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Sustainable Foundation System for Alluvial Region

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Abstract

A structure resting on soil having low bearing capacity and where differential settlement due to erratic nature of soil is expected, raft foundation is recommended to cope-up with mixed or poor ground condition and simultaneously to transfer heavy loads to ground while controlling the differential settlement. The essential task in the analysis of a 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 supporting soil. The IS: 2950 (Part I)-1981 recommends the analysis based on the assumption of liner distribution of contact pressure. In this paper, an attempt has been made to design a raft foundation based on its geotechnical analysis. An extensive survey of research works devoted to study the geotechnical parameters affecting the behavior of raft foundation is carried out with detailed experiments raft foundations are increasingly being recognized as an economical and effective foundation system for high rise buildings. This paper sets out some principles of design for such foundations, including design for the geotechnical ultimate limit state, the structural ultimate limit state, and the serviceability limit state. Attention will be focused on the improvement in the foundation performance due to the raft being in contact with, and embedded within, the soil.

Keywords

Rigid raft Foundation, Safe bearing capacity of soil, Conventional approach, Deflection, Moment, Soil pressure, Soil modulus of elasticity.

1. Introduction

In this age of rapid growth in population in India, there is scarcity of land in prime locations especially in metro cities of the country. So, to overcome this problem we are moving towards vertical construction (that is towards high rise buildings). The main problem in moving towards vertical construction is foundation system, if the foundation system in high rise buildings is not planned and designed smartly and economically then there are different problems related to foundation system that is going to arise, the soil in that area also plays a very important role in designing of economical and stable foundation system. It is always beneficial to have a raft foundation on alluvial soil for high rise buildings. however, it is a matter of great concern that what foundation will be proposed on such type of natural soils or man-made refills [12]. In this paper, an attempt has been made to design a raft foundation based on its geotechnical analysis. An extensive survey of research works devoted to study the geotechnical parameters affecting the behavior of raft foundation is carried out with detailed experiments raft foundations are increasingly being recognized as an economical and effective foundation system for high rise buildings. This paper sets out some principles of design for such foundations, including design for the geotechnical ultimate limit state, the structural ultimate limit state, and the serviceability limit state. Attention will be focused on the improvement in the foundation performance due to the raft being in contact with, and embedded within, the soil.

2. Types of high-rise buildings

The use of a building has considerable influence on its security and fire life safety needs. There are different types of high-rise buildings classified according to their primary use. This Article addresses the following ones:

i. Office buildings. An office building is a "structure designed for the conduct of business, generally divided into individual offices and offering space for rent or lease."

ii. Hotel buildings. "The term 'hotel' is an all-inclusive designation for facilities that provide comfortable lodging and generally, but not always food, beverage, entertainment, a business environment, and other 'away from home' services." There are also hotels that contain residences. Known as hotel-residences, this type of occupancy is later addressed in mixed-use buildings.

iii. Residential and apartment buildings. A residential building contains separate residences where a person may live or regularly stay. Each residence contains independent cooking and bathroom facilities and may be known as an apartment, a residence, a tenement, or a condominium. An apartment building is "a building containing more than one dwelling unit."54 "Apartment buildings are those structures containing three or more living units with independent cooking and bathroom facilities, whether designated as apartment houses, … condominiums, or garden apartments."

iv. Mixed-use buildings. A mixed-use building may contain offices, apartments, residences, and hotel rooms in separate sections of the same building. Hotel-residences are another type of mixed-use occupancy. "The hotel residences trend is notably different from its predecessors such as fractional/time share hotel units, which are not wholly owned, or condo hotels, which are wholly owned hotel rooms without, for example, kitchens. Not only do hotel residences have kitchens and everything else an owner would expect in a typical abode, but they also include amenities such as maid and room service, plus restaurants, spas, and gyms. Typically, [these] residences are on the top floors of hotels. In addition, there are two types of structures commonly associated with buildings that technically are classified as high-rises but usually are not required to conform to high-rise building laws, codes, and standards (particularly the laws requiring the installation of approved automatic sprinkler systems). These structures are:

(a) buildings used solely as open parking structures and

(b) buildings where all floors above the high-rise height limit are used for open parking.

High rise buildings are usually founded on some form of piled foundation which is subjected to a combination of vertical, lateral, and overturning forces. Conventional methods of assessing foundation stability may not be adequate when designing such foundations because they tend to focus primarily on foundation resistance under vertical loading (Harry G. Poulos, 2002) [19].

3. Related Work

Urbanization is a dynamic and socioeconomic process that transforms the rural landscape to the urbanized area. The United Nation report on the world's population prospects asserts that the majority of Indian populace will reside in cities by 2050 (United Nation, 2014).

Being the capital of the largest state of India, Lucknow is found to be burdened by the surrounding environs and continually being extending its boundary to accommodate the large population. A Shukla (2019) [4]. It covers a total surface area of 349 square kilometers (135 square miles). In combination with the growing number of residents in Lucknow, the population density comes to 8,100 residents per square kilometer. The exploding population, largely urban, creates an increasing demand for tall buildings. The ever-increasing population and growing economies in major cities of the world mean increasing urbanization globally and the continuing rise in population density in urban areas. Arable land areas are constantly being eaten away by urban spreading through suburban developments. The tall building can accommodate many more people on a smaller piece of land than would be the case with low-rise building on the same land. A tall building is in effect a vertical transformation of horizontal expansion. It is generally [acknowledged] that there has been evident neglect of the human factors in urban design at the expense of livability and quality of life. The outward expansion of cities into the suburbs has resulted in increased travel time and traffic gridlock. The prospect of traveling for a long time, to and from work, is detrimental to the social well-being of the commuter and results in losses of fuel and productivity. Clustering of buildings in the form of tall buildings in densely built-up areas is the opportunity for creating open spaces like playgrounds, plazas, parks, and other community spaces by freeing up space at the ground level. Besides the impact on the city skyline, tall buildings thus influence the city fabric at the level where they meet the ground. The improvement of the "public realm" has become a necessity exerted by planning authorities in major cities [1].

According to Feng Fu (2018) [2], the definition of a tall building is ambiguous in design practice. We normally define buildings below eight stories as low-rise buildings. For building with 8 and 20 stories it is called mediate-rise building. For buildings over 20 stories, it is called a tall building. However, with the fast development of modern construction technology, and the increasing number of supertall buildings, the above definition is not accurate. "A 'tall building' is a multi-story structure in which most occupants depend on elevators [lifts] to reach their destinations. The most prominent tall buildings are called 'high-rise buildings' in most countries and 'tower blocks' in Britain and some European countries. The terms do not have internationally agreed definitions' Challinger (2008) [3]. For most purposes, the cut-off point for high-rise buildings is around seven stories. M. Cubrinovski (2005) [5]. "Generally, a high-rise structure is one that extends higher than the maximum reach of available fire-fighting equipment. In absolute numbers, this has been set variously between 75 feet (23 meters) and 100 feet (30 meters)," or about seven to ten stories (depending on the slab-to-slab distance between floors) [17]. The exact height above which a particular building is deemed a high-rise is specified by fire and building codes for the country, region, state, or city where the building is located.

According to the IS CODE 1670:2017 [23] a building with height greater than 50 m but less than 250 m is termed as a Tall Building.

4. Work Plan of Research

From the literature it is observed that there are no guidelines for providing type of foundation in alluvial region for high rise buildings, some are providing raft, and some are providing pile for the same conditions.

Study will be performed to find out sustainable option for foundation of high-rise buildings in Lucknow and nearby regions, Design and comparison will be done for 10,15,20,25,30,35 and 40 story high rise buildings in alluvial region of Lucknow and nearby area, all these buildings will be designed for both raft and Combined pile Raft foundation and suitable and sustainable option will be suggested for foundation after comparison of various aspects and after the study suitable and sustainable option will be suggested.

5. Objectives

i. **Research problem1**: To find out sustainable option for foundation of high-rise buildings in Lucknow and nearby regions, and after the study suitable and sustainable option will be suggested.
ii. **Research problem2**: Design and comparison will be done for 10,15,20,25,30,35 and 40 story high rise buildings in alluvial region of Lucknow and nearby area, all these buildings will be designed for both raft and Combined pile Raft foundation and suitable and sustainable option will be suggested for foundation after comparison of various aspects.
iii. **Research problem3:** In this study we will take several high-rise buildings of Lucknow and nearby region and the same buildings will be designed and compared for both raft as well as pile foundation in alluvial region.
iv. **Research problem4:** Dynamic Analysis of combined pile raft foundation (CRPF) for 10,15,20,25, 30,35 and 40 story high rise buildings in alluvial region of Lucknow and nearby area have been done.
v. **Research problem5:** cross checking and verification of Manual design have been done through software to compare the results with the theoretical and manual calculation.

6. Tools Used

i. **SAFE V20.2.0** is floor system design and analysis software. SAFE is ideal for modeling, analyzing and sizing reinforced concrete slabs.
ii. **STAAD Pro V8i ss6** is also structural design analysis software for civil engineers.
iii. **Bentley STAAD Foundation Advanced** is a comprehensive structural foundation design and analysis software that includes specialized features for foundations.

7. Performance Evaluation and Validation

7.1. Problem 1. Design and analysis of raft foundation have been done for 10,15,20,25, 30,35 and 40 story high rise buildings in alluvial region of Lucknow and nearby area based on collected data.

7.1.1. Raft Dimensions The spacing of raft in x- side is 6 meters and the spacing of the raft in y-side is also 7 meters. There is one meter of edge around the edge's columns. In figure 1, the plan of the raft has been shown.

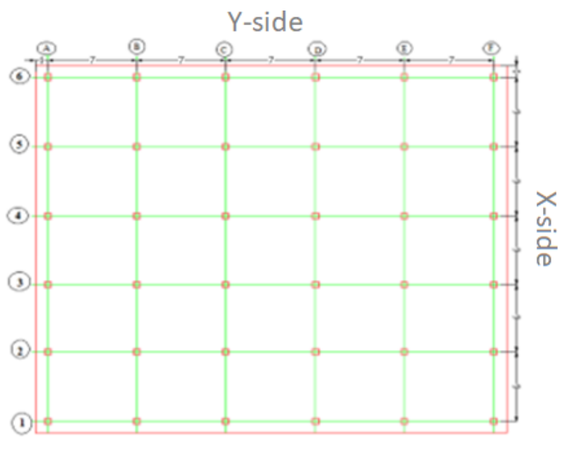

Figure 1. Raft layout

Total area of the raft under raft foundation = [(5x6) +1+1) x (5x7) +1+1)]

=(32x37)

=1184 m^2

7.1.2. Loads of columns in raft:

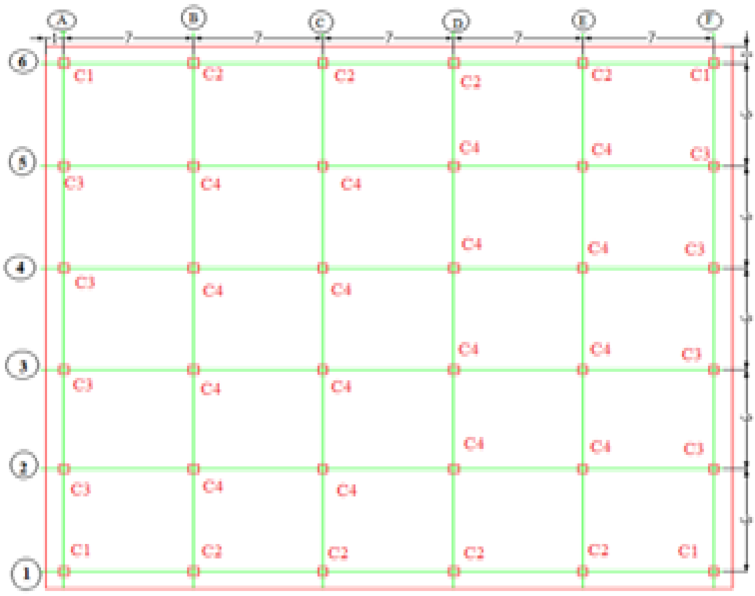

Figure 2. Raft dimensions and column spacing

Loads per square meter are calculated as:

$$\text{General Dead load stress} = (5 + 2.5 + 1)\frac{\text{KN}}{\text{m}^2} \times (\text{number of floors})$$

$$\text{General Dead load stress} = (5 + 2.5 + 1)\frac{\text{KN}}{\text{m}^2} \times (10) = 85\frac{\text{KN}}{\text{m}^2}$$

$$\text{General Life load stress} = (2)\frac{\text{KN}}{\text{m}^2} \times (10) = 20\frac{\text{KN}}{\text{m}^2}$$

7.1.3. Columns Loads

$$\text{Axial Dead load} = \text{stress per unit area}\frac{\text{KN}}{\text{m}^2} \times \text{Turbidity area}$$

Column type (1):

$$\text{Axial unfactored Dead load} = 85\frac{\text{KN}}{\text{m}^2} \times 4 \times 4.5\text{m}^2 = 1530\ \text{KN}$$

$$\text{Axial unfactored Live load} = 20\frac{\text{KN}}{\text{m}^2} \times 4 \times 4.5\text{m}^2 = 360\ \text{KN}$$

$$\text{Total Service Axial load} = 1530\ \text{KN} + 360\ \text{KN} = 1890\ \text{KN}$$

$$\text{Ultimate axial load} = 1.2(1530) + 1.6(360) = 2412\ \text{KN}$$

Column type (2):

$$\text{Axial unfactored Dead load} = 85\frac{\text{KN}}{\text{m}^2} \times 4 \times 7\text{m}^2 = 2380\ \text{KN}$$

$$\text{Axial unfactored Live load} = 20\frac{\text{KN}}{\text{m}^2} \times 4 \times 7\text{m}^2 = 560\text{ KN}$$
$$\text{Total Service Axial load} = 2380\text{KN} + 560\text{ KN} = 2940\text{ KN}$$
$$\text{Ultimate axial load} = 1.2(2380) + 1.6(560) = 3752\text{ KN}$$

Column type (3):

$$\text{Axial unfactored Dead load} = 85\frac{\text{KN}}{\text{m}^2} \times 4.5 \times 6\text{m}^2 = 2295\text{ KN}$$
$$\text{Axial unfactored Live load} = 20\frac{\text{KN}}{\text{m}^2} \times 4.5 \times 6\text{m}^2 = 540\text{ KN}$$
$$\text{Total Service Axial load} = 2295\text{ KN} + 540\text{KN} = 2835\text{ KN}$$
$$\text{Ultimate axial load} = 1.2(2295) + 1.6(540) = 3618\text{ KN}$$

Column type (4):

$$\text{Axial unfactored Dead load} = 85\frac{\text{KN}}{\text{m}^2} \times 7 \times 6\text{m}^2 = 3570\text{ KN}$$
$$\text{Axial unfactored Live load} = 20\frac{\text{KN}}{\text{m}^2} \times 7 \times 6\text{m}^2 = 840\text{ KN}$$
$$\text{Total Service Axial load} = 3570\text{ KN} + 840\text{ KN} = 4410\text{ KN}$$
$$\text{Ultimate axial load} = 1.2(3570) + 1.6(840) = 5628\text{ KN}$$

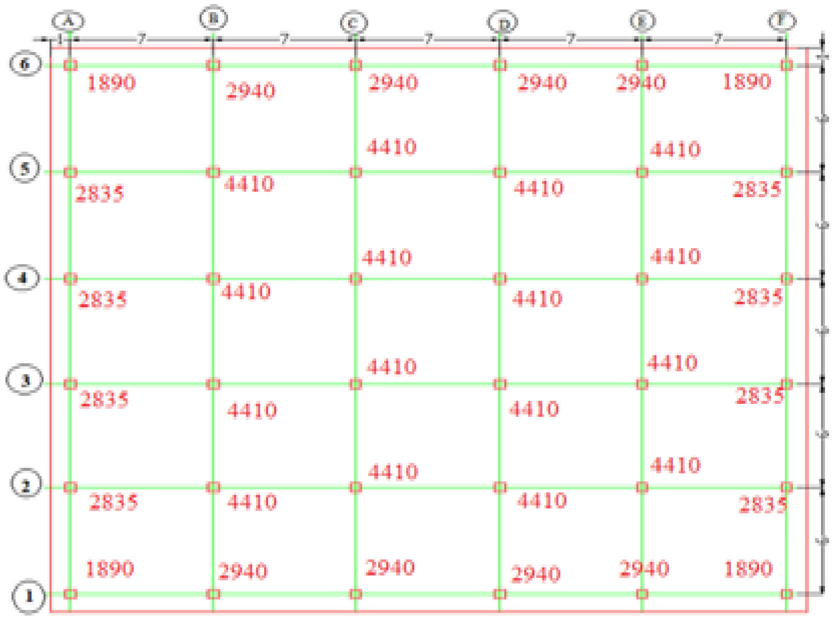

Figure 3. columns total service loads

7.1.4. Soil Pressure Check

In soil pressure check, the net pressure must be checked at every point of the raft foundation. The effect of moments on the raft must be checked to make sure that the stresses on the raft under all columns are less than the net allowable stress, of 120KN/m2.

$$q = \frac{Q}{A} \pm \frac{M_y x}{I_y} \pm \frac{M_x y}{I_x}$$

$A = Area\ of\ the\ mat = [(5 \times 6) + 1 + 1) \times (5 \times 7) + 1 + 1)]$
$A = (32 \times 37) = 1184 m^2$

$$I_x = \frac{bh^3}{12}$$

$$I_x = \frac{(32) \times (37)^3}{12} = 135075\ m^4$$

$$I_y = \frac{bh^3}{12}$$

$$I_y = \frac{(37) \times (32)^3}{12} = 101035\ m^4$$

$Q = sum\ of\ all\ service\ colums\ loads$
$Q = 4(C1) + 8(\text{C2}) + 8\ (\text{C3}) + 16\ (\text{C4})$
$Q = 4(1890) + 8(2940) + 8\ (2835) + 16\ (4410)$
$Q = 7560 + 23520 + 22680 + 70560$
$Q = 118650 KN$

7.1.5. Soil pressure due to total service axial loads and moments

$$q_i = -\frac{Q}{A} \mp \frac{M_y x}{I_y} \mp \frac{M_x y}{I_x}, i = 1,2,3\ and\ 4$$

In the above equation (-) minus signs indicate compression stress. In all the four corners of the raft, soil pressure will be checked with the help of the above equation. The calculated soil pressure should not be more than the allowable stress of the soil and not less than 0 KN/m2, this is to make sure that no tension could occur in any part of the raft.

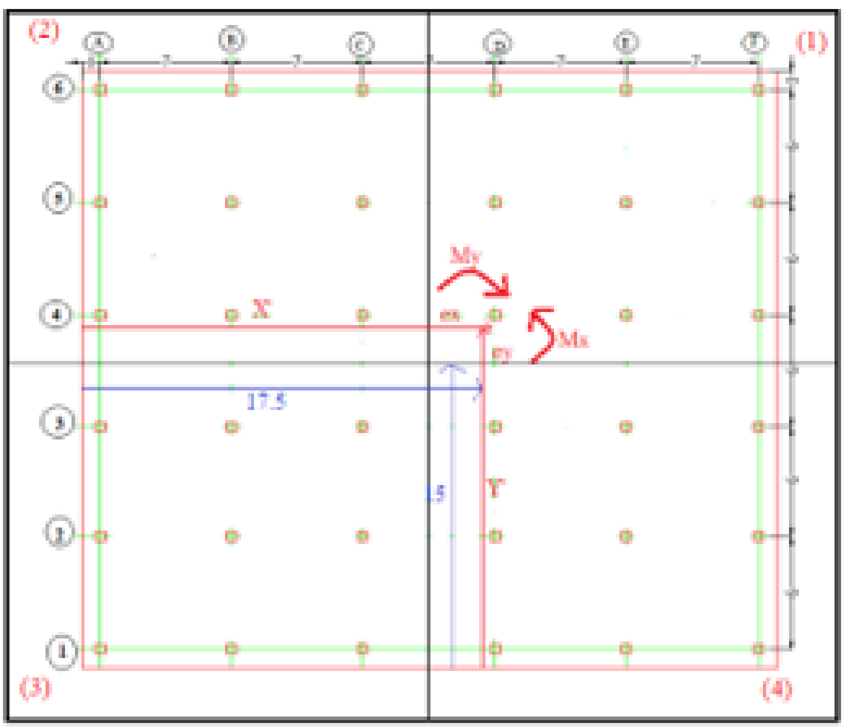

Figure 4. Corners of raft

$$q_i = -\frac{Q}{A} \mp \frac{M_y x}{I_y} \mp \frac{M_x y}{I_x}$$

$$q_1 = -\frac{(118650)}{(1184)} - \frac{(98479)\times(17.5)}{(101035)} - \frac{(84241)\times(16.5)}{(135075)}$$

$$q_1 = -\,100 - 17 - 10$$

$$q_1 = -117\ < q_{net} = 120\,KN/m^2\ OK$$

$$q_2 = -\frac{(118650)}{(1184)} + \frac{(98479)\times(17.5)}{(101035)} - \frac{(84241)\times(16.5)}{(135075)}$$

$$q_2 =\ -100 + 17 - 10$$

$$q_2 = -93\ < q_{net} = 120\,KN/m^2\ OK$$

$$q_3 = -\frac{(118650)}{(1184)} + \frac{(98479)\times(17.5)}{(101035)} + \frac{(84241)\times(16.5)}{(135075)}$$

$$q_3 =\ -100 + 17 + 10$$

$$q_3 = -83\ < q_{net} = 120\,KN/m^2\ OK$$

$$q_4 = -\frac{(118650)}{(1184)} - \frac{(98479)\times(17.5)}{(101035)} + \frac{(84241)\times(16.5)}{(135075)}$$

$$q_4 =\ -100 - 17 + 10$$

$$q_4 = -107\ < q_{net} = 120\,KN/m^2\ OK$$

7.1.6. Result / conclusion

a. As per the Indian Standards, safety requirements were provided while designing the Raft foundation corresponding to Alluvial type of soil. In this paper, the design of the raft foundation along with its reference to various geotechnical aspects are studied and implemented in the design required to be completed.

b. For loose soil bending moment is sagging in nature, over entire of raft. However, as soil stiffness increases tension zone is created. From the edge as we proceed toward center the intensity and extent of tension zone goes increasing. However, the effect is more in X direction as compared to Y direction.

c. For loose soil, pressure distribution beneath the raft is lower at edge and goes on increasing towards the center. In the central zone, in between columns, it remains almost constant. For medium soil, at the edge, pressure distribution is high and goes on reducing towards the center with very mild rate. For hard soil, pressure distribution at the edges is high, reduces under the edge columns and then after increases in the central part.

d. The punching shear factors are less than 1 and settlement is less than 50 mm.

7.2. Problem 2. Dynamic Analysis of combined pile raft foundation (CRPF) for 10,15,20,25, 30,35 and 40 story high rise buildings in alluvial region of Lucknow and nearby area have been done.

Validation of results (in terms of Load transfer by pile and raft). For validating the results obtained from analytical modelling as above, the problem of Piled Raft was first analyzed using SAFE software using Finite element method. This result is then compared with the result obtained from Analytical solution. For this purpose, the size of raft, soil property, end bearing resistance of pile, skin friction of pile, ultimate load carrying capacity of pile, length of pile and diameter of pile are to be considered.

Data

1. Size of raft $= 45\text{mx}35\text{m}$
2. Length of pile $= 20\text{m}$
3. Diameter of pile $= 600\text{mm}$
4. Soil bearing capacity $= \dfrac{15\,T}{m^2}$
5. End bearing resistance of pile $= \dfrac{350KN}{m^2}$
6. Skin friction of pile $= \dfrac{25KN}{m^2}$
7. Assume permissible ultimate load carrying capacity of pile $= 1500\text{KN}$

$From$ IS 2911, the ultimate load carrying capacity is given by

$$Q_u = \frac{\pi}{4} \times \text{d2} \times \text{end bearing resistance} + \pi \times \text{d} \times \text{L} \times \text{skin friction}$$

$$Q_u = \frac{\pi}{4} \times 0.62 \times 350 + \pi \times 0.6 \times 20 \times 25$$

$Q_u = 1101.43$ KN

$Numbers$ of piles $= 242$

Total load carrying capacity of Pile $= 242 \times 1101$

Total load carrying capacity of Pile $= 266442$ KN

$Total$ permissible load carrying capacity of Pile $= 363000$ KN

$Total\ load\ on\ foundation = 487898$ KN (is taken from ETABS file)

$Therefore,\ Load\ taken\ by\ the\ raft = 221456N$

$The\ load\ shared\ by\ pile\ and\ raft\ using\ SAFE\ software\ is\ 277985KN\ and\ 199913KN$

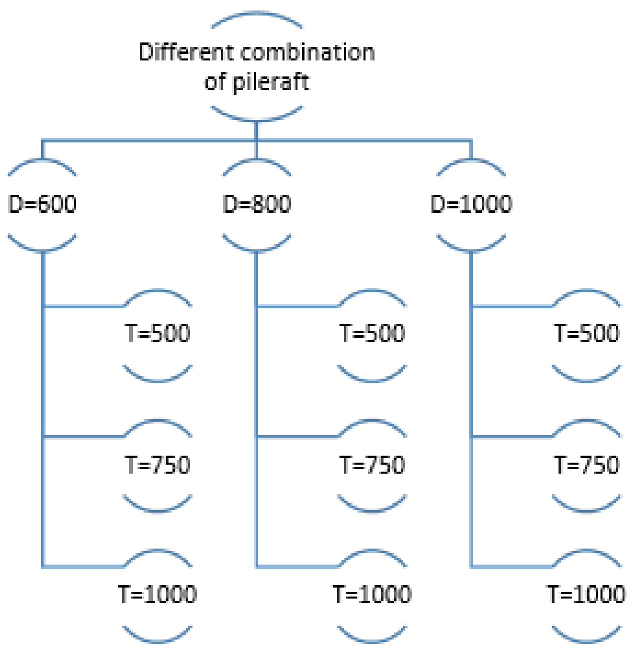

Figure 5. Different combination of pile raft

7.2.1. Results for Different Parameters

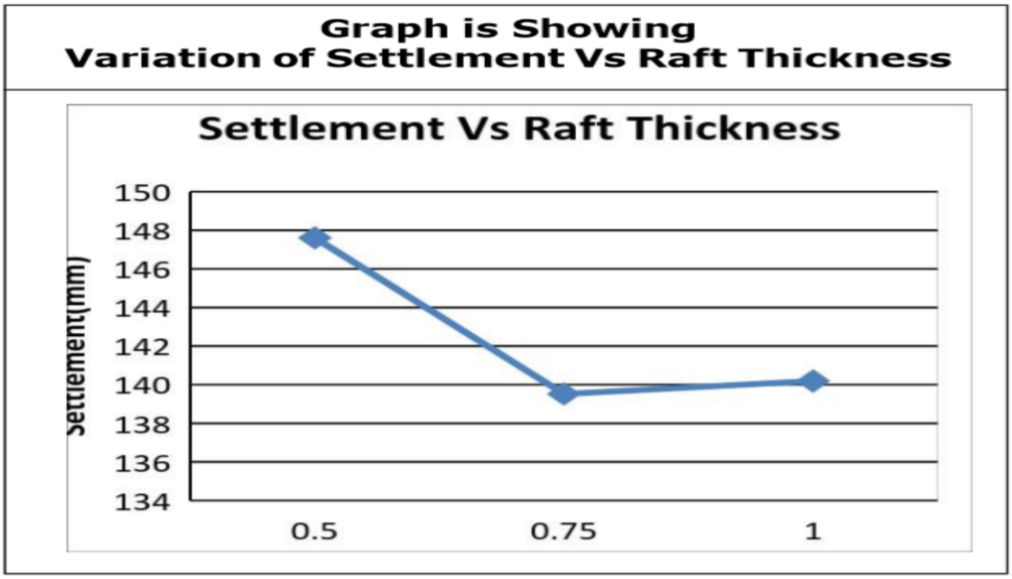

Figure 6. Settlement Vs Raft Thickness

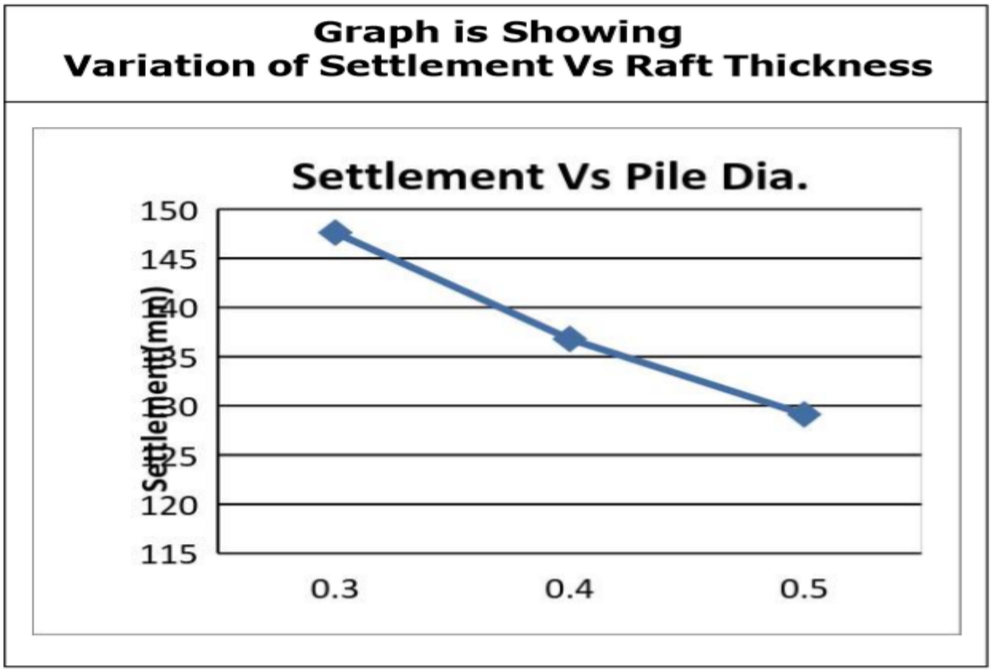

Figure 7. Settlement Vs Pile Dia.

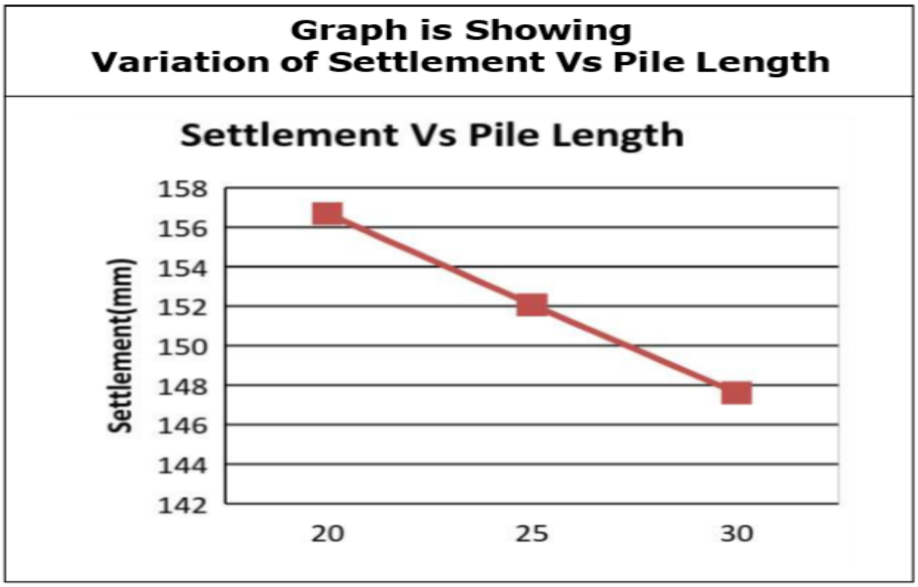

Figure 8. Settlement Vs Pile Length

7.2.2. Conclusion/result

i. Effect of Raft Thickness: - As shown in chart, the study was carried out for different pile diameters with thickness of the raft. It was observed that maximum settlement of the raft decreases as the diameter of the pile increases.
ii. Effect of Pile Diameter: - As shown in chart, as per the analysis as the pile diameter increases, the settlement reduces.
iii. Effect of pile spacing: - As shown in chart, as per the analysis as spacing increases, settlement increases
iv. It has been observed that piled raft foundation concept has significant advantages in comparison to conventional foundation for some soft clay for high rise buildings.
v. The ultimate bearing capacity of Piles will be increased as the Pile diameter increases.
vi. The settlement of Pile is reduced as the diameter of Pile increases.
vii. To reduce the differential settlement and moment the piles should be placed strategically using some trial and error or using parametric study.

7.3. Problem 3. Comparison of raft and combined pile raft foundation for high rise building

Two different types of foundation are taken into consideration for dynamic analysis of building model i.e., raft foundation and pile raft foundation. Raft foundation is a type of footing in which continuous slab is provided throughout the area of footing to support the building and transfers its load to the hard strata below ground level. When raft foundation does not provide required support, it can be increased by addition of piles. In pile raft foundation additional piles are provided at the bottom of the raft foundation. Piles are made up of reinforced concrete in rectangular or in circular shape. Figure no 3 shows the 3D view of raft foundation provided at the base of building while Figure no.4 shows the piles are provide at base of raft foundation.

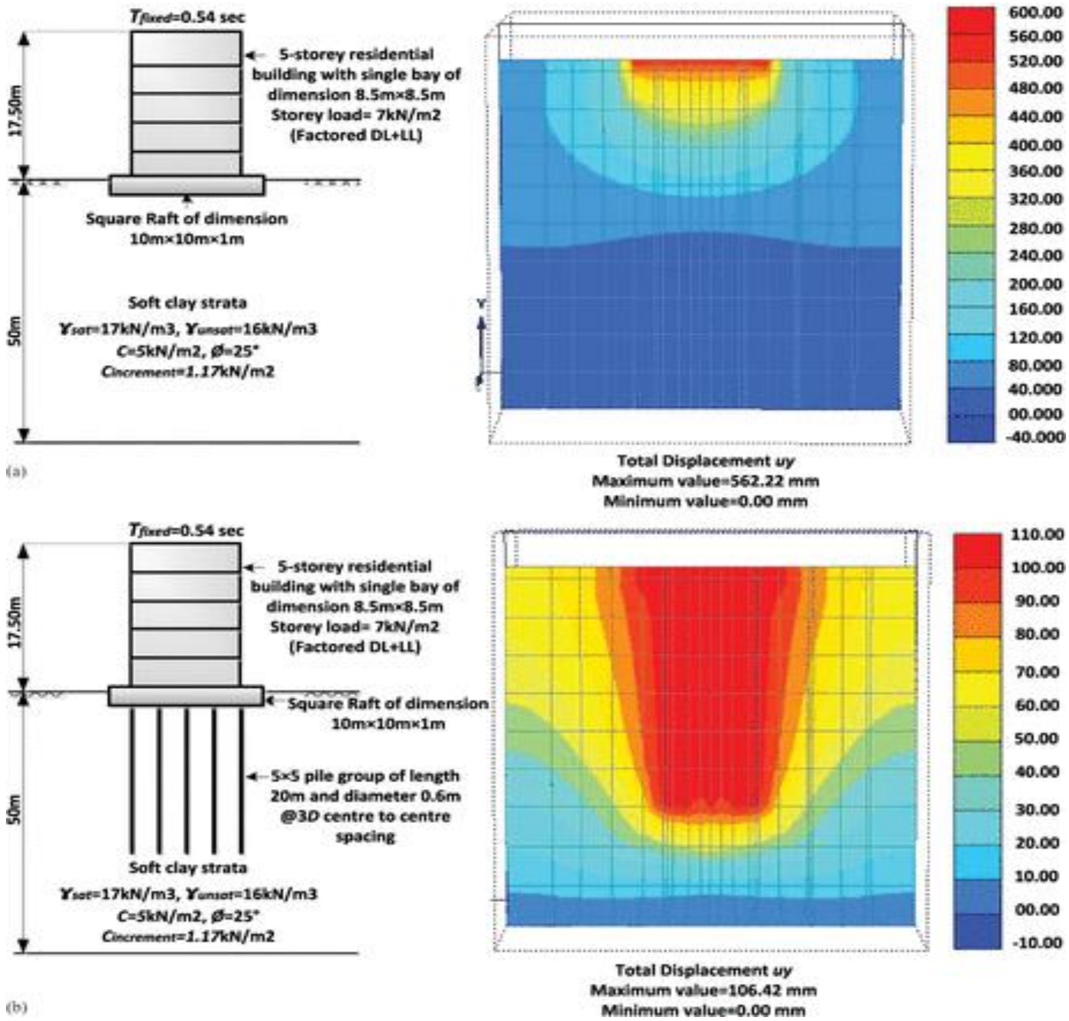

Figure 9. Comparison of raft and pile raft

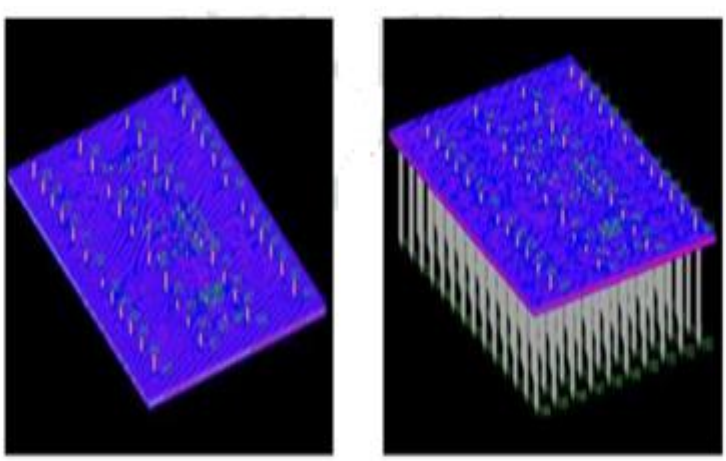

Figure 10. Comparison of raft and pile raft load

Table 1. Variation in Displacements

	Maximum displacement at various Nodes (mm)	
	Building with raft foundation	Building with piled raft foundation
Max Dx	60.15	1.11
Max Dy	54.26	0.95
Max Dz	50.38	1.2
Min Dx	48.92	0.023
Min Dy	40.94	0.7
Min Dz	34.96	0.5

Table 2. Variation in Stresses

	Raft Foundation			Piled Raft Foundation		
	Mx	My	Mxy	Mx	My	Mxy
Maximum Stresses (KN-m/m)	3306.78	3268.17	802.65	477.76	533.76	151.79
Minimum Stresses (KN-m/m)	1399.77	1399.25	761.47	158.46	158.46	114.54

7.3.1. Conclusion /result

a. The displacement can be reduced much more by providing pile raft foundation than raft foundation.
b. The raft settlement can be reduced with piled raft foundation and settlement of pile is within permissible limit.
c. More stresses are developed in raft foundation as compared to pile raft foundation.
d. Base pressure can be reduced much more by providing piled raft foundation than raft foundation, base pressure is more in raft, chances of tilting of raft.
e. Soil pressure intensity is less in piled raft foundation as compared to raft foundation.

8. Conclusion

As per the Indian Standards, safety requirements were provided while designing the Raft foundation corresponding to Alluvial type of soil and it was found that up to 20 story, high rise building with all safety features can be constructed on alluvial type of soil, variation of thickness of raft also plays a very important role in minimizing the settlement of the raft foundation. In the case of combined pile raft foundation system, the thickness of the raft, diameter of the pile and pile spacing plays a very important role and variations in all above factors shows variation in overall settlement of the foundation system. To reduce the differential settlement and moment the piles should be placed strategically using some trial and error or using parametric study. When comparison was done between raft foundation and pile raft foundation system for same type of building it was seen that raft foundation was more economical, if there is problem of displacement at the site it can be reduced only by providing pile raft foundation. More stresses are developed in raft foundation as compared to pile raft foundation. Base pressure can be reduced much more by providing piled raft foundation than raft foundation, base pressure is more in raft, chances of tilting of raft. Soil pressure intensity is less in piled raft foundation as compared to raft foundation.

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