A STUDY OF COMBINED PILED RAFT FOUNDATION USING PLAXIS 3D AE

A dissertation submitted in

Partial Fulfillment of the Requirement for the Award of the Degree of

MASTERS OF TECHNOLOGY

In

CIVIL ENGINEERING

(With Specialization in Geotechnical Engineering)

Of

Assam Science & Technology University
Session 2021-2023

By
NASREEN BEGUM
ROLL NO: PG-C-017

ASTU Registration No.: 002406221

Under the Guidance of
DR. DIGANTA GOSWAMI
ASSOCIATE PROFESSOR

ASSAM ENGINEERING COLLEGE
DEPARTMENT OF CIVIL ENGINEERING

ASSAM ENGINEERING COLLEGE
JALUKBARI, GUWAHATI-781013

DECLARATION

I hereby declare that the work presented in the dissertation entitled "A STUDY OF COMBINED PILED RAFT FOUNDATION USING PLAXIS 3D AE" in partial fulfillment of the requirement for the award of the degree of “MASTER OF TECHNOLOGY” in Civil Engineering (with specialization in Geotechnical Engineering), submitted in the Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13, under Assam Science & Technology University, is a real record of my work carried out in the said college for a period of twelve months under the supervision of Dr. Diganta Goswami, Associate Professor, Department of Civil Engineering, Assam Engineering College, Jalukbari, Guwahati-13.

Do hereby declare that this project report is solemnly done by me and is my effort and that no part of it has been plagiarized without citation.

Date: NASREEN BEGUM

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Date:

Dr.DIGANTA GOSWAMI
(Associate Professor)
Civil Engineering Department
Assam Engineering College

CERTIFICATE

This is to certify that the work presented in the project report entitled “A STUDY OF COMBINED PILED RAFT FOUNDATION USING PLAXIS 3D AE” is an independent report submitted by Nasreen Begum, Roll No: PG-C-017, a student of M. Tech 4th Semester, Department of Civil Engineering, Assam Engineering College, to the Assam Science and Technology University in partial fulfillment of the requirement for the award of the degree of Master of Technology in Civil Engineering with Specialization in Geotechnical Engineering under my guidance and supervision.

Date:

Place: Guwahati

Dr. DIGANTA GOSWAMI
(Associate Professor)
Civil Engineering Department
Assam Engineering College
Jalukbari, Guwahati-781013

CERTIFICATE FROM HEAD OF THE DEPARTMENT

This is to certify that the project report entitled "A STUDY OF COMBINED PILED RAFT FOUNDATION USING PLAXIS 3D AE" has been submitted by NASREEN BEGUM, bearing Roll No: PG-C-017, a student of M.Tech. 4th Semester, Geotechnical Engineering (Civil Engineering Department), Assam Engineering College, in partial fulfillment of the requirements for the award of the degree of Master of Technology in Geotechnical Engineering of Assam Science & Technology University.

Date:

Place: Guwahati

Dr. JAYANTA PATHAK
(Professor & Head of the Department)
Department Of Civil Engineering
Assam Engineering College
Jalukbari, Guwahati-781013

ACKNOWLEDGEMENT

At the very outset I would like to express my deepest gratitude and sincere thanks to my respected guide Dr. Diganta Goswami, Associate Professor, Department of Civil Engineering, Assam Engineering College for his invaluable supervision, guidance and constructive suggestion throughout the course of my work .

I also express my sincere thanks and gratitude to Dr. Jayanta Pathak, Professor & Head of the Department of Civil Engineering, Assam Engineering College for his kind co-operation while carrying out my work.

I extend my grateful thanks to all the faculty members and laboratory staff of the Department of Civil Engineering, Assam Engineering College for their free exchange of ideas and for lending their helping hand whenever I needed them.

I also like to thank all my classmates and well-wishers for their constant encouragement, valuable advice and inspiration throughout the work.

Lastly, I acknowledge my indebtedness to all my family members for their whole hearted moral support and constant encouragement.

NASREEN BEGUM
M.TECH 4th Semester
(Geotechnical Engineering)
Department of Civil Engineering
Assam Engineering College
Jalukbari, Guwahati-13

ABSTRACT

In conventional design methods of raft foundations, the raft is found to be safe from shear criteria but in certain cases it may not satisfy the settlement criteria which often leads to increase in construction costs for the raft foundation. On the other hand, in designing pile groups, the role of pile group is hardly taken into account in transferring and distributing the superstructure load to the subsoil which again becomes conservative in nature. Therefore, a concept of combining the raft and piles was suggested by many researchers which in turn would be safe and beneficial for geotechnical engineers. This combination is often called Combined Pile Raft Foundation (CPRF).

The main objective of this study is to learn how to use PLAXIS 3D AE modelling and carry out a study for the Raft and Combined Pile Raft Foundation using a powerful finite element based software called PLAXIS 3D AE. A parametric study is being done for only raft and then for combined piled raft foundation under a system of point loads and also for structural load by varying the parameter of raft thickness, pile diameter and pile length. Dynamic analysis is done by considering a arbitrary earthquake data and analysis is done based on displacement and acceleration criteria for only Raft and also for Combined Pile Raft Foundation (CPRF). Based on the findings of the parametric study an attempt has been made to suggest the most suitable type of foundation on given soil conditions.

LIST OF TABLES

LIST OF FIGURES

SYMBOLS AND ABBREVIATIONS

Symbols and Abbreviations	Description
CPRF	Combined Pile Raft Foundation
GL	Ground Level
kN	Kilo Newton
m	Metre
mm	Millimetre
υ_s	Poisson's ratio of soil
E_s	Modulus of soil
c	Cohesion of soil
ϕ	Angle of internal friction
γ_{sat}	Saturated unit weight
γ_{unsat}	Unsaturated unit weight
E_r	Modulus of raft
γ_{raft}	Unit weight of raft
υ_r	Poisson's ratio of raft
γ_{pile}	Unit weight of pile
E_p	Modulus of pile
δ	Distortion angle

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 GENERAL

A geotechnical engineer faced with design of foundations considers shallow foundation for supporting a given simple structure. As 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 deep foundations such as pile foundations.

In the conventional design approach, a raft foundation is usually provided when the soil at shallow depth has low bearing capacity and the load from the superstructure applied is very high. The raft may be able to withstand the high stresses from the superstructure because of its large dimension but may experience excessive uniform and differential settlement. This severely affects the serviceability requirements of the structure. Hence, the best option in such cases is to provide piles in a systematic manner under the raft so that the settlements are under permissible limits. This composite foundation consisting of raft and piles is called a Combined Pile Raft Foundation (CPRF) or piled raft foundation.

1.1.1 COMBINED PILE RAFT FOUNDATION

A combined pile raft foundation consists of three load bearing elements: the raft, piles and the subsoil so that the applied load is transferred by means of a load sharing mechanism between piles and raft. The applied load is shared because of the following interactions between the piles, raft and subsoil:

a. Pile-soil interaction
b. Pile-pile interaction
c. Raft-soil interaction
d. Pile-raft interaction

The above mentioned interactions between the foundation elements and the subsoil are shown in Fig. 1.1.

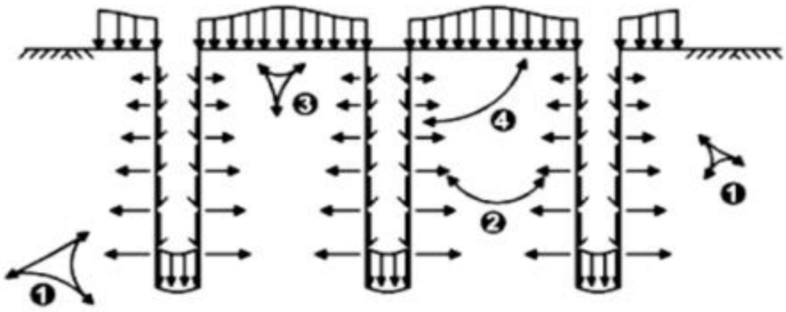

Fig 1.1 Soil-Structure Interactions in a CPRF

(Courtesy:- "Numerical Analyses of Piled Raft Foundation in Soft Soil Using 3D-FEM" By K. Watcharasawe, P. Kitiyodom and P. Jongpradist)

1.1.2 ADVANTAGES OF USING CPRF

Combined pile raft foundation has been widely recognized as economic and rational foundation for buildings when subjected to vertical loading due to its effectiveness in load sharing by both raft and pile components.

In a CPRF, piles act as settlement reducers because of which the total and differential settlements are under acceptable limits. In addition to settlements, the bearing capacity of the whole system of foundation also improves and there is an overall increase in stability of the foundation.

Unlike the conventional design methodology for pile group, where the piles are required to carry the entire load from superstructure, the number of piles required at the end of the design is generally high. But in a CPRF, since the piles are used to carry only the additional loads that cause settlements, the number of piles is generally lower as compared to the conventional pile foundation.

Hence, an adequate design of CPRF can lead to considerable economy without compromising the safety of the foundation.

1.1.3 FAVOURABLE AND UNFAVOURABLE CONDITIONS FOR CPRF

Poulos (1991) has examined a number of idealized soil profiles and has found that the following situations may be favourable:

a) Soil profiles consisting of relatively stiff clays.
b) Soil profiles consisting of relatively dense sand.

In both circumstances, the raft can provide a significant proportion of the required load capacity and stiffness, with the piles acting to boost the performance of the foundation, rather than providing the major means of support.

Conversely, there are some situations that are unfavourable, including:

a) Soil profiles containing clays near the surface
b) Soil profiles containing loose sands near the surface
c) Soil profiles that contain soft compressible layers at relatively shallow depths
d) Soil profiles that are likely to undergo consolidation settlements
e) Soil profiles that are likely to undergo swelling movements due to external causes

In the first two cases, the raft may not be able to provide significant load capacity and stiffness, while in the third case, long-term settlement of the compressible underlying layers may reduce the contribution of the raft to the long-term stiffness of the foundation. The latter two cases should be treated with considerable caution. Consolidation settlements may result in a loss of contact between the raft and the soil, thus increasing the load on the piles and leading to increased settlement of the foundation system. In the case of swelling soils, substantial additional tensile forces may be induced in the piles because of the action of the swelling soil on the raft.

1.2 OBJECTIVES AND METHODOLOGY OF THE STUDY

The main objectives of this thesis are listed below:-

- Behaviour of raft under a system of point loads.

  Settlement: Maximum settlement for varying total load and differential settlement as well as distortion angle for varying raft thickness of 200mm, 300mm, 400mm, 500mm. is studied

- Behaviour of CPRF under the same system of point loads.

  Settlement: Maximum settlement for varying total load and differential settlement as well as distortion angle for varying raft thickness of 200mm, 300mm, 400mm, 500mm is studied Parametric: Pile diameter and pile length for CPRF foundation.

- Behaviour of raft under a ten storeyed structural load for varying raft thickness of 150mm, 200mm, 250mm, 300mm, 400mm is studied.

Settlement: Differential settlement is studied and is within permissible limit and distortion angle is also studied.

- Behaviour of CPRF under a ten storeyed structural load for varying raft thickness of 150mm, 200mm, 250mm, 300mm, 400mm is studied.

  Settlement: Differential settlement is studied and is within permissible limit and distortion angle is also studied.

- Behaviour of CPRF under a ten storeyed structural load for varying pile diameter and pile length is studied.
- Behaviour of raft under a ten storeyed structural load is studied under Dynamic analysis.
- Behaviour of combined pile raft foundation (CPRF) under a ten storeyed structural load is studied under Dynamic analysis.

For a satisfactory performance of a structure, total and differential settlement as well as distortion angle is calculated and should be within permissible limit. In this study response of the raft foundation and combine pile raft foundation (CPRF) when subjected to a system of point loads and superstructure load, with respect to total, differential settlement and distortion angle is studied.

First of all, a group of point loads supported by rafts of various thickness are analysed for the resulting differential settlement and distorsion angle .This is followed by analyzing the same group of point loads but supported by combined pile raft foundation system for varying parameters like raft thickness, pile diameter and pile length. The response in terms of total, differential settlement and distorsion angle is for the two foundation systems namely raft foundation and combine pile raft foundation (CPRF) is critically examined.

Next the group of point loads are replaced by a realistic ten storeyed building and the response of raft foundation and combine pile raft foundation (CPRF) system in terms of total, differential settlement and distorsion angle is studied

Finally the ten storeyed building supported by raft foundation and combine pile raft foundation (CPRF) system under earthquake loading in terms of displacement and acceleration are analysed.

All the analyses are carried out numerically by finite element formulation with the help of the finite element code, PLAXIS 3D AE.

1.3 LAYOUT OF THE THESIS

Based on the type of the thesis this study is divided into following chapters:

Chapter one discusses the topic of study in general and also describes the objective and methodology of the study.

A detailed state of the art literature review covering the research area is presented in chapter two.

Chapter three contains method of analysis in which discussion is done on which methods can be cited in terms of their ability to predict load-settlement behavior of a piled raft foundation and also finite element method is discussed alongwith steps for modelling the structure in PLAXIS 3D AE.

Chapter four includes a parametric study between a raft foundation and a combined pile raft foundation considering various parameters like raft thickness, diameter of piles, length of piles by using PLAXIS 3D AE and dynamic analysis of a ten storeyed building is also discussed.

Chapter five includes interpretation of results considering various parameters presented in tabular and graphical format comparing maximum and differential settlement.

Chapter six contains conclusion and recommendation for the study.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The study of Combined Pile Raft Foundation (CPRF) was done by different researchers at different times. The researchers have conducted both analytical as well as experimental studies of CPRF considering various soil types. The studies range from simple analysis methods by taking a number of assumptions to sophisticated analysis tools like finite element analysis, boundary element analysis and case studies with site measurements. This chapter deals with some of the research works in regard to the Combined Pile Raft Foundation (CPRF).

2.2 REVIEW OF LITERATURE

Butterfield and Banerjee (1971) were the first to study the behavior of pile group embedded in elastic half space continuum with rigid cap. The analysis used Mindlin's solution for a point load. The point load was further distributed over the pile cap and an integral equation was developed for vertical displacements of all points in the medium. This elastic analysis calculates only the total settlement. It does not include the interaction between the pile and cap, which influence the shear redistribution and bending moment of the raft element.

Poulos and Davis (1972) performed an elastic analysis on a Combined Pile Raft Foundation(CPRF) considering soil as semi-infinite elastic medium. The analysis is based on the interaction between two units, where each unit consists of a rigid floating pile connected with a rigid circular cap subjected to a point load.

Sommer, Wittmann and Ripper (1985) conducted a parametric study with an ultimate goal reducing settlement. The analysis was carried using finite element analysis for a monolithic raft and a piled raft for five computations with 15m, 20m, 30m long piles. They found that for CPRF there is a decrease in settlement as compared to the raft. There is also decrease in settlement of CPRF with increase in pile length. In addition to that they observed that for piles greater than 20 m in length, no significant decrease in settlement was observed.

Zhuang G.M. and Lee I.K. (1994) used a finite element method to understand the load sharing between the piles and piled raft system. They observed that load sharing between the piles in piled raft system was affected by pile stiffness, raft rigidity and pile length to width ratio. They also observed that as pile length increases and raft and pile rigidity decreases, the load distribution becomes more uniform.

Cunha, Poulos and Small (2001) investigated the design of piled rafts, outlining the influence of major external variables that affect their design under concentrated column loads. According to the authors, the most important parameters that influence the design of piled raft foundation are those related to the pile characteristics (number, length and disposition) and raft characteristics (thickness). The analysis was carried out using GARP6 program which is a simplified form of Boundary element program, The study considered 26 distinct parametric design alternatives, They observed that both differential and maximum settlement tend to decrease as the raft thickness increase. They also observed that the maximum pile load, for a specific raft thickness, is mainly dependent on both the number and length of the piles in the raft. It was also noted that the load carried by the piles continuously decreases with an increase in raft thickness. This means that by increasing the raft thickness more load is absorbed by the raft.

Maharaj (2004) presented three dimensional nonlinear analysis of piled raft foundation consisting of 16 piles each of 48m length and a square raft under the application of uniformly distributed load. Load settlement curves of raft and piled raft foundation were provided for different raft and pile stiffness. He observed that increase in stiffness of pile increases the load carrying capacity of piled raft foundation and reduces the overall settlement upto a limiting value of pile stiffness. He also concluded that there is a specific combination of stiffness of raft and pile in a pilled raft foundation beyond which further increase in stiffness of raft and pile neither increases the load carrying capacity nor reduces settlement.

Reul and Randolph (2004) studied 259 different piled raft configuration using three dimensional elasto-plastic 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 were varied. In the parametric study, square unpiled rafts and piled rafts with an edge length of 38m were considered. Three basic pile configurations were considered. In the first pile configuration, the piles were uniformly distributed under the whole raft area. In the second configuration, the piles were placed only in the central area of the raft. In the third configuration, the piles were placed under the central area of the raft as well as under the edges of the raft. The number of piles were varied between 9 and 169, pile length was varied between 10m and 50m, pile spacing was varied between 3m and 6m. The pile diameter was held constant at 1m. They observed that average settlement is the only parameter that is reduced compared to the unpiled raft, for all configurations. The raft-soil stiffness affect the differential settlement more than average settlement. They concluded that for a raft under uniform loading or core edge loading, differential settlements can be reduced by installation of piles only under the central area of the raft.

Sharma, Vasanvala and Solanki (2011) modified the concept of piled raft to develop a modified version and named it as composite piled raft. In the system of composite piled raft, the short piles made of flexible materials were used to reduce the settlements at shallow depths and the cushion beneath the raft was used to redistribute and adjust the stress ratio of piles to subsoil. Finite element analysis was used by using a software called Midas GTS. They observed that for shorter piles, increasing lengths have much more obvious effects on reducing settlement of foundation than improving the elastic modulus of short piles. They concluded that the cushion used can adjust the load-sharing ratios evenly among the piles and help to make better use of the bearing capacities of short piles.

S.J Shukla, A.K Desai, and C.H Solanki (2013) attempted to study the behaviour of tall building resting on different types of subsoil with piled raft foundation system during earthquake.The effect of subsoil on the behaviour of tall building was checked by time history analysis of Bhuj and El Centro earthquake. In this piled raft foundation the piles are not required to ensure the overall stability of the foundation but to reduce the magnitude of settlements, differential settlements and the resulting tilting of the building and guarantee the satisfactory performance of the foundation system. So overall it have been concluded that piled raft foundation with dense sand type of subsoil was a very good combination for good bearing behaviour of the structure.

Joy and Hassan (2014) conducted permuted arrangement of piles rather than a uniform arrangement. For the study, a 10 storeyed building was analyzed in STAAD PRO and the foundation was later analyzed in PLAXIS 3D AE. They observed that combination of piles of different diameter performs better than piles of equal diameter. They also observed that arranging piles of larger diameter in the interior area is the best choice to reduce settlement.

Kumar, Choudhury, Kartzenbach et. al. (2015) reported the effect of pile head connection condition on the behavior of CPRF using PLAXIS 3D AE. A square raft of side 400mm and thickness 40mm, four piles of 40mm diameter and length 600mm were modelled in a two layered soil. A vertical load of 3.384 kN was applied at the top of CPRF and then a horizontal loads of 1.92 kN and 3.84 kN were applied. They observed that pile head connection has little influence on vertical settlement under application of vertical load alone. However, it was observed that connection condition played an important role in load sharing between foundation components where raft shared 30% to 54% of total load depending on connection rigidity. It was also observed that load sharing by raft decreased with the increase in horizontal load and corresponding displacement. Lastly, it was concluded that piles in CPRF with hinged connection experienced greater lateral displacement as compared to piles with rigid connection.

P. Halder and B. Manna (2019) performed three-dimensional analyses using geotechnical finite element (FE) software PLAXIS 3D to investigate the seismic response of piled raft foundations embedded in sand under pseudostatic loading condition. A verified 3D piled raft model was used for the entire analyses. Two earthquake motions i.e. Sikkim (2011) and Uttarkashi (1991) having different peak ground accelerations (PGA) were used for estimating the pseudoptotic loads on the piled raft.They observed that with higher magnitude of the pseudo-static force i.e. higher PGA of the earthquake motion used in the study, both the lateral displacement and bending moment become higher in magnitude as well.

CHAPTER 3

METHODS OF ANALYSIS

3.1 INTRODUCTION

A number of methods can be cited in terms of their ability to predict load-settlement behavior of a piled raft foundation. Some of these methods have been compared by Poulos et. al. (1997). But three broad classes of analysis methods are identified according to the assumptions, complexity and numerical methods employed:

a. Simplified calculation methods
b. Approximate computer-based methods
c. More rigorous computer-based methods

3.2 SIMPLIFIED CALCULATION METHODS

In the methods under this category, a number of simplifications in relation to the modelling of the soil profile and the loading conditions on the raft are involved. Simplified methods include those of Poulos and Davis (1980), Randolph (1983, 1994) and Burland (1995).

3.2.1 Poulos and Davis's Approach

Poulos and Davis (1980) presented a convenient method for hand calculation which may be used as a preliminary design tool. Elastic solutions are considered for stiffness and ultimate capacity calculations. The resulting load-settlement relationship is tri-linear. This method does not take into account of the flexibility of the raft.

3.2.2 Randolph's Approach

Randolph (1983, 1994) developed very approximate equations for the stiffness of piled raft system and load-sharing between the piles and the raft. This method is restricted to linear behavior of the piled raft system which indicates that the foundation is designed essentially as a pile group with allowance for the load carried by the raft.

3.2.3 Burland's Approach

Burland (1995) developed a simplified process of design for piled raft foundations where piles are designed to act as settlement reducers and to develop their full capacity at the design load.

Following steps are suggested by Burland:

a. Estimate the total long-term load-settlement relationship for the raft without piles (Fig 3.2).The design load P_O gives a total settlement S_o.

b. Assess an acceptable design settlement S_a including the margin of safety.

c. P_1 is the load carried by the raft corresponding to S_a.

d. The load excess P_O - P_1 is assumed to be carried by settlement-reducing piles. A mobilization factor of 0.9 is to be applied to the ultimate shaft capacity, P_{su}.

e. If the piles are located below columns which carry load in excess of P_{su}, the piled raft may be analyzed as a raft on (Figure 3.1) which reduced column loads act. At such columns, the reduced load Q_r is: $Q_r = Q - O.9\ P_{su}$ …eq.3.1

Where Q is the total load acting on the column.

f. The bending moment in the raft can be obtained by analyzing the piled raft as a raft subjected to the reduced loads, Q_r.

The process of estimating the settlement of the piled raft is not explicitly set out by Burland.

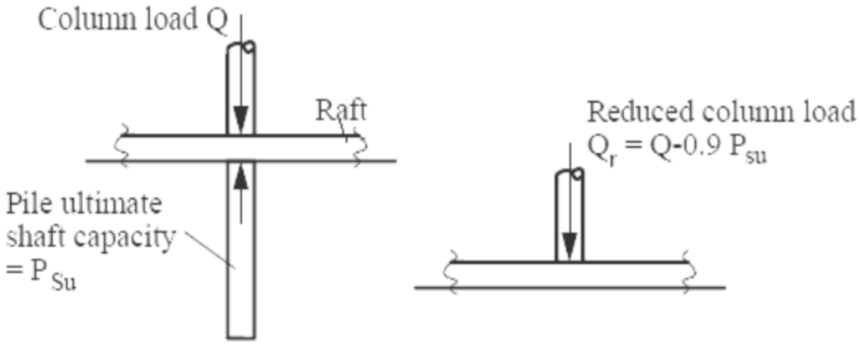

Fig 3.1 Simplified representation of pile-raft unit (Burland,1995)

(Courtesy:- “Different Analysis Methods of Piled Rafts”, by Ripunjoy Deka)

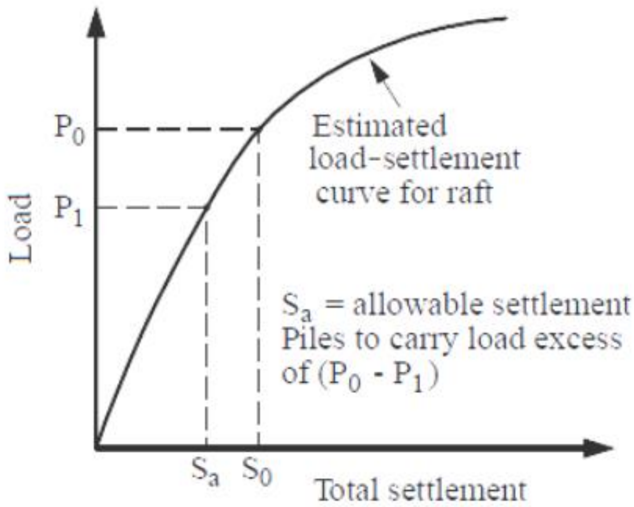

Fig: 3.2 : Load-settlement curve for raft (Burland, 1995).
(Courtesy:- "Different Analysis Methods of Piled Rafts", by Ripunjoy Deka)

3.3 APPROXIMATE COMPUTER-BASED METHODS

The approximate approaches include two main approaches: Strip on string approach and Plate on spring approach.

3.3.1 Strip on Spring Approach

Poulos (1991) modelled piled raft foundation as a strip supported on springs in which the strip represents the raft in one direction and the springs represent the piles. Approximate allowance is made for all four components of interaction. The effects of the parts of the raft outside the strip section being analyzed are taken into account by computing the free-field soil movements due to these parts and interaction with strip section.

The method is versatile and has been shown to give reasonable agreement with more complete analysis. But some limitations are observed. It cannot consider torsional moments within the raft and thus it may not give consistent settlements at a point if strips in two directions through that point are analyzed.

3.3.2 Plate on Spring Approach

In this approach the raft is represented by an elastic plate and the piles by springs. Some early approaches in this category e.g. (Hongladaromp, Chen and Lee, 1973) neglected some of the interactions and hence gave stiffness which were too large, as revealed by studies made by

(Brown and Wiesner, 1975) who compared such methods with more complete methods. Poulos (1994) employed a finite difference method for the plate and allowed for the various interactions via approximate elastic solutions. Allowance was also made for the efforts of piles reaching their ultimate capacity, the development of bearing capacity failure below the raft and the presence of free-field vertical soil movements acting on the foundation system.

3.4 MORE RIGOROUS COMPUTER-BASED METHODS

The more rigorous computer-based methods include the following:

3.4.1 Boundary Element Methods

In this approach, discretization is required only on the boundary of the system under consideration. Since only the boundaries are discretized, the number of sets of equations to be solved is generally smaller than the finite element or finite difference methods. Also, interpolation errors are confined to the boundaries. Solutions such as stresses and displacements can be obtained directly by solving the set of system equations.

3.4.2 Simplified or Two-Dimensional Finite Element Analysis

It involves the presentation of pile group or piled raft as either a plane strain problem or as an axially symmetric problem. In both cases significant approximations need to be made, especially with respect to the piles. The main problem in such a simplified approach is that only regular loading patterns may be analyzed. It is also not possible to obtain torsional moments in the raft.

3.4.3 Three-Dimensional Finite Element Analysis

In terms of ability to model a real problem, three-dimensional finite element analysis are usually considered to be the ultimate weapon, at least as far as analysis is concerned. For analysis commercially available computer programs are used. The use of such a program eliminates the need of approximate assumptions inherent in all of the above analyses. Normally, in such analysis the superstructure is modelled as a three dimensional space frame, the raft discretized as plate bending elements and piles as compressible elastic axial elements.

3.5 FINITE ELEMENT METHOD

The Finite Element Method (FEM) has become the premier numerical tool for the analysis of a wide range of problems in engineering science. The FEM is the most widely used numerical method for solving a variety of problems governed by partial differential equations in all areas of engineering.

The finite element method in general involves the following six basic steps:

a) **Discretization:** The discretization involves division of a continuum into an equivalent system of smaller continua, called the finite elements

b) **Selection of approximation function:** A pattern of solution for the unknown quantity such as the displacement over each element is assumed through the use of functions or models.

c) **Derivation of element equation:** Either variational or residual methods are used in this case. The resulting equation is: [K] {q} = {Q} …eq.3.2

   Where, K = stiffness matrix

   {q} = displacement vector

   {Q} = force vector

d) **Assembling the element properties to form global equations:** In this step, the addition of individual element equation is carried out.

   The global relation is of the form: [K] {r) = {R} …eq.3.3

   Where,

   [K] = global stiffness matrix

   {r} = global displacement vector

   {R} = global nodal force vector

e) **Computation of primary and secondary quantities:** Primary unknown displacements are obtained. Stresses and strains, the secondary quantities are then computed from the nodal displacements.

f) **Interpretation of the results:** In this step, the results obtained are plotted in different forms and are studied.

3.6 STEPS FOR MODELLING IN PLAXIS 3D AE

Following are the general steps to be followed for modelling any structure in PLAXIS 3D AE:

a) **Creation of Geometry:** A geometry model is created by defining co-ordinates along x-axis and y-axis for the required area.

b) **Creation of Soil model:** A borehole is created at any point of the model as and the depth of the borehole required is entered along z-axis. Water head is to be entered if required. After the borehole is created the material properties for the soil are given as inputs.

c) **Creation of Structure:** The structure is created using several structural elements such as plates, embedded beams, surface, line etc. Loads in the form of point, surface or uniformly distributed form are applied once the structure is created.

d) **Mesh Generation:** Once the structure is created and loads are applied, the model is meshed by selecting 3D mesh generation from the Mesh menu. In this way a 3D mesh composed of 15-noded elements are formed.

e) **Performing Calculations:** Different phases are created starting from the initial phase where only the soil is activated; phase 1 where the soil model and structural elements are activated and phase 2 where soil model, structural elements and loads are activated. As required by the user number of phases can be created depending upon the construction stages of the structure.

CHAPTER 4

PARAMETRIC STUDY

4.1 GENERAL

In order to determine the suitable foundation it is important to study the behavior of piled raft foundation when the raft and pile parameters are varied. Hence, a parametric study for the combined pile raft foundation has been carried out in this chapter. At the beginning, a study between a raft foundation and a piled raft foundation is made using PLAXIS 3D AE. Afterwards, the effect of various parameters like raft thickness, diameter of piles, length of piles is studied on the performance of piled raft foundation using the above mentioned software.

4.1.1 STEPS USED FOR MODELLING COMBINED PILE RAFT FOUNDATION IN PLANS 3D AE

Following are the steps used for modelling the piled raft foundation in this study using PLAXIS 3D AE:

a) The soil model is made of 150 m in both horizontal directions i.e. x and y axis. It is then extended 30 m downwards along the negative z-axis.
b) Soil parameters, material models, water level depth are entered as inputs while describing the borehole which is made at one of the corners of the soil model.
c) The raft is created on the ground surface and is modelled as a plate. The corresponding material properties are assigned to the raft. On the other hand, piles are created below the raft surface as embedded beams and the corresponding material properties are assigned.
d) Once the structure is created, loads are assigned to it. In this study, one point load is applied at the centre of magnitude 1000 kN and eight other point loads are applied at the corners of the raft of magnitude 500 kN.
e) The 3D finite element mesh is generated and the coarseness is set to medium.
f) In the staged construction phase, in addition to the initial phase three other phases are created named as phase 1, phase 2 and phase 3. In phase l and phase 2 the structural elements including the raft and piles are activated. In phase 3, the loads applied are activated along with the structural elements.
g) After creating all the phases, the calculation is executed. The program runs the calculation and upon completion, the results are displayed in the output program.

4.2 CASE 1: COMPARISON BETWEEN RAFT FOUNDATION AND CPRF

4.2.1 Problem Statement: In this case, a raft foundation of dimension 30 m x 30 m is considered resting on a soil mass of dimension 150 m x 150 m x 30 m and subjected to eight point loads at the corners of the raft of magnitude 500 kN and a central point load of 1000 kN as shown in Fig. 4.1. The loads are applied and the settlement for each set of varying total load is recorded.

The same procedure is repeated for a combined piled raft foundation consisting of nine piles of 10 m length (designated as PI, P2, P3, P4, P5, P6, P7, P8, P9) for the same raft and subjected to same loading conditions as shown in Fig.4.2. A comparison is made for both the foundations in a tabular format based on maximum settlement. It is observed that the maximum settlement occurs at the centre of the raft for all the thickness of raft considered. The permissible total settlement of the foundation is considered to be 75 mm as per I.S.code 1904-1986. The results are shown in Table 4.2 and Fig.4.4.

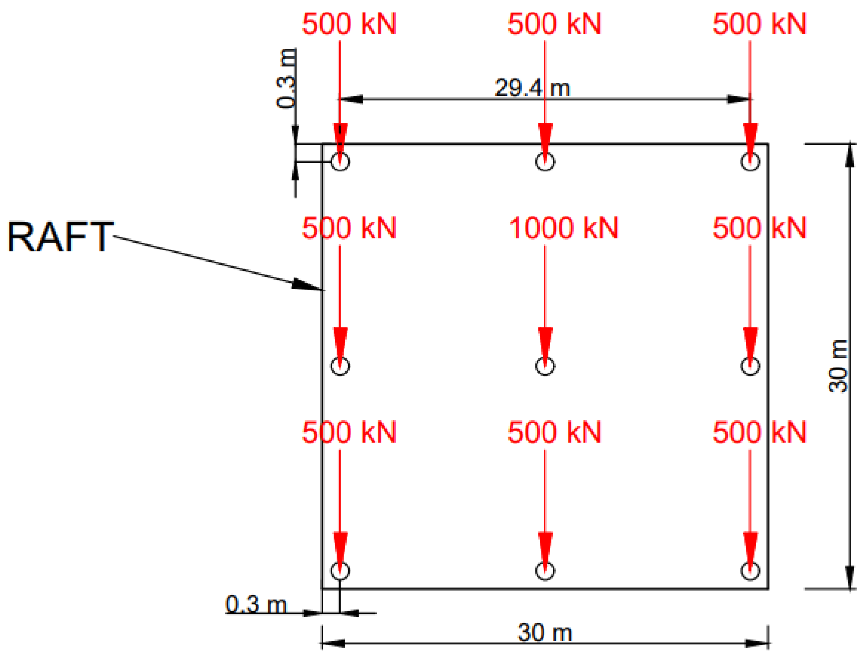

Fig. 4.1: Plan Showing Arrangement of Loads in Pile-Raft Foundation

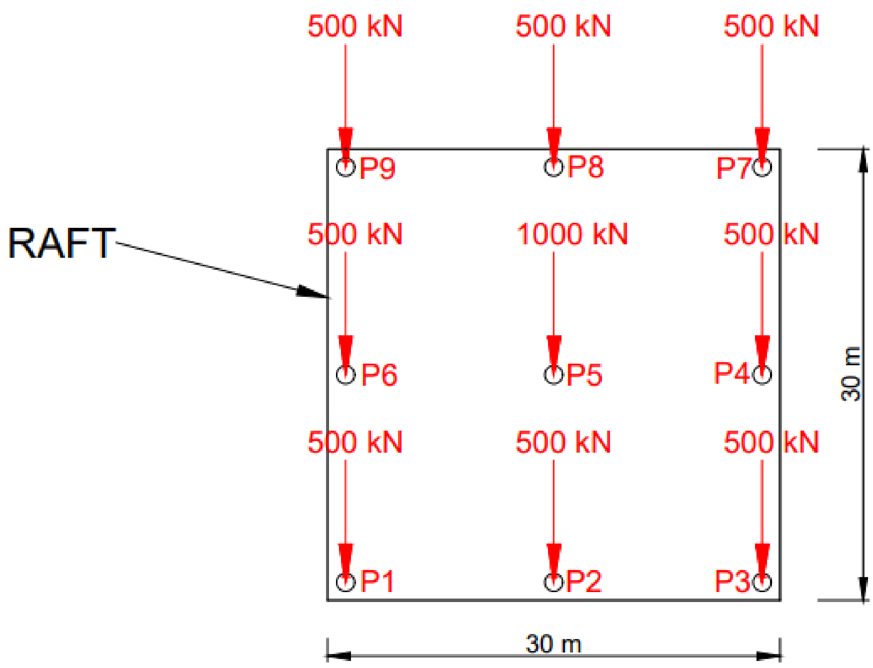

Fig. 4.2: Plan Showing Arrangement of Piles in Piled Raft Foundation.

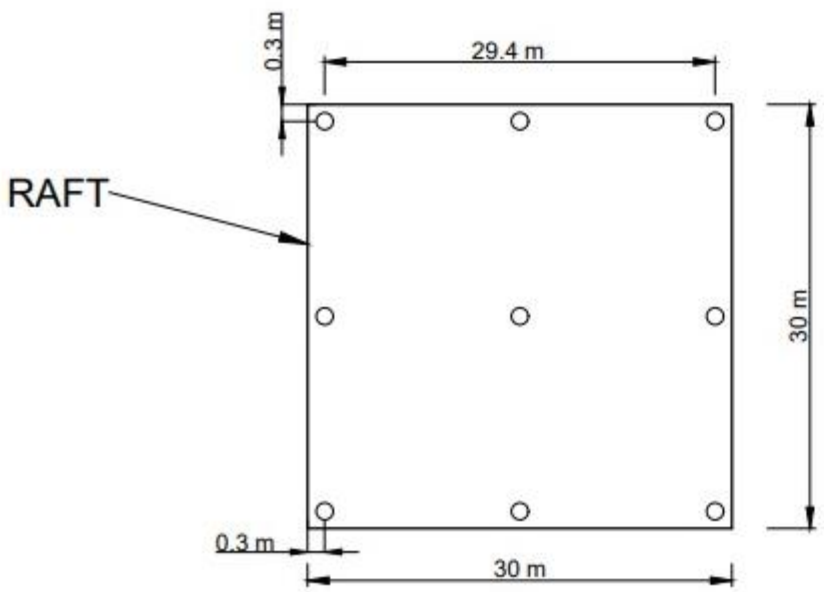

Fig. 4.3: Plan showing dimensions of Piled Raft Foundation.

4.2.2 Geometry Data

a) Raft thickness = 500 mm

b) Raft dimension = 30 m x 30 m

c) Pile diameter = 300 mm

d) Pile length = 10 m

e) Pile Spacing = 14.7 m

f) Number of piles = 9

Table 4.1: Material Properties of the Model.

Element	Property	Values
Soil	Modulus of soil, E_s	12×10^3 kN/m^2
	Poisson's ratio of soil, υ_s	0.4
	Drainage type	Drained
	Cohesion of soil, c	0.1kN/m^2
	Angle of internal friction, ϕ	35^0
	Saturated unit weight, γ_{sat}	19 kN/m^3
	Unsaturated unit weight, γ_{unsat}	18 kN/m^3
Raft	Modulus of raft, E_r	30×10^6 kN/m^2
	Unit weight of raft, γ_{raft}	15 kN/m^3
	Poisson's ratio of raft, υ_r	0.15
Pile	Unit weight of pile, γ_{pile}	6 kN/m^3
	Modulus of pile, E_p	30×10^6 kN/m^2

4.2.3 Load Data: Eight point loads of 500 kN are placed at the corners of the raft at a distance of 14.7m. A point load of 1000 kN is also applied at the centre.

4.2.4 Finite element data

a) Raft is modelled as a plate element,

b) Piles are modelled as embedded beams.

c) Soil is modelled as Mohr-Coulomb.

4.2.5 Results

The raft and Combined piled raft foundation are being analyzed for different sets of loading and the corresponding maximum settlement is recorded. The values of maximum settlement are presented in Table 4.2 and Fig. 4.4 below.

Table 4.2 Load-Settlement Data for Raft Foundation and CPRF

Point Load		Total Load (kN)	Maximum Settlement in Raft foundation (mm)	Maximum Settlement in CPRF (mm)
At eight Corners (kN)	At the Centre (kN)			
500	800	4800	20.33	9.49
500	1000	5000	23.12	10.10
500	1200	5200	27.09	12.26
500	1400	5400	33.16	13.64

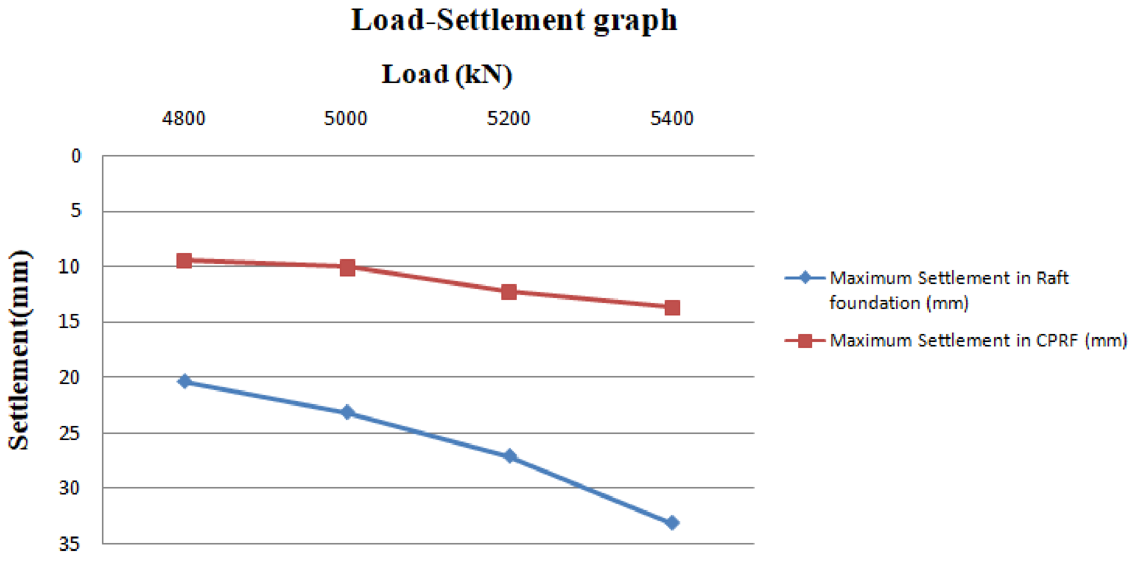

Fig 4.4 Load Settlement Plot for Raft Foundation and CPRF

4.2.6 Conclusion: As seen from the above results, a raft foundation experiences more settlement as compared to a Combined Pile Raft Foundation (CPRF) for the same set of loads. The presence of piles in a Combined Pile Raft Foundation is responsible for the significant reduction of settlement and it is also below the value of permissible limit (75 mm).

4.3. CASE 2: EFFECT OF RAFT THICKNESS ON RAFT FOUNDATION AND CPRF

4.3.1 Problem Statement: In this case, raft foundation and a combined pile raft foundation (CPRF) of dimension 30 m x 30 m consisting of nine piles of length 10m is considered resting on a soil mass of dimension 150 m x 150 m x 30 m and subjected to eight point loads at the corners of the raft of magnitude 500 kN and a central point load of 1000 kN. The thickness of the raft is increased from 200 mm by 100 mm upto 500 mm.

The settlement under the pile number P5 and P7 are recorded and accordingly the differential settlement and the distortion angle are calculated.

4.3.2 Geometry Data: All the data are kept same as Clause no. 4.2.2 except the raft thickness.

4.3.3 Material Properties of the Model: Same as Table 4.1

4.3.4 Load Data: Same as Clause no. 4.2.3 except there is no increment of loads.

4.3.5 Finite Element data: Same as Clause no. 4.2.4

4.3.6 Results: The maximum settlement for each raft thickness occurs at the centre of the raft and combined pile raft foundation (CPRF).Considering the centre (P5) and one of the corner (P7) the corresponding settlements are noted and their Differential Settlement and Distortion angle are calculated and their values are shown in Table 4.3 and Fig. 4.5 and Fig. 4.6.

4.3.7 Calculation of differential settlement and distortion angle, δ: The differential settlement was calculated for different raft thickness. The differential settlement is obtained by taking the difference maximum and minimum settlement. The permissible differential settlement as per IS. code 1904-1986 is given by 0.0025*L, where L is the centre-centre distance which is 14.7m. Hence, the permissible differential settlement in this case is 0.0025 x 14.7 = 0.03675 m = 36.75 mm.

In this case, the maximum and minimum settlement is observed below pile 5 and pile 7.

Distortion angle is calculated by dividing the differential settlement by the distance between points of related maximum and minimum settlement. The results are shown in Table 4.3 and Fig. 4.5 and Fig 4.6.

Distortion angle, $\delta = \tan^{-1}\left(\frac{\text{Differential Settlement (mm)}}{\text{Distance between the two points}}\right) = \tan^{-1}\left(\frac{\text{Differential Settlement (mm)}}{\sqrt{14.7^2+14.7^2}}\right)$ ..eq.4.1

Table 4.3 Variation of Differential Settlement and Distortion Angle for Raft and CPRF

Raft Thickness (mm)	Foundation type	Settlement at		Differential Settlement (mm)	Distortion Angle(δ)
		P5 (mm)	P7 (mm)		
200	Raft only	25.443	4.396	21.047	45.35
	CPRF	12.031	3.126	8.905	23.18
300	Raft only	24.155	3.616	20.327	44.35
	CPRF	11.097	2.875	8.223	21.58
400	Raft only	23.028	2.978	20.05	43.96
	CPRF	10.195	2.530	7.665	20.23
500	Raft only	21.872	2.060	19.812	43.62
	CPRF	9.295	2.013	7.282	19.30

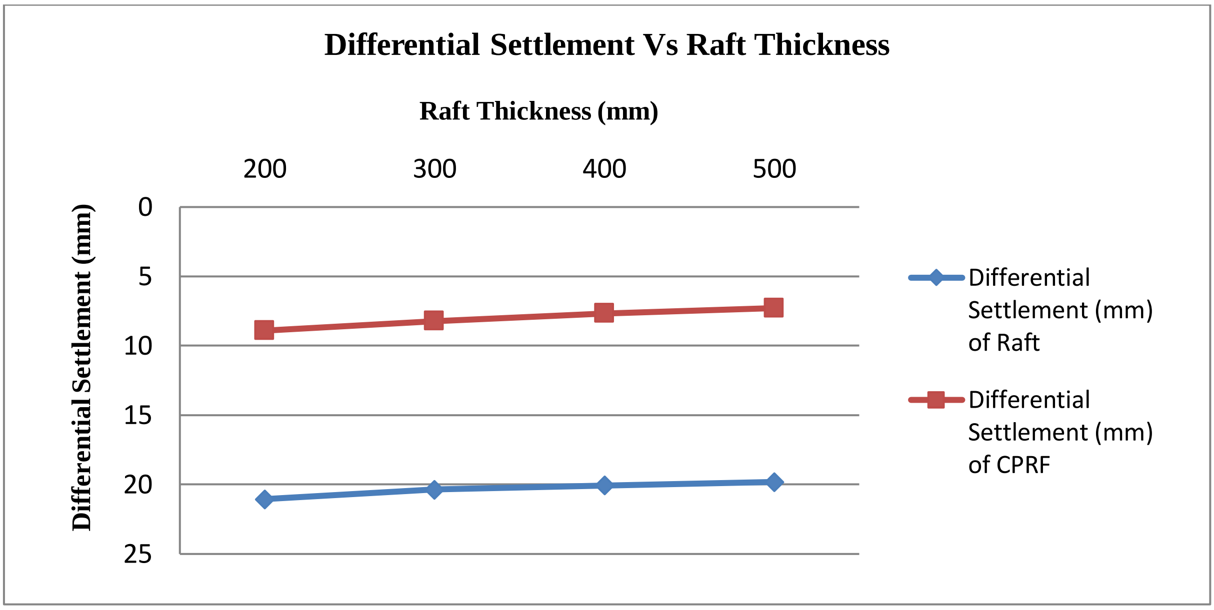

Fig 4.5 Variation of Differential Settlement with Raft Thickness

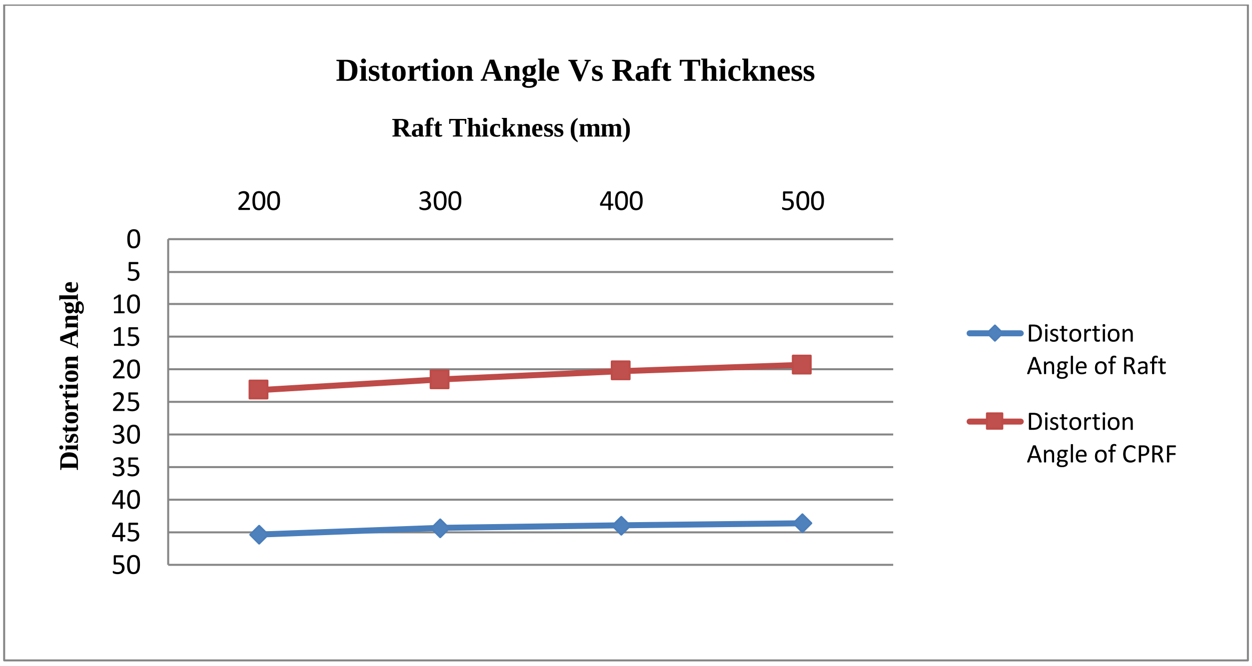

Fig 4.6 Variation of Distortion Angle with Raft Thickness

4.3.8 Conclusion: As seen from the above results the differential settlement of the raft and combined pile raft foundation decreases with the increase in raft thickness and it is also below the value of permissible limit (36.75mm). Also the distortion angle for raft and CPRF decreases with the increase in raft thickness.

4.4 CASE 3: EFFECT OF DIAMETER OF PILES ON CPRF

4.4.1 Problem Statement: In this case, a combined piled raft foundation of dimension 30 m x 30 m consisting of nine piles of length 10m is considered resting on a soil mass of dimension 150 m x 150 m x 30 m and subjected to eight point loads at the corners of the raft of magnitude 500 kN and a central point load of 1000 kN. The diameter of piles in this case are varied from 150 mm to 500 mm. The maximum settlement for each set of piles is recorded after the analysis is complete.

4.4.2 Geometry Data: All the data are kept same as Clause no. 4.2.2 except the diameter of piles.

4.4.3 Material Properties of the Model: Same as Table 4.1

4.4.4 Load Data: Same as Clause no. 4.2.3 except there is no increment of loads.

4.4.5 Finite Element data: Same as Clause no. 4.2.4

4.4.6 Results: The maximum settlement occurring at the centre of Combined Pile Raft Foundation (CPRF) for each set of pile diameter is presented in Table 4.4 and Fig. 4.7

Table 4.4: Effect of Diameter of Piles on Settlement of CPRF

Diameter of Piles (mm)	Maximum Settlement in CPRF (mm)
150	20.84
200	17.93
300	15.78
400	14.07
500	12.67

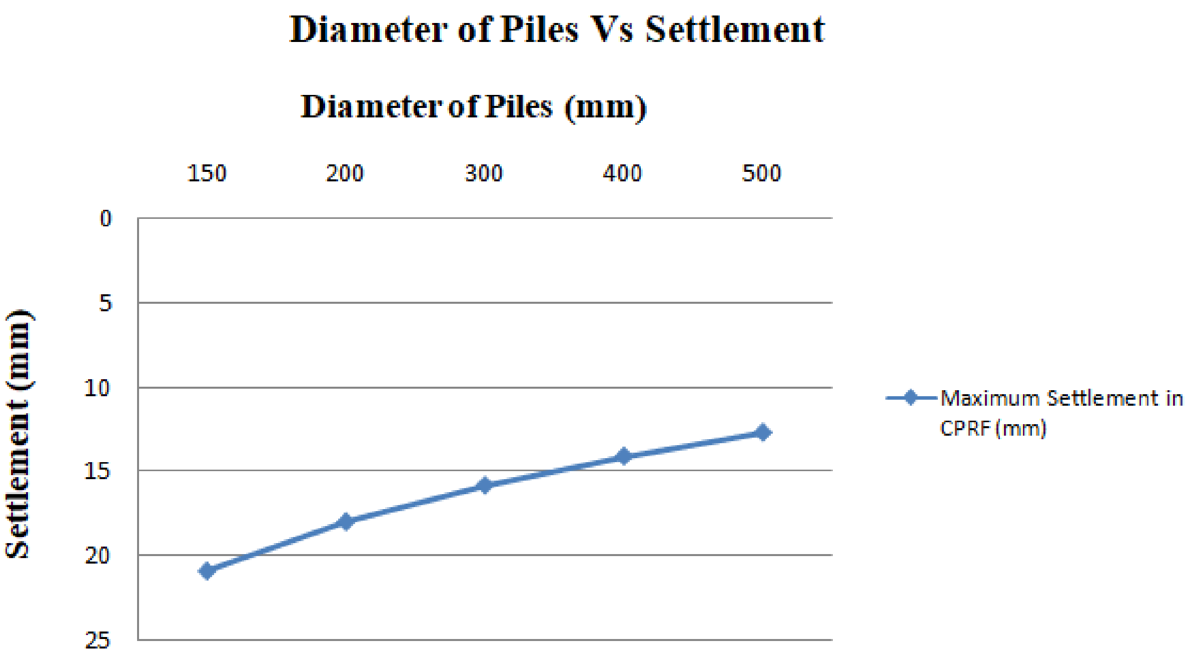

Fig 4.7 Variation of Diameter of Piles with Settlement.

4.4.7 Conclusion: As seen from the above results, the settlement in combined pile raft foundation decreases with the increase in diameter of piles.

4.5 CASE 4: EFFECT OF LENGTH OF PILES ON CPRF

4.5.1 Problem Statement: In this case, a piled raft foundation of dimension 30 m x 30 m consisting of nine piles is considered resting on a soil mass of dimension 150 m x 150 m x 30 m and subjected to eight point loads at the corners of the raft of magnitude 500 kN and a central point load of 1000 kN. The length of piles in this case are varied from 8m to 22m. The maximum settlement for each set of piles is recorded after the analysis is complete.

4.5.2 Geometry Data: All the data are kept same as Clause no. 4.2.2 except the diameter of piles.

4.5.3 Material Properties of the Model: Same as Table 4.1

4.5.4 Load Data: Same as Clause no. 4.2.3 except there is no increment of loads.

4.5.5 Finite Element data: Same as Clause no. 4.2.4

4.5.6 Results: The maximum settlement occurring at the centre of Combined Pile Raft Foundation (CPRF) for each set of pile length is presented in Table 4.5 and Fig. 4.8.

Table 4.5: Effect of Length of Piles on Settlement of CPRF

Length of Piles (m)	Maximum Settlement in CPRF (mm)
8	19.94
10	17.77
14	16.53
18	15.04
22	13.58

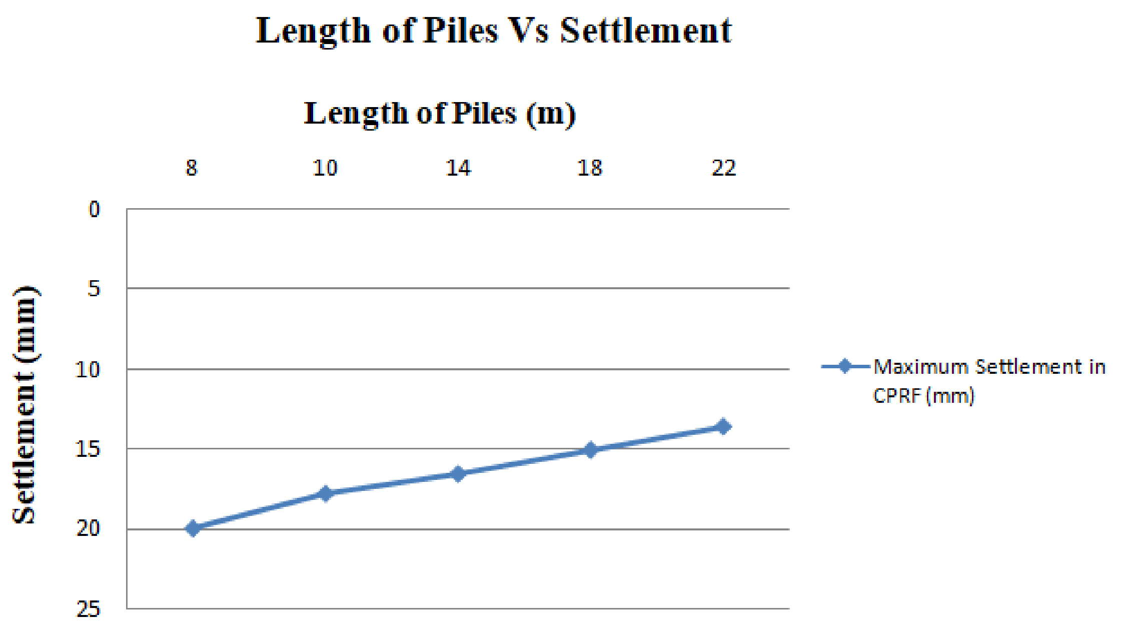

Fig 4.8 Variation of Length of Piles with Settlement.

4.5.7 Conclusion: As seen from the above results, the settlement in combined pile raft foundation decreases with the increase in length of piles.

4.6 CASE 5: STUDY OF A TEN STOREYED BUILDING ON RAFT AND CPRF AND ALSO BY DYNAMIC ANALYSIS

4.6.1 Problem Statement: In this case a 10 storeyed building of height 30 m is considered and it is studied with only raft foundation and also combined piled raft foundation. The size of the raft is considered as 30 m x 30 m. Based on the findings from the previous cases and in order to keep the total and differential settlement under permissible limit following three options are taken into consideration:

A. Increasing the thickness of raft in raft foundation and in combined piled raft foundation

B. Increasing the diameter of piles in combined piled raft foundation

C. Increasing the length of piles in combined piled raft foundation

Form the previous cases it is seen that increasing the thickness of raft in a piled raft foundation upto a certain extent helps in reducing the maximum settlement, differential settlements and also distortion angle . This is also applicable to a foundation consisting of only raft. Hence, the thickness of raft is increased from 150 mm to 400 mm to check if the differential settlements are under the permissible limit.

It is also observed that increasing the diameter of piles in combined piled raft foundation significantly helps in decreasing the maximum settlement.

Finally, the last option considered is increasing the length of piles in combined piled raft foundation. As already seen from the comparison between raft and piled raft foundation in the previous cases, combined piled raft foundation shows significant reduction in settlement as compared to raft foundation.

Hence, in this study a combined piled raft foundation consisting of nine piles is considered and the diameter and length of Piles are varied in order to get the most optimum performance of the foundation. Also the effect of dynamic analysis is studied in raft foundation and in combined piled raft foundation

4.6.2 MATERIAL PARAMETERS

The material parameters of soil, foundation and building components are presented below in tabular format below:

Table 4.6: Material Properties of the Model for a ten storied building

Element	Property	Values
Soil	Soil is model	Mohr-Coulomb.
	Modulus of elasticity in soil, E_s	12×10^3 kN/m^2
	Poisson's ratio of soil, υ_s	0.4
	Drainage type	Drained
	Cohesion of soil, c	0.1kN/m^2
	Angle of internal friction, ϕ	35^0
	Saturated unit weight, γ_{sat}	19 kN/m^3
	Unsaturated unit weight, γ_{unsat}	18 kN/m^3
Raft	Size of Raft	30 m x 30 m
	Modulus of elasticity in raft, E_r	25×10^6 kN/m^2
	Unit weight of raft, γ_{raft}	25 kN/m^3
	Poisson's ratio of raft, υ_r	0.15
Pile	Pile diameter	300 mm
	Unit weight of pile, γ_{pile}	25 kN/m^3
	Modulus of elasticity in pile, E_p	25×10^6 kN/m^2
	Poisson's ratio of pile, υ_p	0.15

Table 4.7: Material Parameters of Beams and Columns

Property	Values
Cross-sectional area of beams	300mm x 500mm
Cross-sectional area of columns	700mm x 700mm
Unit weight of RCC	25 kN/m^3
Modulus of beams and columns, E_{bc}	25 x 10^6 kN/m^2
Poisson's ratio of beams and columns, υ_{bc}	0.15

Table 4.8: Material Parameters of Slab

Property	Values
Thickness of slab	120 mm
Modulus of Slab, E_{sl}	25 x 10^6 kN/m^2
Poisson's ratio of Slab, υ_{sl}	0.15

4.6.3 Load data: Here a point load is applied at the centre of magnitude 5000kN and other eight point loads are applied at the corners of magnitude 2500 kN and a live load in the form of surface load of magnitude 5.3 kN/m^2 is applied across all the floors.

4.6.4 Finite element data:

a. Raft and slab are modelled as plate elements.

b. Piles are modelled as embedded beams.

c. Beams and columns are modelled as beam elements

4.6.5 STEPS INVOLVED IN FINITE ELEMENT MODELLING

a) A soil model of dimension 150 m x 150 m x 30 m is made in x, y and z direction respectively.

b) Soil parameters, material models, water level depth are entered as inputs while describing the borehole made at one of the corners of the soil model. A constant water level is considered at the ground level and hydrostatic pore-water pressure is assumed to be developed.

c) The raft is created on the ground surface and is modelled as a plate element. The corresponding material properties are assigned to the raft. In case the raft is to be laid at a depth from the ground level, the soil is first excavated upto the required depth and then afterwards the raft is created.

d) In case of piles are created below the raft surface as embedded beams and the corresponding material properties are assigned.

e) Once the requisite foundation is modelled, beams and columns are created and modelled as beam elements. The slab is created as a plate element. The necessary material parameters are assigned to the building members.

f) A live load in the form of surface load of magnitude 5.3 kN/m^2 is applied across all the floors.

g) The 3D finite element mesh is generated and the coarseness is set to medium.

h) In the staged construction phase, in addition to the initial phase, three other phases are created named as phase 1, phase 2 and phase 3. In phase l, the foundation i.e. the raft and piles are activated. In phase 2, the building is created i.e. the beams, columns and slabs are activated. Finally, in phase 3 the surface load is activated.

i) After creating all the phases, the calculation is executed. The program runs the calculation and upon completion, the results are displayed in the output program.

j) All the required data like total and differential settlements, etc. are obtained from the output program.

4.6.6 ANALYSIS AND RESULTS

The three options available for this building are discussed below along with their results and conclusions.

Option A: Increasing the Thickness of Raft

4.6.6.A. Problem statement: In this case the 10 storeyed building of 30 m height, each storey being 3 m high is considered only with the raft foundation of size 30 m x 30 m and then with combined piled raft foundation as shown in Fig.4.9 and Fig. 4.10. The column spacing is taken as 14.7 m and 14.7 m along x and y axis. As we have observed in the previous cases that increasing the thickness of raft helps in reducing the settlement, so an attempt has been made to bring the differential settlement under permissible limit by increasing the raft thickness. The thickness of the raft is varied from 150 mm to 400 mm as shown in Table 4.9. The material parameters of the soil and raft are considered as per Clause 4.6.2.

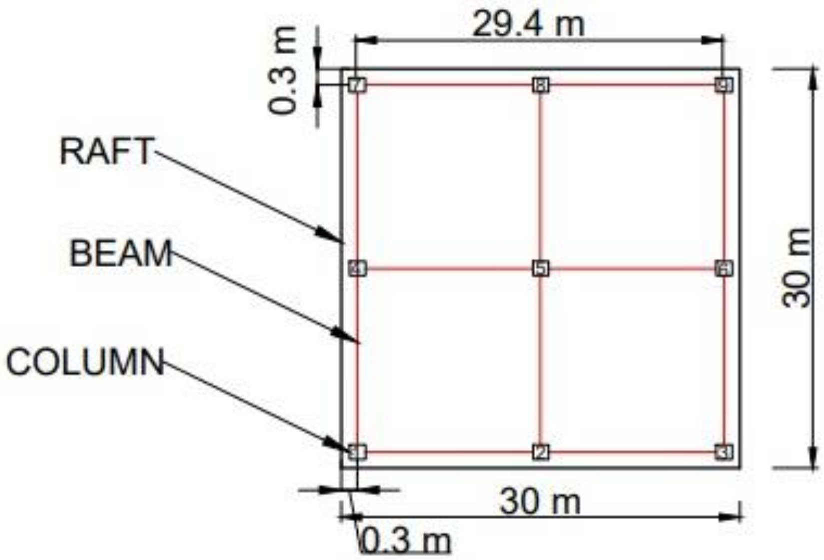

Fig. 4.9: Building Plan Showing Arrangement of Beams and Columns

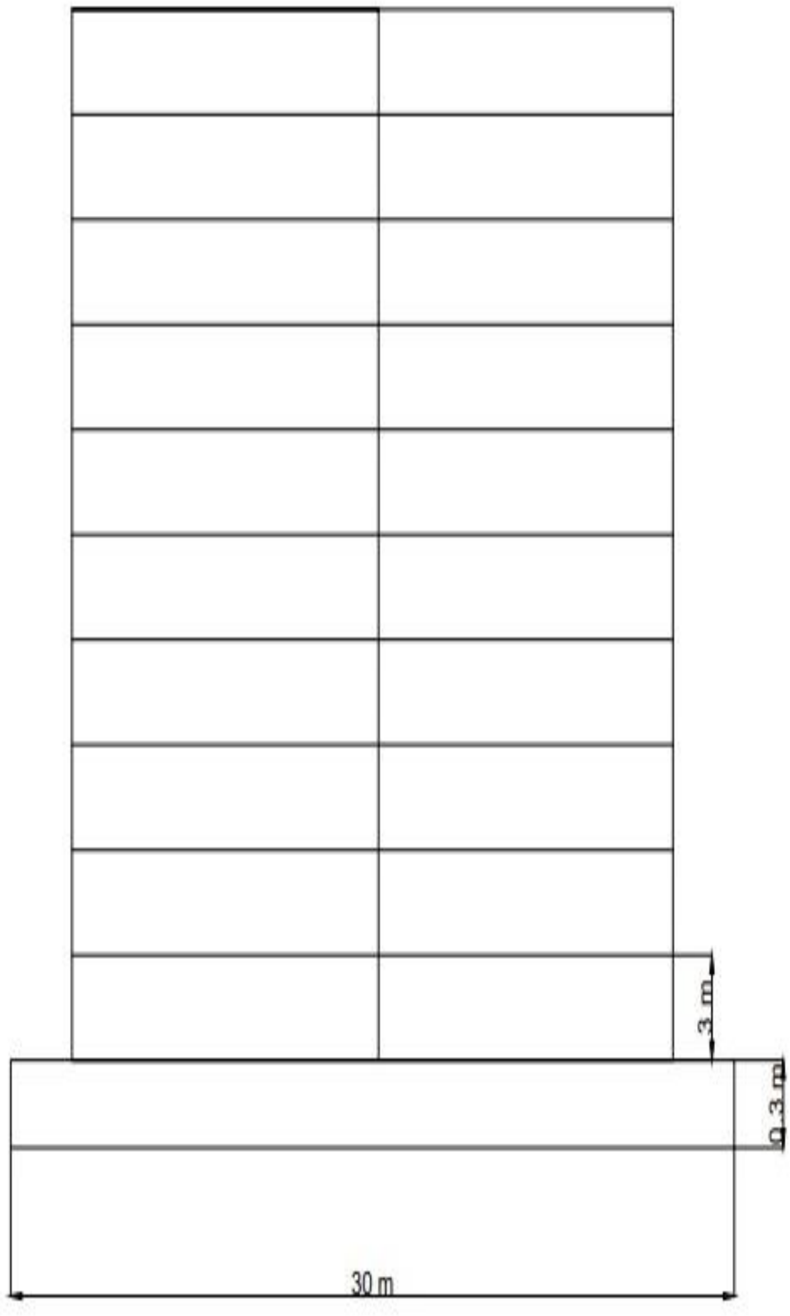

Fig. 4.10: Skeletal Building Elevation with Raft Foundation

Calculation of differential settlement: In this case, the thickness of the raft is increased from 150 mm upto 400 mm and the settlement at centre and at one corner are recorded and accordingly the differential settlement and the distortion angle is calculated in raft and combined pile raft foundation.

The differential settlement is obtained by taking the difference between maximum and minimum settlement. It occurs as a result of the non-uniform movement of the underlying soils at different rates and can result in cracking, exterior cladding, and interior finishes to the foundation.

The permissible differential settlement as per I.S. code 1904-1986 is given by 0.0025*L, where L is the centre-centre distance between the columns which is 14.7m. Hence, the permissible differential settlement in this case is 0.0025 x 14.7 = 0.03675 m = 36.75 mm.

Distortion angle is calculated by dividing the differential settlement by the distance between the points of related maximum and minimum settlement. The results are shown in Table 4.9 and Fig. 4.11 and Fig.4.12. Distortion angle, $\delta = \tan^{-1}\left(\frac{\text{Differential Settlement (mm)}}{\text{Distance between the two points}}\right)$

$$= \tan^{-1}\left(\frac{\text{Differential Settlement (mm)}}{\sqrt{14.7^2+14.7^2}}\right) \qquad \ldots\text{eq.4.2}$$

Table 4.9. Variation of Differential Settlement and Distortion Angle for Raft and CPRF

Raft Thickness (mm)	Foundation type	Settlement (mm)		Differential Settlement (mm)	Distortion Angle(δ)
		Maximum	Minimum		
150	Raft only	124.25	85.19	39.06	61.97
	CPRF	82.63	68.69	13.94	33.84
200	Raft only	119.11	82.17	36.94	60.63
	CPRF	70.43	58.27	12.16	30.32
250	Raft only	113.36	80.23	33.36	58.07
	CPRF	59.12	52.3	6.82	18.16
300	Raft only	108.11	77.61	30.5	55.72
	CPRF	53.81	48.71	5.1	13.78
400	Raft only	104.27	75.34	28.93	54.29
	CPRF	48.36	44.42	3.94	10.73

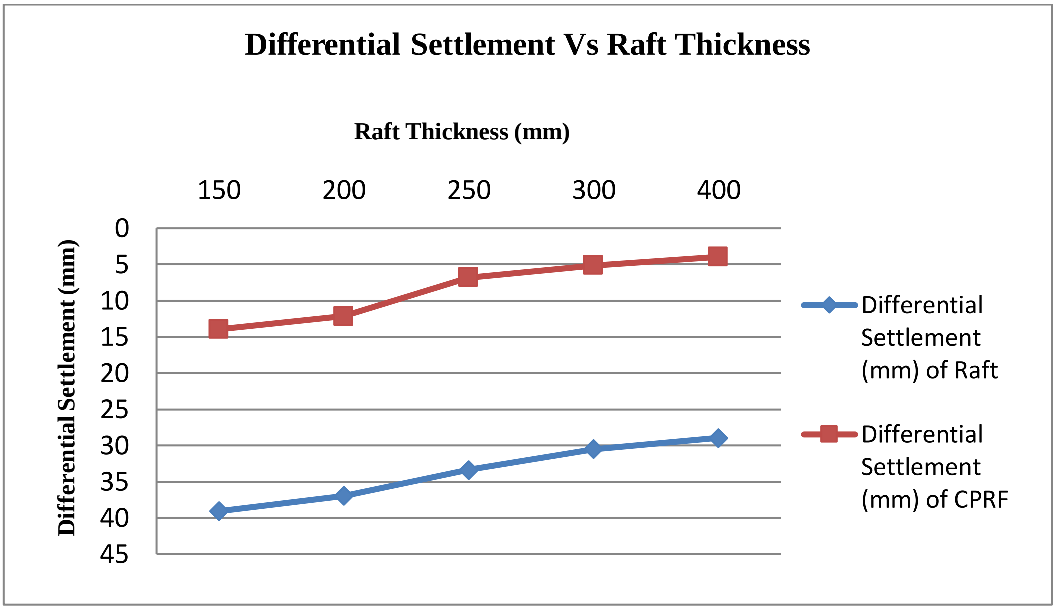

Fig 4.11 Variation of Differential Settlement with Raft Thickness

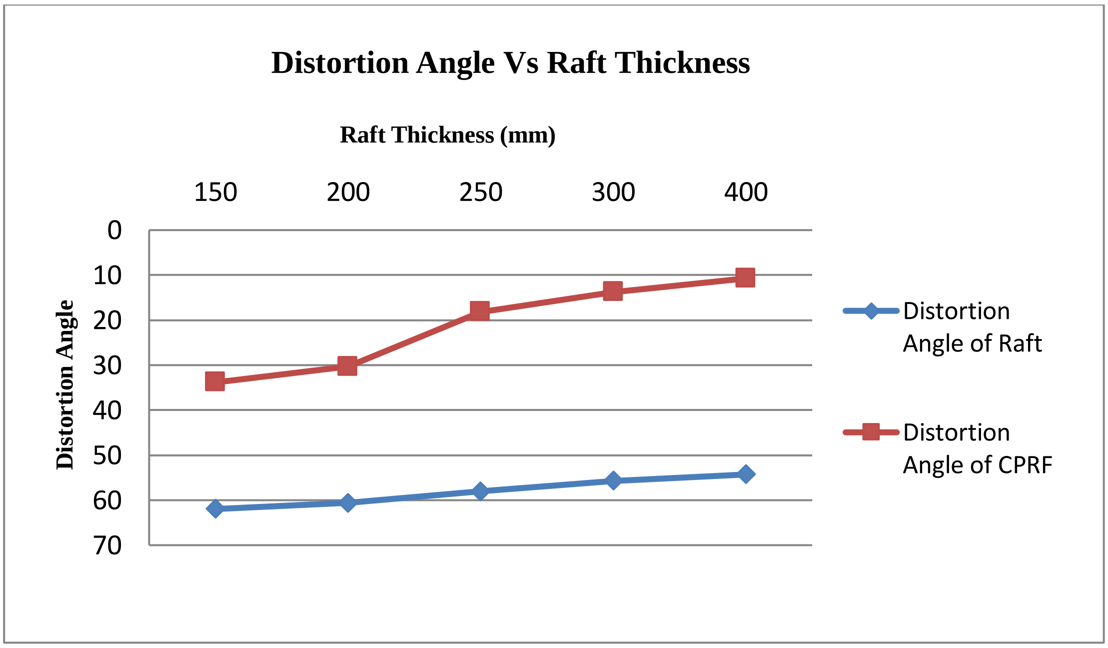

Fig 4.12 Variation of Distortion Angle with Raft Thickness

Conclusion: As seen from the above results the differential settlement of the raft and combined pile raft foundation decreases with the increase in raft thickness and it is also below the value of permissible limit (36.75mm), except for thickness 150 mm and 200 mm which is above the permissible limit. Also the Distortion angle for raft and CPRF decreases with the increase in raft thickness.

OPTION B: Increasing the diameter of piles in Piled Raft foundation

4.6.6.B Problem statement: In this case the 10 storeyed building of 30 m height, each storey being 3 m high is considered with a combined piled raft foundation of size 30 m x 30 m consisting of nine piles of varying diameter as shown in Fig.4.13 and Fig.4.14 The column spacing is taken as 14.7 m along x and y axis. As we have seen from the previous cases that piled raft foundation is a good alternative to raft foundation for reducing settlement. In addition to that increasing the diameter of piles further helps in reducing settlement in a piled raft foundation. The thickness of the raft is considered as 300 mm. The diameter of the piles is varied from 150 mm to 500 mm. The material parameters of the soil and raft are considered as per Clause 4.6.2.

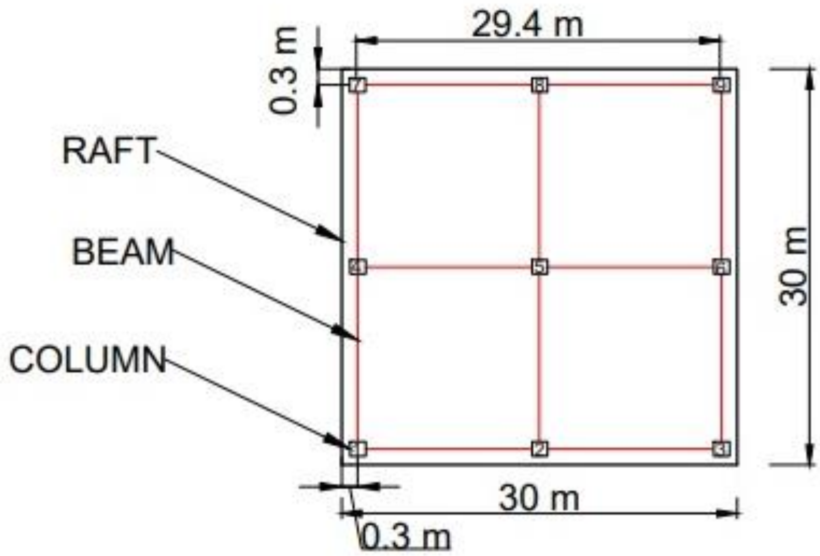

Fig. 4.13: Building Plan Showing Arrangement of Beams and Columns

Fig 4.14 Skeletal building elevation with Combined Piled Raft Foundation consisting of 10 m long piles

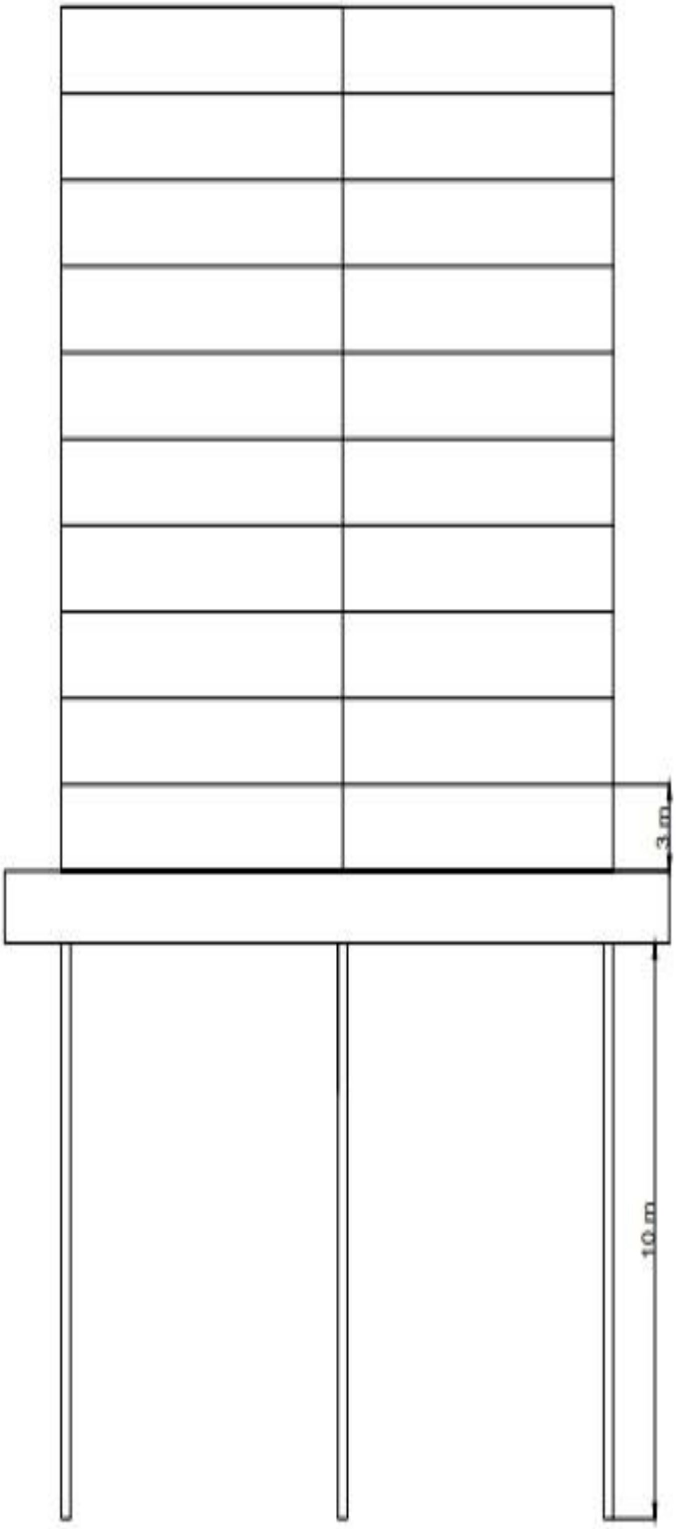

Fig 4.14 Skeletal building elevation with Combined Piled Raft Foundation consisting of 10 m long piles

Calculation of differential settlement: In this case, the diameter of the piles is varied from 150 mm to 500 mm and the settlement at centre and at one corner are recorded and accordingly the differential settlement is calculated.

The differential settlement is obtained by taking the difference between maximum and minimum settlement. In this case, the maximum and minimum settlement is observed below column 5 and column 9. The permissible differential settlement as per I.S. code 1904-1986 is given by 0.0025*L, where L is the centre-centre distance between the columns which is 14.7m. Hence, the permissible differential settlement in this case is 0.0025 x 14.7 = 0.03675 m = 36.75 mm. The results are shown in Table 4.10 and Fig.4.15.

Table 4.10: Variation of Differential settlement with Pile diameter of CPRF

Diameter of piles (mm)	Maximum Settlement (mm)	Minimum Settlement (mm)	Differential Settlement (mm)
150	112.73	81.55	31.18
200	109.76	79.83	29.93
300	102.25	75.22	27.03
400	95.39	71.83	23.56
500	89.30	69.37	19.93

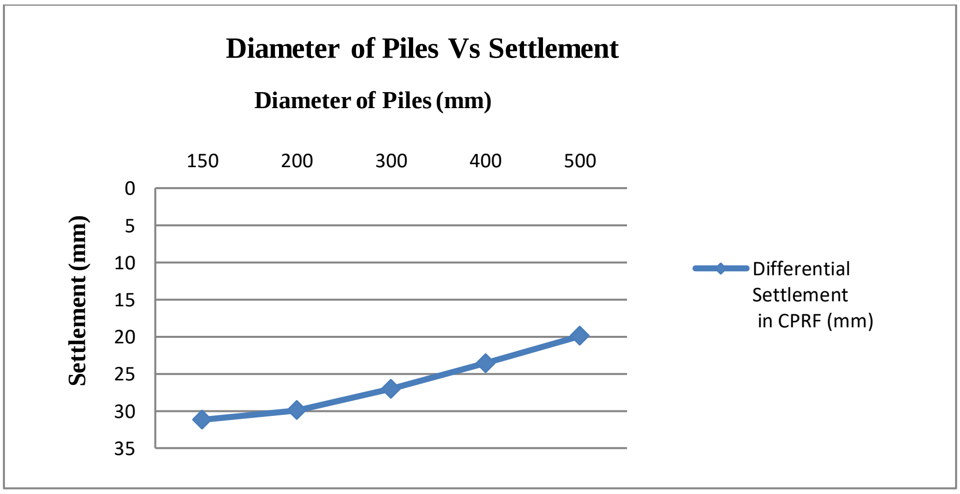

Fig.4.15: Variation of Differential Settlement with Pile Diameter in CPRF

Conclusion: As seen from above results increasing the pile diameter in Combined Piled Raft Foundation (CPRF) does help in decreasing the differential settlement. For all the pile diameter above, the differential settlement is below the permissible limit (36.75 mm).

OPTION C: Increasing the length of piles in Combined Piled Raft foundation (CPRF).

4.6.6.C Problem statement: In this case the 10 storeyed building of 30 m height, each storey being 3 m high is considered with a combined piled raft foundation of size 30 m x 30 m consisting of nine piles of varying length as shown in Fig.4.16 and Fig.4.17. The column spacing is taken as 14.7 m along x and y axis. As we have seen from the previous cases that piled raft foundation is a good alternative to raft foundation for reducing settlement. In addition to that increasing the length of piles further helps in reducing settlement in a piled raft foundation. The thickness of the raft is considered as 300 mm. The length of the piles is varied from 8 m to 22 m. The material parameters of the soil and raft are considered as per Clause 4.6.2.

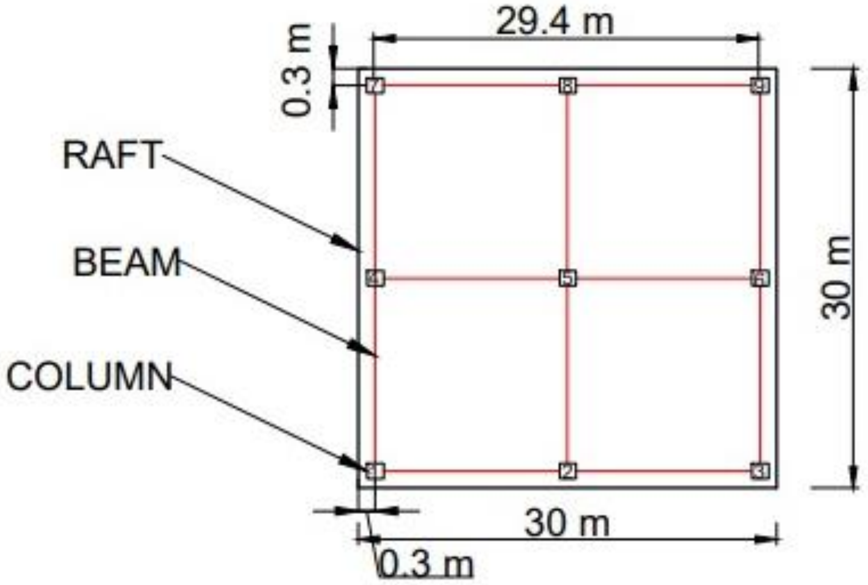

Fig.4.16: Building Plan Showing Arrangement of Beams and Columns

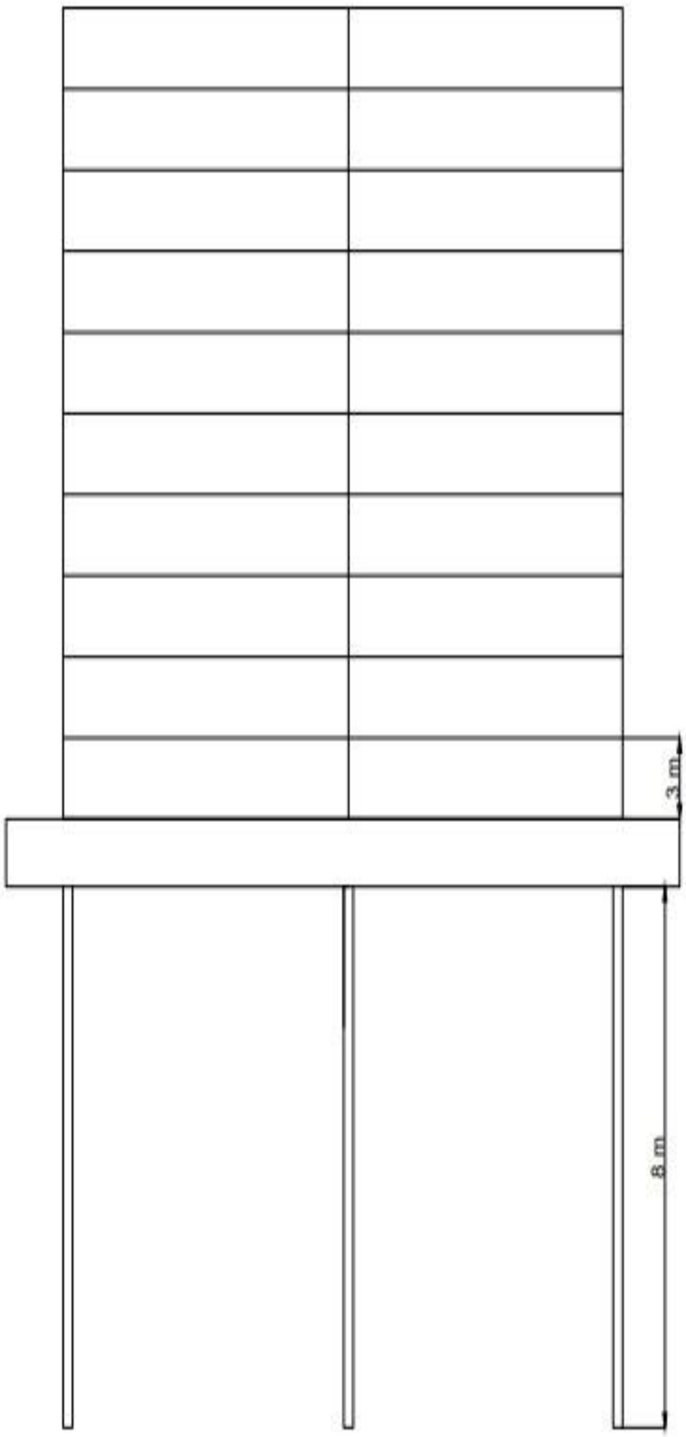

Fig 4.17 Skeletal building elevation with Combined Piled Raft Foundation consisting of 8 m to 22 m length varying piles

Calculation of differential settlement: In this case, the length of the piles is varied from 8 m to 22 m and the settlement at centre and at one corner are recorded and accordingly the differential settlement is calculated.

The differential settlement is obtained by taking the difference between maximum and minimum settlement. In this case, the maximum and minimum settlement is observed below column 5 and column 9. The permissible differential settlement as per I.S. code 1904 -1986 is given by 0.0025*L, where L is the centre-centre distance between the columns which is 14.7m. Hence, the permissible differential settlement in this case is 0.0025 x 14.7 = 0.03675 m = 36.75 mm. The results are shown in Table 4.11 and Fig.4.18.

Table 4.11: Variation of Differential settlement with Pile length of CPRF

Length of pile (mm)	Maximum Settlement (mm)	Minimum Settlement (mm)	Differential Settlement (mm)
8	114.75	90.71	24.04
10	107.94	86.11	21.83
14	97.40	79.45	17.95
18	88.05	73.84	14.21
22	81.29	70.43	10.86

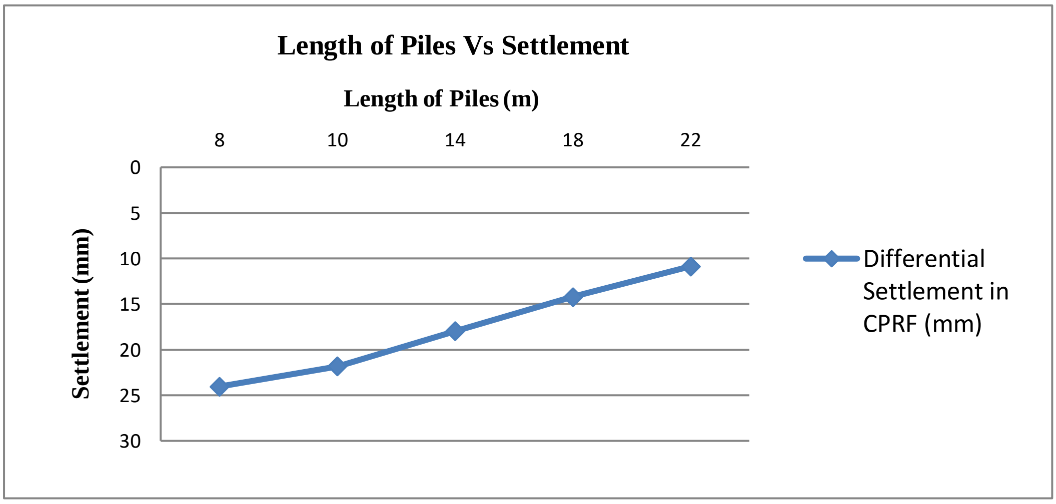

Fig.4.18: Variation of Differential Settlement with Pile Length in CPRF

Conclusion: As seen from above results increasing the pile length in Combined Piled Raft Foundation (CPRF) does help in decreasing the differential settlement. For all the pile length above, the differential settlement is below the permissible limit (36.75 mm).

4.6.7. Behaviour of raft and combined piled raft foundation under Seismic loading.

- In this study, an attempt is made to understand the seismic response of raft foundation and combined piled raft foundation in terms of lateral displacement and acceleration under the earthquake loading conditions. The finite element simulations are performed using PLAXIS 3D AE to investigate this under earthquake loading conditions.
- Combined pile raft foundation behaviour under earthquake loads is considered very significant and can influence the stability of structure and its performance. A study is done dealing with the effect of earthquake loading conditions on the behaviour of raft foundation and combined piled raft foundation for a building under a real earthquake data with time history. It is a composite construction consisting of three bearing elements: piles, raft and subsoil.

  By finite element technique with using PLAXIS 3D AE program the raft and combined piled raft foundation is modelled as solid elements with finite meshing and the frame system is modelled as a 3D frame. The soil mass is modelled by Mohr-Coulomb and the piles are assumed as embedded beam elements.

  After modelling and exerting a static lateral force of 10kN/m applied on the top left corner of the building and earthquake data on base of the model, the execution of the analysis is then started, by considering certain nodes.
- For raft foundation analysis under seismic load node 86, node 83 and node 82 are considered in the building and node 79 is considered in the raft foundation as shown in fig.4.21.

  For CPRF node 86 and node 83 are considered in the building and node 79 is considered in the raft foundation and node 3383 is considered in pile foundation as shown in fig.4.22.
- Earthquake Modelling - To study the effects of lateral displacement and acceleration characteristics on the raft and combined piled raft foundation response, a real earthquake data from earthquake in Japan on August 5, 1990 with a magnitude of 5.4 is considered.
- Studies on the piled raft foundation response under lateral loads or when subjected to seismic action, however are rare. Few numbers of literatures have been published to understand the complex behaviour of piled raft subjected to real earthquake loading conditions. Since the behaviour of a piled raft foundation during earthquakes is considered fairly complex due to dynamic interaction among a raft, piles and a soil, the design procedure should include the effect of this mechanism in an appropriate manner. In other words, the behaviour of piled raft foundations under earthquake loading is an important factor affecting the performance of structures.

  Summarily, it can be said that the studies related to the seismic analysis of piled raft foundations are very few and therefore, can be investigated further using earthquake loads.

4.6.7.1 Representation of acceleration (m/s^2) and displacement (m) with respect to time (s) for the given earthquake load.

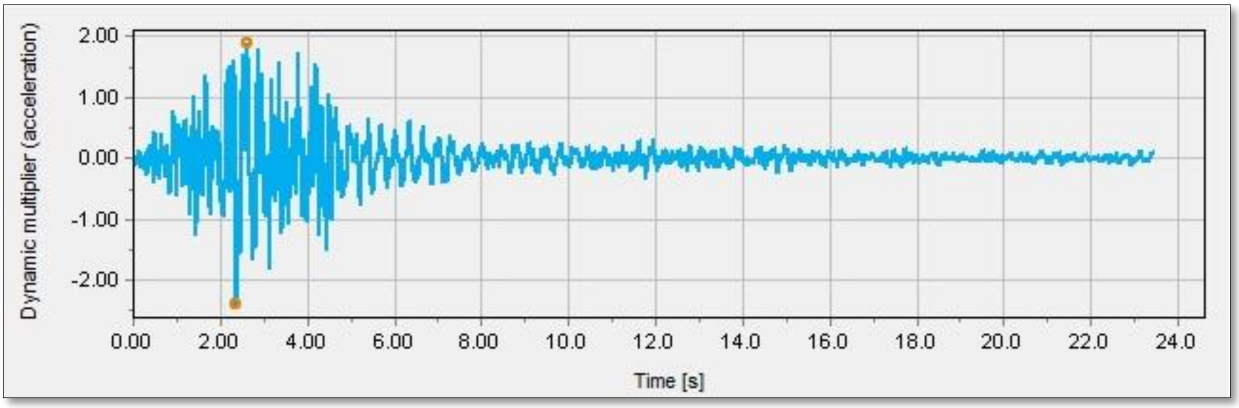

Fig 4.19. Acceleration (m/s^2) Vs Time(s) plot for an earthquake.

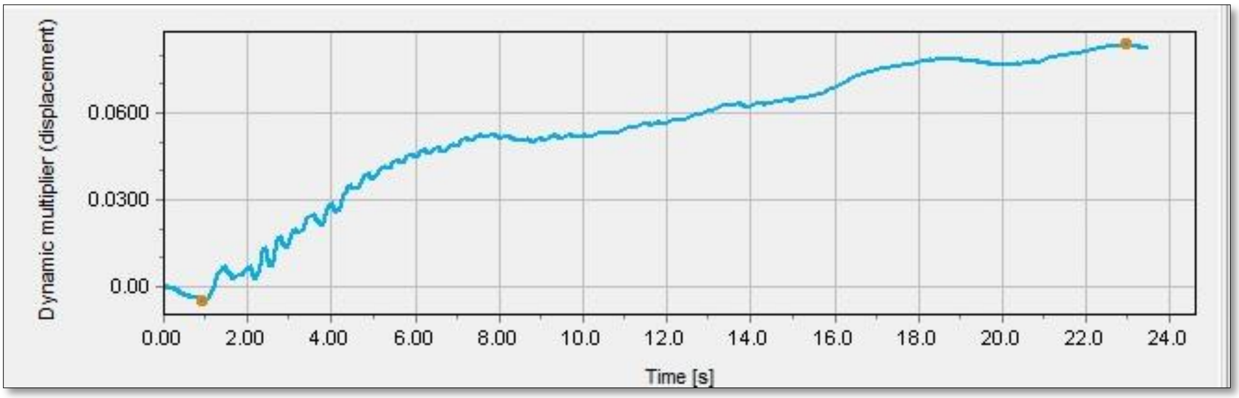

Fig 4.20. Displacement (m) Vs Time(s) plot for an earthquake.

4.6.7.2 Response of raft and combined piled raft foundation under seismic load

Values of displacement and acceleration with respect to dynamic time for only raft and CPRF under effect of earthquake load is shown below.

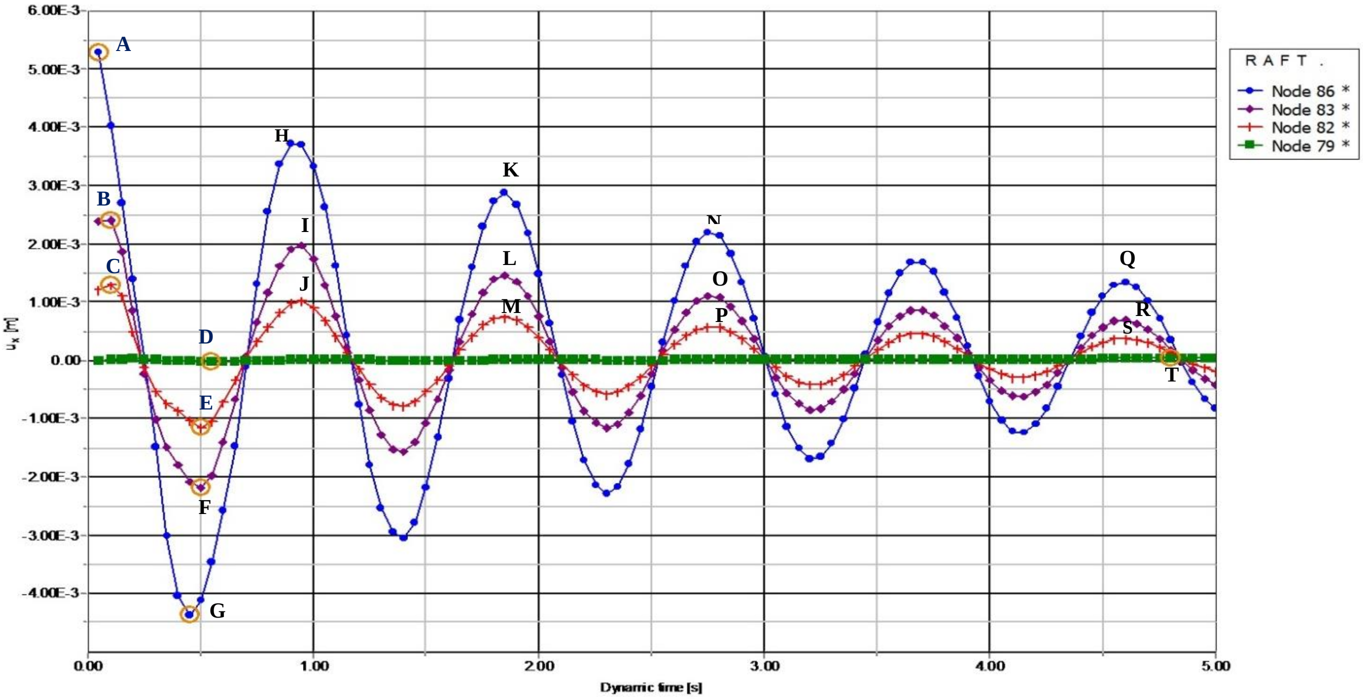

Fig.4.21: Displacement (m) Vs Dynamic time (sec) plot in Raft foundation.

Table 4.12 Displacement (m) values at various points with respect to time(sec) in raft foundation

A = 5.273 x 10^{-3} m	K = 2.865 x 10^{-3} m
B = 2.398 x 10^{-3} m	L = 1.447 x 10^{-3} m
C = 1.302 x 10^{-3} m	M = 7.462 x 10^{-3} m
D = -1.844 x 10^{-5} m	N = 2.2 x 10^{-3} m
E = -1.149 x 10^{-3} m	O = 1.114 x 10^{-3} m
F = -2.193 x 10^{-3} m	P = 5.793 x 10^{-4} m
G = -4.368 x 10^{-3} m	Q = 1.339 x 10^{-3} m
H = 3.697 x 10^{-3} m	R = 6.89 x 10^{-4} m
I = 1.967 x 10^{-3} m	S = 3.73 x 10^{-4} m
J = 1.032 x 10^{-3} m	T = 3.731 x 10^{-5} m

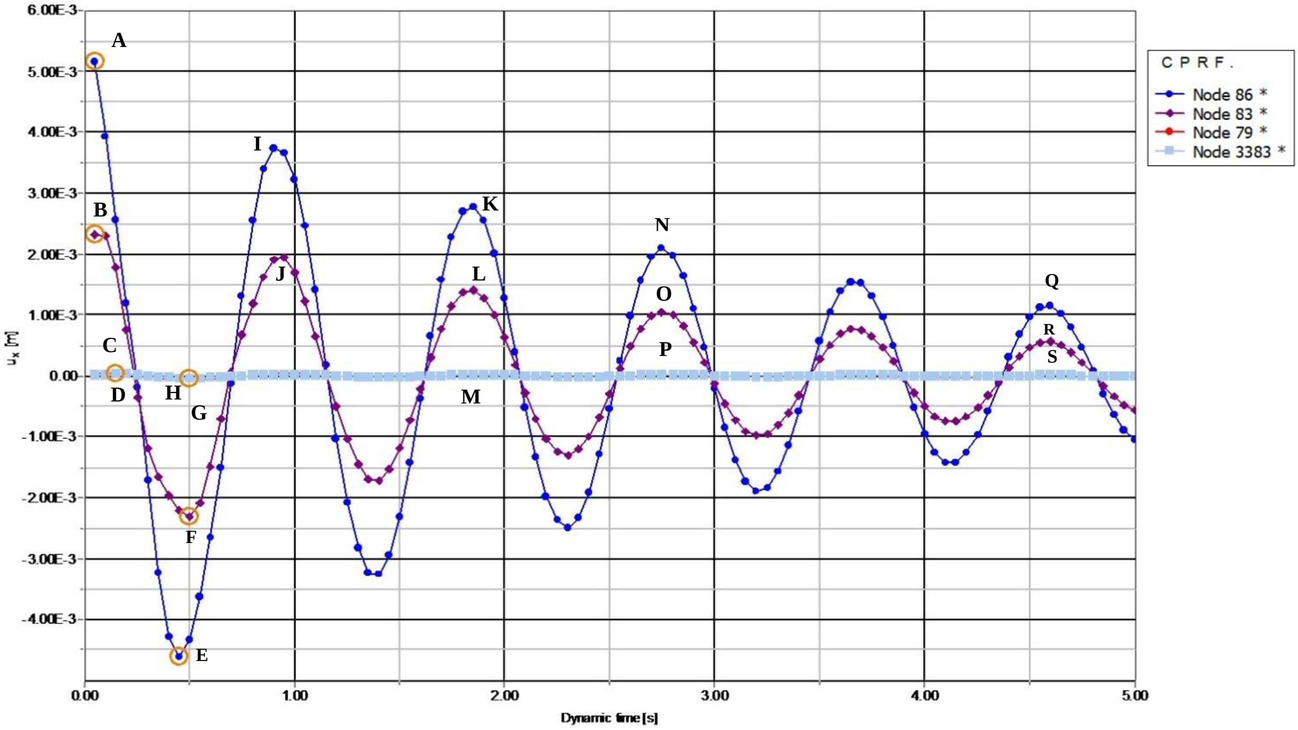

Fig.4.22: Displacement (m) Vs Dynamic time (sec) plot in Combined pile raft foundation.

Table 4.13 Displacement (m) values at various points with respect to time(sec) in CPRF

A = 5.159 x 10^{-3} m	K = 2.775 x 10^{-3} m
B = 2.321 x 10^{-3} m	L = 1.409 x 10^{-3} m
C = 3.95 x 10^{-5} m	M = 1.949 x 10^{-5} m
D = 2.402 x 10^{-5} m	N = 2.085 x 10^{-3} m
E = -4.274 x 10^{-3} m	O = 1.049 x 10^{-3} m
F = -2.305 x 10^{-3} m	P = 1.5 x 10^{-5} m
G = -4.871 x 10^{-5} m	Q = 1.149 x 10^{-3} m
H = -4.01 x 10^{-5} m	R = 5.718 x 10^{-4} m
I = 3.536 x 10^{-3} m	S = 8.61 x 10^{-6} m
J = 1.944 x 10^{-3} m	

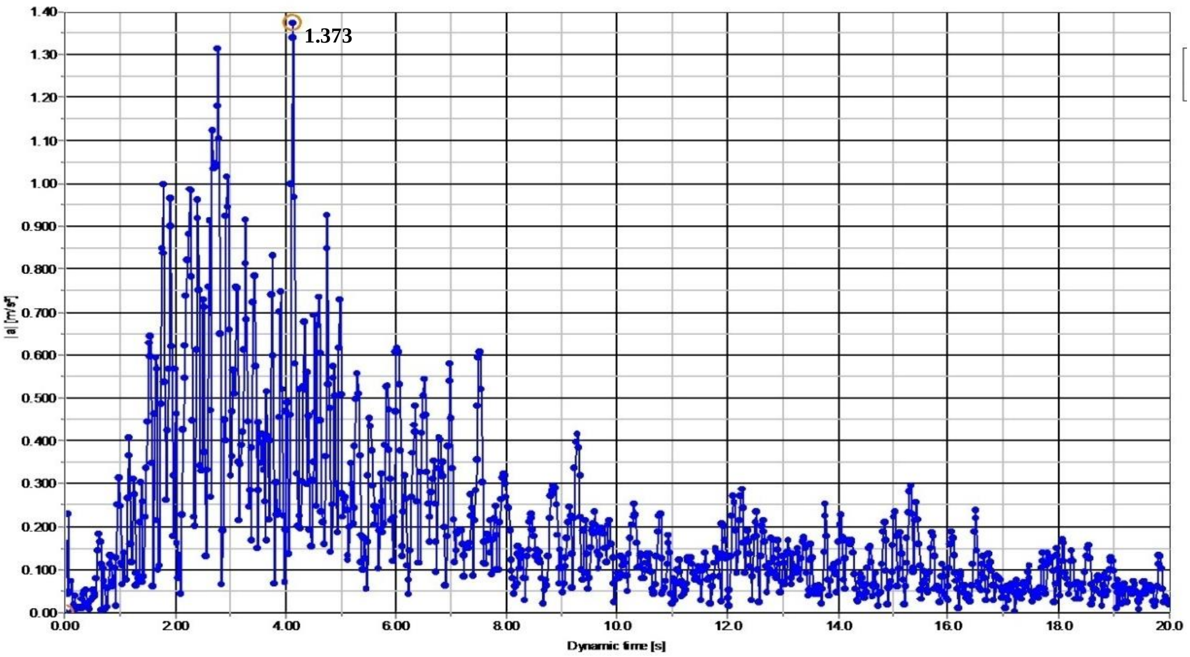

Fig.4.23. Acceleration (m/s^2) Vs Dynamic time (sec) plot in Raft foundation .

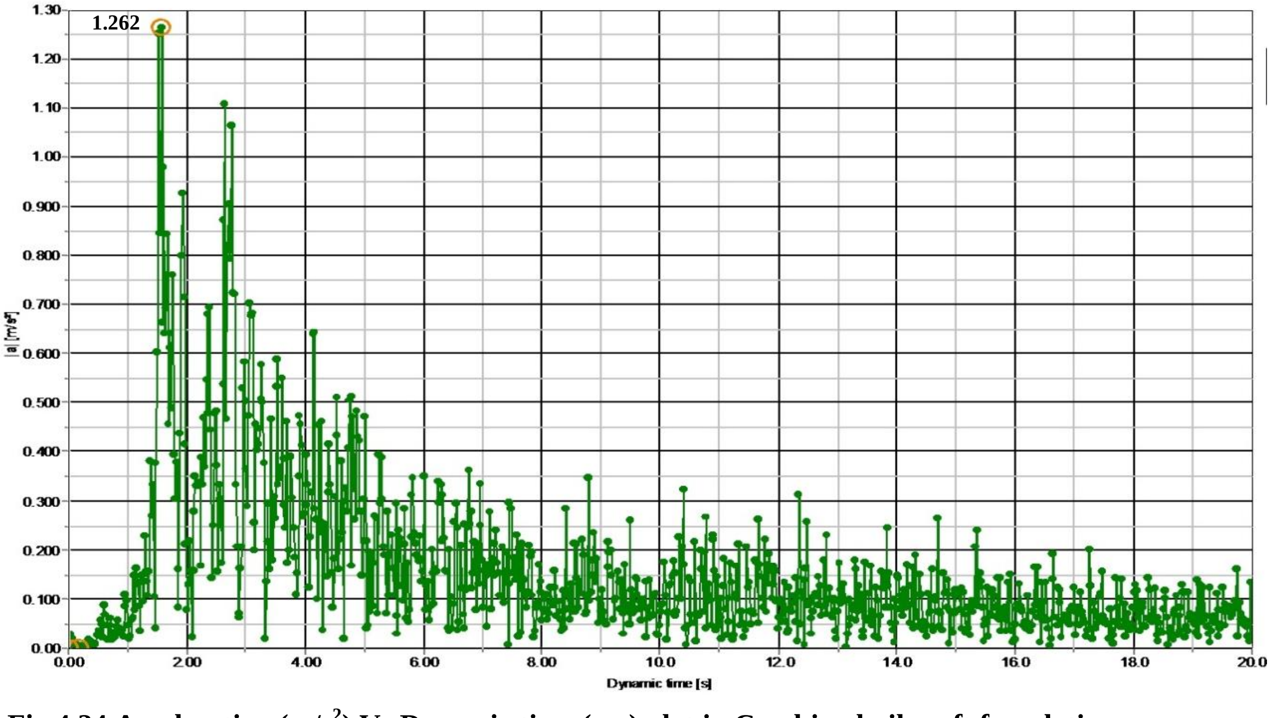

Fig.4.24 Acceleration (m/s^2) Vs Dynamic time (sec) plot in Combined pile raft foundation.

4.6.7.3 Conclusion Thus it is seen that on applying combined piled raft foundation with 250 mm raft thickness, pile diameter of 200 mm and 10 m length for a ten storeyed structural load is better then only raft foundation of 500 mm thickness as an effective parameter for limiting both displacements and accelerations under the application of seismic loads during an earthquake.

CHAPTER 5

INTERPRETATION OF RESULTS

5.1 COMPARISON OF THE PARAMETERS CONSIDERED.

The results of the parameters considered are presented below in tabular and graphical format for comparison in terms of maximum settlement and differential settlement.

Table 5.1: Comparison of maximum settlement under a system of point loads for different foundation types.

SI No	Abbreviation	Type of foundation	Maximum settlement (mm)	Permissible settlement (mm)	Remarks
1	A1	Raft with 4800 kN total load	20.33	75	Within limit
2	A2	Raft with 5000 kN total load	23.12	75	Within limit
3	A3	Raft with 5200 kN total load	27.09	75	Within limit
4	A4	Raft with 5400 kN total load	33.16	75	Within limit
5	B1	CPRF with 4800 kN total load	9.49	75	Within limit
6	B2	CPRF with 5000 kN total load	10.10	75	Within limit
7	B3	CPRF with 5200 kN total load	12.26	75	Within limit
8	B4	CPRF with 5400 kN total load	13.64	75	Within limit
9	C1	CPRF with 150 mm pile diameter	20.84	75	Within limit
10	C2	CPRF with 200 mm pile diameter	17.93	75	Within limit
11	C3	CPRF with 300 mm pile diameter	15.78	75	Within limit
12	C4	CPRF with 400 mm pile diameter	14.07	75	Within limit
13	C5	CPRF with 500 mm pile diameter	12.67	75	Within limit
14	D1	CPRF with 8 m pile length	19.94	75	Within limit
15	D2	CPRF with 10 m pile length	17.77	75	Within limit
16	D3	CPRF with 14m pile length	16.53	75	Within limit
17	D4	CPRF with 18 m pile length	15.04	75	Within limit
18	D5	CPRF with 22 m pile length	13.58	75	Within limit

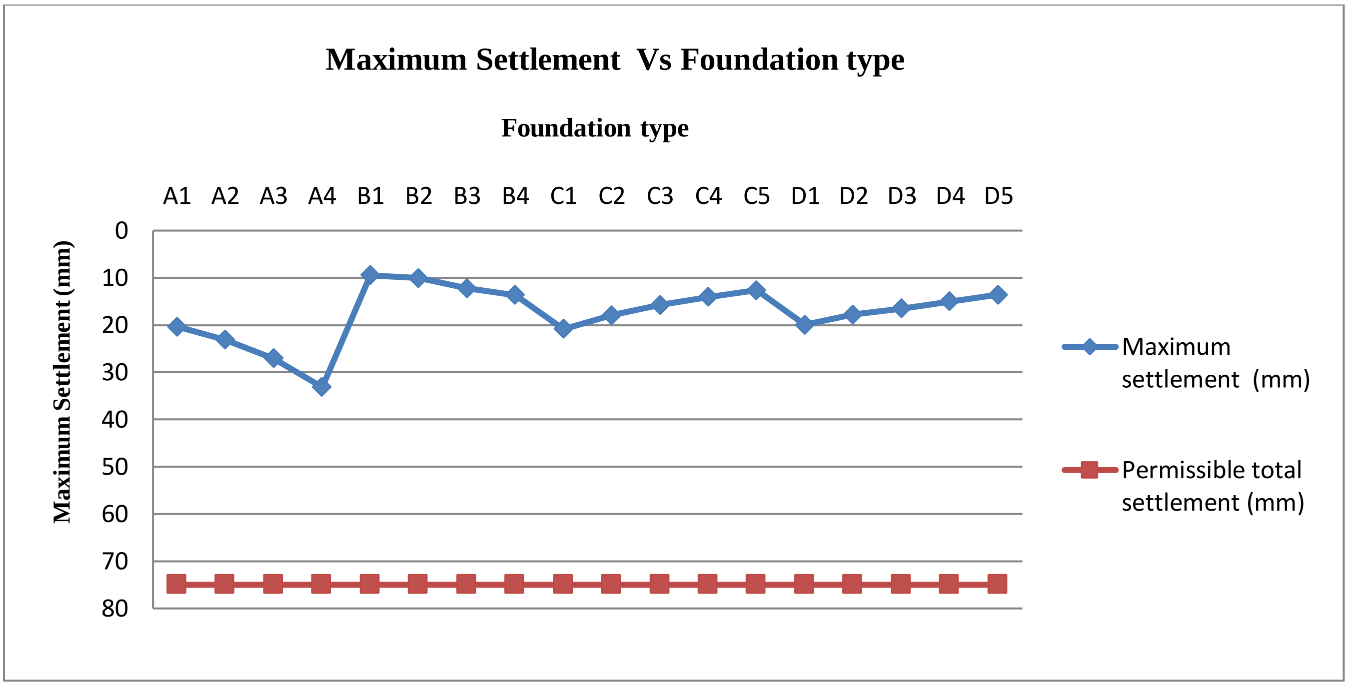

Fig. 5.1: Variation of Maximum Settlement with Foundation Type

From the above table and graph, it is quite clear that the maximum settlement is under permissible limit (75 mm) for all foundation type, the lowest being for B1 which is the CPRF with a total load of 4800 kN.

Table 5.2 : Comparison of differential settlement under a system of point loads for different foundation types.

SI No	Abbreviation	Type of foundation	Differential settlement (mm)	Permissible settlement (mm)	Remarks
1	A1	Raft with 200 mm thickness	21.047	36.75	Within limit
2	A2	Raft with 300 mm thickness	20.327	36.75	Within limit
3	A3	Raft with 400 mm thickness	20.05	36.75	Within limit
4	A4	Raft with 500 mm thickness	19.812	36.75	Within limit
5	B1	CPRF with 200 mm thickness	8.905	36.75	Within limit
6	B2	CPRF with 300 mm thickness	8.223	36.75	Within limit
7	B3	CPRF with 400 mm thickness	7.665	36.75	Within limit
8	B4	CPRF with 500 mm thickness	7.282	36.75	Within limit

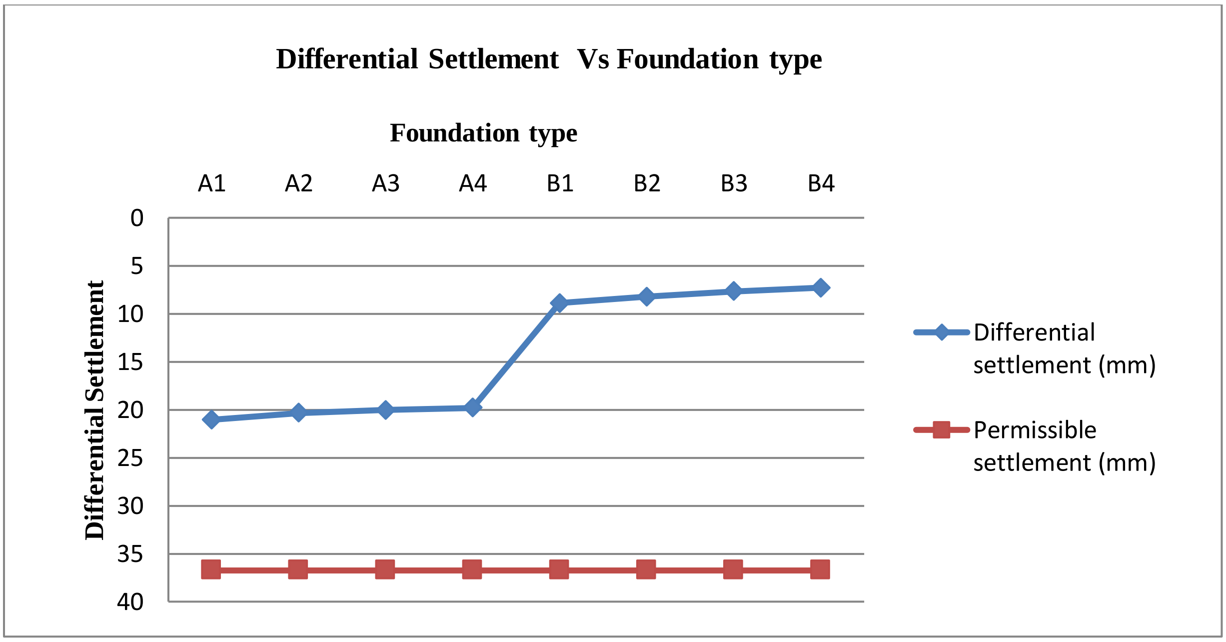

Fig. 5.2: Variation of Differential Settlement with Foundation Type

From the above table and graph, it is quite clear that the differential settlement is under permissible limit for all foundation type, the minimum settlement is B4 which is the CPRF with a 500 mm raft thickness.

Table 5.3: Comparison of differential settlement under ten storeyed structural load for varying parameters for different foundation types.

SI No	Abbreviation	Type of foundation	Differential settlement (mm)	Permissible settlement (mm)	Remarks
1	A1	Raft with 150 mm thickness	39.06	36.75	Exceeds limit
2	A2	Raft with 200 mm thickness	36.94	36.75	Exceeds limit
3	A3	Raft with 250 mm thickness	33.36	36.75	Within limit
4	A4	Raft with 300 mm thickness	30.5	36.75	Within limit
5	A5	Raft with 400 mm thickness	28.93	36.75	Within limit
6	B1	CPRF with 150 mm thickness	13.94	36.75	Within limit
7	B2	CPRF with 200 mm thickness	12.16	36.75	Within limit
8	B3	CPRF with 250 mm thickness	6.82	36.75	Within limit
9	B4	CPRF with 300 mm thickness	5.1	36.75	Within limit
10	B5	CPRF with 400 mm thickness	3.94	36.75	Within limit
11	C1	CPRF with 150 mm pile diameter	31.18	36.75	Within limit
12	C2	CPRF with 200 mm pile diameter	29.93	36.75	Within limit
13	C3	CPRF with 300 mm pile diameter	27.03	36.75	Within limit
14	C4	CPRF with 400 mm pile diameter	23.56	36.75	Within limit
15	C5	CPRF with 500 mm pile diameter	19.93	36.75	Within limit
16	D1	CPRF with 8 m pile length	24.04	36.75	Within limit
17	D2	CPRF with 10 m pile length	21.83	36.75	Within limit
18	D3	CPRF with 14m pile length	17.95	36.75	Within limit
19	D4	CPRF with 18 m pile length	14.21	36.75	Within limit
20	D5	CPRF with 22 m pile length	10.86	36.75	Within limit

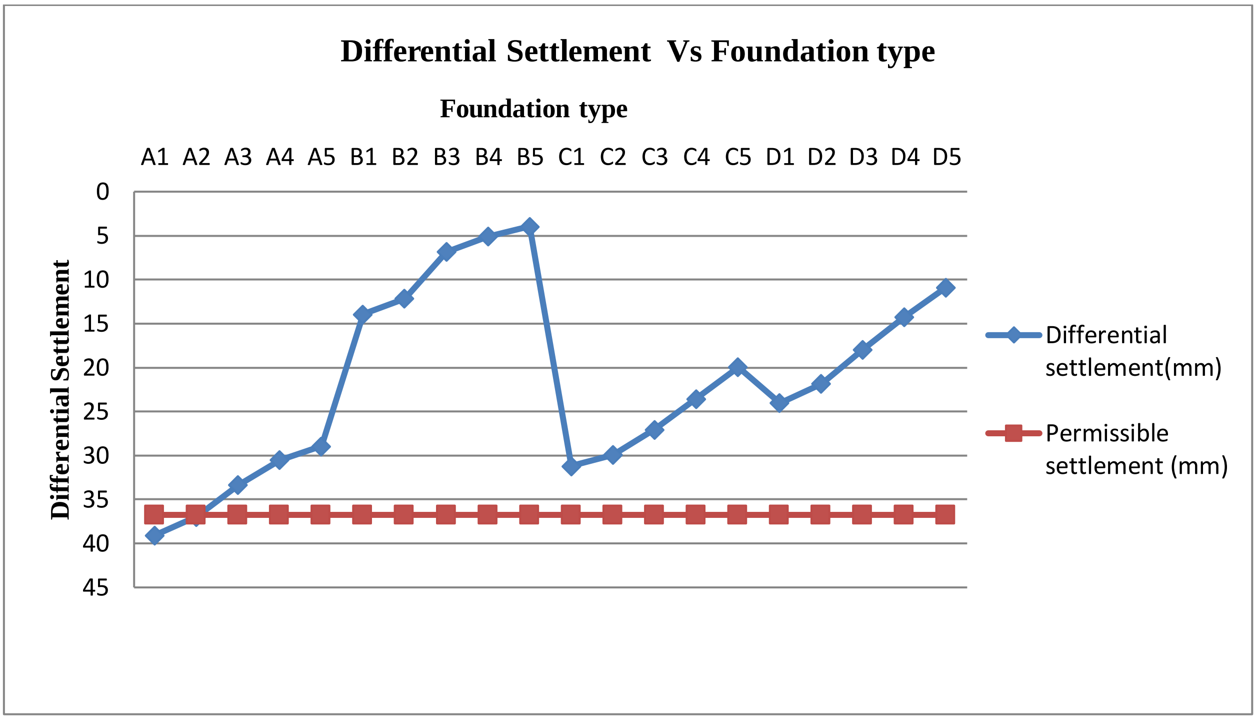

Fig. 5.3: Variation of Differential Settlement with Foundation Type

From the above table and graph, it is quite clear that the differential settlement is under permissible limit, except for thickness 150 mm and 200 mm, the lowest being for B5, C5, D5 which is the CPRF with a 400 mm raft thickness alongwith 500 mm pile diameter and 22 m of pile length.

5.2 Conclusion: From settlement point of view it can be seen from the above results that applying combined piled raft foundation is better then only raft foundation to get the minimum differential settlement.

CHAPTER 6

CONCLUSION AND SCOPE OF FURTHER STUDY

6.1 INTRODUCTION

Based on the study of Combined Pile Raft Foundation, the conclusions which can be drawn are incorporated in this chapter including a few suggestion of scope for further study in these contents.

6.2 CONCLUSIONS

Following conclusions can be made from the parametric study of Combined Pile Raft Foundation:

1. Combined Pile Raft Foundation is a better alternative as compared to a raft foundation as the maximum and differential settlement induced is higher in the latter one.
2. A raft foundation experiences more settlement as compared to a combined pile raft foundation (CPRF) for the same set of loads. The presence of piles in a combined pile raft foundation is responsible for the significant reduction of settlement.
3. Increasing thickness of raft helps in decreasing the settlement of the raft and combined pile raft foundation and also same in case of the differential settlement and distortion angle.
4. Increase in diameter of piles leads to decrease in the settlement in combined pile raft foundation
5. The settlement in combined pile raft foundation decreases with the increase in length of piles.
6. In analyzing the ten storied building, it was found that increasing the thickness of raft to a certain value does help in bringing the differential settlement under permissible limit.
7. In analyzing the ten storied building, it was found that increasing the diameter and length of piles in a combined pile raft foundation does help in bringing the differential settlement under permissible limit.
8. In analyzing the ten storied building, it is seen that on applying for dynamic loads acting on the building, combined piled raft foundation is better then only raft foundation as an effective parameter for limiting both displacements and accelerations during an earthquake.

6.3 SCOPE OF FURTHER STUDY

This study can be further continued taking the following points under consideration:

a) The parametric study of Combined Pile Raft Foundation can be done for a layered soil deposit

b) Layered soil deposit can also be considered for analyzing the ten storied building.

c) The cost analysis for the types of foundation in the ten storied building can also be done.

REFERENCES

J. Burland, (1995), "Piles as Settlement Reducers", Pavia, Italy: Keynote Address, 18th Italian Congress on Soil Mechanics.

R. Butterfield, and P.R. Banerjee, (1971), "The Problem of Pile Group-Pile Cap Interaction".Geotechnical. Vol. 21, Issue 2.

R. P. Cunha, H. G. Poulos, and J. C. Small, (2001), "Investigation of Design Alternatives for a Piled Raft Case History", Journal of Geotechnical and Environmental Engineering, pp.635-641.

N. Joy, and H. Hassan, (2014), "Study on Settlement Characteristics of Combined Pile Raft Foundation Founded on Sand with Various Arrangements of Pile using Plaxis-3D AE",International Journal of Engineering Technology and Advanced Engineering, Vol. 4, Issue 10

A.Kumar, D. Choudhury and R. Kartzenbach, (2015), "Behavior of Combined Pile-Raft Foundation (CPRF) under Static and Pseudo-static Conditions using PLAXIS 3D", 6th International Conference on Earthquake Geotechnical Engineering.

D. K. Maharaj, (2004), "Three Dimensional Nonlinear Finite Analysis to Study the effect of Raft and Pile Stiffness on the Load-Settlement Behaviour of Piled Raft Foundations", The Electronic Journal of Geotechnical Engineering.

H.G. Poulos, (1991), "Analysis of Piled Strip Foundations.", Computer Methods & Advances in Geomechanics, (ed. Beer et al, Balkema), pp. 183-191.

H.G. Poulos, and E.H. Davies, (1972), "The Analysis of Piled Raft System". Asst. Geomechanics Journal, Vol. G2, No. 1, pp. 21-27.

H. Poulos, and E. Davis, (1980), "Pile Foundation Analysis and Design", New York: Wiley.

M.F. Randolph, (1994), "Design Methods for Pile Groups and Piled Rafts", State of the Art Report, Proc. 13 thInternational Conference Soil Mechanics Foundation Engineering, pp. 6182.

0. Reul, and M. Randolph, (2004), "Design Strategies for Piled Rafts Subjected to non-uniform Vertical Loading", Jl. of Geotechnical and Geo Environmental Engineering,Vol. 130, No. 1, pp. 1-10.

V.J Sharma, S.A.Vasanvala, and C.H. Solanki, (2011), "Effect of Cushion on Composite Piled-Raft Foundation", Journal of Engineering Research and Studies, Vol. 2, Issue 4.

H. Sommer, P. Wittmann, and P. Ripper, (1985), "Piled Raft Foundation of a Tall Building in Frankfit-t Clay", Proc. 11 ICSMFE, pp. 2253-2257.

G. Zhuang, Lee and X. Zhao, X. (1991), "Interactive Analysis of Behaviour of Raft-Pile Foundations", Proc. Geo-Coast '91, pp. 759-764.

K. Watcharasawe , P. Kitiyodom and P. Jongpradist, "Numerical Analyses of Piled Raft Foundation in Soft Soil Using 3D-FEM", (2015) Geotechnical & Foundation Engineering Co., Ltd (GFE) .

Ripunjoy Deka , "Different Analysis Methods of Piled Rafts", (2014) International Journal of Engineering Technology, Management and Applied Sciences.

S.J Shukla, A.K Desai and C.H Solanki, (2013) “A dynamic behavioural study of 25 storey building with piled raft foundation with variable subsoils” International Journal Of Structural And Civil Engineering Research, Vol. 2, No. 1.

P. Halder and B. Manna (2019), “Seismic analysis of piled raft foundation of pseudostatic approach”, Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions.