ANALYSIS AND DESIGN OF PILED RAFT FOUNDATION

Dissertation

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CERTIFICATE

This is to certify that the Major Project entitled "**Analysis and Design of Piled raft foundation**" submitted by **Mr. Saraf Shripad V. (03MCL13)**, towards the partial fulfillment of the requirements for the award of degree of **Master of Technology (CIVIL)** in field of **Computer Aided Structural Analysis and Design (CASAD)** of Nirma University of Science and Technology is the record of work carried out by him under my supervision and guidance. The work submitted has in my opinion reached a level required for being accepted for examination. The results embodied in this dissertation, to the best of my knowledge have not been submitted to any other university or institution for award of any degree or diploma.

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Title: Analysis and Design of Piled raft Foundation

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Abstract

The Piled raft foundation has gained popularity in the field of construction. Construction of raft at shallow depth on soil having low bearing capacity to get uniform settlement is very well known. In the situations where the raft foundation alone dose not satisfy the design requirements, and then it may be possible to enhance the performance of the raft by addition of piles. The use of a strategically located limited number of piles, may improve both the ultimate load capacity and settlement performance of raft.

The analysis of Piled raft is a complex problem, even more complex than that of a soil supported raft, as too many parameters influence the behavior of the system. There are various parameters which influence the sharing of load between piles and raft, between piles themselves and between piles and soil and as such the exact behavior is unpredictable for Piled raft system.

The thesis explores the analysis and design of Piled raft system, outlining the influence of major structural parameters of both raft and pile. Simplified method is used for analysis of Piled raft system. The settlement is also calculated by approximate method of analysis by using Structural Analysis and Design software Staad. Pro. 2003. A typical Plied raft design problem is presented in this study. A parametric study is carried out to study the influence of various structural parameters of pile on Piled raft load sharing and Piled raft settlements sharing. The settlement response is studied for various variations of pile diameter, pile length and pile numbers in case of Simplified method while in case of approximate method raft thickness is considered additional to this.

The response of Piled raft system is stiffer with increased load carrying capacity and with less settlement which leads to economical design.

Keywords: raft, pile, modeling and analysis, settlement, stiffness.

Lay out of Chapters:

Chapter 1

In this chapter an introductory part of Piled raft is mentioned. The necessity of Piled raft foundation is explained. The objective of study which is in two parts is explained.

Chapter 2

The literature collected for analysis and design of Piled raft foundation is cited in this chapter. The literature is in two parts, first covers geotechnical aspects while other covers design aspects.

Chapter 3

The types of foundation namely shallow foundation and deep foundation and their classification is explained. The need and classification of Piled raft foundation of in mentioned.

Chapter 4

The analysis methods of raft foundation are explained. The way in which the computerized finite element method is used by Staad.Pro software is mentioned step by step, starting with program and end at final result out put. The way in which absolute stiffness of raft is calculated is mentioned in the last.

Chapter 5

The type in which pile foundation is classified on the basis of load transfer phenomenon is explained. The axial load capacity, stiffness and the settlement of single as well as group of pile is explained.

Chapter 6

Classification of methods of analysis and design for Piled raft foundation is point out.

Simplified method of analysis and design of Piled raft foundation is explained in detail.

Design issues in case of Piled raft foundations are also discussed. The way in which approximate analysis of Piled raft foundation carried out is explained in short. Theory of Poulos design method for localized column loading is briefly explained.

Chapter 7

A complete analysis and design of Piled raft foundation is carried out for a particular raft. A parametric study is carried out by Simplified analysis method of Piled raft foundation.

Chapter 8

The way in which an Approximate analysis and design of Piled raft foundation is carried out in Staad.Pro is explained in this chapter. A separate parametric study is also carried out to find variation in settlement as well as moment for Piled raft and unpiled raft.

Chapter 9

Conclusions of the study and future scope is explained.

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Nomenclature

A	Total area of the raft
A_b	Area of pile base
A_s	Area of the pile shaft
B	Width of raft foundation
c	Unit cohesion
C_u	Coefficient of consolidation
d_p	Diameter of pile
E_p	Modulus of elasticity of pile material
E_s,	Modulus of elasticity of soil
e_x,	Eccentricity about X axis
e_y	Eccentricity about Y axis
G	Shear modulus of soil
G_0	Shear modulus at ground surface
G_l	Shear modulus at level of pile tip
G_b	Shear modulus at the base of pile.
G*	Average shear modulus between ground surface and pile tip.
Gr	Shear modulus of soil for raft absolute stiffness
H'	Apparent depth contributing to the settlement
I	Influence factor
Iw	Influence factor
I_x	Moment of inertia about X axis
I_y	Moment of inertia about Y axis
K	Stiffness of the pile group
k	Stiffness of a single pile
K_{pr}	Stiffness of Piled raft
K_p	Stiffness of the pile group
K_r	Stiffness of the raft alone
K_s	Modulus of subgrade reaction
L_p	Length of pile

m	Rate of increase of soil shear modulus with depth
n	Number of pile
P	Load value
P_l	Load up to ultimate value of pile system
P_r	Load carried by the raft
P_t	Total applied load.
P_u	Ultimate load
Q	Total vertical load on the raft,
Q_u	Ultimate capacity of pile under axial load
q_a	Allowable bearing pressure
q_b	End bearing pressure
q_f	Average unit skin friction
r_b	Radius of under-ream incase of under-reamed pile
r_m	Maximum radius of influence of pile under axial loading
r_c	Average radius of pile cap
r_0	Radius of pile
Sr	Immediate settlement of raft foundation
S_{pl}	Settlement of pile due to unit load on pile system
S_{pu}	Settlement of raft due to unit load on raft
S_{pg}	Settlement of pile group
S_p	Settlement of single pile
S_{pr}	Settlement of Piled raft
t_r	Thickness of raft
w_t	Axial displacement at top of pile
X, Y	Co-ordinates of any given point on the raft with respect to the X and Y axes passing through the centroid of the areas of the raft
X_r	Proportion of load carried by the raft
vl	Parameter in solution for axial pile response which measure of pile compressibility
z	Depth perpendicular to ground surface
δ	Deflection or settlement in case of foundation

μ_s	Poisson’s ratio for soil
Δq	Ultimate bearing capacity of soil
α	Adhesion factor
η_w	Efficiency of pile group
η	Ratio of under ream for under reamed piles
ξ	Ratio of end bearing for end bearing piles
ρ	Variation of shear modulus with depth
λ	Pile – soil stiffness ratio
ζ	Measure of radius of influence of pile
α_{cp}	Raft – pile interaction factor

Chapter 1

Introduction

1.1 General

The foundations are classified mainly as shallow foundation and deep foundation. In shallow foundation load is transferred to the shallow strata through the foundation element i.e. footing or mat, while incase of deep foundation load is transferred to the deep strata by element like pile or pier. The stability of the foundation mainly depends on the type of strata/soil on which it is resting. According to this, the foundation type is decided. One has to go for a suitable option among these two types.

It is common in foundation design to consider first the use of individual footing or raft foundation to support a structure when good soil strata is available at small depth near ground surface, and if this is not adequate one has to go for pile foundation. Under some circumstances like multi storey construction with basement in poor soil and high water table condition, the combination of both raft and pile is significant. In that situation, the piles are necessary to transmit the superstructure loads to a deeper strata and raft is required to transmit the superstructure load evenly on the piles and also to resists buoyancy forces of ground water. Piles are also significant to reduce settlement of raft. Such foundation is called as Piled raft foundation.

1.2 Why Piled raft foundation?

In situations where a raft foundation alone does not satisfy the design requirements, it may be possible to enhance the performance of the raft by the addition of pile. The piles must be located by an engineering judgment. Strategically located pile may improve both the ultimate load capacity and the settlement performance of raft. The Piled raft foundation is stiffer than that individual raft or pile foundation.

Piled raft foundation transmits structural loads to the soil by way of both pile-soil contact stresses and raft – soil contact stresses. In such foundation design, contribution of raft in bearing the load is generally ignored. This results in conservative estimate of foundation performance and therefore it is an over design of foundation. With proper analysis technique one can calculate load sharing interaction among raft, pile and soil. A Piled raft design considering interaction between pile, raft and soil be an economical design than pile group design with pile cap not taking any load.

1.3 Objective of Study

The analysis of Piled raft is a complex problem even more than that of a soil supported raft as too many parameters influence the behavior of the system. The exact behavior is unpredictable for Piled raft system. The problem is to analyse the entire system by considering composite behavior of superstructure and substructure, like raft, piles and the soil medium. There are various parameters which influence the sharing of load between piles and raft, between piles themselves and between piles and soil. The important parameters are,

1. Stiffness of raft and pile
2. Number of piles
3. Spacing of piles
4. Action of pile
5. Modeling of soil strata etc.

First objective of study will be of load sharing between raft and piles in a Piled raft foundation considering above all parameters. Not only the load sharing between pile and raft is important, but the shear and moments sharing in the raft and piles are also important. The settlement behaviour for piled raft foundation is also one of the important criteria and that will be the second objective of the study.

A typical Piled raft design problem will be presented in this study with Staad.Pro analysis and PDR method of analysis and design for Piled raft foundation.

The entire problem is divided as under,

1. Analysis and design of raft foundation
2. Analysis and design of Piled raft foundation
3. Parametric study of settlements of Piled raft foundations with various variations like, pile diameter, pile number and pile length.

1.3.1 Analysis and design of raft foundation

For the analysis and design of raft different practices are followed by various designers. Most simple method followed is the conventional rigid approach, wherein the raft is assumed to be rigid. Another approach for raft analysis and design is FGM (finite grid method) where FEM principles are used. Here in this study the adopted analysis and design methods are,

- Conventional Rigid Method

In conventional method, continuous beam analogy is used by treating raft as a combined footing and with an inverted floor, The moments and shears of the continuous beam is determined by principle of simple static and method of moment distribution respectively.

- Finite Element Method.

While in case of Finite Element Analysis three dimensional FEM package is used, in the present study raft has been analyzed for moment and shear using Staad.Pro.2003.The software is most efficient in the structural analysis and design of mat foundations and universally adopted. The raft has been modeled with shell element having six degrees of freedom at each node. This includes three moments and three displacements. The whole raft is discretised in small elements by meshing tool available in the software. The modeling of soil can not be done in this software but this allows the user to create spring supports for independent footings and mat foundations. The stiffness of spring assigned to the selected nodes must be based on engineering judgment. The stiffness of spring in case of soil supported raft is then calculated from immediate settlement criteria. Shear and moment in each shell and settlement at each node is then calculated. For analysis of raft, the principle of the plate or mat on elastic foundation is utilized. In Staad.Pro both these options have the program to calculate the influence area of the nodes which define the surface area, and then multiply that area by the subgrade modulus of the medium depending upon the type of soil to get spring stiffness. The pile stiffness below the raft is calculated from the formula mentioned by Randolph. The spring having equivalent stiffness as that of pile is placed below the raft, for combined Piled raft analysis.

1.3.2 Analysis and design of Piled raft foundation:

The analysis of piled raft foundation is done as per simplified method mentioned in the literature of Poulos H.G. and Randolph M.F. This Simplified method was first given by Poulos and Davis in 1980 and later on Randolph (1983, 1994) gave further improvement in this method. This method involves number of simplifications in relation to the modeling of the soil profile and the loading conditions on the raft. The combined stiffness of the Piled raft foundation is calculated along with the calculation of individual pile and raft stiffness. Methods employing a “plate on springs” approach, in which the raft is represented by a plate and the piles as springs (e.g. Clancy and Randolph, 1993; Poulos, 1994;). Approximate analysis of localized behavior of piled raft foundation under individual column is also carried out as mentioned by Poulos. This gives an approximate idea about where to place pile below column. The load sharing between raft and piles is also studied. One design problem of Piled raft foundation is also solved.

1.3.3 Parametric Study :

The parametric study is carried out to study the influence of various structural properties of both raft and pile on Piled raft load sharing and Piled raft settlements. The settlement response is studied for variations of pile diameter, pile length and pile numbers. First the response for immediate settlement is studied and then by considering soil properties and various variations, the load sharing among the raft and pile is calculated for these variations. Parametric study includes settlement verses all these variations.

Chapter 2

Literature Survey

2.1 Geotechnical Aspects:

The design of foundation directly deals with geotechnical aspects of soils. The deep knowledge of soil engineering is a must to understand exact behavior of both cohesive and cohesion less types of soils. The geotechnical parameters which influence foundation design must be given equal importance in analysis and design of Piled raft foundation.

2.2 Design Aspects:

This covers the design aspects of piled raft foundation for economical and efficient structural design. Literature survey covering geotechnical and design aspects for Piled raft foundation system are presented below.

Arora K.R.(2001). Soil Mechanics and Foundation Engineering, 5th edition, Standard Publication House, New Delhi.

Principles for design of raft on both, cohesion-less and cohesive soils are covered. In the description of raft types, it signifies Raft-Pile construction on highly compressible soil where water table is high. This method of construction reduces the settlement and also controls buoyancy.

Bowles J.W. (1996). Analysis and Design of Foundation, 5th edition, The McGraw-Hill Co., New York.

The book covers analysis and design of both rectangular and circular Mat foundation. It also includes mat settlement effect. The analysis of the raft /mat foundation includes three methods of analysis namely,

i) Approximate Method,

ii) Approximate Flexible Method

iii) Discrete Element Method.

Teng W.C. (1988). Foundation Design, 12th edition, Prentice - Hall Inc. New Jersey

In the conventional method, it is assumed that the mat is infinitely rigid and the bearing pressure against bottom of the mat follows the planner distribution. The mat is analyzed as a whole in each of two perpendicular directions .Thus the total shear forces acting on any section across the entire mat is equal to the arithmetic sum of all forces and the reactions (bearing pressure) to the left or right of the section. The total bending moments acting on such section is equal to the sum of all moments to the left or right of this section. The simple static principles like $\sum V = 0$ and $\sum M = 0$ are used to analyze the raft.

Das B.M. (1999). Principle of Foundation Engineering, 4thedition, PWS publication

The book covers various types of raft foundation, their bearing capacity and the settlement criteria according to ACI norms. The analysis and design example of raft is solved by using conventional method only. It includes raft problem solved by conventional method.

Poulos H.G. (1980). Pile Foundation Analysis and Design, 1st edition, John Wiley and Sons, New York.

This book, deals with Piled raft system. The Piled raft foundation mainly based on reduction of settlement of whole structure. Though the raft foundation alone has adequate factor of safety against bearing failure, the settlement of raft is also an important thing of concern. If the settlement is more and to reduce that settlement piles are used, it is illogical to design piles on the basis of ultimate load. According to author, once the piles have been introduced solely for the purpose of reducing the settlement design question becomes not " how many piles are required to carry weight of the structure" but "how many piles are required to reduce the settlement to an acceptance level.

Fleming W.G.K.et al. (1992). Piling Engineering, 2nd edition, Blackie & Sons, London.

The book covers detailed analysis and design of pile foundation. The combination of pile and raft foundation increases the stiffness of the foundation and is most economical solution to reduce the settlements. A simple approach of combining the separate stiffness of the raft and pile group has been suggested by author.

Hooper J.A.(1984)."Raft Analysis and Design-Some practical examples" The Structural Engineer, Vol. 62A/No.8, pp 233-244

This paper describes the way in which the principle of soil-structure interaction has been applied in the analysis and design of raft with pile and the other surface foundations. Piled raft may be analyzed by modeling the combined raft and pile group by a plain raft located at or near pile base level. Various techniques of the modeling of the soil and the structure are outlined. The general approach to design is also discussed, and summaries are given of eight structural design projects ranging from simple strip footing to complex raft foundation including Piled raft foundation.

Hooper J.A.(1973).“Observation on the behavior of a Piled-Raft Foundations on London Clay.” The Structural Engineer, Vol. 62A/No.8, pp 233-244.
The behavior of the Piled raft foundation supporting a tower block in the central London has been studied in detail. Paper explains Piled raft analysis by modeling the combined raft and pile group by a plain raft located at or near pile base level.

Xio Dong Cao,Ing Hieng Wong,(2004). “Behavior of Model raft resting on Pile, Reinforced sand “JE&GE, Vol.130, pp129-138, Feb. 2004
Piles in a Piled raft are sometimes considered as settlement reducers, not load-carrying members. The foundation considers the pile as reinforcement in the base soil, and not as a structural member. Serving as a soil stiffener, the pile can tolerate a lower safety margin against structural failure without violating building codes. The paper describes experimental investigations by load tests of model rafts resting on pile reinforced sandy soil. By varying factors such as raft stiffness, pile length, pile arrangement, and pile number, results indicates that structurally disconnected piles are effective in reducing the settlement and bending moments in the model rafts.

Cunha, R.P., H.G. Poulos and J. C. Small (2001). “Investigation of design alternatives for a piled raft case history”, Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol.127, No.8, pp. 635-641
This paper explores the design of Piled rafts, outlining the influence of the major external variables that affect their design under concentrated column loads. The design alternative adopted was pile characteristics which were varied against the raft thickness. This paper extends the design philosophy for piled rafts by exploring the factors that control the design of a published case history where the Piled raft was instrumented.

Poulos H.G. (2002). “Simplified Design Procedure for Piled Raft Foundation”, Deep Foundation, ASCE, pp 441-457
This paper outlines the use of Piled raft foundation for situation in which the performance of raft only does not satisfy the design requirements. Under these circumstances, the addition of

limited number of piles may improve both the ultimate load capacity and the settlement and differential settlement performance of raft. The philosophy of using pile as settlement reducers is discussed. The two stage design process is proposed, first being approximate preliminary stage to assess feasibility and second to obtain detail design information. The first stage establishes the effects of number of piles on load carrying capacity and settlement via simplified analysis. The second is a detailed design phase, and involves the use of more refined analysis techniques to assess the optimum number and location of piles, as well as providing essential information for structural design of raft and the piles.

Maybaum G., Vittinghoff T. & Rodatz W. (2001) "Proof of the Bearing Capacity and the Serviceability of Piled Rafts" pp 1-6.
The authors presented two concepts for the investigation into the bearing capacity and the serviceability of Piled rafts using finite-element-analysis. The calculation is treated as a soil-structure interaction problem as specified by the Euro code.

Carsten Ahner, Dmitri soukhov, Gert Konig (1998). "Reliability Aspects of Design of Combined Piled-Raft Foundations", 2nd Int. PhD Symposium in Civil Engineering, Budapest, pp 1-8,
The reliability aspects of structural behavior of Combined Piled raft foundation are investigated. The problem is connected with the stochastic model of soil properties. In this approach the influence of autocorrelation of soil parameters is considered. The calculations are made by means of the first order reliability method (FORM) according to Level II of the reliability analysis.

Hain S.J. & Lee I.K. (1978). "The Analysis of Flexible Raft-Pile Systems" Geotechnique, Vol. 28, No 1, pp 65-83
An analysis has been developed to predict the behavior of a raft – pile foundation system. The analysis is used to establish the effectiveness of pile group in reducing settlement of raft considering the effect of raft flexibility and size, and pile group.

Kuwabara F. (1989). "The Elastic Analysis for Piled raft Foundations in a homogeneous soil", Soils and Foundations, JSSMFE, Vol.29, No 1, pp 82-92
A boundary element analysis based on an elastic theory is performed to analyze the behavior of Piled raft foundation subjected to vertical load. The paper concludes that the reduction of

settlement caused by presence of the raft is very small, although the raft transmits 20 – 40% of the applied load direct to the soil.

Randolph M.F. & Clancy P. (1993). “Analysis and Design of Piled raft Foundations”, Int. J. NAM Geomechanics, Vol. 17. pp 313- 328.
A hybrid method of analysis has been developed, by which complete foundation system analysis (using quadrant symmetry) may be performed. The paper outlines the hybrid finite element – elastic continuum method of Piled raft analysis, and describes an approximate method for calculating overall foundation and load distribution.

Poulos, H. G. (2001). “Piled raft foundations: Design and Applications” Geotechnique, Vol.51, No.2, pp.95-113
This paper describes the philosophy of using piles as settlement reducers and the condition under which such an approach may be useful. Some of the characteristics of Piled raft behavior are also described. The design process of Piled raft is explained in three stages. The first is preliminary stage in which the effect of number of piles on the capacity and the settlement are assessed via an approximate analysis. The second is a more detail study to asses to find out where piles are required. The third is detailed design phase in which a more refined analysis is employed to confirm optimum number and locations of piles.

El-Mossallamy Y. (2002). “Innovative Application of Piled raft foundation in stiff and soft subsoil”, Deep Foundations, ASCE, pp 426-439
The analysis of Piled raft foundation is based on mixed technique of finite element method and boundary element method. Understanding of the effects of the interaction between structure and subsoil is studied considering 1.appropriate theoretical knowledge, 2.experienced application of techniques and 3.numerical modeling together with tested and proven implementation design method.

Horikoshi K. & Randolph M.F. (1998). “A Contribution of Optimum Design of Piled rafts”, Geotechnique Vol. 48, No.3, pp 307-317
The treatment of the pile group and raft are based on Mindlin’s solution, but the load transfer model of Randolph was used for each single pile response. The flexible raft was modeled using plate bending finite element. The method can efficiently solve the complex Piled raft behavior with full consideration of interaction between raft, pile and soil.

Yamashita K. et al.(1994). "Investigation of Piled raft foundation on Stiff Clay", 13th International Conf. on Soil Mech. and Foundation Engg. New Delhi, Vol 2. pp 543-546

This paper describes the design of raft foundation with piles at a large spacing to support a five storey building and the field observations performed during construction. An analytical simulation of the settlement behavior of the building is presented taking in to account the interaction between piles, soil and the raft. The calculated settlement and the load sharing between raft and piles compare favorably with the field observation.

Reul O.& Randolph M.F. (2004). "Design Strategies for Piled raft Subjected to Nonuniform Vertical Loading", JG & GE, ASCE, Vol. 130, No.1, pp 1-13

The Piled raft is a geotechnical composite construction, consisting of the three elements piles, raft, and soil, which is applied for the foundation of tall buildings in an increasing number. In a parametric study, 259 different Piled raft configurations have been analyzed by means of three-dimensional elasto-plastic finite element analyses. In the 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 has been varied.

Sanctis L. et al. (2002). "Some Remarks on Optimum Design of Piled raft", Deep Foundation, ASCE, pp 405-425.

The present paper discusses the guidelines for an optimum design of small as well as large Piled raft. It suggests different criteria for both small and large piled raft. In small Piled rafts, piles are added to achieve adequate factor of safety, while in case of large Piled rafts, piles are used to reduce settlement.

Terzaghi, K. (1955). ''Evaluations of coefficients of subgrade reaction.'', *Geotechnique*, Vol. 5, 297–326.

The paper deals with theories of vertical and horizontal subgrade reaction which are based on the simplifying assumption that the subgrade obeys Hook's law. A rigid centrally loaded plate resting on the horizontal surface of the subgrade has the same subgrade modulus value at every point of the base.

Bowles J.E.(1986). "Mat Design" JACI, Vol-83, No.6, Nov-Dec.pp1010-1017

A brief survey of computerized methods for mat design is given with particular advantages and disadvantages of finite difference, finite grid and finite element method. The modulus of subgrade reaction (Ks) is considered in some detail both in obtaining reasonable initial design estimates and simple method to couple node effect.

Gupta S.C. (2000). "Raft Foundations, Design and Analysis with Practical Approach" first edition, New Age International publishers. New Delhi.

This book completely includes the design aspect of Raft and Raft Pile Foundation for the considered practical problem. A design aspect for the raft design is according to Indian Standards. An excellent study is carried out on analysis and design of Piled raft. It completely explains method of analysis same as raft i.e. Conventional Rigid method and finite element method. Complete study of the parameters likely influence raft behavior etc. is covered. In this book structural analysis software SAP IV for the Finite Element Analysis (Flexible Analysis) of both raft and raft with pile foundation is used.

Chapter 3

Types of Foundations

The various types of structural foundations may be grouped into two broad categories, shallow foundation and deep foundation. A foundation is shallow if its depth is equal to or less than its width and deep when it exceeds the width.

3.1 Shallow foundation

Loads are assumed to be transmitted to the underlying ground directly by the foundation elements (footings or mat (raft)). The classification is shown in **fig. 3.1**

3.1.1. Need of raft foundation

Generally raft foundation is suggested in following situations:

1. Whenever building loads are heavy or the allowable pressure on soil is small that individual footing would cover more than floor area.
2. Whenever soil contains compressible lenses or the soil is sufficiently erratic and it is difficult to define and assess the extent of each of the weak pockets or cavities and, thus, estimate the overall and differential settlement.
3. When structure and equipment to be supported are very sensitive to differential settlement.
4. Where structures naturally lend themselves for the use of raft foundation such as silos, chimneys, water towers, etc.
5. Floating foundation cases wherein soil is having very poor bearing capacity and the weight of the superstructure is proposed to be balanced by the weight of the soil removed.
6. Buildings where basements are to be provided or pits located below ground water table.
7. Building where individual foundation if provided, will be subjected to large widely varying bending moments which may result in differential rotation and differential settlement of individual footing causing distress in the building.

3.1.2 Classification of Raft Foundation.

Raft can be classified into various types on the basis of criteria used for classification.

Based on the method of their support raft can be,

1. Raft supported on soil,
2. Raft supported on piles,
3. Buoyancy raft.

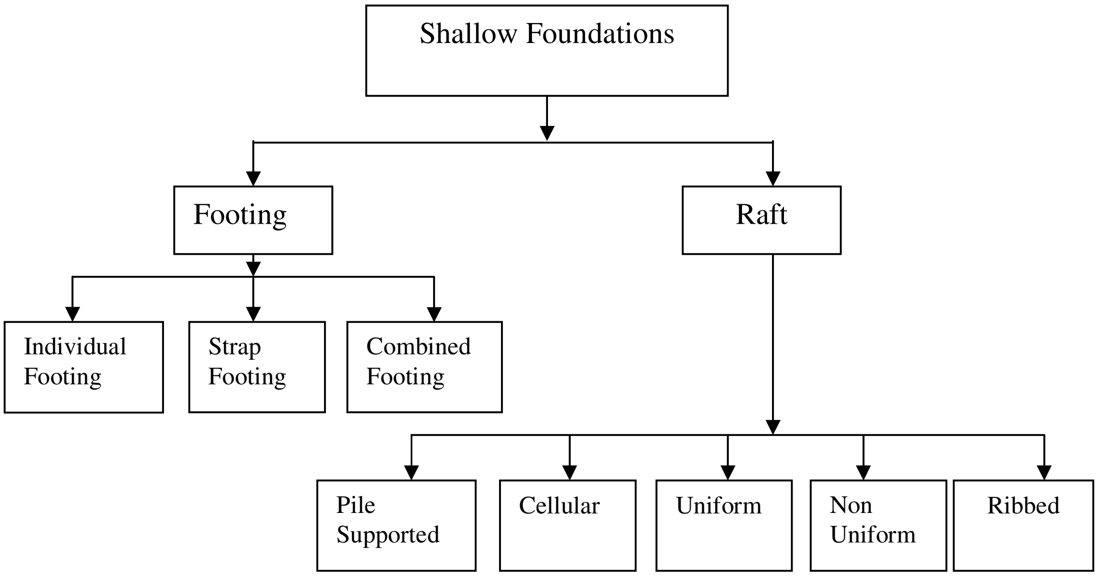


Fig 3.1 Classification of Shallow Foundation

Raft can be further classified as below (Refer fig.3.2):

1. Plain slab rafts with pedestals or without pedestals.
2. Beam and slab raft
3. Cellular raft or framed raft.

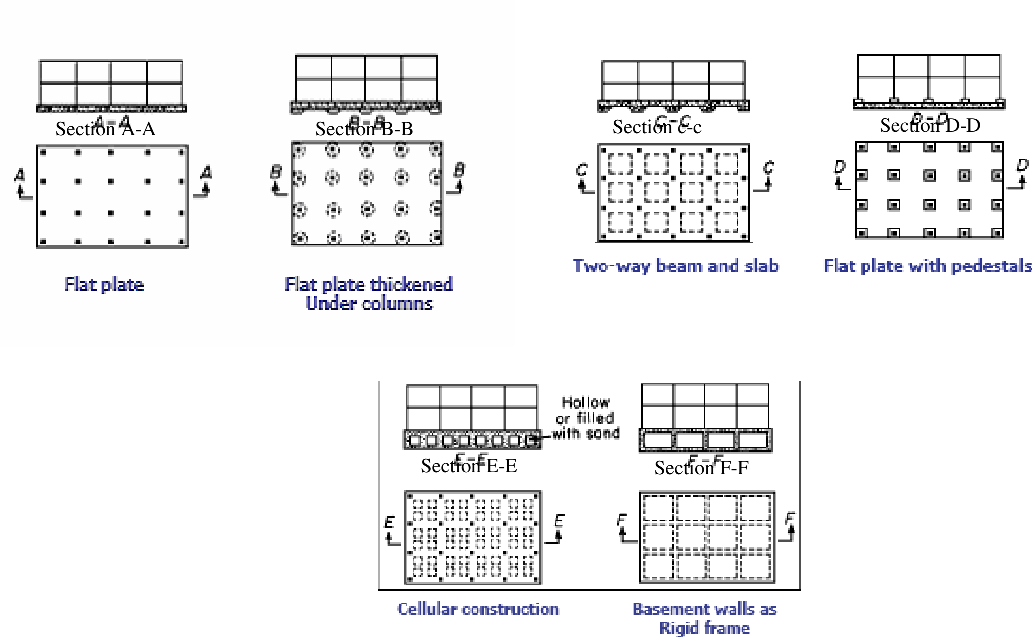


Fig. 3.2 Various Types of Raft Foundation.

Raft of uniform depth is most popular due to its simplicity of design and construction. This type is most suitable where the column loads are moderate and column spacing fairly small and uniform. Pedestal is utilized to distribute the load on a bigger area in case of heavy column loading.

Raft as a slab of uniform thickness, has an additional advantage of providing better water-proofing treatment, ease of reinforcement fabrication and lying of concrete. This type of raft is more commonly used.

3.2 Deep foundation.

In deep foundations the piles or drilled shafts carry all superstructure loads. These foundations are the connecting link for superstructures and bearing stratum.

3.2.1 Need of Pile foundation:

a. When strata at or just below the ground surface is highly compressible and very weak to support load transmitted by the structure.

b. When the plan of structure is irregular relative to its outline and load distribution. It will cause non uniform settlement if a shallow foundation is constructed. Pile foundation is required to reduce differential settlement.

c. Pile foundation is required for the transmission of structural loads through deep water to a firm stratum for offshore construction.

d. Pile foundations are used to resist horizontal forces in addition to support the vertical loads in earth retaining structures and tall structures that are subjected to horizontal forces due to wind and earthquake.

e. Piles are required when soil conditions are such that a wash out, erosion or scour of soil may occur from a underneath a shallow foundation.

f. Piles are used for foundation of some structures like transmission towers, which are subjected to uplift.

g. In case of expansive soil, such as black cotton soil, which swell and shrink as the water content changes, piles are used to transfer load below the active zone.

3.2.2 Classification of Pile Foundation

Piles can be classified according to material used, mode of transfer of load, method of installation, the use and the displacement of soil. The fig. 3.3 shows classification chart of pile foundation.

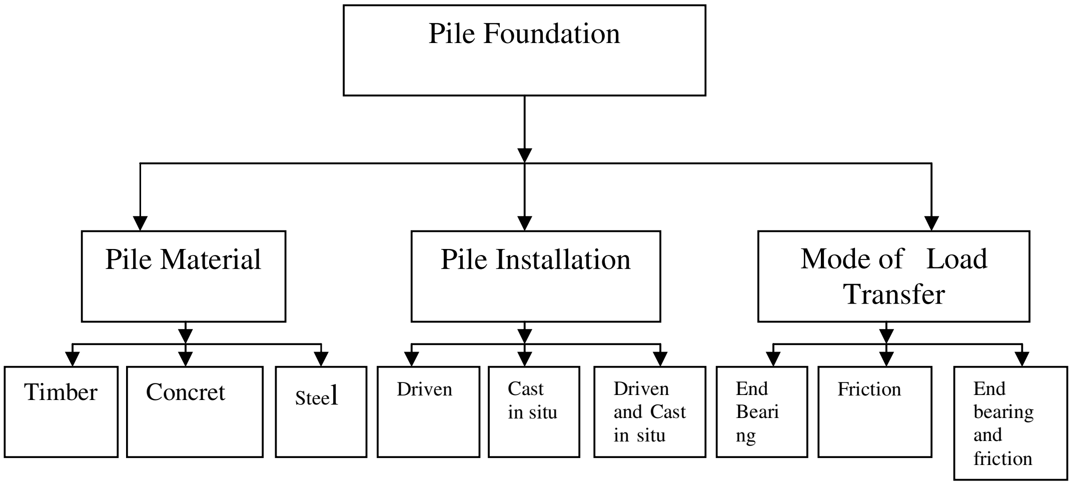


Fig. 3.3 Classification of Pile Foundation

3. 3 Piled raft foundation:

Raft supported on piles are increasingly used for multi-storey buildings with basements in poor soil and with high water table conditions. Figure (3.4) shows some cases considered from literature.

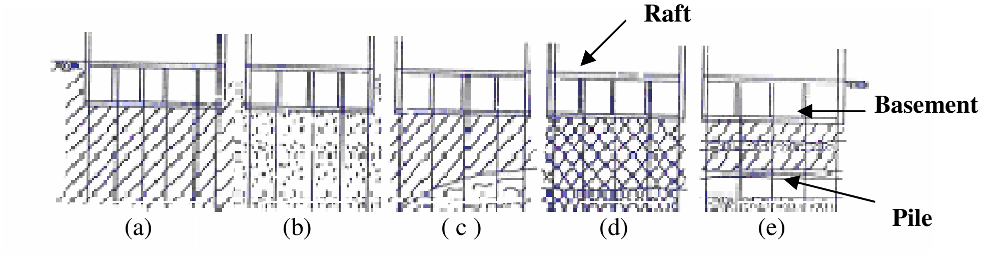


Fig. 3.4 Piled basements: (a) Piles in clay; (b) Piles in sand; (c) Piles through clay to rocks; (d) Piles through soft clay to hard clay; (e) Piles in layers of clay and sand

Case a: Piled raft with piles wholly in compressible clay.

Case b: Piled raft with piles driven into loose sand.

Case c: Piled raft with piles installed through compressible soils in to hard rock.

Case d: Piled raft with piles installed through soft clay to stiff clay.
Case e: Piled raft with piles installed in alternate layer of soft clay and sand.

The piles are necessary to transmit the super-structure loads to a deeper soil strata and the raft is required to transmit the column/wall loads evenly to the piles and also to resist the buoyancy forces of the ground water. Where a primarily raft foundation is planned, a few piles may be incorporated beneath central part of raft in order to reduce differential settlements to an acceptable level. Such piles provide some measure of reinforcement to the soil and help to prevent dishing of raft in center. From design point of view, they may be regarded absorbing some part of the overall load applied to the raft. Literature suggests that even relatively flexible raft could undergo minimum differential settlement, provided that optimum design is achieved. This design concept is schematically shown in fig (3.5.a).Making the raft flexible and placing piles strategically located beneath the raft can reduce the differential settlement more effectively along with raft contact pressure distribution shown in fig (3.5.b).

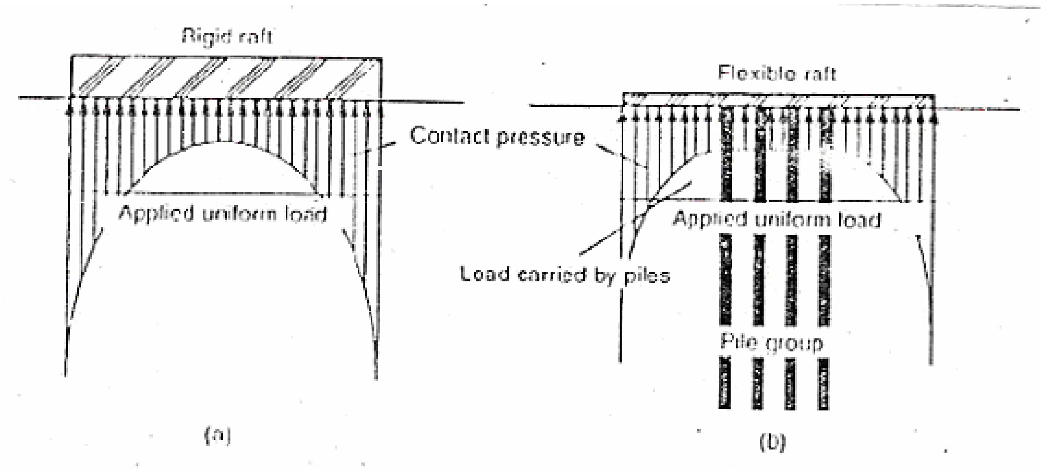


Fig 3.5. Principle of settlement reducing piles: (a) rigid raft, (b) flexible raft with central pile group.

The combination of these both types, that is raft and pile the cumulative performance will result in structurally efficient foundation system for tall structures. The most effective application of Piled raft occurs when the raft can provide adequate load capacity, but the settlement and the differential settlement of the raft alone exceed the allowable value. Poulos has examined a number of idealized soil profiles, and has found that the following situations may be favorable for Piled raft foundation.

- Soil profile consisting of relatively stiff clays.

- 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.

The unfavorable situations for Piled raft are as follows,

- Soil profiles containing soft clays near the surface
- Soil profile containing loose sand at the surface
- Soil profiles that contain soft compressible layers at relatively shallow depths.
- Soil profiles that are likely to undergo consolidation settlement
- Soil profiles that are likely to undergo swelling movement 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 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 (such as those due to dewatering and shrinking of an active clay soil) may result in a loss of contact between raft and soil, thus increasing load on the piles, and increase in settlement of the foundation system. Additional tensile forces may be induced in the piles because of the action of the swelling soil on the raft and as such Piled raft foundation is not suitable for swelling type of soil.

3.3.1 Classification of Piled raft foundation:

Piled raft are classified into two types,

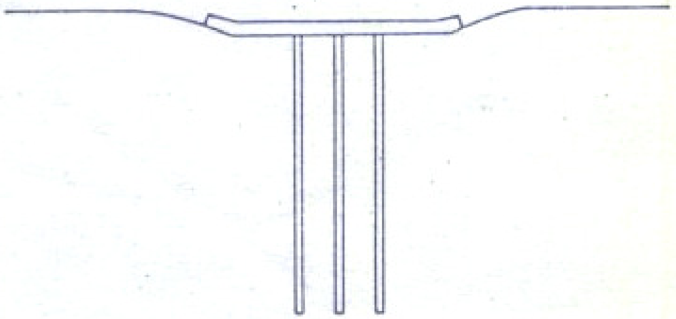
1. Piled raft for settlement reduction
2. Piled raft for load transfer.

These two types are described below:

Piled raft for settlement reduction:

In some situations though the raft is safe from bearing capacity consideration, it may fail on permissible settlement criteria. The traditional solution of this problem is to provide a basement and basement raft, so that the effective load is reduced. In other case some piles are placed under the raft so that the piles relieve the raft of a part of total load. As the piles do not have to take all loads the number of piles required will be much smaller than the traditional piled foundation. Because of some relief of the load, the raft settlement will also fall within allowable limits.

(a) Dishing of unpiled raft



(b) Effect of settlement reducing piles

Fig. 3.6 Use of settlement reducing piles to minimize settlement

Piled raft for load transfer:

The second type of Piled raft is conventional type which is used in situations where the subsoil is very weak with high water level and rafts have to be adopted. This raft should resist the buoyancy forces from the structure to the piles to be carried to deeper and stronger layers of foundation. The numbers of piles required in this case are much more than those required in the former case.

De Sanctis et al (2001) and Viggiani (2001) have distinguished between two classes of Piled raft foundations:

1. “Small” Piled rafts, where the primary reason for adding the piles is to increase the factor of safety (this typically involves rafts with widths between 5 and 15 m);

2. “Large” Piled rafts, whose bearing capacity is sufficient to carry the applied load with a reasonable safety margin, but piles, are required to reduce settlement or differential settlement. In such cases, the width of the raft is large in comparison with the length of the piles (typically, the width of the raft exceeds the length of the piles).

Chapter 4

Analysis of raft foundation

4.1 Methods of Analysis of raft foundation:

The essential task in the analysis of raft foundation is the determination of the distribution of contact pressure underneath the raft which is a complex function of the rigidity of the superstructure, raft itself and the supporting soil.

Once the distribution of contact pressure is determined, design bending moments and shear can be computed based on application of simple static. The following methods of analysis are suggested which are distinguished by the assumption involved. Choice of particular method should be governed by the validity of the assumptions in the particular case.

4.1.1 Rigid conventional foundation analysis:

This is based on the assumption of linear distribution of contact pressure. The basic assumptions of this method are,

a) The foundation is rigid relative to the supporting soil and the compressible soil layer is relatively shallow.

b) The contact pressure variation is assumed as planar, such that the centroid of the contact pressure coincides with the line of action of the resultant force of all loads acting on the foundation.

The raft is analyzed as a whole in each of the two perpendicular directions. The contact pressure distribution is determined by the equation (4.1) with usual notations.

$$\boxed{q = Q/A \pm (Q*e_y/I_x)*Y \pm (Q*e_x/I_y)*X} \tag{4.1}$$

where,

Q= Total vertical load on the raft,

A= Total area of the raft,

e_x, e_y,I_x.I_y= eccentricities and the moments of inertia about the principal axes through the centroid of the section, and

X, Y = Co-ordinates of any given point on the raft with respect to the X and Y axes passing through the centroid of the areas of the raft.

4.1.2 Flexible foundation analysis (Simplified method):

This method assumes that the subgrade is consisting of an infinite array of individual elastic springs each of which is not affected by the others .The spring constant is equal to modulus of subgrade reaction ,K_s .The contact pressure at any point under the raft is, therefore, linearly proportional to the settlement at the point.

The flexible foundation analysis was explained by Winkler in 1867 as “Winker’s bed”. In this approach the force and vertical displacement relationship of soil is expressed in terms of a constant ‘K_s’ called modulus of subgrade reaction. It is easy to incorporate the effect of soil by simply including a spring (fig 4.1) with a stiffness factor in terms of force per unit length beneath each node. The modulus depends on the size of loaded area and the time duration for which it is loaded. In this method mat is treated as assemblage of linear plate/shell element. The magnitude of Winkler’s spring constant at each node is calculated on the basis of area contributed.

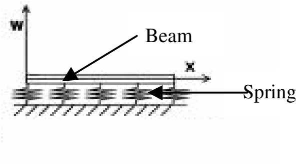


Fig. 4.1 Winkler’s Model

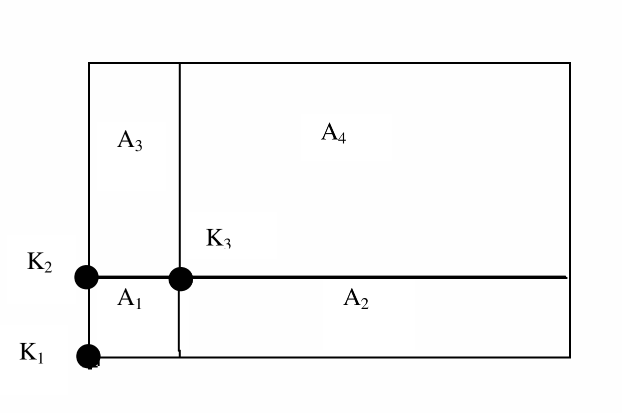


Fig. 4.2 Stiffness on the basis of tributary area

Fig. 4.2 shows the location of spring having stiffness K_1,K_2 and K_3 for four raft areas A_1,A_2,A_3,A_4. To calculate the spring stiffness K_1,K_2 and K_3 all raft areas A_1,A_2,A_3 and A_4 are considered. For spring location near area A1, stiffness of this spring will be K_1 which will be equal to one forth of the contributing area A_1. Similarly K_2 will be one forth of both areas A_1 and A_3 and K_3 will be one forth of all areas A_1,A_2,A_3 and A_4.

4.1.3 Computer Method (Discrete Element Method):

Computer analysis of raft foundation is based on approximation that the mat is divided into number of discrete (finite) elements using grid lines. These methods include the following.

a) Finite –Difference Method

b) Finite – Element Method

c) Finite – Grid Method.

Out of above three methods only one method i.e. Finite Element method with use of Staad. Pro software is used for analysis of Piled raft foundation.

Finite element method with use of Staad -Pro software:

In the approximate analysis of Piled raft foundation this method is used. By using this method raft is first discretized into a number of rectangles and or/ triangular plates/shell elements. Mainly all computer software analysis is based on this approach. Step by step explanation of the use of Staad.Pro in discretizing the raft is explained below.

Starting with Staad. Pro

Step-by-step instructions for modeling and analysis of a raft supported on soil are as under:

1. Starting the Program
2. Creating a new structure
3. Creating raft structure
4. Modeling the raft using STAAD.Pro
5. Specifying element properties
6. Specifying material constants
7. Specifying supports
8. Specifying loads
9. Specifying the analysis type and performing Analysis
10. Viewing the Output File
11. Viewing results for individual plates

1. Starting the program: Fig (4.3) and Fig (4.4)

Select the *STAAD.Pro* icon from the STAAD.Pro 2003 program group.(fig 4.3).

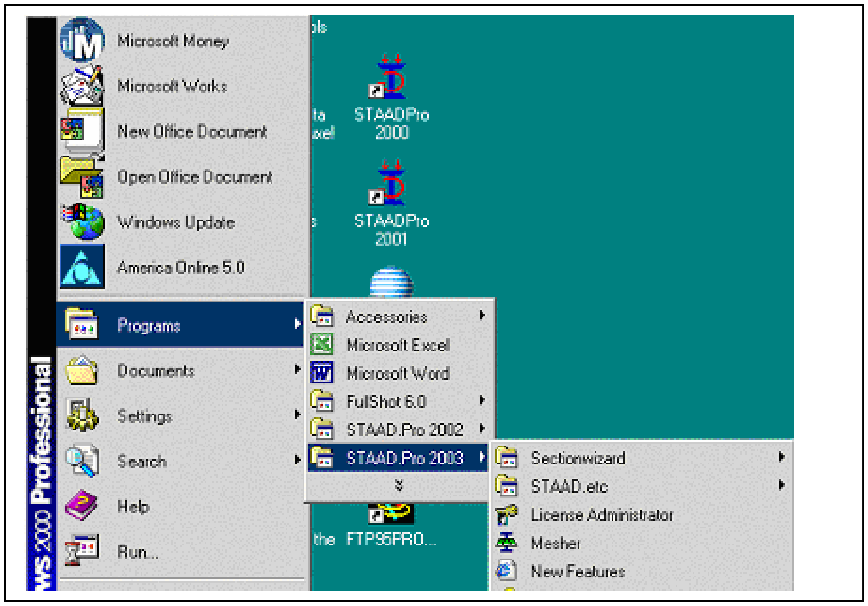


Fig. 4. 3 Step 1

The STAAD.Pro Graphical Environment will be invoked and the following screen comes up. (fig 4.4)

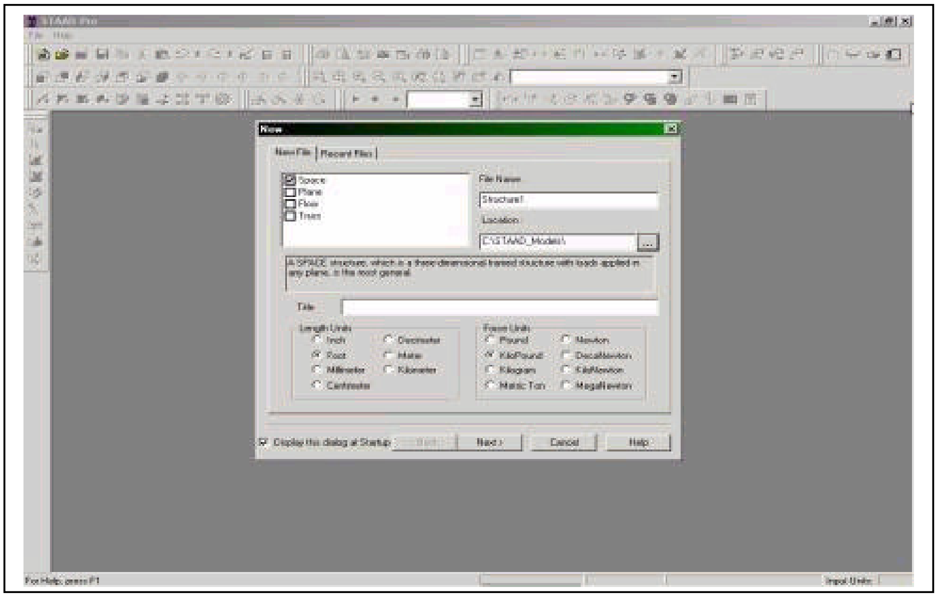


Fig. 4. 4 Step 2

The new dialog box will come up every time when program starts.

2. Creating new structure: Fig (4.5), (4.6) and (4.7)

While creating a new structure, define first unit system very and then start to create structure.

1. Unit system:

There are two base unit systems in the program which control the units (length, force, temperature, etc.) in which, values, specifically results and other information presented in the tables and reports, are displayed in. These two unit systems are English (Foot, Pound, etc.) and Metric (KN, Meter, etc.). The place from where one can change this setting is under the *File* | *Configure* menu (fig 4.5). For this project i.e analysis and design of Piled raft foundation, choose the *Metric* units as (fig 4.6) KN, Meter, etc.

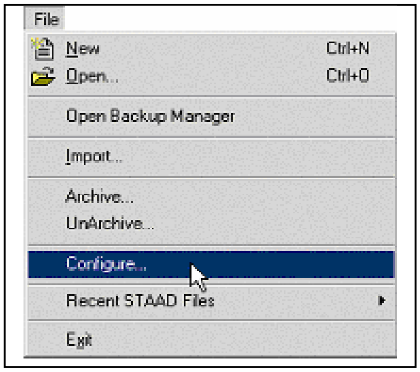
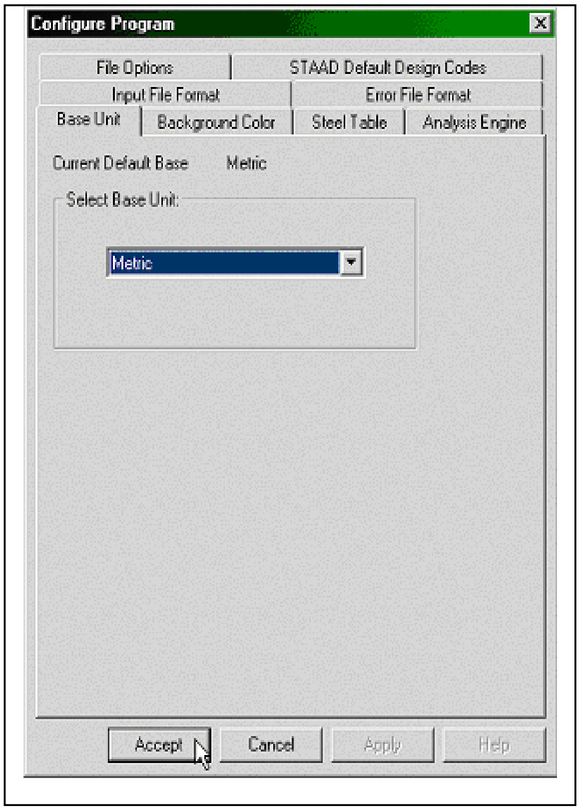


Fig. 4. 5 Step 1



Current Default Base Metric

Select Base Unit: Metric

Fig. 4. 6 Step 2

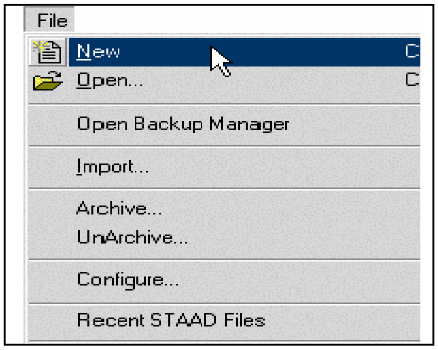


Fig. 4. 7 Step 3

Click on the *Accept* button to close the above dialog box. Following this, select *File* | *New* once again (fig 4.7)

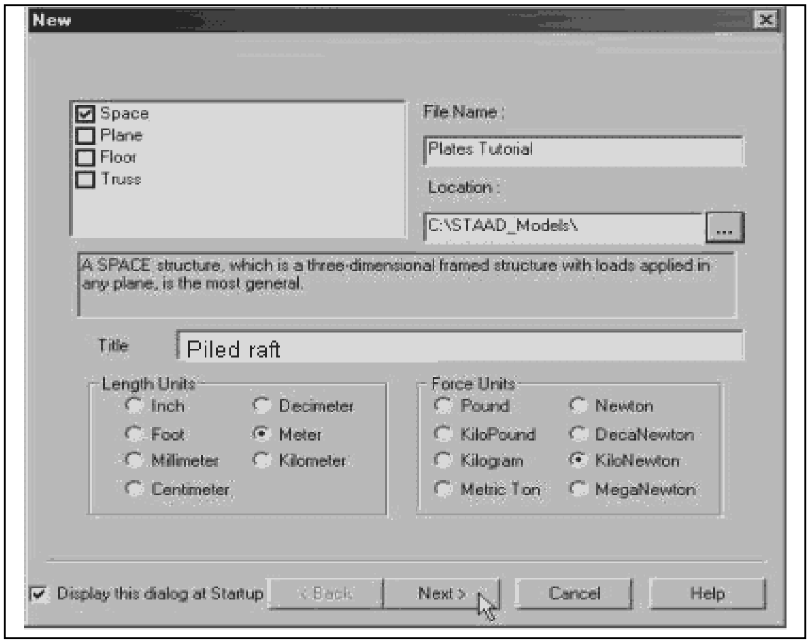
3. Creating a Raft structure: Fig (4.8) and (4.9)

In the *New* dialog box, provides some crucial initial data necessary for building the raft model. The structure type is to be defined by choosing from among *Space*, *Plane*, *Floor* and *Truss*. A *Space* type is one where the structure, the loading or both, cause the structure to deform in all 3 global axes (X, Y and Z). In a *Plane* type, the geometry, loading and deformation are restricted to the global X-Y plane only. A *Floor* type is a structure whose geometry is confined to the X-Z plane. A *Truss* type of structure carries loading by pure axial action. Truss members are deemed incapable of carrying shear, bending and torsion. Therefore here for raft analysis whole modeling is done by choosing Space.

Provide a name in the *File Name* edit box (fig 4.8). This is the name under which the structure data will be saved on the computer hard disk. The name "Structure?" (? will be a number) is recommended by the program by default, but this can change it to any name as desired. Choose the name *Plates Tutorial*.

A default path name - the location on the computer drive where the file will be saved - is provided by the program under *Location*. If one wish to save the file in a different location, type in the name, or click the button and specify the desired path.

An optional title for the project may be entered in the *Title* edit box. Give it the title Piled raft.



New

☑ Space
☐ Plane
☐ Floor
☐ Truss

File Name : Plates Tutorial

Location : C:\STAAD_Models\

A SPACE structure, which is a three-dimensional framed structure with loads applied in any plane, is the most general.

Title: Piled raft

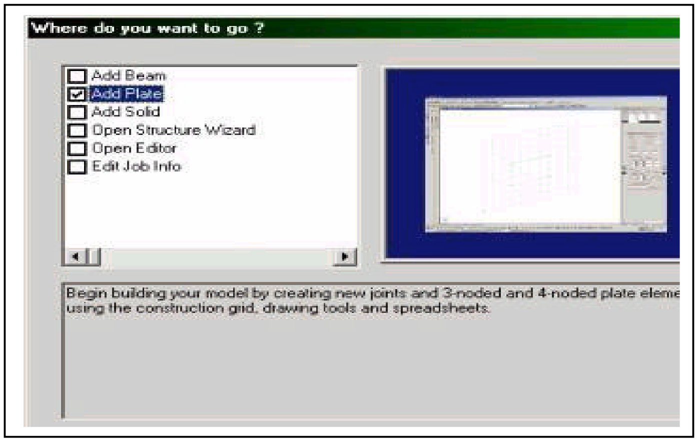
Length Units: ○ Inch ○ Foot ○ Millimeter ○ Centimeter ○ Decimeter ● Meter ○ Kilometer

Force Units: ○ Pound ○ KiloPound ○ Kilogram ○ Metric Ton ○ Newton ○ DecaNewton ● KiloNewton ○ MegaNewton

☑ Display this dialog at Startup

Fig 4. 8 Step 1

In the next dialog box, choose the tools to be used to initially construct the model like *Add Beams*, *Add Plates* or *Add Solids* are, respectively, the starting points for constructing beams, plates or solids. For raft model, check the *Add Plate* option (fig 4.9). Click on the *Finish* button. The dialog box will be dismissed and the STAAD.Pro graphical environment will be displayed.



☐ Add Beam
☑ Add Plate
☐ Add Solid
☐ Open Structure Wizard
☐ Open Editor
☐ Edit Job Info

Begin building your model by creating new joints and 3-noded and 4-noded plate eleme
using the construction grid, drawing tools and spreadsheets.

Fig. 4. 9 Step 2

4. Modeling the raft using STAAD.Pro: Fig (4.10), (4.11), (4.12), (4.13), (4.14) and (4.15) Now start building the model geometry. The steps and, wherever possible, the corresponding STAAD.Pro commands (the instructions which get written in the STAAD input file) are described in the following sections.

Generating the model geometry

The structure geometry consists of joint numbers, their coordinates, member numbers, the member connectivity information, plate element numbers, etc. From the standpoint of the STAAD command file, the commands to be generated are:

```
JOINT COORDINATES
1 0 0 0 ; 2 23.18  0 0 ; 3 23.18 0 29.28 ; 4 0 0 29.28
ELEMENT INCIDENCES SHELL
1 1 2 3 4;
```

For mesh generation, either click on the *Generate Surface Meshing* icon (fig 4.10) or go to *Select* | *Mesh Generation Cursor* menu option as shown below.(fig 4.11)

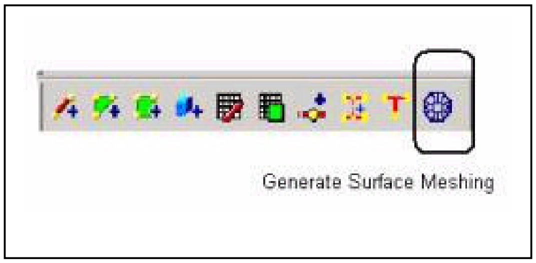


Fig. 4.10 Step 1

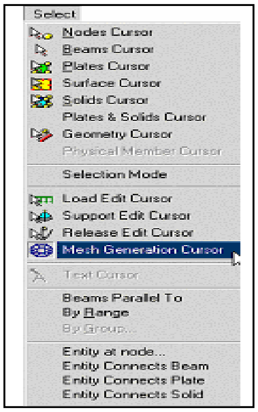


Fig. 4.11 Step 2

Now select the points which form the boundary of the super element from which the individual elements will be created. The four viz. 1,2,3,4 points are created. So, click at the four node points in succession as shown below (fig 4.12). Lastly, close the loop by clicking at the start node (or the first clicked point) again.

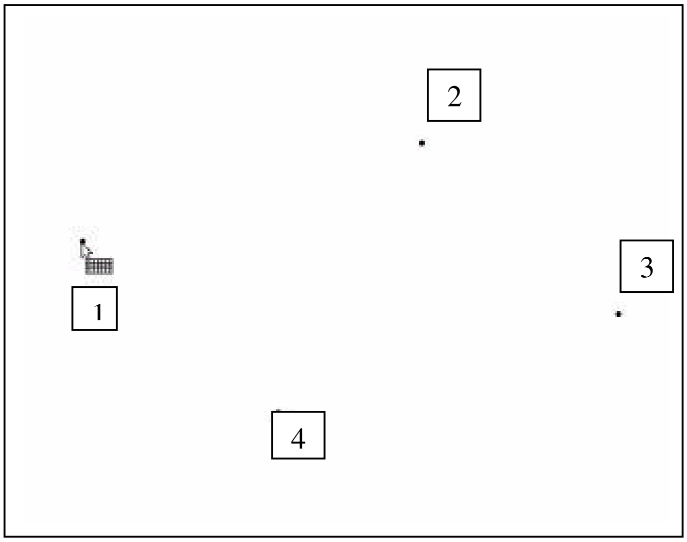
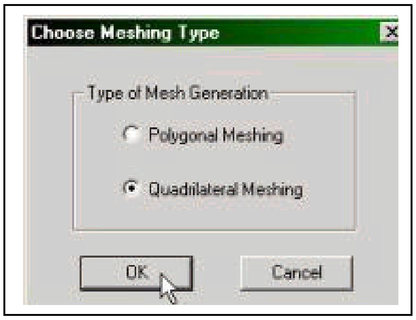


Fig. 4.12 Step 3

Click at the start node, 1 the second time, the following dialog box comes up as shown in fig. (4.13). Choose the *Quadrilateral Meshing* option and click on the *OK* button.


Choose Meshing Type

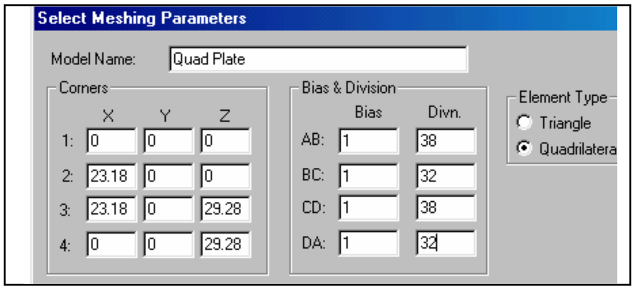
Type of Mesh Generation

○ Polygonal Meshing

● Quadrilateral Meshing

Fig 4.13 Step 4

The *Select Meshing Parameters* dialog box comes up and this time the data for the four corners is automatically filled in. The program used the coordinates of the four selected nodes A, B, C, and D. Provide the *Bias* and the *Divisions* of the model as shown in the figure below (fig 4.14). Click on the *Apply* button.


Select Meshing Parameters

Model Name: Quad Plate

Corners

	X	Y	Z
1:	0	0	0
2:	23.18	0	0
3:	23.18	0	29.28
4:	0	0	29.28

Bias & Division

	Bias	Divn.
AB:	1	38
BC:	1	32
CD:	1	38
DA:	1	32

Element Type

○ Triangle

● Quadrilatera

Fig 4.14 Step 5

Click on the *Apply* button, our model will appear in the drawing area as the one shown below (fig 4.15). The element size will be 0.61m x 0.915 m. The numbers of shell elements generated are **1216.**

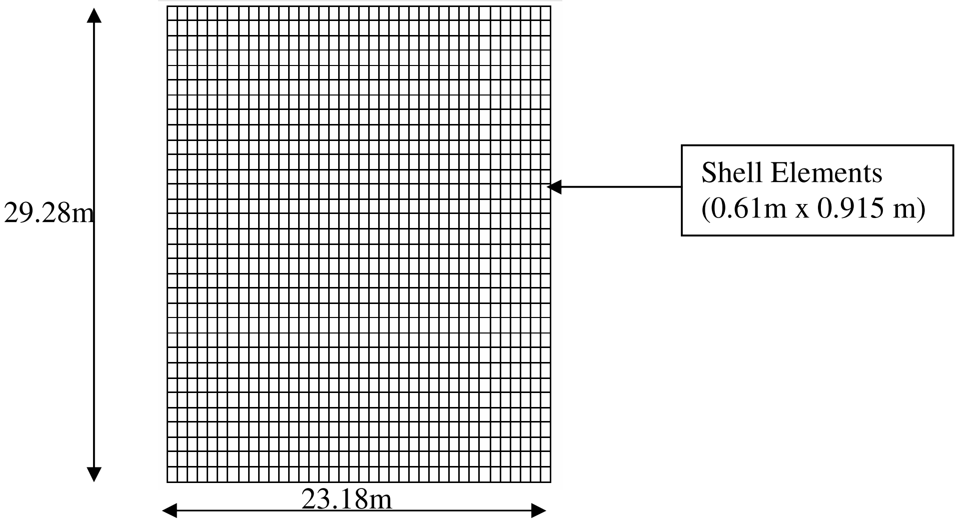


Fig 4.15 Discretized raft

5. Specifying raft element properties: Fig (4.16), (4.17), (4.18), (4.19), (4.20), (4.21), (4.22), (4.23), (4.24) and (4.25).

Properties of Shell Element are based on the hybrid element formulation. The element can be 3-noded (triangular) or 4-noded (quadrilateral). If all the four nodes of a quadrilateral element do not lie on one plane, it is advisable to model them as triangular elements. The thickness of the element may be different from one node to another.

"Surface structures" such as walls, slabs, plates and shells may be modeled using finite elements, Fig 4.16. For convenience in generation of a finer mesh of plate/shell elements within a large area, a MESH GENERATION facility is available. The following quadratic stress distribution is assumed for plate bending action:

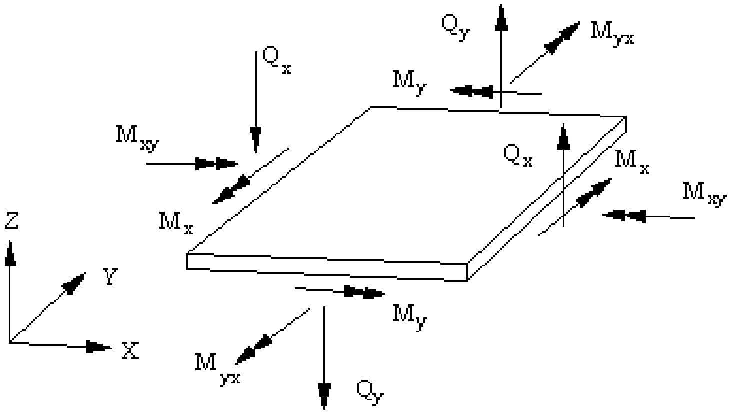


Fig 4.16 A typical plate element

Complete quadratic assumed stress distribution is as under

$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \\ Q_x \\ Q_y \end{Bmatrix} = \begin{bmatrix} 1 & x & y & 0 & 0 & 0 & 0 & 0 & 0 & x^2 & xy & y^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & x & y & 0 & 0 & 0 & 0 & 0 & 0 & x^2 & xy & y^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & x & y & -xy & 0 & 0 & 0 & 0 & -xy & x^2 & y^2 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & x & y & 0 & 0 & 0 & -x & 0 & 2y \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & -y & 0 & 0 & 0 & x & y & 2x & 0 \end{bmatrix} \begin{Bmatrix} a_1 \\ a_2 \\ a_3 \\ . \\ . \\ a_{17} \end{Bmatrix}$$

a_1 through a_{17} = constants of stress polynomials.

The distinguishing features of this finite element are:

1) Displacement compatibility between the plane stress component of one element and the plate bending component of an adjacent element which is at an angle to the first (see Fig. 4.17 below) is achieved by the elements. This compatibility requirement is usually ignored in most flat shell/plate elements.

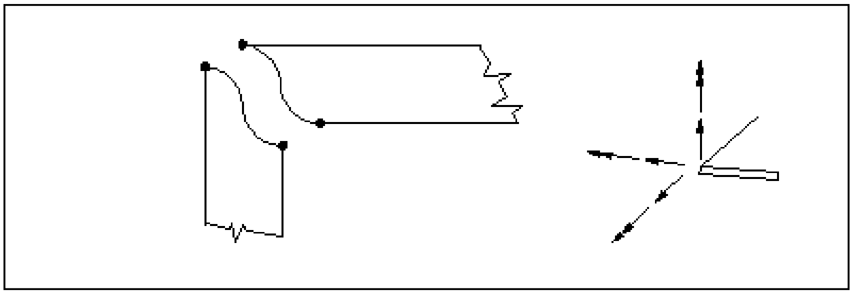


Fig 4.17 Displacement compatibility at nodes

2) The out of plane rotational stiffness from the plane stress portion of each element is usefully incorporated and not treated as a dummy as is usually done in most commonly available commercial software.

3) Despite the incorporation of the rotational stiffness mentioned previously, the elements satisfy the patch test absolutely.

4) These elements are available as triangles and quadrilaterals, with corner nodes only, with each node having six degrees of freedom.

5) These elements are the simplest forms of flat shell/plate elements possible with corner nodes only and six degrees of freedom per node. Yet solutions to sample problems converge rapidly to accurate answers even with a large mesh size.

6) These elements may be connected to plane/space frame members with full displacement compatibility. No additional restraints/releases are required.

7) Out of plane shear strain energy is incorporated in the formulation of the plate bending component. As a result, the elements respond to Poisson boundary conditions which are considered to be more accurate than the customary Kirchoff boundary conditions

8) The plate bending portion can handle thick and thin plates, thus extending the usefulness of the plate elements into a multiplicity of problems. In addition, the thickness of the plate is taken into consideration in calculating the out of plane shear.

9) The plane stress triangle behaves almost on par with the well known linear stress triangle. The triangles of most similar flat shell elements incorporate the constant stress triangle which has very slow rates of convergence. Thus the triangular shell element is very useful in problems with double curvature where the quadrilateral element may not be suitable.

10) Stress retrieval at nodes and at any point within the element.

Following are the items included in the ELEMENT STRESS output.

SQX, SQY: Shear stresses (Force/unit length/unit thickness)
SX, SY, SXY: Membrane Stresses (Force/unit length/unit thickness)
MX, MY, MXY: bending moments per unit width (moment/unit length)
SMAX, SMIN: Principal stresses (Force/unit area)
TMAX : Maximum shear stress(Force/ unit area)
ANGLE: Orientation of the principal plane (Degrees)
VONT, VONB: Von Mises stress

$$\mathrm{VM} = 0.707\sqrt{(\mathrm{SMAX} - \mathrm{SMIN})^2 + \mathrm{SMAX}^2 + \mathrm{SMIN}^2}$$

Notes:

1. All element stress output is in the local coordinate system. The direction and sense of the element stresses are shown in Fig. 4.18and 4.19

2. To obtain element stresses at a specified point within the element, the user must provide the coordinate system for the element. Note that the origin of the local coordinate system coincides with the center node of the element.

3. Principal stresses (SMAX & SMIN), the maximum shear stress (TMAX), the orientation of the principal plane (ANGLE), and the Von Mises stress (VONT & VONB) are also printed for the top and bottom surfaces of the elements. The top and the bottom surfaces are determined on the basis of the direction of the local z-axis.

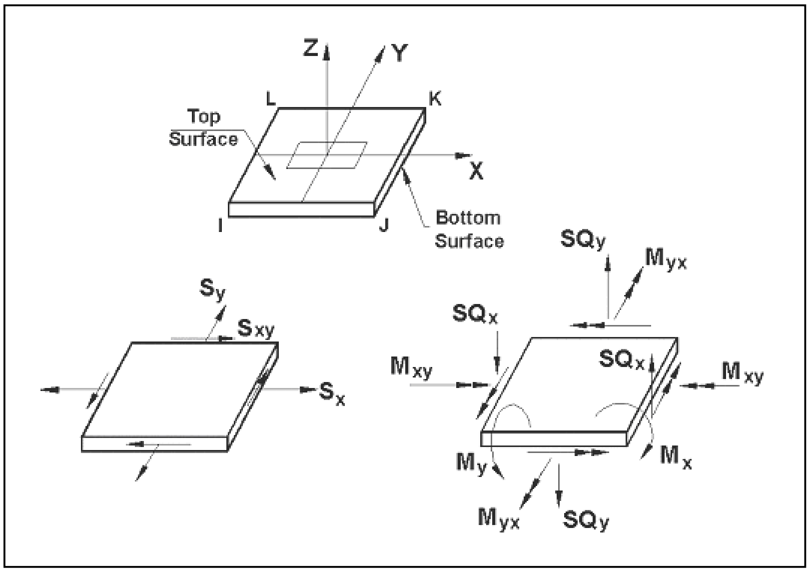
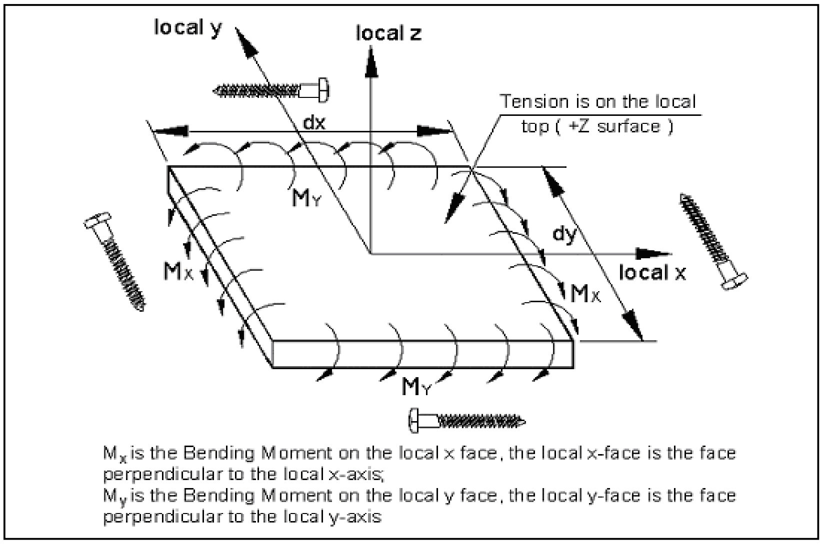


Fig 14.18 Element stress direction



M_x is the Bending Moment on the local x face, the local x-face is the face perpendicular to the local x-axis;
M_y is the Bending Moment on the local y face, the local y-face is the face perpendicular to the local y-axis

Fig 4.19 Element moment direction

Just as properties are assigned to members, properties must be assigned to plate elements too. The property required for plates is the plate thickness (or the thickness at each node of elements if the slab has a varying thickness).The corresponding command which should be generated in the STAAD command file is:

ELEMENT PROPERTY

1 TO 1216 THICKNESS 0.5

Steps:

1. Click on the *Property Page* icon located on the *Structure Tools* toolbar (fig 4.20).

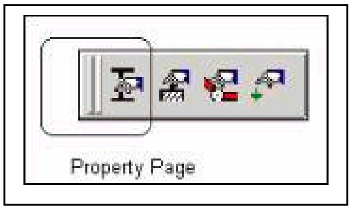


Fig. 4.20 Step 1

Alternatively, one may go to the *General* | *Property* page from the left side of the screen as shown below (fig 4.21).

Fig. 4.21 Alternative way to assign element property

2 In either case, the *Properties* dialog box comes up as shown below (fig 4.22). Plate thickness is specified through the dialog box available under the *Thickness* button.

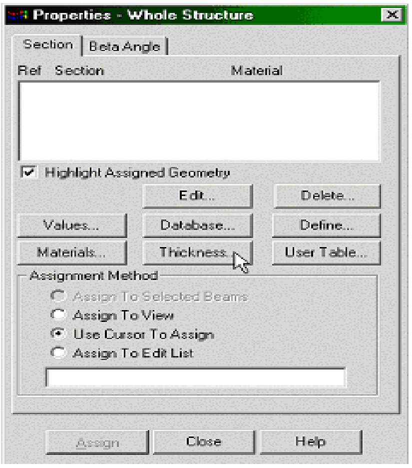
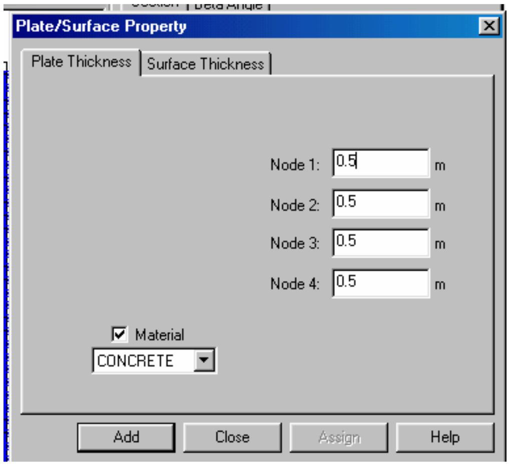


Fig. 4.22 Step 2

3 The dialog box shown below comes up. Provide the *plate thickness* as *0.5m*.(fig.4.23).The material properties of concrete (E, Poisson, Density, Alpha, etc.) will be assigned along with the plate thickness. At this point, the *Properties* dialog box will look as shown below (fig 4.24).



Node 1: 0.5 m

Node 2: 0.5 m

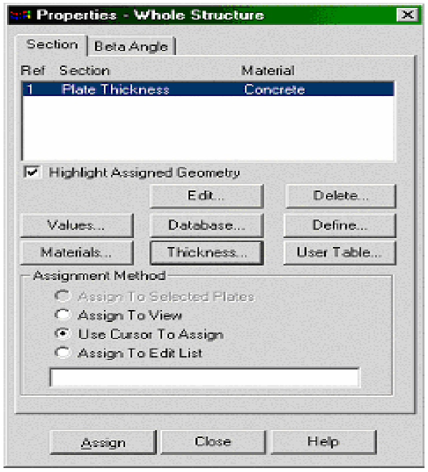
Node 3: 0.5 m

Node 4: 0.5 m

☑ Material

CONCRETE

Fig 4.23 Step 3



Ref	Section	Material
1	Plate Thickness	Concrete

☑ Highlight Assigned Geometry

Assignment Method
- ○ Assign To Selected Plates
- ○ Assign To View
- ● Use Cursor To Assign
- ○ Assign To Edit List

Figure 4.24 Step 4

The thickness to be applied to all elements of the structure, select the *Assignment Method* called *Assign To View* and then click on the *Assign* button as shown in the above figure. For convenience a typical view of raft now look as shown below (fig 4.25).In this figure the first number represents element number while R1 is material property of that element.

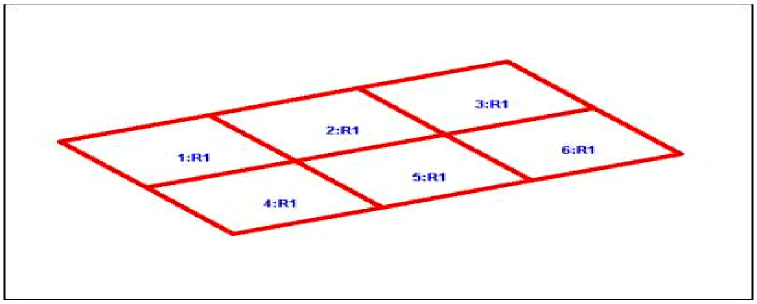


Fig. 4.25 Typical plates with material property

6. Specifying Material Constants: Fig (4.26)

Consequently, the material constants (E, Density, Poisson's Ratio, etc.) of concrete got assigned to the plates along with the properties, and the following commands were generated in the command file:

```
UNIT METER KN
CONSTANTS
E 2.17185e+007 MEMB 1 TO 1216
POISSON 0.17 MEMB 1 TO 1216
```

DENSITY 23.5616 MEMB 1 TO 1216

ALPHA 5.5e-006 MEMB 1 TO 1216

Hence, there is no longer a need to assign the constants separately. However, one could go to the menu option *Commands* | *Material Constants* and assign them explicitly as shown in the (fig.4.26) below.

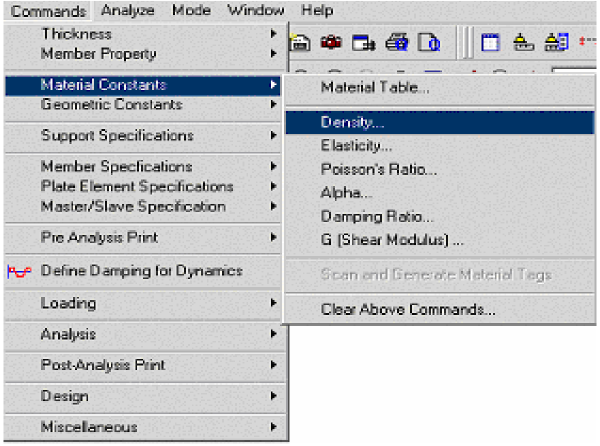
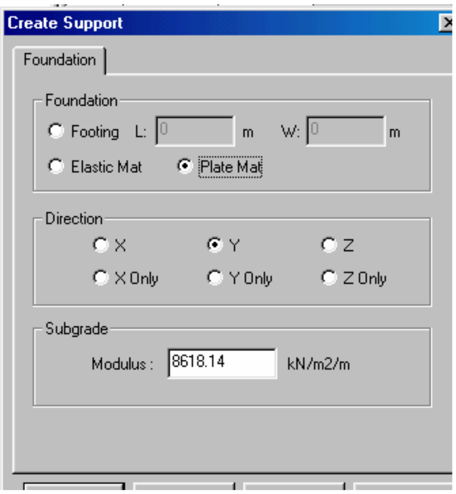


Fig. 4.26 Specifying material constant

7. Specifying Support: Fig (4.27) and (4.28)

When a slab is resting on soil and carries the weight of the structure above. Model the entire slab as finite elements and wish to generate spring supports at the nodes of the elements. This allows the user to create spring supports for independent footings and mat foundations and to assign them to selected nodes. Supports can be created and assigned.

When *Foundation* menu option selected, the *Create Support* dialog box appears, as shown in the next figure 4.27


Create Support

Foundation

Foundation

○ Footing L: 0 m W: 0 m

○ Elastic Mat ● Plate Mat

Direction

○ X ● Y ○ Z

○ X Only ○ Y Only ○ Z Only

Subgrade

Modulus : 8618.14 kN/m2/m

Fig. 4.27 Window to create elastic support.

To define a spring support for an isolated footing, click the *Footing* radio button. Provide the dimension of the footing in current units and choose the *Direction* of spring action. Provide the soil *Subgrade* value in the edit box. Click the *Add* button to add the foundation support tag to the structure, or click *Assign* to assign this support to selected nodes.

In generating spring supports for mat foundations, there are 2 methods available in STAAD. Both those options require the program to calculate the influence area of the nodes which define the surface, and then multiply that area by the subgrade modulus of the medium. The difference between these 2 options lies in the way the influence area is calculated.

In case of elastic mat, the area is calculated using a Delaunay triangle principle. Hence, the candidates for this option are the nodes which define the mat. To achieve best results, one needs to ensure that the contour formed by the nodes form a convex hull.

If the foundation slab is modeled using plate elements, the spring supports can be generated using an influence area calculated using the principles used in determining the tributary area of nodes from the finite element modeling standpoint. Hence, the candidates for this option are the plates which define the mat. When the mat is modeled using plates, this produces superior results than the ELASTIC MAT type. Therefore in this thesis plate mat option is used.

The X,Y, Z, XONLY, YONLY, and ZONLY indicate the direction of resistance of the spring supports. If X, Y or Z is selected, then a spring support is generated in that direction only whereas the associated rotational degree of freedom and the other two translational d.o.f receive a fixed support. For example, if Y is selected, then FY is supported by a spring support, where as MY, FX and FZ are fixed supports; and MX and MZ are free. If XONLY, YONLY, or ZONLY is selected, then a spring support in that direction alone is generated, and every other d.o.f is set to be free to deform.

Choose the *Direction* of spring action. Provide the soil *Subgrade* value in the edit box. Click the *Add* button to add the foundation support tag to the structure, or click *Assign* to assign this support to selected nodes.

Modulus of subgrade reaction (K_s)

One of the important terms required in analyzing foundation on the basis of flexible footings is the value of sub-grade reaction also called coefficient of sub-grade reaction for the particular soil in the foundation of buildings.

The modulus of subgrade reaction is defined as,

$K_s=q/\delta$ (4.2)

and is related to the other elastic soil parameters (E_s,μs) using well known settlement equation,

$Sr=\Delta q*B*(1-\mu_s^2/E_s)*Iw$ (4.3)

to give,

$K_s=\Delta q/Sr=[Es/(B*(1-\mu_s^2)*Iw)]=E_s/H'$ (4.4)

where H' is the apparent depth contributing to the settlement. A number of equation can be found in the literature which convert the elastic parameter (E_s,μ_s) to Ks; however eq.(4.4) is as reliable as any ,is well known and easy to use. This equation has appeal in converting laboratory (triaxial test) values of E_s. Field values of Es from pressure meter testing can also be used; however, some caution is advised since the vertical Es should be used and the pressure meter provides a horizontal value.

A major problem of using eq. (4.4) is that Es tends to increase with depth and if some kind of weighted average value in the zone of influence is not used, the computed value of Ks is too small and the resulting displacements computed too large.

Where estimation is necessary, it is suggested that the site condition can be included by computing Ks from the furnished allowable bearing pressure q_a as,

$K_s=SF\ (q_a)/(1/12)$ (4.5)

where SF(safety factor) is commonly 2 for sand and 3 for clay to reduce the ultimate soil bearing pressure to the allowable q_a (or implicitly assumed if the cone or SPT data is used ,as is most common). This q_a would be adjusted by the geotechnical consultant so further size effects would not be required. Equation 4 gives for allowable bearing pressure in kips/ft^2 or kN/m^2 and the displacement of 1/12ft = 0.0254 m the following equation for use in design

K_s= 80 to 120 qa kN/m^2. (4.6)

The qa value for this raft is 100 kN/m^2 and by using the above formula for clay, the stiffness of equivalent spring will be, 120x 100 = 10000 kN/m **.**The accuracy of the work depends on the degree of discretisation. The raft is descretised in finite shell element with six degree of freedom at each node(fig 4.15). The size of each element is 0.61m x 0.915 m.

The support 2 in the following (fig 4.28) mention the soil support below each shell. The stiffness of the spring supporting the foundation is calculated as per the criteria discussed by Bowle. The stiffness of spring adopted here is 10000 kN/m.

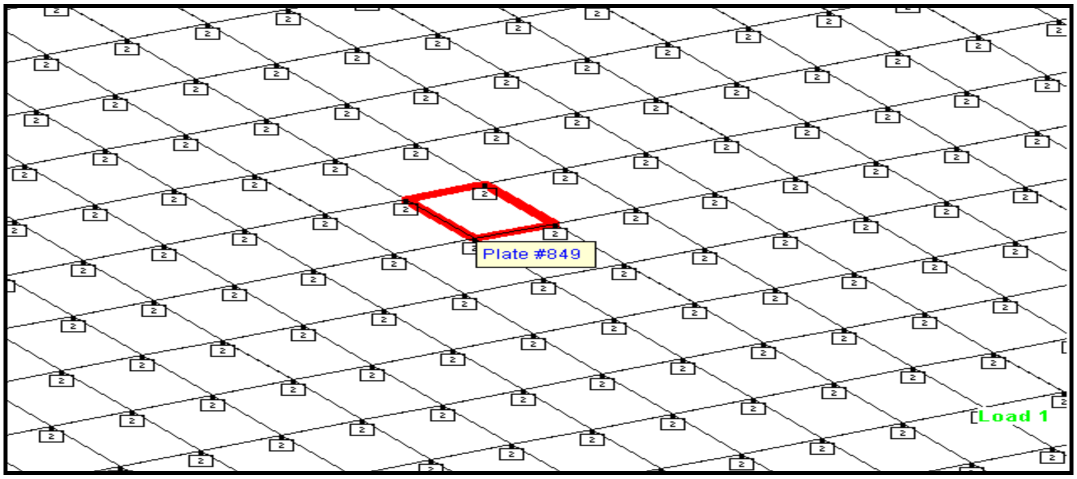


Fig. 4.28 Spring support equivalent to soil stiffness.

In case of Piled raft foundation the spring having stiffness equal to that of soil will replace by the spring having stiffness equal to that of pile at respective pile positions only..

8 Specifying Primary Load Cases: Fig(4.29),(4.30),(4.31),(4.32),(4.33),(4.34) and (4.35). Three primary load cases have to be created for this structure. Details of these load cases are available at the beginning of this tutorial. The corresponding commands to be generated are listed below.

UNIT METER KN
LOAD 1 COLUMN LOAD
LOAD 2
SELF Y -1.0

Steps:

To create loads, click on the *Load Page* (fig 4.29) icon located on the *Structure Tools* tool bar.

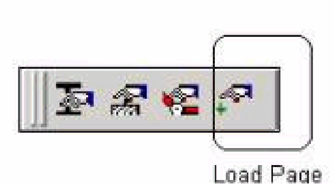


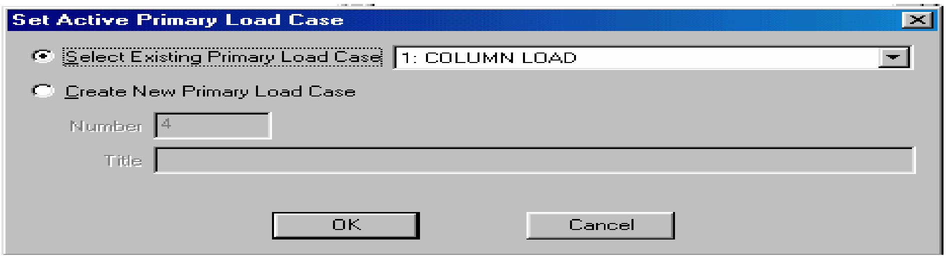
Fig. 4.29 Load page

Click on the *New Primary* button in the *Loads* dialog box that comes up to initiate the first load case. Alternatively, one may go to the *General* | *Load* Page from the left side of the screen (fig 4.30).

Fig. 4.30 An alternative to load page

LOAD CASE 1 (Column Loads)

In the *Set Active Primary Load Case* dialog box that comes up, specify COLUMN LOAD as the *Title* for *Load Case 1* and click on *OK* (see figure 4.31 below).



Set Active Primary Load Case

● Select Existing Primary Load Case: 1: COLUMN LOAD

○ Create New Primary Load Case

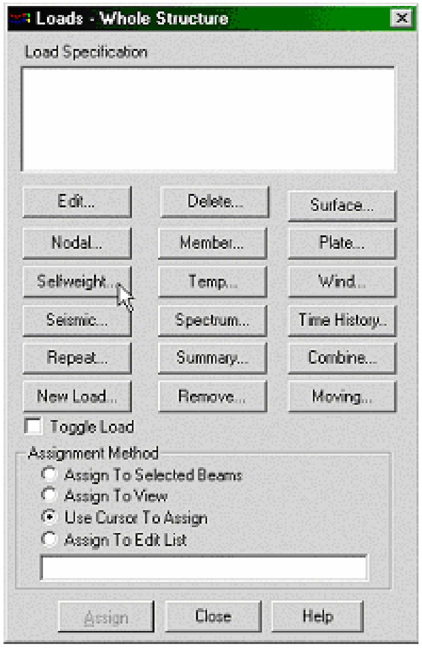
Number: 4

Title:

Fig. 4.31 Load case 1

LOAD CASE 2 (Self weight)

The *Loads* dialog box will now appear. To generate and assign the self weight, click on the *Selfweight* button as shown (fig 4.32) below.

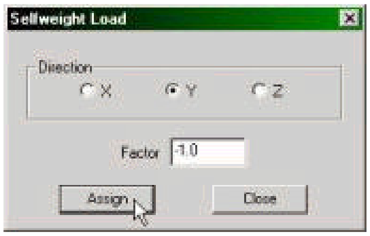


☐ Toggle Load

Assignment Method
○ Assign To Selected Beams
○ Assign To View
● Use Cursor To Assign
○ Assign To Edit List

Fig. 4.32 Load case 2

In the next dialog box, specify the *Direction* as *Y* and the *Factor* as *-1.0* (negative value indicates that the load acts opposite to the positive direction of global Y). Since the selfweight has to be applied to the entire structure, we can straightaway click on the *Assign* button as shown (fig 4.33) below.



Direction
○ X ● Y ○ Z

Factor -1.0

Fig. 4.33 Self weight factor

Creating load combinations

The column loads(Case 1) and the selfweight (Case 2) of slab is combined to find the total response. The way in which they are to be combined is as follows.

LOAD COMBINATION 101 CASE 1 + CASE 2

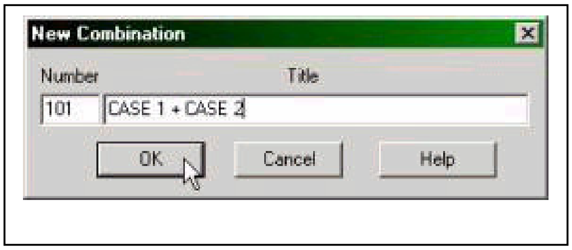
1 1.0 2 1.0

Steps:

<u>LOAD COMBINATION 101 (Column load + Self weight)</u>

The *Define Combinations* dialog box appears. Press the *New* button to initiate the first combination load case.

When the *New* button pressed, the following dialog box comes up. Enter the *Number* as *101* and the *Title* as *CASE 1 + CASE 2*. Then, click on the *OK* button (fig 4.34).



Number: 101
Title: CASE 1 + CASE 2

Fig. 4.34 Load combination

Next, in the *Define Combinations* dialog box, enter *1.0* in the *Factor* edit box (see figure below). Select load cases 1 and 2 from the left side list box (by holding down the 'Ctrl' key) and click on the button. The Load Cases along with the Combination Factor appear in the right side list box as shown in the figure below. (These data indicate that we are adding the two load cases with a multiplication factor of 1.0 and that the load combination results would be obtained by algebraic summation of the results for individual load cases.) Exit this dialog box by clicking on the *OK* button.

It is also worth noting that as load cases are created, a facility for quickly switching between the various cases becomes available at the top of the screen in the form of a load case selection box as shown (fig 4.35)below.

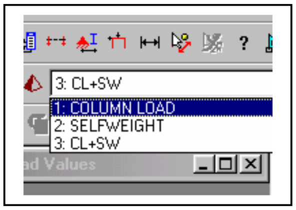


Fig. 4.35 Load case selection box

This will complete the task of creating all load cases.

9 Specifying the analysis type and performing analysis: Fig (4.36),(4.37) and (4.38)

The analysis type required is a linear static type. This will also give a static equilibrium report. This requires the command:

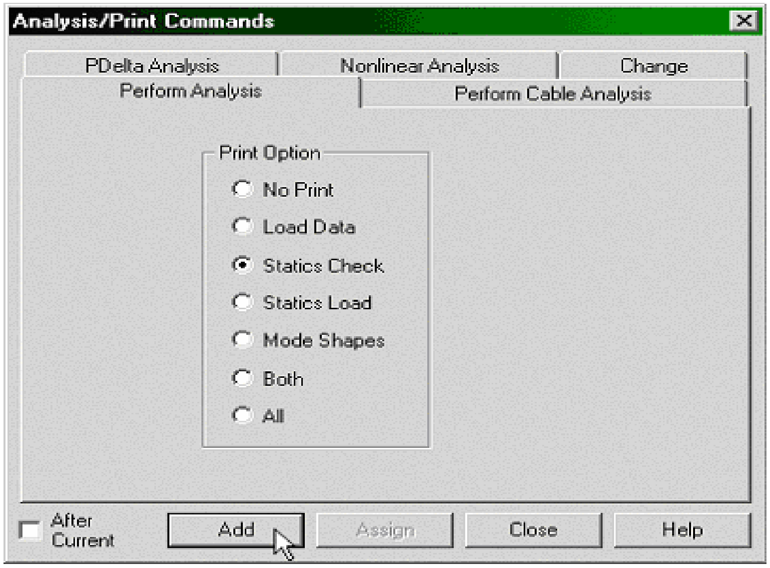
PERFORM ANALYSIS PRINT STATICS CHECK

Steps:

1. To specify the Analysis command, first go to *Analysis/Print* Page from the left side of the screen. Then, click on the *Analysis* sub-page from the second row of pages as shown below (fig 4.36)

Fig. 4.36 Tool bar for analysis command

2. In the *Analysis/Print Commands* dialog box that appears(fig 4.37), the instruction for specifying a linear elastic type analysis is provided using the *Perform Analysis* tab. To obtain the static equilibrium report, check the *Statics Check* print option.



Print Option
○ No Print
○ Load Data
● Statics Check
○ Statics Load
○ Mode Shapes
○ Both
○ All

☐ After Current

Figure 4.37 Linear analyses for static check

Finally, click on the *Add* button followed by the *Close* button. The *Analysis* dialog box in the data area with the newly added instruction will look as shown below (fig 4.38).

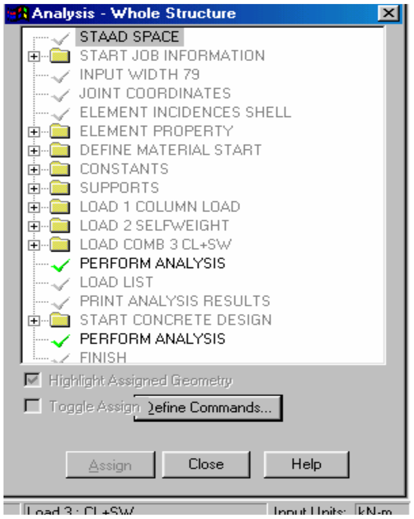
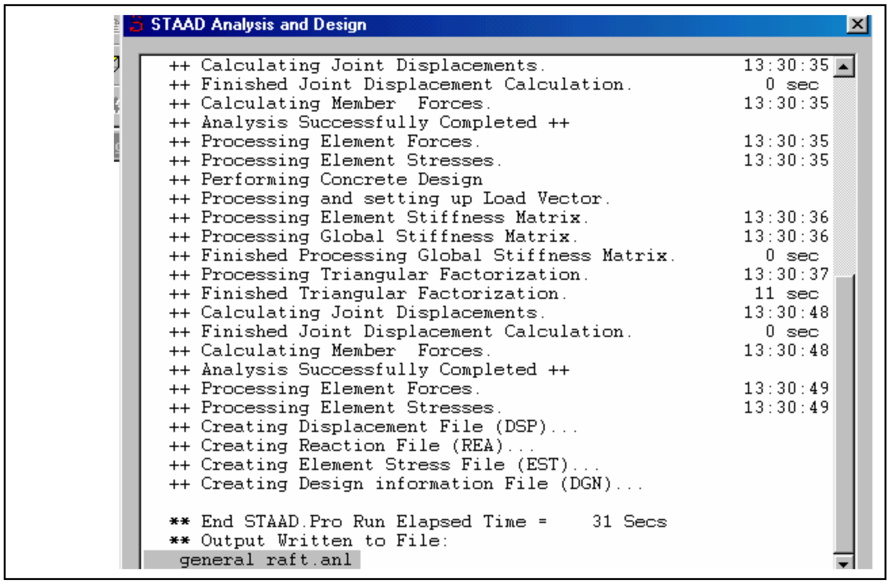


Fig. 4.38 Whole structural data files

Save the data once again using the *File* | *Save* option

10 Viewing out put file: Fig (4.39)

Once the analysis is completed the output file with all analysis and design results can be seen by clicking on view output file option (fig 4.39).



```
++ Calculating Joint Displacements.                    13:30:35
++ Finished Joint Displacement Calculation.              0 sec
++ Calculating Member  Forces.                         13:30:35
++ Analysis Successfully Completed ++
++ Processing Element Forces.                          13:30:35
++ Processing Element Stresses.                        13:30:35
++ Performing Concrete Design
++ Processing and setting up Load Vector.
++ Processing Element Stiffness Matrix.                13:30:36
++ Processing Global Stiffness Matrix.                 13:30:36
++ Finished Processing Global Stiffness Matrix.          0 sec
++ Processing Triangular Factorization.                13:30:37
++ Finished Triangular Factorization.                   11 sec
++ Calculating Joint Displacements.                    13:30:48
++ Finished Joint Displacement Calculation.              0 sec
++ Calculating Member  Forces.                         13:30:48
++ Analysis Successfully Completed ++
++ Processing Element Forces.                          13:30:49
++ Processing Element Stresses.                        13:30:49
++ Creating Displacement File (DSP)...
++ Creating Reaction File (REA)...
++ Creating Element Stress File (EST)...
++ Creating Design information File (DGN)...

** End STAAD.Pro Run Elapsed Time =     31 Secs
** Output Written to File:
 general raft.anl
```

Fig 4.39 Staad.Pro run file

11. Viewing results for individual plates: Fig (4.40) and (4.41)

In the finite element analysis of raft type structure values of moment in both directions, shear force at each node and the settlement can be seen by clicking on the plate of interest. In the following figures i.e. fig. 4.40 and fig. 4.41 that values are mentioned. In the first figure displacement at each node for plate no 1 is shown while in the second figure moments in both directions for plate 1 are shown.

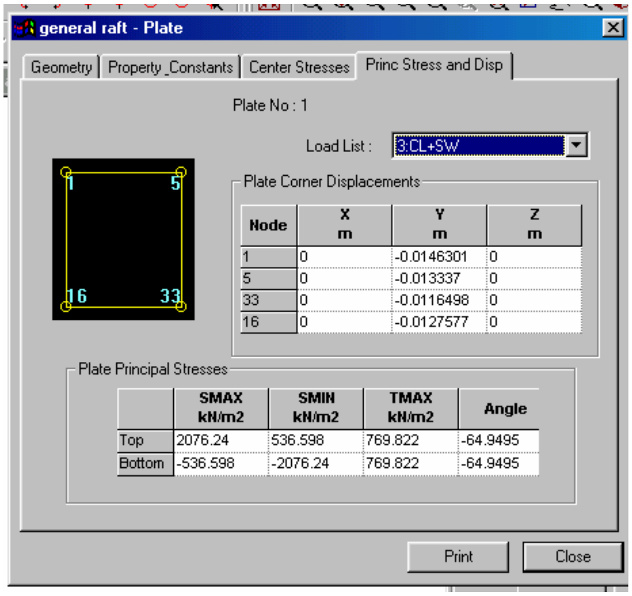


Plate No : 1

Load List : 3:CL+SW

Plate Corner Displacements

Node	X m	Y m	Z m
1	0	-0.0146301	0
5	0	-0.013337	0
33	0	-0.0116498	0
16	0	-0.0127577	0

Plate Principal Stresses

	SMAX kN/m2	SMIN kN/m2	TMAX kN/m2	Angle
Top	2076.24	536.598	769.822	-64.9495
Bottom	-536.598	-2076.24	769.822	-64.9495

Fig. 4.40 Settlement at each node for a plate

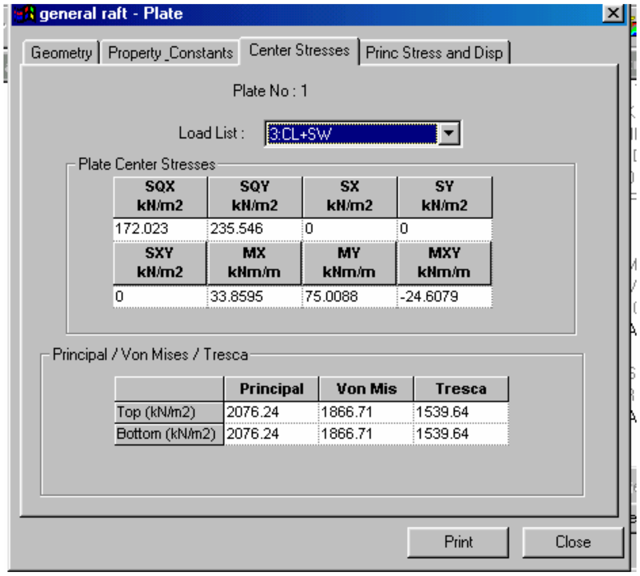


Plate No : 1

Load List : 3:CL+SW

Plate Center Stresses

SQX kN/m2	SQY kN/m2	SX kN/m2	SY kN/m2
172.023	235.546	0	0

SXY kN/m2	MX kNm/m	MY kNm/m	MXY kNm/m
0	33.8595	75.0088	-24.6079

Principal / Von Mises / Tresca

	Principal	Von Mis	Tresca
Top (kN/m2)	2076.24	1866.71	1539.64
Bottom (kN/m2)	2076.24	1866.71	1539.64

Fig. 4.41 Moments in X and Y direction for a plate

4.4 Absolute stiffness of raft :

When raft is totally supported on the soil the absolute stiffness of raft or pile cap is calculated from the formula given (Poulos and Davis, 1974)

$$Kr = \frac{2G}{I\,(1-\mu s)}\sqrt{\text{Area of raft}} \qquad (4.7)$$

where,

G is shear modulus of soil

I is influence factor calculated from Newmark's charts. In the present study as it restrict to a particular raft, this value is directly taken as 1.2 (K.R.Arora).

μ_s = Poisson's ratio for soil.

This stiffness is absolute stiffness of raft which does not depend on thickness of raft. It mainly depends on the area of the raft.

Chapter 5

Pile Foundation

5.1 General

Piles are generally used to transfer the load of a structure to a deep seated, strong stratum. Piles can be classified according to material used, the mode of transfer of load, the method of construction, the use, and the displacement of soil. The mode of transfer of load is most important for the pile load carrying capacity and design. In this, pile types are classified into three categories as,

1. End Bearing Piles
2. Friction Piles
3. Combined End Bearing and Friction Piles.

End Bearing Pile:

End bearing piles transmit the load through their bottom tips. Such pile act as column and transmit the load through a weak material to a firm stratum below. If bed rock is located within reasonable depth, piles can be extended to the rock. The ultimate capacity of pile depends upon bearing capacity of rock. If instead of bed rock, a firmly compact and hard stratum exists at a reasonable depth, pile tip is extended a few meters into hard stratum. End bearing piles are also known as point bearing piles. The ultimate load carried by the pile (Q_u) is equal to load carried by the point or bottom end (Q_p)

Friction Pile:

Friction piles do not reach the hard stratum. These piles transfer the load through the end friction between embedded surface of the pile and the surrounding soil. Friction piles are used when a hard stratum does not exit at a reasonable depth. The ultimate load (Q_u) carried by pile is equal to the load transferred by skin friction (Q_f). The friction piles are also known as floating piles, as these do not reach the hard stratum.

Combined End Bearing and Friction Piles:

These piles transfer load by combination of end bearing at the bottom of the pile and friction along the surface of the pile shaft. The ultimate load carried by pile is equal to sum of the load carried by the pile tip point (Q_b) and load carried by skin friction (Q_f)

5.2 Axial load capacity :

5.2.1 Axial load capacity of single pile:

A pile subjected to load parallel to its axis will carry the load partly by shear generated along the shaft , and partly by normal stresses generated at the base of pile (Fig 5.1). The ultimate capacity Q_u, of the pile under axial load is equal to the sum of the base capacity Q_b and the shaft capacity Q_f, thus

$$Q_u = Q_b + Q_f = A_b\, q_b + A_f\, q_f \qquad (5.1)$$

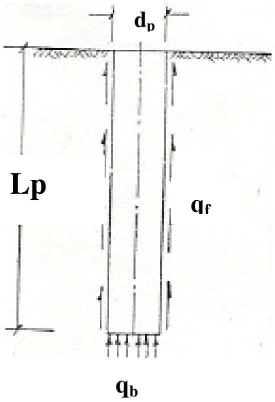


Fig 5.1 Load bearing action by single pile

where A_b = area of pile base = $\pi/4 * d_p^2$
q_b = end bearing pressure
A_s = area of the pile shaft = $\pi * d_p * L_p$
q_f = average unit skin friction
d_p = diameter of pile
L_p = length of pile

The method of evaluating q_b and q_f are explained below;

Average point bearing resistance

$$q_b = c\, Nc \qquad (5.2)$$

where, c = unit cohesion

According to Skempton, for deep foundations, Nc = 9

Therefore,

$$q_b = 9\, c \qquad (5.3)$$

Average unit skin friction ,

$$q_f = \alpha\, c \tag{5.4}$$

where, α = adhesion factor, which depends on the consistency of soil.

$$\therefore \qquad Q_u = c\, Nc\, A_b + \alpha\, c\, A_s \tag{5.5}$$

5.2.2 Axial load capacity of group of piles:

The majority of piled foundation will consist not of a single pile, but of a group of piles, which act in dual role of reinforcing soil, and also of carrying applied load down to deeper and stronger strata. The effectiveness of pile, in particular in respect of its stiffness, is generally reduced by the proximity of other piles. In recognition of this, current trends are towards the use of fewer, widely spaced piles, where the reinforcement role of piles is emphasized. Modern analytical techniques allow more realistic estimate to be made of the response of pile group under working loads, thus giving the designer more scope to minimize the foundation layout.

There are two areas to concern about piled foundation. The first concerns the design of pile group to withstand horizontal loading and the other area of progress concerns the use of pile in conjunction with raft foundation. Where reasonably competent soil extends to a ground surface, the decision to include piles in a foundation may be made on the basis of excessive settlement of a raft foundation alone. The traditional approach has been to design the foundation solely on the basis of piles, ignoring any contribution from the raft or pile cap to the load carrying capacity of the foundation. Burland suggested that the inclusion of a limited number of piles beneath a primarily raft foundation, reduces the settlement to an acceptable level.

A group of piles may be viewed as providing reinforcement to a particular body of soil. Failure of the group may occur either by failure of individual piles or as failure of the overall block of soil. When considering failure of individual piles, it must be remembered that the capacity of each pile may be affected by the driving of subsequent piles in close proximity. This is because of high normal effective stresses acting on piles driven in groups than a single pile. In other situations, the capacity of a pile within a group may be reduced by comparison with a single, isolated pile. In particular piles driven into sensitive clays, the effective stress increase in the surrounding soil may be less for piles in group, than for individual piles. This will result in lower shaft capacities.

The axial capacity of a pile group failing as a block may be calculated in a similar fashion to that for an individual pile, by means of equation,

$$Q_u = q_b * A_b + q_s * A_s \tag{5.6}$$

In this equation A_b as the base area of the block and A_s as the block surface area.
Since the end bearing pressure q_b is much greater than the average skin friction q_s, block failure only becomes more likely than the failure of individual piles where the increase in base area, A_s. That means, group of a large number of long slender piles at a particular spacing are more likely to fail as block than group consisting a few, short stubby piles at the same spacing.

5.2.3 Axial load capacity of pile group in cohesive soil:
For pile groups in cohesive soil, the block capacity may be calculated assuming end - bearing pressures given by equation
$q_u = c\ N_c$, with an appropriate value of N_c, and assuming full shear strength of soil is mobilized round the periphery of the block. The factor may be estimated approximately by Skempton as,

$N_c = 5(1+0.2B_g/L_g)[\ 1+(\ L_p/12B)]$
(5.7)

where B_g and L_g are breadth and length of pile group in plan and L_p is the embedded pile length.
In certain types of soil, particularly sensitive clays, the capacity of individual piles within a closely spaced group may be lower than for equivalent isolated piles. A more rational method recommended by Terzaghi and Peck. According to this method the ultimate bearing of pile group equals the sum of the ultimate bearing capacity of block occupied by the group and shearing resistance mobilized along the perimeter of the group.

$$Q_g = q_u\ B_g L_g + D_f\ (\ 2B_g + 2L_g\ )s - \gamma_s\ D_f B_g L_g \tag{5.8}$$

where,

Q_g = ultimate bearing capacity of the pile group.

q_u = ultimate bearing capacity per unit area of the stressed area at a depth D_f

B_g, L_g = width and length of pile group

γ_s = unit weight of soil.

s = average shearing resistance of soil per unit area between ground surface and bottom of pile.

D_f = depth of embedment of piles.

The safe load on the pile group is given by,

$$Q_{sg} = Q_g / F_s \tag{5.9}$$

The minimum value of Fs should be taken as 3.0. The above equation is applied for cohesive soils.

5.3 Stiffness of single pile and group of piles:

The stiffness of axial member in theory of elasticity is calculated from AE/L, where A stands for cross sectional area, E for modulus of elasticity and L for length of member. This formula is also valid for piles, if they are assumed as elastic. In this thesis work piles are assumed to be rigid one.

5.3.1 Stiffness of single pile:

Stiffness is an engineering property. Stiffness of a structural member is defined as the force required for unit displacement. That means if axial force acting on the member and the stiffness of the member is known one can calculate the deformation in the member. Thus, if the stiffness of a single pile under a given form of loading is k, then a load, P will give rise to deformation δ, given by,

$$\delta = P/k \tag{5.10}$$

In case of Piled raft foundation deformation of the system can be calculated from same concept. The way in which the stiffness of single pile is calculated is explained below.

5.3.2 Stiffness of pile group:

In case of stiffness of pile groups under axial loading, may be evaluated from the stiffness of single piles and use of appropriate interaction factors. A convenient way to regarding the effect of interaction within a pile group has been suggested by Butterfield and Douglas (1981). The stiffness K, of the pile group (load divided by settlement) may be expressed as a fraction η_w of the sum of individual stiffness k. Thus for group of n piles,

$$K = \eta_w * n * k \tag{5.11}$$

The factor η_w is the inverse of the settlement ratio, Rs, and may be brought of as an efficiency (the subscript w denoting settlement, to distinguish it from efficiency in terms of capacity).For no interaction between the piles, η_w would equal unity. Butterfield and Douglas showed that plotting the efficiency η_w against number of piles in a group gave essentially straight line on the logarithmic axes. The precise layout of the piles appeared to have little influence on the computed efficiency, rectangular groups of piles having same efficiency as square groups at the same pile spacing.

Since the curves of efficiency against number of piles are approximately straight on the logarithmic axes, the efficiency may be written as,

$$\eta_w = n^{-e} \tag{5.12}$$

where the exponent e will lie between 0.4 and 0.6 for most of pile groups. The actual value of e will depend on,
pile slenderness ratio, (pile length/ pile diameter , L_p/d_p)
pile stiffness ratio,(Young's modulus of pile / shear modulus of soil at depth l, $\lambda = E_p/G_l$)
pile spacing ratio,(Spacing of pile / diameter of pile, s/d_p)
homogeneity of soil, characterized by ρ,
Poisson's ratio for soil, μ_s
For a given combination of the above factors, the value of e may be estimated using the curves mention by same author.

5.4 Load – deformation relation of single pile and group of piles:

Deformation of the system is always observed in the direction of the application of load. Only vertical load is acting on piles and therefore the deformation in vertical direction is studied.

5.4.1 Load deformation relation of single pile:

The load deformation response of piles under axial load has been examined extensively, using numerical methods, particularly integral equation or boundary element methods. Such methods enable charts to be developed showing how the settlement of pile depend on the various parameters of pile geometry and stiffness, and soil stiffness. Poulos and Davis have complied extensive collection of such charts, enabling the load settlement response of any given pile to be estimated readily and the manner in which a pile transfers load settlement response in elastic soil. The solution leads to an expression for the pile stiffness (applied load divided by settlement) in close form, which is used here as an alternative to charts.

In developing this solution, a manner in which the load is transferred to the soil from the pile shaft, and the pile base, will be examined separately, before combining the two to give response, of the complete pile. In the first instance, the soil will be treated as an elastic material characterized by an appropriate secant value of elastic modulus, varying with the depth.

Basic solution for deflection of a rigid pile:

Pile Shaft: In finite element and boundary element analyses the response of friction piles (Frank.1974; Randolph 1977) have shown that load is transferred from the pile shaft by shear stresses generated in the soil on vertical and horizontal planes, with little change in vertical normal stress (except near base of pile).In this study a pile consider as surrounded by concentric cylinder of soil, with shear stress on each cylinder is considered. For vertical equilibrium, the magnitude of the shear stress at each cylinder must decrease inversely with the surface area of cylinder.

This approximate analytical experiment shows a number of important features of the response of a pile to axial load.

1. Stress changes induced in the soil are primarily shear stresses, decreasing inversely with distance from the pile axis; thus, only soil very close to pile is ever highly stressed.
2. The resulting deflection decreases with the logarithm of distance from pile axis; thus significant deflection extends some distance away from the pile (up to one pile length).

3. The deflection of the pile shaft, w_s, normalized by the pile radius r_0, is ζ times the local shear strain, $\gamma_0 = \tau_0/G$, in the soil (where τ_0 = shear stress at pile shaft); the parameter found to vary between 3 and 5 , with an average value of about 4.

The shear modulus variation with depth may be idealized as linear, according to

$$G = G_0 + mz \tag{5.13}$$

where,

G is shear modulus of soil

G_0 is shear modulus at ground surface

G_l is shear modulus at depth l

z is depth perpendicular to ground surface

m is rate of increase of soil shear modulus with depth, with the possibility of sharp rise to G_b below the level of pile base(see fig 5.2).

Figure shows variation of shear modulus with depth as per Randolph (1994)

G_b is shear modulus at the base of pile.

G^* is average shear modulus between ground surface and pile tip.

Defining parameters

$\rho = G^*/ G_l$,

and

$\xi = G_l/ G_b$,

the constant ζ has been found to fit the expressions,

$$\zeta = \ln\{[0.25 + (2.5 \rho (1-\mu_s) - 0.25)\xi] l/r_o\} \tag{5.14}$$

$$\zeta = \ln [(2.5 \rho (1-\mu_s) l/r_o] \qquad \text{for } \xi = 1 \tag{5.15}$$

where,

μ_s = Poisson's ratio for soil.

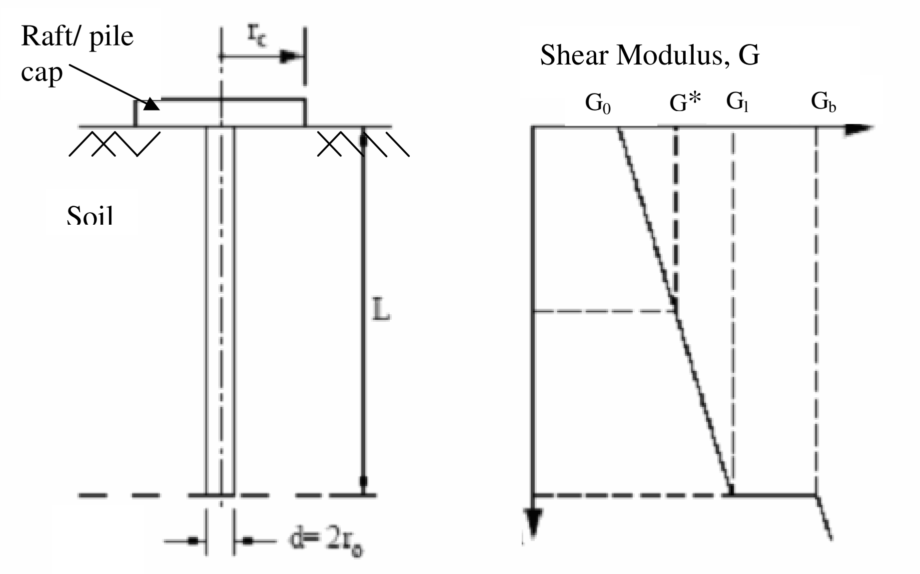


Fig 5.2 Simplified representation of pile-raft unit (Randolph, 1994)

It is expected that the stiffness of pile increases nearly linearly with pile length, holding other factors that is ρ, ξ, μ_s constant. However this is true for rigid pile only.

5.4.2 Axial deformation of group of piles:

In a group of piles, all piles will settle equally, because of the rigidity of the pile cap. But this settlement of a pile group is always found to be greater than the settlement of a corresponding single pile, mainly due to the overlapping of the individual influence zone of the piles, while in the group. The pile groups in clays generally fail due to their excessive settlement rather than by bearing pressure. The traditional approach of replacing the pile group by an equivalent raft foundation in order to estimate settlement, has been replaced by techniques where the group stiffness may be calculated in terms of combined stiffness of individual piles, making due allowance for interaction between pile in group.

One of the most useful concepts emerges from the analytical work is the use of interaction factors. An interaction factor, α, is defined as the fractional increase in deformation (that is defection or rotation at the pile head) of a pile due to presence of a similarly loaded neighboring pile. Thus, if the stiffness of a pile group under a given form of loading is K (eq.5.11) then a load, P will give rise to deformation δ, given by,

$$\delta = P/K \tag{5.16}$$

The way by which the settlement of pile group calculated is same as that for single pile.

5.5 Pile compression

Most piles exhibit some shaft compression at working loads and this should be allowed for in estimating pile deflection. The pile deflection is given in the form of an expression for the load settlement ratio of the pile head as under.

$$\boxed{\frac{P_t}{G_l r_o w_t} = \frac{\dfrac{4\eta}{(1-\mu_s)\xi} + \dfrac{2\pi\rho}{\zeta}\,\dfrac{\tanh(vl)}{vl}\,\dfrac{l}{r_o}}{1 + \dfrac{4\eta}{\pi\lambda(1-\mu_s)\xi}\,\dfrac{\tanh(vl)}{vl}\,\dfrac{l}{r_o}}} \qquad (5.17)$$

where, summarizing the various dimensionless parameters,

$\eta = r_b/r_0$ (ratio of underream for underreamed piles)

r_b is the radius of underrram incase of underreamed pile.

r_0 is radius of pile

ξ(constant) = G_l/G_b (ratio of end bearing for end bearing piles)

ρ(constant) = G^*/ G_l (variation of shear modulus with depth)

λ (constant)= Ep/ G_l (pile – soil stiffness ratio)

$\zeta = \ln (r_c/r_o)$ (measure of radius of influence of pile)

where,

Ep is modulus of elasticity of pile material

r_c is maximum radius of influence of pile under axial loading.

$vl = \surd 2/\zeta\lambda * (l/r_o)$ (vl = parameter in solution for axial pile response which measure of pile compressibility)

P_t is total load

w_t is axial displacement at the top of pile.

Chapter 6

Analysis of Piled raft foundation

6.1 General

From the analytical viewpoint, the Piled raft represents one of the most complex of all foundation systems. The general problem, which is fully three dimensional, is essentially one of determining the stresses and displacements within a foundation consisting of a raft of finite flexibility in contact with the soil and connected to a group of piles embedded in a homogeneous soil layer. Some attempts at Piled raft systems have been made using numerical methods. They are mainly for homogeneous soil and it is assumed that the piles are to be capped with rigid raft. By the way of an alternative approach, a solution of the problem can be sought by means of the finite element method. Some studies have been carried out for the Piled raft problem solution through simplified approximate method also.

6.2 Piled raft analysis:

6.2.1 Classification of methods of analysis:

The methods mentioned by Poulos for analyzing Piled raft foundations are (**fig 6.1**),

1. Simplified method
2. Approximate computer-based method
3. More rigorous computer-based method

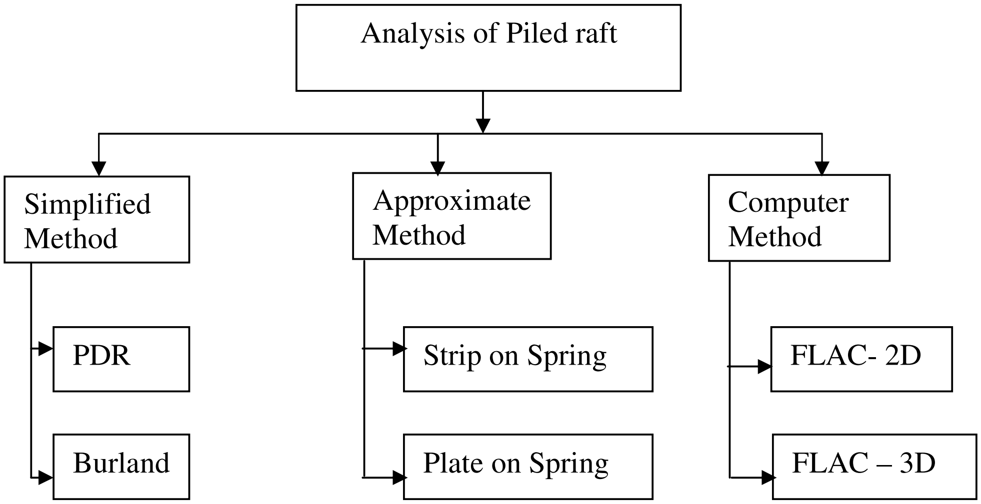


Fig 6.1 Classification of methods of analysis for Piled raft

Simplified methods include those of Poulos and Davis (1980), Randolph (1983,1994), van Impe and Clerq (1995), and Burland (1995). All involve a number of simplifications in relation to the modeling of the soil profile and the loading conditions on the raft. In the above methods, only Poulos, Davis and Randolph simplified method (PDR) is convergent with response characteristics and problem modeling for Piled raft foundations. In the following section, a more detailed description is given of simplified analysis method, this is then be used to analyze a relatively simple hypothetical problem.

6.2.2 Analysis methods

Analysis methods are also varying according to the type of Piled raft mentioned above. First find the stiffness of Piled raft and calculate the settlement and second find bending moments produced in a raft which has to carry part of the superstructure load directly to the soil and has to transmit the rest of the load to the piles.

6.2.2.1 Poulos-Davis-Randolph (PDR) Method

This method is called as Simplified method which is used for assessing vertical bearing capacity of a Piled raft foundation using simple approaches. The ultimate load capacity can generally be taken as the lesser of the following two values:

- The sum of the ultimate capacities of the raft plus all the piles
- The ultimate capacity of a block containing the piles and the raft, plus that of the portion of the raft outside the periphery of the piles.

For estimating the load-settlement behavior, an approach similar to that described by Poulos and Davis (1980) can be adopted. However, a useful extension to this method can be made by using the simple method of estimating the load sharing between the raft and the piles, as outlined by Randolph (1994).

The stiffness of the piled raft foundation can be estimated as follows:

$$\boxed{K_{pr} = (K_p + K_r (1- 2\alpha_{cp})) / (1-\alpha_{cp}{}^2 K_r / K_p)} \tag{6.1}$$

where K_{pr} = stiffness of Piled raft

K_p = stiffness of the pile group

K_r = stiffness of the raft alone

α_{cp} = raft – pile interaction factor.

The raft stiffness K_r can be estimated via elastic theory, for example using the solutions of Fraser and Wardle (1976) or Mayne and Poulos (1999). The pile group stiffness can also be estimated from elastic theory, using approaches such as those described by Poulos and Davis (1980), Fleming et al (1992) or Poulos (1989). In the latter cases, the single pile stiffness is computed from elastic theory, and then multiplied by a group stiffness efficiency factor which is estimated approximately from elastic solutions.

The proportion of the total applied load carried by the raft is:

$$\boxed{P_r / P_t = K_r\,(1-\alpha_{cp}) / (K_p + K_r\,(1-\alpha_{cp})) = X} \qquad (6.2)$$

where P_r = load carried by the raft

P_t = total applied load.

The raft – pile interaction factor a_{cp} can be estimated as follows:

$$\boxed{\alpha_{cp} = 1 - \ln (r_c / r_0) / \zeta}\ . \qquad (6.3)$$

where r_c = average radius of pile cap, (corresponding to an area equal to the raft area divided by number of piles)

r_0 = radius of pile

$\zeta = \ln (r_c / r_0\,)$

$r_c = \{0.25 + [2.5\,(1-\mu_s) - 0.25) * L_p$

ξ , (ratio of shear modulus at depth l, G_l, and that below the pile base,G_b) = G_l / G_b

ρ , (parameter giving relative homogeneity of the soil)= G^* / G_l

μ_s= Poissons ratio of soil

L_p = pile length

G_l = shear modulus at level of pile tip

G_b = shear modulus of bearing stratum below pile tip

G^* = average soil Young’s modulus along pile shaft.

The above equations can be used to develop a tri-linear load-settlement curve as shown in Figure 6.2. First, the stiffness of the Piled raft is computed from equation (6.1) for the number of piles being considered. This stiffness will remain operative until the pile capacity is fully mobilized. Making the simplifying assumption that the pile load mobilization occurs simultaneously, the total applied load, P_1, at which the pile capacity is reached, is given by:

$P_1 = P_u / (1-X_r)$ (6.4)

where P_u = ultimate load capacity of the piles in the group

X_r = proportion of load carried by the raft (Equation 6.2).

Beyond that point (Point A in Fig.6.2), the stiffness of the foundation system is that of the raft alone (K_r), and this holds until the ultimate load capacity of the Piled raft foundation system is reached (Point B in Figure 6.2). At that stage, the load-settlement relationship becomes horizontal.

Thus the total settlement S_{pr} for a working load P_u corresponding to point B can be expressed as follows:

$S_{pr} = P_1 {*} S_{p1} + (P_u - P_1)S_{pu}$

(6.5)

where,

P_1 = load up to ultimate value of pile system

S_{p1} = settlement of pile due to unit load on pile system (P_1/ K_p)

P_u = Ultimate load

S_{pu} = settlement of raft due to unit load on raft (P_u-P_1/ K_r)

The load – settlement curves for a raft with various numbers of piles can be computed with the aid of a computer worksheet In this way, it is simple to compute the relationship between the number of piles and the average settlement of the foundation. Such calculations provide a rapid means of assessing whether the design philosophies for creep piling or full pile capacity utilization are likely to be feasible.

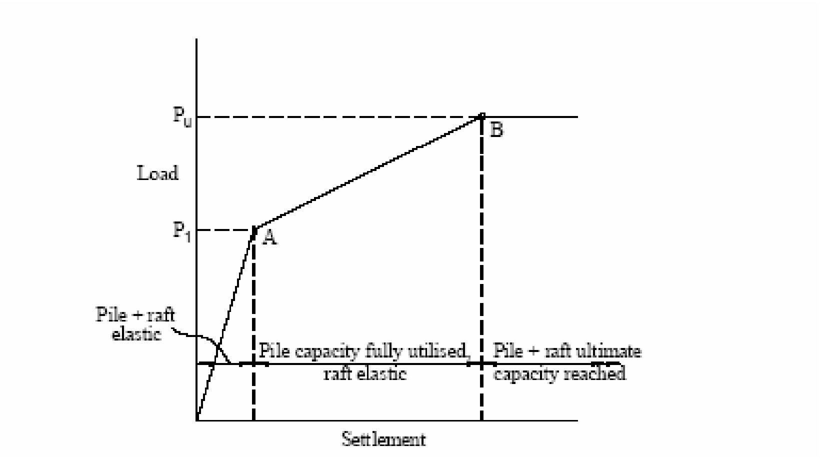


Figure 6.2 Simplified load-settlement curve for preliminary analysis.

6.2.2.2 Approximate computer based method:

In this type of analysis, the raft is represented by an elastic plate, the soil is represented by an elastic continuum and the piles are modeled as interacting springs. Poulos et al. (2001) have concluded that the use of thin shell elements to represent the raft will lead to reasonable estimates of deflections, and therefore moments, as long as the raft is not extremely thick. Stresses in the soil will be higher for the thin shell analysis, and this effect may become important if yield of the soil due to concentrated loads is of concern.

A more sophisticated method of analysis models the complete system, viz., superstructure, raft, piles and soil medium with appropriate finite element types and carries out analysis by considering the interaction between these components. In such analysis, the raft is discretized as plate bending elements, piles as compressible elastic axial elements .The supporting soil is treated as consisting of different layers of homogeneous linear elastic material with corresponding elastic modulus and shear modulus determined with reference to the soil properties. Normally the soil medium is discretized into number of rectangular prism elements. This generalized approach requires enormous computational efforts, time consuming and quite expensive and hence cannot be used in normal design practice.

However, simplified version of finite element approach is commonly adopted with the use of computers. In this study a general purpose Staad.Pro 2003 has been used. This software is universally accepted for structural analysis and design. Unfortunately soil can not be modeled in this software. In the present case of Piled raft, the raft has been modeled as shell elements and the piles are modeled as axial spring elements. To incorporate the pile influence in raft moments and settlement, stiffness of pile separately calculated by the formula given by Randolph (1994). That value of stiffness of pile is placed at respective pile location to study the response. However its stiffness contribution on the overall behavior of the system has to be considered.

6.3 Piled raft design:

6.3.1 Alternative Design Philosophies:

Randolph (1994) has defined clearly three different design philosophies with respect to Piled raft foundations.

- The “conventional approach”, in which 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.

- “Creep Piling” in which 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 preconsolidation pressure of the soil.

- Differential settlement control, in which the piles are located strategically in order to reduce the differential settlements, rather than to substantially reduce the overall average settlement.

In addition, there is a more extreme version of creep piling, in which the full load capacity of the piles is utilized, i.e. some or all of the piles operate at 100% of their ultimate load capacity. This gives rise to the concept of using piles primarily as settlement reducers, while recognizing that they also contribute to increasing the ultimate load capacity of the entire foundation system.

Clearly, all the three approaches are most conducive to economical foundation design, and will be given special attention. However, it should be emphasized that the analysis and design methods to be used, allow any of the above design philosophies to be implemented.

Figure 6.3 (Poulos, 2001) illustrates, conceptually, the load-settlement behavior of Piled rafts designed according to the first two strategies. Curve O shows the behavior of the raft alone, in this case settles excessively at the design load. Curve 1 represents the conventional design philosophy, for which the behavior of the pile-raft system is governed by the pile group behavior, and which may be largely linear at the design load. In this case, the piles take the great majority of the load. Curve 2 represents the case of creep piling where the piles operate at a lower factor of safety, but because there are fewer piles, the raft carries more load than for Curve 1. Curve 3 illustrates the strategy of using the piles as settlement reducers, and utilizing the full capacity of the piles at the design load.

Consequently, the load-settlement may be nonlinear at the design load, but nevertheless, the overall foundation system has an adequate margin of safety, and the settlement criterion is satisfied. Therefore, the design depicted by Curve 3 is acceptable and is likely to be considerably more economical than the designs depicted by Curves 1 and 2.

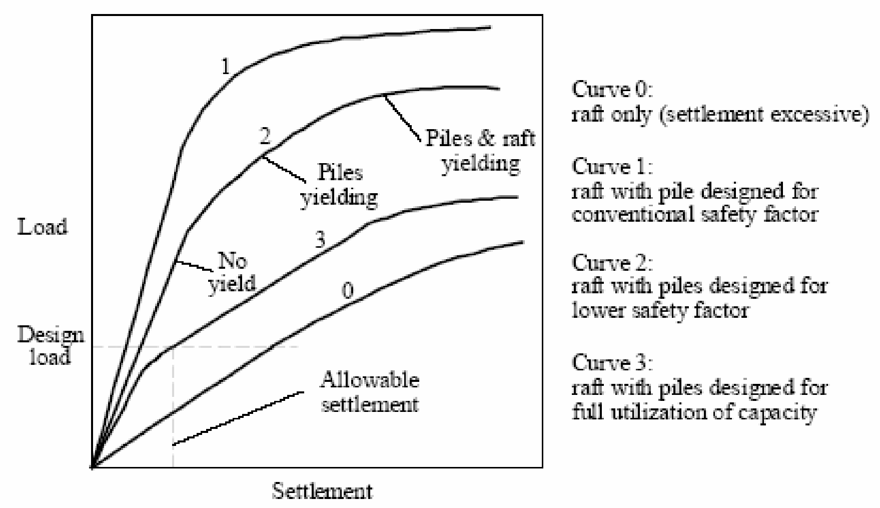


Fig. 6.3 Load Settlement curves for piled raft according to various design philosophy, Poulos (2001)

6.3.2 Design Issues:

As with any foundation system, a design of a Piled raft foundation requires the consideration of a number of issues, including:

1. Ultimate load capacity for vertical, lateral and moment loadings
2. Maximum settlement
3. Differential settlement
4. Raft moments and shears for the structural design of the raft
5. Pile loads and moments, for the structural design of the piles.

In much of the available literature, emphasis has been placed on the bearing capacity and settlement under vertical loads. While this is a critical aspect, the other issues must also be addressed. In some cases, the pile requirements may be governed by the overturning moments applied by wind loading, rather than the vertical dead and live loads. In this study, the design of Piled raft foundation is carried out only for vertical loading and also considering all piles as a rigid pile.

6.3.3 Steps for Piled raft design:

Design of Piled raft foundation is mainly divided in two steps,

The first steps is to, find numbers, dimension and deposition of piles required to reduce the settlement to an allowable value and then comes the design of raft which requires the bending moment for raft which has to carry part of total superstructure load.

The second step is a structural engineering design for finding the area of steel for raft and pile. Piles are assumed to be having uniform strength and are closely spaced. Raft is assumed to act by uniform pressure from below.

Steps for design of Piled raft foundation:

- First calculate the maximum pressure acting on the raft because of vertical loadings.
- Decide number of piles to be placed below the raft node points.
- Piles should be closely spaced. The total area of raft is divided by number of piles to get spacing required between piles.
- Then using flat slab approach, calculate maximum axial force acting on the pile head. Check whether pile will sustain under the same loading or not. Several trails are required to get design safety for piles.
- Calculate the load sharing interaction among raft and pile for the ultimate design load.
- The raft is designed for the maximum load so that it can efficiently transfer load to the piles. Raft is designed as inverted slab/flat slab approach.
- Then piles are designed for reduced percentage of total design load.

6.3.4 Poulos design method for localized column loading:

Much of the existing literature does not consider the detailed pattern of loading applied to the raft foundation, but assume uniformly distributed loading over the raft area. While this may be adequate for the preliminary stage described above, it is not adequate for considering the details like where the piles should be located when column loadings are present. This section presents an approach which has been developed by Poulos (2001), and which allows for an assessment of the maximum column loadings which may be supported by the raft without a pile below the column.

There are at least four circumstances in which a pile may be needed below the column:

- If the maximum moment in the raft below the column exceeds the allowable value for the raft Pc_1=Critical load based on maximum moment criteria

- If the maximum shear in the raft below the column exceeds the allowable value for the raft Pc_2
- If the maximum contact pressure below the raft exceeds the allowable design value for the soil Pc_3
- If the local settlement below the column exceeds the allowable value Pc_4.

If the actual design column load at a particular location is Pc, then a pile will be required if Pc exceeds the least value of the above four criteria, that is, if:

$$Pc > Pcrit \tag{6.6}$$

where Pcrit = minimum of Pc_1, Pc_2, Pc_3, or Pc_4.

Pc_1=Critical load based on maximum moment criteria

Pc_2=Critical load based on maximum shear criteria

Pc_3=Critical load based on maximum contact pressure criteria

Pc_4=Critical load based on maximum settlement criteria

If the critical criterion is maximum moment, shear or contact pressure (i.e. Pcrit is Pc_1, Pc_2 or Pc_3), then the pile should be designed to provide the deficiency in load capacity. Burland (1995) has suggested that only about 90% of the ultimate pile load capacity should be considered as being mobilized below a piled raft system. On this basis, the ultimate pile load capacity, P_{ud}, at the column location is then given by:

$$P_{ud} = 1.11\ Fp.\ [Pc - Pcrit] \tag{6.7}$$

where Fp = factor of safety for piles.

When designing the piles as settlement reducers, Fp which is generally taken as unity.

Chapter 7

Design of Piled raft foundation

General

The analysis and design of Piled raft foundation is carried out in two parts. In the first part a simple problem of raft foundation as given in Braja Das, book is analyzed. The raft is analyzed by conventional rigid foundation approach. The pressure distribution below the raft at different points is calculated. The maximum pressure value below raft does not exceed the net allowable bearing pressure value. Once these values are calculated raft is designed by flat slab or inverted floor approach.

In Piled raft foundation when raft is supported on piles (fig 7.1). In this case piles are analyzed first. They were checked for the ultimate bearing capacity against the acting vertical load. The load is transferred on the piles as per the area supported by each pile. The piles are designed as per IS code. Design of raft is carried out as per flat slab criteria.

Sometimes in case of Piled raft, part of total load will be taken by raft also. Taking advantage of percentage of load sharing, between raft and pile, the loads for raft and pile are calculated and then area for raft and pile is decided and then for that load capacity raft and pile design is carried out. In Piled raft foundation design, following steps are considered.

- Calculation for the maximum pressure because of vertical loading below the raft.
- Design of pile foundation assuming that the whole load (100% vertical load, no lateral load on raft) will be taken by piles.
- Design of raft foundation on the basis of flat slab approach.
- Calculation for the load sharing among pile and raft for the same problem.
- Deign of pile foundation for the reduced load.
- Design of raft foundation for the reduced load.

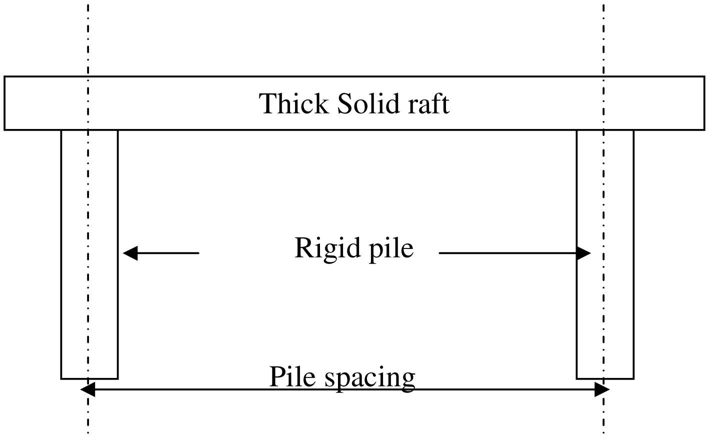


Fig 7.1 Typical side view of Piled raft foundation

7.1 Design of Raft

The plan of a raft foundation with column load is as shown in fig. (7.2). The size of raft is 23.18 m x 29.28 m. All columns are 0.6 m x 0.6 m in section and q_{all}(net) = 100 kN/m^2.While designing raft foundation, the care must be taken that the soil does not fail in shear. Therefore in the first stage of design calculate the soil pressure beneath the raft. This pressure should not exceed the net allowable bearing pressure of soil.

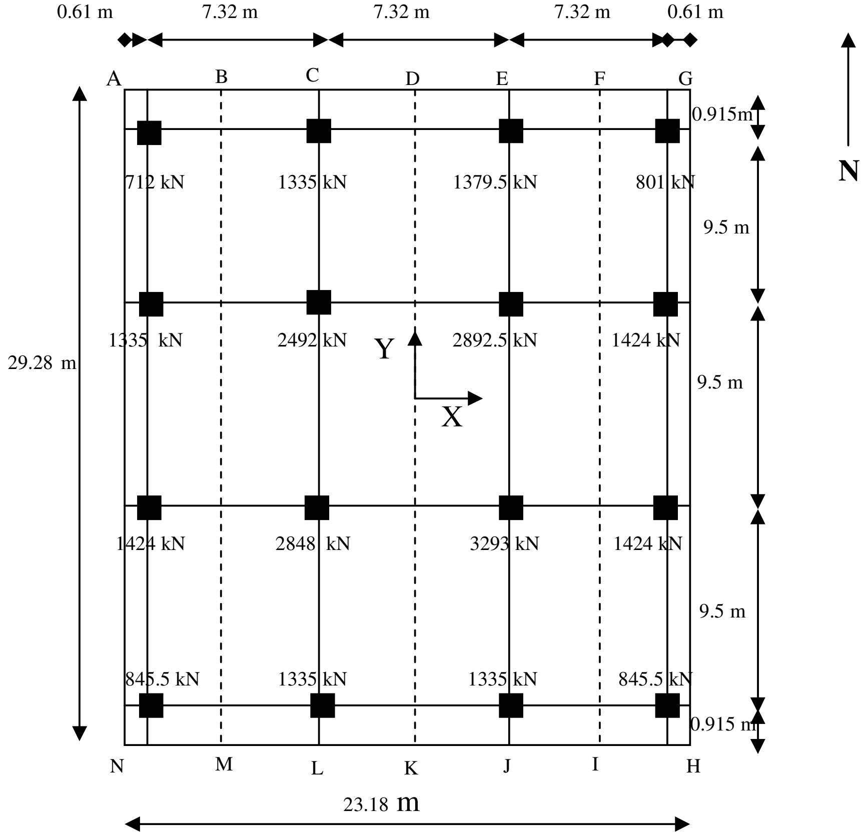


Fig 7.2 Plan of raft foundation

In figure 7.2 Load values are shown for the respective column locations. The values are for combined live and dead load at a particular location.

7.1.1 Materials:

For raft slab M25 grade of concrete is used

Clear cover to any reinforcement:

Raft Slab: 50mm

7.1.2 Permissible Stresses:

Stresses in concrete:

For M25

$\sigma cbc = 8.5\ N/mm^2$

$\sigma cc = 6.0\ N/mm^2$

Stresses in Steel:

For raft slab:

σst (bending tension) = $150\ N/mm^2$

σst (direct tension) = $150\ N/mm^2$

σsc (compression) = $150\ N/mm^2$

7.1.3 Design Constants:

For design as per IS: 456-2000

For M25 and Fe 415

$m = 280/(3x\ \ \sigma cbc) = 10.98$

$k = m/(m+r) = 0.29$

$j = 1-k/3 = 0.9$

$Q = 0.5\ x\ \sigma cbc\ x\ jx\ k = 1.109$

7.1.4 Minimum reinforcement:

For raft slab:

In each of the two direction at right angles (in two layers one on each face for thickness = 225 or more)

0.24% for 100mm thick section

0.16% for 450mm thick section

linearly varying for in between thickness 0.16% for sections>450 mm thick.

7.1.5 Soil pressure below raft:

The pressure below the raft is calculated by conventional method. There are following four steps are involved in calculation of soil base pressure.

Step 1

Load calculation:

Column Dead Load=

445+801+845.5+489.5+801+1602+1780+890+845+1780+1958+890+534+801+801+ 534

=15798 kN

Column Live Load =

267+534+534+311.5+534+890+1112.5+534+578.5+1068+1335+534+311.5+534+534+312

= 9924 kN

Total Service load is equal to sum of total dead load and live load

Service Load = Dead load + Live load

= 15798 + 9924

= 25722 kN

Factored Load = 1.5 (25722)

= 38582 kN

Step 2:

Moment of Inertia calculation for foundation,

In X- direction:

Ix = (1/12) x 23.18 x 29.283

= 48489.24 m^4

Iy = (1/12) x 23.183 x 29.28

= 30389.9 m^4

Step 3:

Calculation of eccentricities e_x, e_y in both x and y direction

For calculation of ex, taking moment about y axis,

25721 x’ = 7320x (1335+2492+2848+1335)+ 14640x(1379.5+ 2892.5 + 3293+ 1335)

+ 21960 x (801+1424+1424+845.5)

x’ = 11.82 m

e_x = 11.82 -10.98

e_x =Eccentricity @ X axis = 0.202 m

Similarly for calculating eccentricity in y direction i.e. e_y taking moment in x direction,

25721 y' = 9150 x (1424 +2848+ 3293+1424) + 18300 (1335 +2492 + 2892.5 +1424)

+ 27450 (712 +1335+ 1379.5 +801)

y' = 13.504 m

e_y = 13.504 – 13.725

e_y = Eccentricity @ Y axis = - 0.22 m

The moments caused by eccentricity are,

Mx = Q x e_y

Mx = 38581.5 x 0.221

Mx = 8526.5 kNm

My = Q x e_x

My = 38581.5 x 0.202

My = 7793.46 kNm

Step 4 : calculation for the pressure on soil.

Using equation

$$q = Q/A \pm (Q\ e_y/Ix)\ Y \pm (Q\ e_x/Ix)\ X$$

Putting all above calculated value in the equation, a simplified equation will get, i.e.,

$q = 56.84 \pm 0.176\ Y \pm 0.256\ X$

Putting the co-ordinate values of all points A to N about X and Y axis, pressure on soil because of the loading on raft is calculated for different locations (Table 7.1)

Table 7.1 Soil pressure at various points

Location	X co-ordinate (m)	Y co-ordinate(m)	q (Soil pressure, kN/m^2)
A	-11.59	14.64	51.3
B	-7.32	14.64	52.39
C	-3.66	14.64	53.55
D	0	14.64	54.26
E	3.66	14.64	55.2
F	7.32	14.64	56.14
G	11.59	14.64	57.23
H	11.59	-14.64	**62.38**
I	7.32	-14.64	61.29
J	3.66	-14.64	60.35
K	0	-14.64	59.42
L	-3.66	-14.64	58.48
M	-7.32	-14.64	57.54
N	-11.59	-14.64	56.46

The maximum soil pressure due to the loading will be at point H. This value comes to be 62.38 kN/m^2.

Average soil reaction for each strip as consider in fig. (7.2)

For strip A- B- M-N width is 7.92 m

$q_1 = q_A + q_B / 2 = (51.3 + 52.39)/2 = 51.84$ kN/m^2

$q_2 = q_M + q_N / 2 = (57.54 + 56.45)/2 = 57.00$ kN/m^2

Here subscript 1 and 2 indicates soil pressure at two ends of strip while suffix A, B. etc. are the soil pressure at respective points.

For strip B-C-D-K-L-M width is 7.32 m.

$q_1 = (q_B + q_C + q_D)/3 = (52.39 + 53.55 + 54.26)/3 = 53.3$ kN/m^2

$q_2 = (q_K + q_L + q_M)/3 = (59.42 + 58.48 + 57.54)/3 = 58.48$ kN/m^2

For strip D-E-F-I-J-K width is 7.32 m

$q_1 = (q_D + q_E + q_F)/3 = (54.26 + 55.3 + 56.14)/3 = 55.2$ kN/m^2

$q_2 = (q_I + q_J + q_K)/3 = (61.29 + 60.35 + 59.42)/3 = 60.35$ kN/m^2

For strip F-G- H-I width is 7.92 m

$q_1 = q_F + q_G / 2 = (56.13 + 57.23)/2 = 56.68$ kN/m^2

$q_2 = q_H + q_I /2 = (62.38 + 61.29)/2 = 61.84$ kN/m^2

These calculations shows that the maximum avg. soil reaction will be for last strip F-G-H-I. This value come upto 61.84 kN/m^2.

7.1.6 Load calculation:

Downward Loads:

Maximum base pressure = 62.38 kN/m^2

Self weight of slab = 0.5 x 25 = 12.5 kN/m^2

Total design pressure = 62.38 +12.5 = 74.88 kN/m^2 (Raft is taking 100% vertical load)

The raft is designed for total design pressure of 74.88 kN/m^2, which includes the downward load plus the self weight of raft. Area of raft supported by one pile is equal to total area of raft divided by number of piles. There are total 64 piles provided which covers the entire raft. Raft area equal to 10.6 m^2 will be supported by one pile. Therefore area of raft under one pile will be 3.6m x 3.6m. The longer span of 4.95 m is considered for moment calculations. (Fig. 7.3)

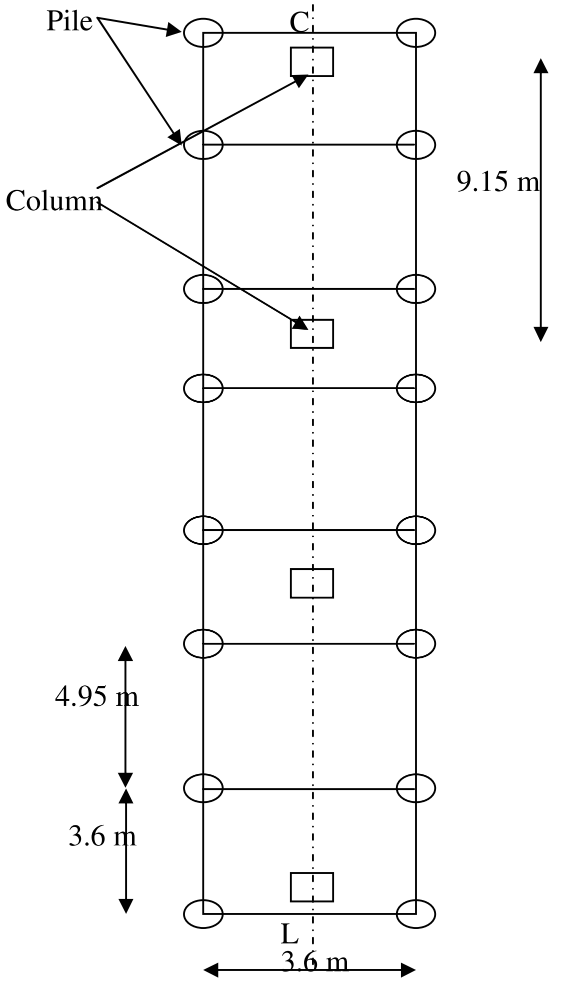


Fig. 7.3 Typical layout of a consider strip 'C-L'

7.1.7 Moment calculation:

The moments are calculated for one strip of 3.6 m width and the length 4.95m between two piles of adjacent pile group, which is covering four piles in a group for one particular column.

Maximum pressure intensity, w: = 74.88 kN/m^2

Clear span = 4.95-0.9x 0.5 = 4.5 m

Total moment Mo = w x 4.95 x $l^2/8$

= 74.88 x 4.95 x $4.5^2/8$

= 938.2 kNm

Negative bending moment = 0.65 x 938.2 = 609.8 kNm

Positive bending moment = 0.35 x 938.2 = 328.4 kNm

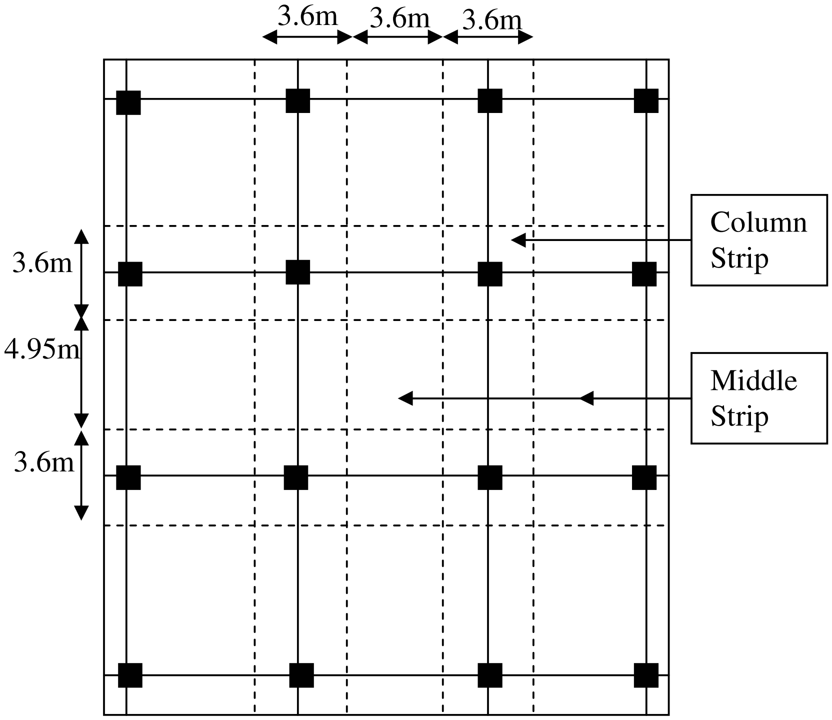


Fig 7.4 Layout of raft with strip locations

Distribution of negative bending moment:

Column strip: 0.75 x 609.8 = 457.4 kNm

Middle strip: 0.25 x 609.8 = 152.5 kNm

Distribution of positive bending moment:

Column strip: 0.6 x 328.4 = 197 kNm

Middle strip: 0.4 x 328.4= 131.4 kNm

Table 7.2 Raft design moment table

Negative Bending Moment (for top reinforcement)	Bending Moment kNm
Column strip	457.4
Middle strip	152.5
Positive Bending Moment(for bottom reinforcement)	Bending Moment kNm
Column strip	197
Middle strip	131.4

From all above moments, the maximum bending moment value is = **457.4** kNm

Check for thickness:

$d_{\text{effective (req)}} = \sqrt{M/Q*b}$

for M25 , Q = 1.109 (as calculated very initially of the design calculations)

Width of strip, b = 3.6m

$d_{\text{effective (req)}} = \sqrt{457.4/1.109*3.6}$

$d_{\text{effective}}$ = 339 mm

d_{eff}. provided = 500-50 = 450mm > d_{eff}. required ………Hence O.K.

Check for Punching Shear:

Maximum intensity = 62.38 kN/m^2

d_{eff} = 450mm

Considering critical section at d/2 from face of pile for punching shear,

Plan area of periphery at which punching shear acts

$A = \pi(D + d)^2/4$

$A = \pi(0.5 +0.45)^2/4$

A = 0.71 m^2

Punching shear force (Vp) = 62.38x(X_2 –A)

Here X_2 is the area enclosed by pile (4.95 x 3.6 =17.8m^2)

$Vp = 62.38 \times (17.8 - 0.71)$

$Vp = 1067$ kN

Shear stress $\tau = Vp / (\pi \times (D + d) \times d)$

$= 1067 \times 1000 / (\pi \times (500 + 450) \times 450)$

$= 0.79$ N/mm^2

$< 0.16\sqrt{25} = 0.8$ N/mm^2

Above calculation shows that section assumed for slab is correct.

7.1.8 Settlement Calculation for raft:

From immediate settlement criteria, settlement (Sr) is calculated from the formula,

$$Sr=q*B*(1-\mu_s^2/E_s)*Iw$$

Here in the design the net allowable bearing pressure is assumed as 100 kN/m^2, taking factor of safety as 3 for clay type soil, the ultimate bearing pressure (q) will be 300 kN/m^2.The influence factor (Iw) is assumed as 1.2.The Poisson's ratio of soil is 0.25.Width of raft, B is 23.18m.

The shear modulus of soil (G) is assumed as 15000 kN/m^2. The modulus of elasticity of soil is calculated from the formula,

$$\boxed{Es = 2 * G (1+ \mu_s)}$$

$$\boxed{Es = 2*15000 (1+ 0.25)}$$

Es = 37500 kN/m^2

The settlement is,

$$\boxed{Sr=300*23.18*(1-0.25^2/ 37500)*1.2}$$

$$\boxed{Sr= 208mm}$$

The settlement calculated is too much, more than permissible limits.

7.1.9 Design of raft for full load capacity:

Above bending moments are for full width of strip. Reinforcement calculated is also for full width of strip.

Area of reinforcement is calculated from working stress method,

$$Ast = M /(\sigma st^* \ j \ ^*d)$$

M is the value of moment.

σst = Stress in steel , Here it is taken as 150 N/mm^2 .

j = calculated at very first stage in design constant calculations = 0.9

d = effective depth, adopted here 420 mm.

Table 7.3 Moments and Steel with spacing in raft.

Negative Bending Moment (for top reinforcement)	Bending Moment kNm	Ast required mm^2	Bar and Spacing	Ast provided mm^2
Column strip	457.4	7529	25mm @ 65mm c/c	7548
Middle strip	152.5	2510	20mm @ 125mm c/c	2512
Positive Bending Moment (for bottom reinforcement)				
Column strip	197	3243	20mm @ 95mm c/c	3305
Middle strip	131.4	2163	20 mm @ 145mm c/c	2166

Total area of steel required for a strip which includes column and middle strip is summation of all Ast = 7529 + 2510+ 3243 + 2163

= 15445 mm^2

Result Summary:

All above results are grouped in Table 7.4.

Table 7.4 Result summary for 100% load on raft

Raft for 100% load	
Thickness (t)	500 mm
Area of steel (Ast)	15445 mm^2
Central settlement (Sr)	208 mm

Bottom Reinforcement Details:

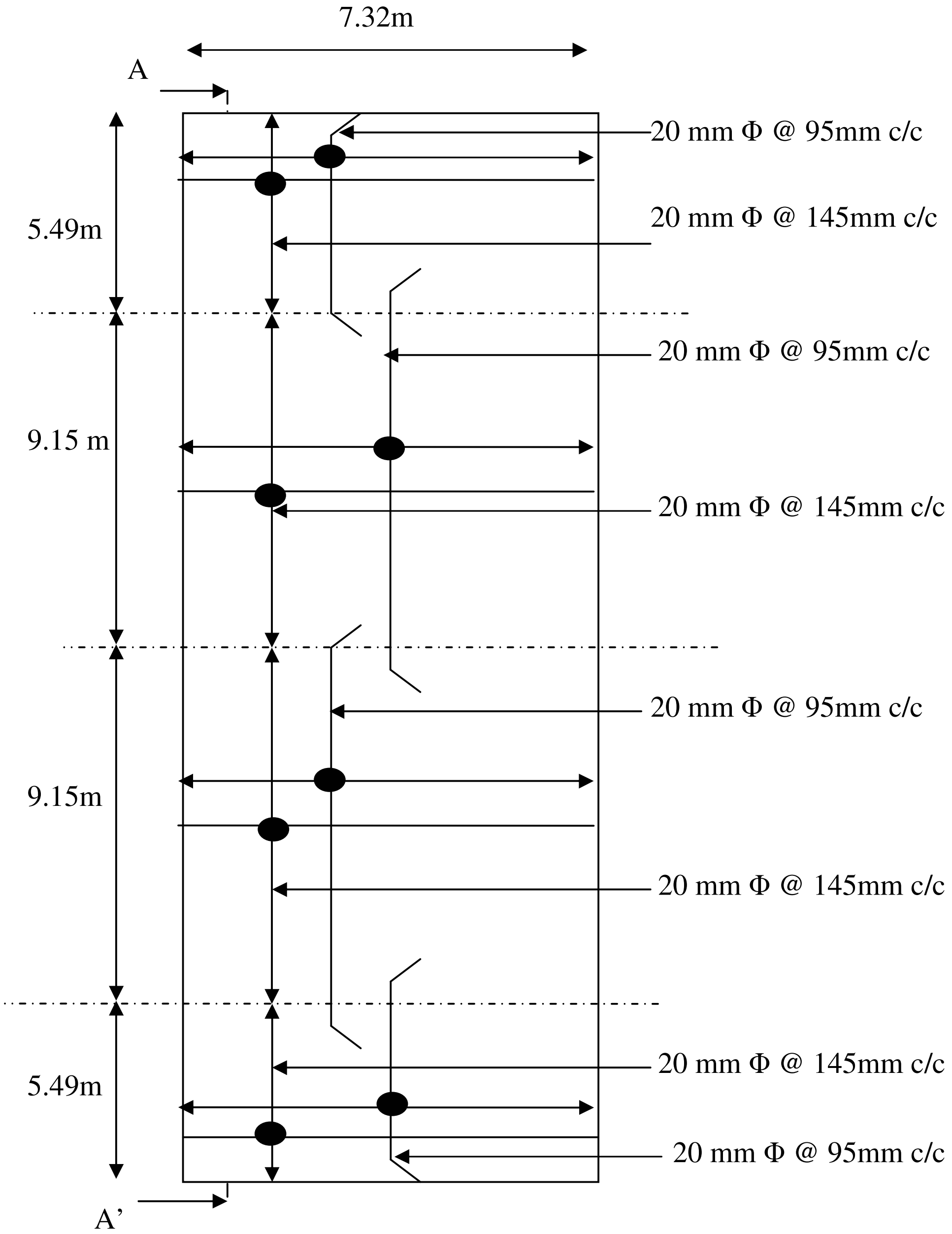


Fig 7.5 Bottom reinforcement details for the raft's strip

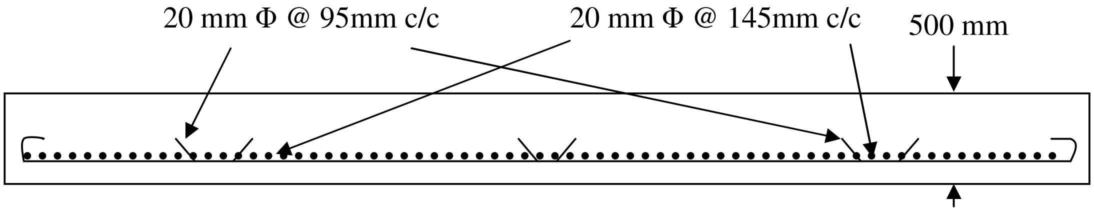


Fig 7.6 Section A-A' for bottom reinforcement.

Top reinforcement details:

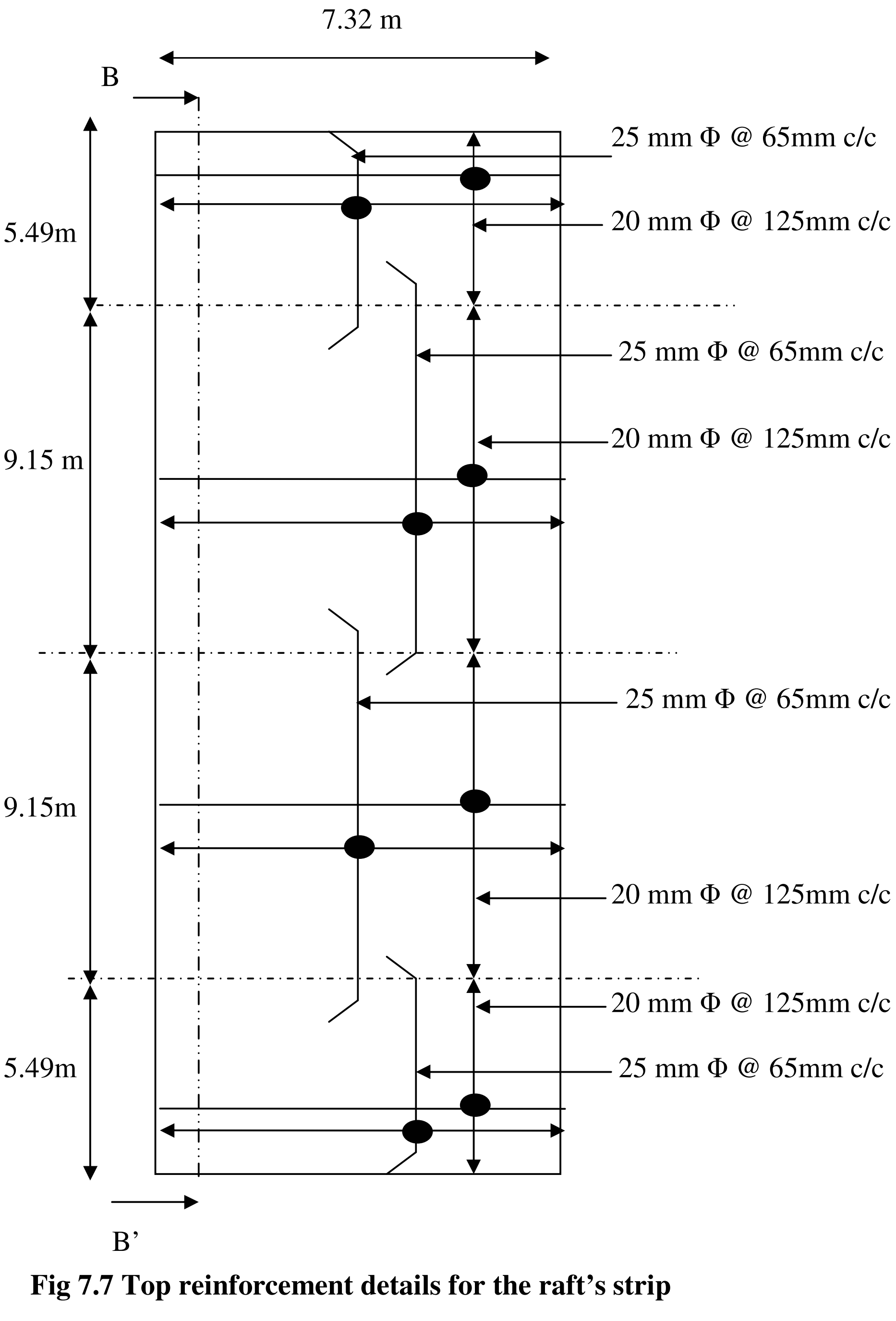


Fig 7.7 Top reinforcement details for the raft's strip

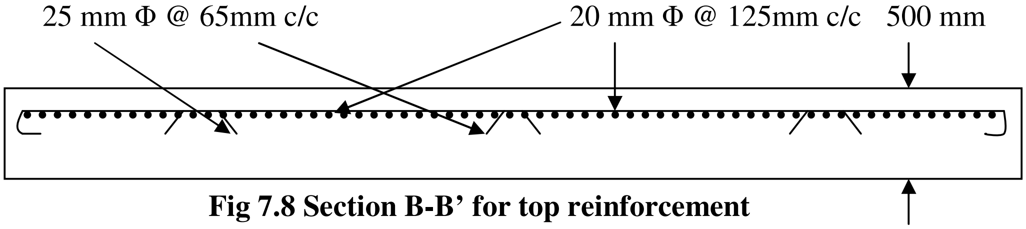


Fig 7.8 Section B-B' for top reinforcement

7.2 Design of Piles under raft

As the pile is completely embedded in soil it will be treated as short column as per Cl. B-3 of Annex B of IS 456:2000 .The pile design is carried out by assuming all piles as rigid piles.

7.2.1 Materials:

The same concrete grade adopted for pile also i.e. M25

Piles : M25

7.2.2 Permissible Stresses:

Stresses in concrete:

For M25

$\sigma cbc = 8.5$ N/mm^2

$\sigma cc = 6.0$ N/mm^2

Stresses in Steel:

For Piles

$\sigma st = 230$ N/mm^2

$\sigma sc = 190$ N/mm^2

7.2.3 Design Constants:

For design as per IS:456-2000

For M25 and Fe 415

$m = 280/(3x \ \sigma cbc) = 10.98$

$k = m/(m+r) = 0.29$

$j = 1-k/3 = 0.9$

$Q = 0.5 \ x \ \sigma cbc \ x \ jx \ k = 1.109$

7.2.4 Settlement Calculation:

To calculate the settlement of pile, the pile is assumed as rigid one and the stiffness of pile is calculated from the formula suggested by Randolph,

7.2.4.1 For single pile:

The pile stiffness is calculated from the formula given by Randolph for rigid pile.

$$\frac{P_t}{G_l r_o w_t} = \frac{\frac{4\eta}{(1-\mu_s)\xi} + \frac{2\pi\rho}{\zeta}\frac{\tanh(vl)}{vl}\frac{l}{r_o}}{1 + \frac{4\eta}{\pi\lambda(1-\mu_s)\xi}\frac{\tanh(vl)}{vl}\frac{l}{r_o}}$$

The parameters mentioned in the above formula are as follows,

Assuming shear modulus for stiff clay type of soil (London clay), G as =150 C_u

This is a random assumption as made in literature after lot of experiments on London clay.

The shear strength profile of soil is approximated as

$C_u = 100 + 7.2\ z$

(This profile is taken from literature based on Piled raft foundation on London clay.)

This variation is linear and directly proportional to the depth.

The depth of foundation is assumed as 10m.

Similarly the value of C_u at the pile tip, is (putting z =10 m),

$C_u = 100 + 7.2\ (10)$

$C_u = 172\ kN/m^2$.

Length of pile $L_p = 10m$

Radius of pile, $r_o = 0.25$ m.

The value of Cu at the head of pile or at the ground level for stiff clay type of soil assumed as 100 kN/m^2

Therefore the shear modulus at the ground surface,

Go = 150 x 100

Go = 15000 kN/m^2

Similarly,

Shear modulus at depth l=10m

G_l or G_b = 150 x 172

$G_l = 25800\ kN/m^2$

The average shear modulus, $G^* = (15000 + 25800) / 2 = 20400\ kN/m^2$

The constants ρ,ξ,λ,η for above formula are calculated in following way,

$\rho = G^*/ G_l$

= 20400/ 25800

$\rho = 0.791$

$\xi = G_l / G_b$

= 25800/25800

$\xi = 1.0$

$\lambda = Ep / Gl$

= 2.5x107 / 25800

$\lambda = 969$

$\eta = r_o / r_b$

= 0.25/0.25

$\eta = 1$

The raft pile interaction factor calculated as,

$$\boxed{\alpha_{cp} = 1 - \frac{\ln(r_c/r_o)}{\zeta}}$$

r_c = average radius of pile cap (corresponding to the area of the raft equal to the raft area divided by number of piles)

Here total 64 numbers of piles are assumed to be placed below the raft. This means raft area supported by each pile will approximately,

A_p (supported) = 678.7 / 64

$A_p = 10.60\ m^2$

The arrangement of pile placed below the raft is shown in fig.(7.2) Piles are strategically located in the form of 4 x 4 group near the columns.

From this area radius of pile cap is calculated as,

$r_c = 1.84$ m

r_o = radius of pile =0.25 m

The constant ζ is calculated as,

$$\zeta = \ln (r_m/r_o);$$

Here, radius of influence, rm = { 0.25 + ξ [2.5 ρ (1-µs)-0.25]} x Lp

$r_m = \{0.25 + 1.0 [2.5 \times 0.791 (1-0.25) - 0.25]\} \times 10$

$r_m = 14.83$ m

$$\zeta = \ln(14.83/0.25);$$

$$\zeta = 4.08$$

$$\boxed{\alpha_{cp} = 1 - \frac{\ln(1.84/\ 0.25)}{4.08}}$$

$$\boxed{\alpha_{cp} = 0.512}$$

In the main formula the parameter ‘vl’ is calculated separately as,

$$vl = (2/\zeta\lambda)^{0.5} * Lp/r_o$$

Putting all known values in the above formula,

$$vl = (2/4.08*969)^{0.5} * 10/0.25$$

$$vl = 0.89$$

Putting all values in formula the main formula,

$$\frac{Pt}{G_l\, r_o\, w_t} = \frac{\dfrac{4*1}{(1-0.25)1} + \dfrac{2\pi*0.79}{4.08}\ \dfrac{\tanh(0.89)}{0.89}\ \dfrac{10}{0.25}}{1 + \dfrac{4*1}{\pi*969(1-0.25)1}\ \dfrac{\tanh(0.89)}{0.89}\ \dfrac{10}{0.25}}$$

$$\frac{Pt}{G_l\, r_o\, w_t} = 41.85$$

$$\frac{Pt}{w_t} = 41.85 * 25800 * 0.25$$

$$\frac{Pt}{w_t} = 269932.5 \text{ kN/m}$$

This means the stiffness of single pile of 0.5 diameter and 10 m length comes upto k = 269932.5 kN/m.

The settlement of single pile (S_p) is calculated as,

$$\boxed{S_p = P/k}$$

Maximum load acting on pile, P = 1335 kN.

S_p =1335/269932.5

S_p = 5.0 mm

7.2.4.2 Settlement of group of piles:

There are 64 numbers of piles; randomly the group stiffness can be calculated by summing all individual stiffness. This value comes as,

K_p(random) = 64*269932.5

K_p (random) = 17275648 kN/m

This stiffness is not used in study as the actual group behavior is far different from the group behavior of piles. Considering the influence of efficiency factor, the way in which the stiffness of pile group calculated is as follow,

$Kp = \eta_w nk$

Here n = 64, number of piles placed below the raft. Considering efficiency exponent as, e = 0.5, the efficiency factor calculated as,

$\eta_w = n^{-e}$

$\eta_w = 64^{-0.5}$

$\eta_w = 0.125$

Then the group stiffness of pile is calculated as,

K_p = 0.125 * 64 * 269932.5

K_p = 2159460 kN/m

This value is group stiffness of pile only.

The settlement of pile group (S_{pg}) is calculated as,

$S_{pg} = Pu / K_p$

Maximum load acting on pile, P = 74.88 * 23.18 * 29.28 = 50822 kN.

S_{pg} = (50822 /2159460)

S_{pg} = 23.6 mm

7.2.4 Design Assumptions:

Total number of piles = 64

Spacing between piles is calculated from area supported by every pile (i.e. Area of raft divided by Number of piles will give area shared by single pile, and arranging piles in square form the spacing is calculated).

Minimum reinforcement:
For piles 2.0 % of the sectional area.
Diameter of Pile = 0.5 m
Length of Pile = 10m
Grade of concrete for piles M 25
Grade of reinforcement Fe 415
Clear cover to any reinforcement
For piles = 50mm

7.2.5 Load Calculation

Thickness of raft assumed = 500 mm
Diameter of pile = 500mm

Total number of piles are 64 (4 piles in a group).Piles location is as per given sketch. For each pile area shared is 3.6 m x 3.6 m.

Downward Loads:
Maximum base pressure = 62.38 kN/m^2
Self weight of slab = 0.5 x 25 = 12.5 kN/m^2
Total pressure = 74.88 kN/m^2
Maximum raft span supported by each pile is 4.95m x 3.6 m
Total Downward load on each pile = 74.88 x 4.95 x 3.6 = 1335 kN

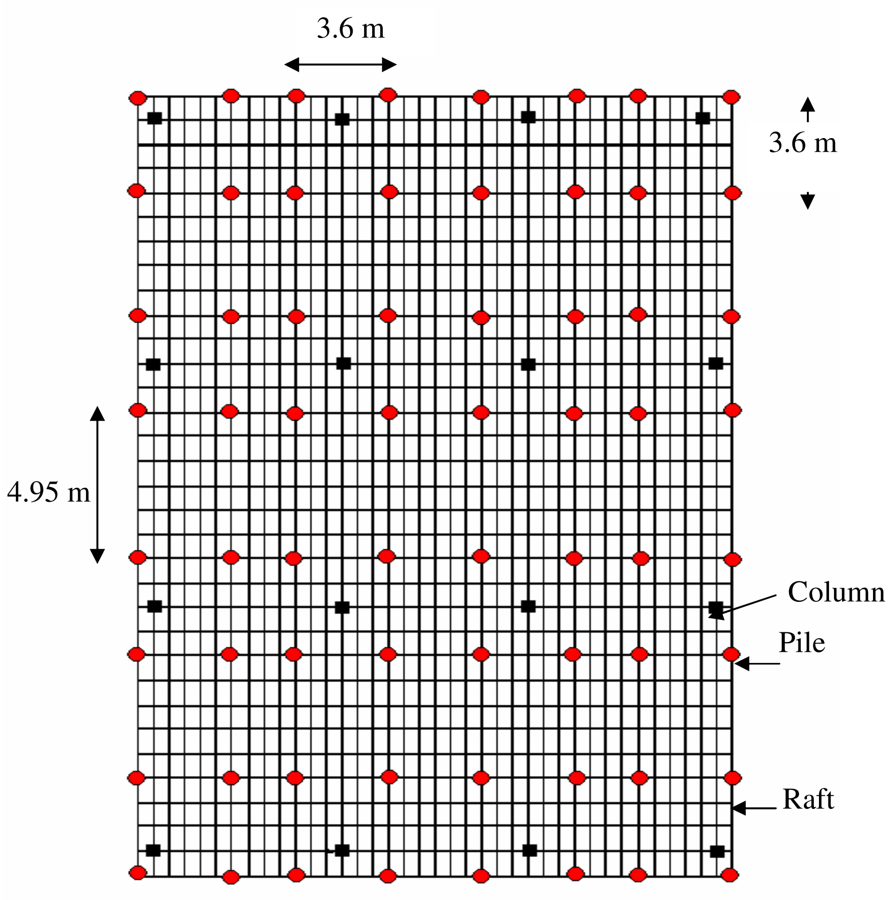


Fig 7.9 Layout of Raft with Pile location

7.2.6 Design of piles for full load capacity:

Structural design for compressive load.

Capacity in compression:

Pu = 1.05 (σcc x Ac + σsc x Asc)

Gross area of Pile:

$Ag = \pi/4 \times 500^2$

$Ag = 196250\ mm^2$

Assuming 2.0 % of steel of the gross area Ag,

Asc = 0.02 x 196250

$Asc = 3925\ mm^2$

Ac = 196250 – 3925

$Ac = 192325\ mm^2$

Pu = 1.05 (6.0 x 192325 + 190 x 3925)

$Pu = 1995 \text{ kN} > 1335 \text{ kN}$ ……………………Hence o.k.

$Asc = 3925 \text{ mm}^2$

Provide 9 numbers of 25mm bars. This means, Asc provided is 4415 mm^2

Assuming helical reinforcement of 8mmΦ,

$Ash = \pi/4 * 8^2$

$Ash = 50 \text{mm}^2$.

Diameter of core,

$Dk = (500 - 2*50 + 2*8)$

$Dk = 416 \text{ mm}$

Area of core,

$Ak = \pi/4 * 416^2 - 4415$

$Ak = 131434 \text{ mm}^2$

Using clause 39.4.1 (IS 456:200), the ratio of volume of helical reinforcement to the volume of core calculated as, 0.36* (Ag/Ak-1)fck/fy

Volume ratio for, volume of helical reinforcement to volume of core,

$Vr = 0.36 *((196250 / 131434)-1)* 25/415$

$Vr = 0.011$

The spacing among the helical reinforcement is calculated as,

$\boxed{\text{Spacing} = (\pi*Dk*Ash) / (Ak *Vr)}$

$\boxed{\text{Spacing} = (\pi*416*50) / (131434 *0.011)}$

$\boxed{\text{Spacing} = 45\text{mm}}$

Reinforcement Details for a Pile:

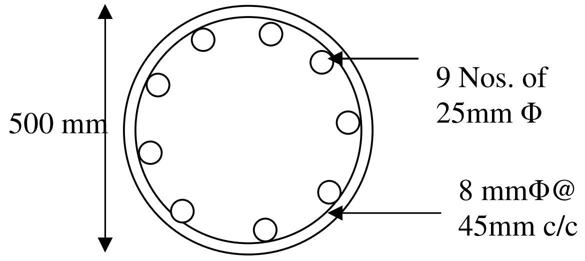


Fig 7.10 Plan of a typical pile with reinforcement

Result Summary for Pile foundation:

Table 7.5 Result summary for Pile foundation:

	Single pile (100% load)	Group of pile (100% load)
Diameter of pile (dp)	500 mm	500 mm
Length of pile (Lp)	10 m	10 m
Ast	4415 mm^2	4415 mm2
Settlement	5.0 mm	23.6 mm

7.3 Design for Piled raft in combination:

This design is different from above. In the above case raft and pile both were designed for a fixed pressure load of 74.88 kN/m^2 and with 100 % load on raft, piles taking no load and pile for 100% load and raft taking no load. While in case of Piled raft foundation it is predicted that the some part of load will be taken by raft and remaining will be taken by piles.

The same problem is solved here by considering concept of Simplified method of analysis of piled raft foundation. The raft is designed according to the percentage of total load taken by the raft.

The entire design process of a Piled raft foundation system is consist of,

1. Design of piles: Design of piles below raft (i.e. pile diameter, pile length, number and their location below raft).Here in this study the piles are checked for load carrying capacity for assumed dimensions and location. The piles are designed by Working stress method as per IS 456- 2000.
2. The design of raft: The raft is designed for the load shared by raft from total load. The raft is supported on piles and it is designed as a flat slab.

7.3.1 Load Sharing between raft and pile:

The stiffness of Piled raft foundation is calculated from formula,

$$\boxed{K_{pr} = \frac{K_p + K_r\,(1-2\alpha_{cp})}{1-\alpha^2_{cp}\,K_r\,K_p}}$$

The raft stiffness is calculated from formula,

$$\boxed{K_r = \frac{2Gr\sqrt{\text{Area of Raft}}}{I\,(1-\mu_s)}}$$

The pile stiffness is calculated from the formula given by Randolph for rigid pile.

$$\frac{P_t}{G_l r_o w_t} = \frac{\dfrac{4\eta}{(1-\mu_s)\xi} + \dfrac{2\pi\rho}{\zeta}\,\dfrac{\tanh(vl)}{vl}\,\dfrac{l}{r_o}}{1 + \dfrac{4\eta}{\pi\lambda(1-\mu_s)\xi}\,\dfrac{\tanh(vl)}{vl}\,\dfrac{l}{r_o}}$$

The parameters mentioned in the above formula as follows,

The value of shear modulus ‘Gr’, in calculation of absolute stiffness of raft is as follow,

The raft stiffness is calculated as follow,

$$K_r = \frac{2Gr}{I\,(1-\mu s)}\sqrt{\text{Area of Raft}}$$

Breadth of raft , B = 23.18 m

Length of raft, L = 29.28 m

Area of raft, Ar = B x L = 23.18 m x 29.28 m

Ar = 678.71 m^2

The influence factor for a raft of this aspect ratio is adopted 1.2 from book of K.R. Arora,

The value of Gr is taken as the value at a depth of B (1-0.5B/L). After putting value of B and L of the raft, the influence depth comes as 14 m.

The Gr value = 150x (100 + 7.2 x 14)

Gr = 30120 kN/m^2

μ_s = Poisson’s ratio of soil = 0.25

$$K_r = \frac{2\times 30120}{1.2\,(1-0.25)}\sqrt{678.71}$$

$$K_r = 1743751.4 \text{ kN/m}$$

The stiffness of pile is calculated from Randolph’s formula. This formula is based on load settlement ratio of pile head. This is main formula for pile stiffness calculation.

$$\frac{P_t}{G_l r_o w_t} = \frac{\dfrac{4\eta}{(1-\mu_s)\xi} + \dfrac{2\pi\rho}{\zeta}\,\dfrac{\tanh(vl)}{vl}\,\dfrac{l}{r_o}}{1 + \dfrac{4\eta}{\pi\lambda(1-\mu_s)\xi}\,\dfrac{\tanh(vl)}{vl}\,\dfrac{l}{r_o}}$$

Putting values of the constants ρ,ξ,λ,η for above formula, the pile stiffness is calculated in following way,

$$\frac{P_t}{G_l\, r_o\, w_t} = \frac{\dfrac{4*1}{(1-0.25)1} + \dfrac{2\pi*0.79}{4.08}\;\dfrac{\tanh(0.89)}{0.89}\;\dfrac{10}{0.25}}{1 + \dfrac{4*1}{\pi*969(1-0.25)1}\;\dfrac{\tanh(0.89)}{0.89}\;\dfrac{10}{0.25}}$$

$$\frac{P_t}{G_l\, r_o\, w_t} = 41.85$$

$$\frac{P_t}{w_t} = 41.85 * 25800 * 0.25$$

$$\frac{P_t}{w_t} = 269932.5 \text{ kN/m}$$

This means the stiffness of single pile of 0.5 diameter and 10 m length come up to
k = 269932.5 kN/m.

Then the group stiffness of pile is calculated as,
$K_p = 0.125 * 64 * 269932.5$
$K_p = 2153498.7$ kN/m

This value is group stiffness of pile only. The combined stiffness of Piled raft can be calculated as,

$$K_{pr} = \frac{K_p + K_r\,(1-2\alpha_{cp})}{1-\alpha^2_{cp}\,K_r/K_p}$$

$$K_{pr} = \frac{2153498.7 + 1743751 *(1-2*0.512)}{1-0.512^2* 1743751.4/ 2153498.7}$$

K_{pr} = 2679940.43 kN/m

This is combined group stiffness of Piled raft. The load sharing among pile and raft calculation are as follow,

Percentage of total load shared by raft is calculated as,

$$\frac{Pr}{Pr + Pp} = \frac{Kr\,(1\text{-}\alpha cp)}{Kp + Kc(1\text{-}2\alpha cp)}$$

$$\frac{Pr}{Pr + Pp} = \frac{1743751.4{*}\,(1\text{-}0.512)}{2153498.7 + 1743751.4(1\text{-}2{*}0.512)}$$

$$\frac{Pr}{Pr + Pp} = 0.40$$

This means the raft will take 40% of total load and the piles will carry 60% of total load incase of Piled raft foundation. In Piled raft piles will yield first, that means piles can be designed for reduced load capacity of 60%. In this case piles were designed for 60% of total load while raft load is designed for reduce load capacity of 40%.

That means 60 % of load is taken by pile.
Total load acting = 74.88 kN/m^2
Design load for piles = 0.6 x 74.88 = 45 kN/m^2
Design pressure load for raft = 0.4 x 74.88 = 30 kN/m^2
Total Downward load on each pile = 45 x 4.95 x 3.6 = 802 kN

7.3.2 Design check of Pile for reduced load capacity:

Structural design for compressive load:

As the pile is completely embedded in soil it will be treated as short column as per Cl. B-3 of Annex B of IS 456:2000

Capacity in compression:

Pu = 1.05 (σcc x Ac + σsc x Asc)

Gross area of Pile:

Ag = π/4 x 500^2

Ag = 196250 mm^2

Assuming 0.5% of steel of the gross area Ag,

Asc = 0.005 x 196250

Asc = 981.25 mm^2

Ac = 196250 – 981.25

Ac = 195268.75 mm^2

Pu = 1.05 (6.0 x 195268.75 + 190 x 981.25)

Pu = 1425.95 kN > 802 kN ……………………Hence o.k.

Asc = 981.25 mm^2

Provide 6 numbers of 16mm bars. This means, Asc provided is 1206 mm^2

Assuming helical reinforcement of 8mmΦ,

Ash = π/4* 8^2

Ash = 50mm^2

Diameter of core,

Dk = (500 – 2*50 + 2*8)

Dk = 416 mm

Area of core,

Ak = π/4* 416^2 – 1206

Ak = 134643 mm^2

Using clause 39.4.1 (IS 456:200), the ratio of volume of helical reinforcement to the volume of core calculated as, 0.36* (Ag/Ak-1)fck/fy

Volume ratio for, volume of helical reinforcement to volume of core,

Vr = 0.36 *((196250 / 134643)-1)* 25/415

Vr = 0.01

The spacing among the helical reinforcement is calculated as,

Spacing = (π*Dk*Ash) / (Ak *Vr)

Spacing = (π*416*50) / (134643 *0.01)

Spacing = 48mm

Reinforcement Details for a Pile:

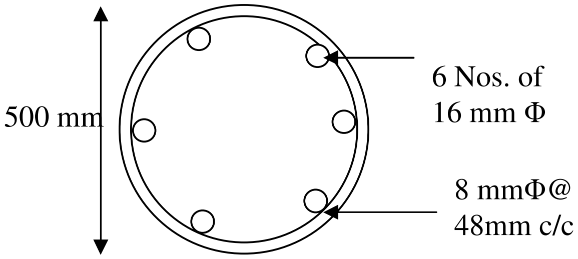


Fig 7.11 Plan of a typical pile with reinforcement

7.3.3 Design of Raft for remaining 40% load:

Grade of concrete for raft slab: M25

Grade of reinforcement : Fe 415

Clear cover: 50mm

Downward Loads:

That means 40 % of load is taken by raft.

Total load acting including self weight = 74.88 kN/m^2

Design load for piles = 0.4 x 74.88 kN/m^2 = 30 kN/m^2

Total downward pressure load due to column loads on raft is w = 62.38 kN/m^2

Clear span, l = 4.95 -0.9 x 0.5 = 4.5 m

Width of column strip =3.6 m

Width of middle strip = 3.6 m

Total moment Mo = w x 4.95 x 4.5^2 /8 = 30 x 4.95 x 4.5^2/8

= 376 kN m.

Negative bending moment = 0.65 x 376 = 244.4 kNm

Positive bending moment = 0.35 x 376 = 132 kNm

Distribution of negative bending moment:
Column strip: 0.75 x 244.4= 183.3 kNm
Middle strip: 0.25 x 244.4= 61.1 kNm

Distribution of positive bending moment:
Column strip: 0.6 x 132 = 79.2 kNm
Middle strip: 0.4 x 132 = 53 kNm

Table 7.6 Piled raft design moment

Negative Bending Moment (for top reinforcement)	Bending Moment kNm
Column strip	183.3
Middle strip	61.1
Positive Bending Moment(for bottom reinforcement)	Bending Moment kNm
Column strip	79.2
Middle strip	53

From all above moments, the maximum bending moment value is = **183.3** kNm

Check for thickness:

Assuming raft thickness as 300mm.The effective thickness will be 220mm

$$d_{\text{effective (req)}} = \sqrt{M/Q*b}$$

for M25 , Q = 1.109 (as calculated very initially of the design calculations)
Width of strip, b = 3.6m

$$d_{\text{effective (req)}} = \sqrt{183.3/1.109*3.6}$$

$d_{\text{effective}}$ = 215 mm

$d_{\text{eff.}}$ provided = 300-80 = 220mm > $d_{\text{eff.}}$ required ………Hence O.K.

Check for Punching Shear:

Maximum intensity = 0.4 x 62.38 kN/m^2 = 25 kN/m^2

d_{eff} = 220mm

Considering critical section at d/2 from face of pile for punching shear,

Plan area of periphery at which punching shear acts

$A = \pi(D + d)^2/4$

$A = \pi(0.5 +0.22)^2/4$

A = 0.41 m ^{2}

Punching shear force (Vp) = 25 x(X_2 –A)

Here X_2 is the area enclosed by pile, (X_2 = 4.95x3.6= 17.82)

Vp = 25 x (17.82 –0.41)

Vp = 435.3 kN

Shear stress τ = Vp / (π x (D + d) x d)

= 435.3 x1000/ (π x (500 + 220) x 220)

= 0.87 N/mm^2

< $0.16\sqrt{25}$ = 0.8 N/mm^2

Above calculation shows that section assumed for slab is incorrect. So adopting effective raft thickness as 420. The total depth of raft is then 500mm.

The bending moments are for full width of strip. Reinforcement calculated is also for full width of strip. Area of reinforcement is calculated from working stress method,

$$\boxed{Ast = M /(\sigma st* j *d)}$$

M is the value of moment.

σst = Stress in steel , Here it is taken as 150 N/mm^2 .

j = calculated at very first stage in design constant calculations = 0.9

d = effective depth, adopted here 420 mm.

Table 7.7 Moments and Steel with spacing in raft.

Negative Bending Moment (for top reinforcement)	Bending Moment kNm	Ast required mm^2	Bar and Spacing	Ast provided mm^2
Column strip	183.3	3233	20 mm @ 95mm c/c	3306
Middle strip	61.1	1078	20 mm @290 mm c/c	1083
Positive Bending Moment (for bottom reinforcement)				
Column strip	79.2	1397	20 mm @220mm c/c	1427
Middle strip	53	935	16 mm @ 210mm c/c	957

Total area of steel required for a strip which includes column and middle strip is summation of all Ast = 3233 + 1078 + 1397 + 935

= 6642 mm^2

Bottom Reinforcement Details:

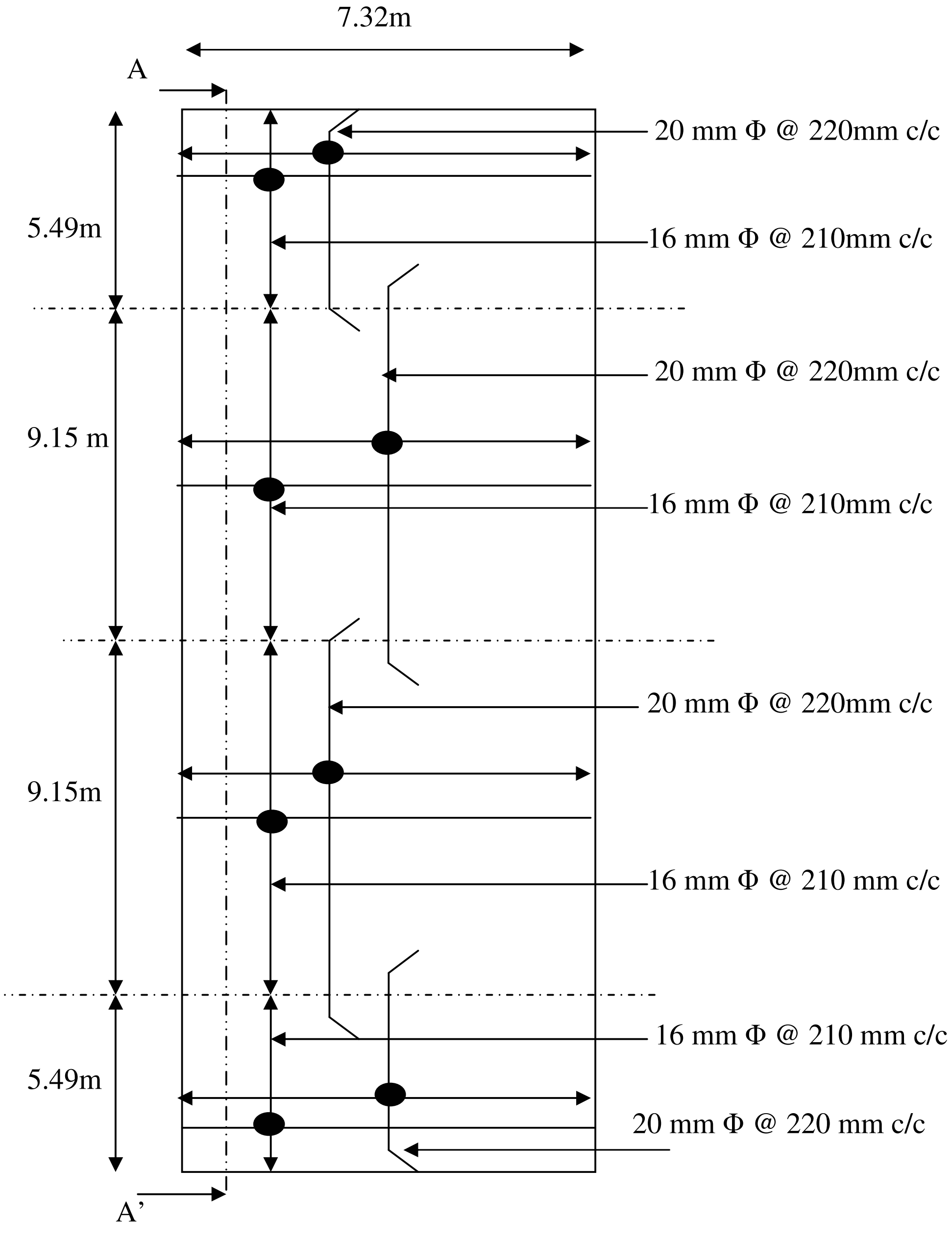


Fig 7.12 Bottom reinforcement details for the raft’s strip

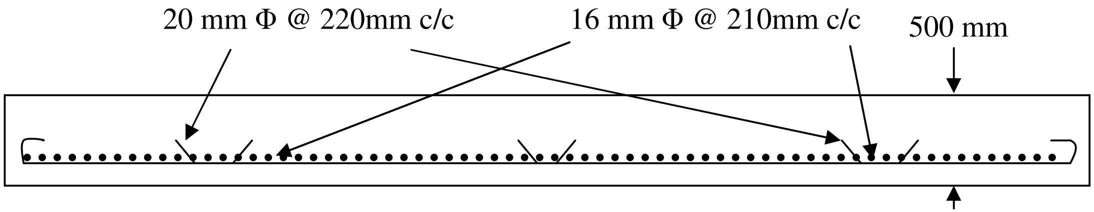


Fig 7.13 Section A-A’ for bottom reinforcement.

Top reinforcement details:

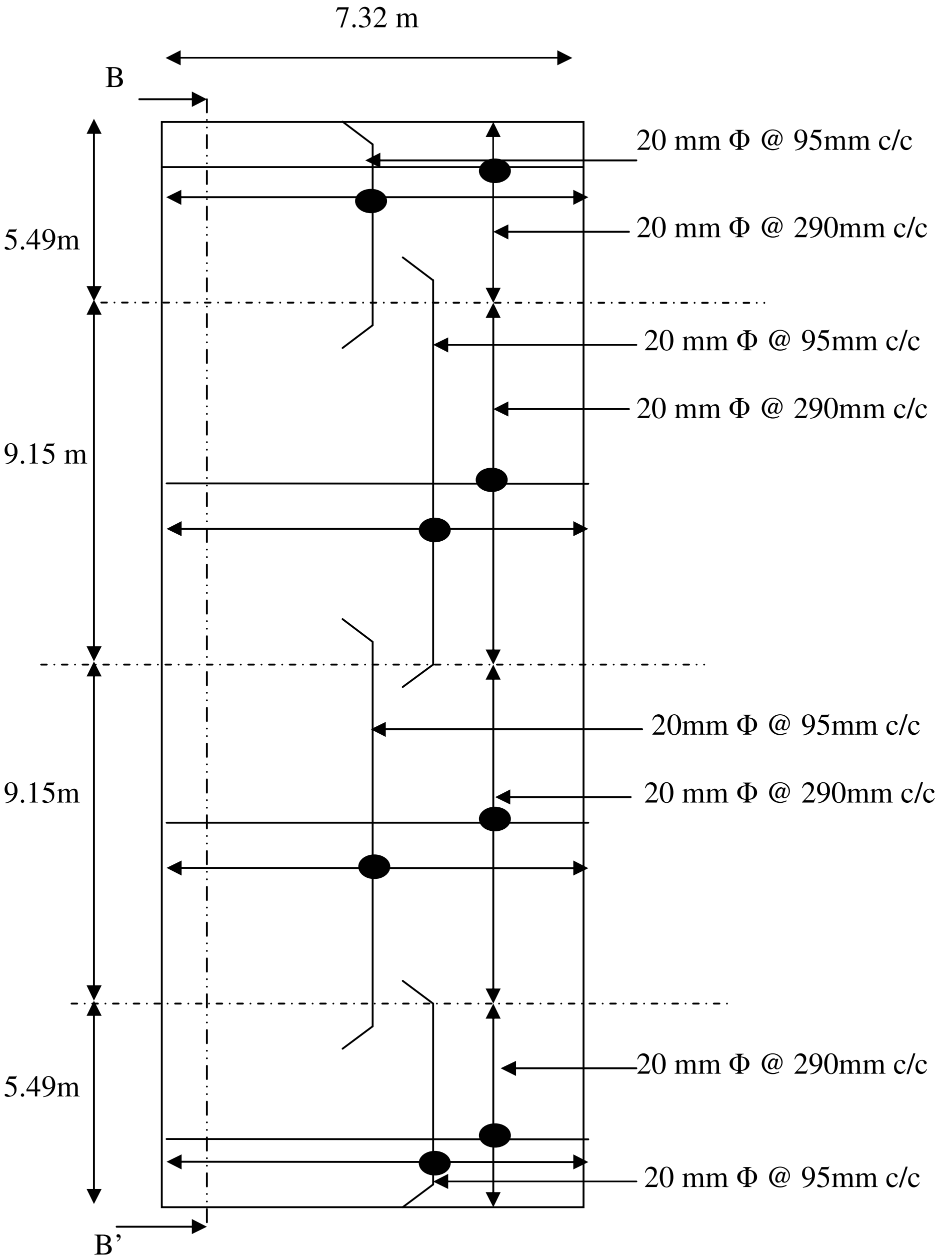


Fig 7.14 Top reinforcement details for the raft's strip

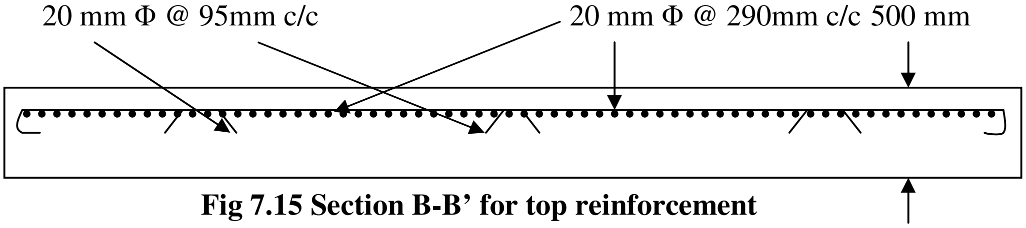


Fig 7.15 Section B-B' for top reinforcement

7.3.4 Settlement calculation for Piled raft:

Total Load on Piled raft, P_{tl} = 74.88 x Area of raft

P_{tl} =74.88 x 23.18 x 29.28

P_{tl} =50822 kN.

The stiffness of Piled raft is calculated as,

K_{pr} = 2678009.9 kN/m

The settlement of Piled raft will be,

$S_{pr} = P_{tl} / K_{pr}$

S_{pr} = 50822/ 2678009.9

S_{pr} = 19 mm

7.4 Result Summary:

The whole design includes the design of raft foundation, pile foundation and Piled raft foundation for maximum load. The result each foundation for settlement are summarized in following table.

Table 7.8 Summary of results for all foundations

Type of foundation	Thickness (mm)	Diameter (mm)	Length (m)	Area of steel ,Ast (mm^2)	Settlement (mm)
Raft only	500	---------	---------	15445	208
Pile foundation		500	10	4415	23.6
Piled raft (40% raft + 60%) foundation	500	500	10	7848	19

Though Pile foundation also reduces the settlement by much extent, they are not that much of economical as that of Piled raft foundation.

7.5 Parametric Study:

The parametric study is carried out to study the influence of variation in pile length, pile diameter and pile number on the settlement of Piled raft foundation. The type of soil is homogeneous stiff clay. The parametric study is divided in two types. In first type a computer

Excel sheet is prepared for Simplified PDR method. The variations were made in pile length, pile diameter and pile number to study settlement response only. The second one is based on approximate analysis by Staad.Pro

7.5.1 Parametric Study based on Simplified PDR method.

Case I: Variation in Pile diameter.

In the first case the variations were made in pile diameter. Numbers of piles in this case are 64. Spacing between piles is 3.6 m. The reference length of pile is adopted as 10m.Table 7.9 shows the calculated values of Piled raft stiffness and load shared among pile and raft.

Table 7.9 Stiffness of Piled raft with variation in pile diameter

Pile No.	Pile Length (L_p)	Diameter of Pile (d_p)	Raft Thickness (tr)	Raft Stiffness (K_r)	Pile Stiffness (K_p)	Piled raft Stiffness (K_{pr})	% Load by raft(X_r)
	(m)	(m)	(m)	kN/m	kN/m	kN/m	
64	10	0.5	0.5	1741057.8	2153498.7	2679940.4	40.2
		0.75	0.5	1741057.8	2765678.5	3173047.8	29.7
		1.0	0.5	1741057.8	3245061.3	3566737.9	23.5

The stiffness of pile is directly proportional to the diameter of pile. As the diameter of pile increases the stiffness of pile also increases and the stiffness of Piled raft also increases and there is increase in the load shared by pile, in Piled raft foundation for a constant raft dimensions. It indicates that the load shared by raft gets reduced with increasing the diameter of pile, making pile stiffer. The graphical figure (7.16) clears the above observations.

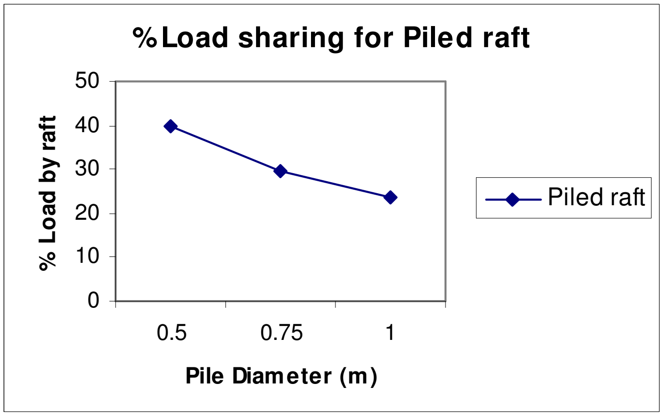


Fig 7.16 Variation of load sharing for various pile diameter

Case II: Variation in Pile length:

In this case pile length is varied by keeping pile diameter constant. The reference diameter considered is 0.5m.The pile diameter and raft thickness both were 0.5m.Number of piles were same as that of previous case i.e. 64. In table 7.10 calculated stiffness of Piled raft is enlisted with percentage of load sharing between raft and pile.

Table 7.10 Stiffness of Piled raft with variation in pile length

Pile No.	Pile Length (L_p)	Diameter of Pile (d_p)	Raft Thickness (t_r)	Raft Stiffness (K_r)	Pile Stiffness (K_p)	Piled raft Stiffness (K_{pr})	% Load by raft(X_r)
	(m)	(m)	(m)	kN/m	kN/m	kN/m	
64	10	0.5	0.5	1741057.8	2153498.7	2679940.4	40.2
	20	0.5	0.5	1741057.8	2797794.6	3173047.8	29.4
	30	0.5	0.5	1741057.8	2995238.7	3345778.9	26.3

The influence of length variation is of same nature as that of pile diameter. As the length increases pile stiffness is increases and so Piled raft stiffness also increases. The percentage of total load taken by raft decreases as the pile length increases, and load taken by pile increases. (Fig. 7.17).

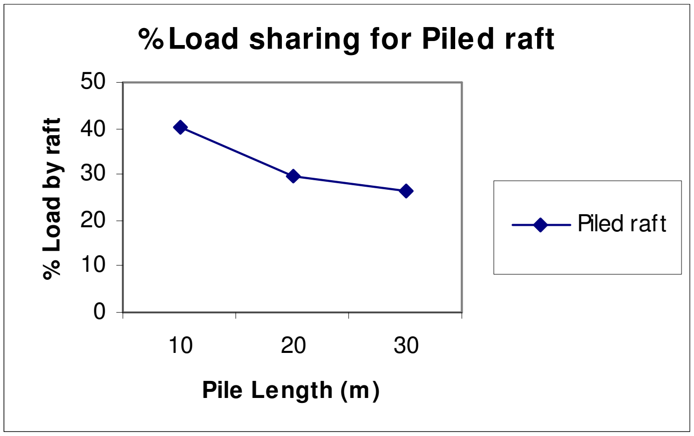


Fig 7.17 Variation of load sharing for various pile length.

Case III Variation in Pile Number:

The number of piles required to get desired adoptable settlement is main objective of concern. Here the pile numbers are decreased from 64 to 16. There are 16 numbers of column in the raft. In case of 64 piles the piles are distributed as, 4 below each column. In case of 48 piles, 3 below each column while each pile below each column in case of 16 numbers of piles. The diameter of pile and raft thickness is kept constant. The calculated values of stiffness of Piled raft are shown in Table 7.11

Table 7.11 Stiffness of Piled raft with variation in pile number

Pile No.	Pile Length (L_p)	Diameter of Pile (d_p)	Raft Thickness (t_r)	Raft Stiffness (K_r)	Pile Stiffness (K_p)	Piled raft Stiffness (K_{pr})	% Load by raft(X_r)
	(m)	(m)	(m)	kN/m	kN/m	kN/m	
64	10	0.5	0.5	1741057.8	2153498.7	2679940.4	40.2
48	10	0.5	0.5	1741057.8	1864984.6	2470347.5	46.0
16	10	0.5	0.5	1741057.8	1076749.3	2006341.3	70.4

Though the numbers of piles are 64 the raft is efficient to take 40.2% load. It is obvious as the number of piles get reduced more load has to bear by raft. Raft has to take 70% of total load when single pile is placed below each column.

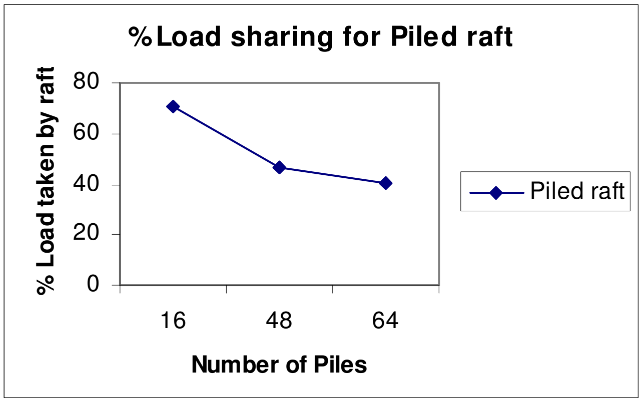


Fig 7.18 Variation of load sharing for pile number.

7.5.2 Settlement of Piled raft:

Settlement of Piled raft is calculated from the simple formula,

$$\delta = P/k.$$

Here P stands for total load acting and k for stiffness of the Piled raft. As the load coming on the system is known and the stiffness too. The piles will yield first and settlement of piles is calculated from the load taken by piles. Then raft will yield at the load value shared by raft. After the complete yield in both raft and pile, the Piled raft will settle at constant amount under the influence of total load.Table7.12 shows calculated values for stiffness of Piled raft and the settlement caused.

Table 7.12 Settlement of Piled raft foundation with % of load sharing.

Pile No.	**% Load by raft (X_r)**	**Load taken by raft (Pr)**	**Load taken by Pile (Pp)**	**Stiffness of raft 'K_r'** (kN/m)	**Stiffness Of Pile group 'K_p'** (kN/m)	**Stiffness of Piled raft 'K_{pr}'** (kN/m)	**Pile settlement S_{p1}** (mm)	**Raft Settlement S_{pu}** (mm)	**Piled raft Settlement S_{pr}** (mm)
16	70.4	27174	11426	1741058	1076749.3	2006341	4.05	15.61	19.24
48	46.8	18065	20535	1741058	1522753.6	2470374.5	6.29	10.38	15.63
64	40.2	15517	23083	1741058	2153499	2679940	0.97	8.91	14.40

Above results are plotted in graphical format to get clear idea about settlement variation in three cases of Piled raft foundation. In above table Pr is percentage of load taken by raft this means the load taken after complete yielding of pile while Pp is load taken by piles.S_{p1} is value of the settlement of pile foundation, S_{pu} is settlement of raft foundation and S_{pr} is settlement of Piled raft foundation. The following graph shows the pattern of settlement of Piled raft foundation. The settlement is total settlement at the center of raft. Final settlement in the figure is the cumulative settlement of both pile and raft system in Piled raft foundation.

Fig 7.19, 7.20 and 7.21 shows the variation in settlement of Piled raft foundation with different pile combinations for unique thick raft.

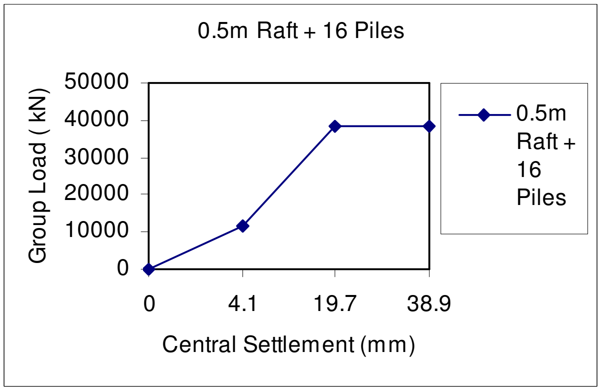


Fig 7.19 Variation of load sharing for various pile numbers.

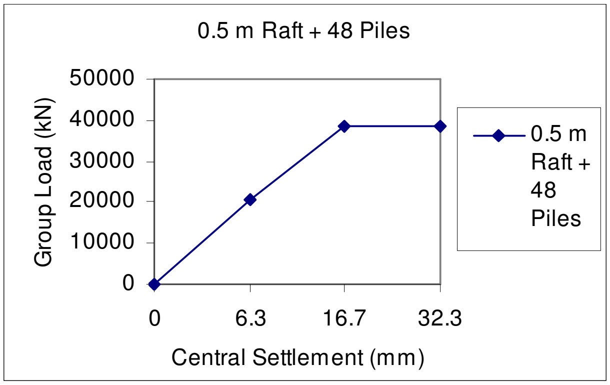


Fig 7.20 Variation of load sharing for various pile numbers.

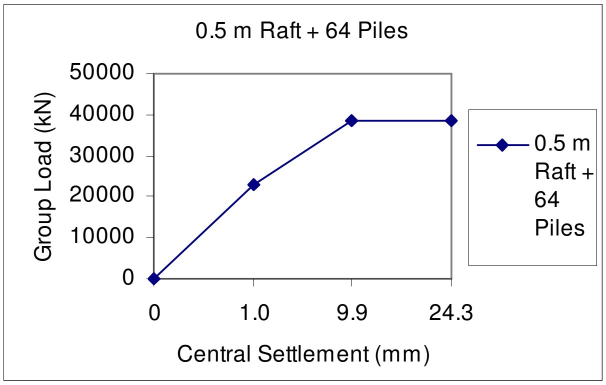


Fig 7.21 Variation of load sharing for various pile numbers.

The above graph indicates that:

With increase in number of piles, with constant raft stiffness

1. Load taken by pile is more compared to the load taken by raft.
2. Stiffness of Piled raft foundation increases and the settlement of Piled raft foundation decrease.
3. Piled raft emerge as economic type of foundation compared with only raft or only pile foundation.

Chapter 8

Analysis and design of Piled raft by using Staad. Pro

8.1 General

The analysis and design of Piled raft foundation, which is based on approximate analysis using Staad .Pro is explained in this chapter. The way in which Staad.Pro used is explained in the chapter 4 of raft foundation analysis. The only addition over and above chapter 4 content is of the assigning of pile support. The stiffness of soil is calculated from the formula given by Bowle's, while the stiffness of pile is calculated from the formula given by Randolph. The input file and out put file that are generated in the software is mentioned here in this chapter. The complete input and output file is not possible to attach because of their volume. A single strip is considered for response, out of total raft and for this single strip input and out put file is given.

The input file generated in the software is as given below. The results from out put files are also mentioned wherever they required. The input file includes all steps of analysis and design of Piled raft foundation.

Keeping a specific task for response of Piled raft foundation, the input file is generated. Following are the tasks of the analysis and design:

1. Settlement of node.
2. Moment in each plate.
3. Area of top and bottom reinforcement.

The sequence of input to generate file in Staad Pro is mentioned below,

1. Node generation.
2. Element indices
3. Element property
4. Define material
5. Support generation
6. Load generation
7. Analysis of Piled raft foundation
8. Design of Piled raft foundation

8.2 Staad's input file for Piled raft foundation.

The input file that generates in Staad.Pro is having following format

```
STAAD SPACE
START JOB INFORMATION
ENGINEER DATE 06-Dec-04
END JOB INFORMATION
INPUT WIDTH 79
UNIT METER KN
```

8.2.1 Node generation.

First define the plane in which geometry is to be created. For each node the location is specified with respect to global X,Y and Z axis. As shown in fig 8.1 the joint co-ordinate of the node 1 are 0 0 0 with respect to all axis. This means this is origin point of geometry.

While in case of node 16 the co-ordinates are 0 0.915 0.

JOINT COORDINATES

```
1 0 0 0; 2 23.18 0 0; 3 23.18 0 29.28; 4 0 0 29.28;
```

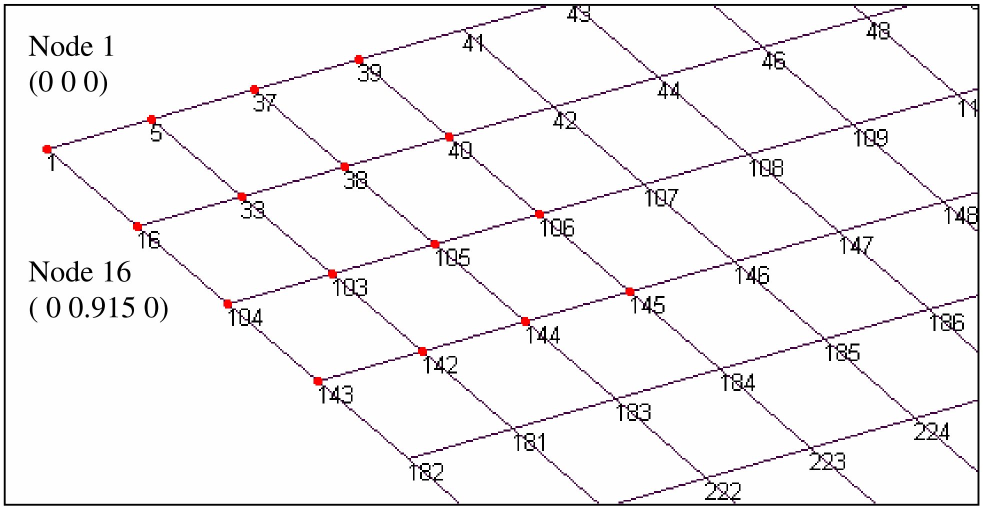


Fig 8.1 Typical sketch of Joint co- ordinates for nodes

8.2.2 Element generation

The connecting nodes to create a plate/shell element are get specified first.

The first number represents plate number while other four numbers are the nodes forming the element. In fig 8.2 , the 62 number plate is connected by four node viz. 1,16,33 and 5.

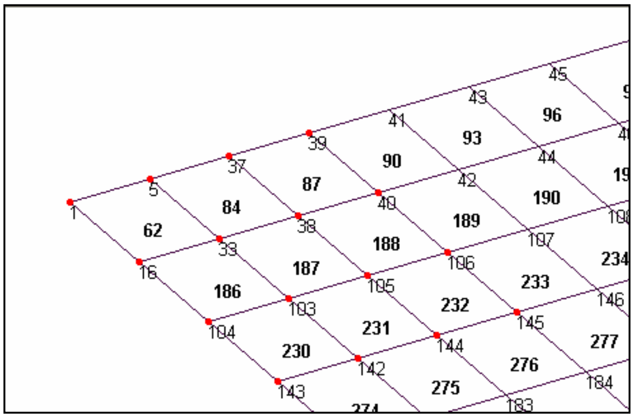


Fig 8.2 Typical sketch of element geometry

ELEMENT INCIDENCES SHELL

115 57 6 34 58; 118 6 59 60 34; 199 58 34 116 115; 200 34 60 117 116; 243 115 116 155 154; 287 154 155 194 193; 331 193 194 233 232; 375 232 233 272 271; 419 271 272 311 310; 463 310 311 350 349; 507 349 350 389 388; 551 388 389 428 427; 603 427 428 30 464; 666 464 30 500 499; 710 499 500 539 538; 754 538 539 578 577; 798 577 578 617 616; 842 616 617 656 655; 886 655 656 695 694; 930 694 695 734 733; 974 733 734 773 772; 1018 772 773 812 811; 1072 812 813 849 26; 1133 848 26 884 883; 1177 883 884 923 922; 1221 922 923 962 961;1265 961 962 1001 1000; 1353 1039 1040 1079 1078; 1397 1078 1079 1118 1117; 1441 1117 1118 1157 1156; 1485 1156 1157 1196 1195; 1537 1195 1196 22 1232; 1607 1232 22 11 1265;

8.2.3 Element property

ELEMENT PROPERTY

57 TO1653 THICKNESS 0.5

8.2.4 Element material property

DEFINE MATERIAL START

ISOTROPIC CONCRETE

E 2.5e+007

POISSON 0.17

DENSITY 25

ALPHA 5.5e-006

DAMP 0.05

END DEFINE MATERIAL

CONSTANTS

MATERIAL CONCRETE MEMB

57 TO1653

8.2.5 Support generation:

SUPPORTS

* The software is having plate on elastic foundation option. That tool is used here. There are two types of support first is soil support, assigned as number 2 while another is pile support assigned as number 3. Fig 8.3 shows the support differentiation at the nodes. Below node 1 pile is placed, because of that it is assigned by number 3 (piled support 3) while 5 and 16 placed on soil support and assigned as 2 (soil support 2).

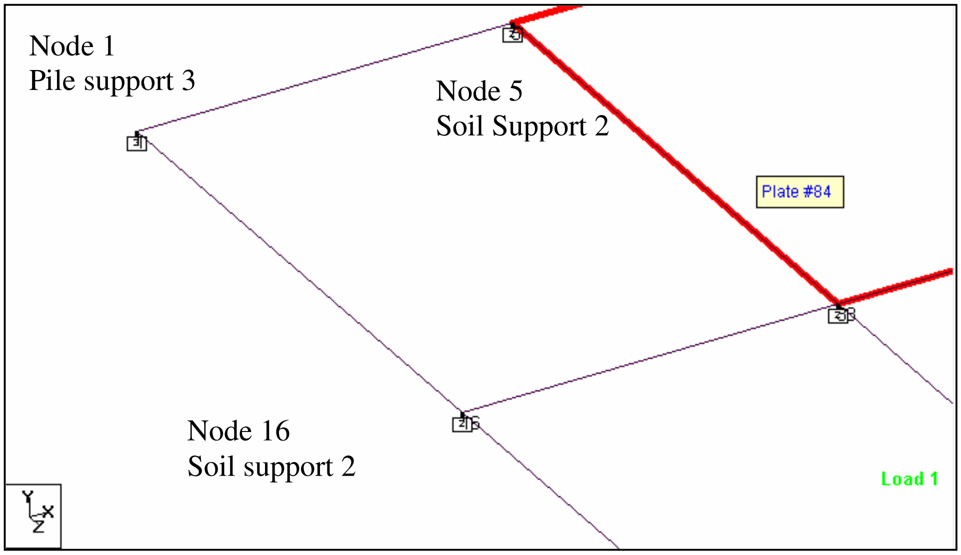


Fig 8.3 Support identification at different nodes.

SOIL SUPPORT

5 TO 44 46 TO 52 54 TO 62 64 TO 74 76 TO 84 86 TO 92 94 TO 181 183 TO 186 -

188 TO 190 192 TO 196 198 TO 202 204 TO 208 210 TO 212 214 TO 218 -

220 TO 376 378 TO 381 383 TO 385 387 TO 391 393 TO 397 399 TO 403 -

405 TO 407 409 TO 413 415 TO 526 528 TO 531 533 TO 535 537 TO 541 -

543 TO 547 549 TO 553 555 TO 557 559 TO 563 565 TO 760 762 TO 765 -

767 TO 769 771 TO 775 777 TO 781 783 TO 787 789 TO 791 793 TO 797 -

799 TO 910 912 TO 915 917 TO 919 921 TO 925 927 TO 931 933 TO 937 -

939 TO 941 943 TO 947 949 TO 1105 1107 TO 1110 1112 TO 1115 1117 TO 1120 -

```
1122 TO 1126 1128 TO 1132 1134 TO 1136 1138 TO 1142 1144 TO 1258 -
1260 TO 1262 1264 TO 1267 1269 TO 1273 1275 TO 1278 1280 TO 1282 -
1284 TO 1287 ELASTIC MAT DIRECT Y SUBGRADE 10000
```

PILE SUPPORT

The stiffness of pile is calculated assuming it as a rigid one. Using Randolph's formula for the stiffness of rigid pile. The stiffness of a single pile of 0.5m diameter and 10m length came as 269187 kN/m. That stiffness value is assigned to the generated support in Staad.Pro

```
1 TO 4 45 53 63 75 85 93 182 187 191 197 203 209 213 219 377 382 386 392 398 -
404 408 414 527 532 536 542 548 554 558 564 761 766 770 776 782 788 792 798 -
911 916 920 926 932 938 942 948 1106 1111 1116 1121 1127 1133 1137 1143 1259 -
1263 1268 1274 1279 1283 FIXED BUT FX FZ MX MY MZ KFY 269187

SLAVE FX FZ MX MY MZ MASTER 34  JOINT 53 63 191 197
SLAVE FX FZ MX MY MZ MASTER 30  JOINT 386 392 536 542
SLAVE FX FZ MX MY MZ MASTER 26 JOINT  770 776 920 926
SLAVE FX FZ MX MY MZ MASTER 22 JOINT  1111 1116 1263 1268
```

8.2.6 Load generation:

LOAD GENERATION

```
LOAD 1 CL
JOINT LOAD
21 FY -712
22 25 34 35 FY -1335
24 FY -801
26 FY -2492
27 FY -2892.5
28 29 32 FY -1424
33 36 FY -845.5
30 FY -2848
31 FY -3293
23 FY -1379.5
LOAD 2 SW
```

```
SELFWEIGHT Y -1
LOAD COMB 3 CL+SW
1 1.0 2 1.0
```

* The created geometry with loads is as shown in fig.8.4

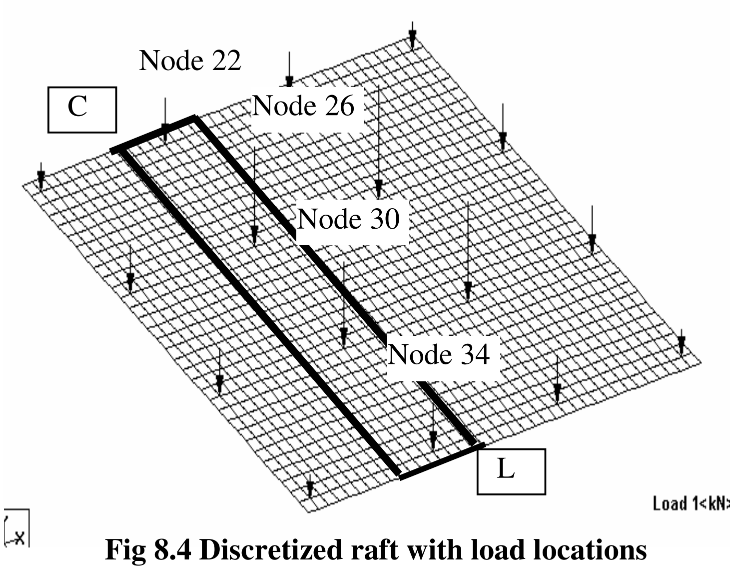


Fig 8.4 Discretized raft with load locations

8.2.7 Analysis of Piled raft foundation

PERFORM ANALYSIS

```
LOAD LIST 3
PRINT ANALYSIS RESULTS
```

8.2.8 Design of Piled raft foundation:

START CONCRETE DESIGN

```
CODE INDIAN
FYMAIN 415000 MEMB 57 TO1653
DESIGN ELEMENT ALL
```

8.3 View out put file:

The out put file contains all the required result of analysis for Piled raft foundation. In very first stage it displays joint displacements of all nodes. A typical out put shown by Staad.Pro is shown on next page.

JOINT DISPLACEMENT

PROBLEM STATISTICS

```
NUMBER OF JOINTS/MEMBER+ELEMENTS/SUPPORTS = 1287/ 1216/ 1287
```

Above line describe numerical features of nodes and elements. There are 1287 joints and support. The numbers of elements are 1216.

```
ORIGINAL/FINAL BAND-WIDTH=  1278/    54/    330 DOF
TOTAL PRIMARY LOAD CASES =    2, TOTAL DEGREES OF FREEDOM =   7722
SIZE OF STIFFNESS MATRIX =    2549 DOUBLE  KILO-WORDS
REQRD/AVAIL. DISK SPACE  =    45.9/ 18547.6 MB,  EXMEM = 1446.0 MB
```

This completes the analysis of Piled raft foundation using Staad.Pro.

```
JOINT DISPLACEMENT (CM   RADIANS)    STRUCTURE TYPE = SPACE

JOINT  LOAD   X-TRANS   Y-TRANS   Z-TRANS   X-ROTAN   Y-ROTAN   Z-ROTAN


   1    3    0.0000   -0.0231    0.0000    0.0001    0.0000   -0.0006
   2    3    0.0000   -0.0248    0.0000    0.0001    0.0000    0.0006
   3    3    0.0000   -0.1431    0.0000   -0.0009    0.0000    0.0004
   4    3    0.0000   -0.1278    0.0000   -0.0008    0.0000   -0.0004
   5    3    0.0000   -0.0608    0.0000   -0.0001    0.0000   -0.0006
   6    3    0.0000   -0.3022    0.0000   -0.0002    0.0000    0.0000
   7    3    0.0000   -0.3014    0.0000   -0.0002    0.0000    0.0000
   8    3    0.0000   -0.0624    0.0000   -0.0001    0.0000    0.0006
   9    3    0.0000   -0.1747    0.0000   -0.0004    0.0000    0.0001
  10    3    0.0000   -0.3090    0.0000    0.0002    0.0000    0.0000
  11    3    0.0000   -0.2975    0.0000    0.0002    0.0000    0.0000
  12    3    0.0000   -0.1568    0.0000   -0.0004    0.0000   -0.0001
  13    3    0.0000   -0.1927    0.0000   -0.0001    0.0000    0.0001
  14    3    0.0000   -0.3529    0.0000    0.0000    0.0000    0.0006
  15    3    0.0000   -0.3756    0.0000    0.0000    0.0000    0.0006
  16    3    0.0000   -0.0059    0.0000    0.0000    0.0000   -0.0010
  17    3    0.0000   -0.0086    0.0000    0.0000    0.0000    0.0010
  18    3    0.0000   -0.3728    0.0000    0.0000    0.0000   -0.0006
  19    3    0.0000   -0.3732    0.0000    0.0000    0.0000   -0.0006
```

```
    20   3    0.0000  -0.2148   0.0000  -0.0001   0.0000  -0.0002
    21   3    0.0000  -0.1881   0.0000  -0.0001   0.0000   0.0002
    22   3    0.0000  -0.2882   0.0000   0.0004   0.0000   0.0000
    23   3    0.0000  -0.3010   0.0000   0.0004   0.0000   0.0000
    24   3    0.0000  -0.2088   0.0000  -0.0001   0.0000  -0.0002
    25   3    0.0000  -0.3265   0.0000   0.0000   0.0000   0.0007
    26   3    0.0000  -0.4192   0.0000   0.0000   0.0000  -0.0001
    27   3    0.0000  -0.4827   0.0000   0.0000   0.0000   0.0001
    28   3    0.0000  -0.3450   0.0000   0.0000   0.0000  -0.0007
    29   3    0.0000  -0.3476   0.0000   0.0000   0.0000   0.0007
    30   3    0.0000  -0.4759   0.0000   0.0000   0.0000  -0.0001
    31   3    0.0000  -0.5465   0.0000   0.0000   0.0000   0.0001
    32   3    0.0000  -0.3453   0.0000   0.0000   0.0000  -0.0007
    33   3    0.0000  -0.0668   0.0000   0.0000   0.0000  -0.0005
    34   3    0.0000  -0.2943   0.0000  -0.0003   0.0000   0.0000
    35   3    0.0000  -0.2937   0.0000  -0.0003   0.0000   0.0000
    36   3    0.0000  -0.0686   0.0000   0.0000   0.0000   0.0005
    37   3    0.0000  -0.0867   0.0000   0.0000   0.0000  -0.0002
    38   3    0.0000  -0.0807   0.0000  -0.0001   0.0000  -0.0002
    39   3    0.0000  -0.0899   0.0000  -0.0001   0.0000   0.0000
    40   3    0.0000  -0.0839   0.0000  -0.0001   0.0000   0.0000
    41   3    0.0000  -0.0807   0.0000   0.0000   0.0000   0.0002
    42   3    0.0000  -0.0792   0.0000   0.0000   0.0000   0.0001
    43   3    0.0000  -0.0673   0.0000   0.0001   0.0000   0.0002
    44   3    0.0000  -0.0731   0.0000   0.0000   0.0000   0.0001
    45   3    0.0000  -0.0561   0.0000   0.0002   0.0000   0.0000
    46   3    0.0000  -0.0717   0.0000   0.0001   0.0000   0.0000
    47   3    0.0000  -0.0657   0.0000   0.0002   0.0000  -0.0002
    48   3    0.0000  -0.0785   0.0000   0.0001   0.0000  -0.0002
--------------------------------< PAGE 17 Ends Here >---------------------------
   STAAD SPACE                                   -- PAGE NO.   18
```

To study the effectiveness of Piled raft foundation only few locations are decided, as it will be very lengthy to consider for each node or plate. For visualization of response only one strip of raft ‘C-L’ is considered. The parametric study is carried out for this strip at two different nodes, Node 22 and Node 26 as shown in fig.8.4. In table 8.1 joint displacements including rotation in all directions are shown for nodes 22, 26, 30, and 34.

Table 8.1 Specific node displacement for considered strip C-L

Node	LOAD	X-T	Y-T	Z-T	X-R	Y-R	Z-R
	(kN)	(cm)	(cm)	(cm)	(rad)	(rad)	(rad)
22	3	0.0000	-0.2882	0.0000	0.0004	0.0000	0.0000
26	3	0.0000	-0.4192	0.0000	0.0000	0.0000	-0.0001
30	3	0.0000	-0.4759	0.0000	0.0000	0.0000	-0.0001
34	3	0.0000	-0.2943	0.0000	-0.0003	0.0000	0.0000

After analysis of Piled raft, the design command will execute. The design out put file contains positive as well as negative bending moment for each plate. Then the reinforcement is calculated for respective positive and negative moment value.

Moment and reinforcement:

In the following table, moments in X and Y directions are mentioned along with the area of steel required for the raft for particular plate. All the results that obtained are for the maximum load that means the load case 3.

```
 ELEMENT DESIGN SUMMARY


   ELEMENT    LONG. REINF      MOM-X /LOAD    TRANS. REINF      MOM-Y /LOAD
           (SQ.MM/ME)     (KN-M/M)        (SQ.MM/ME)      (KN-M/M)


     57 TOP :      576.        96.27 /    3        886.        149.57 /    3
       BOTT:      576.         0.00 /    0        576.          0.00 /    0


     61 TOP :      634.       107.86 /    3        996.        167.56 /    3
       BOTT:      576.         0.00 /    0        576.          0.00 /    0
```

```
 62 TOP :    622.     105.80 /   3      576.      21.97 /   3
    BOTT:    576.       0.00 /   0      576.       0.00 /   0

 66 TOP :    623.     105.89 /   3      576.      24.00 /   3
    BOTT:    576.       0.00 /   0      576.       0.00 /   0

 84 TOP :    993.     166.98 /   3      576.      26.33 /   3
    BOTT:    576.       0.00 /   0      576.       0.00 /   0

 87 TOP :    576.      96.86 /   3      576.      24.77 /   3
    BOTT:    576.       0.00 /   0      576.       0.00 /   0

 90 TOP :    576.      43.49 /   3      576.      12.21 /   3
    BOTT:    576.       0.00 /   0      576.       0.00 /   0

 93 TOP :    576.       0.00 /   0      576.      10.52 /   3
    BOTT:    576.      -3.55 /   3      576.       0.00 /   0

 96 TOP :    576.       0.00 /   0      576.      23.04 /   3
    BOTT:    576.     -55.06 /   3      576.       0.00 /   0

 99 TOP :    576.       0.00 /   0      576.      23.56 /   3
    BOTT:    576.     -75.64 /   3      576.       0.00 /   0

102 TOP :    576.       0.00 /   0      576.      12.51 /   3
    BOTT:    576.     -67.86 /   3      576.       0.00 /   0

105 TOP :    576.       0.00 /   0      576.      17.60 /   3
    BOTT:    576.     -74.44 /   3      576.       0.00 /   0

108 TOP :    576.       0.00 /   0      576.      57.80 /   3
    BOTT:    592.    -100.77 /   3      576.       0.00 /   0
```

```
111 TOP :     576.       0.00 /    0       576.       67.45 /    3
  BOTT:     576.     -40.07 /    3       576.        0.00 /    0


114 TOP :     706.     119.81 /    3       576.       58.92 /    3
  BOTT:     576.       0.00 /    0       576.        0.00 /    0


115 TOP :    1820.     298.70 /    3       576.       93.76 /    3
  BOTT:     576.       0.00 /    0       576.        0.00 /    0
```

The following table is generated in the software and presented as it is. The reinforcement location and the values of required reinforcement comes first then the moments. The moments values arrived are for the specific plate only. Table 8.2 shows the moment values of plates in considering strip CL

Table: 8.2 Moments and reinforcement for Plates.

Plate No.	Reinforcement Location	Ast (mm^2)	Mx (kNm/m)	Load case	Ast (mm^2)	My (kNm/m)	Load case
115	TOP :	1820.	298.70	3	576.	93.76 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
118	TOP :	1802.	295.80	3	576.	93.79 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
199	TOP :	1402.	233.04	3	750.	127.15 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
200	TOP :	1386.	230.36	3	751.	127.19 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
243	TOP :	732.	124.16	3	576.	5.26 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
287	TOP :	576.	65.87	3	576.	0.00 /	0

	BOTT:	576.	0.00	0	576.	-50.22 /	3
331	TOP :	576.	39.26	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-71.24 /	3
375	TOP :	576.	26.92	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-71.78 /	3
419	TOP :	576.	31.26	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-71.61 /	3
463	TOP :	576.	58.89	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-75.28 /	3
507	TOP :	667.	113.34	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-60.48 /	3
551	TOP :	1317.	219.42	3	576.	44.58 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
603	TOP :	2387.	384.85	3	2169.	352.05 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
666	TOP :	2387.	384.89	3	2155.	349.98 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
710	TOP :	1318.	219.60	3	576.	38.69 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
754	TOP :	670.	113.82	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-69.07 /	3
798	TOP :	576.	60.03	3	576.	0.00 /	0

	BOTT:	576.	0.00	0	576.	-85.10 /	3
842	TOP :	576.	33.86	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-81.19 /	3
886	TOP :	576.	32.06	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-79.54 /	3
930	TOP :	576.	53.48	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-80.65 /	3
974	TOP :	587.	99.94	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-64.95 /	3
1018	TOP :	1148.	192.16	3	576.	31.08 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
1072	TOP :	2046.	333.47	3	1867.	305.88 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
1133	TOP :	2065.	336.35	3	1881.	308.08 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
1177	TOP :	1143.	191.48	3	576.	39.22 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
1221	TOP :	577.	98.27	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-52.87 /	3
1265	TOP :	576.	49.69	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-66.27 /	3
1309	TOP :	576.	23.54	3	576.	0.00 /	0

	BOTT:	576.	0.00	0	576.	-64.47 /	3
1353	TOP :	576.	17.00	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-67.24 /	3
1397	TOP :	576.	26.62	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-77.21 /	3
1441	TOP :	576.	53.15	3	576.	0.00 /	0
	BOTT:	576.	0.00	0	576.	-57.49 /	3
1485	TOP :	673.	114.38	3	576.	5.89 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
1537	TOP :	1363.	226.77	3	754.	127.80 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0
1607	TOP :	1792.	294.36	3	576.	94.10 /	3
	BOTT:	576.	0.00	0	576.	0.00 /	0

```
END CONCRETE DESIGN
FINISH
END OF ELEMENT DESIGN***************************
 869. END CONCRETE DESIGN
 870. FINISH
```

After completing analysis and design of Piled raft foundation, a graph for maximum moment is plotted. The same strip ‘C-L’ is considered. The moment variation in the plates in that strip is observed. It is obvious that the maximum moment would be in Y direction because of the maximum span in that direction. This graph is compared with only raft type of foundation. The graph gives clear indication of reduction in both positive as well as negative bending moment in case of Piled raft foundation. The variation in the moments for the strip in Y direction is as shown in fig 8.5

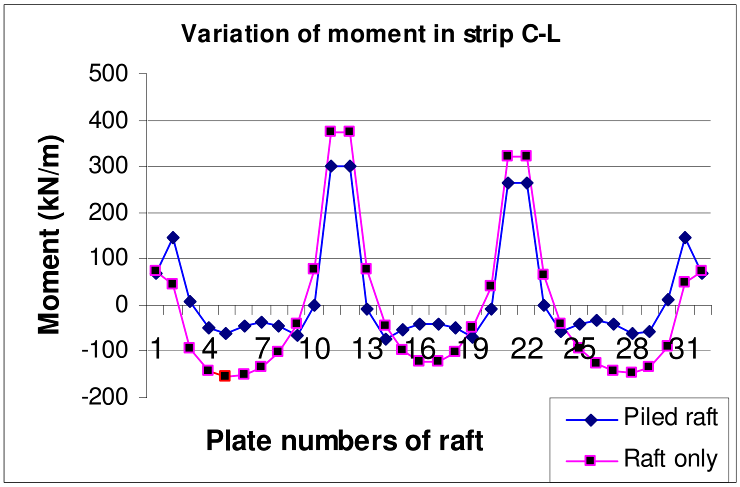


Fig 8.5 Variation in moments for raft and Piled raft

8.4 Parametric Study:

This is a study which is related to the particular Piled raft foundation. In this case the soil is assumed to be homogeneous and not modeled. A spring of stiffness matching with the soil properties is placed at each supported end of the plate. The response for the influence of pile is studied. The pile of particular stiffness is placed below the specific node. The node is that node where the pile is actually going to placed. In the parametric analysis, influences of following parameters on settlement of Piled raft foundation are studied.

1) Raft thickness
2) Pile diameter
3) Pile length
4) Pile number

1. **Raft Thickness**: - The first variation was made with raft thickness. The raft thickness varied from 0.5 m., 0.75m, 1 m. and 1.5 m. The variation is considered for nodes viz. Node 22 and Node 26 of similar fashion. The settlement of raft is mainly influenced by two criteria, first is stiffness of the raft while other is increase in dead weight of raft. The settlement response is linearly increases from the raft thickness of 0.75m. (Fig. 8.6 and Fig 8.7)

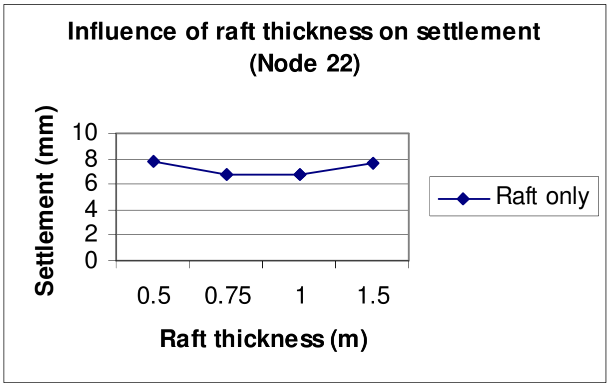


Fig 8.6 Influence of raft thickness on settlement

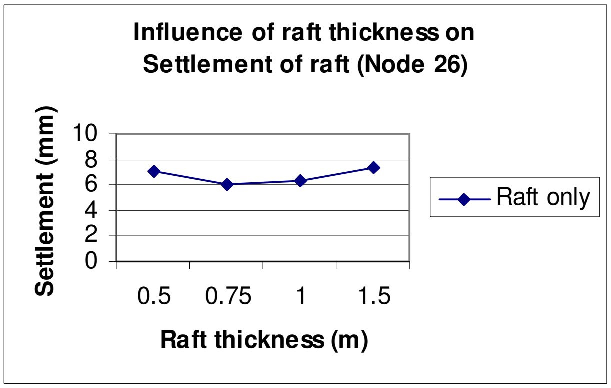


Fig 8.7 Influence of raft thickness on settlement

2) Pile Diameter: - The diameter of piles is varied from 0.5 m to 0.75 m and 1.0 m. Pile with 0.5 m. diameter is considered as reference pile. Type of pile considered in this case is end bearing. The stiffness of such pile is directly proportional to the area i.e. diameter of pile. As the diameter of pile increases naturally the stiffness of pile also increases and that cause decrease in settlement of raft. (Fig. 8.8 and Fig 8.9)

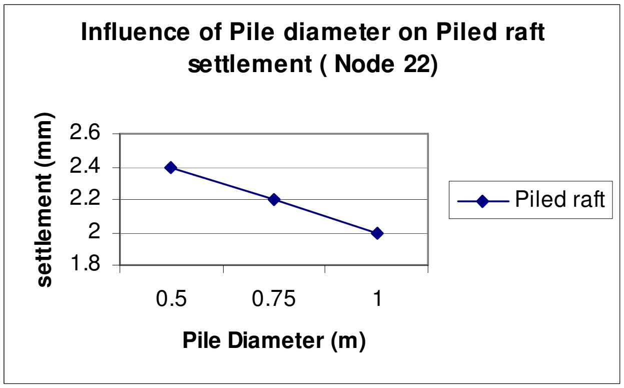


Fig 8.8 Influence of pile diameter on Piled raft settlement

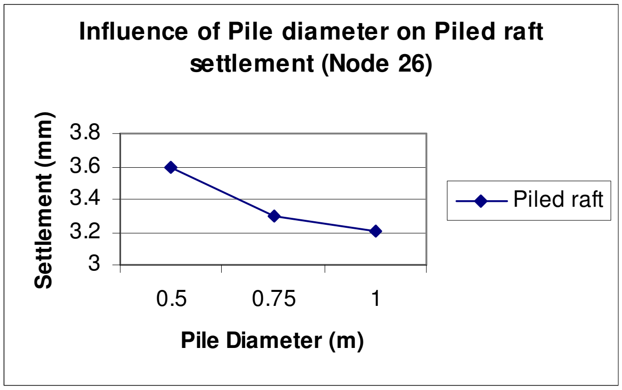


Fig 8.9 Influence of pile diameter on Piled raft settlement

3) Pile Length: - Pile response as end bearing pile is considered. The reference length is 10 m. while piles with 20 m and 30 m. length were also analyzed. The stiffness of piles is inversely proportional to the length of the piles. As the length of pile increases it's stiffness decreases. But this is valid for an elastic pile. As here the pile is considered as rigid one and such rigid pile the stiffness of pile increases with the increase in length which ultimately reduces the settlement of Piled raft foundation.(Fig 8.10 and Fig 8.11)

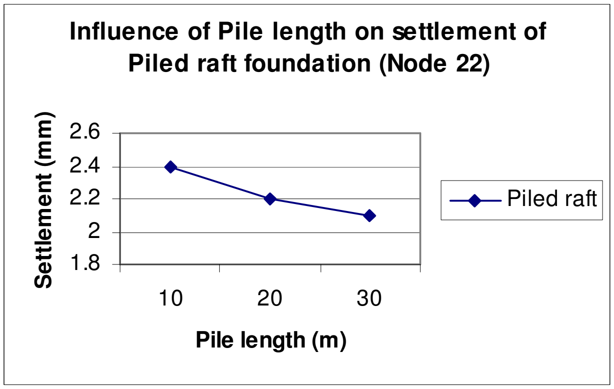


Fig 8.10 Influence of pile length on settlement of Piled raft foundation

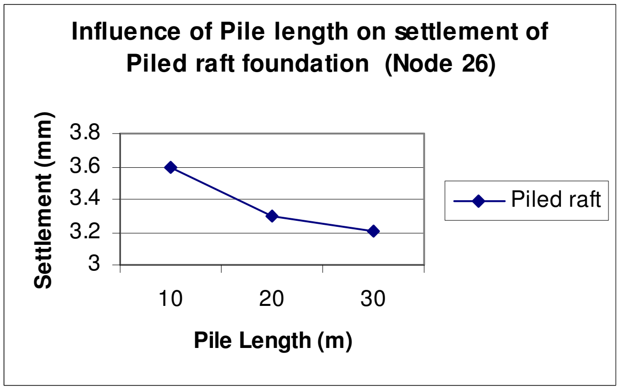


Fig 8.11 Influence of pile length on settlement of Piled raft foundation

4) Pile Number:-Piled raft for only two cases were studied. In first case a single pile was placed below each column location. While in other, a group of four piles is used arranged in square pattern. The spacing between the two adjacent piles was 3.6 m. As the number of piles increases, the settlement of Piled raft foundation reduces. This is hypothetical case where only four piles are used to study the response of increase in number of piles from one to four. This is universally known that up to certain number of piles in group reduces settlement effectively. (Fig. 8.12 and Fig. 8.13)

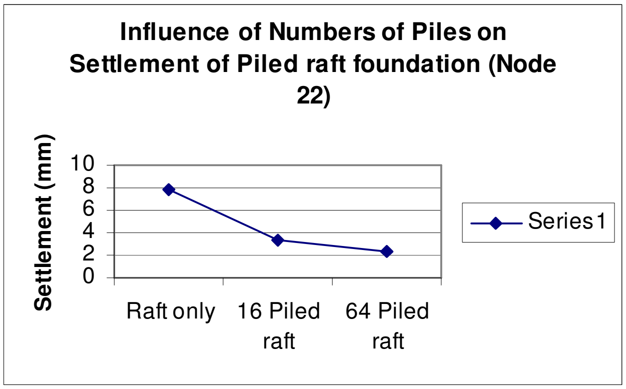


Fig 8.12 Influence of number of piles on settlement of Piled raft foundation

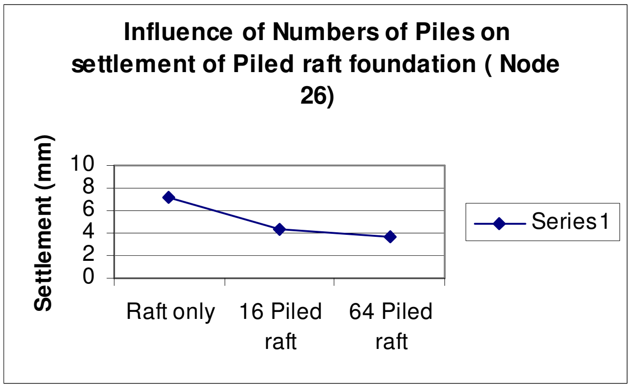


Fig 8.13 Influence of number of piles on settlement of Piled raft foundation

The parametric study clears the significance of raft's and pile's structural properties on Piled raft foundation. The Piled raft reduces the design moment values compared with only raft type foundation. Increase in diameter, length and number of pile reduces settlement of Piled raft foundation at a particular node.

These results deal with a particular node and a particular plate only in case of approximate analysis. The behavior of raft as rigid body is ignored. The assumptions made in both cases that is Simplified method and approximate method of analysis and design of Piled raft foundation are different even though the soil properties are same. The influence depth of soil in both cases is different. In case of Simplified method the total depth of soil is considered for the influence while in Approximate analysis influence depth considered is one feet only, so actual settlement values calculated by both these methods can not be compared.

However both these methods gives a common conclusion that the Piled raft foundation is stiff and less settlements compared to individual raft or pile foundations. The role of piles below raft is very important in reducing the settlement of Piled raft foundations. Therefore Piled raft foundations are best situated in situations where settlement is a problem.

Chapter 9

Conclusion & Future scope of work

9.1 Conclusions:

A study is carried out to analyze and design "Piled raft foundation". This analysis and design is done by Simplified method as well as by approximate method. Both methods have different assumptions, made regarding behavior of the foundation system. In case of Simplified method, raft and pile were assumed as rigid one while in approximate analysis raft and pile both were assumed as elastic one. Though the analysis and design were different, (with same soil strata,) they both are having unique conclusions.

After parametric study of the Piled raft foundation system, subjected to vertical loading only, following conclusions can be made,

- In case of Simplified method the total depth of foundation is considered while in case of approximate analysis the depth is considered as one feet only and as such even though the soil strata is same, exact settlement value of Piled raft foundation can not be compared. The piled raft system is more stiff compare to only raft foundation or only pile foundation. Comparison of results of both the methods shows that, by providing piles below raft the settlement of Piled raft foundation reduces.

- Out of total load, part of the load is shared by piles also and therefore the load on raft reduces. It is observed that the load taken by piles increases with increase in pile numbers. As the full capacity of the raft and pile is utilized in Piled raft foundation system, this system is more economical than any other foundation system.

- The comparison for moments of one strip calculated separately by both this method shows that the variation in values of moments is not much.

- The location of pile and number of piles influences the settlement of Piled raft foundation. Adequate number of piles, strategically located reduces the settlement of the raft to the permissible limits.

- As the number of piles increases, the stiffness of Piled raft foundation increases. As the stiffness of piles increases the load shared by raft gets reduced and load transferred to the piles increases. Variation of load sharing with increasing pile numbers and constant raft thickness shows the same nature of reducing settlement. The settlement is more for 16 numbers of piles compared to 64 numbers of piles.

- As the length of pile increases, percentage load taken by raft reduces (for a constant thickness of raft).Increase in pile length increases the stiffness of pile approximately in the same proportion as that of increase in diameter. As the stiffness of Piled raft increases, settlement of foundation reduces.

- In Piled raft foundation the design moment (positive and negative) values for a particular strip is reduced compared to moments of only raft type foundation. This gives saving in steel area for raft.

- The moments in the discretized raft element at a particular node depends on loads at that node and also depends on location of the node for that raft element.

- In study of influence of raft thickness on settlement of Piled raft foundation it is observed that , as the thickness of raft increases the settlement reduces because of flexible behavior of raft, but later on with increase in thickness of raft , the settlement increases because of rigid behavior of raft.

9.2 Limitations:

- The Piled raft foundation under study has assumed soil strata of stiff clay all through out the depth, which is an ideal situation to use Piled raft foundation, but this type of foundation is not suitable for every circumstance. If soft clay soil exists near the surface only this type of foundation is not a suitable option.
- In Simplified method the behavior of raft as a rigid body is ignored.
- The analysis is for vertical loading only. Earthquake load and lateral loads are not considered in this analysis.
- The assumed soil strata is stiff clay (London clay) and the strata is same all through out the depth so the analysis can not be applied to layered clay soil having different soil property for each strata.

- The pile below raft is assumed to be rigid and its stiffness is calculated accordingly. The results will be different for elastic pile.
- Actual soil and piles are not modeled; they both are represented by a spring support of equivalent stiffness at proper nodes. The spring supports are generated using the influence area of raft for a particular pile support at a particular node.

9.3 Future scope of work:

In this study the Piled raft is analyzed and designed for vertical loads only. This is very general but most important to start with. The Piled raft will not always act by only vertical loadings but also by vertical loading plus lateral loadings.

- The laterally loaded Piled raft will be an interesting topic of study for the structure situated in earthquake dominated area.

- Piled raft foundation response under influence of cyclic loading in case of Industrial building structures is also a topic for further studies.

- Piled raft foundation analysis can be studied by modeling soil and pile also. By using advance 3-D modeling software such as Plaxis- 3D foundation and Ansys can improve the analysis results by much extent.

- Raft supported on under-reamed piles, and influence of under-reamed bulb will also be again a interesting topic for study.

In India very few people have worked about design and construction aspects of Piled raft foundation systems. This is a very advance topic and any above suggested work including present study will surely get universal attention.

Future scope of work:

In this study the Piled raft is analyzed and designed for vertical loads only. This is very general but most important to start with. The Piled raft will not always act by vertical loadings but also by lateral loadings.

- The laterally loaded Piled raft will be an interesting topic to work out for the structure situated in earthquake dominated area.

- Piled raft foundation response under influence of cyclic loading in case of Industrial building structures.

- Piled raft foundation analysis can be deeply studied by modeling soil also. By using advance 3-D modeling software such as Plaxis- 3D foundation, Ansys can improve the analysis results by much extent.

- Raft supported on under rimmed piles, and influence of under rimed bulb will be again a interesting topic for study.

- An experimental study for a model Piled raft will always appreciable.

In India very few people had worked and know about Piled raft foundation. This is a very advance topic and any above suggested work including present study will surely get universal attention.

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