not change significantly after a raft thickness of 1.5m as shown in Figure 4.16. Raft top differential settlement profile for various raft thickness are described in Table 4.2.
Figure 4.14 Raft top centre settlement profile for various raft thickness

Figure 4.15 Raft top corner settlement profile for various raft thickness
Table 4.2 Raft top differential settlement profile for various raft thickness

<table>
<thead>
<tr>
<th>Raft thickness (m)</th>
<th>Centre settlement (m)</th>
<th>Corner settlement (m)</th>
<th>Differential settlement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.16</td>
<td>0.05</td>
<td>0.11</td>
</tr>
<tr>
<td>1</td>
<td>0.17</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>1.5</td>
<td>0.178</td>
<td>0.172</td>
<td>0.006</td>
</tr>
<tr>
<td>2</td>
<td>0.18</td>
<td>0.176</td>
<td>0.004</td>
</tr>
<tr>
<td>2.5</td>
<td>0.183</td>
<td>0.18</td>
<td>0.003</td>
</tr>
</tbody>
</table>

From the plot of $\xi_s$ versus normalized load in Figure 4.17, it can be observed that as the thickness of the raft increases for ($t \leq 1.5$ m), $\xi_s$ decreases and for each plot $\xi_s$ decreases up to a certain load level (in this case about 700 kPa) beyond which $\xi_s$ increases with the applied load.
4.5 Effect of pile length

Rabiei (2009) observed that the settlement of piled-raft foundations decreases as the length of the piles increases. Similarly, Seo et al. (2003) observed that the total settlement of piled-raft foundations on clay soil reduced as pile length increased. Further numerical investigation was done with these 3D finite element models to study the pile length variation effects on the differential settlement of the pile raft. The settlement difference between the raft centre and corner point has been taken into consideration for this purpose.

Nine models have been developed for the varying pile length of 13 m, 18 m and 24 m. These three types of pile length categories have been simulated numerically for 2D, 7D and 10D pile spacing for which the soil continuum model, boundary conditions, soil properties, the concrete property for raft and piles and modeling technique mentioned in the previous section were used in the same fashion. And the same UDL of 1 MPa was applied on Raft top in each case. Raft top settlement from the output of the numerical analyses by means of ABAQUS/CAE for various pile length has been shown in Figure 4.18 to 4.20. The settlement pattern of the raft top is same for all the pile spacing and length variation. However, this pattern for 10D pile spacing in Figure 4.20 is steeper, which reflects the more differential settlement for 10D spacing of any pile length.
Figure 4.18 Raft top settlement for various pile length (s=2D)

Figure 4.19 Raft top settlement for various pile length (s=7D)
In addition to the raft top settlement profile, the influence of pile length on raft centre settlements have been investigated for each of the 2D, 7D and 10D pile spacing. For each case, the centre point settlement is decreased with the increased pile length as shown in Figure 4.21. It shows that the settlement reduction rate is steeper for smaller pile spacing and flatter for the larger pile spacing. It can be concluded therefore, the larger spacing of the piles reduces the effectiveness of increased pile length. So to develop the optimum design strategy a balance in between the spacing and pile length should be established.
This study also includes the numerical investigation on the effects pile length variation on the differential settlement of the pile raft foundation where the settlement difference between the raft centre and corner point has been considered. Figure 4.22 shows that the differential settlement variations with varying pile length for the pile spacing of 2D, 7D and 10D. The differential settlement does not vary significantly with the pile length variation and the patterns for all the spacing is same, though the large magnitudes in the differential settlements are observed for the pile spacing of 10D. The length does not have any influence on the differential settlement as the rate of differential settlement does not vary significantly with the changes in pile length for any spacing of pile.
As shown in Figure 4.23, the settlement reduction factor ($\xi_s$) initially increases with the applied load until a certain limiting load and decreases with further load application (in this case about 450 kPa) and the highest pile length has the lowest $\xi_s$ while increasing the load. These results indicate that piled raft foundation is more effective in reducing $\xi_s$ for very high loads.
This study also investigated the effect of weak layer which located under the raft on the settlements behavior of piled raft foundation. Among the different parameters, two parameters were selected in order to study the weak layer effect. It shows the influence of two important factors relating to the weak layer, namely the location of weak layer and the stiffness of the weak layer on the settlement behavior of piled raft foundation. This was done by varying one parameter and keeping all other parameters constant. There were four different locations of the weak layer at the raft location, 12 m below the raft, 18 m below the raft and 25 m beneath the raft. And also four different stiffness ratio of weak layer to stiffness ratio of soil layer below the raft were considered in the numerical model.

Figure 4.24 shows the effect of the stiffness of the weak layer on settlement reduction factor ($\xi_s$) using the contour plot of $\xi_s$ and stiffness ratio, as stiffness ratio is the ratio of the stiffness of weak layer to the stiffness of the soil layer below the raft ($\frac{E_{\text{weak layer}}}{E_{\text{soil layer below the raft}}}$).
For lower stiffness ratios (<0.6), the settlement reduction factor ($\xi_s$) is decreasing with increasing stiffness ratios. And $\xi_s$ becomes insignificant for stiffness ratio values greater than 0.6. This shows that, a slight reduction of the soil stiffness in the weaker range results in an excessive increase in settlements of the foundation.

![Graph showing the effect of stiffness ratio on $\xi_s$ relative to midpoint of the raft.](image)

**Figure 4.24** Effect of stiffness ratio on $\xi_s$ relative to midpoint of the raft

It can be observed in Figure 4.25 that as the distance of the location of weak layer from the raft increases, $\xi_s$ decreases for various stiffness ratios. For the stiffness ratios beginning from 0.14 to 0.9, the lowest stiffness ratio has the highest $\xi_s$ and piled raft foundation is not affected significantly if the weak stratum is located below 18 m.
Figure 4.25 Effect of location of weak layer below raft on $\xi_s$ relative to midpoint of the raft
CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of this study is to investigate the settlement behavior of piled raft foundation in weak layered soil using 3D-numerical modeling, conducting parametric studies for the effect of pile diameter, pile length, pile spacing, raft thickness and location of weak layer beneath the raft. The model was validated by comparing its results with other numerical models available in the literature. The results of the developed numerical model were found in reasonable agreement with the results of other numerical models based on three dimensional analyses. The effect of mesh density on maximum settlement (sensitivity analysis) has been conducted and fine mesh was used to investigate the settlement behavior of piled raft foundation. The main Conclusions drawn from model results and recommendations drawn for future works are summarized in this chapter.

Based on the results of the present detailed numerical investigation carried out in this study, the most important observations regarding load-settlement behavior of piled-raft foundations which can assist in conducting an efficient design of piled-raft foundations are described as follows:

➢ Parametric study reported that pile spacing have no effect on the load –settlement relationship of piled-raft foundations when supported by a small number of piles. And it can be concluded that the maximum pile spacing for pile raft foundation, should not be greater than seven times the pile diameter (7D).

➢ Based on the results of the numerical investigation, the larger spacing of the piles reduces the effectiveness of increased pile diameter and pile length. And comparing from others, 1.5 m thick raft shows good performance, further increase in the raft thickness to 2 m is not recommended as it increases the cost.

➢ This research suggests the optimum load level normalized by the ultimate bearing capacity of the raft for various parameters. For pile spacing and raft thickness the application of combined piled raft foundation is more effective up to a certain load level
(700 kPa) which is equivalent to 0.33; beyond this load the settlement reduction factor \( (\xi_s) \) increases with the applied load. For pile length and pile diameter the application of combined piled raft foundation is more effective up to a certain load level (450 kPa) which is equivalent to 0.22; beyond this load the settlement reduction factor \( (\xi_s) \) increases with the applied load for the respective pile diameter and \( \xi_s \) decreases with the applied load for the respective pile length.

- Based on the result, it can be concluded that the effect of weak layer located below the raft on the settlement reduction factor \( (\xi_s) \) relative to midpoint of the raft is negligible for relative stiffness of the weak layer to the stiffness of the soil layer below the raft greater than 0.6. For all stiffness ratios (0.14 to 0.9) considered in this study, the piled raft behavior is not affected if the weak stratum is located below 18 m.

- On centre settlement model, raft center settlements for various parameters have been investigated and results show that the raft top centre settles more than any other point of the foundation.

- To control differential settlement, few piles strategically located at the central area of the raft (region of maximum settlement) are more efficient in reducing differential settlement rather than a larger number of uniformly distributed piles. But in reverse the result can give a negative differential settlement if central piles result in a different raft deformed shape compared to uniformly distributed pile group (settlement at raft corner greater than that at raft center).
5.2 Recommendations

➢ This study focuses on the static loads on piles and rafts in piled raft foundations. Therefore, lateral and dynamic/cyclic loads can be considered in the further studies, which may lead to discover a proper/realistic behavior of piled rafts under dynamic conditions.

➢ In this thesis the influences of pore water pressure was not considered as it was assumed that water table is very deep from the soil surface. It is therefore recommended to extend this study to investigate the effect of changing water table on the settlement behavior of piled-raft.

➢ It is recommended to investigate the performance of piled –raft foundations supported by different types of piles. For example, using tapered piles may have some effect on the settlement characteristics of piled-raft foundations in terms of foundation stiffness or the load sharing between the raft and the piles.
REFERENCE


APPENDIX

Appendix A-Typical values of soil Young's modulus for different soils according to USCS.

In general, the soil elastic modulus depends on the consistency and density of the soil. Typical values of soil Young’s modulus are given below as guideline.

Table A.1 Typical values of Young's modulus (MPa) for granular materials (Kézdi&Rétháti, 1974 and Prat et al., 1995).

<table>
<thead>
<tr>
<th>USCS</th>
<th>Description</th>
<th>Loose</th>
<th>Medium</th>
<th>Dense</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW,SW</td>
<td>Gravels/sand well-graded</td>
<td>30-80</td>
<td>80-160</td>
<td>160-320</td>
</tr>
<tr>
<td>SP</td>
<td>Sand, uniform</td>
<td>10-30</td>
<td>30-50</td>
<td>50-80</td>
</tr>
<tr>
<td>GM,SM</td>
<td>Sand/gravel silty</td>
<td>7-12</td>
<td>12-20</td>
<td>20-30</td>
</tr>
</tbody>
</table>

Table A.2 Typical values of Young's modulus (MPa) for cohesive materials (Kézdi and Rétháti, 1974 and Prat et al., 1995).

<table>
<thead>
<tr>
<th>USCS</th>
<th>Description</th>
<th>Very soft to soft</th>
<th>Medium</th>
<th>Stiff to very stiff</th>
<th>Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML</td>
<td>silts with slight plasticity</td>
<td>2.5-8</td>
<td>10-15</td>
<td>15-40</td>
<td>40-80</td>
</tr>
<tr>
<td>ML,CL</td>
<td>Silts with low plasticity</td>
<td>1.5-6</td>
<td>6-10</td>
<td>10-30</td>
<td>30-60</td>
</tr>
<tr>
<td>CL</td>
<td>Clays with low-medium plasticity</td>
<td>0.5-5</td>
<td>5-8</td>
<td>8-30</td>
<td>30-70</td>
</tr>
<tr>
<td>CH</td>
<td>Clays with high plasticity</td>
<td>0.35-4</td>
<td>4-7</td>
<td>7-20</td>
<td>20-32</td>
</tr>
<tr>
<td>OL</td>
<td>Organic silts</td>
<td>-</td>
<td>0.5-5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>OH</td>
<td>Organic clays</td>
<td>-</td>
<td>0.5-4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>