A Study of Piled Raft Foundation

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Abstract. Now a days Piled Raft Foundation are increasingly being used not only in developed countries but also in developing countries like India. This paper is based on the study of piled raft foundation constructed in Uttarakhand, India, with the help of Finite Element software ELPLA and Finite Difference software GROUP. In analysis with ELPLA methods considered are Linear as well as Non-linear method such as Hyperbolic stress-strain function and method as per DIN (4014) standard. The software is validated with results of the on-site Pile Load-settlement test conducted on individual pile. The results are compared also with analysis carried out using PLAXIS 3D.

Keywords: Piled Raft, ELPLA, GROUP, Nonlinear Hyperbolic stress-strain function for soil and DIN (4014) standards, Plaxis3D.

1 Introduction

In the conventional design of pile foundations, the entire load of the structure must be carried safely by the piles. Those parts of the load which are directly transmitted by the raft are normally ignored in calculating the overall stability of a pile foundation. The use of piled raft foundation is an effective way of minimizing both total and differential settlements, of improving the bearing capacity of a shallow foundation, and of reducing in an economic way the internal stress levels and bending moments within a raft. This concept of piled rafts combines the load-bearing elements of the piles, raft and soil in a composite structure. Zeevert advocated piled rafts under the weak clay conditions of Mexico City, and measurements for piled rafts in stiffer clay were reported by Cooke et al. The use of piles as settlement reducers was outlined by Burland et al., with the piles below rafts designed to reach their failure state under working load. Mandolini/ Viggiani (1997), (1998) and Russo (1998) considered piles as nonlinear interacting springs based on the method of interaction factors. A piled raft foundation is a hybrid foundation system that combines the bearing capacity of a foundation raft and piles or barrettes. This paper is about analyzing the re-designed piled foundation, on which an Industrial RCC Building of about 35m height is to be constructed. The site is situated in Uttarakhand India. The revised foundation design has been analyzed using the finite-element-based software ELPLA and finite-difference-software GROUP. The obtained results are compared with finite-element-software PLAXIS3D. The analysis carried out with above software are based on soil data provided by geotechnical investigation report.

The influence of the piles to reduce the settlements of a raft depends on the piled raft coefficient, which in turn depends on the subsoil conditions and the geometric proportions of the piled raft. For the same subsoil conditions and same area of the raft, the piled raft coefficient is a function of the number and length of the piles. The concept of piled raft foundation is by no means new, and has been described by several authors, including Zeevaert, Davis and Poulos, Hooper, Burland et al., sommer et al., Price and Wardle and Franke, among many others.

2 Site soil condition

As per report, soil investigation involved the drilling of the three-bore hole. Standard Penetration test was also carried out. From which it is concluded that site is predominantly consists of clayey silt to sandy silt layers with few interbedded layers of sand. However, in most of the cases, % of silt fraction are more than 50, which indicate that strength behavior of these silt layer can be conservatively estimated as fine grained soil in presence of free water i.e. below water table/saturated conditions. In absence of sufficient lab tests data for drained and undrained soil strength assessment, pile capacity calculations in the soil investigation data, largely depend upon the SPT N-values. Top 3 m soil will be excavated and removed from the foundation thereby reducing severity of the liquefaction susceptibility on the foundation as whole. The geotechnical properties of each layer are given in Table 1. Fig 1. Indicates borehole data considered for numerical analysis.

3 Loading details

There are structures in utility building within the construction site of area 40m x 30m. Bored cast-in situ piles are selected for all structures as per the soil investigation report. More than 90% of the piles were misaligned (minor to major, leading to severe eccentricity of loading) during the construction process which indicates poor construction supervision and inappropriate construction methods were practiced at site (or there may be wrong layout reference for pile construction). The thickness of raft for utility area is kept as 1.0 m. The utility building is divided into chiller building (PC 2 to 21) and office building (PC 4A,4B,5 and 6). In which the pile length of chiller building is 15m whereas of office building is of 18 m. There are total of 12 pile caps in the chiller building area and 4 in the office building area the loading details of the foundation of utility area is shown in Table 2.

Table-1 Geotechnical Properties for soil Layers

Layer No.	Depth (m)	Thickness (m)	Soil Type	Bulk Unit weight (kN/m3)	Saturated Unit weight(kN/m3)	Cohesion (kPa)	Friction angle (ϕ)	Young's modulus (MPa)	Poisson's ratio (μ)	Soil Model- Mohr Coulomb	SPT 'N'
1	3	3	Fill (Ignored)	19	20	0	32	40	0.32	Drained	18
2	4.5	1.5	Silty fine sand	19	20	0	30	40	0.32	Drained	20
3	6	1.5	Clayey Silt(CL)	18.63	20	30	0	8	0.35	Undrained	21
4	7.5	1.5	Silty Clay	18.63	20	40	0	10	0.49	Undrained	7
5	9	1.5	Silty Clay	19.03	20	55	0	15	0.35	Undrained	10
6	12	3	Silty Clay	19.03	20	30	0	8	0.4	Undrained	17
7	15	3	Silty Clay	19.03	20	50	0	20	0.3	Undrained	17
8	18	3	Sandy Silt	19.22	20	0	32	40	0.33	Drained	26
9	21	3	Silty Clay	19.62	20	140	0	80	0.4	Undrained	37
10	24	3	Silty Clay	20.01	21	90	0	60	0.42	Undrained	37
11	27	3	Silty Clay	20.5	20	90	0	60	0.42	Undrained	48
12	29	2	Silty fine Dense sand	20.5	20	0	32	40	0.32	Drained	-
13	32	3	Very stiff low plastic clay	20.5	20	100	0	70	0.42	Undrained	-
14	40	8	Fine sand with Gravel	20.5	20	0	34	80	0.3	Drained	-
Note: Fill layer is ignored while routine pile load tests validation.											

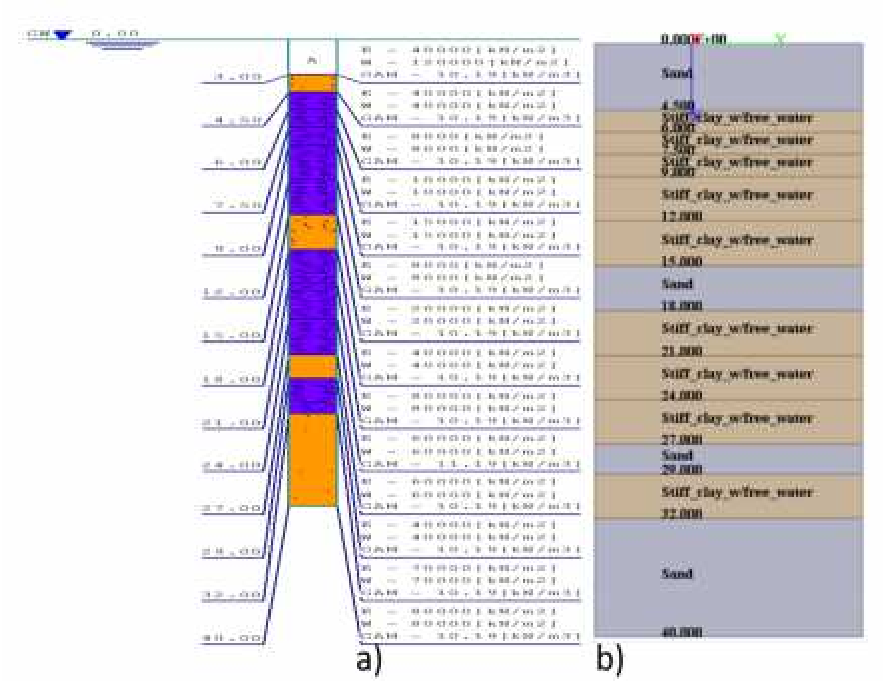


Figure 1: Bore hole data considered for numerical analysis a) ELPLA Borehole data b) Group Borehole data

4 Field routine compression load test on pile and validation of ELPLA model

On the site routine compression pile load test conducted are validated with the developed numerical model in order to simulate actual field condition, four numbers of vertical pile load tests were conducted at the site as per IS 2911:part 4, on bored cast-in situ pile of diameter 600 mm and length 18 m. The tests were conducted up to test load of 930 KN. All the four pile-load test attained different settlement levels at the same load of 930 KN. To decide the reliability of the output using a computer-based method, model of single pile is analyzed with ELPLA software in order to simulate field test results. A single pile was modeled considering raft of zero mm thickness, and zero-unit weight. The load- settlement curve developed by using ELPLA is on the conservative side when compared with Test-1 and Test-3. However, the developed curve is clearly validating with the worst-case scenario i.e. Test-1 up to working load. Hence, it can be established that numerical model simulated in ELPLA is in close agreement with the test load result both qualitatively and quantitatively as compared to field condition, Fig.2.

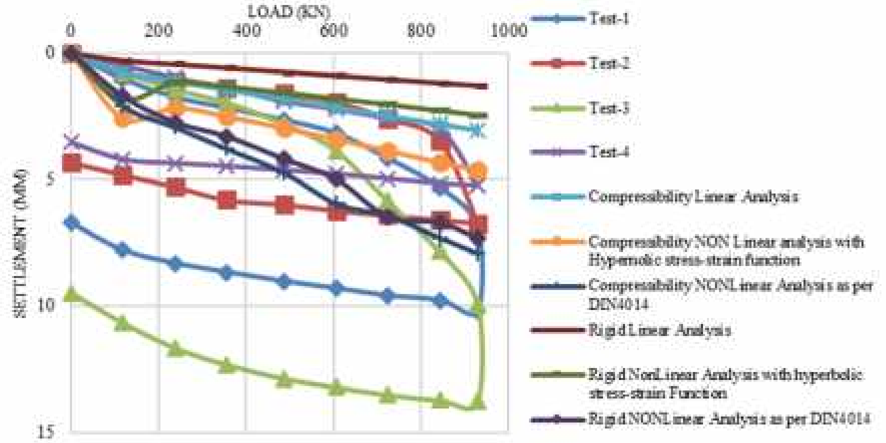


Figure 2: Load -settlement curve comparison for single pile b/w field and Numerical analysis with ELPLA.

5 Numerical methods and Assumptions for analysis

The programs ELPLA (**E**lastic **P**late by M. El Gendy and A. El Gendy) was adopted to evaluate the behavior of the piled raft foundation. Each node of plate or grid elements has three degrees of freedom, vertical displacement 'w' and two rotations θx and θy about x- and y-axis, respectively. ELPLA methods used over here are based on Continuum model (Ohde, 1942), which states that the settlement will occur not only under the loaded area but also outside. Continuum model assumes continuum behavior of the soil, where the soil is represented as isotropic elastic half-space medium or layered medium. This model overcomes the assumption of winkler's model, which does not take into account the interaction between the different points of the soil medium. The maximum difference between the settlements in step i and next step i + 1 is considered as an accuracy number. In this case study, the accuracy number was chosen to be 0.0001 [cm]. In case of compressibility methods when it does not reach convergence; the analysis get stopped itself after some iteration. The elemental length of pile for ELPLA varies between 1 to 2 m and the approximate size of the grids varies between 0.2 m minimum to 0.5m.

Hyperbolic stress strain function:
Hyperbolic-stress strain relationship: Analyzing nonlinear behavior by hyperbolic function was used by Mandolini/ Viggiani (1997) for pile groups and was used by Russo (1998) for piled raft. The nonlinear behavior of the pile head force-settlement at the piled raft-soil interface may be represented as:

$$Ph = \frac{wn}{\frac{1}{ks} + \frac{wn}{Ql}} \tag{1}$$

Where,
Wn = Nonlinear settlement of the pile(m)
Ql= Limit pile load [KN]

The initial tangent modulus for single pile is easily obtained from linear analysis of the pile, which is equal to the modulus of soil stiffness Ks. The limit load *Ql* is a geometrical parameter of the hyperbolic relation. In some cases, the value *Ql* is different from the actual ultimate pile load. For a single pile, the force on the pile head Ph is known. Therefore, Eq. (1) gives directly the nonlinear settlement of the pile *wn*.

DIN 4014 presents pile load in two components: tip force on the base of the pile and skin friction force acting along the pile shaft. In the analysis of the numerical model, the self-settlement of a pile is determined from DIN 4014 load-settlement relationship while the settlement due to pile-pile, pile-raft and raft-soil interactions is determined numerically using flexibility coefficients.

The program **GROUP** (by Lymon C. Reese, Shin-Tower Wang, Luis Vasquez for ENSOFT, INC, May 2016) was adopted to evaluate the behavior of pile group, without considering the contribution of Cap in load bearing. The cap is assumed to act as a rigid body, and may settle, translate and rotate. The program internally generates the nonlinear response of the soil. A solution requires iteration to accommodate the nonlinear response of each of the piles. In the solution, the equations of equilibrium are satisfied, and compatibility is achieved between pile movement and soil response, and between the movement of the cap and the pile-head movement. Finite-difference equations are employed to achieve compatibility between pile displacement and load transfer along a pile, and between displacement and resistance at the tip of the pile.

GROUP has six degrees of freedom, i.e. three displacement and three rotations one in each direction respectively.

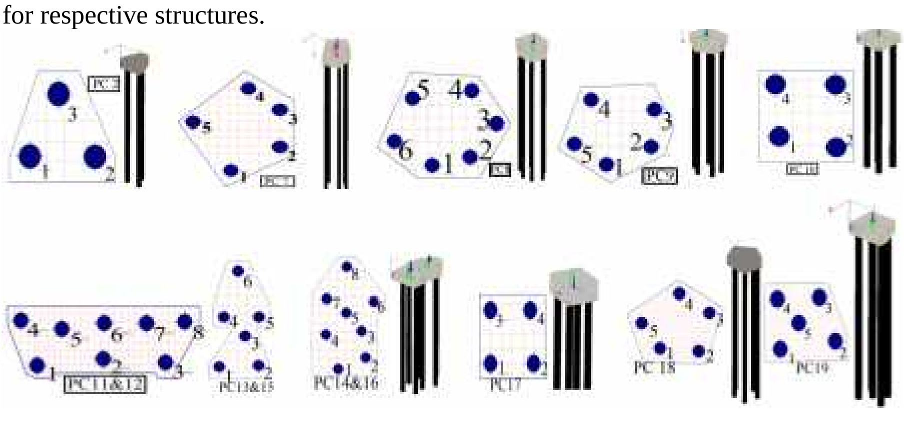
Table 2. Loading details considered in the present study

PC	Col. No.	Force (kN)			Moment (kN.m)		
		F_X	F_Y	F_Z	M_x	M_y	M_z
2	C4	-70	13.75	-556	-13.34	-74.47	1.16
7	C5	213.5	143.4	-971.18	-89.19	281.94	23.912
8	C6	-24.76	-130.28	-2204	444.24	-104.67	13.57
9	C7	-34.45	136.67	1434.48	-478.38	-117.44	5.45
10	C8	0.04	133.93	-1337.2	-480.92	-2.284	0.223
11	C9	37.37	127.51	-1338.4	-456.18	118.78	10.45
12	C10	116.38	38.802	-1031.8	-126.86	383.46	1.77
13	C11	-45.9	-70.86	-926.79	-15.71	138.01	-1.36
14	C12	27.57	147.45	-1593.2	-313.63	99.559	-0.517
15	C13	-14.7	31.88	-945.45	80.39	46.73	0.09
16	C14	-44.55	161.84	-1701.4	330.02	-142.96	-12.92
17	C15	36.03	-125	-1448	434.69	116.9	-11
18	C16	-41.82	-138	-1436.2	485.45	-137.74	-4.118
19	C17	-3.382	-134.2	-1403.1	482.2	-10.67	0.722
20	C18	38.06	-126.7	-1457	453.99	122.06	11.77
21	C19	126.34	-35.61	-1114	115.69	-416.5	5.39
4A	C21	134.79	8.275	-727	-16.85	297.86	-1.26
4B	C28	158.51	7.54	-568.84	-2.12	-333.98	-6.79
5	C14	111.61	6.73	-737.83	-16.25	-256.82	-0.26
6	C7	239.22	42.46	-543.74	-48.71	-354.94	5.77

The unit weight of concrete, young's modulus and Poisson's ratio considered is 25 KN/m^3, 27390000 Kpa and 0.15 for both pile cap and piles.

6. Results

The value of axial support reaction obtained with all six methods of ELPLA, GROUP and PLAXIS 3D are compared. Bar-chart for all piled raft with pile cap notation are shown in figure 4. The layout of respective piled raft is shown beside each graph. The modeling in ELPLA (Top view) and GROUP(3-D) is shown in figure 3 side by side for respective structures.



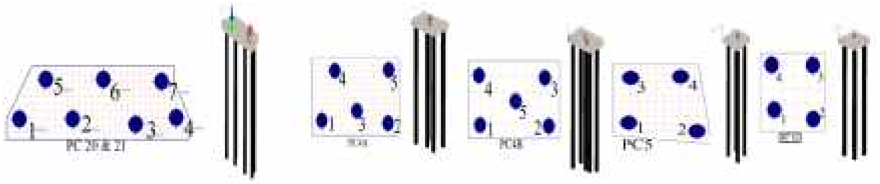
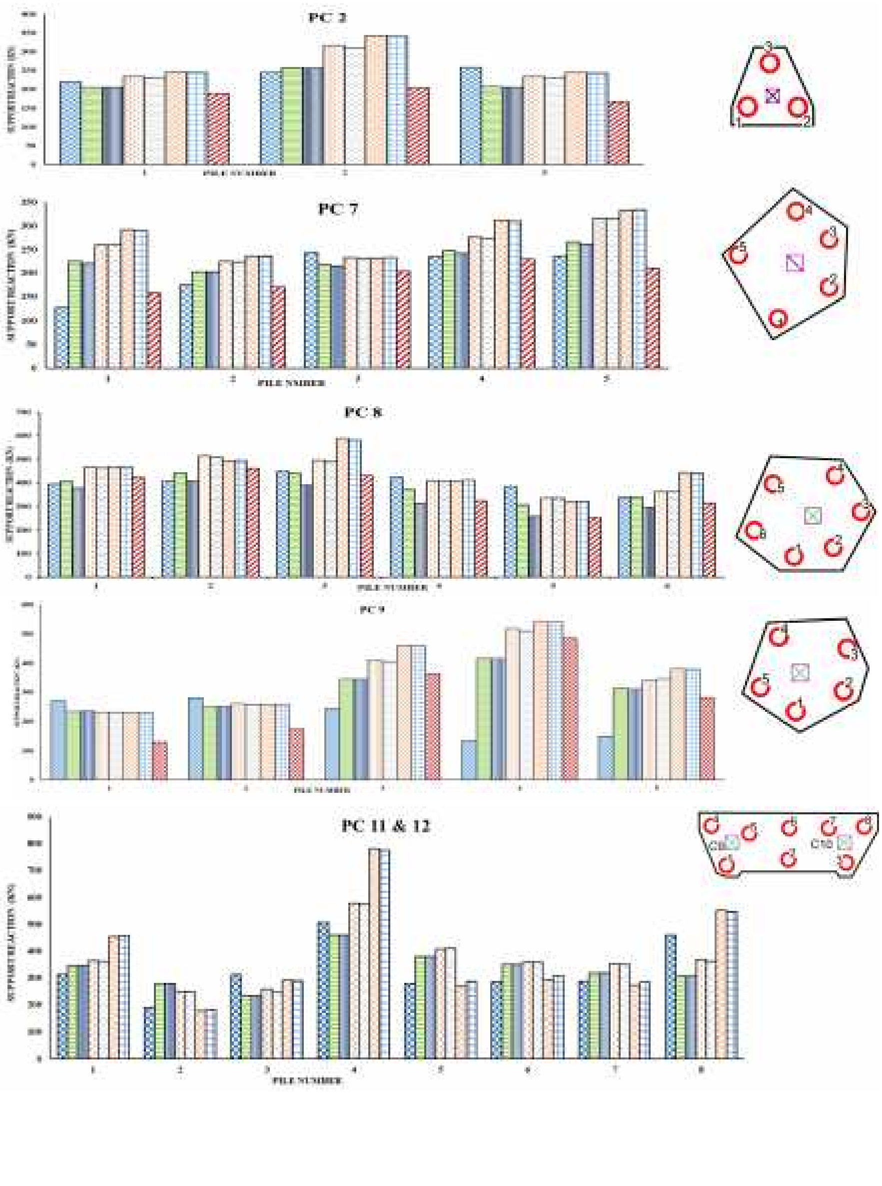
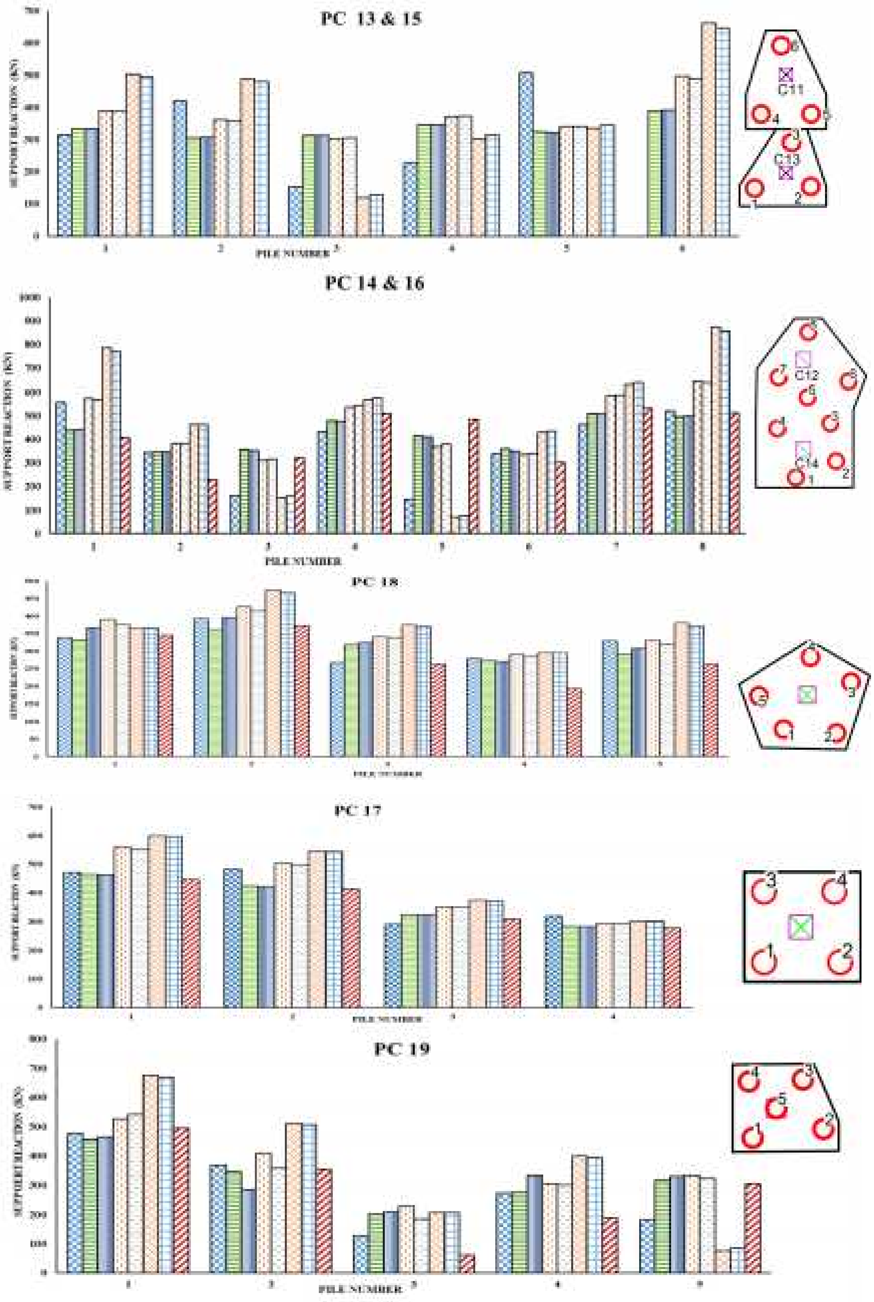


Figure 3: Modelling of piled raft in ELPLA (plane view) and GROUP (3D modelling).




PC 13 & 15
SUPPORT REACTION (kN)
PILE NUMBER
C11
C13
PC 14 & 16
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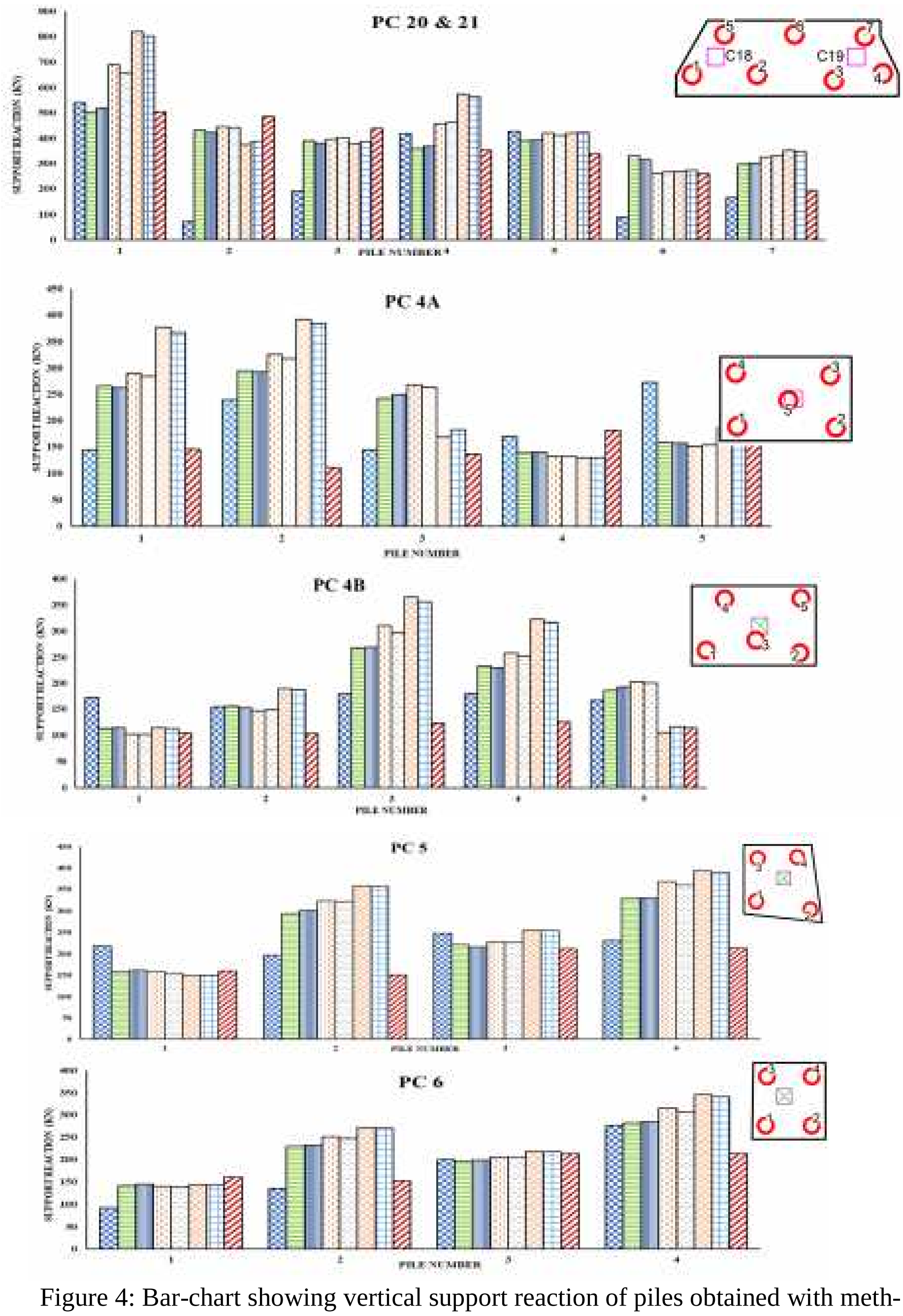

Figure 4: Bar-chart showing vertical support reaction of piles obtained with method 1 to 8 for each pile group and pile group configuration beside each Bar-chart.

LEGENDS:

Method 1	PLAXIS3D
Method 2	Rigid RAFT Non-Linear Analysis with DIN (4014)-ELPLA
Method 3	Compressible RAFT Non-Linear Analysis with DIN (4014)- ELPLA
Method 4	Compressible RAFT Linear analysis- ELPLA
Method 5	Compressible RAFT Non-Linear analysis using Hyperbolic stress-strain function-ELPLA
Method 6	Rigid RAFT Linear analysis-ELPLA
Method 7	Rigid RAFT Non-Linear analysis using Hyperbolic stress-strain function- ELPLA
Method 8	Analysis with GROUP

Table 3 shows Piled raft coefficient (Bearing factor) αkpp derived with all six ELPLA methods. The bearing capacity factor αkpp indicates the percentage of load sharing i.e. percentage total load and load taken by piles.

Table -3 Piled raft coefficient (bearing factor) αkpp derived with all ELPLA methods

Pile Cap Number	Col. No.	Piled raft Coefficient αkpp					
		Method 2	Method 3	Method 4	Method 5	Method 6	Method 7
PC 2	C4	79.15	78.93	92.69	91.25	98.4	98
PC7	C5	81.38	80.19	92.07	91.79	98.8	98.6
PC8	C6	83.7	81.51	93.6	92.92	98.8	98.7
PC9	C7	81.94	82.1	92.88	92.31	98.6	98.4
PC10	C8	82.7	83.28	94.24	92.8	99.5	99.4
PC 11 & 12	C9,10	85.59	85.24	94.09	93.13	99	100
PC 13 & 15	C11,13	82.7	82.76	93.06	92.61	99.1	99
PC 14 & 16	C12	84.55	83.96	92.95	93.35	98.8	98.7
PC 17	C15	81.74	81.53	93.24	92.45	99.5	99.4
PC 18	C16	82.81	87.62	93.61	92.8	99.5	98.6
PC 19	C17	84.69	85.85	92.46	90.4	98.7	98.5
PC 20 & 21	C18, 19	83.91	83.81	93	92.42	98.9	98.8
PC 4A	C21	85.02	85.09	90.22	88.97	96.9	96.3
PC 4B	C28	84.34	84.43	89.86	88.13	96.7	95.9
PC 5	C14	84.04	84.57	90.21	89.07	97	96.4
PC 6	C7	84.31	85.49	90.65	89.07	97.1	96.4

7 Conclusion

1) The load-settlement curve developed by using PLAXIS3D, ELPLA is on the conservative side when compared with Test-1 and Test-3. Hence, it can be established that numerical model simulated in PLAXIS3D and ELPLA are in close agreement

with the test load results both qualitatively and quantitatively as compared to field condition.
2) The percentage variation in vertical support reaction b/w methods 2 and method 3 is marginally 5% for PC2, PC7, PC9, PC10, PC 11 &12, PC13 & 15, PC14&16, PC17, PC20 &21, PC4A, PC4B, PC5, PC6. This variation for PC8, PC18 and PC19 is 17%, 12 % and 20 % respectively. From this it can be said that analysis with DIN (4014) method gives almost same results whether piled raft is considered as rigid or flexible, for small piled rafts.

3) When vertical support reaction obtained with method 4 is compared with method 5, there is marginally 5 % variation b/w results of these two methods for all piles. This means linear analysis and non-linear analysis with Hyperbolic stress-strain function for compressible piled raft give similar results for given problem.

4) When vertical support reaction obtained with method 6 is compared with method 7, there is marginally 7% variation b/w this two methods for all piles. From this it can be concluded that irrespective of size of raft, numbers of piles in piled raft and spacing between piles, method 6 can be used in alternate of method 7, i.e. ELPLA piled rigid raft can be analyzed with linear method or using nonlinear hyperbolic stress-strain function.

5) The maximum and minimum percentage variation in vertical support reactions obtained with method 8 is compared with method 1 for PC2, PC7, PC8, PC9, PC10, PC 14 &16, PC17, PC 18, PC19, PC 20&21, PC 4A, PC4B, PC5 and PC 6 and is 35 %, -24 to 2 %, -13 to 35 %, -226 to 53 %, -11 to 21 %, -237 to 35 %, -6 to 14 %, -2 to 32 %, -67 to 51 %, -565 to 22 %, -7 to 54 %, 40 %, 27 %, -75 to 23 % respectively. Here percentage value with negative sign indicates amount of support reaction obtained with method 8 is more than that obtained with method 1. The positive value indicates the amount of vertical reaction obtain with method 8 is less than that obtained with method 1.

8) The maximum and minimum percentage variation in vertical support reactions obtained with method 2 is compared with method 1 for PC2, PC7, PC8, PC9, PC10, PC11 &12, PC13&15, PC 14 &16, PC17, PC 18, PC19, PC 20&21, PC 4A, PC4B, PC5 and PC 6 and is -6 to 20 %, -75 to 11 %, -9 to 20 %, -212 to 14 %, -26 to 2 %, -48 to 34%, -107 to 37 %, -189 to 22 %, -11 to 13 %, -20 to 12 %, -74 to 6 %, -489 to 15%, -85 to 19 % ,-50 to 35 %, -50 to 28 %, -70 to 2 % respectively. Here percentage value with negative sign indicates amount of support reaction obtained with method 2 is more than that obtained with method 1. The positive value indicates the amount of vertical reaction obtain with method 2 is less than that obtained with method 1. Here the positive variation for all piles ranges near to 20-35 percentage. As percentage variation between method 2 and method 3 has marginal variation of 5 %, the variation in axial reaction between method 1 and method 3 will about ±5 % with that of method 1 and method 2.

9) The maximum and minimum percentage variation in vertical support reactions obtained with method 6 is compared with method 1 for Utility Building Structures PC2, PC7, PC8, PC9, PC10, PC11 &12, PC13&15, PC 14 &16, PC17, PC 18, PC19, PC 20&21, PC 4A, PC4B, PC5 and PC 6 and is -41 to 6%, -127 to 5%, -27 to 13%, -290 to 15%, -32 to -21 %, -46 to 7 %, -101 to 33 %, -70 to 52 %, -29 to 6 %, -41 to -6%, -64 to 59%, -411 to 2%, -161 to 32 %, -103 to 38 %, -82 to 32 %, -101 to -9 % respectively. Here percentage value with negative sign indicates amount of support reaction obtained with method 6 is more than that obtained with method 1. The positive value indicates the amount of vertical reaction obtain with method 2 is less than that obtained with method 1. As percentage variation between method 6 and method 7 has marginal variation of 7 %, the variation in axial reaction between method 1 and method 7 will about ±7 % with that of method 1 and method 6.

10) The piled raft coefficient obtained with method 2 and method 3 ranges between 0.8 to 0.85, same with method 4,5,6 and 7 is between 0.9 to 1 for all structures in utility area.

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