ANALYSIS OF PILED-RAFT FOUNDATION WITH COHESIVE SOIL

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Abstract: Piled-raft foundations are an enhancement to conventional raft and pile foundation systems. Piled-raft foundation is recognized widely as an economical and efficient foundation system for tall buildings over weaker strata of soil. In the present study, analysis of piled raft foundations for a structure subjected to lateral seismic and wind forces is performed with a cohesive type of soil. Cohesive soil mainly uses internal cohesive forces and adhesion as skin friction to resist the imposed loads. This study includes an analysis of conventional raft and pile foundations, and their failure criterion, to get a feasible solution with piled raft system. The governing criterion for performance failure of the foundation would be an excessive settlement, higher bearing pressure, and higher pile reaction than its specified limits. The comparative study of different foundation systems will predict the feasibility aspect of the Piled-raft system over other conventional systems of foundations. On the other hand, developed bending moments and shear forces in a piled raft are also studied. The effect of strategic placement of piles in piled-raft is studied to reduce the required number of piles. Additionally, the effects of variation in different parameters like the length of the pile, the diameter of the pile, the spacing of the pile, the thickness of the raft and soil stiffness will also be studied to optimize the piled raft foundation system.

Keywords: Piled-raft, Strategic placement, Parametric studies, Soil stiffness.

Introduction: The field of Piled-raft foundation is relatively younger, in this foundation type, the interacting system act as a composite construction consisting of the three bearing elements; piles, raft and sub-soil. The finite element method and finite layer method is proven to be one of the most powerful tools for the analysis of complex piled raft system. Revolutionary studies and experiments have been done in this area to understand the combined complex load sharing behavior of piles and raft; some of which are described as follows;

The behavior of piled raft in layered soil has been studied by combining the finite element method for raft and finite layer method for pile group. The method is also suitable for layered soils and the soil can be homogeneous, non-homogeneous or have cross-anisotropic properties. Further, the load distributions along the shafts of piles in layered soils are affected by the relative thickness and stiffness of soil layers, an early example of analysis of piled raft was given by Bogner et al. [1], which is further explained by Ta and Small [2], in which raft is assumed to be a thin elastic plate and is divided into a number of rectangular elements, each element having four nodes and 16 degrees of freedom. The piles are assumed to have a solid circular cross-section. Further, soil is divided into number of layers. Loads over soil can be categorized into two parts: Firstly, the load which is transmitted directly from raft of piled-raft to underneath soil called as the contact pressure or load. Secondly, loads which is transmitted from piled-raft to the soil through pile shafts, which are frictional load and the base load.

A method is developed for piled raft subjected to general loadings, which has a good agreement to full-scale pile group test results performed on site. By parametric studies influence of S/d ratio, Raft-soil stiffness ratio, pile-soil stiffness ratio and variation of developed moments in piles had also been studied by Small and Zehang [3].

The rational design process for Piled Rafts involves three main stages:(a) A preliminary stage to assess the feasibility of using a piled raft, (b) A second stage to assess where piles are required and (c) A final detailed design stage to obtain the optimum number, location and configuration of the piles, and to compute the detailed distributions of settlement, bending moments and shear in the raft, and the pile loads and moments. Additionally, a detail description of Poulos-Davis-Randolph (known as PDR method) is also described by Poulos [4]. In order to analyze piled raft foundation, an iterative based design approach for piled raft foundation using settlement reducing piles with varying length of piles in soft ground. Longer piles are provided in the central portion of building and progressively shorter length of pile on the edge of building was conducted by Tan *et al.* [5].

A detailed analysis shows that the behavior of a piled raft is governed by the soil-structure interactions. The use of long piles underneath the heavily loaded area can help to minimize the risk of tilting as well as to reduce the overall and differential settlements. The finite layer method can be used for analysis of piled-raft, computational time for the finite layer analysis is about four times less than for the finite element analysis as studied by Chow and Small [6]. A case study of the foundation for a liquid gas storage tank constructed in Gdansk, Poland. The study shows that reasonably good prediction of foundation settlement could be obtained with GARP programme. The Raft is modeled as thin shell element and soil as uniform block of pressure corresponding to raft element which is divided into eight noded isoparametric elements. The analysis is based on elastic theories, but allows for the important Non-linear features of the system such as the development of limiting pressures below the raft and utilization of piles up to is ultimate capacities, it has been performed by Small and Poulos [7].

The design analyses and the back analyses have been performed with relatively simple procedures based on the availability of a pile load test and using the computer code NAPRA [Russo 1998]. Shallow foundations would have been safe against a bearing capacity failure, while the predicted settlement was beyond the allowed limit. Accordingly, piles were designed to reduce the settlement and improve the overall performance of the foundations. The substantial contribution of the raft in supporting almost half of the total applied load is an indirect result of a design approach where the piles have only the role of settlement reducers. This approach led to a substantial saving in the total number of piles without significantly affecting the overall performance of the piled rafts. This work was carried out by De Sanctis and Russo [8]. A parametric study on pile configuration, pile number, pile length and raft thickness on piled raft foundation behavior was computed by Meisam [9] and it has been found that the maximum bending moment in raft increases with increase raft thickness, decrease pile number and decrease in pile length. Central and differential settlement decreases with increase raft thickness and uniform increase in pile length. It has also been found that pile configuration is very important in pile raft design.

Finite element analysis predicts results which are agreed with measured field values. The predicted and measured settlements for the two Boilers of second phase of the Waigaoqiao power plant, China. In this paper a simplified but helpful analysis method, considering the interaction of soil-pile-raft but avoiding the complicated calculation is employed by Cheng [10]. The principles of a limit state design approach for piled raft foundation for tall buildings. Ultimate limit state, serviceability limit state and cyclic loading conditions are addressed. The effect of considering embedment of pile cap in estimation of piled raft behavior has been examined for a small-scale test and for a full-sized structure. The calculations for the small-scale test indicate that the effect of the soil against the buried cap is quite significant, and therefor to use a conventional pile group analysis where this is neglected will result in a considerable underestimate of lateral load capacity and an overestimate of lateral deflection was conducted by Poulos *et al* [11].

The parametric studies and optimization of piled raft foundations has concluded that load carrying capacity of piled raft increases with increases in pile-aspect ratio. Further, increase in diameter of pile (d) enhances the load carrying capacity of piled-raft. Spacing to diameter ratio up to 5 shows increase in capacity of pile-raft continuously. Differential settlement reduces with the increase in raft thickness and optimum thickness is found as 2.3 to 2.5 times the thickness required safeguarding against punching shear, which has been performed by Jha *et al.* [12].

A series of parametric studies on a combined piled raft foundation (CPRF) in a multi-layered soil are performed by varying the pile spacing and the raft thickness using a three-dimensional finite element method. In a CPRF system, the initial stiffness is provided by the pile group by mobilizing the skin frictional resistance but as the settlement of a CPRF increases, the load sharing by the raft also increases until the failure point is reached. The pile spacing and its diameter play a major role in optimizing the behavior of a piled raft. Larger diameter pile provides more initial stiffness than a small diameter pile, if all the other parameters are kept constant. A design methodology is suggested by creating a balance between the FOS of piles in a piled raft, assuming it to be not less than 2 and that for the raft in a piled raft not greater than 4 has studied by Bandyopadhyay *et al.* [13].

A few studies have been made for piled raft foundations for higher structures with cohesive soil, foundation system with cohesive soil will be studied here as characteristics of both cohesive and non-cohesive soil differ from each other. Comparative studies for analysis of conventional raft, pile and piled raft foundation is not studied yet; this is required because the adoption of piled-raft foundation depends on failure for performance of the others. Further, it is observed that for a complex geometry of piled-raft solution to matrices of higher order will be difficult and time consuming, hence recent commercially adopted FEA software's which are programmed to solve this type of problem will be used, analysis performed by software have a verified International reference manual Computers and Structures Inc., [14]. The FEA tool used here are ETABS v18.1.1 for super structure analysis and SAFE v16.0.0 for piled raft analysis by Computers and Structures Inc (CSI).

Methodology: In the present study, for super structure analysis, Hostel building of Basement+ Ground+15 upper floors have been modeled and analyzed in commercially available software (ETABS v 18.0.0). The Plan of building is rectangular with floor to floor height of 3m. Further, in addition to dead and imposed loads, static lateral forces have also been applied as per IS-1893-Part 1 (2016)[15] (seismic force) and IS 875-Part3 (2015)[16] (wind forces). The structure has been analyzed for fixed base conditions. The fixed base reactions obtained after analysis are exported to SAFE v 16.0.0 for further foundation analysis.

Analysis of foundation is done in SAFE 2016, the method of analysis is based on Winkler's modulus of subgrade reactions. The foundation types are analyzed and verified for performance criteria, if failed then next foundation type is verified.

Raft foundation Analysis: Raft having overall 600mm projection beyond building line as per plot restriction, are of size 31.39 × 16.12 m is modeled as thin shell element. Thickness of raft is conservatively taken as 1000mm, in order to meet two-way (punching) shear requirements. The Winkler's soil-spring model or modulus of sub-grade reaction, K is calculated as;

$$K = \frac{\text{SBC of Soil}}{\text{Permissible settlement}} \tag{1}$$

Where, SBC of soil is 75 KN/m^2 for settlement of 75mm as per soil report.

Hence, $K = \frac{75}{75} \times 1000 = 1000\ \text{KN/m}^2/\text{m}$ is used.

Raft foundation is modeled in SAFE, with raft as thin shell element with automatically generated mesh (four noded rectangular element), soil subgrade modulus (Winkler's soil-spring) are provided below entire raft with K=1000 KN/m^2 /m. Figure 1 below shows 3-dimnesional view of raft foundation model. After analysis the settlement and bearing pressure are observed to be higher than permissible values.

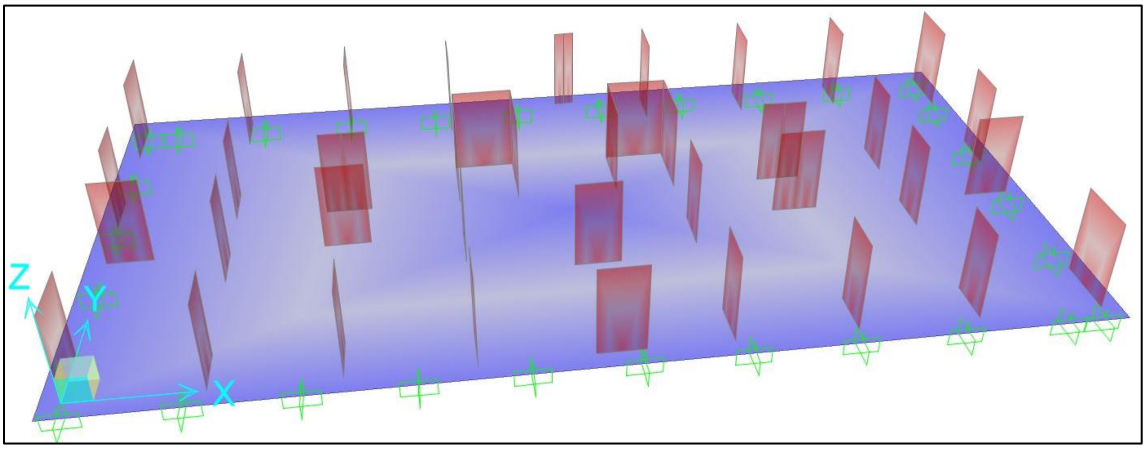

Figure 1: Raft foundation model with soil subgrade modulus

Pile foundation Analysis: Pile foundation system with uniform Pile-cap thickness of 1400mm is adopted (to meet anchorage-bond length requirements) which is supported over group of piles. Piles of diameter 600mm with length of 26.5m having 930KN and 42KN as safe vertical and lateral load carrying capacity respectively as per geotechnical report. The number of piles required are 190, which are provided with uniform spacing below entire pile cap. In SAFE, piles with uniform spacing are modeled as equivalent point spring below the raft with a uniform spacing of 2.8 times diameter of pile in both X and Y directions. The spring stiffness is calculated from the formula;

$$K = \frac{F}{\delta} \tag{2}$$

where, F= Pile capacity and Δ= Permissible settlement.

For Calculation of point spring values, inelastic settlement of axially loaded pile,

$$\delta = \frac{PL}{AE} = 3.183\ \text{mm} \tag{3}$$

Gross permissible vertical settlement of Pile as per soil report=14.6mm

Net permissible Settlement at the head of Pile =14.6-3.183=11.417 $\cong$ 10mm, Permissible Lateral deflection at cut of level as per soil report=5mm,

Hence, point spring values are $K_{vertical} = \frac{930}{10} = 93$ KN/mm for vertical and

$K_{lateral} = \frac{42}{5} = 8.4$ KN/mm for lateral pile displacement.

Pile foundation is modeled in SAFE, with overall pile cap as thin shell element with automatically generated mesh (four noded rectangular element), and individual point springs of stiffness $K_{vertical}$ = 93 KN/mm and $K_{lateral}$ = 8.4 KN/mm are provided at desired location of piles to support pile cap. Figure 2 shows 3-dimnesional view of pile foundation model.

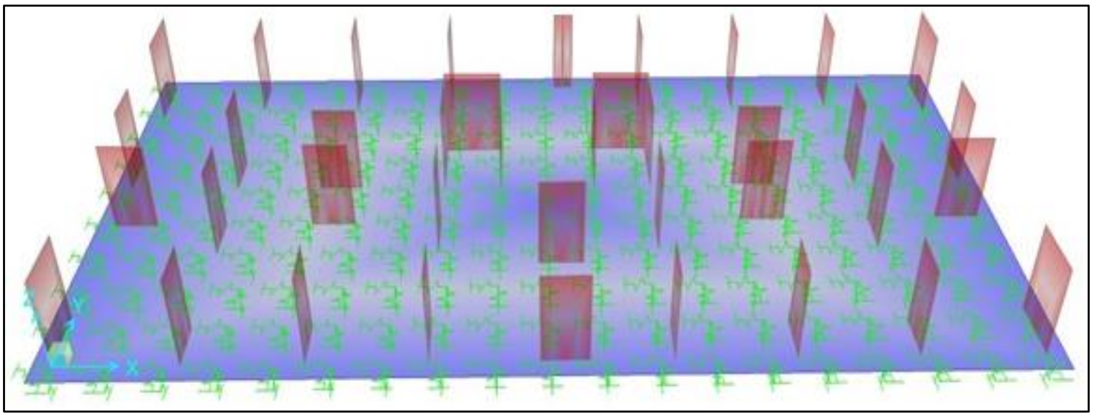

Figure 2: Pile foundation model with point springs

The settlement obtained from analysis are very conservative than permissible settlement and reaction on each pile is also lesser than safe load carrying capacity of pile i.e., 930KN. In this case the required number of piles are very high.

Piled-raft foundation Analysis: The philosophy of modeling piled raft can be achieved by combined load sharing between raft and piles, where piles are used up to its optimum capacity and balance loads will be share by raft. In this method, the piles are attached as point spring of equivalent stiffness while raft are modeled as thin shell element and soil support are as Winkler's subgrade reaction spring below raft. The basic difference between modeling of pile and piled-raft foundation is, the raft of piled-raft will be assigned soil supports, whereas pile-cap of pile foundation will not have any soil support it will rest on piles only. In piled raft foundation system, the soil below raft is modeled as Winkler's Subgrade reaction as in case of raft foundation, but here the settlement of raft will be restricted to 25mm for raft supported over piles, settlements higher than 25mm are not feasible for piled raft system. Hence, using equation (1), stiffness calculated as,

$$K = \frac{75}{25} \times 1000 = 3000 \text{ KN/m}$$

Now number of piles required by simplified method,

$$N = \frac{\text{Total load taken by piled-raft} - \text{Load taken by raft}}{\text{Increased capacity of pile}} \quad (4)$$

where, N= Number of piles required.
Ultimate Pile capacity = 2520 KN,

Instead with previous safety factor of 2.75 a lower factor of 2 will be adopted.

So, revised pile capacity for piled raft, i.e., $\text{Increase safe pile capacity} = \frac{2520}{2} = 1260 \text{ KN.}$

$$\therefore N = \frac{176580 - (31.39 \times 16.12 \times 75)}{1260} = 110.02$$

Using Equation (2),

$K_{vertical} = \frac{1260}{10} = 126 \cong 120 \text{ KN/mm},$ as spring stiffness with 126KN/mm was leading to loads slightly higher than 1260 KN in of some piles, hence in order to restrict loads on that piles, the stiffness of spring $K_{vertical}$ has been approximately reduced to a lower value of 120 KN/mm considering slight allowance for settlement as settlement in piles are conservative in this case.

Piled-raft foundation is modeled in SAFE, with raft as thin shell element with automatically generated mesh (four noded rectangular element), soil subgrade modulus (Winkler's soil-spring) are provided below entire raft with K=3000 KN/m. In addition to soil subgrade modulus, individual point springs of stiffness $K_{vertical}$ = 120 KN/mm and $K_{lateral}$ = 8.4 KN/mm are provided at desired location of piles to support the raft. This is a combined piled-raft modelling, in this model both supports from underneath soil and piles are considered, whereas previously in pile foundation model only piles and in raft foundation only underneath soil is used to support. Figure 3 below shows piled-raft foundation modelling with various spring support used to model.

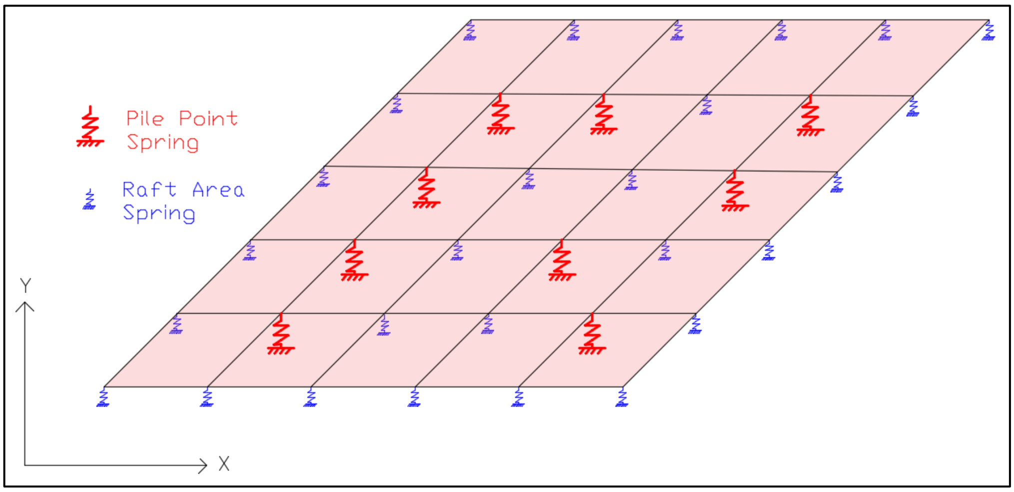

Figure 3: Piled-raft foundation with various types of springs

After Trial analyses, 112 Numbers of piles and 1000mm thick raft are required such that the point reaction of each pile is less than 1260 KN and bearing pressure, settlement of raft are also within permissible limits.

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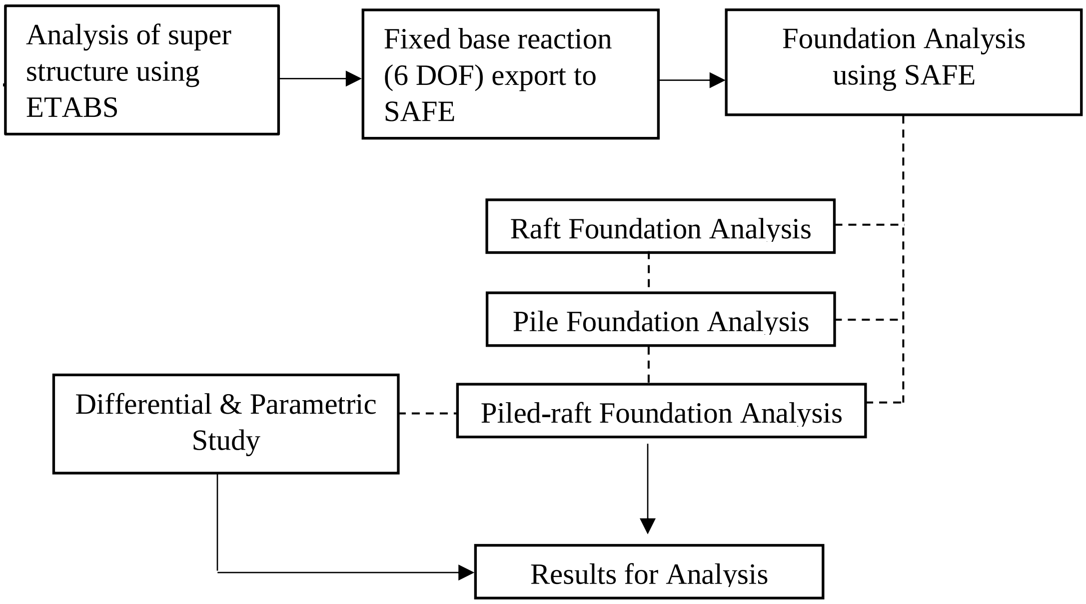
Analysis process flow chart



Results and Discussions: A Hostel building of B+G+15 upper floors have been analyzed with fixed bases. The base reactions were used to analyze the raft foundation system, which shown unsatisfactory performance with excessive settlements. Further, in order to restrict settlement pile foundation option was tried which although restricts the settlement within permissible limit but the required number of piles are very high leading to uneconomical foundation. Hence, piled-raft foundation system is adopted.

Raft foundation with raft of size 31.39 × 16.12m with uniform thickness of 1000mm has been used. The variation in settlement of raft is shown in figure 4.

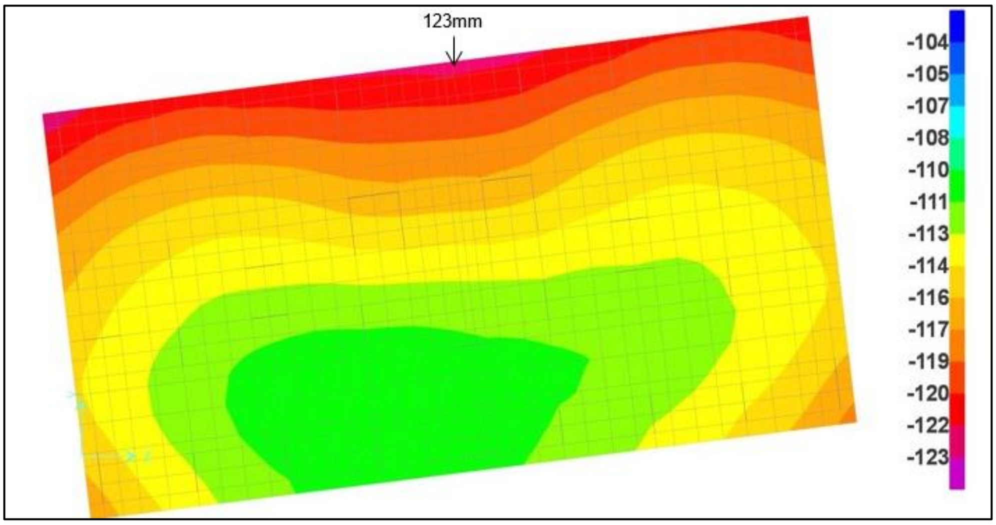


Figure 4: Variation in settlement of 1000mm thick raft foundation

The variation in bearing pressure of raft is shown in figure 5.

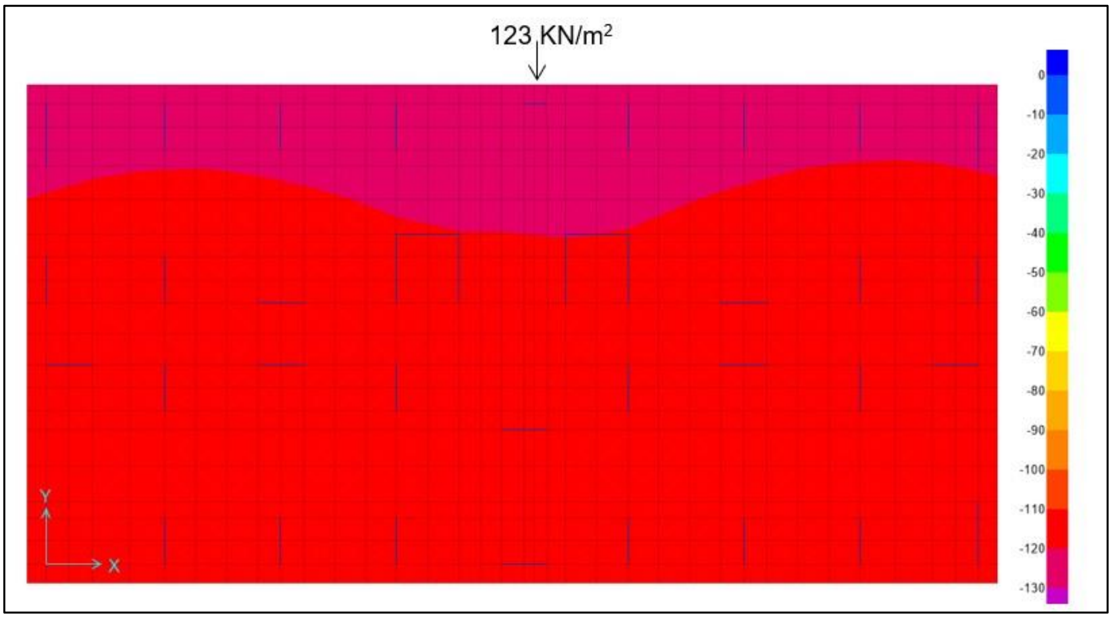


Figure 5: Variation in bearing pressure of 1000mm thick raft foundation

In figure 4, the settlement contours of 1000mm thick raft foundation shows that the settlement is in the range of 108mm to 123mm which higher than permissible limit of 75mm, whereas in figure 5, the corresponding bearing pressures are in the range of 100KN/m^2 to 123KN/m^2 which are also higher than S.B.C of 75KN/m^2.

Pile foundation with 1400mm thick uniform pile cap and Piles of 600mm diameter with 190 numbers of piles spaced at 2.8 times diameter of pile i.e., 1.68m center to center in both directions are used for analysis. The variation in settlement of pile cap of pile foundation is shown in figure 6.

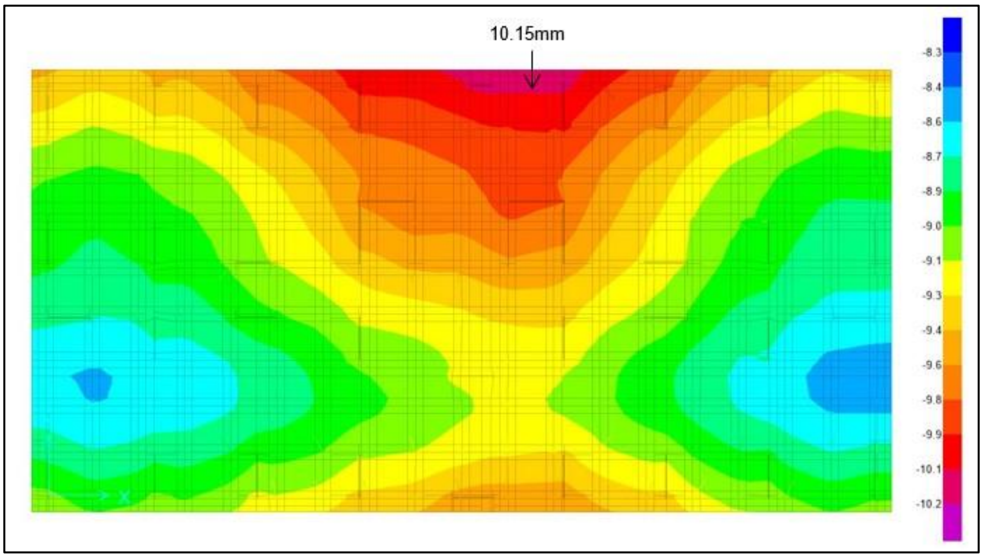


Figure 6: Variation in settlement of 1400mm thick pile cap

The reaction on each individual pile is checked to be lesser than pile group capacity. Figure 6 shows the settlement contours of pile cap for pile foundation system which is in the range of 8.4mm to 10.15mm. The settlement of pile cap is well within permissible limit of 75mm, but the required numbers of piles are very high.

Pile-raft foundation with 1000mm thick uniform raft, piles of 600mm diameter with 112 numbers of piles placed at 3.8 times diameter of pile i.e., 2.32m and 3.5 times diameter of pile i.e., 2.13m in

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X and Y directions respectively. As per Clause 6.9 of IS 2911-Part I/Sec-2 (1979)[17] and IS 1893-Part I (2016) the increase over safe load capacity of pile for lateral loads is up to 25%, considering it, the load combination with 1.0DL+1.0LL in our case seems to be critical load combination for analysis and design of the foundation system. Figure 7 shows the variation in settlement of raft in piled-raft foundation.

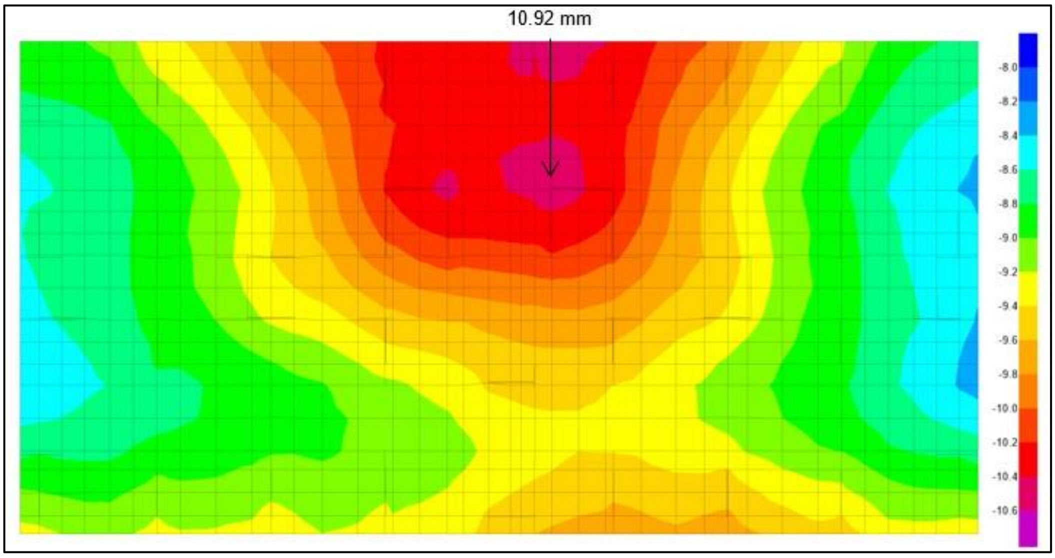

Figure 7: Variation of settlement of 1000mm thick raft of Piled-raft foundation

Figure 8 shows variation in bearing pressure on raft of pile raft foundation,

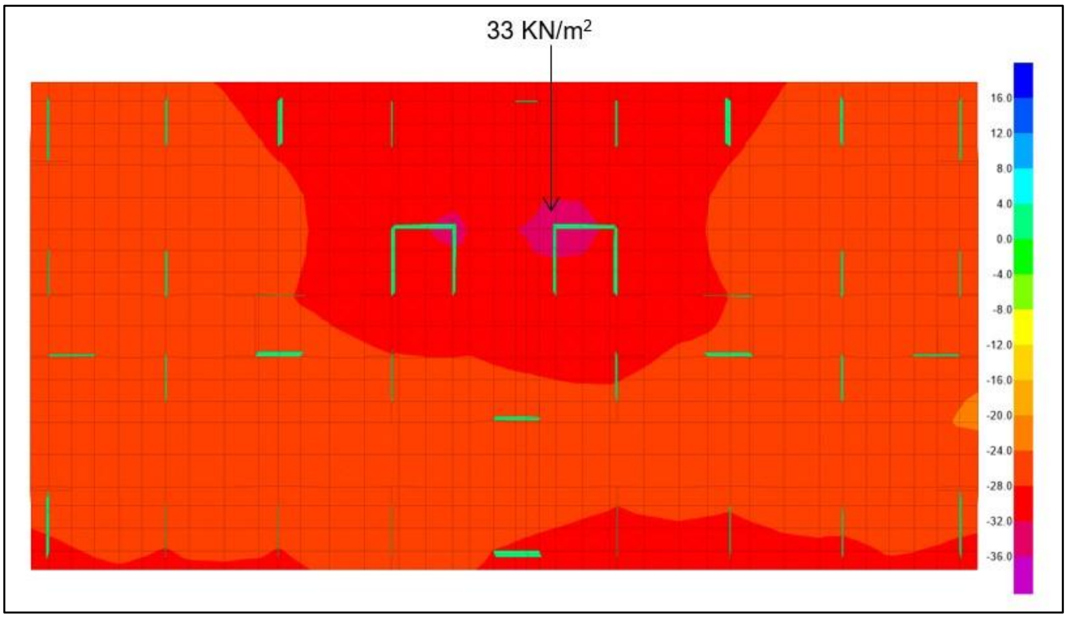

Figure 8: Variation in bearing pressure of 1000mm thick raft of Piled-raft foundation.

The load on each individual pile (point reactions on each of pile top) is verified to be lesser than capacity of pile with lower factor of safety of 2. The figure 7 shows the settlement contour of raft of Piled raft foundation is in the range of 0mm to 10.52mm. While in figure 8, soil pressure is up to 33 KN/m2. The settlement and soil pressure of raft is in permissible limit of 25mm and 75KN/m^2 respectively.

Effect of Strategic placement of piles with respect to differential settlement

The differential settlement is calculated as per cl.16.3.4 IS:1904-1986,
Differential Settlement = 10.925 – 7.95 = 2.975 mm;
Permissible differential settlement = 0.0025L = 38.475mm>2.975 mm, Hence SAFE.
Although differential is well within limits, but in order to study the effect of strategic placement of pile with respect to differential settlement the same has to performed, depending upon the settlement contour of raft of piled raft and reaction on piles, entire raft is divided in 3 zones symmetrically viz., Zone I for high loading zone, Zone II for intermediate loading zone and Zone III for lowest loading zone. Further, it has been noticed that the zoning of loads also depends on the location of columns. The pile spacing and arrangement of piles required are shown in figure 9.

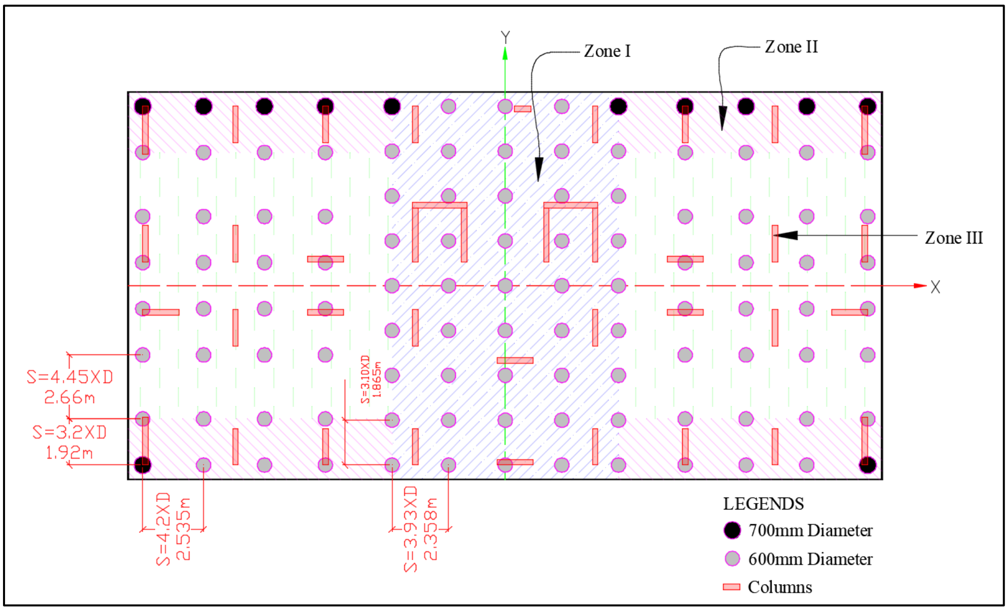

Figure 9: Arrangement of piles with strategic spacing

After analysis, the individual pile reaction is verified to be lesser than the capacity of each piles, settlement, differential settlement and bearing pressure below raft are also well within specified limits. The optimization by strategic placement can be tabulated as in Table1 below,

Table 1: Comparison of results of uniform spacing and strategic spacing of piles in piled-raft foundation

Description	Piles of Piled-Raft foundation		Reduction
	Uniform spacing	Strategic spacing	
Number of Piles	112	109	3
Bending Moment (kN-m)	788.79	652.27	17.3%
Shear Force (kN)	1129.81	936.3	17.1%

Parametric study of piled-raft foundation

Parametric studies are often used in optimization of piled-raft system. A through studies of it on a case basis can optimize the piled-raft system in terms of reduction in raft thickness, diameter, spacing, settlement, bearing pressure and loads on individual or group of piles. The parametric studies performed here are as follows;

Effect of varying length of pile for a diameter of pile: In this case effect of varying length of pile for same diameter of pile is studied, the shaft length of piles is varied from; 26.5m, 28m, 30m and 31.5m with diameter as 600mm each. It is observed that as L/d ratio increases the overall and differential settlement of piled-raft foundation decreases as shown in figure 10. Further, if L/d ratio increases load shared by pile also increases whereas load shared by raft decreases in piled-raft system. The negative bending moment increases while, positive bending moment decreases. Shear forces in raft is increased with increase in length of pile.

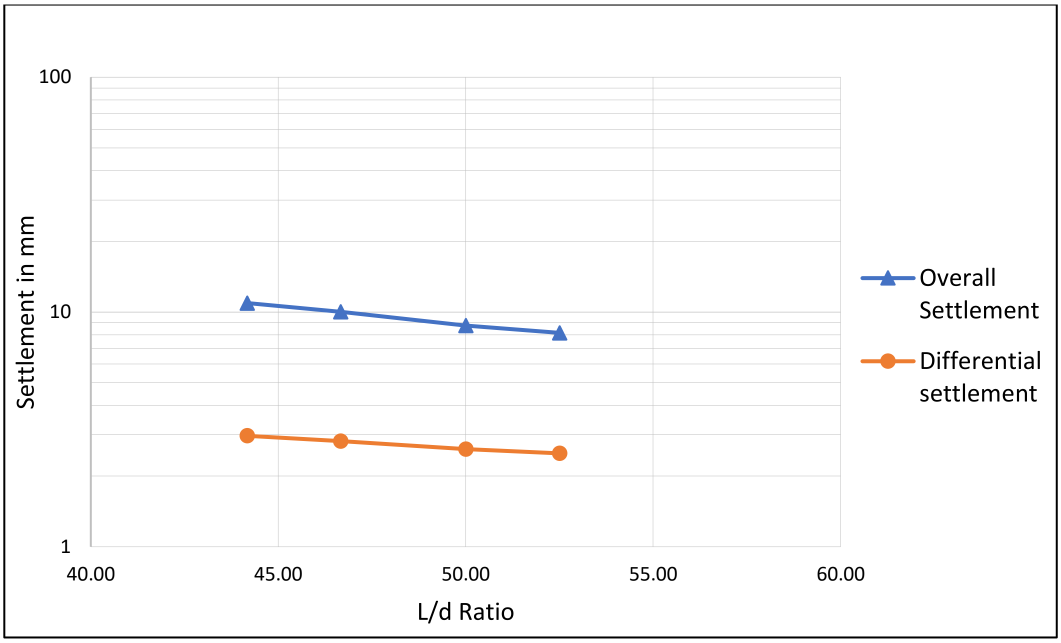

Figure 10: Effect of increase in length of pile on settlement of piled-raft

Effect of varying diameter of pile for a Length of pile: In this case effect of varying diameter of pile for a constant length of pile as 26.5m is studied, the diameter of piles is varied from; 600mm, 650mm, 700mm, 750mm, and 800mm. It is observed that as diameter of pile increases the overall and differential settlement in piled-raft system decreases. Further, if diameter of pile increases load shared by pile increases while load shared by raft decreases in piled-raft system as shown in figure 11. The negative bending moment increases whereas, positive bending moment decreases. Shear forces in raft is increased with increase in diameter of pile.

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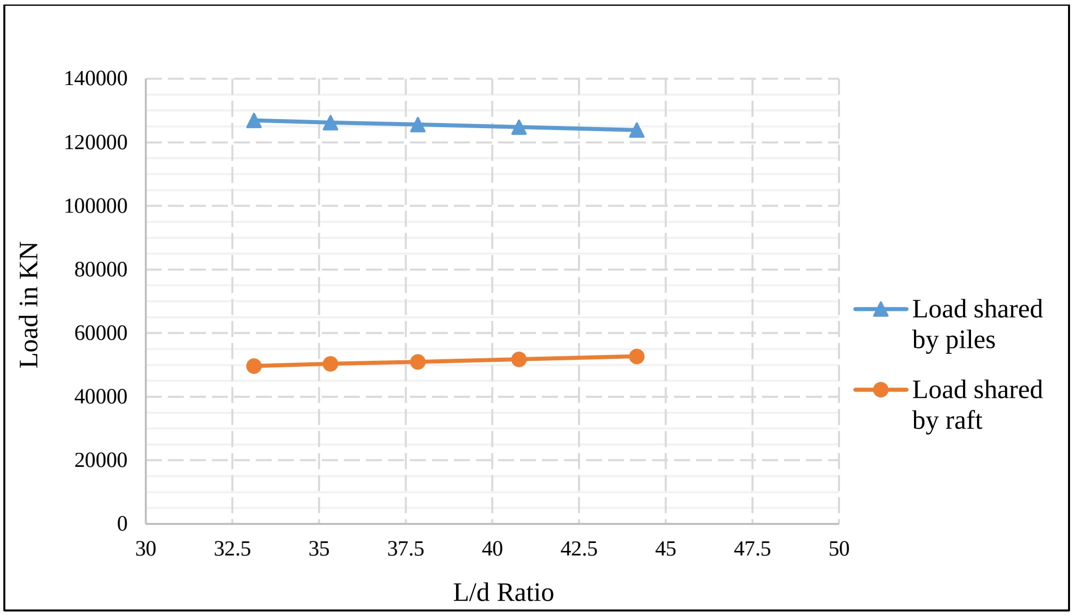

Figure 11: Effect of increase in diameter of pile on behavior of load sharing between pile and Raft

Effect of varying spacing of pile for a diameter of pile: In this case effect of increase in spacing between piles is studied, as spacing is increased the S/d ratio also increases. It is observed that if S/d ratio increases the overall and differential settlement of piled-raft foundation increases. Further, if S/d ratio increases load shared by pile decreases while load shared by raft increases in piled-raft system as shown in figure 12. Both bending moment and shear force increases with increase in S/d ratio.

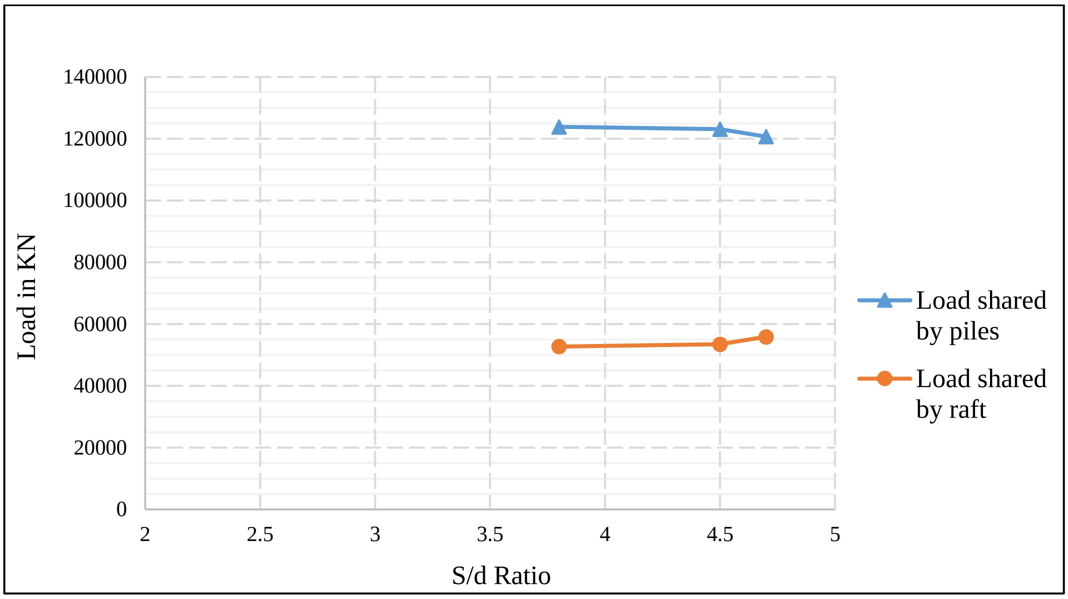

Figure 12: Effect of increase in spacing of pile on behavior of load sharing between pile and Raft

Effect of varying thickness of raft of piled-raft: In this case effect of increase in raft thickness of piled-raft is studied. It is observed that after increasing raft thickness there is decrease in settlement

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up to certain extent and beyond which further increase in raft thickness increases the settlement as shown in fig. 13,

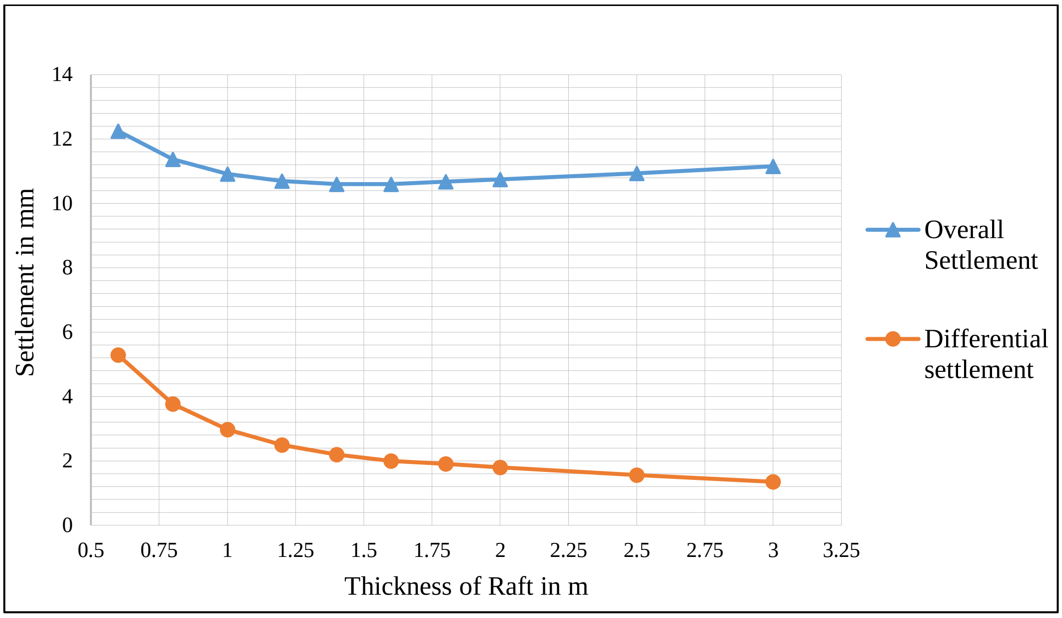

Figure 13: Effect of increase in thickness of raft on settlement of piled-raft

Initially, the thickness of raft was kept 0.8m corresponding settlement was 11.37mm. After increasing raft thickness in specific intervals up to 3m, it was found that settlement was found to be minimum of 10.6mm at a thickness of raft being 1.4m, after which it is observed that further increment in thickness increases the settlement. Increase in raft thickness increases the load shared by piles and also increases the bending moment and shear force in piled-raft.

Effect of varying soil stiffness on piled-raft: In this case effect of varying soil stiffness on piled-raft is studied. Initially, the stiffness of soil below raft of piled-raft is taken as 3000KN/m^3, the corresponding load shared between raft and pile is 52720.5KN and 123859.5KN respectively. After increasing stiffness of soil to 10000KN/m^3, it was found that load shared by raft also increases and correspondingly load shared by pile reduces as shown in figure 14. This means that stiffer the soil below raft, higher is the load shared by raft. Further, the overall and differential settlement decreases as soil stiffness is increased, while bending moment and shear forces increases as soil stiffness is increased.

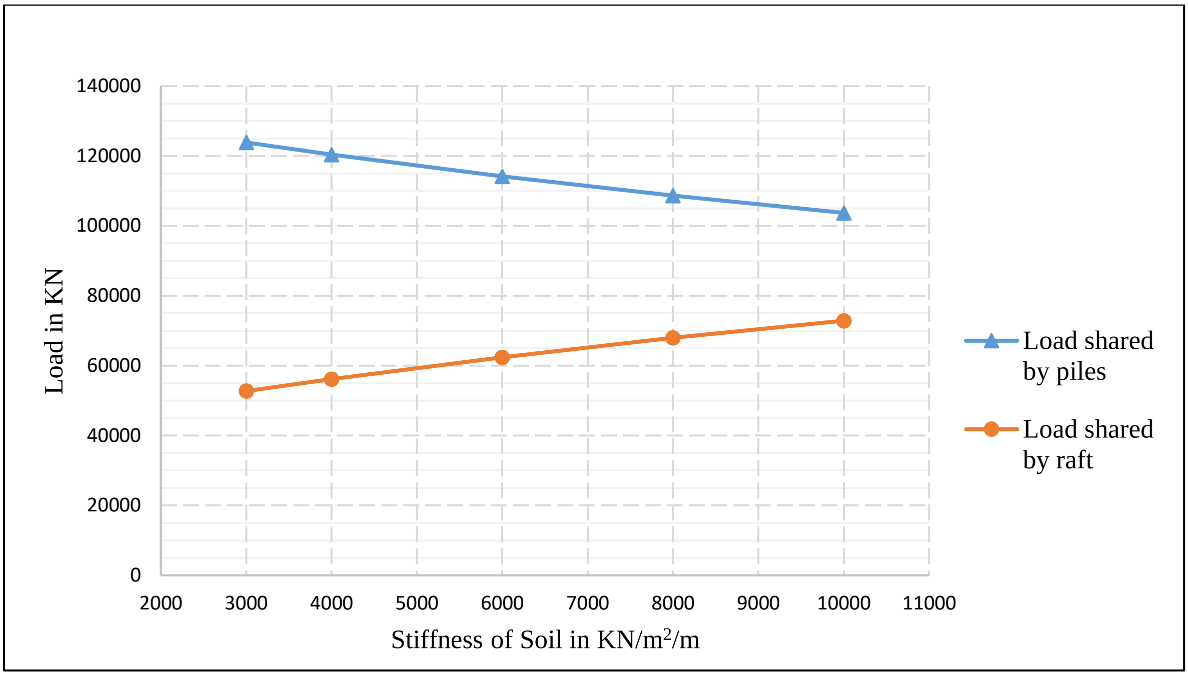

Figure 14: Effect of increase in stiffness of soil on settlement of piled-raft

1 Conclusions:

The comparative analysis of conventional raft foundation, pile foundation and piled raft foundation system has been performed by Winkler's approach. On the other hand, effect of strategic placement of piles and parametric studies are performed. On the basis of results the following categorized conclusion are made:

Analysis of Foundation systems:

- In case of raft foundation, settlement and soil pressure both are higher than permissible limits.
- In case of pile foundation, the settlement is well within limits, but required numbers of piles are very high.
- In case of piled raft foundation, required numbers of piles are lower than pile foundation; with soil pressure and settlements also well within permissible limits.
- Bending moment, shear force and settlement of foundation is considerably reduced in piled raft system, as both piles and raft shares the imposed loads.

Parametric Study of Piled-raft:

- Strategic placement of piles below higher load zone as per settlement contours reduces required number of piles and proves efficient piled raft action.
- Increase in length or diameter of pile, reduces settlement and differential settlement of piled-raft.
- Spacing of piles influences the load sharing behavior between piles and raft, higher the spacing higher the load share of raft of piled-raft.
- Increase in thickness of raft up to certain point shows reduction in settlement, further increment of thickness increases the settlement of piled-raft.
- Soil stiffness plays a key role in load distribution between piles and raft, higher is the stiffness of soil higher is the load share of raft of piled-raft.

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