INFLUENCE OF PILES ON LOAD-SETTLEMENT BEHAVIOUR OF RAFT FOUNDATION

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ABSTRACT: A raft foundation transfers load directly to the subsoil. The concept of piled raft foundation combines raft, subsoil and piles as load-bearing elements into a composite structure. The behaviour of the foundation system is determined by a complex interaction between the elements, and an understanding of this is essential for a reliable design. The study investigates the load-settlement behaviour of raft foundation when supported by both subsoil and piles by means of both simplified analysis and finite element analysis. The effects of number of piles, soil modulus and raft thickness are presented, and axial pile load distributions for different pile positions are discussed.

Keywords: Piled raft; soil stiffness; bearing capacity; settlement.

1. Introduction

Rafts are being increasingly used for buildings, with or without basement, even in subsoil conditions even with a high water table. If the soil shear strength is very low, long load-bearing piles are necessary to transfer the entire load to deeper and stiffer soil layers (Fig. 1). If the shear strength is adequate for giving the required bearing capacity of only a raft foundation, the settlement may be very large. For such situations, a piled raft foundation can be opted to reduce settlements. The most effective application occurs when the raft can provide adequate load capacity, but the total or differential settlements of the raft alone exceed the allowable values. In cases where the soil conditions allow the raft to develop adequate capacity and stiffness, this foundation system will be very suitable. It is not an effective option if soft clays or loose sands exist near the surface. The applicability of this foundation concept is also limited in cases of stratified subsoil with large differences in the stiffness of particular layers.

The piled raft foundation consists of three load-bearing elements: piles, raft and subsoil. According to their stiffness, the raft distributes the total load transferred from the structure as contact pressure below the raft and load over each of the piles. In conventional foundation design, it has to be shown that either the raft or the piles will support the building load with adequate safety against bearing capacity failure and against loss of overall stability. In piled raft foundation, the contributions of the raft and piles are taken into consideration to verify the ultimate bearing capacity and the serviceability of the overall system. Several studies of analyzing piled rafts have been reported in the literature. The approaches can be divided into simplified analytical methods and numerical methods such as finite element methods, boundary element methods or hybrid methods, all with various assumptions and constitutive laws.

Randolph (1994) presented new analytical approaches for the design of pile groups and piled raft foundations to focus on the settlement issue rather than the capacity. An equivalent pier analogue of pile groups and piled raft was proposed as the most direct method of estimating the stiffness of the foundation. Design principles were introduced for piled rafts with the aim of minimizing differential settlements by optimal location of the piles beneath the raft.

Russo (1998) presented an approximate numerical method for the analysis of piled raft foundation, in which the raft is modelled as a thin plate and the piles as interacting non-linear springs. Both the raft and the piles are interacting with the soil which is modelled as an elastic layer. Two sources of non-linearity are accounted for: the unilateral contact at the raft-soil interface, and the non-linear load-settlement relationship of the piles. Both theoretical solutions and experimental results were used to verify that, despite the approximations involved, the proposed method of analysis can provide satisfactory solutions in both linear and non-linear range.

Prakoso and Kulhawy (2001) analyzed piled raft foundation using simplified linear elastic and nonlinear plane strain finite element models. The effects of raft and pile group system geometries and pile group compression capacity were evaluated on the average and differential displacements, raft bending moments, and pile butt load ratio. The results were synthesized into an updated, displacement-based, design methodology for piled rafts.

Poulos (2001) demonstrated three different stages of design for piled raft foundation. In the first stage, the effects of the number of piles on load capacity and settlement are assessed through an approximate analysis. The second stage is a more detailed examination to assess where piles are required. The third is a detailed design phase in which a more refined analysis is employed to confirm the optimum number and location of the piles. Procedures for estimating the necessary geotechnical parameters are also described.

Reul (2004) compared the bearing behaviour of a single pile, a freestanding pile group and a piled raft in overconsolidated clay by means of three-dimensional finite-element analysis, and demonstrated the influences of pile-pile interaction and pile-raft interaction. As a result of pile–raft interaction the skin friction was shown to increase with an increase in load or increase in settlement. It was also shown that under practically relevant loads, the piles of a piled raft do not reach their ultimate bearing capacity.

Sanctis and Mandolini (2006) proposed a simple criterion to evaluate the ultimate vertical load of a piled raft from the separate ultimate capacities of its components (the raft and the pile group) based on both experimental evidence and three dimensional finite-element analyses. The proportion of the load taken by the raft at failure is typically less than unity, depending on the pile layout and geometry. The ultimate capacity of the piled raft is at least 80% of the sum of the ultimate capacities of the separate components.

One of the important uses of the analysis is to assess how many piles are required to achieve the desired performance. The attempt is to utilize a significant part of the available capacity of the piles. This paper presents the results of two different types of analysis for the load-settlement behaviour of piled raft foundation, namely simplified analysis using MATLAB program and finite element analysis using ANSYS software.

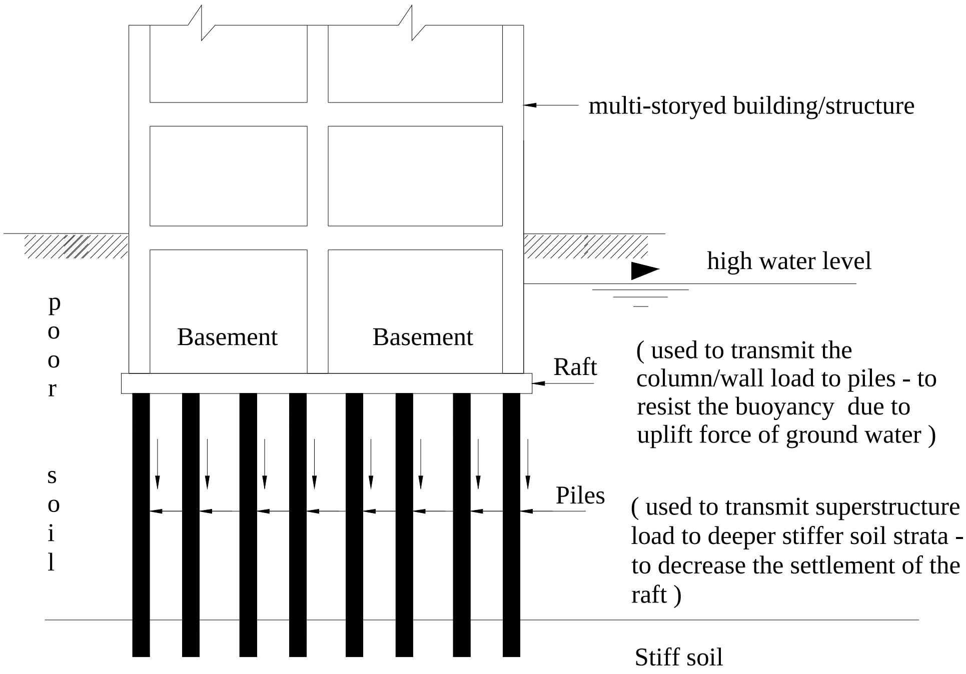


Fig. 1. Load transfer from raft to subsoil and piles.

2. Simplified Analysis

This method is based on the solutions of Randolph (1994) and Poulos (2001). The analysis is illustrated through a rectangular raft of 10 m x 6 m in plan and 0.5 m thickness supported by 15 piles of 0.5 m diameter and 10 m length. The layout of piles is depicted in Figure 2. The applied superstructure load is 12,000 kN. The elastic modulus and Poisson's ratio of the soil and raft/pile are 0.3, 0.2 and 20 MPa, 30,000 MPa respectively. The results of the analysis are presented in Table 1 with the various symbols defined. Other symbols are: X = Ratio of piled raft stiffness to raft stiffness; Bp = proportion of load carried by piles; and V_A = load level at which the full capacity of piles is reached. It can be noted that the pile group capacity is fully mobilized when the total applied load reaches a magnitude of 9990 kN. As the total load is increased further, the additional load is borne by the raft only. Figure 3 shows the proportions of the total applied load that are carried separately by the piles and the raft, whereas the load-settlement curve of the piled raft is illustrated in Figure 4. At the design total load of 12,000 kN,

Load carried by piles = 7,660 kN = 63.8% of total load

Load carried by raft = 4,340 kN = 36.2% of total load

The settlements at the design load are: Elastic settlement = 67 mm; Consolidation settlement = 28 mm

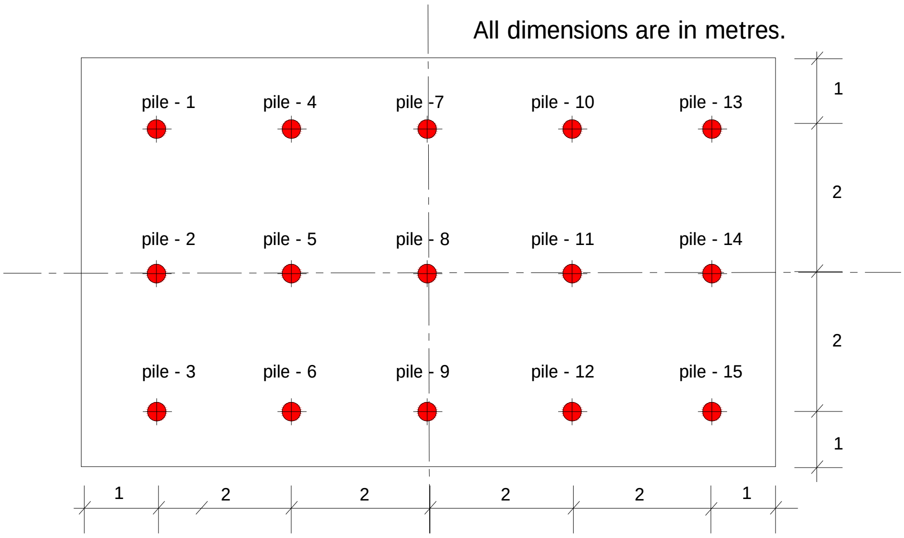


Fig. 2. Layout of piles under raft.

Table 1. Load distribution and settlement of piled raft.

Total load (MN)	Stiffness (MN/m)		X	Bp	Load on (MN)		V_A	Settlement (mm)			
	Pile group	Raft			Pile group	Raft		Imme-diate	Conso-lidation	Differ-ential	Total
V	Kp	Kr			Vp	Vr	MN	Si	Sc	Sdiff	St
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
0.00	456.19	192.10	1.023	0.887	0.00	0.00	8.63	0.00	0.00	0.00	0.00
1.65	412.62	190.53	1.023	0.887	1.46	0.19	8.63	3.91	3.84	0.60	7.75
3.30	370.53	188.54	1.026	0.872	2.88	0.42	8.78	8.67	7.68	1.33	16.35
4.95	330.46	185.98	1.030	0.854	4.22	0.72	8.97	14.53	11.52	2.22	26.05
6.59	293.16	182.64	1.035	0.830	5.47	1.12	9.23	21.73	15.36	3.33	37.09
8.24	259.53	178.25	1.041	0.801	6.60	1.64	9.56	30.50	19.20	4.67	49.70
9.89	230.41	172.59	1.049	0.766	7.58	2.31	9.99	40.92	23.04	6.26	63.97
11.54	228.10	159.33	1.049	0.766	7.66	3.88	9.99	59.93	26.88	9.20	87.00
13.19	228.10	145.42	1.049	0.766	7.66	5.53	9.99	84.14	30.73	12.68	113.56
14.84	228.10	131.51	1.049	0.766	7.66	7.18	9.99	115.81	34.57	16.76	144.05
16.49	228.10	117.59	1.049	0.766	7.66	8.83	9.99	159.09	38.41	21.66	179.89
18.13	228.10	103.68	1.049	0.766	7.66	10.48	9.99	221.27	42.25	27.65	222.88
19.78	228.10	89.76	1.049	0.766	7.66	12.12	9.99	316.06	46.09	35.25	276.33
21.43	228.10	75.85	1.049	0.766	7.66	13.77	9.99	471.46	49.93	44.33	339.51
23.08	228.10	61.94	1.049	0.766	7.66	15.42	9.99	751.75	53.77	115.09	805.52

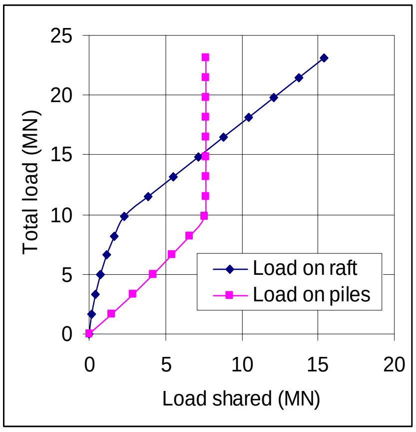


Fig. 3. Sharing of applied load between piles and raft.

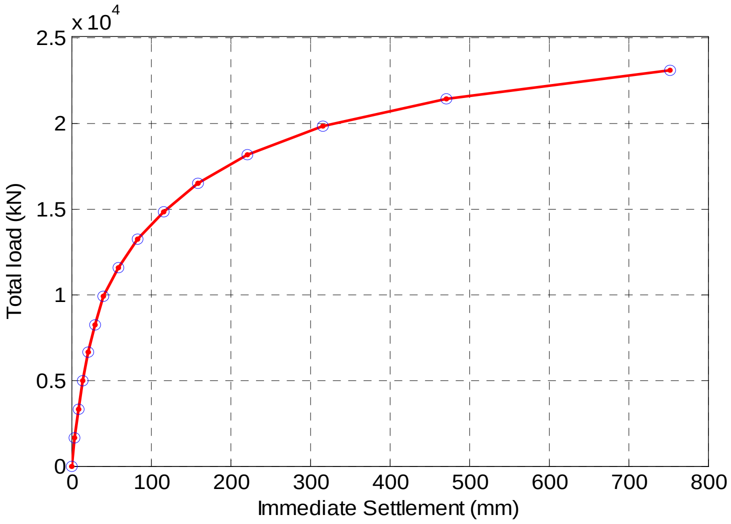


Fig. 4. Load-settlement curve of piled raft.

This concept of using the piles as settlement reducers can lead to a foundation with fewer piles than in a conventional design, but which can still satisfy the specified design criteria of ultimate load capacity and settlement. Figure 5 summarizes the relationship between average settlement and number of piles. It can be seen that beyond about 18 piles, the additional reduction in settlement is very small. Clearly then, there is scope for economy in foundation design by carrying out analyses to assess the minimum number of piles to achieve the required settlement performance. The conventional approach of assuming that the entire load should be carried by the piles can lead to an over-conservative and uneconomical design.

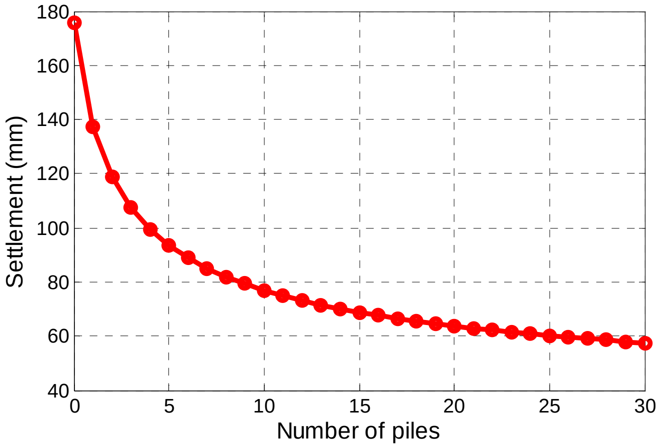


Fig. 5. Influence of number of piles on settlement of piled raft.

3. Finite Element Analysis

In this analysis, a raft of 16 m x 16 m with 16 square piles of 0.4 m x 0.4 m size and 12 m length has been considered in cohesive soil deposits. Only the raft part of the foundation is analysed first, and then piles are added to form a piled raft. Since the foundation structure is symmetrical, ¼ of the plan area (8 m x 8 m) is taken for modelling and analysis. The soil boundary is taken as double of the dimensions of the raft area being considered. The depth of the soil is taken as 3 times the raft length (i.e. 48 m), and is divided into two parts: an upper part of 12 m equal to the length of piles and a lower part of 36 m.

The soil and raft parameters are given in Table 2 and the non-linear behaviour of the soil is depicted in Table 3. Load incremental Newton-Raphson method has been used for solving the non-linear equations involved in the analysis. In this method the load is applied in increments, and in each increment successive iterations are performed, and the stiffness matrix is updated. After the completion of every iteration, the total unbalanced loading is calculated and added to the next step to compute an additional increment of displacement.

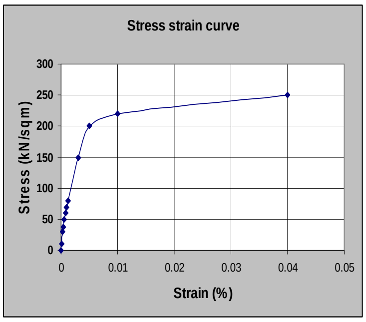
Table 2. Soil and raft parameters.

Property	1st analysis	2nd analysis	3rd analysis
Modulus of soil, E_s (kN/m^2)	25,000	50,000	1,00,000
Poisson's ratio of soil, μ_s	0.45	0.45	0.45
Cohesion of soil, c (kN/m^2)	20	50	83.4
Modulus of raft, E_r (kN/m^2)	2 x 10^7	2 x 10^7	2 x 10^7
Poisson's ratio of raft, μ_r	0.3	0.3	0.3
Raft thickness, t_r (m)	0.50	1.00	2.0

Table 3. Stress-strain data of soil.

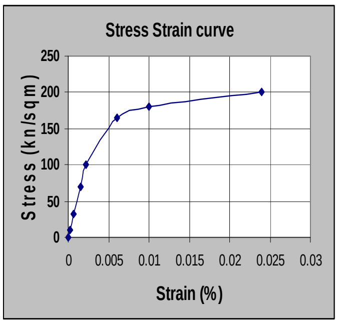
E_s = 100,000 kN/m^2

Stress (kPa)	Strain (%)
0	0
10	0.0001
30	0.0003
38	0.0004
50	0.0006
60	0.0008
70	0.001
80	0.0012
150	0.003
200	0.005
220	0.01
250	0.04



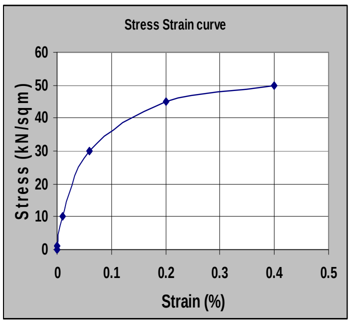
E_s.= 50,000 kN/m^2

Stress (kPa)	Strain (%)
0	0
10	0.0002
32	0.00066
70	0.0015
100	0.0022
165	0.006
180	0.01
200	0.024

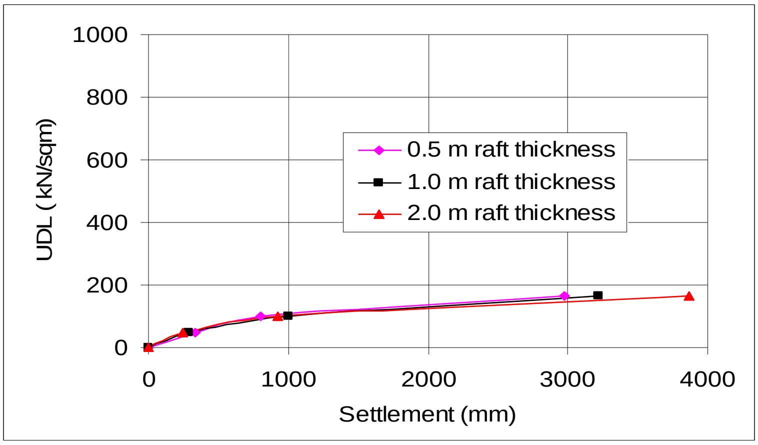


E_s.= 25,000 kN/m^2

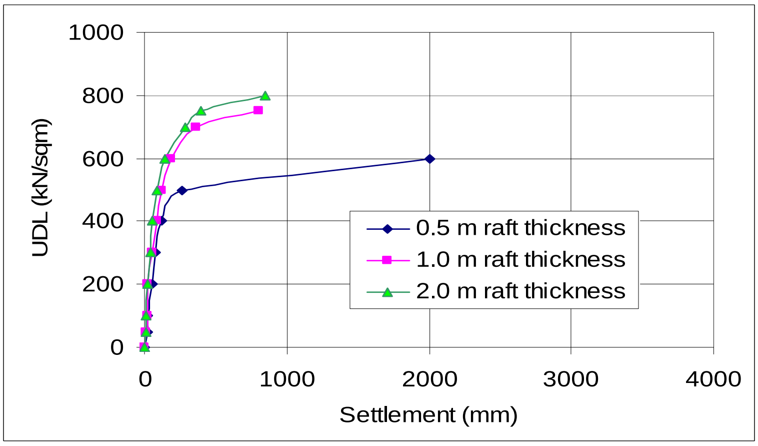
Stress (kPa)	Strain (%)
0	0
1	0.00004
10	0.01
30	0.06
45	0.2
50	0.4



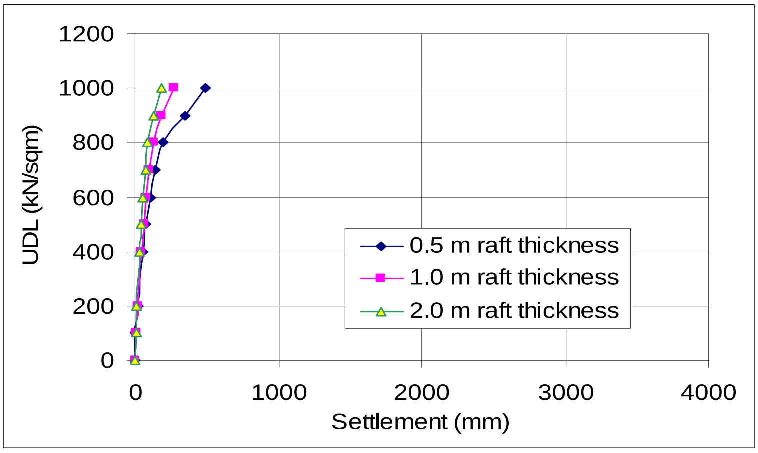
Figures 6(a-c) show the effect of raft thickness on the behaviour of the raft for different soil stiffnesses. It can be noted that for the soft soil (E_s = 25,000 kN/m^2), the load-settlement curves are almost the same for all the three values of thickness ranging from 0.5 to 2.0 m. This is on account of the interaction effect between the raft and the subsoil, as a result of which even a thin raft in a soft soil shows rigid behaviour. As the soil becomes stiffer, the settlement also decreases. A raft in soil with a high modulus becomes flexible, and hence the thickness has to be increased for it to regain rigid behaviour. For stiffer soils, the initial portion of the curve is linear but it bends as the load is increased. At higher load levels, there is a rapid increase in settlement.



(a) E_s = 25,000 kN/m^2



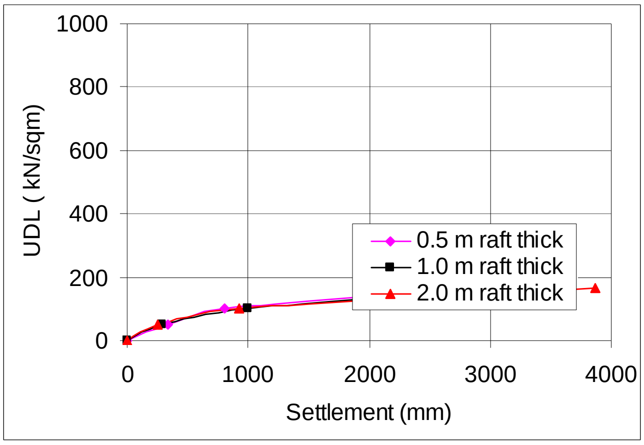
(b) E_s = 50,000 kN/m^2



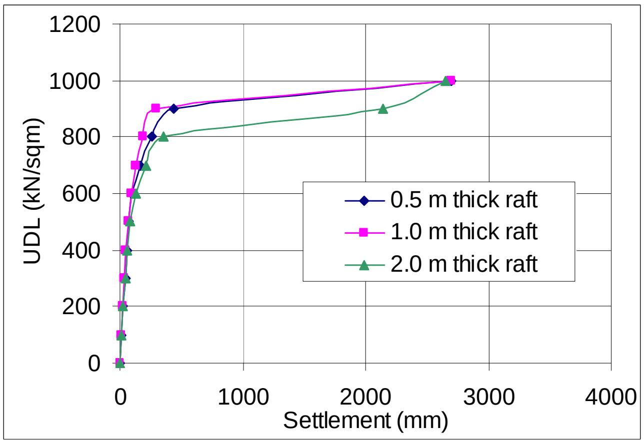
(c) E_s = 100,000 kN/m^2

Fig. 6. Influence of soil modulus and raft thickness on load-settlement behaviour of raft.

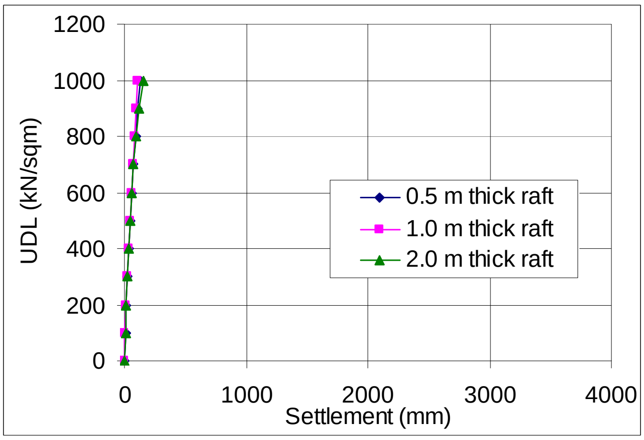
Figures 7(a-c) show the effects of soil modulus and raft thickness on the on the load-settlement behaviour of the piled raft foundation. It can be seen that in the soft soil, the plots are almost the same for all the thicknesses up to 2.0 m. This is mainly due to soil-structure interaction effect, as a result of which even a thin raft with piles 12 m long in a soft soil shows rigid behaviour. As the soil modulus increases, the settlement is observed to decrease substantially. At any loading intensity, the contact stress was found to be lower in the central portion and was higher near the corners. With increase in loading intensity, the contact stress tended to become more uniform.



(a) E_s = 25,000 kN/m^2



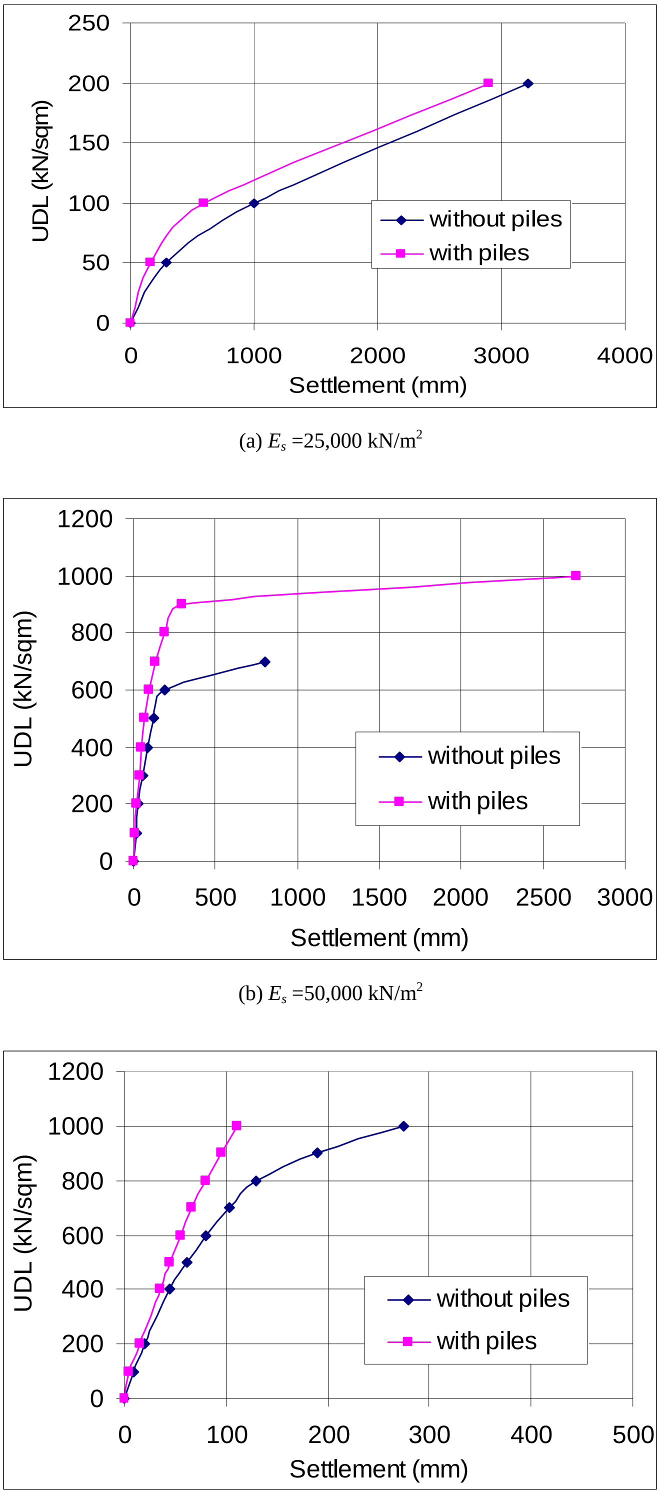
(b) E_s = 50,000 kN/m^2



(c) E_s = 100,000 kN/m^2

Fig. 7. Influence of soil modulus and raft thickness on load-settlement behaviour of piled raft.

The load-settlement curves of the raft and piled raft are depicted together in Figures 8(a-c) for a raft thickness of 1.0 m. From the plots, it can be noted that addition of piles increases the load-carrying capacity of a raft foundation with a reduction in settlement. A piled raft has a greater ultimate load-carrying capacity and undergoes less settlement than the raft alone. The improvement is found to be more for stiffer soils. Increasing raft thickness does not always improve the behaviour of the foundation, and the optimum raft thickness should be determined from a parametric analysis.



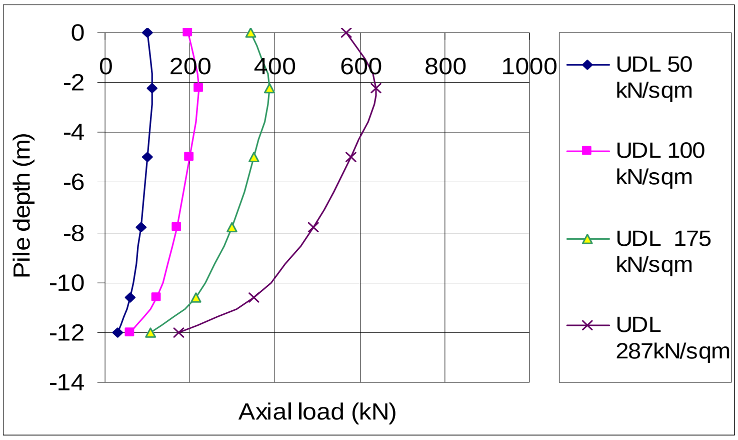
(a) E_s =25,000 kN/m^2

(b) E_s =50,000 kN/m^2

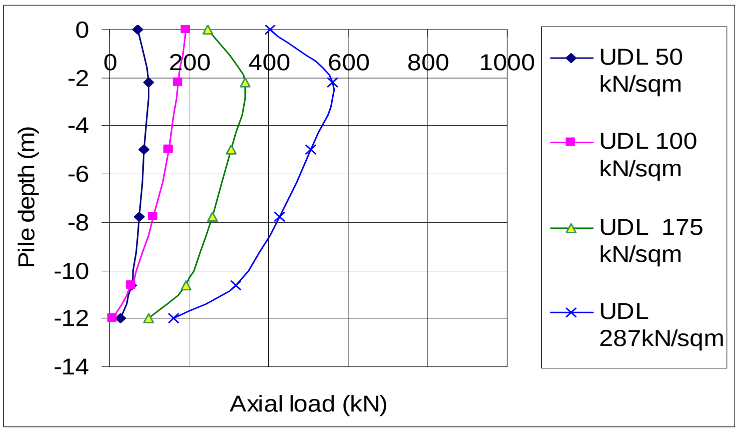
(c) E_s = 100,000 kN/m^2

Fig. 8. Comparison of load-settlement behaviour of raft and piled raft.

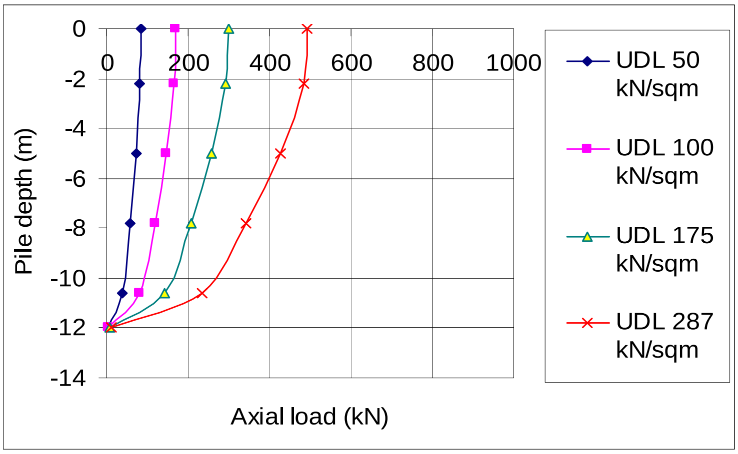
Figure 9 shows the axial load distribution in the piles. The axial load is observed to be a maximum at the top of the pile, and it reduces with depth reaching a minimum at the tip of the pile. With increase in load intensity, the axial load in the pile increases. The piles reach their ultimate capacities earlier than the raft in piled raft foundation. The figure also shows that at any load intensity, the corner pile carries the maximum load, followed by the edge pile and then the centre pile, which carries minimum load. It was also observed that the corner pile reached its ultimate capacity at least settlement, followed by the centre and edge piles at higher settlements.



(a) corner pile



(b) edge pile



(c) centre pile

Fig. 9. Axial load distribution on piles (E_s = 50,000 kN/m^2, Raft thickness = 0.5 m).

4. Conclusions

Based on the simplified analysis, it is found that the load sharing ratio between piles and raft depends on the settlement of the piled raft, and there is no linear relation between them. The addition of even a small number of piles increases the load-carrying capacity of the raft foundation. The piles reach their ultimate capacity earlier than the raft. Increasing the number of piles does not produce the best foundation performance, and there is an upper useful limit. Based on the finite element analysis, it is found that the value of contact stress is found to be a minimum at the centre of the piled raft and is a maximum at the corner. The raft thickness affects differential settlement, but has little effect on maximum settlement or load sharing of the piled raft foundation. For control of differential settlement, optimum performance can be achieved with a small number of piles placed in the central portion, rather than using a large number of piles evenly distributed over the raft area.

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