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PARAMETRIC STUDY OF PILED-RAFT FOUNDATION ONHOMOGENEOUS DRAINED STIFF CLAY SOIL USINGFINITE ELEMENT METHOD-ABAQUS SOFTWARE

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Bahir Dar, Ethiopia
July, 2020

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Tadilo Tezera Mamay

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IN
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July,2020

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This work is dedicated to my beloved mother!

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Abstract

Recently, geotechnical engineers have started to design the piled foundations more optimized by allowing a part of the pressure to be transferred directly from the raft to the ground. Such a foundation, where the raft and the piles interact to transfer the loads to the ground is called a piled raft foundation or piled raft.

*Piled Raft Foundations*have a complex soil-structure interaction. This often requires numerical methods. The behavior of the piled raft foundation systems is influenced by various factors such as raft thickness, pile length, pile diameter, pile spacing and a number of piles, which must be considered for economical and effective design. In this research, a numerical analysis has been carried out by using powerful finite element-based software, ABAQUS, to investigate the influence of the above various parameters.Currently, the piled raft foundation is designed based on conventional group pile or block failure theory, this assumption ignores the bearing contribution from the raft.

The work in this thesis explores the load-deformation behavior of piled raft foundation, using finite element method software, ABAQUS CEA. This finite element analysis was performed on the vertically loaded piled raft. The model was calibrated by comparing the obtained numerical modeling results with experimental results (centrifuge test results) of other researchers.The developed 3D model was able to capture the behavior of the piled raft foundation system. In addition, an extended parametric study in which the effect of different parameters such as raft thickness pile spacing, pile diameter,pile length andthe number of piles on the response behavior of a piled raft was conducted.

A number of parameters areselected from the elements of the piled raft system. According to their effect on the response of the piled raft system, some were taken to be constant while others were varied. A series of numerical simulations for different piled raft models was performed to make comparisons of the settlements between these piled raft models. The compared results will contribute to a more economical design process for the specified type of piled raft foundations.These obtained results were validated by comparing with experimental results from the literature.

The parametric study has been performed for five parameters of the piled raft (raft thickness, number of piles, pile length, spacing of piles and pile diameter). It was observed that, by increasing raft thickness from 0.5 to 2m, the settlement was reduced by 32.51%. When the raft thickness was greater than 1.5m, the induced settlement attained a relatively constant value.By increasing the number of piles from 1 pile to 16 piles, the settlement amount was reduced by 38.76%. Additionally, from the total settlement reduction obtained by increasing pile length, a 44% reduction was obtained by increasing the pile length from 6m to 12m.

Keywords- piled - raft, Finite element method.

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NOMENCLATURE

Symbol	Description	Unit
f_{avg}	Average unit frictional resistance	[kN/m^2]
S_p	Center to center spacing of piles	[m]
c	Cohesion	[kN/m^2]
L_p	Depth of penetration into bearing stratum	[m]
D_p	Diameter of piles	[m]
y	Dilatancy angle	[o]
σ_f	Failure Normal stress	[kN/m^2]
τ_f	Failure shear stress	[kN/m^2]
ø'	Friction angle	[o]
h	Group efficiency	[-]
Q_{pt}	Load carried at the pile tip	[kN]
Q_s	Load carried by skin friction of the pile	[kN]
Q_r	Load carring capacity of the raft	[kN]
Q_p	Load carrying capacity of the pile	[kN]
Q_{pr}	Load carrying capacity of unpiled raft	[kN]
a_r, b_r	model parameters for the normalized hyperbolic load settlement relationship of raft	[-]
n	Number of piles	[No.]
P_g	Perimeter of the cross-section block	[m]
X_g	Pile group effect factor	[-]
L_p	Pile length	[m]
ν	Poisson's Ratio	[-]
L_r	Raft length	[m]
t	Raft thickness	[m]
B_r	Raft width	[m]
γ_{sat}	Saturated unit weight of the soil	[kN/m^3]
s	Settlement	[mm]
E_s	Soil's elastic modulus	[Mpa]
$Q_{g(u)}$	Ultimate load-bearing capacity of each pile without the group effect.	[kN]
γ_{unsat}	Unsaturated unit weight of the soil	[kN/m^3]
E_r	Young's modulus for the raft	[MPa]

ABBREVIATIONS

Abbreviation	**Description**
BiT	Bahir Dar Institute of Technology
CPRF	Combined piled raft foundation
EBP	End Bearing Piles
EPL	Equivalent Point Load
FGP	Floating Granular Piles
FEM	Finite Element Method
UDL	Uniformly distributed load
PDR	Poulos-Davis-Randolph analysis
MC	Mohr-Coulomb
UR	Unpiled raft
PR	Piled Raft

Chapter 1

Introduction

1.1. GENERAL PROBLEM DESCRIPTION

1.1.1. Background

A foundation system is required to safely support the large lateral and vertical loads associated with high-rise buildings/structures and to control total and differential movements of the foundation to within tolerable limits (Poulos, 2011).A geotechnical engineer faced with the design of foundations for structures firstconsiders a shallow foundation for supporting a given structure. 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 (Poulos, 2011). However, when the weight of the structure increases and the bearing capacity of the foundation soil compromise the stability or serviceability of the structure, one needs to resort to other foundation types.Pile groupisone good solution/alternative in site conditions where low bearing capacity and significant settlements are expected. In designing pile group as foundation support for structures, it is a common trend to include a pile cap for joining of the pile heads. The pile cap here is designed for structural section capacity only. But the pile cap has additional influence on the foundation system besides joining of pile heads and simple load transferring. Recent developments have shown that the stiffness of the pile cap influences the load transferring mechanism of the foundation system(Bakroun, 2012). The roleof the pile cap becomes significant if the cap is in direct contact with the foundation soil.

A piled raft is a foundation thatacts as a composite structure consisting of three load-bearing elements: *piles, raft, and subsoil*(H. G. Poulos, 1989). According to its stiffness, the raft distributes the total load of the structure as contact pressure and over the piles in the ground. The piled raft concept needs an evaluation of a number of factors in order to come up with analysis/design models that simulate the actual site conditions.In comparison to a pile group foundation, in the combined piled raft foundation (CPRF), both the piles and the raft transfer the loads into the ground. The loads are transferred by skin friction and end bearing of the piles as well as contact pressures of the raft foundation (Burland, 1977). The piles are used up to their ultimate bearing capacity, which is higher than the permissible design value for a comparable single pile.The CPRF represents a complex foundation system, which requires a qualified understanding of the soil-structure interactions (Quick, 2005).Generally, the construction of a piled raft foundation system is similar to the current practices used to construct a pile group foundation in which a cap is normally cast directly on the ground. Although this installation of a cap will allow a significant percentage of the load to be transmitted directly from the cap to the ground, the pile group is usually designed conservatively by ignoring the bearing capacity of the raft (in this case the pile cap). The raft alone can provide an adequate bearing capacity; however, it may induce excessive settlement. Therefore, the concept of settlement reducing piles was presented by Burland (1977) in which the piles are used to limit the average and differential settlements(Burland, 1977).

In recent years, there are many construction projects constructed on sandy soil. Due to the characteristic of sandysoil, the structures built on it are subject to differential settlements. Raft foundation is one of the available methods suggested for reducing the differential settlement in this case; although it has an adequate bearing capacity; it may, however,cause excessive settlement (Sinha, 1997). Strategically located piles can be used with a raft foundation as a piled-raft foundation system as an alternative. The addition of piles is to reduce the settlements to an acceptable amount.Piled-raft is a common foundation for some structures such as tall and heavy buildings, silos, chimneys and storage tanks constructed on soft soil. In many situations, piles are used to improve the weak soil beneath the raft. In such cases, understanding the behavior of the raft foundation resting on sand soil improved by piles is very significant for the economical and safe design of the piled-raft foundation. Piles beneath the raft may be fully penetrated and resting on strong soil layer (i.e., end bearing piles, *EBGP*) or partially penetrated (i.e., Floating Piles, FGP).

The complex piled raft foundation behavior has not yet been captured by so far developed analytical methods. The major challenge is the complexity generated by the load transfer mechanism between the slab (raft) and the piles. The difficulty arises when determining load versus settlementcurves, which are mechanisms heavily influenced by the interactions between the elements integrating the foundation (i.e. *Slab-Pile-Soil interaction*) (Sales, 2000). Besides, there are no generalized design standards for the CPRF in many countries; consequently, the implementation of such kind of foundations has been slow for engineering projects(Ahner, Soukhov, & König, 1997).

The behavior of piled raft foundations in the sand has been extensively studied in the literature through experimental and numerical analyses (Sinha, 1997). However, the effect of *raft-soil contact* on the load sharing mechanism of piled raft footings is not very well understood.The mixed safety standards are currently employed at most engineering faculties even though, the limit states concepts that employ the partial coefficient standard as a safety method is currently exercised. So, there is a need to investigate the use of the numerical method approach for understanding these complex interactions.Finite element analyses are popular in the field of geotechnical engineering. The analyses of pile raft foundations using the finite element method to investigate the performance of the piled rafts have been done by manytypes of research. This method can yield good results for piled raft analyses (Paravita Sri Wulandari, 2015). 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.The aim of this study is to analyze the geotechnical stability considerations of the Piled-raft foundation by varying raft thickness, pile number, pile length to diameter ratio, and pile spacing.As indicated by many scholars, a numerical investigation is very helpful in verifying the results of the experimental data.

1.1.2. Statement of the Problem

The use of a piled raft foundation has led to a reduction of the total as well as differential settlements. In many cases using a raft foundation only induces excessive settlements that are not acceptable due to serviceability limit state requirements. Placing of piles in a systematic manner however under the raft reduces such settlements to acceptable values. In addition to settlements, the bearing capacity of the whole system of the foundation also improves. The conventional design methods used for pile groups lead to a higher number of piles under the raft. With the concept of the piled raft, however, this number can be reduced. For the design and the computation of the CPRF actually, no standards and definite design strategies are available (Katzenbach. R., U. Arslan, U. & Cbr. Moortnann, 1996). So actually, additional research work is required based on measurements and numerical computer-simulations. This can only be done if the effects of parameters influencing the piled-raft foundation system are properly analyzed. Numerical simulations in this regard give the opportunity to examine the bearing behavior of pile groups or of CPRF in parametric studies varying, for example, the number of piles, the diameter, and length of piles and the distance between adjacent piles for defined boundary conditions.

The spatial interaction analysis of pile foundations in multi-layered soil medium is a very complex engineering problem in three dimensions which especially requires a realistic constitutive law for the soil. Within the frame of this research work, an *elastoplastic constitutive model* is used for simulating the *nonlinear elastoplastic material behavior* of soil in numerical analysis. The economical and serviceability aspect of the piled raft is attracting a number of geotechnical engineers. The parameters that could impact the load sharing mechanism of piled raft foundation are, but not limited to: piled raft settlement, soil density, pile length, pile spacing, raft geometry, and pile installation techniques. Different researchers studied the effect of pile length, number of piles, pile configuration, and cap geometry on piled raft behavior, but less attention has been paid to the other aforementioned parameters. Therefore, the main goal of this study is to investigate the effect of the raft thickness, pile number, pile length, pile diameter and spacing of piles, raft width ratio, and piled raft settlement on load sharing mechanism between piles. Moreover, research needs to be conducted on the ultimate combination of piles and raft parameters that can lead to acceptable design requirements plus cost savings. This researchis expected to have provided a significant understanding of the parameters that affect piled raft performance. Application of this knowledge to our country will improve the performance of structures that are being built and for those, which are going to be built in the future

1.2. RESEARCH OBJECTIVES

This section outlines the general and specific objectives of the research.

1.2.1. General Objective

The aim of this research is to simulate the behavior of a piled raft foundation numerically using a 3D FEM and evaluate the parameters that affect piled raftperformance from a geotechnical stability perspective.This study is mainly aimed at evaluating the performance of piled raft foundation by varying the raft thickness, pile number, pile length, pile diameter and spacing of piles. An indirect economical advantage of this kind of foundation can also be evaluated.

1.2.2. Specific Objectives

The specific objectives of this research are summarized as follows:

a) To undertake a detailed review of the necessary literature on the design and analysis ofpiled-raft foundation using FEM.

b) To investigate the load sharing mechanism between the raft and the piles for the selected piled- raft foundation system. This is done by varying the raft thickness, pile number, pile length, pile diameter and spacing of piles.

c) To analyze the role of *raft thickness* on the settlement of the piled-raft foundation

d) To predict the optimum number of piles needed for the selected piled-raft system.

e) To investigate the effect of length to diameter ratio, L/D , on serviceability limit state response of the piled - raft foundation.

f) To investigate the total and differential settlement behavior of piled raft by a varying number of piles.

g) To investigate the total and differential settlement behavior of piled raft by varying raft thickness.

h) To investigate the total and differential settlement behavior of piled raft foundation by the varying spacing of piles.

1.3. SCOPE OF THE STUDY

The soil contributes to the stiffness of the piled raft system through Young's modulus and Poisson's ratio. The strength parameters of the soil can also be considered. This research will assume uniformly laid *stiff clay soil*up to a depth of 30m. All parameters of the soil will be kept constant throughout the analysis.This research will present a parametric study for investigating the optimum design for a specific piled raft foundation subjected to a vertical distributed load only.A uniform distribution of piles will be mainly considered. In the three-dimensional finite element model, only the quarter of the raft will be modeled due to symmetry.

1.4. SIGNIFICANCE OF THE STUDY

The conventional design methods used for pile groups lead to a higher number of piles under the pile caps. With the concept of the piled raft, this number can be reduced. This can only be done if the effects of parameters influencing the piled-raft foundation system are properly analyzed.

Chapter Two

Literature Review

2.1. INTRODUCTION

2.1.1. High-Rise Building Foundation Alternatives

The objectiveof any foundation is to transmit the load to the soil in order to provide safety, reliability, and serviceability to the structure. Current practice is to provide a deep foundation when the shallow foundation is not sufficient to provide adequate safety and reliability. However, a combination of the shallow and deep foundation can be a cost-effective design approach. The concept of piled raft foundations was originally described by Sievert (1957) and encouraged designers to adopt this approach for high-rise building foundations. The pile raft foundation is such a combination of a deep pile group and a shallow raft foundation, which has gained increasing recognition in very recent years. (Anup S., 2013)

The piled-raft foundation consists of three load-bearing elements; namely piles, raft, and subsoil. According to their relative stiffness, the raft distributes the total load transferred from the structure to the topsoil and the connected piles. In the conventional design of piled foundations, it was usually postulated that the overall load is supported by the piles. In piled raft foundation systems, the contribution of the raft is taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system (Ata, 2014)

The analysis of piled raft foundations has improved over the last few decades to account for the combined contribution of the raft and the piles to provide a more efficient system.Piles are structural members that are made of steel, concrete, or timber. Pile foundations are used when one or more upper soil layers are highly compressible and too weak to support the load transmitted from the superstructure, piles are used to transmit the load to the underlying bedrock or stronger soil layer (Das, 2011).Raft foundation covers the entire area of the structure, transmitting the entire structural load and reduces differential settlements whereas piles are relatively long, slender members that transmit foundation loads through soil strata of low bearing capacity to deeper soil and rock strata having a high bearing capacity (Srilaksh G. and Darshan M., 2013).The schematic design concept of shallow foundations (a), CPRFs (b) and deep foundations (c) (Borel 2001) are shown in Figure 2- 1.

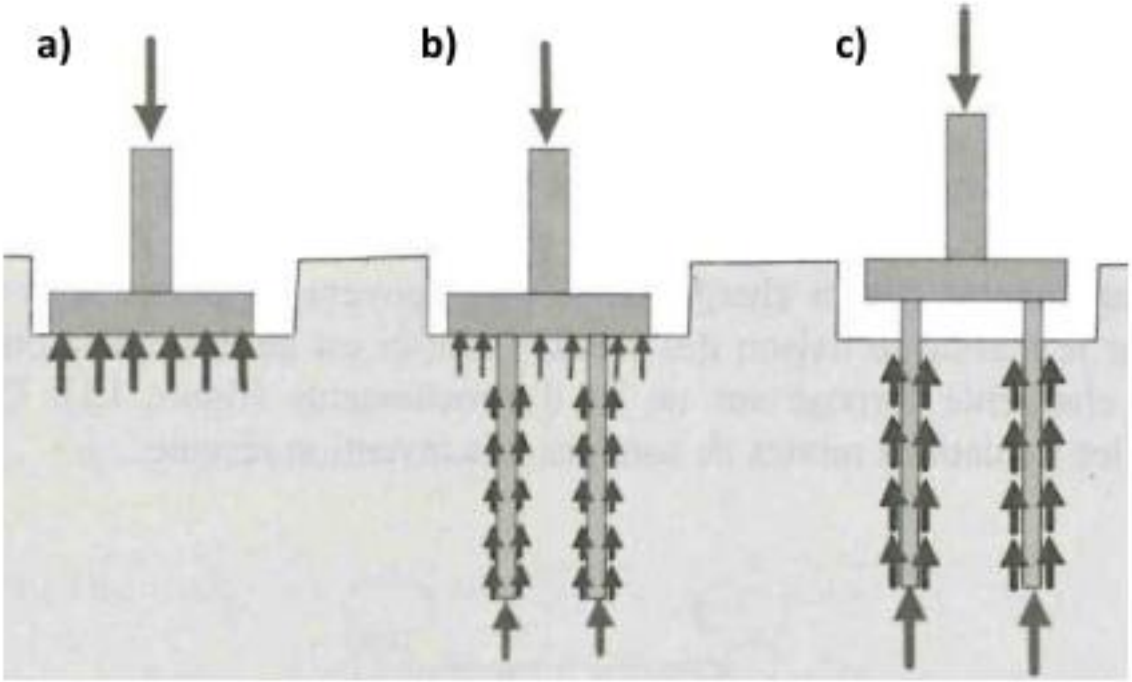


Figure 2- 1: The schematic design concept of shallow foundations (a), CPRFs (b) and (c) deep foundations (Borel 2001).

2.1.2. CPRF Components and Soil-Structure Interaction

According to (Ata, 2014), the piled raft foundation consists of three load-bearing elements; namely piles, raft, and subsoil. According to their relative stiffness, the raft distributes the total load transferred from the structure to the topsoil and the connected piles (Ata, 2014). In the conventional design of the piled foundation, it was usually postulated that the overall load is supported by the piles. In piled raft foundation systems, however, the contribution of the raft is taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system.The study of CPRF systems consists in taking into account the interactions between the different elements in the system (Figure 2-1 2). The raft-soil-interaction and the pile-soil-interaction correspond to the behavior of usual raft foundations and single piles. The pile-pile-interaction corresponds to the group effect. The new element to be considered here is the pile-raft-interaction, representing the effect of loading of the soil on the load-settlement behavior of the pile. The pile-raft interaction has influence mainly on the maximal and mobilized skin friction of the pile, the behavior of the pile tip remaining approximately unchanged for usual pile lengths. Combarieu (1988a) asserts that the raft has no influence on the pile tip for piles longer than the width of the raft, but the zone of influence of a footing is in general considered reaching a depth of 2.5 times the footing width.

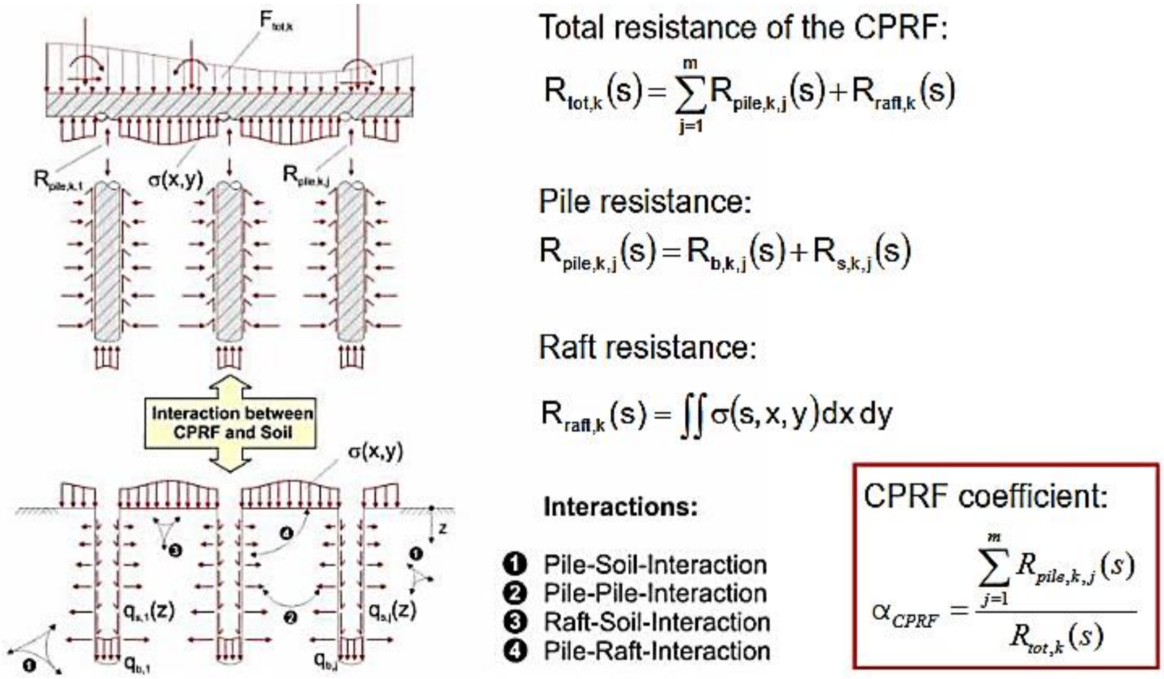


Figure 2- 2. Typical Piled Raft Foundation load-bearing elements; namely piles, raft and subsoil and soil-structure interaction (after Katzenbach, 1998)

In pile group system, the development of the skin friction over the pile length is different from the one in the single pile case. As opposed to the classical pile design where the skin friction would be theoretically first mobilized at the top of the pile due to pile compressibility, the maximum skin friction appears first at the bottom of the pile, if the raft is in contact with the soil, because of the imposed equality of settlements of pile and soil at the top. Typical Piled Raft Foundation load-bearing elements; namely piles, raft and subsoil, and soil-structure interaction effects are indicated in Figure 2- 2.

2.1.3. Advantages of using piled rafts

A piled raft foundation has some advantages over the pile group in terms of the design and from serviceability and economic point of view. They include the following:

A piled raft foundation will require fewer piles in comparison to a pile group to satisfy the same design requirements; this will lead to a more economical design;for a piled raft, the piles will provide sufficient stiffness to control the settlement and differential settlement at serviceability load; and the raft will provide additional capacity at ultimate load;in case any piles in the piled raft become defective or karstic, the raft allows re-distribution of the load from the damaged piles to the other piles, which are not affected (Poulos, 2011) .

A raft in the piled raft foundation can carry 30% to 50% of the applied load and transmit to the soil (Clancy and Randolph, 1993); The pressure applied from the raft to the subsoil may increase the lateral stress between underlying piles and the soil, which can increase the pile bearing capacity accordingly compared to the piles in a pile group (Alnuaim, 2013). According to Teferra, (1992) to in comparison to actually loaded piled foundation, using a piled raft foundation has a significant reduction in pile length. In addition, maximum total settlements and differential settlements are reduced. In recent years' software has been developed which uses the finite element method (Teferra, 1992).In a piled raft, the raft is large enough that classical bearing capacity failure is not possible even without the piles, which are then used to reduce differential settlements or bending moments in the raft. Piles located in an area around the center of the raft lead to the most reduction in a differential settlement with respect to those experienced by an unpiled raft (Salgado, 2009).

A piled raft foundation is assumed to have four kinds of interactions. These interactions are pile-pile, pile-raft, pile-soil, and raft soil. A model for full analysis and design of piled raft foundations has to predict these interactions accurately. (Simeneh A., 2009). The ultimate load-carrying capacity of the piled raft foundation increases significantly with the increase in pile diameter (Anup S., 2013). It is ideal to provide a combination of different diameter piles rather than the equal diameter of piles throughout where different pile diameters lead to better function of foundation (Huang, 2008). it has been observed that the piled raft concept is very advantageous in minimizing the total and differential settlements as compared to the conventional raft foundation (Mekbib M., 2004). It also reduces the number of piles required as compared to the conventional pile foundation. The reduction in the number of piles ranges from 25% to 45% of that required for conventional pile foundation.

According toEl-Garhy, (2013), the length of the pile shall be estimated considering the slenderness ratio of the piles. As the number of settlements reducing piles increases, the load improvement ratio increases, and the differential settlement ratio decreases. The useof piled-raft foundation systems will result in a considerable reduction of number and length of piles, improving serviceability in both total and differential settlements and minimizing tilt and instability probabilities. On the other hand, reducing the number and length of piles contributes to significant savings in the construction costs (Khanmohammadi, 2017).According to the investigation of Alnuaim, (2013)performed on the centrifuge tests, the proportion of the load carried by the raft was increased significantly at about 7% of the total displacement and the increase was gradual beyond 7% point. At about 80% of displacement, the load transmitted by the raft became almost constant.

Some of the buildings in the world with piled raft foundation are: -

a) Incheon Tower (in Korea): - 151 story super high-rise building was constructed on 172 x 2.5m diameter bored piles with 5.5m raft thickness.

b) The La Azteca building in Mexico City, Mexico: - a tall building constructed on a very deep deposit of soft clay. 83 concrete piles, 400 mm in diameter, driven to a depth of 24 m and the piles were about 18 m long below the raft.

c) The Burj Khalifa in Dubai: -the world’s tallest building, founded on a layered deposit of relatively weak rock.

d) The “Brooklyner’’ tower:- the tallest building in Brooklyn, New York with 51 stories 155m high, and the first structure built on a piled-raft foundation in New York City.

e) Tower of Jeddah:- built-in Jeddah, Saudi Arabia. The tower is over 390 m high constructed on karstic limestone (Poulos H. G., 2016)

2.2. THE CONCEPT OF PILED-RAFT FOUNDATION

Shallow foundation systems such as rafts could be viable when the foundation soil near the ground surface is competent (e.g. stiff clay of dense sand). However, even when the factor of safety against bearing capacity failure of the raft is adequate, the raft may settle excessively. Average settlements of the raft can be controlled by reducing the bearing pressures in relation to the bearing capacity of the soil (Reddy, 2010). A piled raft is a composite foundation in which the piles are used as settlement reducers and they share, with the raft, the load from the superstructure. The applied load is transferred from the raft to the shallow soil and to the pile heads, and from the piles, it is diffused through the shaft and the base to deeper soil. The pile raft foundation is a new concept and a lot of investigation needs to be done to expose the interaction among the foundation components. Therefore, it is essential to investigate the full-scale model tests under various conditions and configurations (Anup S., 2013).

A piled raft foundation is a composite system in which both the piles and the raft share the applied structural loadings. Within a conventional piled foundation, it may be possible for the number of piles to be reduced significantly by considering the contribution of the raft to the overall foundation capacity. In such cases, the piles provide the majority of the foundation stiffness while the raft provides a reserve of load capacity. In situations where a raft foundation alone might be used but does not satisfy the design requirements (in particular the total and differential settlement requirements), it may be possible to enhance the performance of the raft by the addition of piles.

In such cases, the use of a limited number of piles, strategically located, may improve both the ultimate load capacity and the settlement and differential settlement performance of the raft and allows the design requirements to be met (Poulos H. G., 2016).Piles can be used with a raft foundation in order to provide adequate bearing capacity or to reduce settlements to an acceptable level. The common design of piled raft is based on the assumption that the total load of the superstructure is supported by the piles, ignoring the bearing contribution of the raft. This results in a conservative estimate of the foundation performance, and therefore an over design of the foundation. A different approach, involving the use of piles as settlement reducers has been reported by different scholars.

The basic concept of this approach is that the foundation comprises only a number of piles that are necessary to reduce settlements to a tolerable amount and the loads from the structure are transmitted, via a raft, in part to the piles and in part to the foundation soil (load shared between the raft and piles). This approach allows the piled raft design to be optimized and the number of piles to be significantly reduced. Figure 2-3 shows schematically the principles behind the design of piles to reduce differential settlement. Assuming that the structural load is relatively uniformly distributed over the area of the raft, andthen there will be a tendency for the unpiled raft todish in the center. A few piles, added beneath the central area of the raft and probably loaded to about their ultimate capacity, will reduce centralsettlement, and thus minimize differential settlement. However, arelatively small number of piles could raise the problems of highbending moments and crack in the raft and a concentration ofaxial stresses in the pile heads(El-Garhy, 2013).Considering the proper identification and usage of the piled raft parameters introducing piles to the unpiled raft foundation results in reduced settlement and improved bearing capacity.Kambala, (2010) have identified two categories of piled raft foundations.

In the first category, piles are required to increase the overall factor of safety against bearing capacity failure and in the second category, piles are required only to reduce the settlements.

SMALL PILED RAFTS:-In this category of piled rafts, the primary reason for adding piles is to increase the overall factor of safety against bearing capacity failure. It typically consists of rafts having widths between 5m and 15m. In this case, the width of the raft is less than the length of the piles.

LARGE PILED RAFTS: - In this second category of piled rafts, the raft itself has sufficient bearing capacity to carry the applied load with a reasonable factor of safety, but piles are required to reduce the average settlement of differential settlement. In such cases, the width of the raft is large compared to the length of piles.According to Maharaj, (2004), clay deposits of large thickness commonly occur in such places as Frankfurt, London, and the coastal belt of India.

To support a heavy building on such a thick clay deposit, the following three options are normally available.Ifthe clay layer has very poor shear strength, the building is supported on load-bearing piles, transferring all load to a deeper, competent layer. This, of course, is the most reliable solution, but the cost of piled foundations could be very high owing to the large pile length that is required.If the clay layer has adequate strength, the building can be supported on a raft foundation. Settlements can be high, but if the structure can functionally permit this, the raft can be provided for the economy.

When the clay layer has intermediate strength, alternative (b) may not be feasible, as the bearing capacity may not be adequate, or settlements may be excessive, which may also cause distresses to adjacent structures. Owing to the high cost of land in urban areas, the normal tendency is to utilize all the available plot area for building construction. Therefore, considerable deformation can be transferred to the foundations of adjacent structures, which may be old and weak. In such situations, where it becomes necessary to reduce settlements, a piled raft can be provided. (Maharaj, 2004)

2.3. PILED RAFT DESIGN PHILOSOPHIES

2.3.1. Conventional Approach

In the conventional approach, the piles are distributed uniformly over the foundation area. The foundation is designed essentially as a pile group to carry a major part of the load, while some allowance is made for the load transmitted from the raft to the ground. This approach is more suitable for the *Small Piled Rafts*where the pile support is required from a capacity point of view (Kambala, 2010).In this approach; the piles are designed as a group to carry the major part of the load, while making some allowance for the contribution of the raft, primarily to ultimate load capacity (Poulos, 2001).

2.3.2. Creep Piling Approach

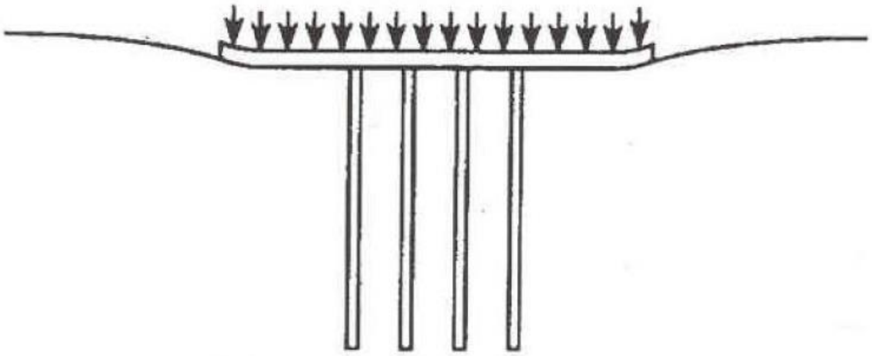
In Creep Piling Approach, the piles are designed to operate at a working load at which significant creep starts to occur, typically 70-80% of the ultimate load capacity; sufficient piles are included to reduce the net contact pressure between the raft and the soil to below *the pre-consolidation pressure of the soil.*The theory behind the principle is to take advantage of the compensation in effective stress created by the excavated soil. A certain percentage (Q_1) of the total applied load (Q), can be carried without piles, due to the compensation. The remaining part of the load (Q-Q1) has to be carried by the pile system. For example, if a raft can carry 80% of the load without causing substantial settlements, the piles have to carry the remaining 20% of the load. Thus, the purpose of using the creep pile is to maximize the pile capacity in order to control that a certain part of the load will be carried by the raft. The pile spacing is chosen to regulate the amount of load carried by piles (Algulin, 2014).

2.3.3. Differential Settlement Control Approach

According to Kambala(2010) the conventional and creep piling approaches described above adopt a uniform distribution of piles beneath the raft. In both cases, the primary aim is to limit the absolute settlement to an acceptable amount. Though the differential settlements are reduced as a consequence of the reduction in absolute settlements, a more direct approach is to design pile support in such a way as to minimize differential settlements, without necessarily reducing the average settlement.In this approach, the piles are located strategically in order to reduce the differential settlements, rather than to reduce the overall average settlement substantially (Poulos, 2001).

Figure 2-3shows schematically the principles behind the design of piles to reduce differential settlements.

Uniformly loaded raft foundation



Raft plus settlement reducing piles

Figure 2-3. Central pile to reduce differential settlement (after Randolph, 1994)

The load-settlement behavior for different design approaches, concerning a piled raft, is presented in Figure 2-4, Curve 0 represents the behavior of a raft acting alone. Curve 1 represents the conventional design approach. Curve 2 illustrates the “creep pile principle”, in which the piles are designed with a lower factor of safety. Curve 3 represents the use of full utilization of the piles at the design load, by strategically placing the piles as settlement reducers. The reduction in the number of piles for curves 2 and 3, results in a larger amount of load carried by the raft. Fewer piles result in a more economical design (Poulos, 2001).The differential settlement control approach could be the economical one, as piles are located strategically to reduce the differential settlement. It will require a smaller 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 numero-geotechnical methods by simulating the complex nature of the pile raft foundation(Anup S., 2013).

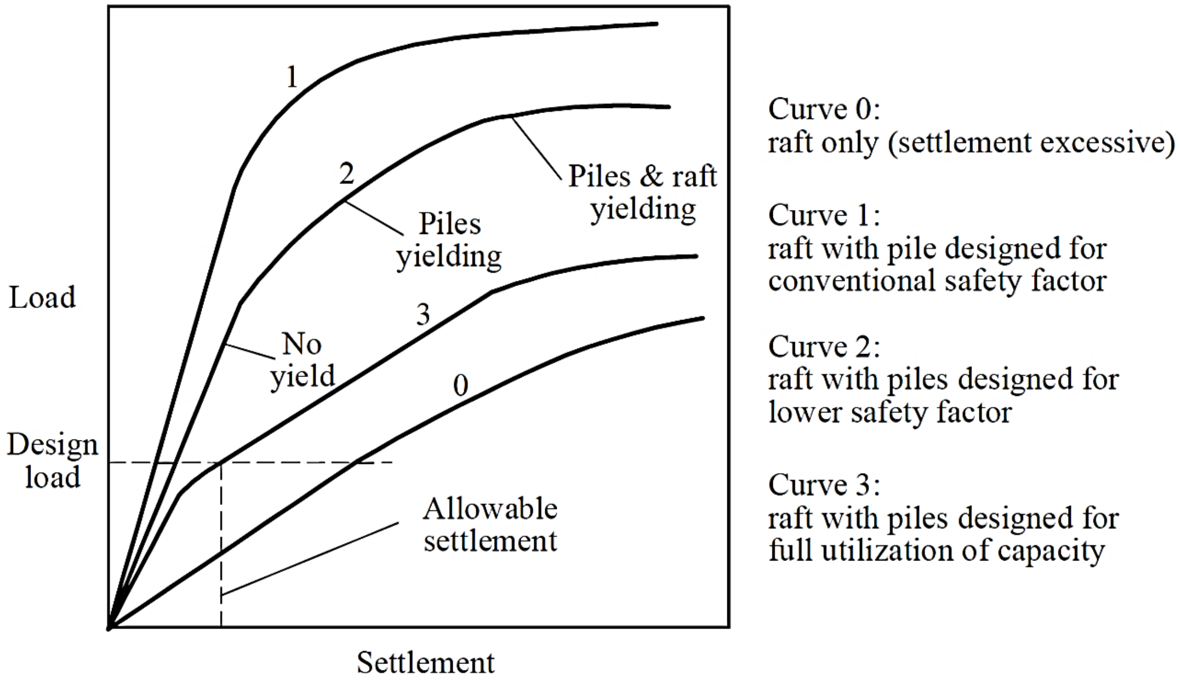


Figure 2-4.Load-settlement behavior for a piled raft, comparing different design philosophies (Poulos, 2001)

2.4. METHODS OF ANALYSIS

CPRF leads to an extremely economic foundation with rather low settlements especially if the stiffness of the soil is increasing with depth (Katzenbach 1993). A number of available methods that have been used for the analysis of piled raft can be ranged from simplified calculations to more rigorous computer-based numerical methods.

2.4.1. Simplified Method

This method is based on the calculation of the total stiffness of the piled raft by means of the stiffness of the pile group and the stiffness of an unpiled raft in isolation and the interaction between one pile with the region of the raft surrounding the pile.One of the simplified methods of analysis is*Poulos-Davis-Randolph* (PDR) Method,in applying this approach, the stiffness of the raft was computed by hand from elastic theory, assuming the raft to be an equivalent circular footing, and considering the center of a flexible raft. The stiffness of the single piles was computed from the closed-form approximate solutions of Randolph and Wroth (1978) while the group settlement ratio (used for computing the pile group stiffness) was approximated by $R_s = n^{0.5}$, where n = the number of piles (Imple, 2001).

2.4.2. Three-Dimensional Finite Element Method Analyses

It is evident from the available literature that the piled raft foundation was constructed about fifty years ago and the attempt to capture its behavior was started in the early eighties, which has intensified in the last few years, but no appropriate design strategy has been formulated yet. This is because of the complex interactions among the raft, pile, and soil, which is three dimensional in nature and cannot be captured by any analytical method so far developed. With the advancement of computer technology and numerical code, the researchers are now trying to model the complex behavior of the piled raft foundation(Anup S., 2013). Examination of the feasibility of the concentrated pile arrangement for reducing the total and differential settlements has been done and verified through comparisons between centrifuge (Nguyen, 2013) test results and calculated results obtained from numerical simulations (i.e. finite element method using PLAXIS 3D) (Nguyen, 2013).

Boundary Element Method requires the transformation of the governing partial differential equation into an integral equation. As only the boundaries have to be discretized, the number of sets of equations to be solved is generally smaller than the finite element methods. Solutions such as stresses and displacements can be obtained directly by solving the system of equations. Since only the boundaries are discretized, interpolation errors are confined to the boundaries (Mekbib M., 2004).In terms of ability to model a real problem, three-dimensional finite element analysis is usually considered to be the “ultimate weapon”, at least as far as the analysis is concerned.

Provided that the appropriate parameters are properly assigned (Lee M., 2014). Simeneh A., (2009) have analyzed three verification examples using PLAXIS 3D foundation software and the results were compared with measured values and other numerical methods. From the comparison made, the results from the software give reliable values. The study suggested further detailed research should be made on parameters affecting the piled raft system (Simeneh A., 2009).

Anup S., (2013) based on his study findings concluded that 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 (i.e., soil strata and its nature, soil type and their properties, moisture level etc.), structural requirements and considerations (i.e., 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.

Randolph & Reul, (2004)have studied 259 different piled raft configurations using three-dimensional elastoplastic finite element analysis. In this study, the pile positions, the pile number, the pile length, and the raft-soil stiffness ratio, as well as the load distribution on the raft,have been varied (Randolph & Reul, 2004).The main purpose of a parametric study is to investigate the piled raft performance under the changes in the geometry of the dimensions. Therefore, the numbers of cases for parametric study are as many as piled raft geometry (Richard & chanaton, 2008).

In this particular research, analysis of piled raft foundations will be conducted. The study will be performed using finite element-based software, Abacus. Major parameters are selected from the elements of the piled raft system. According to their effect on the response of the piled raft system, some will be fixed constant while others will be varied. Among the varying parameters, raft thickness, pile length to diameter ratio, pile spacing, and pile number will be considered.

According toLee C. B., (2002), Owing to symmetry, only a quarter of a whole mesh is used in the 3D simulation. A relatively finer mesh has been used near the pile-soil interface, and it becomes coarser further from the pile. Various sensitivity studies have been performed in order to design the most appropriate FE mesh for 3D analyses (Lee C. B., 2002).

In the numerical modeling of group effects on the distribution of drag loads in pile foundations, Lee has made assumptions like changes in the insitu stress in the soil and changes in the soil stiffness resulting from pile installation are ignored. Therefore, before initiating each analysis, the piles are free of residual stress. Soil settlement, and hence the development of Negative skin friction, is initiated by the application of surface loading on the top of the soil surface. ABAQUS uses the *Coulomb frictional law* in which frictional behavior is specified by an interface frictional coefficient, m, and a limiting displacement, g_{crit}.

The element type, shape, and location, as well as the overall number of elements used in themesh, affect the results obtained from a simulation. The greater the mesh density (i.e., the greaterthe number of elements in the mesh), the more accurate the results. As the mesh density increases,the analysis results converge to a unique solution, and the computer time required for theanalysisincreases. The solution obtained from the numerical model is generally an approximation to thesolution of the physical problem being simulated. The extent of the approximations made in themodel's geometry, material behavior, boundary conditions, and loading determines how well thenumerical simulation matches the physical problem(Getting Started with Abaqus, 2013).

In numerical static analysis, enough boundary conditions must be used to prevent the model from movingas a rigid body in any direction; otherwise, unrestrained rigid body motion causes the stiffness matrixto be singular.According to Nguyen D. D., (2013), in designing piled raft foundations, controlling the total and differential settlements as well as the induced bending moments of the raft is crucial. The majority of piled raft foundations have been designed by placing piles uniformly. In such a design method, the settlements of the piled rafts are likely to be large, which leads to an increase of the pile length and /or the number of piles required to reduce the settlements. However, this increase does not satisfy the requirement for economical design.

On the 3D simulation of the piled raft foundation, different researchers recommend different dimensions of the soil continuum media to make that the boundary condition has no effect on the outcome of the analysis. Alnuaim, (2013)suggested that the bottom of the model shall be more than twice the length of the pile $(2 \times L_{pile})$ and the lateral dimension shall be 1.5 – 2 times the raft width $(1.5 - 2) \times B_{Raft}$ measured from the edge of the raft (Alnuaim, 2013). Whereas Anup S.(2013)specifies the lateral dimension as 30 times the diameter of the piles $(30 \times D_{pile})$.

2.5. LOAD CARRYING BEHAVIOR OF PILED-RAFT FOUNDATION

2.5.1. Load Carrying Behaviorof aSingle Pile

The design of any foundation must meet the following requirements: the total structural load has to be transferred to the soil with an adequate safety factor against a bearing capacity failure; the total and differential settlements should be contained in order to guarantee the safety and the serviceability of the structure. In this context, there are some cases for which the choice of a pilefoundation is practically mandatory (i.e. bridge piers resting on a river-bed under erosion); in othercases, the choice can derive from a comparative analysis of alternative solutions (i.e. pile foundation against shallow foundation on a strengthened soil).

Based on the method employed during installation, concrete piles are divided into two basic categories: (a) Precast Piles and (b) Cast-In-Situ Piles. Precast piles can be prepared by using ordinary reinforcement, and they can be square or circular cross-section.As shown in Figure 2- 5(a) and (b), depending on their lengths and the mechanisms of the load transfer to the soil piles may be divided into two categories: (a) point or end-bearing piles, (b) friction piles.*Point bearing piles* are used if there is bedrock or rocklike material at the site within a reasonable depth so that piles can be extended to the rock surface. In this case, the ultimate capacity of the piles depends entirely on the load-bearing capacity of the underlying rock material (Das, 2011).The ultimate load carried by the pile is given by:

$$R_{ck} = \frac{R_{cm}}{x} \qquad (2\text{- }1)$$

$$R_c = \frac{R_{ck}}{g_t} \qquad (2\text{- }2)$$

$$R_c = \frac{R_{bk}}{g_b} + \frac{R_{sk}}{g_s} \qquad (2\text{- }3)$$

Where:

R_{cm} = the measured value of ultimate bearing resistance

R_{ck} = characteristic value

R_c = design value

R_{bk} = characteristic base resistance

R_{sk} = characteristic shaft resistance

x = factors to apply on measured values

g_t = total factors of safety on the characteristic pile resistance

g_b = partial factors of safety on the base resistances

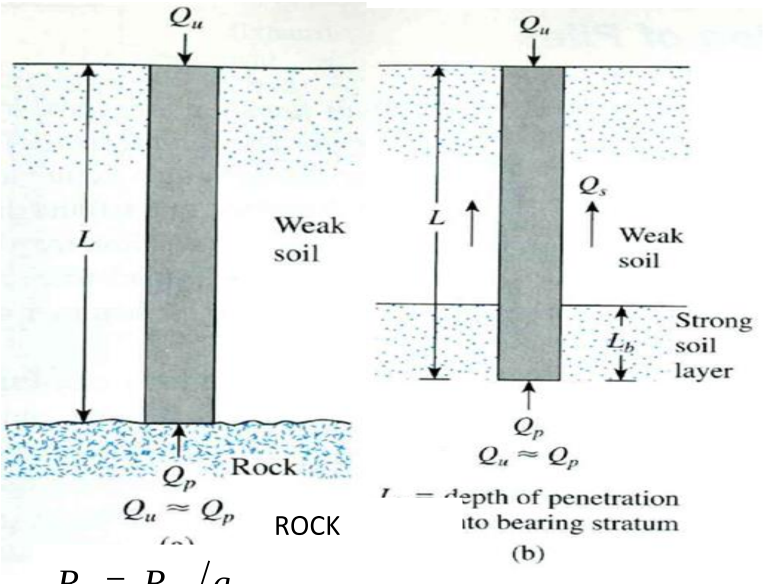
g_s = partial factors of safety on the shaft resistances

When no layer of rock or rocklike material is present at a reasonable depth at the site, point bearing piles become uneconomical. In this type of subsoil, piles are driven through the softer material to specified depths. These types of piles are called friction piles (Murthy). This is because most of their resistance is derived from skin friction.On the other hand, the applied characteristic loads Q *or* F are multiplied by factors g_F in order to establish the c*ompression design load* Q_c *or* F_c , as:

$$Q_c = F_c = g_F F = g_F Q \qquad (2\text{- }4)$$

The basic condition to fulfill for all ultimate limit states (ULS) is:

$$F_{c(ULS)} \pounds R_c \qquad (2\text{- }5)$$



$$R_c = R_{bk} / g_b$$

(a)

Figure 2- 5. The mechanisms of the load transfer to the soil piles: (a) point or end-bearing piles, (b) friction piles ((Das, 2011).

2.5.2. Load Carrying Behavior of Group of Piles

In most cases, piles are used in groups to transmit the structural load to the soil. A pile cap is constructed over group piles. Assuming the stresses transmitted by the piles to the soil will overlap as shown in

Figure 2- 6, reducing the load-bearing capacity of the piles. The number of piles in group $= n_1 \times n_2$.

Considering $L_g \geq B_g$, where:

$$L_g = (n_1 - 1)d + 2\left(D/2\right) \qquad (2\text{- }6)$$

$$B_g = (n_2 - 1)d + 2\left(D/2\right) \qquad (2\text{- }7)$$

the piles in a group should be spaced so that the load-bearing capacity of the group is not less than the sum of the bearing capacity of the individual piles. In practice, the minimum center to center pile spacing, d, is 2.5D and, in ordinary situations, is actually about 3 to 3.5D (Das, 2011).Many structural engineers use a simplified analysis to obtain the *group efficiency* for friction piles, particularly in the sand. Depending on their spacing within the group, the piles may act and fail in one of two ways:

As A Block: with dimensions $L_g \times B_g \times L$, in this case, the skin/*frictional capacity* isgiven by:

$$Q_{g(u)} \approx f_{avg} \times P_g \times L \qquad (2\text{- }8)$$

$$P_g = 2d \times (n_1 + n_2 - 2) + 4D \qquad (2\text{- }9)$$

Where: -

P_g = the perimeter of the cross-section block

f_{avg} = average unit frictional resistance.

As Individual Piles: the estimate of the failure load $Q_{g(u)}$ of a group made by n piles, each of them having a failure load $Q_{(u)}$, is based on the following equation:

$$Q_{g(u)} = \eta \times N \times Q_{(u)} \qquad (2\text{- }10)$$

$$Q_{(u)} = f_{avg} ' \; P_{pile} ' \; L \qquad (2\text{- }11)$$

$$h = \frac{Q_{g(u)}}{N ' \; Q_{(u)}} = \frac{2(n_1 + n_2 - 2)d + 4D}{f_{avg} ' \; P_{pile} ' \; L} \qquad (2\text{- }12)$$

$$Q_{g(u)} = \frac{2(n_1 + n_2 - 2)d + 4D}{f_{avg}' P_{pile}' L} (N' Q_{(u)}) \qquad (2\text{- }13)$$

$Q_{g(u)}$ = the failure load of the group

$Q_{(u)}$ = the failure load of the single pile

N = the total number of piles in the group

h = group efficiency of the load-bearing capacity of a group pile

f_{avg} = average unit frictional resistance.

For piles in granular soils and spacing s 2: 4·d, it was found that $h > 1$. AGI (1984) suggests adopting $h = 1$, except for those cases for which piles were bored without care. Concerning with piles in cohesive soils, Viggiani (1993a) suggests assuming $h = 0.6\text{-}0.7$

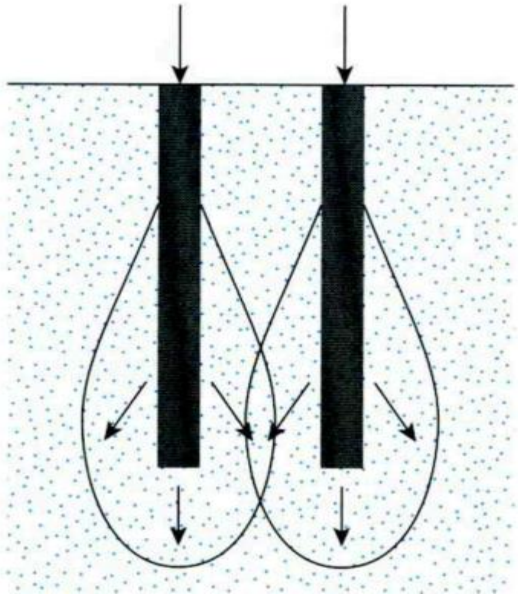
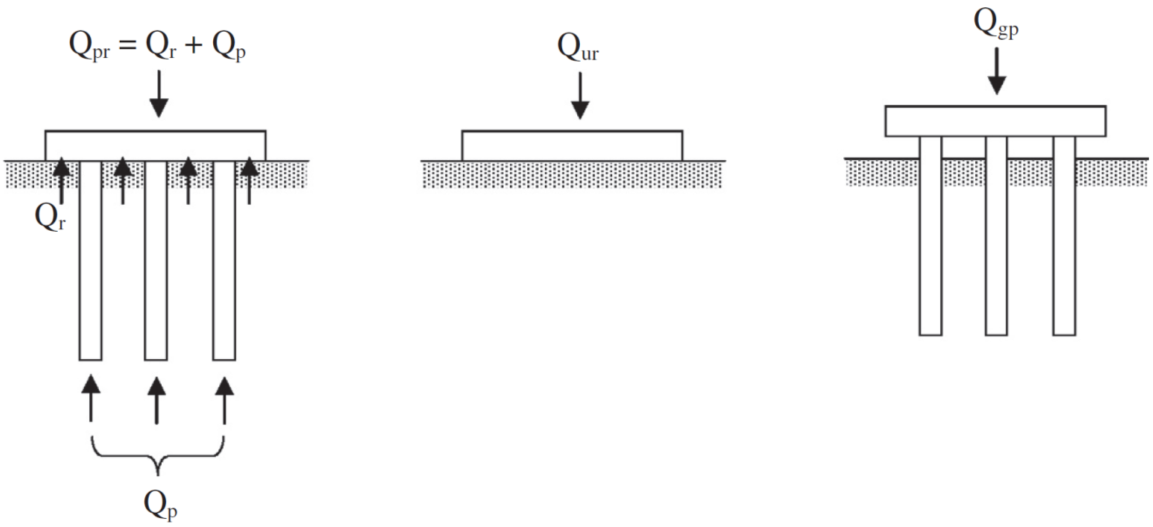


Figure 2- 6. Stress overlap between two piles

2.5.3. Load Carrying Capacity of Piled Rafts

Piled rafts represent complex load responses and load-carrying behavior due to the combined nature of different structural components and interactions between the foundation and surrounding soils. The typical configurations of the piled raft, unpiled raft, and group piles are shown in Figure 2- 7(a), (b) and (c) respectively. For group piles, pile cap is usually used and placed between the superstructure and piles. Although the pile cap is often installed in contact with the soil surface, the load-carrying capacity of the pile cap is not taken into account (Lee J. , 2014).



(a) (b) (c)

Figure 2- 7. A typical configuration of (a) piled raft; (b) unpiled raft; and (c) group piles (Lee J. , 2014)

The load-carrying capacity of piled raft can be decomposed into those of raft and piles, given as follows:

$$Q_{pr} = Q_r + Q_p \tag{2- 14}$$

Where: -

Q_{pr} = the load-carrying capacity of piled raft

Q_r = the load-carrying capacity of the raft

Q_p = the load-carrying capacity of the pile

In terms of the load-carrying capacity of the group piles and unpiled raft, the above equation can be re-written as: -

$$Q_{pr} = h_r \,'\, Q_{ur} + h_p \,'\, Q_{pg} = h_r \,'\, Q_{ur} + h_p \,'\, \left(x_g \,'\, N \,'\, Q_{sp}\right) \tag{2-15}$$

Where: -

Q_{ur} = the load-carrying capacity of the unpiled raft

Q_{gp} = the load-carrying capacity of group piles

Q_{sp} = the load-carrying capacity of single piles

Q_p = the load-carrying capacity of the pile

x_g = pile group effect factor

h_r = load capacity and efficiency factor for raft = Q_r / Q_{ur}

h_p = load capacity and efficiency factor for piles = Q_p / Q_{gp}

The factor x_g represents the pile group efficiency that is often adopted to evaluate the load capacity of group piles in the conventional pile design.The load capacity efficiency factors, h_r and h_p in equation (2-15), represent the ratios of load capacities for raft and pileswhen combinedinto the piled raft to those of unpiled raft and group piles due to theinteractions that may occur between foundation components ofpiled rafts.

For *clayey soils*, the load capacity efficiency factor for the raft can be expressed in the following equation.

$$h_r = 1- 3' \left(\frac{A_g/A_r}{S_p/D_p} \right) \tag{2- 16}$$

Where: -

A_g = the area defined by the perimeter line of piles

A_r = area of the raft

S_p = center to center pile spacing distance

D_p = pile diameter

According to equation(2- 16) h_r varies in the range 0 and 1, this variation indicates the transition from the failure of the unpiled raft (h_r = 1) to the failure of piled raft due to block failure of piles (h_r = 0).The above equation differs from the load-carrying capacities of unpiled raft and group piles because of the interactions between raft and piles when combined into the piled raft.

2.5.4. Load Sharing Behavior of Piled Rafts

The load sharing behavior of the piled raft foundation is dependent on many factors like settlement of the foundation system, the geometry of the raft and the piles and the soil condition of the ground beneath the foundation(Lutenegger, 2006; Lee M., 2014). Recommend that the settlement equal to 10% of the pile diameter or raft width shall be adopted to define the ultimate load capacity in foundation design. As settlement increased, the proportion of load carried by the raft increases and becomes larger.To fully understand the load sharing mechanism of the piled raft foundation a settlement-based load-sharing model proposed by (Lee J. , 2014) is briefly discussed below.

The load sharing behavior of the piled raft system can be described using the load sharing ratio, a_p which represents the ratio of the load carried by piles to the total load imposed on the piled raft as indicated in equation (2- 17).

$$a_p = \frac{Q_p}{Q_{pr}} = \frac{Q_p}{Q_r + Q_p} = 1 - \frac{Q_r}{Q_{pr}} \qquad (2\text{- }17)$$

Horikoshi K, (1996) conducted the centrifuge tests and presented the values of α_p for flexible foundations with different numbers of piles. It was observed that α_p decreases with increasing load level and this load sharing parameter less decreases as the number of piles increases. This indicates that as the settlement increases the load shared by the piles' decreases, which indicates in the increment of the load shared by the raft in piled raft foundation system(Horikoshi K, 1996).

2.5.5. Normalized Load – Settlement Relationship

The load-settlement responses of foundations are non-linear as a result of the non-linear stress-strain behavior of soils. As elaborated by Lee J., (2014),the hyperbolic types of load–settlement relationship has long been used to describe the non-linear load responses of foundations.

The nonlinear load-settlement relationship can be defined as:

$$Q = \frac{S}{a + b + s} \qquad (2\text{- }18)$$

Where:- Q = load s = settlement; and a and b arehyperbolic parameters.

To adjust the difference in geometrical and mechanical characteristics of raft and piles, the normalized load–settlement relationship was introduced in terms of relative settlement and load, normalized with foundation size and ultimate load capacity, respectively.Hence for rafts, when equation (2- 19) is normalized with ultimate load capacity and raft width, the following normalized relationship is obtained:

$$\frac{Q_r}{Q_{r,u}} = \frac{s/B_r}{a_r + b_r\left(s/B_r\right)} \tag{2- 19}$$

Where:

Q_r = load imposed on raft

$Q_{r,u}$ = the ultimate load capacity of the raft

s = settlement

B_r = raft width

a_r, b_r = model parameters for the normalized hyperbolic load settlement relationship of the raft

In a similar manner, the normalized load-settlement relationship for piles can be described as in equation (2-20):

$$\frac{Q_p}{Q_{p,u}} = \frac{s/D_P}{a_p + b_P\left(s/D_P\right)} \tag{2-20}$$

Where:

Q_P = load imposed on piles

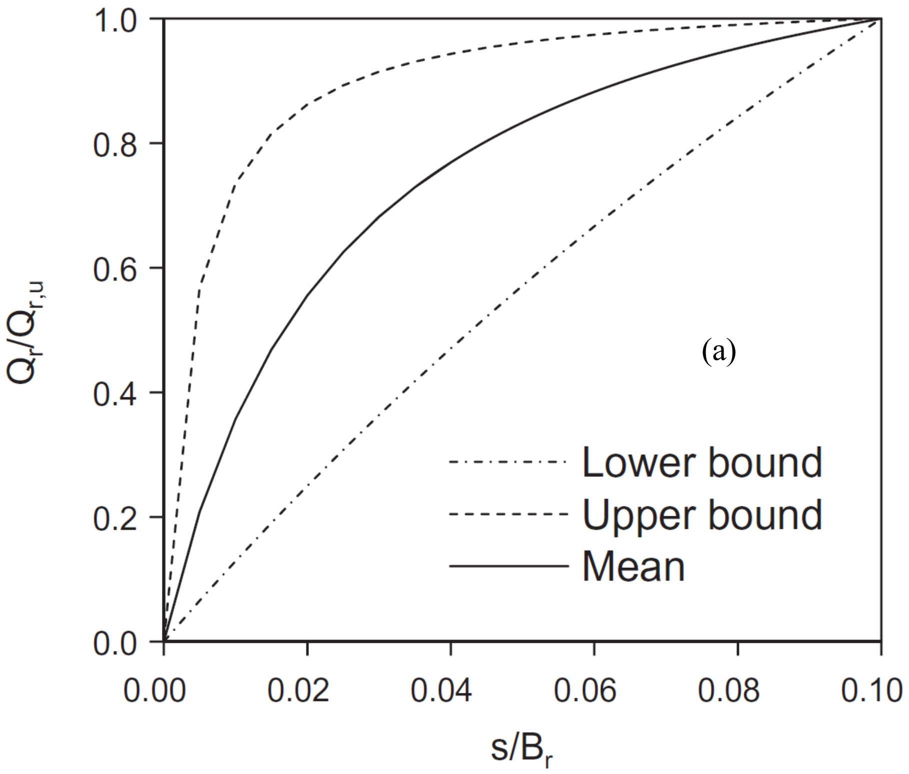
$Q_{P,u}$ = the ultimate load capacity of piles

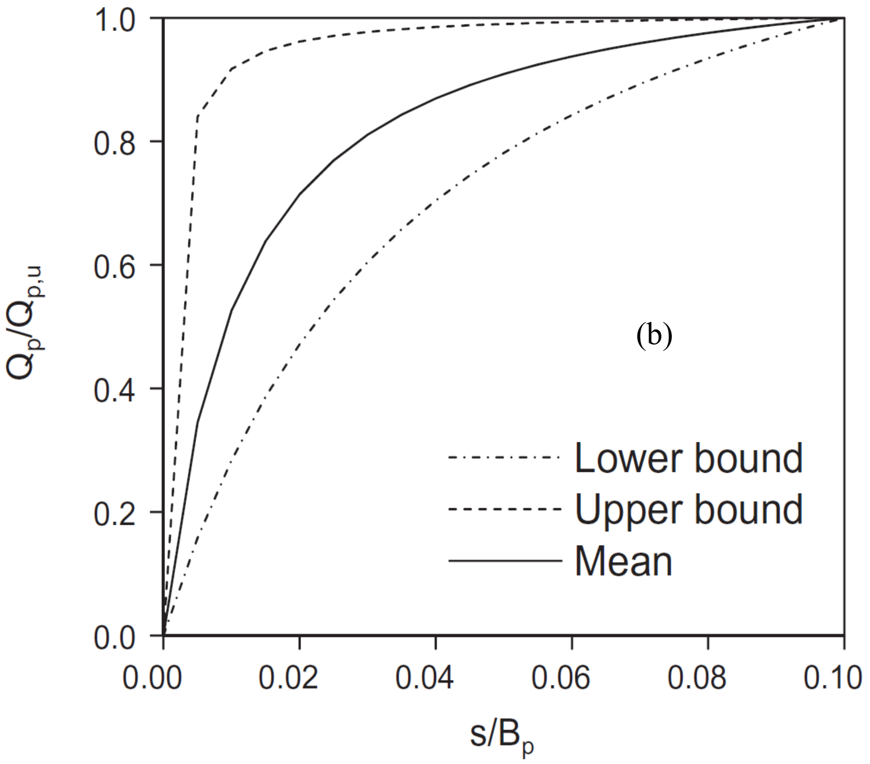
s = settlement

B_r = pile diameter

a_r, b_r = model parameters for the normalized hyperbolic load settlementrelationship for piles.

Equation (2- 19)and(2-20)areflexible applicability to the various foundation and soil conditions, owing to the characteristics of the normalized formulations.Once normalized, the effects of local soil conditions and changes in geometrical and mechanical conditions of foundation can be minimized as those are already included in the normalization process through the ultimate load capacity and foundation size. The original hyperbolic parameters, a and b in equation (2- 18), represent different values for different foundation and soil conditions. The normalized model parameters, a_r, b_r, a_p and b_p, however, can be regarded unique as the model was derived in normalized terms.Hence after the derivation performed by (Lee J. , 2014) the value for these normalized model parameters, a_r, b_r, a_p *and* b_p are found to be 0.02, 0.8, 0.01, and 0.9, respectively.





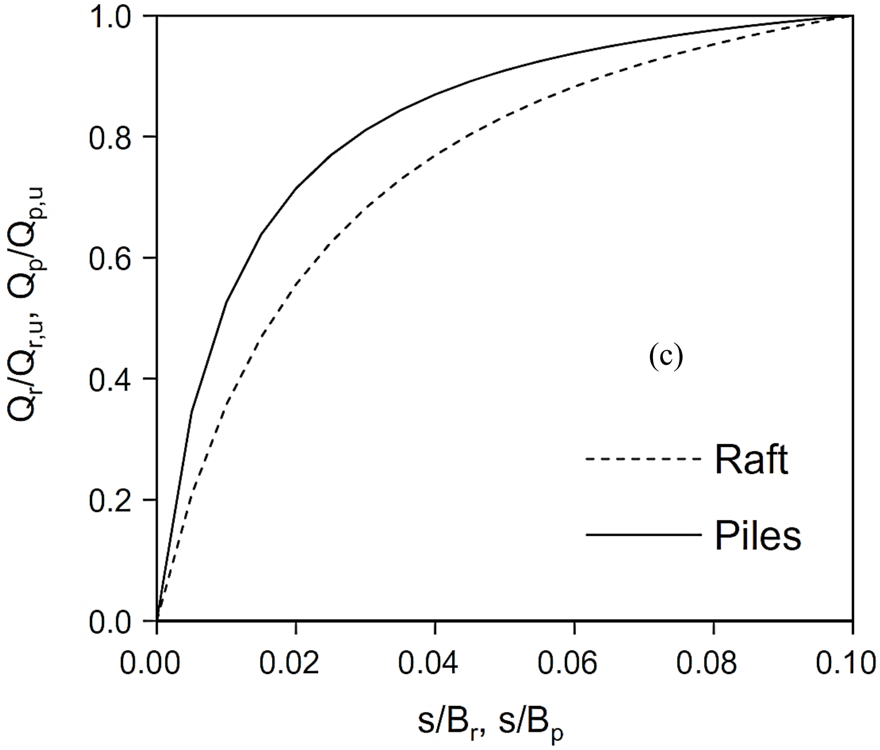


Figure 2- 8: Normalized load–settlement curves of (a) raft; (b) piles; and (c) raft and piles.

The normalized hyperbolic load-settlement curves using equation (2- 19) and (2-20) for raft and piles were plotted as shown in Figure2-8. The values of $Q_r/Q_{r,u}$ and $Q_p/Q_{p,u}$ both vary from 0 to 1 for the range of normalized settlements of s/B_r and s/D_p from 0 to 0.1.

2.6. CENTRIFUGE LOAD TESTS

The purpose of geotechnical centrifuge modeling is to simulate the soil and the piled raft system in a laboratory. Different authors performed a series of centrifuge model tests on group piles to obtain an overview of how the behavior of a soil-pile system is affected by the difference in fundamental conditions, such as single or group pile condition, or under static and dynamic condition (i.e. Shaking table tests). (Tobita.H, 2004).

To check the validity of his proposed normalized load-sharing model of piled rafts.Lee J., (2014)conducted centrifuge load tests using various model foundations as shown in Figure 2- 9. (Lee J. , 2014).

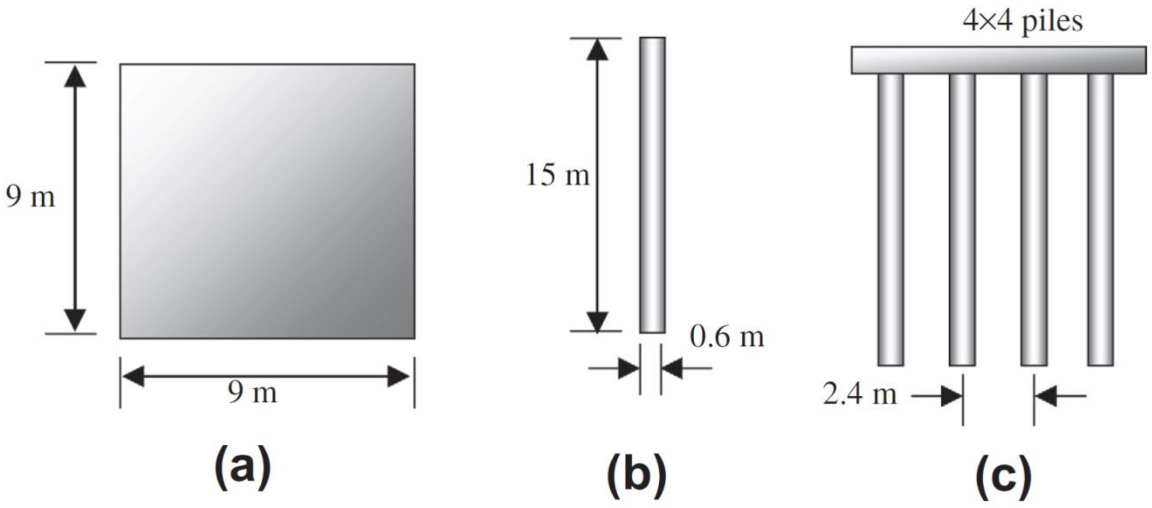


Figure 2- 9: Model foundations used in centrifuge load tests: (a) Unpiled Raft; (b) Single Pile; and (c) Piled Raft.

The geometric dimension of the prototype of piled raft foundation system which evaluated in the centrifuge test as shown in the Figure 2-9 was; diameter of the pile, $D_{pile} =$ 0.6m, Length of pile was 15m, number of piles were 16 piles with 4 by 4 configurations with pile spacing distance of 2.4m corresponding to 4 times pile diameter of 0.6m (i.e., $4D_p$). the raft was square-shaped raft with width and thickness of 9m and 0.5mm respectively as shown in Figure 2-9.

Table 2- 1The geometric parameters used in the centrifuge test (prototype scale).

Diameter ofthe pile, D_{pile} in m	Raftthickness (t)	Length of Pile (Lp), m	Number of Piles (n)
0.6	0.5	15	16

The *load–settlement curves* obtained for the model foundations of the unpiled raft, group piles, and piled raft in stiff clay specimens are shown in Figure 2-10.

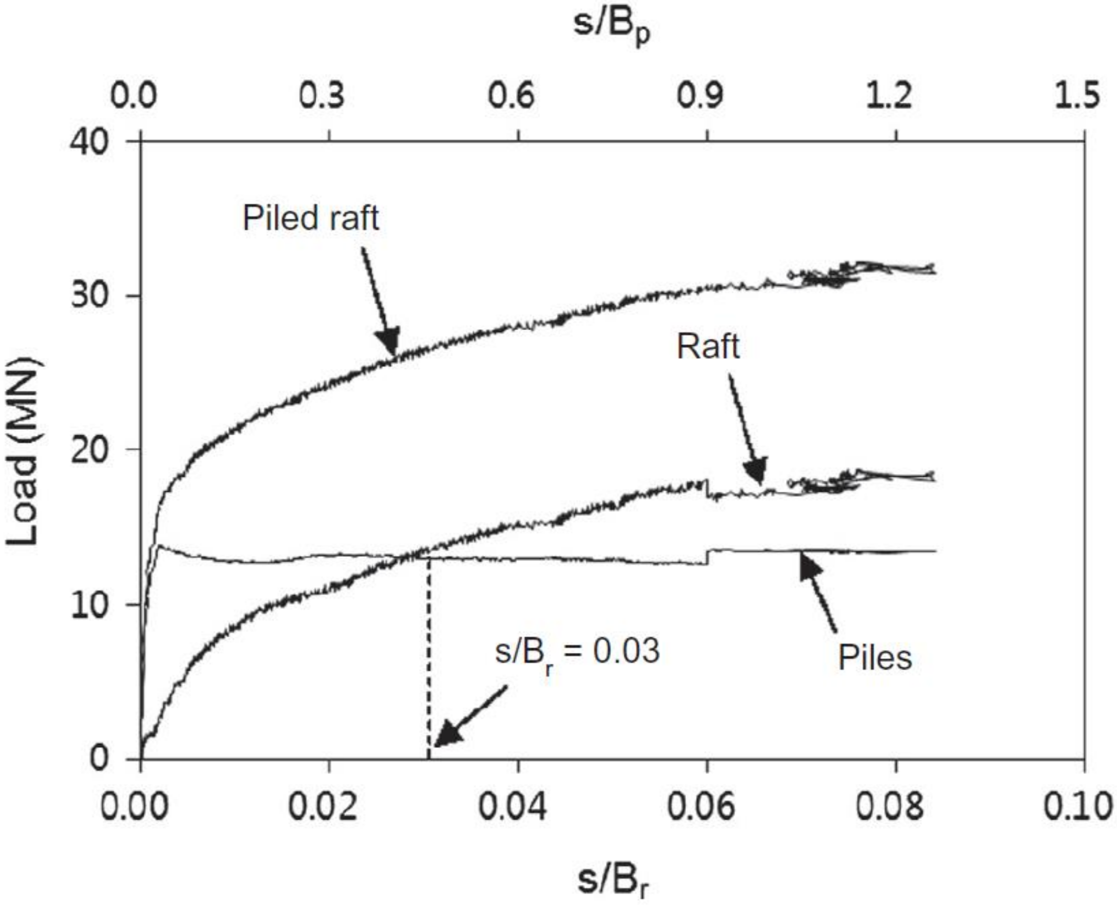


Figure 2- 10Load–settlement curves of piled rafts on stiff clays (Lee J. , 2014)

2.7. PARAMETRIC STUDY

2.7.1. Factors Affecting CPRF

The study of this complex three-dimensional foundation involves a number of geometrical, mechanical and bi-product parameters.The geometrical parameters are related to pile geometry (e.g. pile length, pile diameter, pile spacing&a number of piles) and raft geometry (i.e. raft length, breadth, and thickness).Whereas, the mechanical properties include the soil properties (e.g *modulus of elasticity, Poisson's ratio,etc*.) and the bi-product parameters can include the various interaction factors (e.g. pile-raft, pile-soil, raft-soil, and vice versa) and other derived parameters(Anup S., 2013).

2.7.2. Raft Geometry

2.7.2.1.Raft Thickness

Thin or flexible rafts tend to deform more than rigid or thick rafts; due to this excessive deformation, the flexible raft establishes much more deformation in the subsoil which leads to more load transferred by the raft and this will induce higher reaction force.According to (Alnuaim, 2013)The stiffness of the raft is given by:

$$k_f = \left[\frac{E_f}{E_s}\right]\left[\frac{2t}{s}\right]^3 \qquad (2\text{- }21)$$

Where:

k_f = stiffness of the raft

E_f = young's modulus for the raft

E_s = average soil elastic modulus

t = raft thickness; and

s = spacing between piles

Based on Alnuaim, (2013),the raft can be categorized as: - (i) *Perfectly Rigid*if $k_f > 10$; (ii) *Perfectly Flexible*when $k_f < 0.01$; and (iii) *Intermediate Flexibility*if k_f varies between 0.01 to 10using equation (2- 21).In this study using centrifuge tests, presents the results as the load carried by the raft for two different pile spacing with various raft thicknesses as a function of the piled raft total displacement.The variation in the load carried by the raft was very noticeable at pile spacing to diameter ratio=4 as the load carried by the raft was about 65% and 55% for the t= 0.3 m and t= 2 m respectively.

This is due to a high difference in k_f which was about 0.05 and 2.2 for the t= 0.3 m and t= 2 m respectively. On the other hand, k_f it was very close in the case of pile spacing to diameter ratio =10which is about 0.004 and 0.07 for the t= 0.3 m and t= 1.25 m respectively. Therefore, the variation in the load carried by the raft was very *narrow* at about 75%. This is because, at large spacing, the thick raft is more flexible, which produces much raft soil interaction, compared to the similar raft with less pile spacing.

2.7.2.2.Raft Dimension Ratio (L/B)

Bui M. et.al., (2013) changed the raft dimension ratio (L/B) from 1 to 3, by keeping B constant and the number of piles changed from 3x3 to 3x9. The normalized settlement increased sharply with L/B ratio when the imposed superstructure loadsup to 600kN/m^2 as shown in Figure 2-11.

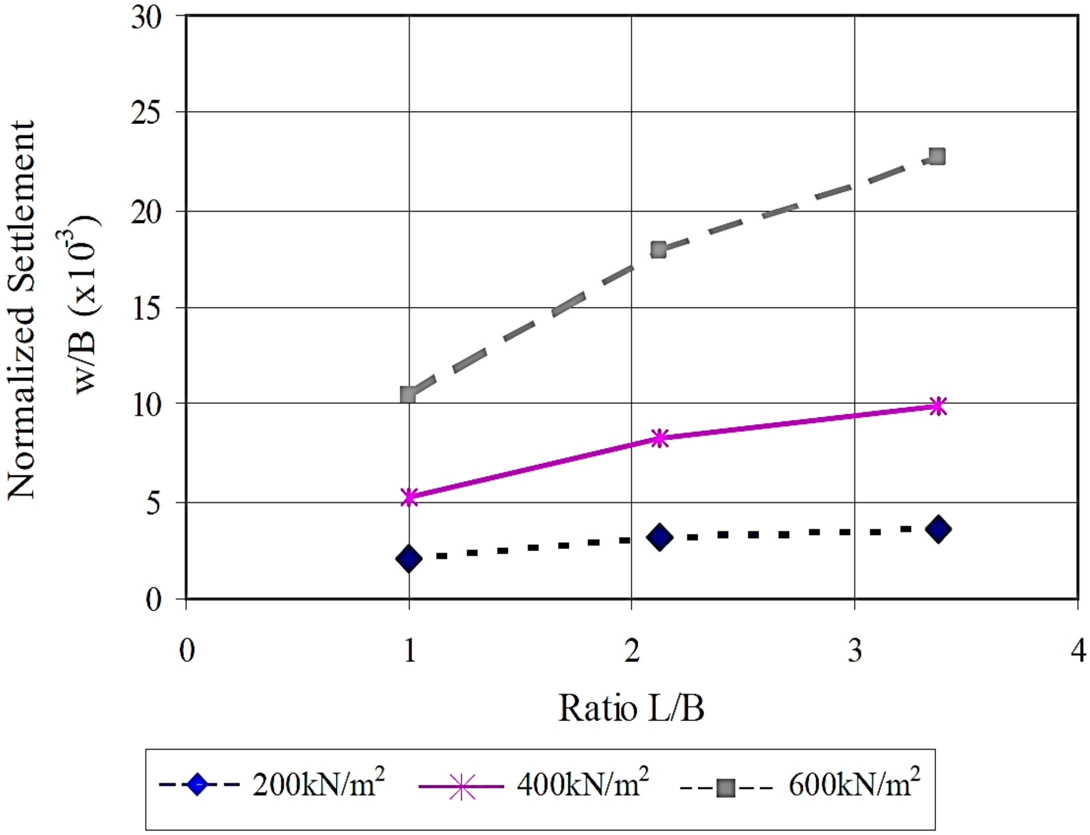


Figure 2- 11: Normalized settlement vs raft dimension ratio (Bui M. et.al., 2013)

2.7.2.3.Influence of Pile Spacing

Alnuaim, (2013) expressed that the piled raft with small pile spacing will not experience a large deformation at the center of the raft compared to the piled raft with large pile spacing.Erwin, (2014)analyzed a 3x3 group piles with a pile spacing variation of 3d, 4d, 5d, and 6d using a constant pile length of 18m and a diameter of the pile at 0.8m. it was observed that as the pile spacing increases, the settlement increases, it was recommended a pile spacing of 2d-3d for future researchers.Maharaj, (2004)have said that it affects greatly the maximum settlement, the differential settlement, the bending moment in the raft, and the load shared by the piles.Referring to Figure 2-12, Lee J., (2015) showedthat the load-carrying capacities of the individual piles of the piled raft foundation increase as the center to center spacing of the pile's increases. when the pile spacing increases, the load-carrying capacity of the piled raft foundation decreases, indicating that the proportion of load taken by piles becomes higher.

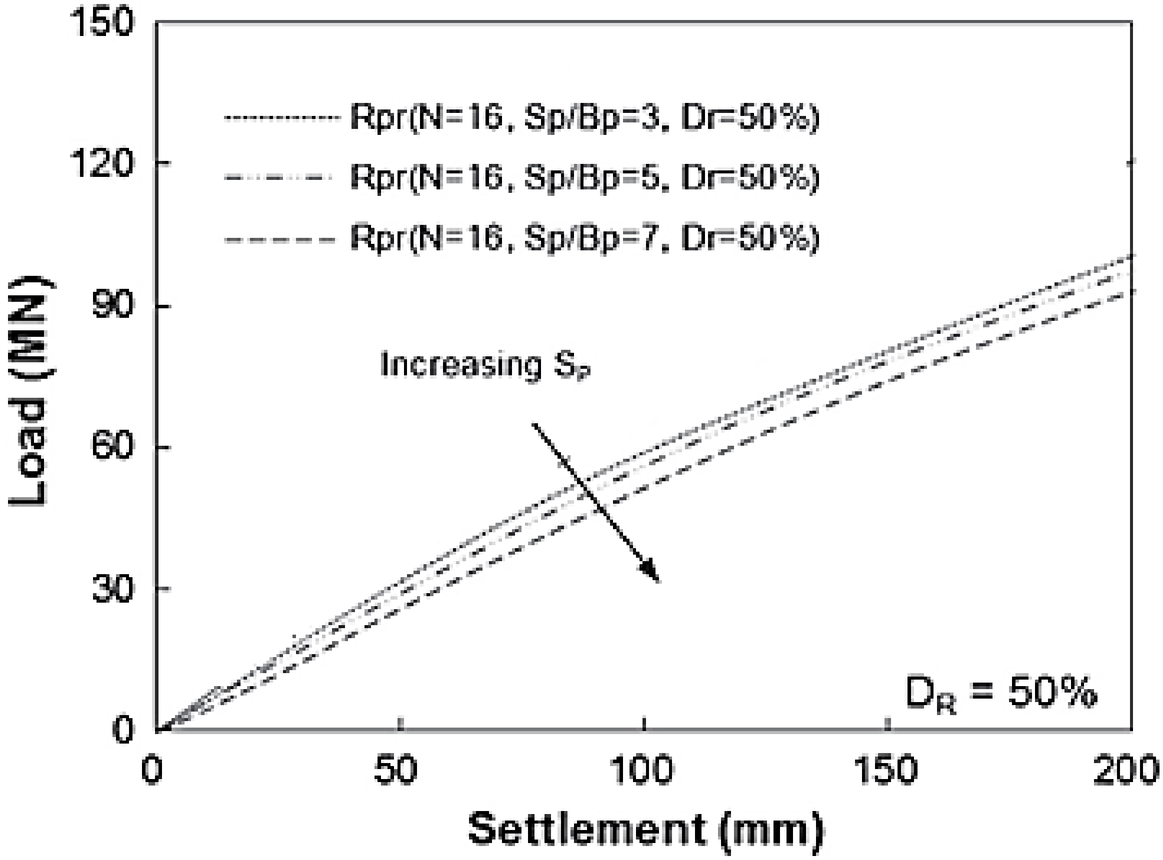


Figure 2- 12: Decomposed load–settlement curves of the piled raft with different pile spacing (Lee J. , 2015)

Lee J., (2015) presented Figure 2-13, which shows the stress fields within soils upon loading on piled rafts. The stress fields around piles increasingly overlap as pile spacing decreases, which tends to produce reductions in the load-carrying capacity of piles. In the study of Samee, (2018), an experimental program and theoretical analysis by finite element were conducted to study the effect of pile spacing on ultimate capacity and load shearing for non-rested and directly rested piled raft foundation on the soil. The spacing between piles (center to center) was 2, 3, 4, 5, 6 and 7 pile diameters. The obtained results showed that the ultimate capacities increase with increasing the spacing of piles in case ofpile cap directly rested on the soil. However, in case of pile cap non-rested on soil, the ultimate capacities after pile spacing more than four the diameter decreases with increasing the spacing of piles.

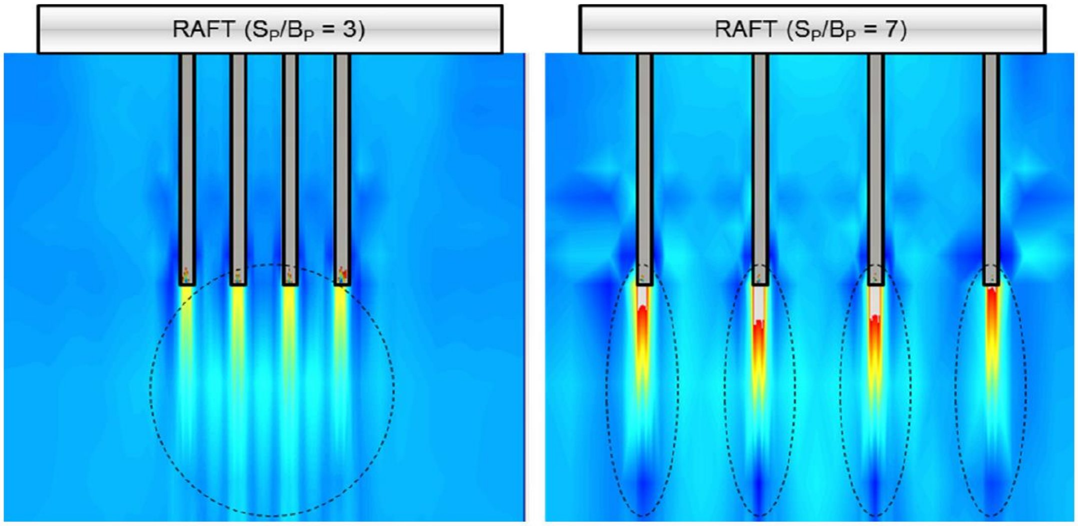


Figure 2- 13: Stress fields within soils for piled rafts with different pile spacing conditions from finite element analysis. (Lee J. , 2015)

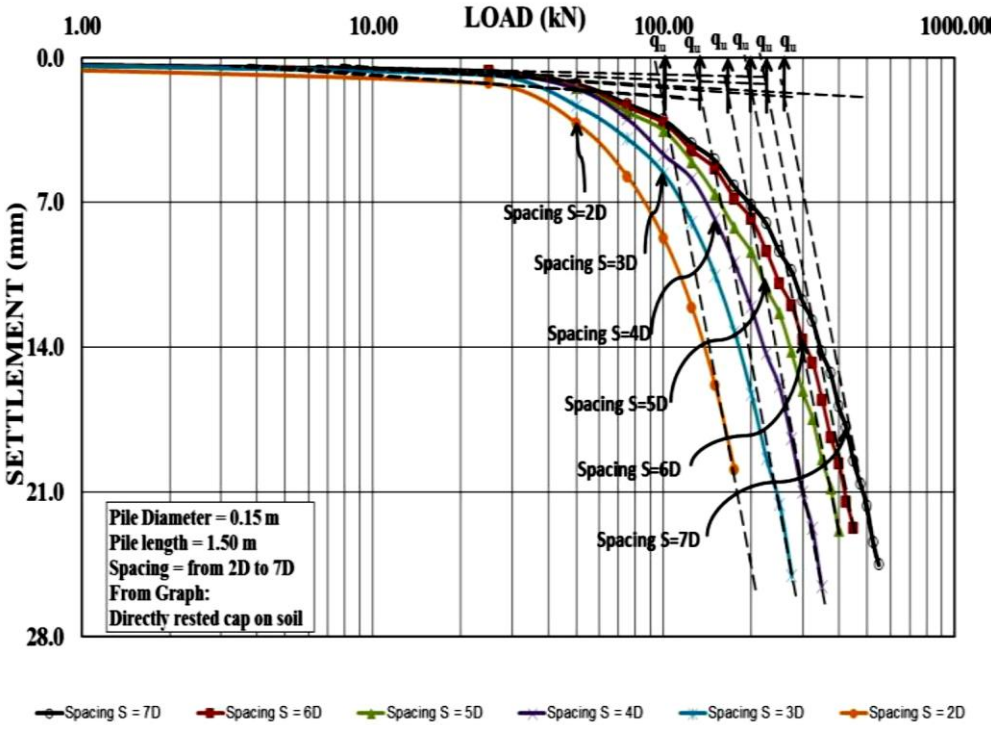


Figure 2- 14: Settlement vs load for different pile spacing (Samee, 2018)

In addition, in case of pile cap non-rested on soil the transferred loads to soil around pile shaft (friction) increase with increasing the spacing of piles. However, in the case of

Pile-Cap directly rested on soil the load transferred to soil by friction increase with increase spacing between piles up to spacing 4 times the pile diameter, after which the values of load transferred to soil by friction decrease with increasing the spacing between piles. Figure 2-14 shows settlement versus the imposed load of the piled raft foundation with specified different pile spacing.

2.7.2.4.Influence of Pile length

Kumar, (2018) observed that the non-uniform length of piles in a piled raft foundation can perform well, serving all the settlement criteria. The proper arrangement of piles in a piled raft configuration was also required under the application of the non-uniform loading of a typical high-rise building. So, the variation of pile length i.e. using non-uniform pile length in the proper arrangement in a piled raft configuration can satisfy the design aspects of the foundation and able to reduce the overall cost of the foundation.

Considering a 0.5m thick raft with 9 piles Imple, (2001)analyzed the effect of varying pile length on the differential and maximum settlement of the specified piled raft foundation system. Figure 2- 15shows the effect of varying the pile length on the maximum settlement, the differential settlement between the center and outer piles, the maximum moment in the raft, and the proportion of load carried by the piles. The analyses have been carried out using the *GARP* program. As would be expected, the settlement, differential settlement and maximum moment all decrease with increasing pile length, while the proportion of load carried by the pile's increases.in this study, it was concluded that increasing the length of the piles isa more effective design strategy for improving foundation performance than increasing the number of piles.

Gopinath, (2010) studied the effect of pile length on the piled raft for the settlement of raft for three different lengths of piles as 6m, 9m, and 12m. In this analysis, the raft thickness was 1m and the spacing between the piles was taken as 2m. The pile diameter was taken as 0.3m for all pile lengths. Allowable load intensity of 90kN/m^2, 150kN/m^2 and 240kN/m^2 was applied for pile groups of length 6m, 9m, and 12m, respectively. The effect of length of the pile on the settlement of piled raft under allowable load is shown in Figure 2-16It can be seen that the overall settlement of the foundation increased as the pile length was increased. However, the differential settlement was still observed to negligible. The load-deformation curves up to failure for different pile lengths were also observed. The load applied was much higher than the allowable load. From Figure 2-17, it can be observed that with the increase in the length of the piles, the load is taken by the foundation also increases.

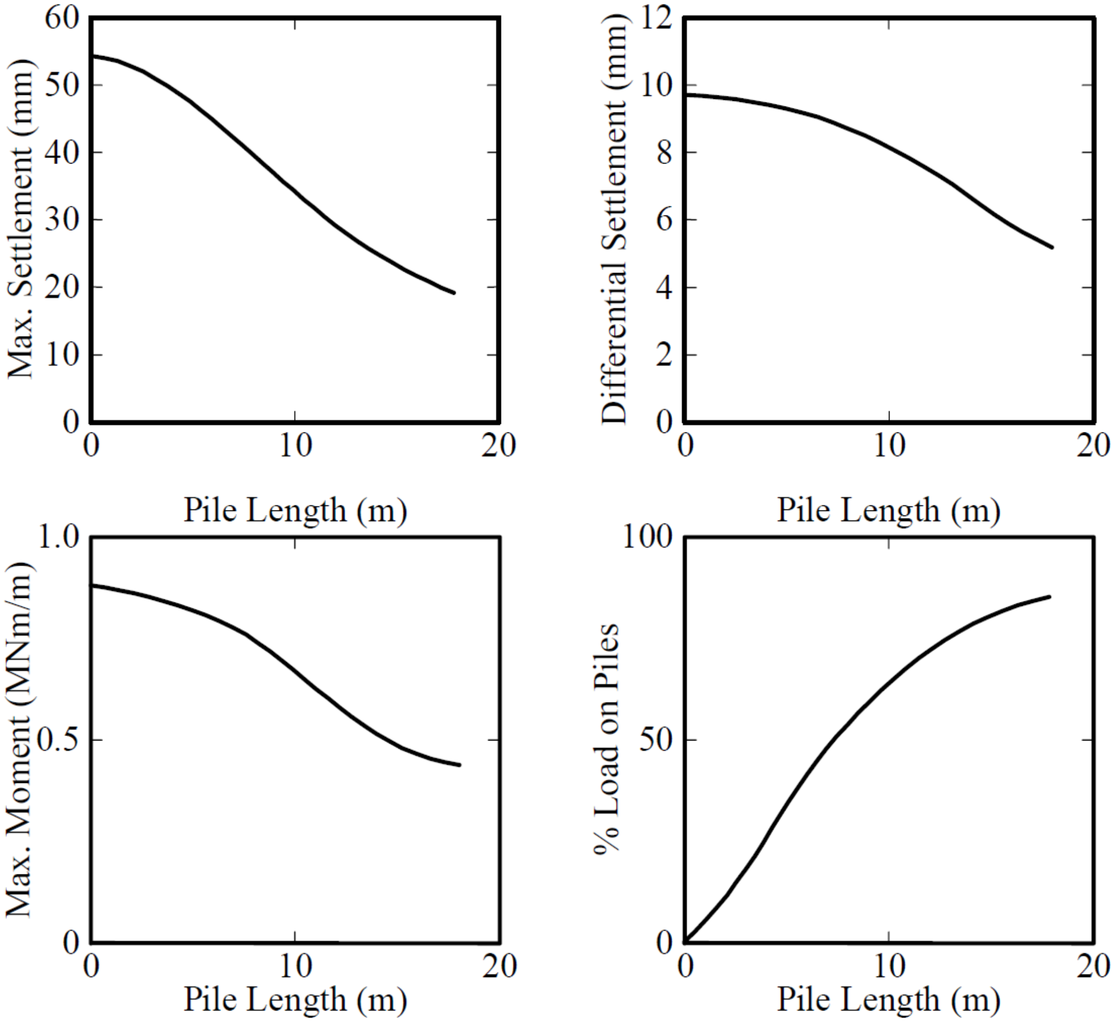


Figure 2- 15: Effect of pile length on foundation performance 0.5m raft with 9 piles, load = 12 MN (Imple, 2001).

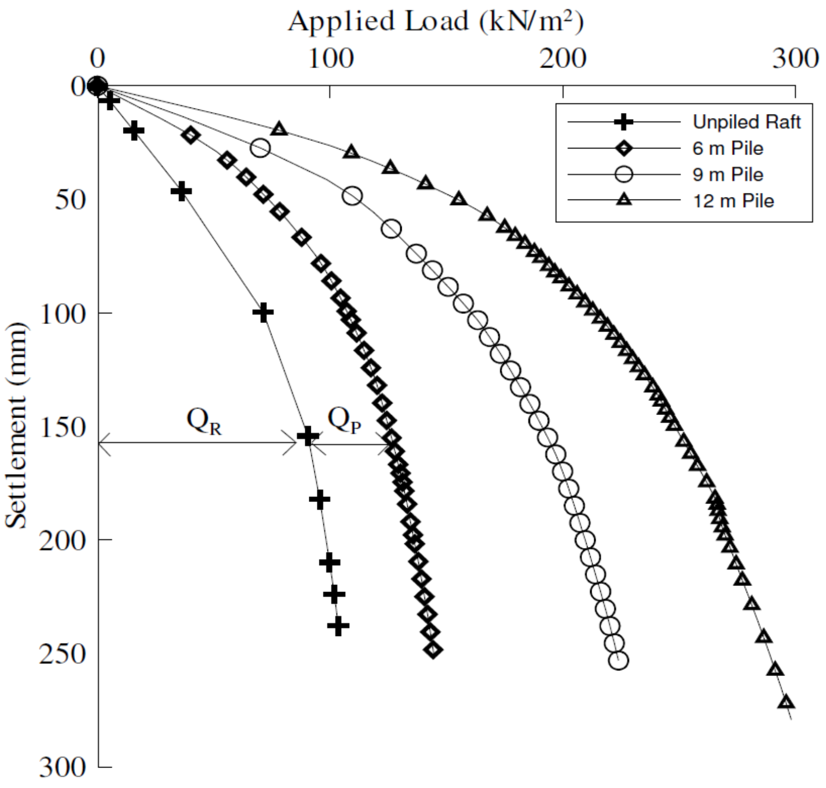


Figure 2- 16: Load settlement curve for different pile lengths (Gopinath, 2010)

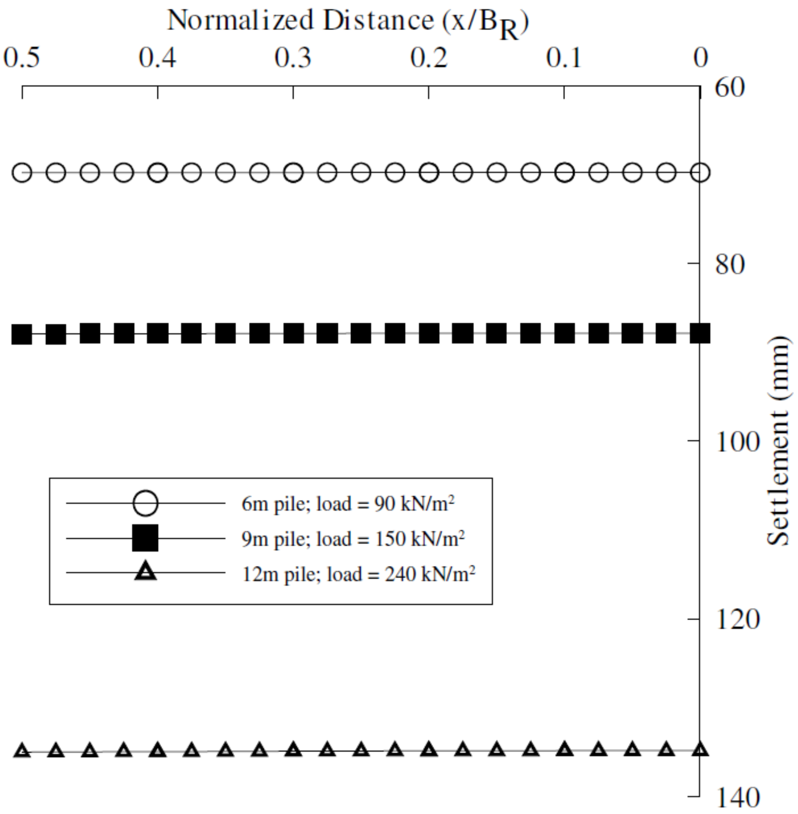


Figure 2- 17: Effect of Pile Length on Settlement of Piled Raft (Gopinath, 2010).

(Gebregziabher and Katzenbach, 2012) performed a number of three dimensional FEM non linear analyses on four-layered subsoil conditions of the West-African city legos. According to this research, by varying the uniform length of 63 piles, the decrease in the maximum settlement of the raft with increasing pile length is substantial at lower pile length ranges (L_p< 25 m) and gradual otherwise (L_p> 30 m), becoming invariant for very long piles as shown in the figure 2-18.

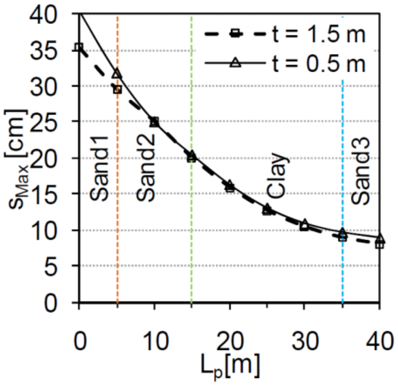


Figure 2- 18: Pile length vs maximum raft settlement (Gebregziabher and Katzenbach, 2012)

2.7.2.5. *Influence number of piles*

One of the important uses of a piled raft analysis is to assess how many piles are required to achieve the desired performance.Bui M. et.al., (2013)analyzed a piled raft with 3x3, 4x4 and 5x5 piles. The increase in the number of piles had little effect on normalized settlements. The effects were more pronounced at higher values of the imposed load when the number of piles increased from 9 to 16 piles as shown in Figure 2-19.

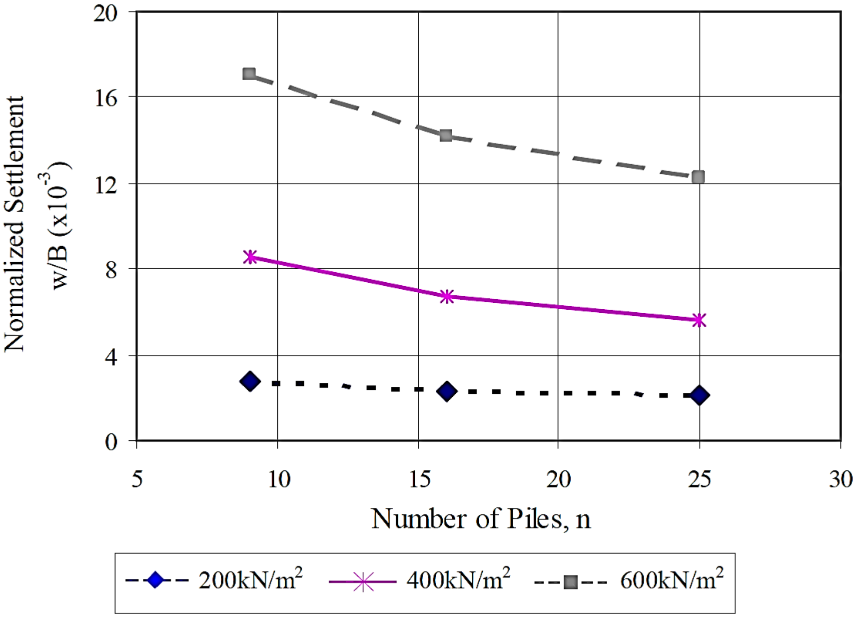
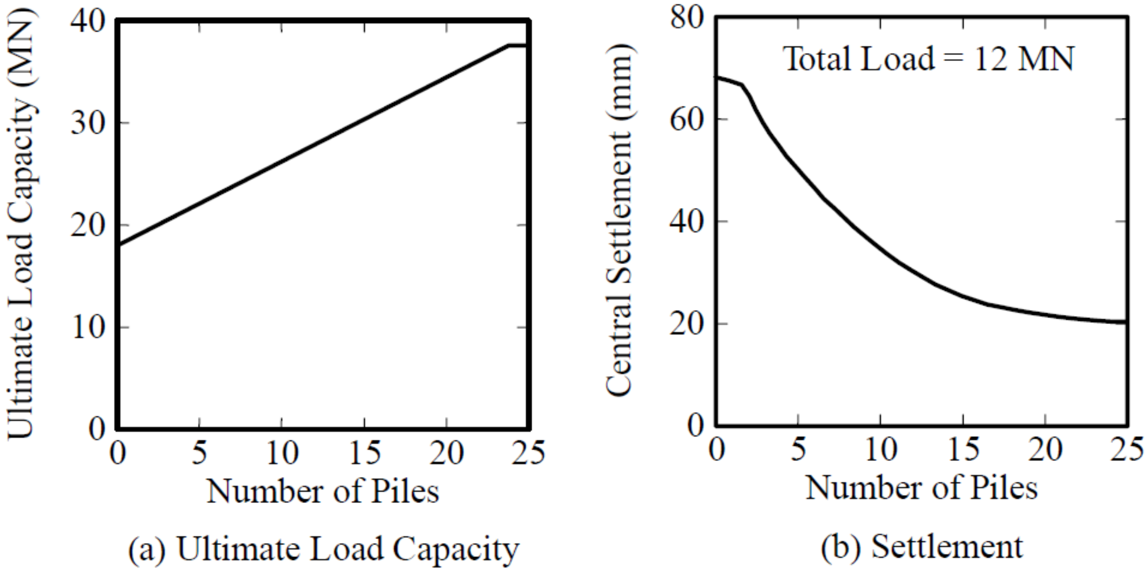


Figure 2- 19: Normalized Settlement vs the number of piles (Bui M. et.al., 2013)

Imple (2001)performed a parametric study by considering the number of piles. In this study, the addition of relatively few piles have a significant effect in reducing the settlement of the raft, but beyond about 15 piles, the additional reduction in the settlement is very small. Clearly then, there is scope for the economy in foundation design by carrying out analyses to assess the minimum number of piles to achieve the required settlement performance.

Figure 2-20 summarizes the relationship between central settlement and number of piles (as obtained from the simplified analysis usingthe PDR analysis method (Poulos-Davis-Randolph analysis) for a load of 12 MN), and the ultimate load capacity and the number of piles. Poulos, (2001) analyzed the effect of the number of piles on the performance of piled raft foundations. It was noted that the maximum settlement decreases with the increasing number of piles, but becomes almost constant for 20 or more piles. It was also observed that for the small number of piles, the maximum settlement for concentrated loading is larger than for uniform loading but the difference becomes less for 10 or more piles.



(a) Ultimate Load Capacity

(b) Settlement

Figure 2- 20: Effect of the number of piles on the ultimate load capacity and settlement. (Poulos, 2001)

In addition, *the percentage of the load carried by the piles increases with increasing pile numbers, but for more than about 15 piles the rate of increase is very small*. Hence, increasing the number of piles, while generally benefit, does not always produce the best foundation performance, and there is an upper limit to the number of piles, beyond which very little additional benefit is obtained.

In conclusion, as mentioned by the aforementioned authors, piled raft foundation offers some advantages such as reducing settlement and increasing the bearing capacity of the foundations. Such advantages can be assessed by varying different parameters of the piled raft foundation system. To study the effect of these parameters on the maximum settlement of piled raft foundation, the finite element method analyses could be carried out and for verification purpose, the results of the finite element method could be compared with the results of other researcher performed on centrifuge tests. With the results obtained, the optimal parameters could be assessed.

Chapter - 3

Development of Finite Element Numerical Modelin ABAQUS

3.1. INTRODUCTION

3.1.1. General

As mentioned in the literature review,the analysis of piled raft foundations geotechnical stability is a complex process. To analyze the interaction between the foundation system and the soil media more accurately and efficiently, it is essential to simulate this complex foundation system and interaction using 3D finite element method-based software. The aim of this chapter is to develop and validate a computationally simple i.e. the efforts and the time will be less, 3D FEM numerical model of the piled raft foundation in clayey soils. To this end, a series of three-dimensional numerical analyses were performed using the ABAQUS CEA/2017 finite element software.

3.1.2. The 3D FEM Numerical Modeling Process

In the design process of the piled rafts, the initial stages of design involve the determination of the optimum number of piles, pile length, and diameter required to be placed in a strategic manner to produce the required settlement reduction along with the load shared by the pile group/raft. This process may require a large number of trials depending on nature and requirement. Hence the analytical procedure has to be computationally simple so that the efforts and the time will be less. The existing methods although produce satisfactory results involve more complicated computational efforts. Further in solving the complicated three-dimensional problems such as piled raft, many simplified assumptions are to be made and the rigorousness of the method may have to be diluted to make the problem computationally viable. Therefore, there is a need for a simple method that can be solved by treating the problem as an axisymmetric or plane strain problem in the case of preliminary design to establish parameters like pile length, numbers diameter, and the layout to be used in the final design.

The development of the FEM numerical model in this study, however,consisted of *three main steps*. First, a 3D FEM was established to simulate the behavior of piled raft foundation considering an appropriate size mesh and number of elements. Second, the results of a centrifuge study of piled raft performed by others were used to calibrate the FEM created in this study. The results obtained were compared with *centrifuge test results* performed by Lee Junhwan (2014). Lastly, the calibrated FEM numerical model was employed to perform a parametric study to evaluate the effect of different parameters on the overall performance of piled raft foundation. A number of parameters were selected from the elements of the piled raft system. According to their effect on the response of the piled raft system, some were taken to be constant while others are varied. Among the varied parameters, *raft thickness, pile length to diameter ratio, pile spacing, and pile number* were considered.To develop the 3D FEM numerical model,the *shape of the pile used, the extent of stress influence zone along with the three directions, the influence of step time increments and stress applications, and the number of finite elements used in the model*wastaken into consideration first.

3.1.3. Constitutive Model of the Continuum

3.1.3.1.Mohr-Coulomb Constitutive Model for Soil

The Mohr-Coulomb model is one of the basic constitutive models provided in ABAQUS CEA/2017, and it belongs to the plastic model group. The models in the plastic model group are characterized by their yield function, hardening/softening functions, and flow rule. In particular, the yield function and flow rule are addressed in the Mohr-Coulomb model, while the hardening/softening functions are not included. The yield function determines the stress condition for which plastic flow takes place. An incremental elastic or plastic behavior is determined by the stress condition below or on the yield surfaces in a generalized stress space, respectively. The main difference between elastic response and plastic response is that plastic flow will be irreversible. The plastic flow formulation in ABAQUS CEA/2017 is based on the assumption that the total strain increment is the sum of elastic and plastic strains. The elastic strain increment is governed by elastic relations and stress increment.

The Mohr-Coulomb failure or strength criterion has been widely used for geotechnicalapplications. Indeed, a large number of routine design calculations in the geotechnical area are still performed using the Mohr-Coulomb criterion. The Mohr-Coulomb criterion assumes that failure is controlled by the maximum shear stress and that this failure shear stress depends on the normal stress. This can be represented by plotting Mohr's circle for states of stress at failure in terms of the maximum and minimum principal stresses. The Mohr-Coulomb failure line is the best straight line that touches es these Mohr's circles (Figure 3-1). Thus, the Mohr-Coulomb criterion can be written as The implementation of the incremental formulation is discussed in detail in the ABAQUS CEA/2017 Constitutive Model Manual. Following the principal stress ordering (i.e.$\sigma_1 \leq \sigma_2 \leq \sigma_3$,), the Mohr-Coulomb failure envelope in the $\tau - \sigma$space is shown in

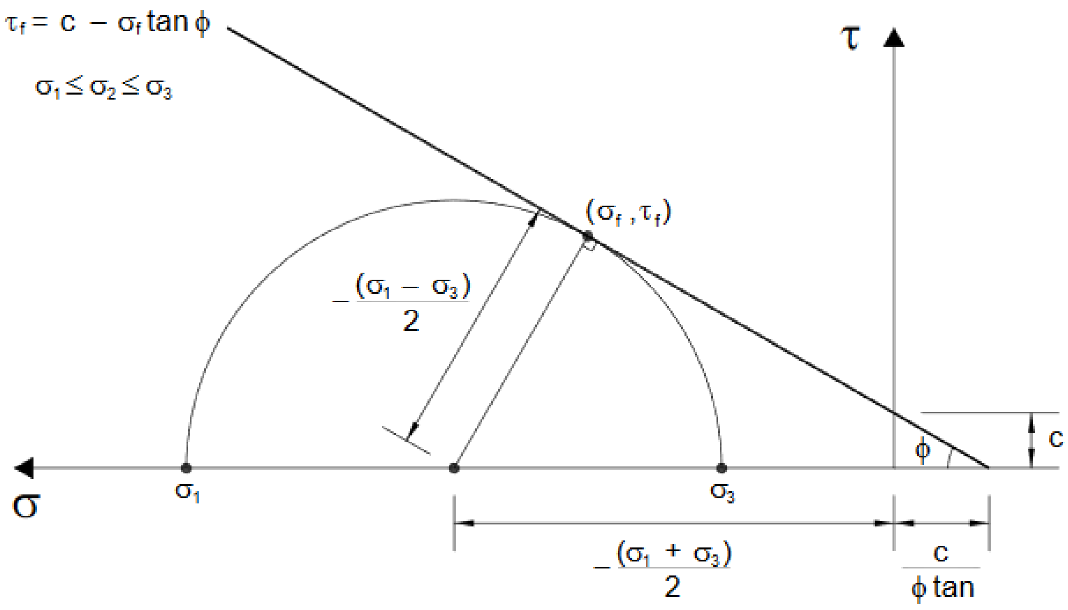


Figure 3- 1: The Mohr-Coulomb failure envelope in space

Figure 3-1. The shear strength (τ_f) of a soil mass at a point on a particular plane is expressed as a linear function of normal stress (σ_f) at the same point on the same plane as:

$$\tau_f = c - \sigma_f \tan \emptyset \qquad [3\text{- }1]$$

where τ is the shear stress, σ is the normal stress (negative in compression), c is the cohesion of the material, and ϕ is the material angle of friction. The relationship between principal stresses at failure and the shear strength parameters can be obtained as:

$$\sin \emptyset = \left\{ \frac{-\frac{1}{2}(\sigma_1 - \sigma_3)}{-\frac{1}{2}(\sigma_1 + \sigma_3) + \frac{c}{\tan \emptyset}} \right\} \qquad [3\text{- }2]$$

Therefore

$$\sigma_3 \left[\frac{1 + \sin \emptyset}{2c \cos \emptyset}\right] - \sigma_1 \left[\frac{1 - \sin \emptyset}{2c \cos \emptyset}\right] = 1 \qquad [3\text{- }3]$$

Or

$$\sigma_1 = \sigma_3 \left[\frac{1 + \sin \emptyset}{1 - \sin \emptyset}\right] - 2c \left[\frac{\cos \emptyset}{1 - \sin \emptyset}\right] = 1 \qquad [3\text{- }4]$$

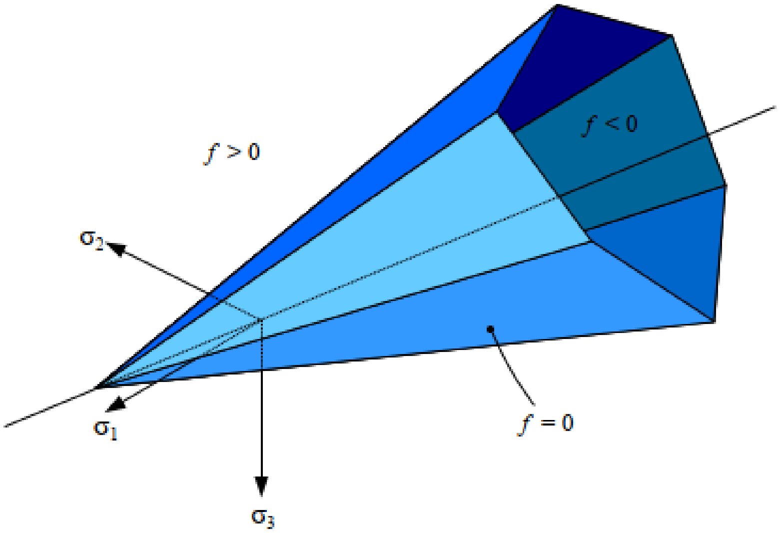


Figure 3- 2: The Mohr-Coulomb failure surface in principal stress space

Using the identity,

$$\frac{\cos \phi}{1 - \sin \phi} = \sqrt{\frac{1 + \sin \phi}{1 - \sin \phi}} = \sqrt{N_\phi} \qquad [3\text{- }5]$$

Equation [3- 4] can be expressed as:

$$\frac{\cos\phi}{1-\sin\phi}=\sqrt{\frac{1+\sin\phi}{1-\sin\phi}}=\sqrt{N_\phi}$$ [3- 6]

Or

$$f^s=\sigma_1-\sigma_3\ N_\phi+2\ c\ \sqrt{N_\phi}$$ [3- 7]

Unlike steel, the soil is not purely elastic and isotropic material. Soil is non-homogeneous and anisotropic material. As stated in the literature review, different scholars represent soil stress-strain behavior with a combination of elastic and plastic behavior. Soil material was defined with a *Linear Elastic Perfectly Plastic model using the Mohr-Coulomb (M-C) failure criterion*.

3.1.3.2.Elastic Constitutive Model for Raft and Piles

The *Isotropic Elastic Model*was assumed for the raft and piles made of concrete. The required parameters for the elastic constitutive model are the modulus of elasticity (E) and Poisson's ratio, n .

3.2. 3D FEM NUMERICAL MODELING

3.2.1. Geometric Modeling of the Continuum

3.2.1.1.Effect of Boundary Zone

The first step of the modeling process is to define the geometry of the piled raft and the soil block. In order to find the extent of the soil solid region to be used in the study, many trial analyses need to be carried out.The axisymmetric analysis was performed by taking only a quarter of the Piled-Raft foundation system/modelusing ABAQUS CEA/2017 Standard. In order to avoid the effect of boundaries/zone included in the modelon any required computed result, laterally in x and y-axis directions, 5 times the width of the raft is used. The vertical depth extent of the soil block used for investigation is two times the length of the pile.

In order to avoid disturbance of the boundary conditions on the output of the analysis, a large soil mass of rectangular cross-section, having a depth equal *to twice the pile length and a width of five times the raft width was considered for this study, and if this trial size used in the model is found in the study creating no appreciable stress and strain* *variation in any section near to the eage and verified so, the boundary size is approved otherwise another trial will be used.*As shown in figure 3-3 and figure 3-4, first the quarter of the soil media was modeled with a depth greater than twice the length of the pile which is 30*m* and the trial lateral extent is assumed 5 times the raft width which is 5*12 = 60m.Figure 3-5 shows the whole geometric modeling of the piled raft.

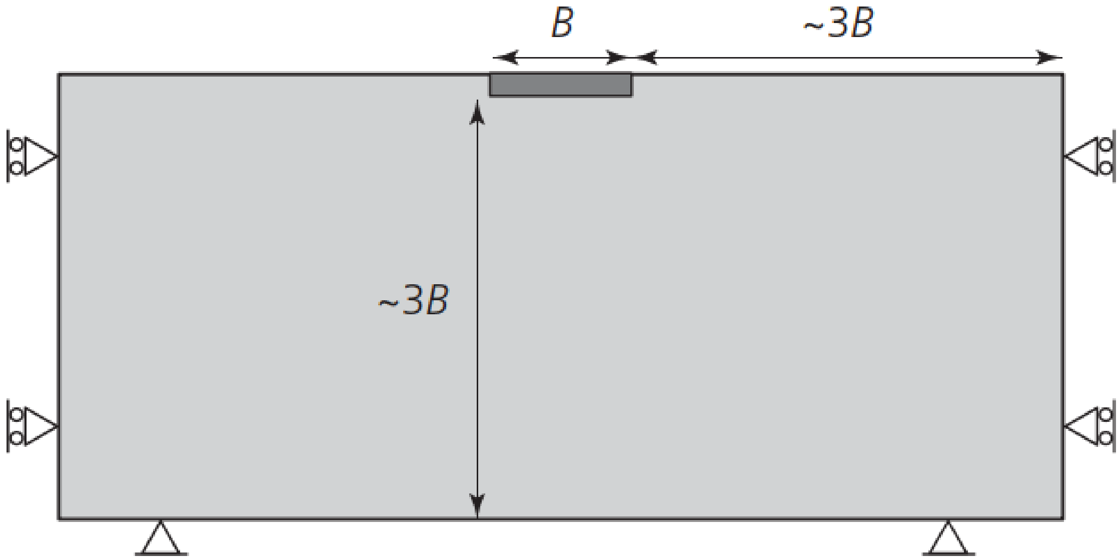


Figure 3- 3: The full soil boundaries/zone included in the 3D FEM numerical model analysis for unpiled raft (Andrew, 2016).

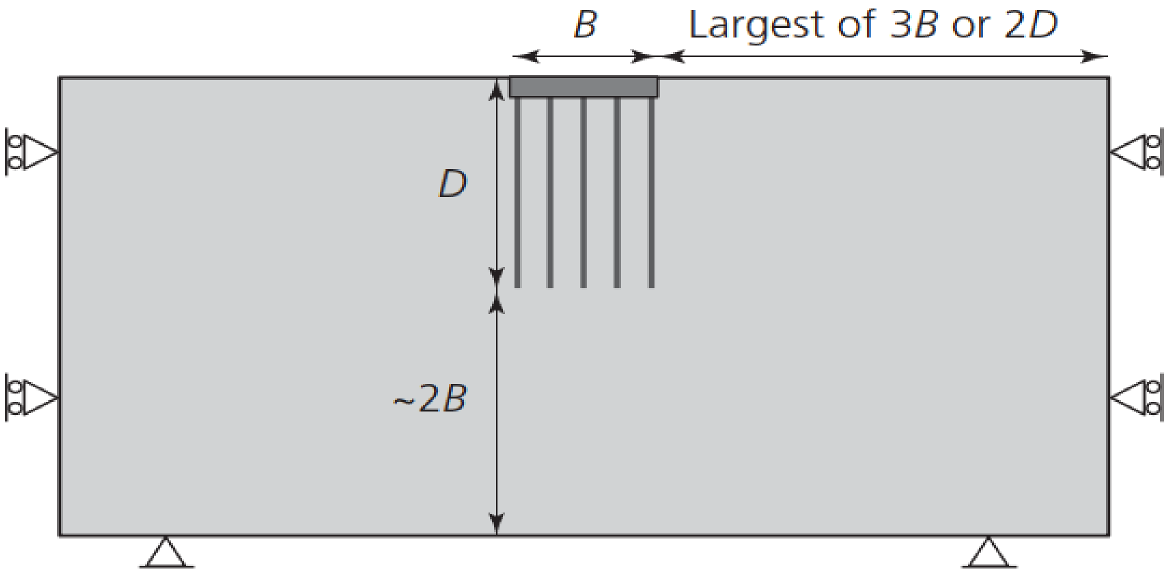


Figure 3- 4: The full soil boundaries/zone/ included in the 3D FEM numerical model analysis for piled raft (Andrew, 2016).

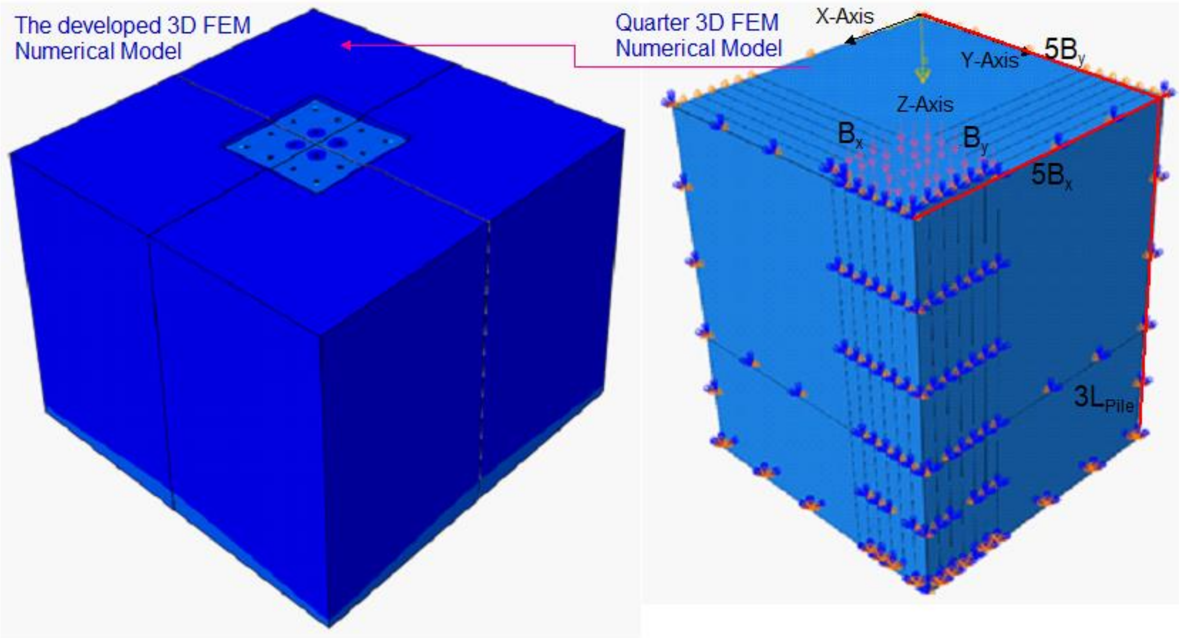


Figure 3- 5: The full and the quarter 3D FEM numerical model developed.

Table 3- 1: Selection of boundary size According to Andrew Lees Geotechnical Finite Element Analysis, A practical guide

Parameter	**Width (m)**	**Length (m)**	**Depth (m)**
Unpiled Raft	Bx/2 + 3(Bx) = 42m	By/2 + 3(By) = 42m	3(Bx) = 36m
Piled Raft Case	Bx/2 + 3(Bx) = 42m	By/2 + 3(By) = 42m	3(By) = 36m
	Bx/2 + 2(Lpile) = 30m	By/2 + 2(Lpile) = 30m	Lpile + 2(B) = 36m
Governing Size	42m	42m	36m

*3.2.1.2.**Modeling of the Unpiled Raft***

The raft considered is a flat slab having uniform thickness resting on the ground surface. After modeling the raft. However, the volume occupied by the raft is much smaller as compared to that of the soil mass. Hence, elements of smaller size are used for meshing the raft. The properties of raft considered for the analysis are presented inTable 3-2.In the present study, a *square-shaped unpiled raft* of size $12m \times 12m$ having a thickness of $1m$ has been first analyzed.

3.2.1.3.Modeling of the Piled Raft

In the case of the piled raft modeling, the same raft is modeled using the pile diameter of $0.6m$ and the center to center spacing of 3 times the diameter of the piles; $3 \times D_{pile}$ which is $1.8m$. The piled raft was established by attaching the square pile(s) to the bottom surface of the raft and the soil was created as a block with a sufficient number of holes to a depth of the length of the pile. The defined parts were assembled by situating the piled raft in the pre-made holes in the soil block. The full and the quarter 3D FEM numerical model developed is shown in Figure 3-5.

3.2.1.4.Modeling of the Piles

Piles are modeled similar to that of the raft, having higher Young's modulus compared to the soil. The raft under each building frame is assumed to be supported by a group of piles of circular cross-section. The properties of the pile considered for the analysis are presented in Table 3-2.

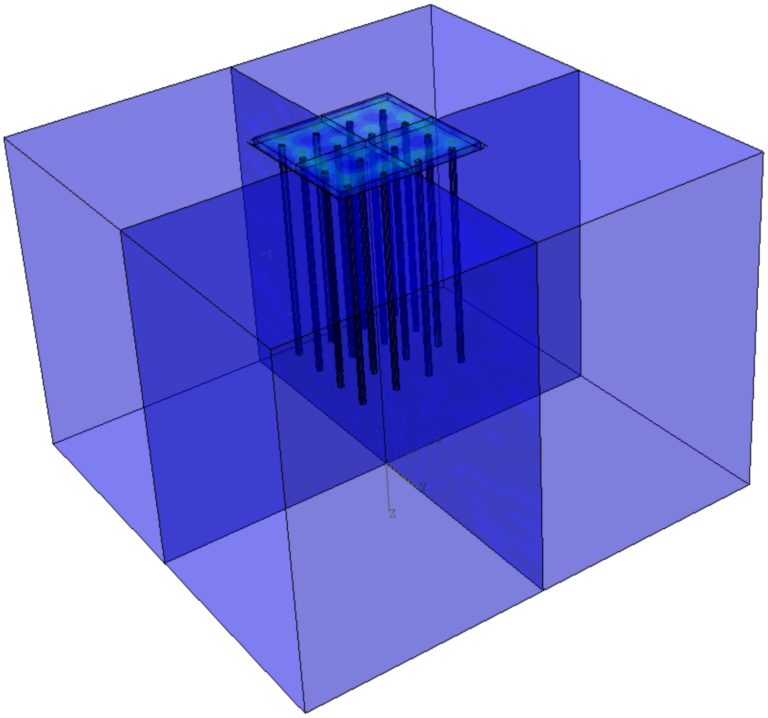


Figure 3- 6: The whole assembled geometric modeling of the piled raft for verification.

3.2.1.5.Boundary Conditions

Translations of bottom nodes were restricted in all three directions (X, Y, and Z-Axis) and the lateralmovement was avoided for the nodes on the sides of the soil block. The boundary condition of the developed model is shown in Figure 3-8 below.

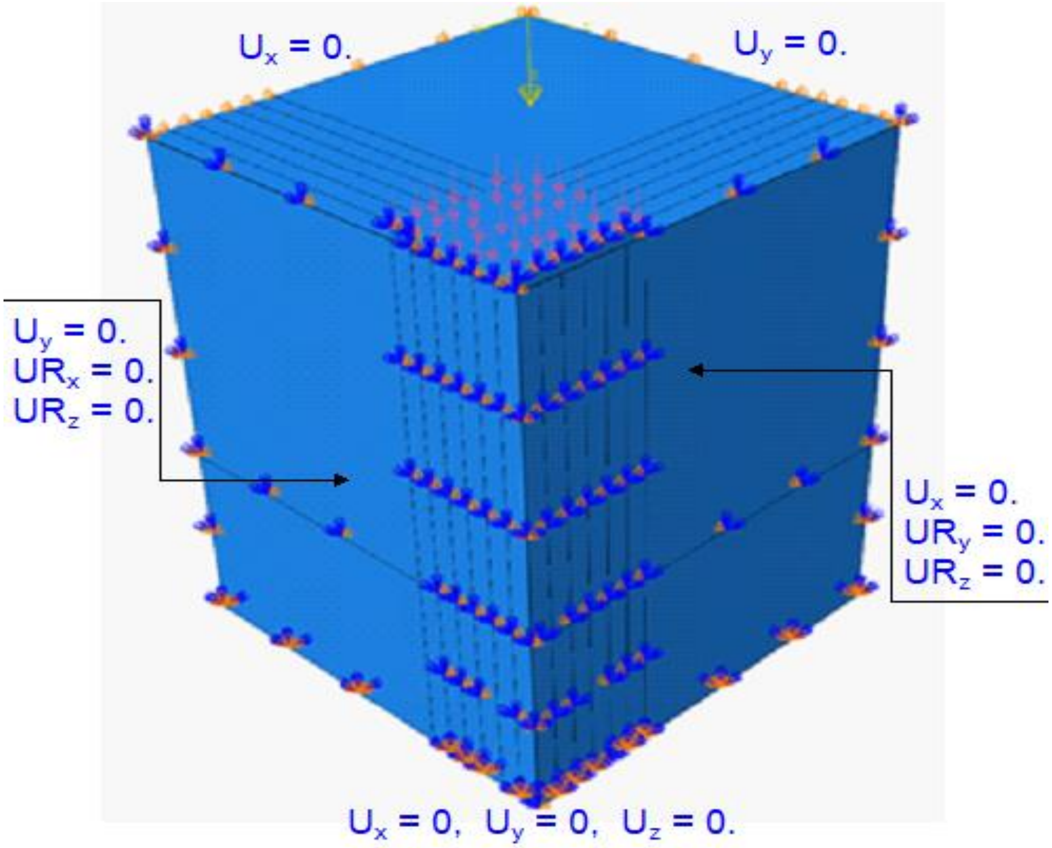


Figure 3- 7: Boundary condition and applied load of the developed model

3.2.2. Selection of Finite Element Type

Hexahedral elements are selected over the tetrahedrons or wedges, due to their capability to simulate the real situation. These elements make it easy to visualize the mesh. the element distortion is relatively less compared to the tetrahedrons and wedge elements. In order to align the meshing between the raft and the soil continuum, the consistent shape was used with hexahedral elements. Hence the whole model including *the raft, soil, and piles was modeled using the solid continuum 8-node brick element with reduced integration* (i.e. *Element Type* – C3D8R).

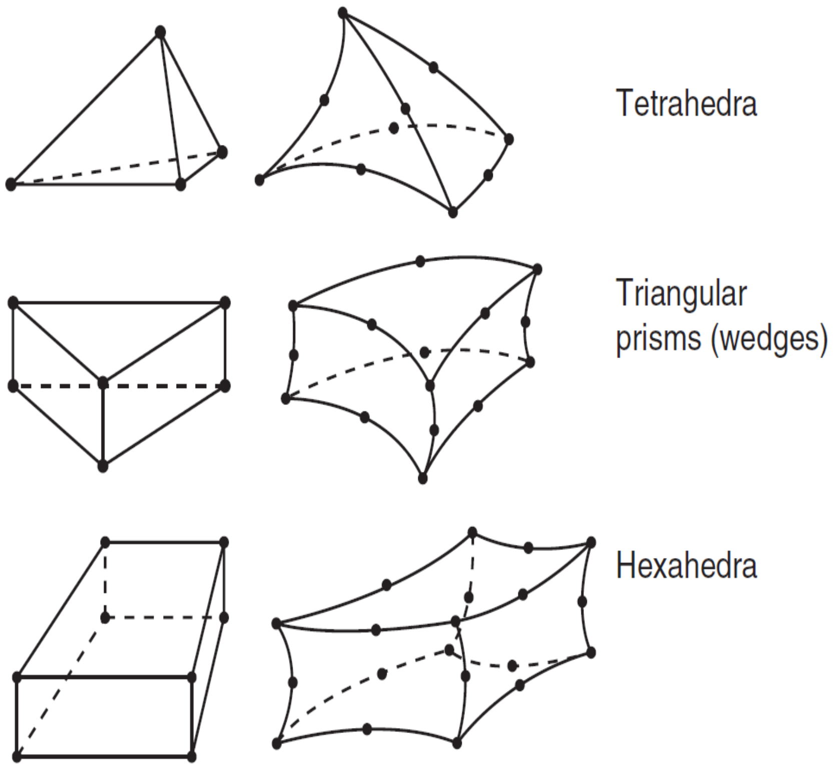


Figure 3- 8: Three-dimensional mesh element types.

Despite the computation time and memory needed, as much as possible relatively higher number of elements with smaller sizeswere employed. The reason for using this large number of elements with a very small size was made to make sure that there will be high accuracy of the results at locations where non-linearity behavior was anticipated, particularly at the mat/raft base, pile base, and pile circumference.In a finite element method analysis, the output is mainly dependent on the mesh size used. Hence the outputs of the pile draft behavior depend on the mesh size, mesh element type and the number of elements used. To get a more accurate output of the simulation, finer mesh/many numbers of elements shall be used. This increases the number of nodes; which intern increases the computational process of the software.

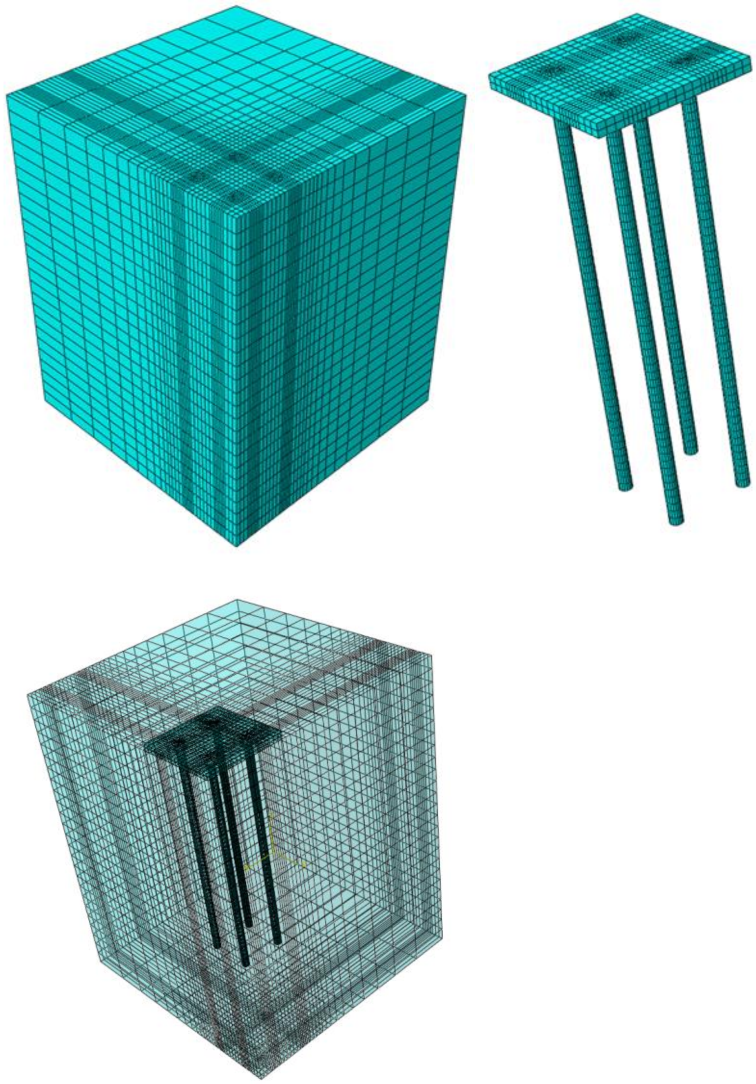


Figure 3- 9: Meshed geometry of the developed Piled Raft and Soil model

The model was partitioned in a systematic manner so that it is possible to create a smooth transition between the coarser and finer meshes. Finer meshes were used within the soil zone around piles and below raft on purpose to enhance the efficiency of calculation. Abaqus has access to simulate the problem with axis-symmetric boundary conditions. Hence only the quarter of the piled raft foundation system was modeled. Doing this decreases the number of mesh elements which intern results in a decrease of the computational time and computer memory consumption. But a relatively finer meshes were used at areas of concern/ i.e. in the vicinity of raft and piles, /and as shown in Figure 3-10 a biased meshing technique was used in order to ensure a smooth mesh transition from finer to coarser mesh elements.Figure 3-9 shows the developed numerical model in this study (i.e. all four quarters in one). Linear Hexahedral volume elements with 8-Nodes (C3D8) are used in the model.These is due to lack of high processor computer resource, linear hexahedral elements with reduced integration (C3D8R) were used in this study to model the different layers of soil and linear wedge elements with reduced integration (C3D8R) for the soil around the piles and for the piles and raft themselves as well. The mesh size of each model is fine immediately under the raft and pile tips and started to grow gradually as the distance to the bottom increases.

3.2.3. Modeling of the Contact Zone

In order to simulate the full behavior of the soil-structure interaction, proper modeling of the contact interface between the soil & the pile/raft is essential. To model this contact, it is critical to get the friction factor between these materials.The soil-structure interaction is the main driving factor of the load sharing mechanism that requires proper modeling to achieve accurate numerical results. Therefore, we first specified the locations where two different surfaces meet (i.e., soil and foundation elements) and applied the surface-to-surface discretization technique to model the soil-structure interaction. The aforementioned technique connects the nodes on one of the two surfaces (master surface) to the face of the other one (slave surface). Each node on the slave surface is constrained to have the same motion as the closest point on the master surface. It is a common practice to consider the surface with higher rigidity as the master surface. In this study, the pile and raft surfaces were treated as master surface and the soil in contact with foundation elements represented the slave surface.

The "*Mechanical Contact Property*" function in ABAQUS CEA/2017 software was used to specify the tangential (friction) and normal interaction between the soil and the structures. The pile peripheral surfaces represented the tangential interaction whereas the soil contact with the raft and the pile tip represented the normal interaction. Furthermore, the stiffness of contact surfaces was simulated by the "*frictional constraint enforcement*" feature within the software. The frictional coefficient for tangential interaction and the stiffness of normal interaction was assumed to be *0.3 and 1,* respectively.In this work, the so-called*Master-Slave Surface*developed by Wriggers, which includes the interface constitutive laws for the normal and tangential stress components in the contact areas is used.

This master-slave surface principle is preferred due to its ability to simulate large deformations.Hence the surfaces of the raft and the piles are considered as master surfaces whereas the soil is treated as a slave surface. In addition, for the option "*Node to Surface*" and "*Surface to Surface*" contact surface to surface contact is chosen as it is a more accurate assumption.

3.2.4. Loading Steps

The numerical analyses were conducted in two steps. Initially, the numerical model was run under gravity load and subsequently, a uniformly distributed load was applied on the raft surface and incrementally increased until it reached the maximum value. The output data was requested for *forces, stresses and displacements* in each load increments at the loading step.

3.2.5. Analysis Step Time Increment

The finite element method software, ABAQUS CEA/2017, uses an incremental loading procedure combined with a *full Newton–Raphson routine*for solving the non-linear equations involved in the analysis. In this method, the load is applied in increments, but in each increment successive iterations are performed, and in each iteration, the stiffness matrix is updated. After each iteration, the portion of the total loading that is not balanced is calculated and used in the next step to compute an additional increment of displacement. The solution is said to have converged and to be in equilibrium after a number of iterations when the restoring force equals the applied load (or at least to some specified tolerance).Next, the piled raft foundation was modeled. after modeling the soil media and the piled raft foundation, application of the self-weight and the *uniformly distributed load of 500 kPa* was performed. Creating the job and undertaking analysis to obtain results.

3.2.6. Soil, Raft and Pile Material Properties

The list of soil and concrete (i.e. raft and pile) properties used in the numerical analysis of ABAQUS CEA/2017are explained in Table 3-2below. The soil properties are based on the literature review on the properties of stiff clay.

Table 3- 2Parameter values used in ABAQUS CEA/2017 software analysis

Parameters	**Soil Property**	**Concrete Property**	
		Pile	**Raft**
FE Model	Elasto-Plastic	Linear Isotropic	Linear Isotropic
Young’s Modulus, E (MPa)	50	50,000	50,000
Poisson’s Ratio, *n*	0.35	0.2	0.2
Angle of internal friction, Ø’(°)	20	-	-
Unit weight, γ,kN/m3	17	24	24
Cohesion, *c* ’ (kPa)	20	-	-
Dilatancy Angle (o)	0	-	-

3.2.7. Overall Procedure Followed

Theprocedure followed in the present research is described in the following sections.

3.2.7.1.***Physical Model of the Structural System***

Creation of three-dimensional physical models of the structural system consisting of *(i) Raft: (ii) Piles and; (iii) Soil.* The super-structure is removed and replaced by the corresponding uniformly load. Each part of the structural system has been modeled separately and then discretized into a large number of finite elements. A sufficiently large zone of the infinite soil mass of length equal to more than five times breadth of raft and depth equal two times the breadth of raft plus length of the pile has been selected as the zone of influence.

3.2.7.2.Application of Imposed Load

The total load applied to the structural system is assumed to be uniformly distributed over the entire surface area of the raft. This type of transmission of the load is expected in a relatively flexible raft. On the application of load, the flexible raft is likely to undergo differential settlements. Due to this, the stress distribution due to the uniform load will be non-uniform. Thus the assumption that loads being uniformly distributed may not give accurate behavior as per actual condition but it can be acceptable for all practical purposes.

3.2.7.3.Output Analysis and Interpretation

The model created by using the above condition is analyzed by using the finite element software ABAQUS to find out the settlement of the structural system.

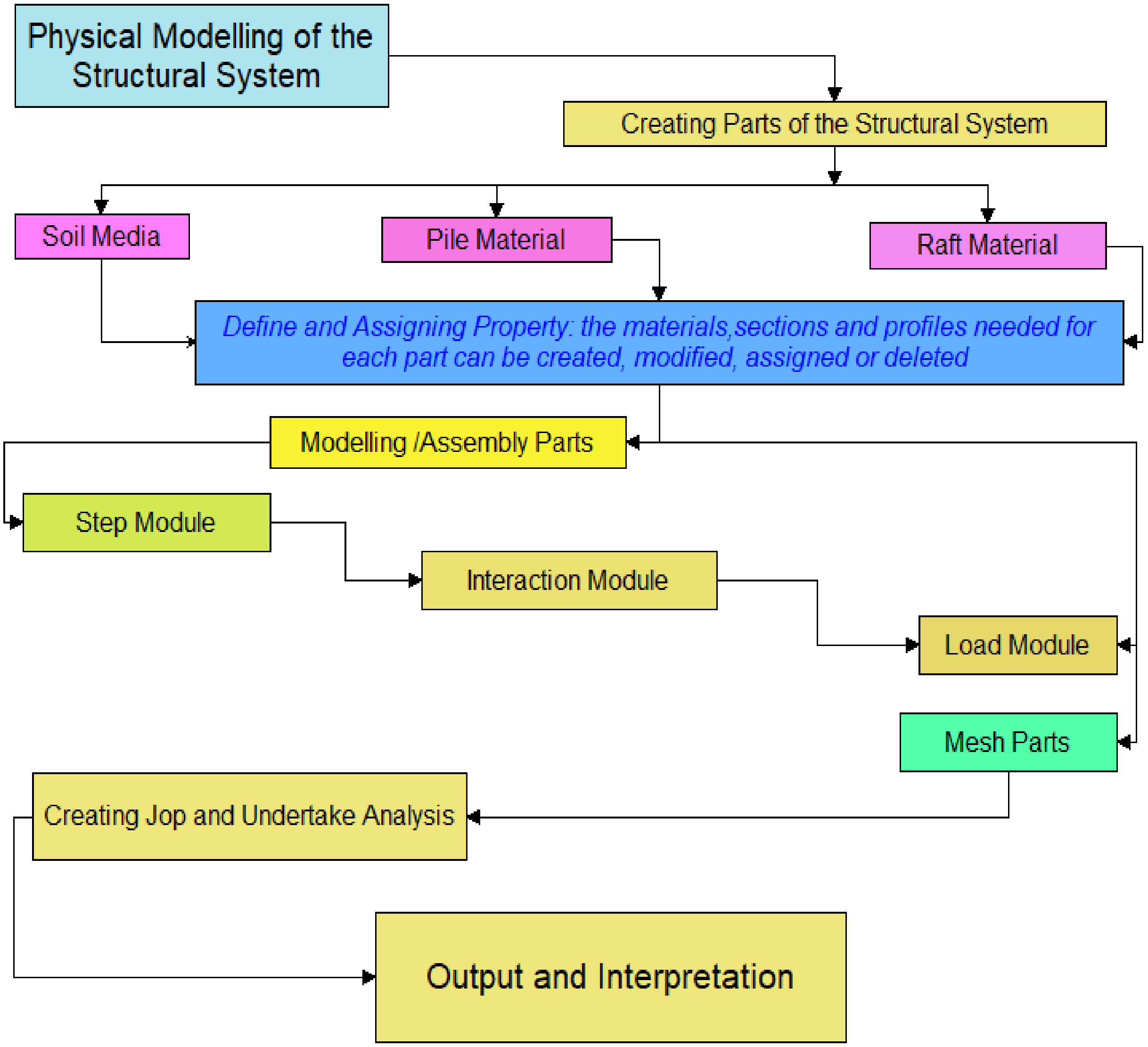


Figure 3- 10: Procedures followed in the finite element analysis.

3.2.8. Mesh Sensitivity analysis

The number of elements on the finite element model will affect the results. To investigate the effect of number of elements or mesh coarseness on the response of the proposed piled raft foundation, four different trials of finite element meshes were performed. These was done by using a biased mesh system, by varying their number and sizes keeping material properties and all other parameters constant. The generated number of elements and the maximum central settlement in the piled raft foundation is given in table 3-3 and Figure 3-11

Table 3- 3:Effect of number of elements on maximum settlement

Trail No.	Mesh coarseness	Number of elements	Maximum central settlement (mm)	Remark
1	Courser mesh	27072	324.25	
2	Medium mesh	41962	352.4	
3	Finer mesh	62944	387.00	Selected for analysis
4	Finest mesh	97568	394.49	

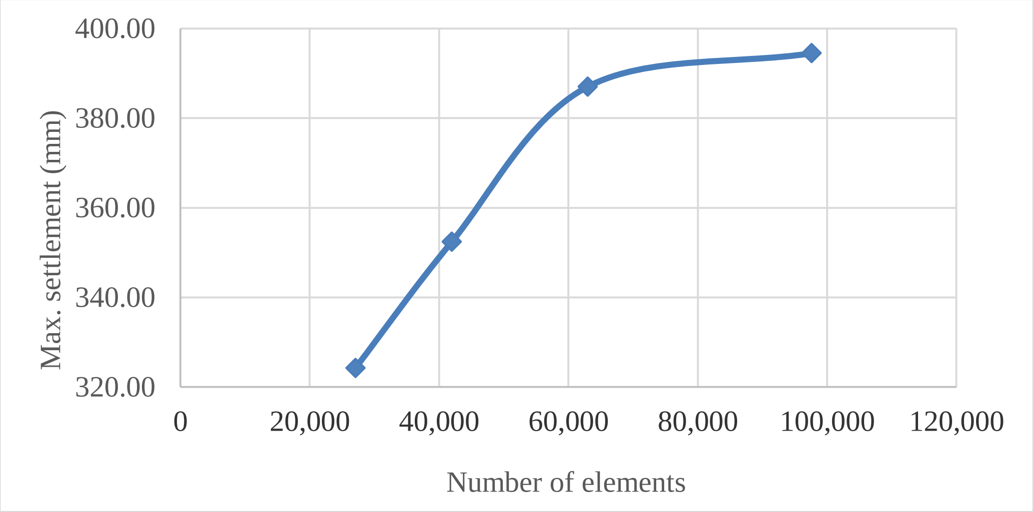


Figure 3- 11: Effect of mesh coarseness on maximum central settlement

As indicated in Figure 3-11, maximum central settlement increases with increasing number of element until the number of elements become 62,944, after which the effect of increasing number of elements on the maximum central settlement becomes insignificant. Hence, the third trial model was selected and used for the analysis.

3.3. RESULT AND DISCUSSION

3.3.1. Introduction

The aim of the developed 3D numerical model is to simulate the behavior of unpiled and piled-raft foundations in stiff clay soil for verification for further parametric study. In order to investigate the hypothesis, three-dimensional numerical modeling with ABAQUS CEA/2017 software is employed, which it's analyses are based on the finite-element method. The unpiled raft and piles are modeled as an 8-Noded element used for the 3-D modeling of solids. While the pile-soil interaction is modeled by *surface to surface contact* element available in ABACUS CEA/2017 program. In order to ensure the reliability of the results obtained by the developed computer pile-raft foundations model, a verification and validation process was carried out and explained in this chapter for both unpiled raft and piled raft. Comparing the results reported by the researcher and the results of the present study, if a maximum of 5% of the difference is reached, indicates the proof of validation. Then, this model is used for a parametric study of the mentioned cases in the project objectives.

3.3.2. The Effect of Boundary Size

3.3.2.1.Unpiled Raft Case

To neutralize/minimize the effect of boundary size on different parameters computedduring analysis using the 3D computer numerical model prepared, a large soil mass of rectangular cross-section, having a depth equal to twice that of the raft width and a width equal to five times the raft width is considered in the unpiled raft model. Also, when outputs are checked, the stress state should not be on the failure envelope to a significant extent at any model boundary, except perhaps on axes of symmetry. As a general rule, stress changes should be less than 5% at model boundaries, and ideally less than 1%. The raft is assumed to be placed just below the ground surface on a deep, homogeneous, stiff clay deposit. The average properties of *this stiff clay considered for the analysis are presented in*Table 3-2. To idealize material non-linearity of soil has been modeled as Mohr-Coulomb Elastoplastic medium.

A square-shaped *12m by 12m* unpiled raft with a raft thickness of 1m has imposed a uniformly distributed load of 0.5MPa. At this load, the vertical settlement of the raft top center element is 693.06 mm. Table 3-4 shows the load and the corresponding settlement of the unpiled raft foundation.

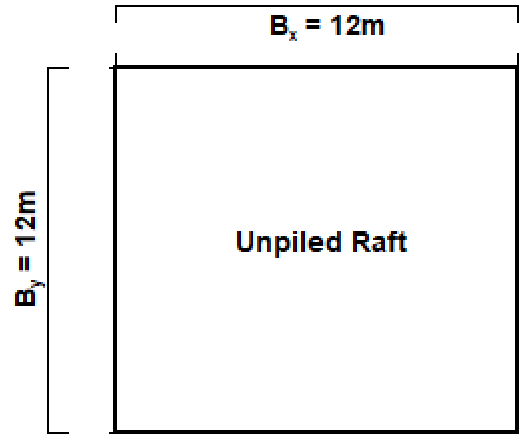


Figure 3- 12: The Unpiled Raft Case/Structural Model

Table 3- 4:the load and the corresponding settlement of the unpiled raft foundation.

Load (MPa)	Settlement (mm)
0.00	0.00
0.02	18.18
0.05	31.81
0.08	53.00
0.10	67.00
0.14	90.00
0.18	128.00
0.24	194.06
0.28	256.32
0.34	347.48
0.38	420.00
0.42	492.56
0.45	589.17
0.50	693.06

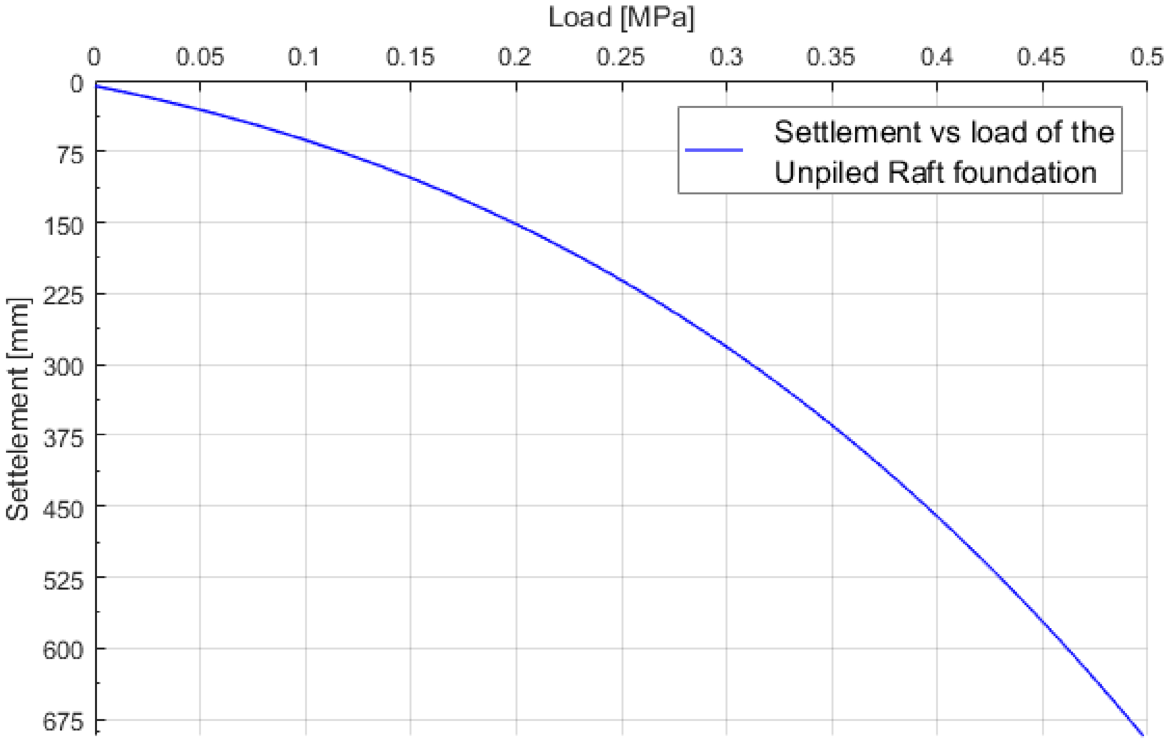


Figure 3- 13: Settlement vs load of the unpiled raft foundation

3.3.2.2. Piled raft case

A square-shaped 12m by 12m piled raft with a raft thickness of 1m, a diameter of pile 0.6m, the spacing of three times the pile diameter which is 1.8m and with a pile length of 12m was imposed a uniformly distributed load of 0.5 MPa.Table 3-5 shows the load and the corresponding central settlement of the piled raft foundation.

Table 3- 5Load vs settlement for piled raft foundation

Load (MPa)	Settlement (mm)
0.00	0.00
0.02	12.11
0.04	16.61
0.07	24.15
0.10	40.78
0.15	57.38
0.19	81.59
0.23	107.32
0.28	140.67
0.33	181.61
0.37	228.65
0.41	280.25
0.45	328.83
0.50	387.00

Applying the specified amount of uniformly distributed load, the central settlement was observed to be 387 mm.

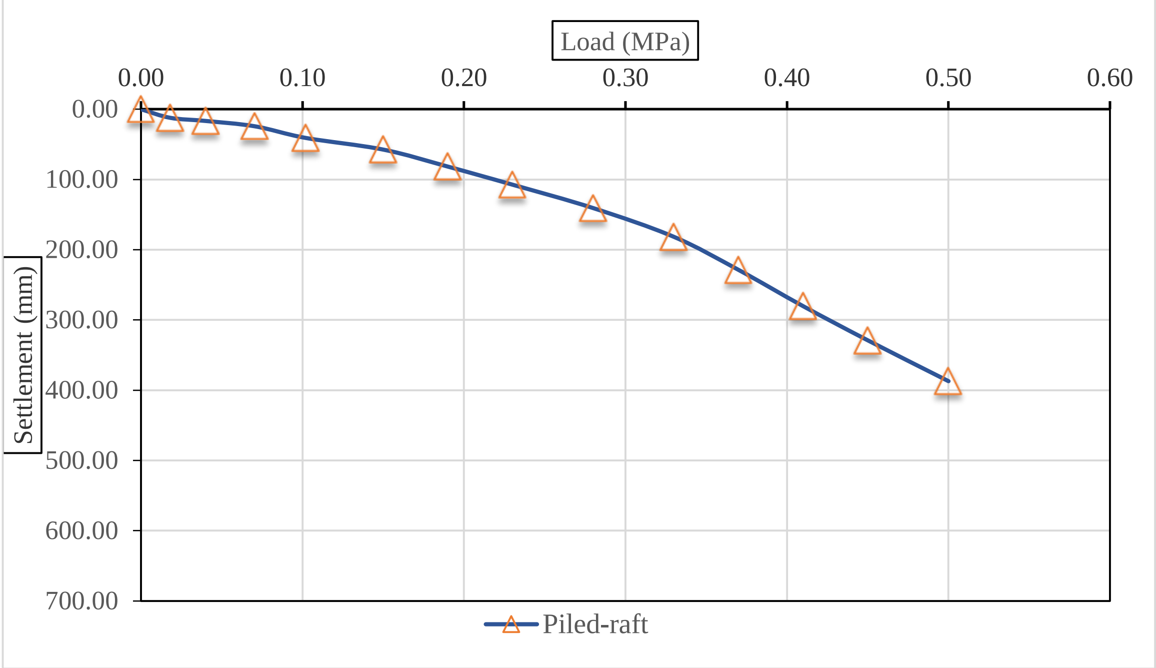


Figure 3- 14: Settlement vs Load for the piled raft foundation

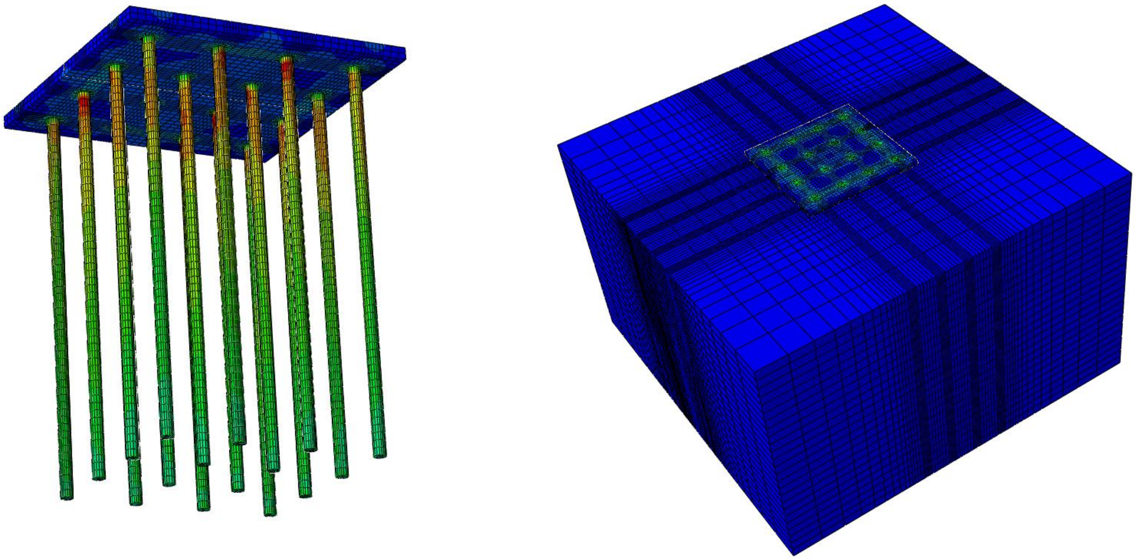


Figure 3- 15: ABAQUS output of the piled raft foundation analysis

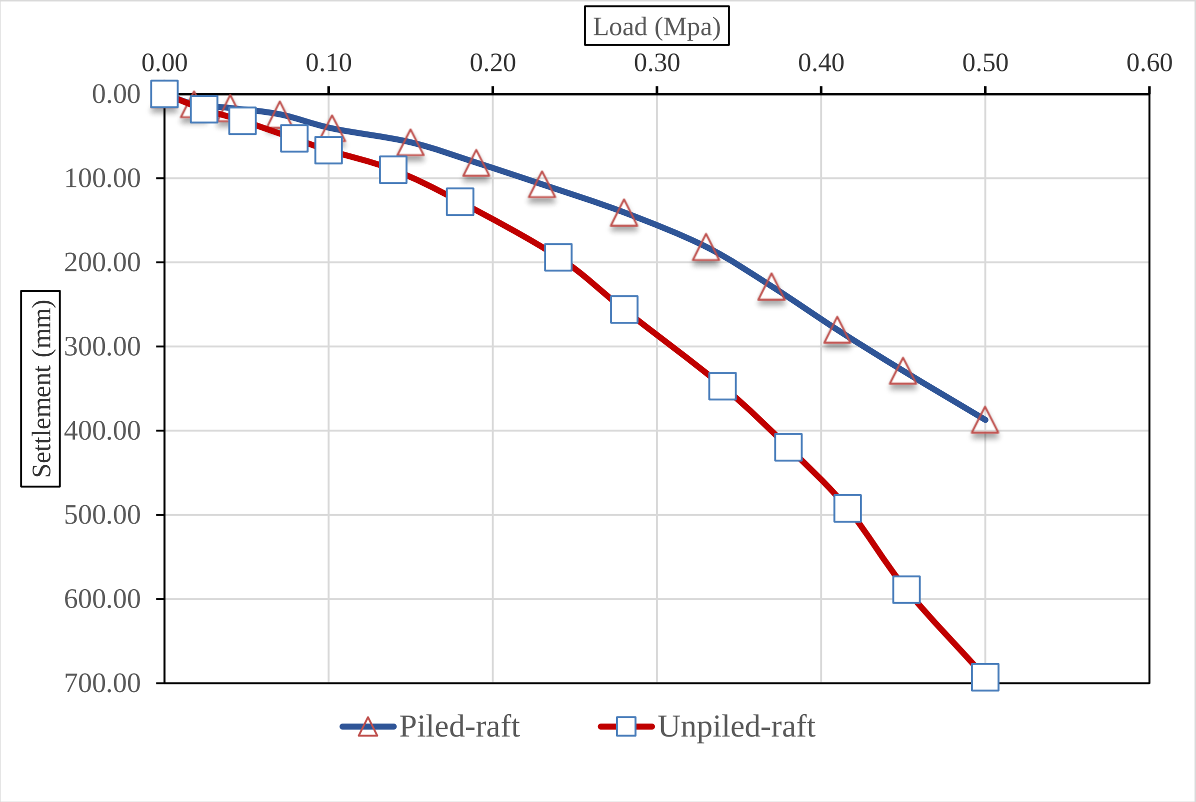


Figure 3- 16: Comparison of piled and unpiled raft foundation systems

As indicated in Figure 3-16, comparing the piled and unpiled raft foundation systems, by introducing the piles, the maximum central settlement was reduced from 693.06 mm to 387 mm. this maximum central settlement reduction is more than 44%. In addition, observing the lower load, e.g : At 100 mm settlement, the unpiled raft can withstand a uniformly distributed load of 0.15 MPa, while for the piled raft a uniformly distributed load of 0.22 MPa is required, which is 46.67 % greater than that of unpiled raft foundation.

3.4. MODEL VALIDATION

In order to validate the exactness of the finite element analysis, the reviewed experimental works of (Lee J. , 2014) was modeled and analyzed with the exact procedure followed to analyze the proposed piled raft foundation. The results obtained from the Finite element analysis agreed with the results obtained from the centrifugal load tests performed by (Lee J. , 2014).

As indicated in the literature review (Lee J. , 2014)conducted a model scale centrifuge test in the laboratory and presented the results on a prototype scale.The geometric dimension of the prototype of piled raft foundation system which evaluated in the centrifuge test was; diameter of the pile (D_p) = 0.6m, Length of pile was 15m, number of piles were 16 piles with 4 by 4 configurations with pile spacing distance of 2.4m corresponding to 4 times pile diameter of 0.6m (i.e., $4D_p$). the raft was square-shaped raft with width and thickness of 9m and 0.5m respectively.

3.5. COMPARISON OF NUMERICAL AND CENTRIFUGE TEST RESULTS

The results obtained from the analysis of the finite element method software are calibrated with the load vs normalized settlement as shown in the Figure 3-17. The results from ABAQUS well agree with the experimental results performed by (Lee, 2014)

This verifies the finite element analysis performed on the proposed piled raft foundation.

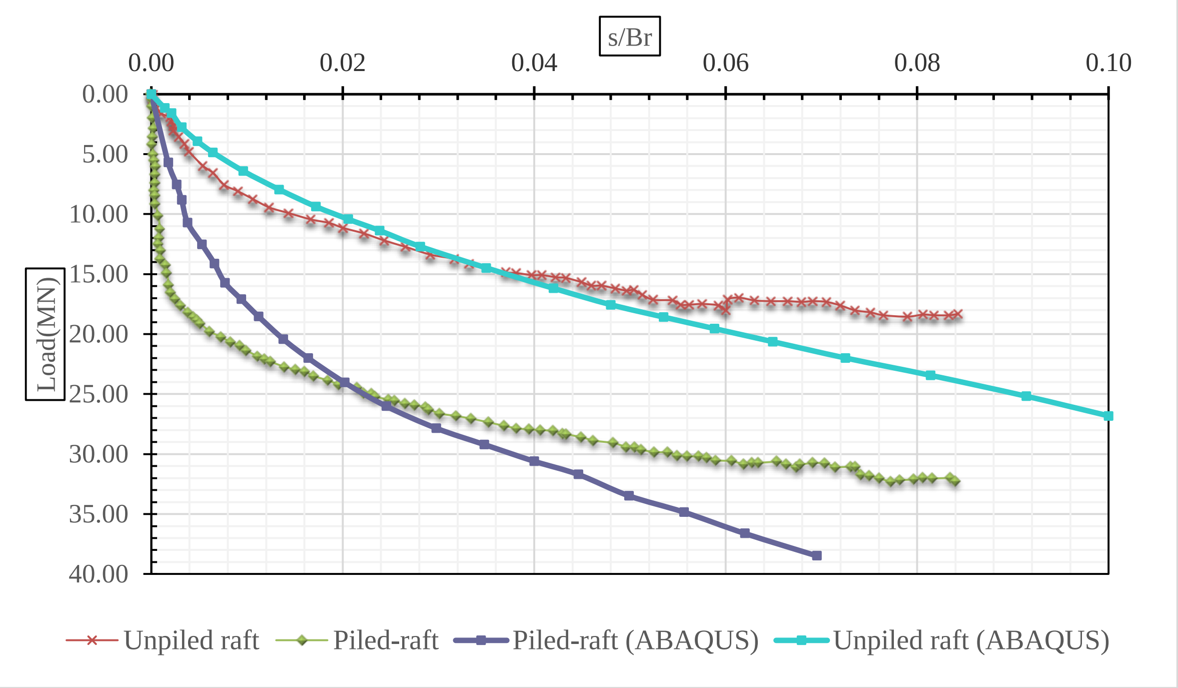


Figure 3- 17: Comparison of normalized settlement vs Load graphs of Experimental results and FEA results

CHAPTER 4

PARAMETRIC STUDY

4.1. GENERAL

The parametric study on this chapter of the thesis is continued after the sensitivity analysisand validation analysis performed in chapter three. This chapter of the study mainly focuses on designing and performing numerical model analysis on piled raft foundation with different varying parameters like raft thickness, pile spacing,pile diameter, pile numberand pile length.

4.2. EXPERIMENT DESIGN

The raft thickness is varied from 0.5m to 2.0m (0.5m, 1.0m, 1.5m, and 2.0m.) by keeping constant the other parameters i.e a piled raft with a square raft size of 12m by 12m, having 16 piles with a 4x4 pile arrangement, a center to center pile spacing of $3D_p$, a pile length of 12m, and a pile diameter of 0.6m.

The number of piles is varied from a single pile to 16 piles (i.e. 1 pile, 4 piles, 9 piles, 16 piles.) by keeping constant the other parameters. A piled raft with a square raft size of 12m by 12m and a raft thickness of 2m was modeled. A center to center pile spacing of $5D_p$, $4D_p$ and $3D_p$was considered for pile number of 4, 9 and 16 piles respectively. A pile length of 12m, and a pile diameter of 0.6m was modeled as shown in table 4-1.

The center-to-center pile spacing was varied From $2D_p$ to $5D_p$(i.e $2D_p$ $3D_p$ $4D_p$ and $5D_p$) by keeping constant the other parameters i.e a piled raft with a square raft size of 12m by 12m, a thickness of 2m, pile length of 12m, a pile diameter of 0.6m having 16 piles with a 4x4 pile arrangement as shown in the following table 4-1.

The other varied parameter was the pile diameter, The pile diameter is varied from 0.3m up to 0.75m (i.e 0.3m, 0.45m, 0.6m, and 0.75m.) by keeping constant the other parameters i.e a piled raft with a square raft size of 12m by 12m with a raft thickness of 2m, having 16 piles with a 4x4 pile arrangement, a center to center pile spacing of $3D_p$, and a pile length of 12m as shown in the table 4-1 below.

The last considered parameter was the pile length, the pile length is varied from 6.0 m to 24m (i.e 6.0m, 12m, 18m, and 24m.) by keeping constant the other parameters i.e a piled raft with a square raft size of 12m by 12m with a raft thickness of 2m, having 16 piles with a 4x4 pile arrangement, a center to center pile spacing of $3D_p$, , and a pile diameter of 0.6m as shown in the following Table 4-1.

For all the above-mentioned parameters, the same modeling technique, boundary condition and loading condition discussed in chapter 3 was employed. A uniformly distributed load of 0.5MPa was applied and the analysis job was submitted and run for the specified different mentioned parameter and the central settlement of the piled raft was filtered as shown in the Table 4-2.

Table 4- 1Summery of parametric study parameters of piled raft foundation

Varied Geometry	Raft Dimensions		Pile Group Geometry			
	Width (m) x Length (m)	Thickness (m)	Pile Spacing	Number of piles	Pile Diameter (m)	Pile length (m)
Raft thickness	12x12	0.5	$3D_p$	4x4	0.6	12
	12x12	1.0	$3D_p$	4x4	0.6	12
	12x12	1.5	$3D_p$	4x4	0.6	12
	12x12	2.0	$3D_p$	4x4	0.6	12
Number of piles	12x12	2.0		1	0.6	12
	12x12	2.0	$5D_p$	2x2	0.6	12
	12x12	2.0	$4D_p$	3x3	0.6	12
	12x12	2.0	$3D_p$	4x4	0.6	12
Pile Spacing	12x12	2.0	$2D_p$	4x4	0.6	12
	12x12	2.0	$3D_p$	4x4	0.6	12
	12x12	2.0	$4D_p$	4x4	0.6	12
	12x12	2.0	$5D_p$	4x4	0.6	12
Pile Diameter	12x12	2.0	$3D_p$	4x4	0.3	12
	12x12	2.0	$3D_p$	4x4	0.45	12
	12x12	2.0	$3D_p$	4x4	0.6	12
	12x12	2.0	$3D_p$	4x4	0.75	12

Pile Length	12x12	2.0	$3D_p$	4x4	0.6	6
	12x12	2.0	$3D_p$	4x4	0.6	12
	12x12	2.0	$3D_p$	4x4	0.6	18
	12x12	2.0	$3D_p$	4x4	0.6	24

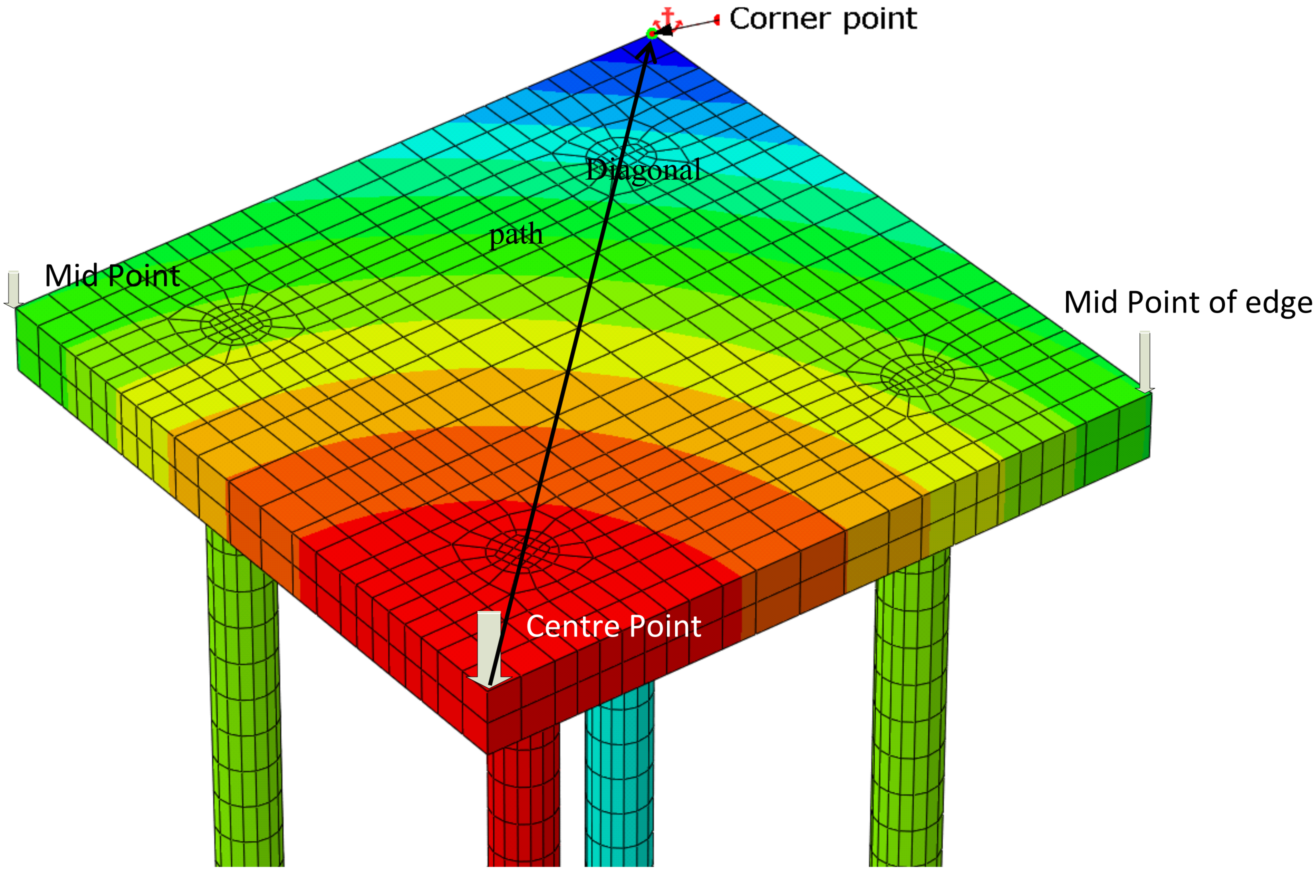


Figure 4- 1: Quarter of the whole piled raft model with center, corner and mid points indicated

4.3. RAFT THICKNESS

4.3.1. Effect of raft thickness on the maximum central settlement

The raft thickness (raft stiffness) is one of the important parameters of piled raft that need to be investigated. As described in the table 4-1 A 12m by 12m square shaped raft was used. 16 piles with a pile diameter of 0.6m and a pile length of 12m was modeled. After modeling and providing the appropriate boundary conditions, 0.5MPa uniformly distributed load was applied and the analysis job was submitted and run for the specified different raft thicknesses and the central settlement of the piled raft was filtered as shown in the table 4-2.

Keeping the mentioned parameters constant and varying raft thickness of 0.5m, 1m 1.5m & 2m, the bearing behavior of the piled raft is investigated.

Table 4- 2 Raft center settlement for various raft thickness

Load (MPa)	*Settlement (mm)*				
	t = 0.5m	t = 1m	t = 1.5m	t = 2m	Unpiled raft
0.00	0.00	0.00	0.00	0.00	0.00
0.01	14.13	4.84	2.60	4.77	6.48
0.03	23.79	11.06	6.47	7.82	12.95
0.04	31.96	21.44	13.02	14.43	22.67
0.07	46.07	34.59	21.50	21.68	38.08
0.10	63.89	53.97	37.80	35.49	58.33
0.14	94.35	78.88	57.37	55.37	84.26
0.19	125.56	105.87	79.54	75.84	112.23
0.24	159.75	141.88	106.96	101.77	158.05
0.28	205.88	184.82	146.80	137.92	214.85
0.33	266.10	240.29	182.06	171.67	296.02
0.37	333.80	301.24	235.63	226.56	391.82
0.42	415.64	374.75	297.72	280.84	501.44
0.45	494.52	444.02	354.57	333.92	597.25
0.50	573.40	513.30	411.43	387.01	693.06

Table 4-2 describes top raft center settlement for various raft thicknesses side by side with the unpiled raft foundation. These values are plotted in the figure 4-2 below. From this figure It can be observed that increasing the raft thickness reduces the raft center settlement.

For instance, for a uniformly distributed load of 0.24 MPa, by increasing the raft thickness from 0.5m to 2m the settlement reduced from 159.75mm to 101.77mm. This is 36.3 % settlement reduction. In different expression, for a raft thickness of 0.5m a uniformly distributed load of 0.24MPa produces 159.75mm central settlement. By increasing the raft thickness from 0.5m to 2m, a uniformly distributed load of 0.32MPa is required to produce the same amount of settlement. Hence increasing the raft thickness reduces the central settlement by increasing the load bearing capacity of the piled raft. A smaller raft thickness, more load is to be carried by the piles only. that's why, a raft thickness of 0.5m has a similar result with that of unpiled raft.

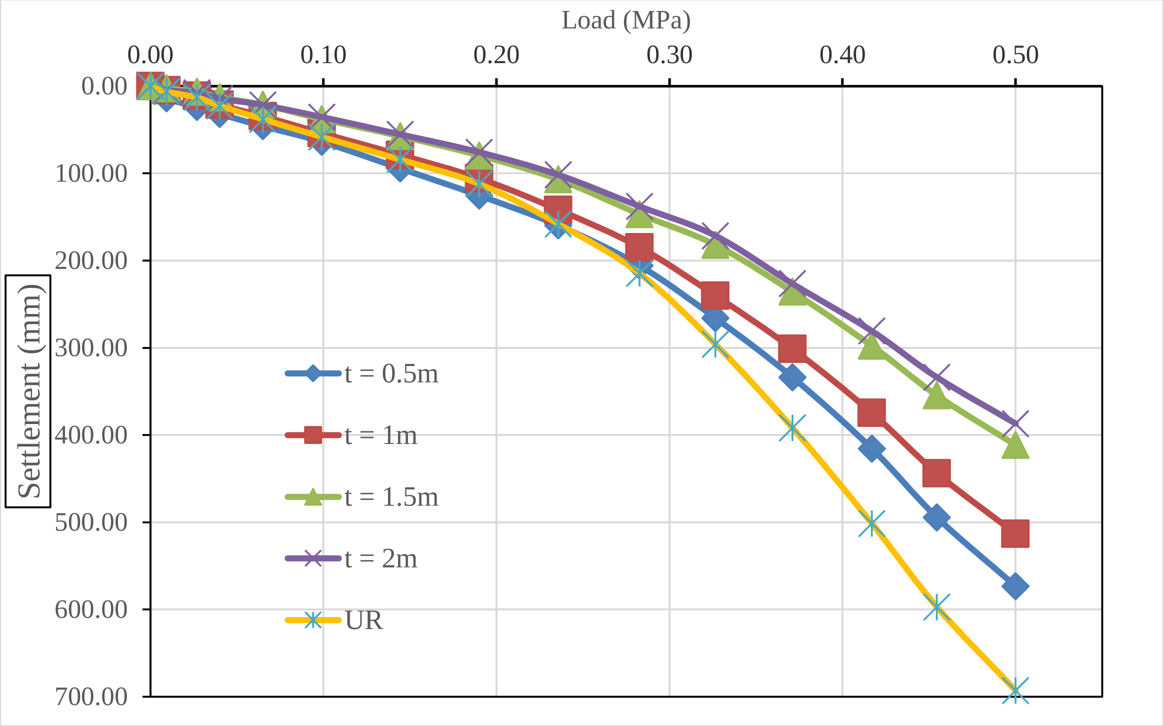


Figure 4- 2: Load vs raft center settlement for various raft thicknesses

Figure 4-2 indicates that after a certain increment in the raft thickness, the settlement reduction is relatively insignificant. This is clearly seen that, changing the raft thickness from 1m to 1.5m have a significant effect on the raft center settlement, whereas further increasing the raft thickness have a relatively less effect on the response variable.

Table 4-3 shows the ultimate maximum raft center settlement after the application of 0.5MPa uniformly distributed load. Comparing with 2.0m thick unpiled raft, a 0.5m thick piled raft showed a 17.27 % settlement reduction. Table 4-3 below shows that increasing the raft thickness from 0.5m to 1m reduces the settlement by 10.48m, and by increasing the raft thickness from 1m to 1.5m reduces the settlement by 19.85% and by further increasing the raft thickness from 1.5m to 2m results a settlement reduction of 5.94 %.

Table 4- 3 :Raft center settlement for different raft thickness

Raft Thickness (m)	Settlement (mm)	Reduction (%)
0.5	573.4	
1	513.3	10.48
1.5	411.43	19.85
2	387.01	5.94

Figure 4-3 shows the ultimate maximum raft center settlement after the application of 0.5MPa uniformly distributed load. As discussed above changing the raft thickness from 1m to 1.5m results a significant reduction in the ultimate maximum raft center settlement. The figure shows further increment in the raft thickness have insignificant effect in the settlement reduction. Hence a raft thickness of 2m is taken as an optimum raft thickness.

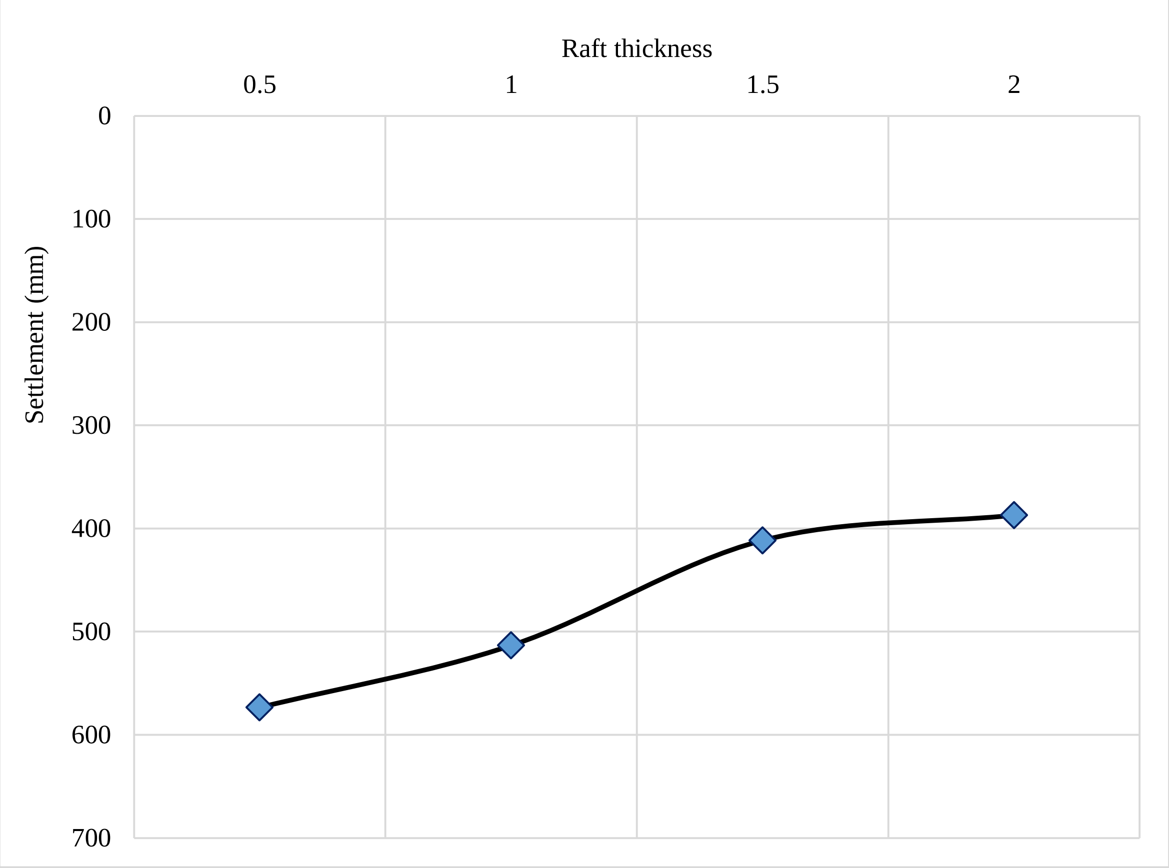


Figure 4- 3: Raft thickness vs the ultimate maximum raft center

From Figure 4-3, Increasing the raft thickness reduces the overall settlement of the piled raft foundation. Specifically increasing the thickness from 1m to 1.5m has a significant effect of the settlement reduction.

In order to observe the influence of raft thickness on the settlement behavior of the piled raft, a diagonal path was created from the raft center to raft corner. The following figure 4-4 describe the variation of raft center settlement for 0.5m, 1.0m, and 2.0m raft thicknesses along this diagonal path from the center of the raft.

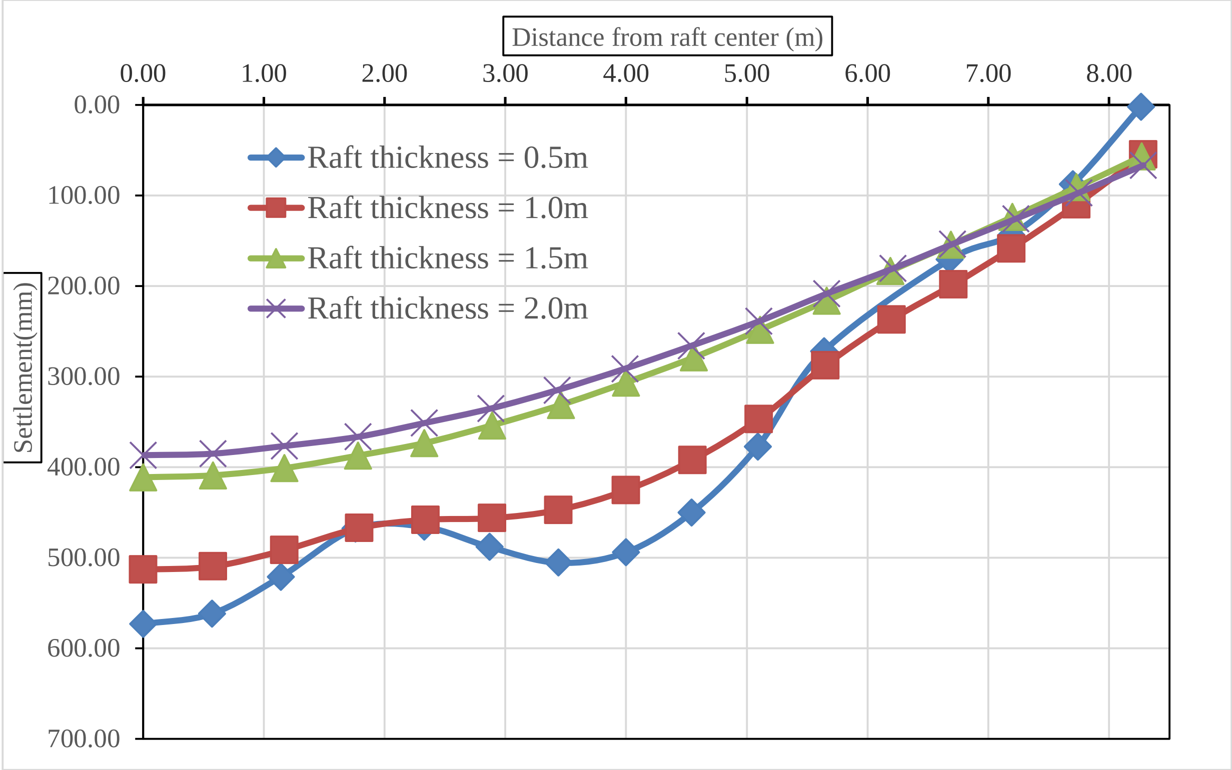


Figure 4- 4: Raft top settlement for various raft thickness along diagonal path from center of the raft

The above figure 4-4 describes Raft top settlement for various raft thickness along diagonal path from center of the raft. It can be observed that a raft thickness of 0.5m piled raft showed undulating result, by further increasing the raft thickness the results showed more realistic value, which have a maximum value at the raft center and a smaller settlement value as we move further from the raft center.

4.4. NUMBER OF PILES

4.4.1. Effect of number of piles on the maximum central settlement

In order to investigate the effect of increasing number of piles on the settlement of the piled raft foundation system, as shown in Table 4-1, a 2x2 (4 piles), 3x3 (9 piles) & 4x4 (16 piles) pile arrangements (Number of piles) were considered.

Table 4-4 below shows the settlement variation of the unpiled raft foundation and the piled raft foundation considering different number of piles considered.

Table 4- 4: Load and settlement for different number of piles

Load (Mpa)	**Pile arrangement (Number of piles)**				
	Raft only	1 pile	2x2 (4 piles)	3x3 (9 piles)	4x4 (16 piles)
	Settlement (mm)	Settlement (mm)	Settlement (mm)	Settlement (mm)	Settlement (mm)
0.00	0.00	0.00	0.00	0.00	0.00
0.03	9.31	8.49	7.76	6.69	5.20
0.06	19.91	18.16	16.60	14.31	11.12
0.08	29.00	26.44	24.18	20.83	16.19
0.11	44.27	40.38	36.91	31.80	24.72
0.13	54.79	49.97	45.68	39.36	30.60
0.15	68.83	62.77	57.38	49.44	38.43
0.18	87.67	79.95	73.09	62.98	48.96
0.19	100.60	94.40	84.40	70.00	55.00
0.22	118.80	113.78	104.02	88.28	67.60
0.25	145.60	134.43	122.90	107.21	81.34
0.29	175.60	163.44	149.42	126.80	97.72
0.30	191.30	177.52	162.30	141.15	108.10
0.33	219.40	211.51	193.37	163.33	127.92
0.37	255.60	242.00	225.00	193.40	152.89
0.40	306.30	290.16	265.28	228.56	177.67
0.42	348.80	331.34	302.93	261.00	208.41
0.45	406.90	384.41	351.45	302.80	235.39
0.47	485.00	461.26	421.71	363.34	279.69
0.49	578.80	536.85	490.81	422.88	328.73
0.50	693.06	632.03	577.83	497.85	387.01

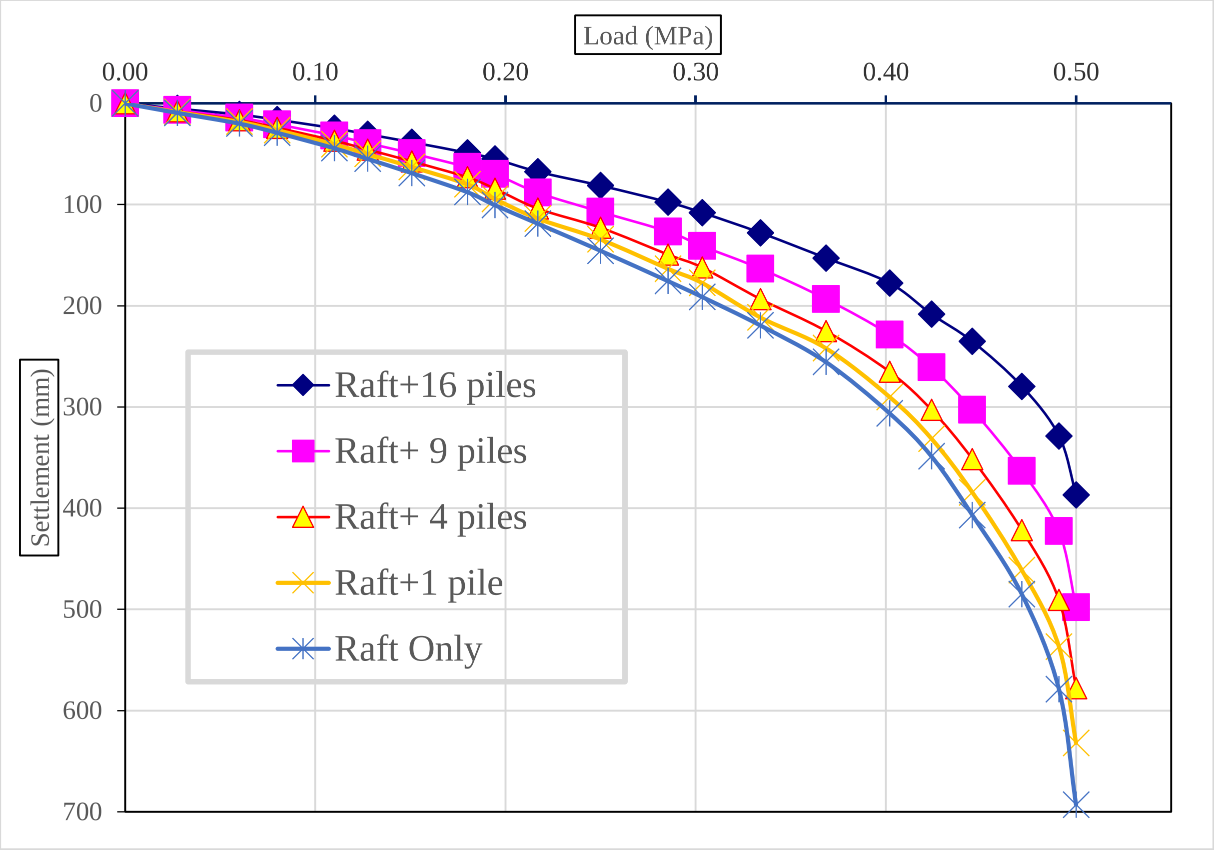


Figure 4- 5: Load vs Settlement for different number of piles

Referring Figure 4-5 , increasing the number of piles reduces the overall settlement of the piled raft foundation. Specifically increasing the number of piles from 9 to 16 has a significant effect on the settlement reduction as indicated in table 4-5.

Additionally, overall settlement behavior of a piled raft with a single pile is more or less similar with that of unpiled raft foundation.

Table 4- 5: Percentage in raft settlement reduction for different number of piles

Number of piles	Settlement (mm)	Settlement reduction (%)
1	632.03	
4	577.83	8.58%
9	497.85	13.84%
16	387.01	22.26%

Table 4-5 shows the percentage in maximum raft center settlement reduction for different number of piles. It describes the ultimate maximum raft center settlement after the application of 0.5MPa uniformly distributed load. Comparing with the unpiled raft, a piled raft with one pile showed a 8.81 % settlement reduction. It can also seen that increasing the number of piles from 1 pile to 4 piles reduces the settlement by 8.58%, and by increasing the number of piles from 4 piles to 9 piles reduces the settlement by 13.84% and further increasing number of piles from9 piles to 16 piles results a settlement reduction of 22.26 %.

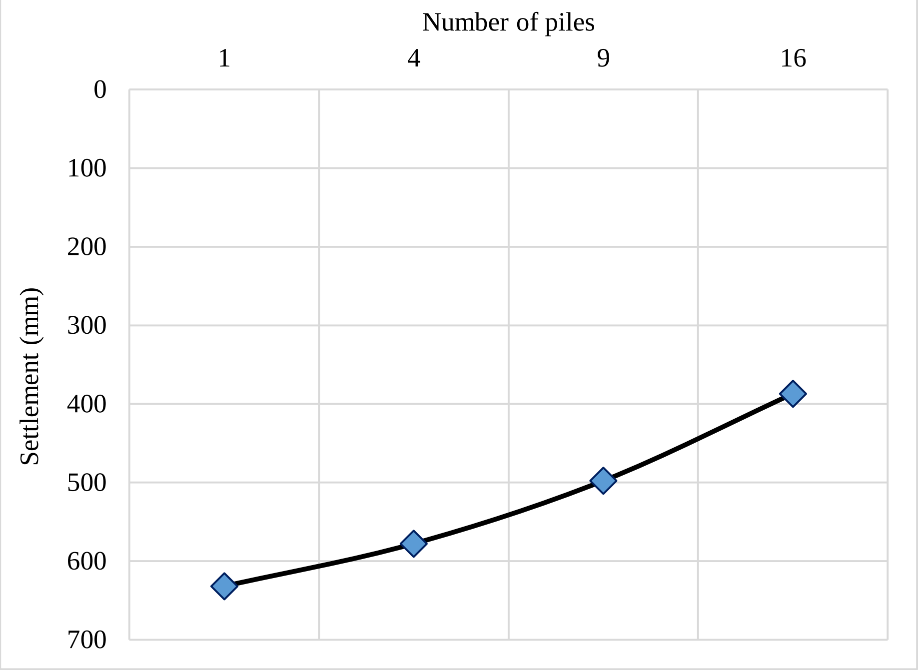


Figure 4- 6: Number of piles vs raft center settlement

In all considered cases the maximum settlement of the raft is always found to be at the center of the raft. In representing the results of settlement, often the raft settlement is normalized with the raft widths/B_r, where s is the raft center settlement and B_r is the width of the raft. As described earlier, the raft width is 12m. Besides the load is normalized by the maximum applied uniformly distributed load of 0.5MPa.

As shown in the figure 4-7 below describes Normalized settlement vs Normalized load for different number of piles. This can be used for different size piled raft foundations, since the plot is unit less.

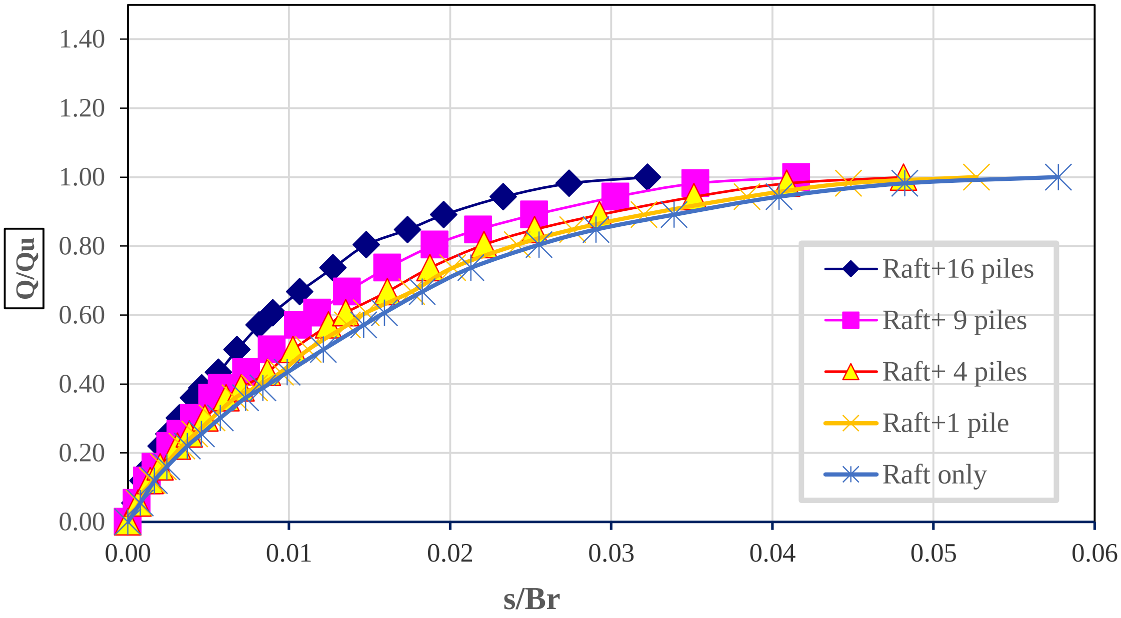


Figure 4- 7: Normalized settlement vs Normalized load for different number of piles

4.5. PILE SPACING

4.5.1. Effect of pile spacing on the maximum central settlement

Center to center pile spacing is one of the geometrical parameters that affect the bearing behavior of the piled raft foundation.

Four different models for four pile spacing's ($2D_p$,$3D_p$, $4D_p$, and $5D_p$) were developed and simulated. In order to model the soil continuum, the same material properties, boundary conditions, modeling technique mentioned in chapter 3 were used.

As indicated in the table 4-1A 12m by 12m square shaped raft with a thickness of 2m was used. 16 piles with a pile diameter of 0.6m and a pile length of 12m was modeled. After modeling and providing the appropriate boundary conditions, 0.5MPa uniformly distributed load was applied and the analysis job was submitted and run for the specified different pile spacings and the central settlement of the piled raft was filtered as shown in the Figure 4-8.

As the center to center spacing between the piles increases the lesser effect of the pile group action on its bearing behavior. i.e the pile's individual effect becomes more dominant than its group effect.

The numerical analysis result of ABAQUS 2017/CAE for different pile spacing, ranging from $2D_p$ to $5D_p$side by side with the previously discussed unpiled raft foundation is plotted in load vs settlement graph as shown in figure 4-8 below.

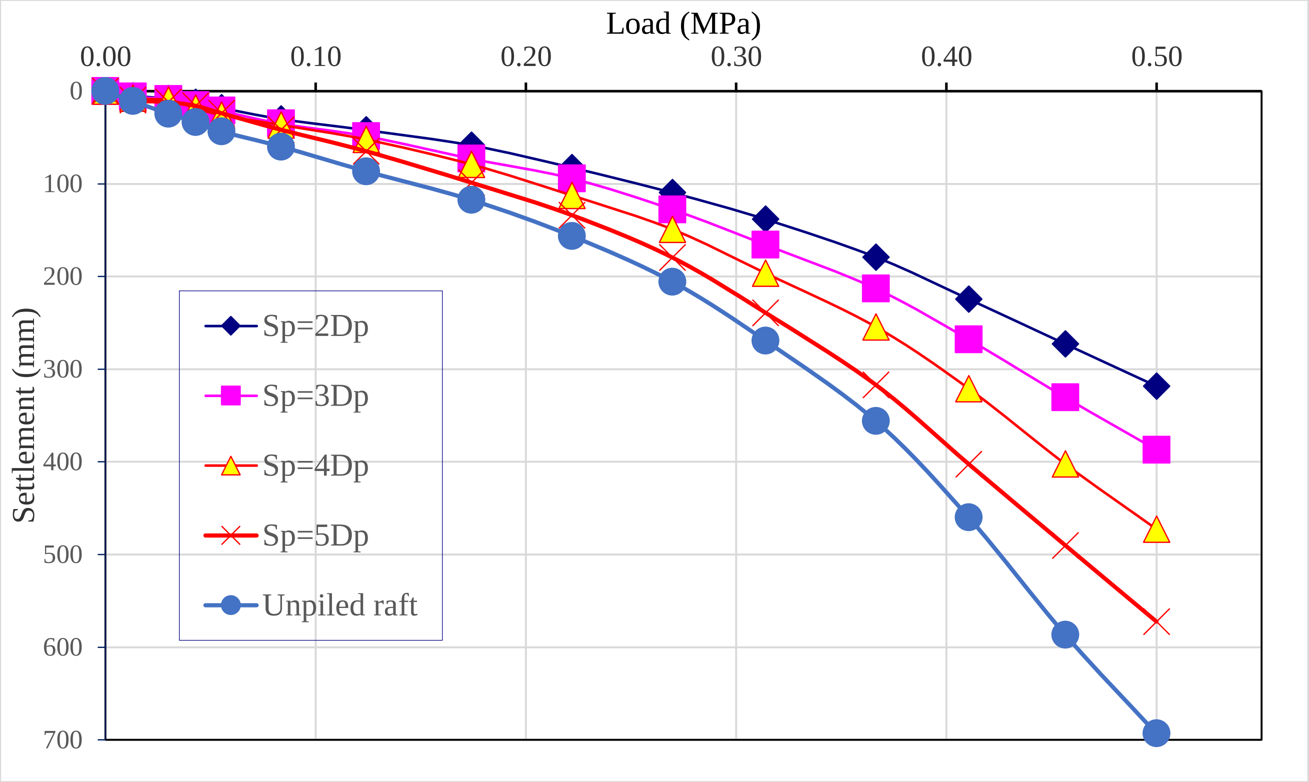


Figure 4- 8: Load vs settlement curve for specified pile spacing

Figure 4-8 shows that the settlement increases with the increase in pile spacing.Increasing the pile spacing beyond $4D_p$results in rapid fall in load bearing capacity of the piled raft and increases the increment rate of the central settlement.

Observing the pile spacing $5D_p$, further increase in pile spacing similar to that of unpiled raft foundation. Which indicates that for pile spacing greater than $5D_p$,only the raft footing is sufficient to carry the imposed structural load.

Table 4- 6: Maximum central settlement for different pile spacings

Spacing of piles		Maximum central settlement (mm)
XD_p	c/c pile spacing (m)	
$2D_p$	1.2	318.38
$3D_p$	1.8	387.00
$4D_p$	2.4	472.62
$5D_p$	3	572.40

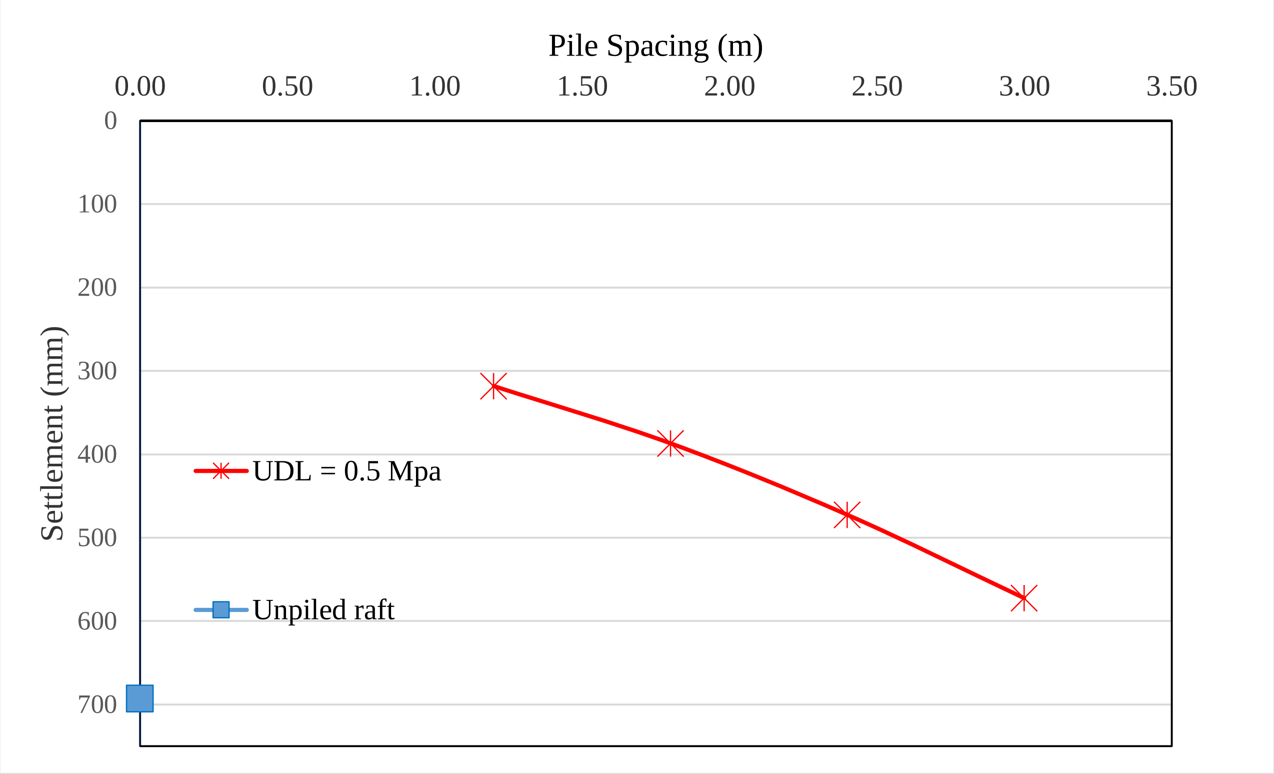


Figure 4- 9: Pile spacing vs central settlement

The raft Centre settlements for different spacing shows that the settlement increases with increase in spacing.As indicated in figure 4-9, the pile spacing and the raft Centre settlement have almost directly proportional relationship.

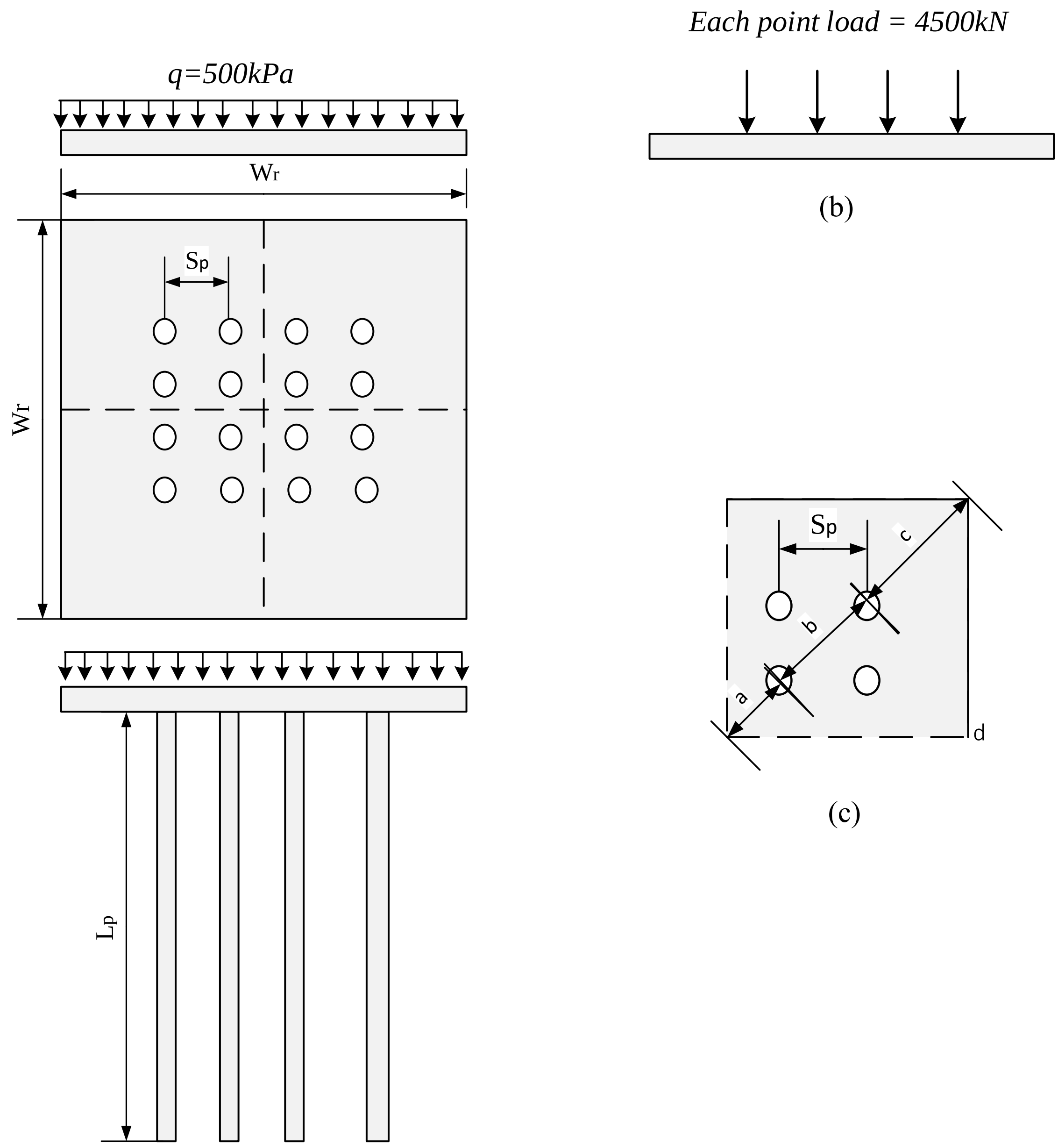
As illustrated, decreasing the pile spacing from $5D_p$to $2D_p$decreased the raft center settlement by 254.02mm,from this total decrement, 39.27% of the raft center settlement reduction was achieved by reducing the pile spacing from $5D_p$ to $4D_p$, 33.70% of the raft center settlement reduction was achieved by reducing the pile spacing from $4D_p$ to $3D_p$, and 27.01 % of the raft center settlement reduction was achieved by reducing the pile spacing from $3D_p$ to $2D_p$.

4.5.2. Effect of pile spacing on the bending moment of the piled raft

Using the same model discussed previously, referring Figure 4-10, in order to assess the effect of bending moment on the pile spacing of the piled raft the applied uniformly distributed load (UDL) is changed to Equivalent point loads (EPL) as shown in the Figure-10(b). First the total applied concentrated load can be obtained by dividing the total uniformly distributed load by the total area of the square shaped raft. Hence the total applied concentrated load becomes 72,000kN. Then by distributing this total concentrated load to the total number of piles, which is 16, then the equivalent point load (EPL) becomes 4500kN.Hence the bending moment is obtained by multiplying the EPL by its corresponding lever arm.

Since the raft considered is a square shaped raft, only the quarter of the model shown in Figure4-10(c) is taken, then the other quarters result is same as the quarter considered due to symmetry.

The bending moment using the EPLs is calculated in two directions; firstly,from the center of the raft to the middle edge corner of the raft (along the path a up to d as indicated in Figure 4-10(c)); And next from the center of the raft along the diagonal path up to the corner of the raft (Along the path a,b & c as indicated in Figure4 -10(c)). The obtained results of the effect of pile spacing on the bending moment of the piled raft is shown in Figure 4-11 and in Figure 4-12 respectively.



(b)

(c)

(a)

Figure 4- 10:(a) A uniformly distributed load (UDL) applied on the piled raft system; (b) Equivalent Point Load (EPL); (c) Quarter of the model considered

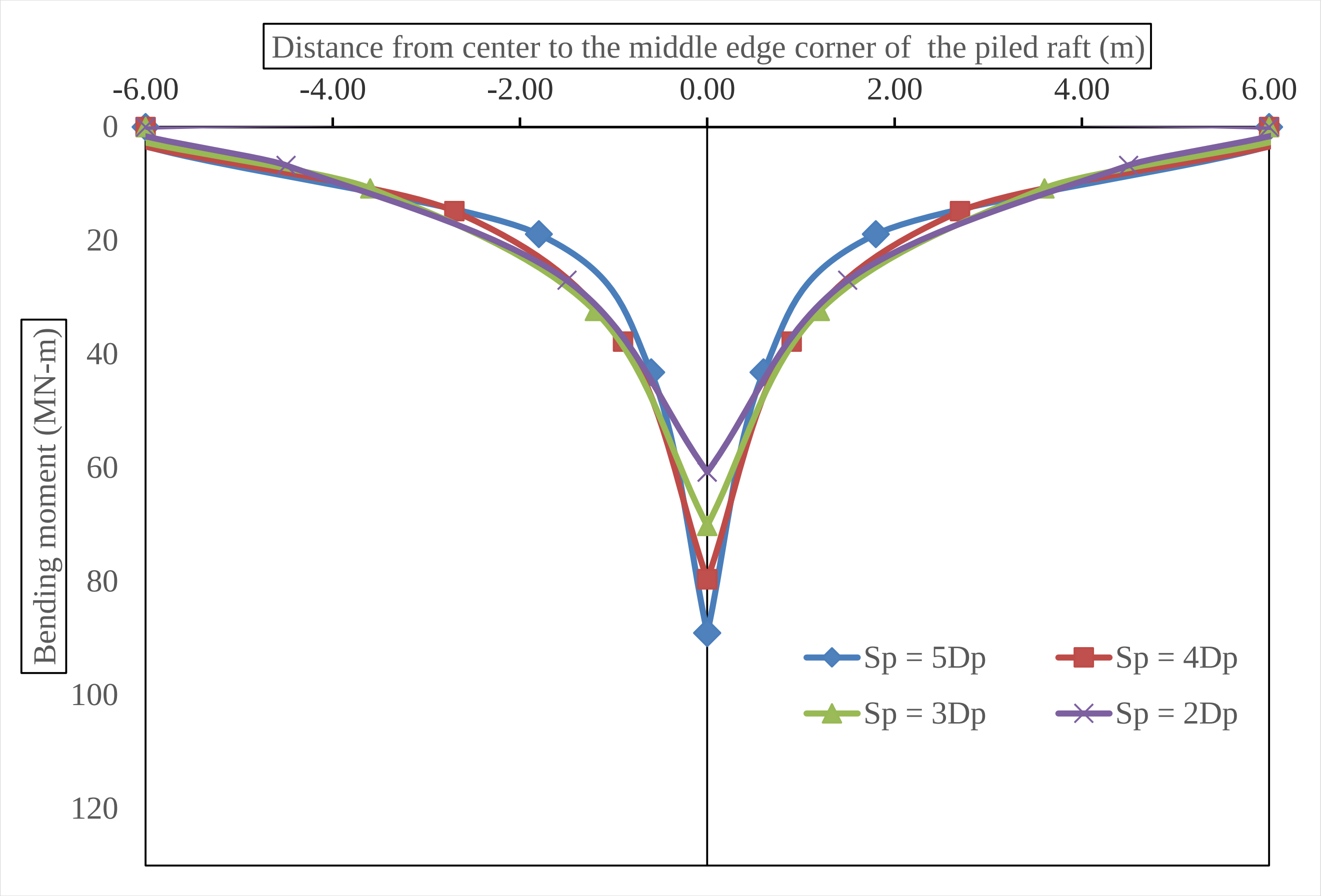


Figure 4- 11:Effect of pile spacing on bending moment of the piled raft from center to the middle corner.

Figure 4-11 indicates Effect of pile spacing on bending moment of the piled raft from center to the middle corner. The bending moment is maximum at the center of the raft, this is due to the uniformly distribution of the load and a uniform pile arrangement. For a larger pile spacing the produced maximum bending moment is larger.

The following Figure 4-12 shows the effect of pile spacing on bending moment of the piled raft along the diagonal path taken from the center of the raft to the corner of the raft. The bending moment decreases from the raft center up to the diagonal corner.

Regardless of the difference in the path direction considered Figure 4-11 and Figure 4-12 have more or less similar pattern. As the pile spacing is reduced the maximum bending moment becomes less. Hence optimum pile spacing minimizes the maximum moment produced in the piled raft system, which reduces cost by reducing reinforcement usage.

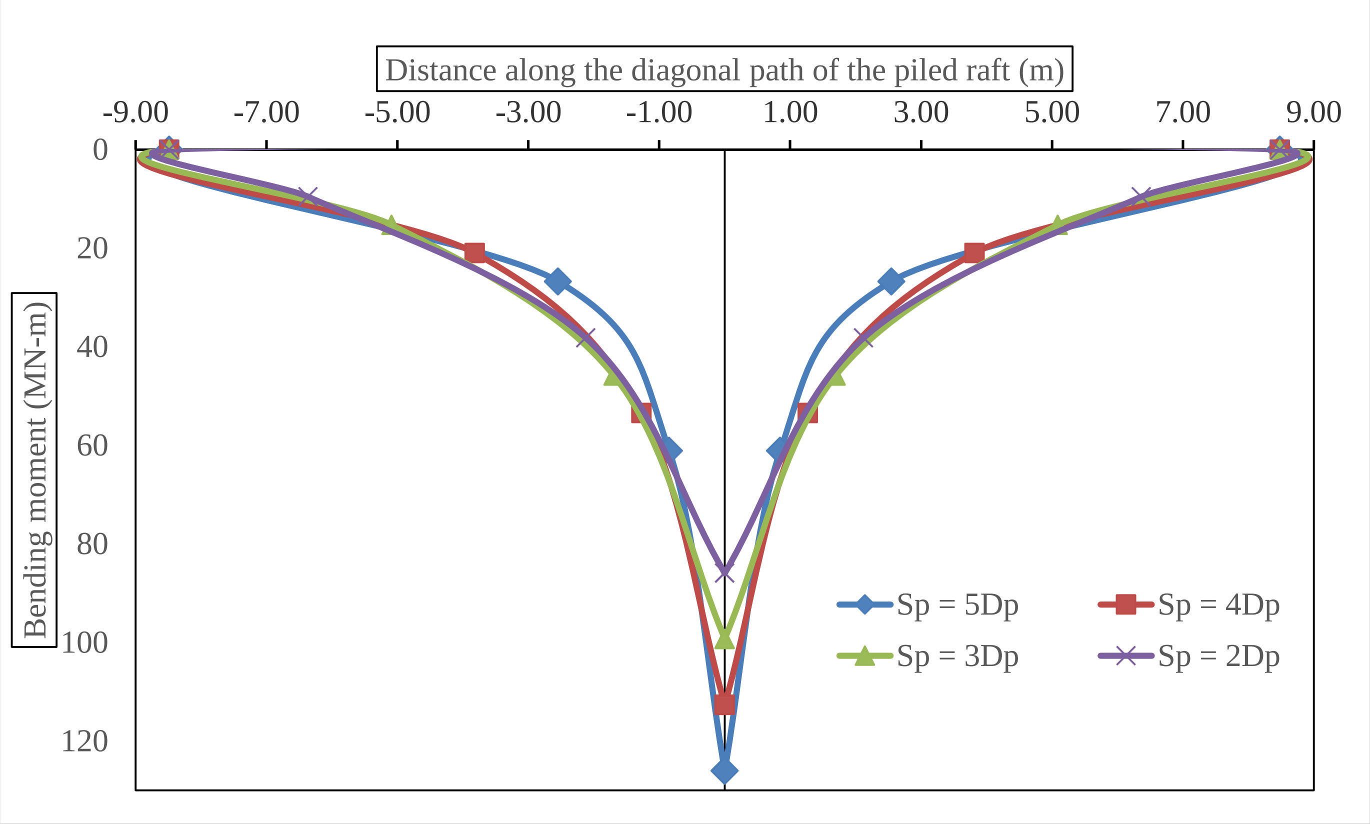


Figure 4- 12: Effect of pile spacing on bending moment of the piled raft along the diagonal path

Filtering the maximum bending moments for each corresponding center to center pile spacing, Figure 4-13 shows Maximum bending moment for various pile spacings. From this Figure the Maximum bending moment have a directly relationship with the pile spacing for this specific case.

Table 4- 7: Maximum bending moment for different pile spacings

c/c pile spacing	***Maximum Bending moment (MN-m)***
$2d_p$	85.91
$3d_p$	99.28
$4d_p$	112.64
$5d_p$	126.01

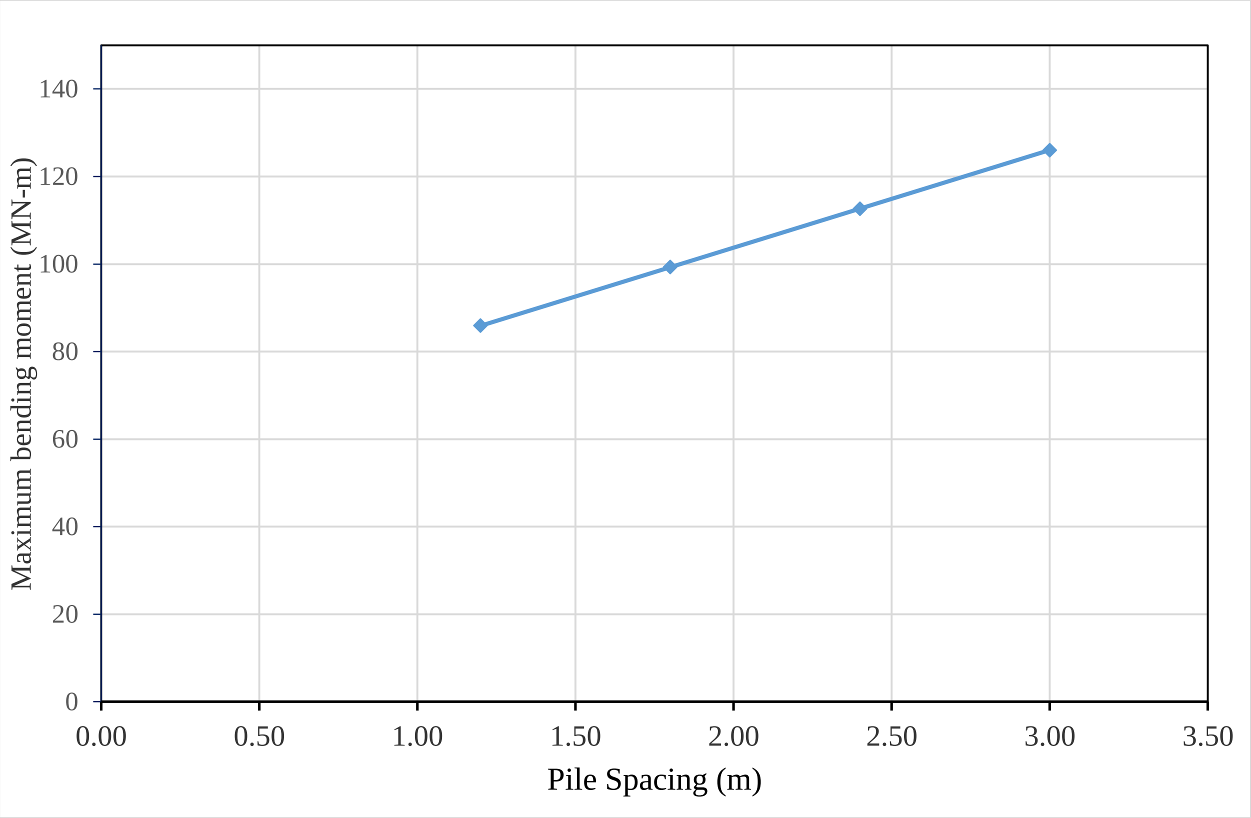


Figure 4- 13: Maximum bending moment for various pile spacings

4.6. PILE LENGTH

4.6.1. Effect of pile length on the maximum central settlement

Pile length have an important role on the bearing behavior of the piled raft. Particularly, when it comes to clayey soil, the pile group acts as floating pile and most of the load is transmitted by the pile shaft friction. This skin friction occurs on the external surface area of the pile, which highly depends on the pile length.

To model the soil continuum, the same boundary condition, same properties and modeling technique, mentioned in chapter 3 is used. For the raft and piles the same concrete property as in previous section and same uniformly distributed load of 0.5Mpa was imposed on top of the raft for each case.

As indicated in the table 4-1: a 12m by 12m with a raft thickness of 2m raft and a 0.6m diameter of pile is modeled with four different length of pile i.e 6m, 12m, 18m and 24m long piles with corresponding length to diameter ratio of 10, 20, 30, and 40 respectively.

Table 4- 8:Raft Centre settlement for different pile lengths

L_p/D_p	Length of pile (m)	Raft Center settlement (mm)
10	6	551.92
20	12	387.01
30	18	261.45
40	24	173.64

As shown in the figure 4-10 belowThe pile length has inverse relation with the central settlement. As length of piles increases from the 6m to 24m, the raft centre settlement reduces from 551.92mm to 173.64mm. Hence a total of 378.28mm settlement is reduced by increasing the pile length from 6m to 24m. from this settlement reduction, 44% is reduction is obtained by increasing the pile length from 6m to 12m,

It can also be observed that by increasing the pile length from 6m to 12m, from 12m to 18m, and from 18m to 24m 44%, 33.2%, and 23.2% of 378.28mm settlement (total settlement reduction) is reduced respectively.

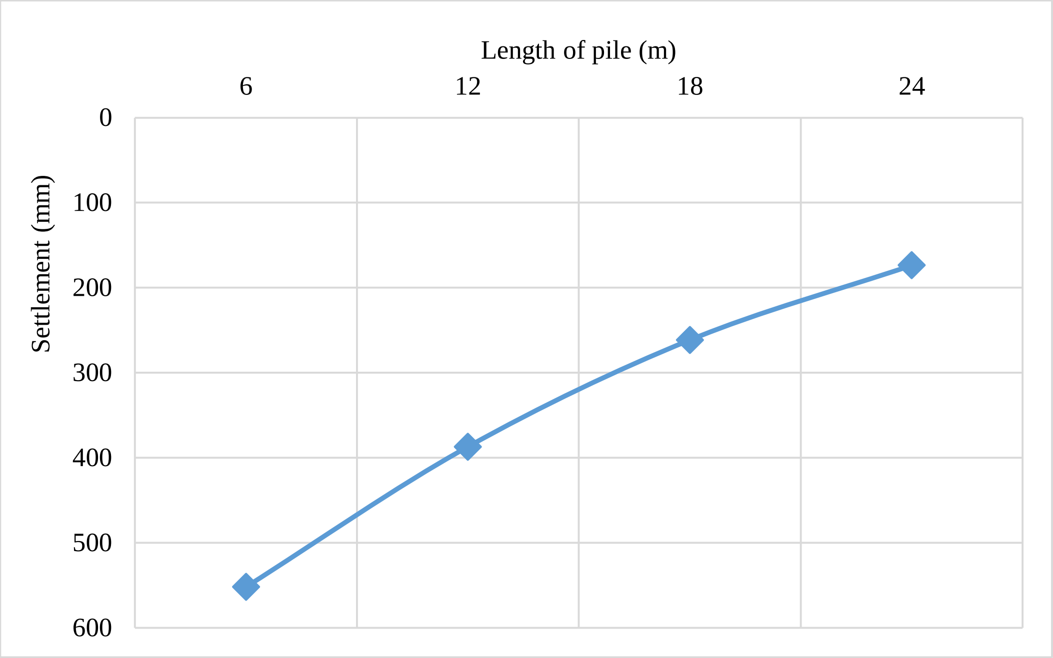


Figure 4- 14: Length of pile vs Raft center settlement

Figure 4-11below indicates that the central settlement is the maximum settlement, the settlement reduces moving from the raft center to the diagonal corner of the piled raft.

In this figure, the settlement of the top of raft for different pile length along a diagonal path. It is observed that as the pile length increases, both the center and corner settlement decreases, which indicates the reduction in the differential settlement.

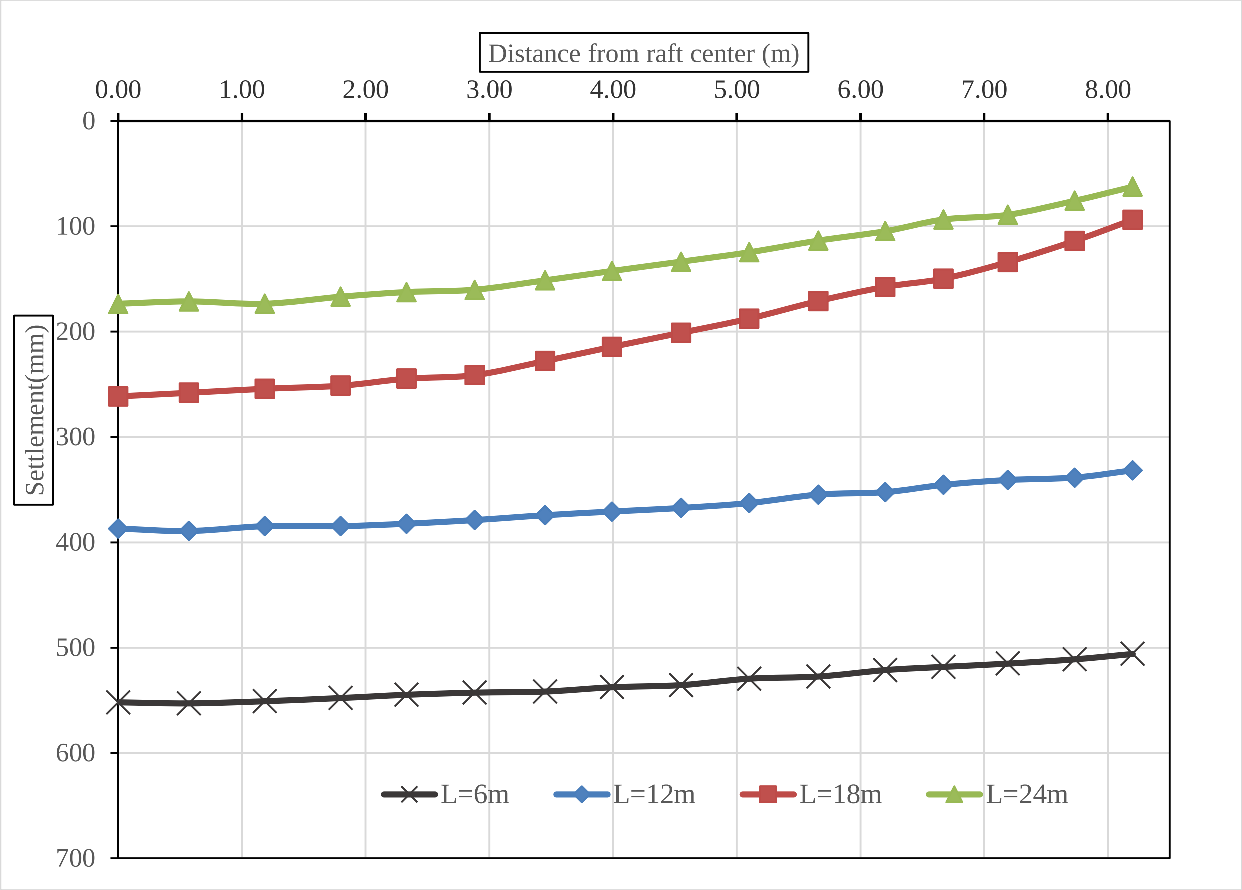


Figure 4- 15: Raft top settlement for various pile length

It can be observed that, it will be feasible or more economical to use a length of 12m.

4.7. PILE DIAMETER

4.7.1. Effect of diameter of piles on the maximum central settlement

The pile diameter is another important parameter in transmitting the load to the underlaying soil. Especially for end bearing piles the pile tip diameter has an influence on the bearing behavior of the foundation system.

To model the soil continuum, the same boundary condition, same properties and modeling technique, mentioned in chapter 3 is used. For the raft and piles the same concrete property as in previous section and same uniformly distributed load of 0.5Mpa was imposed on top of the raft for each case.

As describe in table 4-1The load settlement behavior of a piled raft is observed by modeling four diameters of piles which have a size of 0.3m, 0.45m, 0.6m and 0.75m. The

12m by 12m raft has a thickness of 2m and the length of piles is 12m with center to center spacing of piles 3D$_p$.

The numerical investigation analysis result of ABAQUS/2017 CAE software in the form of raft top settlement is described in the Figure 4-12

In each discussed case, the center point settlement decreased with increased pile diameters. This result is somehow similar to the influences of pile length on settlement behavior.

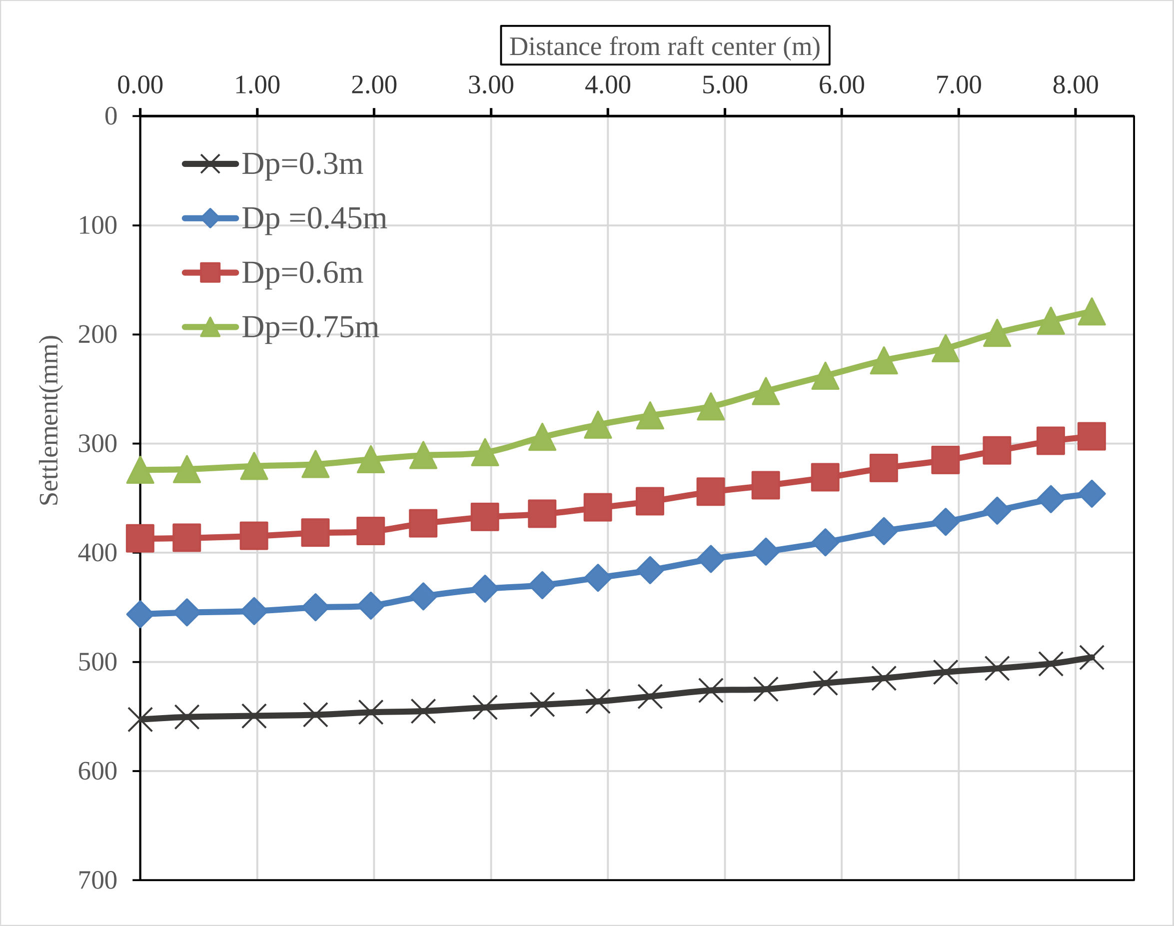


Figure 4- 16: Diagonal distance from raft center vs raft center settlement for various pile diameters

In order to see the effect of maximum raft center settlement for different Diameter the maximum raft center settlements are tabulated in table 4-8and displayed in the figure 4-13.

Table 4- 9: Raft center settlement for various pile diameters

Pile Diameter (m)	**Raft center settlement (mm)**
0.30	552.75
0.45	456.35
0.60	387.01
0.75	324.00

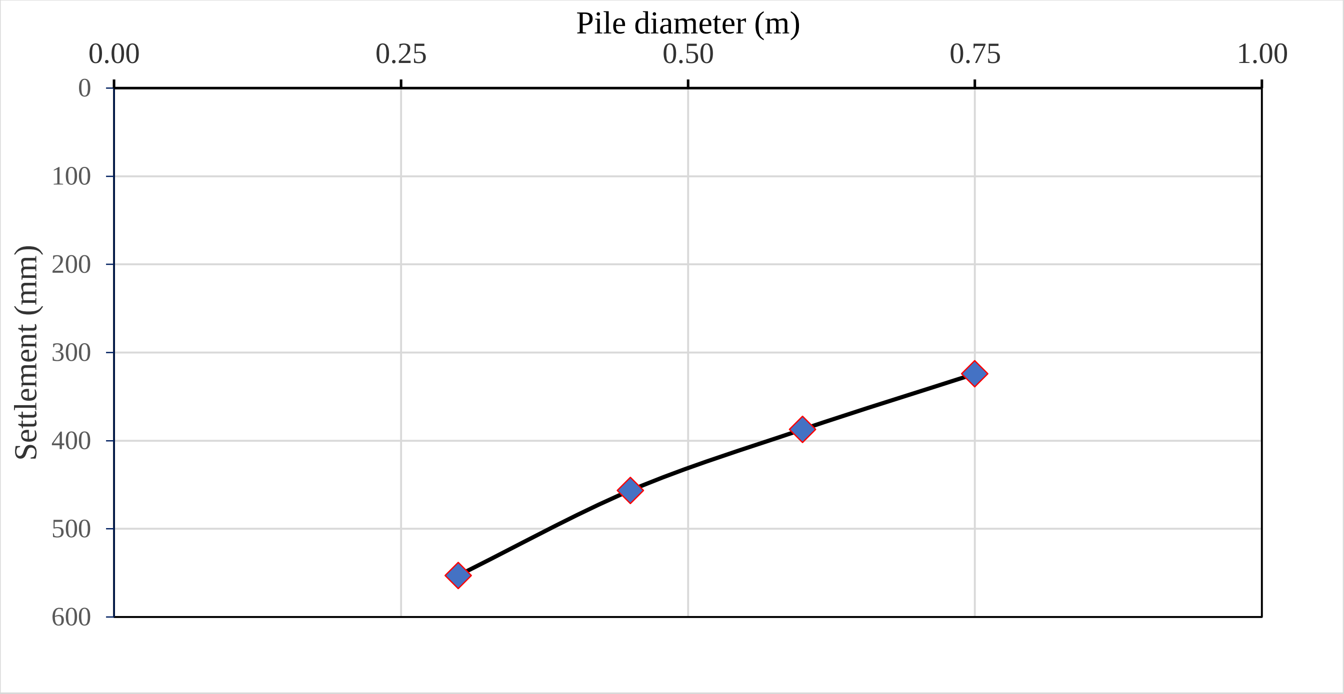


Figure 4- 17: Raft center settlement for different Diameter of piles

An economical design requires the proper optimization of length and diameter hence cross-sectional area to reduce settlement with less pile material usage.

CHAPTER 5

5. CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

a) It was observed that, by increasing raft thickness from 0.5 to 2m, the settlement was reduced by 32.51%. Specifically increasing the thickness from 1m to 1.5m has a significant effect of the settlement reduction. Further increment in the raft thickness have insignificant effect in the settlement reduction.

b) Increasing number of piles from 1 to 16 piles, settlement amount was reduced by 38.76%.Specifically increasing the number of piles from 9 to 16 has a significant effect on the settlement reduction.The addition of even a small number of piles under the central area of the raft increases the load bearing capacity of the piled raft, and this enhancement effect increases as the number of piles increases.

c) By increasing the length of piles from 6m to 24m, the overall settlement of piled raft foundation is reduced. Another point to be considered is that the settlement response of the piled raft was somehow similar for the piles with a length of 18m and 24m.

d) The results indicate that choosing the proper combination of length and spacing for piles can lead to acceptable differential and total settlements while a high percentage of total bearing capacity of piles can be mobilized, which is an efficient solution for piled raft foundation systems. Therefore, an economical design requires the proper optimization of length and diameter hence cross-sectional area to reduce settlement with less pile material usage.

e) The average and differential settlements of the piled raft are dependent on the combination of pile geometries; thus, the design of pile &raft geometries should be carefully considered to satisfy the acceptable settlement criteria.

5.2. RECOMMENDATION

The following recommendations are given for future researchers:

a. The five parameters studied are not the only parameters that affect piled raft foundation. The are many parameters that affect the behavior of piled raft foundation other thanraft thickness, pile number, pile diameter, pile length and pile spacing explained in different literature that are not well studied.

b. Simultaneous variation of pile diameter and pile spacing shall be considered.

c. Laboratory experimentation and validation of the analysis's outputs obtained from ABAQUSon the load sharing, settlement, and differential settlement between rafts and piles.

d. Complex loading patterns like eccentric, lateral loadings and dynamic loading cases shall be studied.

e. The present study shall be extended to complex soil strata conditions. The assumption of homogenous stiff clay through the whole part of soil where pile passes is hypothetical and hardly seems practical. So, there should have to be real strata of soil with known properties to analyze the piled raft foundation.

f. The current study shall be extended by considering dynamic analysis

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APPENDICES

Table A - 1:Normalized settlement and normalized load for different number of piles

Q/Q$_u$	Raft center settlement to raft width ratio (s/B$_r$)				
	Raft only	1 Pile	2x2 (4 Piles)	3x3 (9 Piles)	4x4 (16 Piles)
0.00	0.0000	0.0000	0.0000	0.0000	0.0000
0.06	0.0008	0.0007	0.0006	0.0006	0.0004
0.12	0.0017	0.0015	0.0014	0.0012	0.0009
0.16	0.0024	0.0022	0.0020	0.0017	0.0013
0.22	0.0037	0.0034	0.0031	0.0027	0.0021
0.26	0.0046	0.0042	0.0038	0.0033	0.0025
0.30	0.0057	0.0052	0.0048	0.0041	0.0032
0.36	0.0073	0.0067	0.0061	0.0052	0.0041
0.39	0.0084	0.0079	0.0070	0.0058	0.0046
0.43	0.0099	0.0095	0.0087	0.0074	0.0056
0.50	0.0121	0.0112	0.0102	0.0089	0.0068
0.57	0.0146	0.0136	0.0125	0.0106	0.0081
0.61	0.0159	0.0148	0.0135	0.0118	0.0090
0.67	0.0183	0.0176	0.0161	0.0136	0.0107
0.74	0.0213	0.0202	0.0188	0.0161	0.0127
0.80	0.0255	0.0242	0.0221	0.0190	0.0148
0.85	0.0291	0.0276	0.0252	0.0217	0.0174
0.89	0.0339	0.0320	0.0293	0.0252	0.0196
0.94	0.0404	0.0384	0.0351	0.0303	0.0233
0.98	0.0482	0.0447	0.0409	0.0352	0.0274
1.00	0.0578	0.0527	0.0482	0.0415	0.0323

Table A - 2: Load vs settlement for different spacing of piles

Load(Mpa)	Settlement (mm)			
	Spacing S_p = $2D_p$	Spacing S_p = $3D_p$	Spacing S_p = $4D_p$	Spacing S_p = $5D_p$
0.00	0.00	0.00	0.00	0.00
0.01	5.06	6.09	7.55	9.67
0.03	7.95	8.52	9.60	11.95
0.04	12.08	15.20	18.25	16.04
0.05	18.01	21.28	25.85	24.00
0.08	30.04	35.07	36.48	41.80
0.12	41.99	48.63	52.15	65.00
0.17	58.44	72.94	79.07	98.94
0.22	82.51	94.22	112.55	133.98
0.27	109.63	127.72	149.12	179.71
0.31	138.27	165.81	196.39	239.21
0.37	179.09	213.07	254.36	317.05
0.41	224.49	267.98	326.08	402.54
0.46	272.94	330.54	402.40	498.00
0.50	318.38	387.00	472.62	572.40

Table A - 3: Settlement variation Along diagonal path from center of the raft for a raft thickness of 0.5m

Distance from raft center (m)	Settlement (mm)
0.00	573.40
0.57	561.93
1.14	521.28
1.76	468.10
2.33	466.01
2.87	488.22
3.44	505.63
4.00	494.17
4.54	450.38
5.09	377.40
5.64	272.10
6.68	170.98
7.19	143.87
7.70	87.83
8.26	2.09

Table A - 4: Settlement variation Along diagonal path from center of the raft for a raft thickness of 1.0m

Distance from raft center (m)	Settlement (mm)
0.00	513.30
0.58	509.83
1.17	491.75
1.79	467.36
2.34	458.29
2.89	456.44
3.44	447.34
4.00	425.69
4.55	392.30
5.10	347.19
5.65	287.68
6.20	237.17
6.71	198.40
7.19	158.69
7.73	109.99
8.28	54.98

Table A - 5: Settlement variation Along diagonal path from center of the raft for a raft thickness of 1.5m

Distance from raft center (m)	Settlement (mm)
0.00	411.43
0.58	409.29
1.17	401.32
1.78	387.51
2.33	373.70
2.89	354.05
3.46	331.48
4.00	306.73
4.56	279.10
5.11	248.46
5.66	216.41
6.19	183.63
6.69	154.50
7.20	123.90
7.73	91.12
8.27	56.88

Table A - 6: Settlement variation Along diagonal path from center of the raft for a raft thickness of 2.0m

Distance from raft center (m)	Settlement (mm)
0.00	387.01
0.58	385.33
1.17	376.87
1.78	366.73
2.33	351.52
2.88	335.47
3.43	315.19
3.99	291.53
4.54	266.18
5.10	239.14
5.66	208.72
6.21	180.83
6.70	153.79
7.23	125.91
7.75	97.18
8.28	66.76

Table A - 7: Settlement of the top of raft for different pile length

Distance from raft center (m)	Settlement (mm)			
	L=6m	L=12m	L=18m	L=24m
0.00	551.92	387.01	261.45	173.64
0.57	552.94	389.31	258.08	171.40
1.19	550.90	384.71	254.23	173.62
1.80	547.83	384.71	251.36	166.94
2.33	544.76	382.40	244.67	162.50
2.88	542.70	378.95	241.33	160.28
3.45	541.70	374.33	227.90	151.36
3.99	537.61	370.88	214.49	142.45
4.55	535.57	367.43	201.09	133.55
5.10	529.43	362.81	187.68	124.65
5.66	527.39	354.76	170.94	113.53
6.20	521.26	352.45	157.53	104.62
6.67	518.19	345.54	149.76	93.48
7.19	515.13	340.93	134.07	89.04
7.73	511.04	338.63	113.95	75.68
8.20	505.93	331.72	93.83	62.32

Table A - 8: settlement for various piles along the diagonal path from center of the raft

Distance from the raft center (m)	**Settlement (mm)**			
	D_p=0.3m	D_p=0.45m	D_p=0.6m	D_p=0.75m
0	552.75	456.35	387.01	324.00
0.4	550.53	454.82	386.41	323.28
0.974	549.47	453.48	384.57	320.48
1.498	548.54	450.12	381.73	318.84
1.971	546.21	448.48	380.34	314.28
2.42	545.13	439.94	373.09	310.62
2.95	541.80	433.13	367.32	307.95
3.44	539.18	429.76	364.46	293.90
3.915	536.25	422.94	358.68	282.69
4.36	531.76	416.11	352.88	274.32
4.88	526.17	405.84	344.18	265.97
5.35	525.09	399.01	338.38	251.91
5.86	519.49	390.46	331.13	237.87
6.36	515.01	380.18	322.41	223.83
6.89	509.40	371.64	315.17	212.64
7.33	506.05	361.40	306.48	198.56
7.79	501.74	351.06	297.72	187.35
8.14	495.97	345.95	293.39	178.93

Table A - 9: Normalized settlement and corresponding load for unpiled raft taken from Centrifuge test results from (Lee J. , 2014)

s/B_r	Load (MN)	s/B_r	Load (MN)	s/B_r	Load (MN)
0.00000	0.00	0.02224	11.63	0.05620	17.56
0.00019	0.06	0.02436	12.22	0.05754	17.50
0.00019	0.41	0.02657	12.75	0.05927	17.62
0.00058	1.17	0.02917	13.39	0.06004	18.03
0.00106	1.64	0.03167	13.74	0.06023	17.15
0.00202	1.94	0.03321	14.16	0.06139	16.98
0.00212	2.29	0.03705	14.86	0.06302	17.21
0.00231	2.64	0.03811	14.92	0.06475	17.27
0.00231	3.05	0.03975	15.10	0.06648	17.27
0.00289	3.58	0.04081	15.10	0.06793	17.33
0.00347	4.17	0.04225	15.27	0.06908	17.27
0.00395	4.82	0.04331	15.33	0.07052	17.33
0.00540	5.99	0.04494	15.68	0.07197	17.62
0.00646	6.58	0.04600	15.98	0.07350	18.03
0.00761	7.58	0.04706	15.98	0.07514	18.21
0.00906	8.11	0.04850	16.21	0.07649	18.44
0.01060	8.75	0.04965	16.39	0.07899	18.56
0.01233	9.46	0.05042	16.33	0.08062	18.38
0.01435	9.93	0.05129	16.74	0.08177	18.44
0.01666	10.46	0.05244	17.15	0.08331	18.44
0.01858	10.75	0.05446	17.21	0.08427	18.33
0.02003	11.16	0.05533	17.56		

Table A - 10: Normalized settlement and corresponding load for piled raft taken from Centrifuge test results from (Lee J. , 2014)

s/B_r	Load (MN)	s/B_r	Load (MN)	s/B_r	Load (MN)	s/B_r	Load (MN)	s/B_r	Load (MN)
-	-	0.00097	13.75	0.01511	22.98	0.03819	27.89	0.06194	30.85
0.00010	0.47	0.00155	14.27	0.01608	23.16	0.03954	27.95	0.06280	30.73
0.00010	1.06	0.00165	14.92	0.01704	23.51	0.04070	28.01	0.06541	30.62
0.00021	2.00	0.00185	15.92	0.01849	23.87	0.04205	28.07	0.06637	30.86
0.00031	2.88	0.00205	16.57	0.01965	24.22	0.04302	28.30	0.06744	31.09
0.00022	3.58	0.00253	17.10	0.02158	24.46	0.04340	28.36	0.06782	30.86
0.00013	4.23	0.00312	17.62	0.02226	24.93	0.04495	28.60	0.07042	30.74
0.00023	5.05	0.00389	18.21	0.02303	24.99	0.04621	28.89	0.07149	31.10
0.00033	5.52	0.00447	18.62	0.02342	25.23	0.04833	29.07	0.07313	31.04
0.00052	6.05	0.00486	18.86	0.02487	25.46	0.04968	29.43	0.07361	31.04
0.00043	6.70	0.00515	19.15	0.02545	25.58	0.05055	29.43	0.07419	31.75
0.00044	7.40	0.00612	19.80	0.02661	25.82	0.05123	29.66	0.07506	31.81

s/Br	Load (MN)	s/Br	Load (MN)	s/Br	Load (MN)	s/Br	Load (MN)	s/Br	Load (MN)
0.00035	8.05	0.00738	20.27	0.02757	25.94	0.05258	29.84	0.07612	32.04
0.00045	8.46	0.00834	20.69	0.02873	26.11	0.05402	29.84	0.07728	32.34
0.00045	9.16	0.00931	20.98	0.02902	26.29	0.05499	30.14	0.07824	32.16
0.00075	10.16	0.00999	21.39	0.03018	26.64	0.05605	30.20	0.07969	32.11
0.00095	11.28	0.01115	21.86	0.03192	26.82	0.05721	30.20	0.08065	31.99
0.00086	11.98	0.01192	22.10	0.03346	27.06	0.05808	30.32	0.08162	32.05
0.00076	12.51	0.01250	22.33	0.03530	27.35	0.05904	30.55	0.08355	31.99
0.00106	13.04	0.01395	22.75	0.03694	27.65	0.06068	30.56	0.08403	32.29

Table A - 11: Normalized settlement and corresponding load for unpiled raft obtained from ABAQUS software

s/B_r	Load (MN)	s/B_r	Load (MN)
-	-	0.02810	12.71
0.00121	1.16	0.03500	14.28
0.00139	1.83	0.04200	15.91
0.00237	2.89	0.04800	17.35
0.00387	3.95	0.05350	18.59
0.00543	4.86	0.05882	19.55
0.00861	6.27	0.06380	20.45
0.01334	8.15	0.07200	21.64
0.01720	9.38	0.08140	22.68
0.02057	10.43	0.09140	23.64
0.02385	11.38	0.10000	24.39

Table A - 12: Normalized settlement and corresponding load for piled raft obtained from ABAQUS software

s/B_r	Load (MN)	s/B_r	Load (MN)
-	-	0.01517	21.76
0.00039	6.59	0.01981	23.05
0.00031	7.16	0.02454	24.15
0.00040	8.16	0.02978	25.38
0.00068	11.14	0.03480	26.48
0.00138	12.70	0.04000	27.67
0.00277	15.69	0.04460	28.64
0.00458	17.05	0.04990	29.74
0.00545	17.62	0.05565	30.82
0.00657	18.30	0.06551	32.49
0.00990	19.88	0.07479	33.87

Table A - 13: Calculation of bending moment along diagonal path of the top of the raft

Point number	**Diagonal distance from center(m)**	**Lever arm from corner (m)**	**EPL(kNm)**	**Bending Moment (kNm)**	**Bending Moment (MNm)**
	$S_p = 5D_p$				
1	0.00	8.49	4500	126006.43	126.01
2	0.85	7.64	4500	61094.03	61.09
3	2.55	5.94	4500	26728.64	26.73
4	8.49	0.00	4500	0.00	0.00
4	-8.49	0.00	4500	0.00	0.00
3	-2.55	5.94	4500	26728.64	26.73
2	-0.85	7.64	4500	61094.03	61.09
1	0.00	8.49	4500	126006.43	126.01
	$S_p = 4D_p$				
1	0.00	8.49	4500	112642.11	112.64
2	1.27	7.21	4500	53457.27	53.46
3	3.82	4.67	4500	21001.07	21.00
4	8.49	0.00	4500	0.00	0.00
4	-8.49	0.00	4500	0.00	0.00
3	-3.82	4.67	4500	21001.07	21.00
2	-1.27	7.21	4500	53457.27	53.46
1	0.00	8.49	4500	112642.11	112.64
	$S_p = 3D_p$				
1	0.00	8.49	4500	99277.79	99.28
2	1.70	6.79	4500	45820.52	45.82
3	5.09	3.39	4500	15273.51	15.27
4	8.49	0.00	4500	0.00	0.00
4	-8.49	0.00	4500	0.00	0.00
3	-5.09	3.39	4500	15273.51	15.27
2	-1.70	6.79	4500	45820.52	45.82
1	0.00	8.49	4500	99277.79	99.28
	$S_p = 2D_p$				
1	0.00	8.49	4500	85913.47	85.91
2	2.12	6.36	4500	38183.77	38.18
3	6.36	2.12	4500	9545.94	9.55
4	8.49	0.00	4500	0.00	0.00
4	-8.49	0.00	4500	0.00	0.00
3	-6.36	2.12	4500	9545.94	9.55
2	-2.12	6.36	4500	38183.77	38.18
1	0.00	8.49	4500	85913.47	85.91

Table A - 14:Calculation of bending moment along from the center to the middle edge corner of the raft

Point number	Distance from center(m)	Lever arm from Middle edge corner (m)	EPL(kNm)	Bending Moment (kN-m)	Bending Moment (MN-m)
	$S_p = 5D_p$				
1	0.00	6.00	4500	89100.00	89.10
2	0.60	5.40	4500	43200.00	43.20
3	1.80	4.20	4500	18900.00	18.90
4	6.00	0.00	4500	0.00	0.00
4	-6.00	0.00	4500	0.00	0.00
3	-1.80	4.20	4500	18900.00	18.90
2	-0.60	5.40	4500	43200.00	43.20
1	0.00	6.00	4500	89100.00	89.10
	$S_p = 4D_p$				
1	0.00	6.00	4500	79650.00	79.65
2	0.90	5.10	4500	37800.00	37.80
3	2.70	3.30	4500	14850.00	14.85
4	6.00	0.00	4500	0.00	0.00
4	-6.00	0.00	4500	0.00	0.00
3	-2.70	3.30	4500	14850.00	14.85
2	-0.90	5.10	4500	37800.00	37.80
1	0.00	6.00	4500	79650.00	79.65
	$S_p = 3D_p$				
1	0.00	6.00	4500	70200.00	70.20
2	1.20	4.80	4500	32400.00	32.40
3	3.60	2.40	4500	10800.00	10.80
4	6.00	0.00	4500	0.00	0.00
4	-6.00	0.00	4500	0.00	0.00
3	-3.60	2.40	4500	10800.00	10.80
2	-1.20	4.80	4500	32400.00	32.40
1	0.00	6.00	4500	70200.00	70.20
	$S_p = 2D_p$				
1	0.00	6.00	4500	60750.00	60.75
2	1.50	4.50	4500	27000.00	27.00
3	4.50	1.50	4500	6750.00	6.75
4	6.00	0.00	4500	0.00	0.00
4	-6.00	0.00	4500	0.00	0.00
3	-4.50	1.50	4500	6750.00	6.75
2	-1.50	4.50	4500	27000.00	27.00
1	0.00	6.00	4500	60750.00	60.75