Effect of Pile Group and Pile-Raft System on Uplift Capacity of Cable Stayed Transmission Tower through Soil-Structure Interaction

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Abstract

The transmission tower foundations are subjected to significant uplift loads during its design life due to wind forces and conductor tensile forces acting on the super structure. There are three types of transmission tower viz; Tension tower, Suspended type tower and Line termination tower. The objective of this study is to determine uplift capacity of transmission tower supported by pile group and pile-raft system embedded in sandy-silt soil. In this study the reduced scale model of Line termination tower is fabricated as per IS: 802 -1995 (2006) (code of practice for use of structural steel in overhead transmission line towers) is used. To fulfill the above objective detail experimental program was planned at site of L.D. College of Engineering with cast-in-situ bored concrete piles with L/D ratio of 10 and pile cap was fabricated using steel plates. For the case of pile group system, the cap remains unconnected to the ground surface while in case of pile raft system, the raft (plate) remains connected to the ground surface. The lateral load was applied with the means of rope-pulley arrangements using pre-calibrated dead weights, lateral, vertical displacement and settlement was measured using conventional high precision dial gauges. The effect of soil stiffness (modulus of sub grade reaction) on connected and unconnected structural systems was also evaluated so as to understand the role of various parameters like skin friction resistance, lateral resistance of pile-raft and the lateral earth pressure. Experimental results were validated using Meyerhof (1968) and Tomlinson (1977) equations.

Keywords*: Line termination tower, Lateral load, Pile group, Pile raft.*

1. INTRODUCTION

The transmission tower foundations are subjected to significant lateral loads during its design life due to wind forces and conductor tensile forces acting on the super structure. When the lateral loads are imposed to the tower structure, the loads will transfer to the foundation in the form of either compressive or tensile forces. The tensile forces causes the uplift of the foundation and the compressive forces causes the settlement of the foundation. The foundation for transmission tower should be check in terms of 1) stability analysis and 2) strength design. Stability analysis aims to removing possibility of failure by overturning, sliding and tilting of the foundation. The strength design consist of proportioning components of foundation with respect to maximum moment, shear pull and horizontal thrust.

Few research works has been done based on model testing, material and numerical analysis. Load-carrying behaviour of transmission-tower connected foundations subjected to different load directions (Doohyun Kyung, 2015). Ultimate uplift capacity of transmission tower foundation in undisturbed excavated soil (Dongxue Hao, 2012). In this study the ultimate uplift capacity was obtained from finite element analysis. Lateral resistance of pile cap- an experimental investigation (Nath, 2013). Effect of Pile-group configuration on the lateral load carrying capacity of pile in sandy soil (M. M. Sazzad, 2018). Group interaction effects on laterally loaded piles in clay (S. S. Chandrasekaran, 2010). Also the work is done on uplift performance of transmission tower embedded in clay (M. J. Rattley, 2008). Rollins and Cole (2006) have conducted various model tests, centrifuge tests and full scale tests to study the lateral resistance of pile groups. Franke (1988) conducted model tests on bored piles in the laboratory, the results revealed that the dislocation of pile group when spacing was less than 6d, was more than a single pile.

Most of them are pure uplift loading test performed under controlled laboratory conditions. The effect of pile group configuration was not comprehensively investigated. In few study, the uplift capacity was found under the action of pure uplift load to the foundation system. In few study, the results for singular pile were obtained and based on that the capacity of pile group was obtained with the help of m-multiplier (p-y curves). Very few works are done on model testing to determine uplift capacity of pile group and pile raft foundation under the action of lateral load.

This study aims to determine the uplift capacity of pile group and pile raft under the effect of combination of compressive load and lateral load. The study also aims to determine the lateral resistance of the raft in case of pile raft foundation, To investigate the load resisting parameters those plays an important role for pile group and pile raft system, To obtain the comparative plots between the behavior of pile group and pile raft, To determine the behavior and failure of transmission tower resting on pile group and pile raft system. The benefit of the study is that, it gives the actual field experiment results. Also the effect of pile group and pile raft configuration was comprehensively investigated. To validate these experimental results, the theoretical models were used.

2. MATERIAL

2.1 Soil

The study is done at site of the L.D. College of Engineering. The soil properties of the site are mentioned in table 1.

Table 1 Soil properties

Test	IS- Code	Result
Grain size analysis	IS: 2720-4-1985	Cc=4, Cu=1.8
Soil Classification	IS: 1498-1970	SP-SM (Silty sand)
Standard Proctor test	IS:2720-7-1980	OMC= 12% MDD= 18.5 kN/m^3
Density of soil	IS:2720-29-1975	Bulk density= 15.8 kN/m^3

2.2 Pile

A steel hollow tube of diameter 32 mm is selected as boring tool. Using this tool, the bore holes are created in ground. The piles are cast in situ type. All the piles are reinforced with single reinforcement at the centre. The M25 grade concrete is used to make all the piles. The length of the pile is 320 mm and L/D ratio of all the piles are 10. The piles are cured for the period of 28 days. The spacing between piles is kept 3d where, d is diameter of pile.

2.3 Pile cap and pile raft

The steel plates are used as cap in pile group and as raft in pile raft system. The thickness of the plate is 8 mm. The pile cap and pile raft are connected to the reinforcement of pile. The transmission tower is connected to the pile cap and pile raft with nut and screws.

In pile group, the cap remains unconnected to the ground surface while in pile raft, the raft is connected to the ground surface by placing it on the ground surface as the top surface of the raft will coincide the ground surface.

2.4 Transmission tower model

According to IS: 802-1995(2006) (code of practice for use of structural steel in overhead transmission line towers); the model of transmission tower was fabricated. Model tower made up of mild steel IS angles of following specification.

Main leg angles: IS 35x35x5, Bracings: IS 25x25x3, Height: 1.3 m.

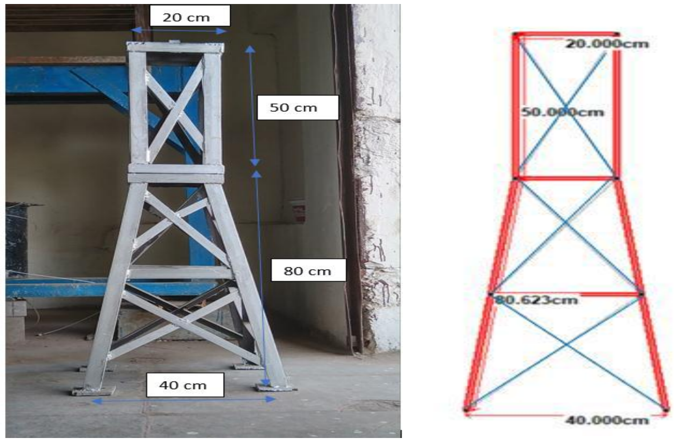

Figure 1 Model of transmission tower

3. TEST SETUP AND METHODOLOGY

The test setup for testing on pile group and pile raft is shown in figure 2 & 3 respectively. The tests are carried out at L.D. College of Engineering, Ahmedabad. The welded hook on the top of the tower is pulled with the help of steel rope of high capacity (7-8 tons). The steel rope is passing from the pulley and at the end the dead load is placed. The opposite pile group from the loading direction will be in tension and other two pile group will be in compression. The overturning moment generated on the transmission tower. The Uplift displacement, Horizontal displacement and settlement are measured with the help of dial gauges with sensitivity of 0.01 mm. At the top of the each cap the dial gauge D1, D2, D3, D4 are placed where D1, D2 are measures the uplift displacement and D2, D4 are measures the settlement. To measure the horizontal displacement dial gauge H1, H2 are placed at the top of the tower.

As the load increments were given to the transmission tower after the permissible limit of uplift displacement, the tilting of the tower was observed as shown in the figure 2 (c). At the end the sudden jerk was observed. Then, the tower did not resist the load.

The test procedure is followed by IS: 2911-1985-part 4. According to the IS code the load increments should be about 20% of the estimated safe load. The next increment should be applied after the rate of displacement is nearer to 0.1 mm per 30 minutes. It also states that the displacements shall be read by using at least two dial gauges of 0.01 mm sensitivity spaced at 30 cm.

Pile group: In case of pile group the cap is placed above the ground level as shown in fig 2.

(a) (b) (c)

Figure 2 Test setup for pile group

Pile raft: In this case the raft is placed on the ground as the top of the raft will coincide with the ground level as shown in figure 3(b).

(a) (b) (c)

Figure 3 Actual test setup for pile raft

4. RESULT AND ANALYSIS

The lateral loading test was performed on the model of transmission tower resting on pile group and pile raft foundation. At each increment of the load, the changes in reading of all dial gauges (D1, D2, D3, D4, H1, and H2) are measured to obtain the uplift displacement, settlement and the horizontal displacement. Various plots obtained from the tests are as follows:

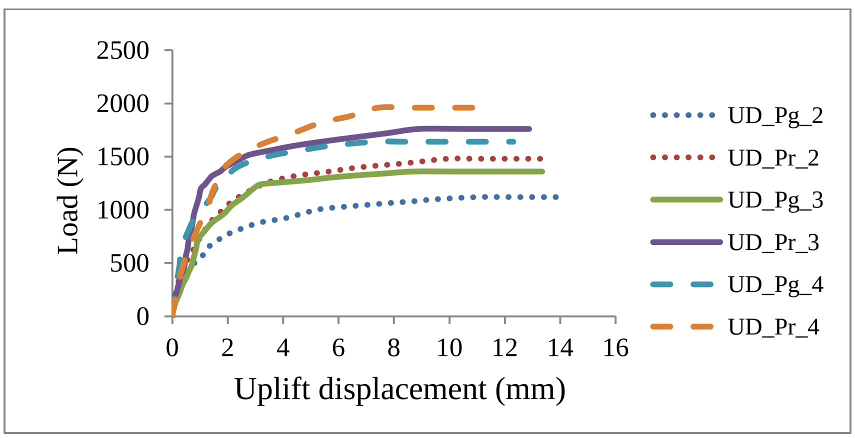

Figure 4 Load vs. Uplift displacement (D1, D2)

Table 2 Comparison of ultimate load

Parameter	UD_Pg_2	UD_Pr_2	UD_Pg_3	UD_Pr_3	UD_Pg_4	UD_Pr_4
Uplift displacement (mm)	12	12	12	12	12	12
Load (N)	1120	1480	1360	1760	1640	1960

From figure 4, it is demonstrated that the capacity of pile group and pile raft against the uplift displacement is non-linear in nature. It is noted that at initial stage of test, the increment of load gives significant uplift displacement of the pile group and pile raft. At the last stage of loading, small increment in load results higher displacement. The test is continued till the uplift displacement of 12 mm is occurred. It is observed that the pile raft system resist higher load as compared to that of pile group, for the same magnitude of displacement of 12 mm as shown in table. As the number of pile increased, the uplift capacity of the system is also increased. It is observed that, as the number of pile increased in pile group and pile raft system, the uplift displacement is decreased.

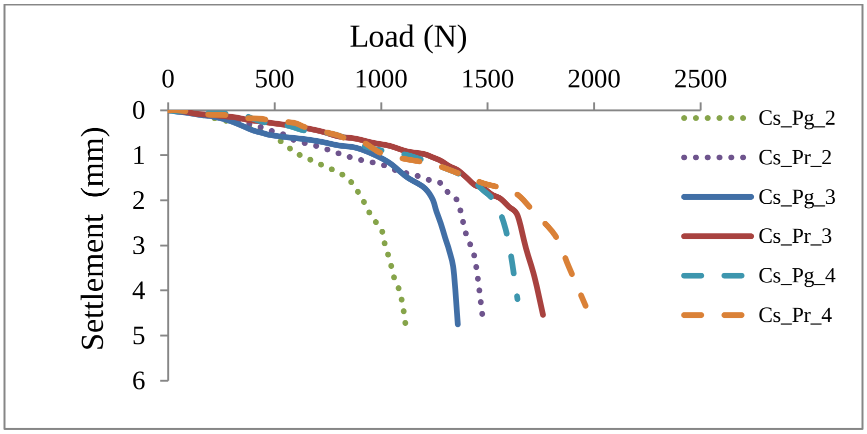

Figure 5 Load vs. Settlement (D3, D4)

Table 3 Comparison of settlement at ultimate load

Parameter	Cs_Pg_2	Cs_Pr_2	Cs_Pg_3	Cs_Pr_3	Cs_Pg_4	Cs_Pr_4
Settlement (mm)	5	4.65	4.7	4.54	4.17	4.37
Load (N)	1120	1480	1360	1760	1640	1960

From figure 5, it is observed that the settlement of pile group and pile raft system is less as compared to the uplift displacement. At the ultimate load capacity the values of settlement is given in table 3. It is noted that the capacity of the pile in compression is higher as compared to the pile is in tension. The same results were also observed in most of the literatures. It is observed that, as the number of pile increase, the settlement of pile group and pile raft system is decreased.

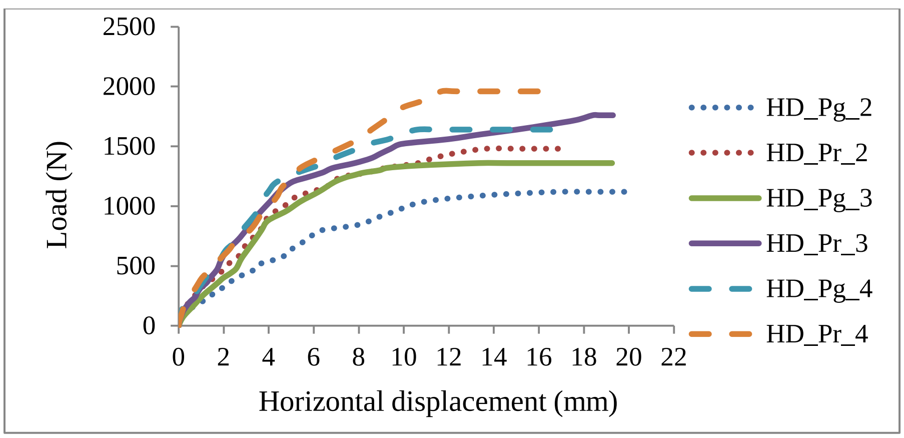

Figure 6 Load vs. Horizontal displacement (H1, H2)

As the tower is loaded laterally at the top, tilting of tower is occurred. The excessive tilting is not allowed for safety of the structure. From figure 6, pile raft system gives less horizontal displacement as compared to the pile group system. It is noted that, as the number of pile increases, the horizontal displacement is decreased. The values of horizontal displacement at the maximum amount of load are given in table 4.

Table 4 Comparison of horizontal displacement at ultimate load

Parameter	HD_Pg_2	HD_Pr_2	HD_Pg_3	HD_Pr_3	HD_Pg_4	HD_Pr_4
Horizontal displacement (mm)	19.7	17.3	19.25	19.15	16.5	16.12
Load (N)	1120	1480	1360	1760	1640	1960

As shown in figure 4, the loading is continued till the uplift displacement of 12 mm is occurred. As per IS: 2911 part-4, 2/3rd of the load at which the total displacement is 12 mm is the safe uplift load capacity. The safe uplift load capacity and ultimate load capacity for all six configurations are shown below:

Table 5 Safe uplift load capacity

Parameter	Pg_2	Pr_2	Pg_3	Pr_3	Pg_4	Pr_4
Safe uplift load capacity (N)	746	986	906	1173	1093	1306
Ultimate load capacity (N)	1120	1480	1360	1760	1640	1960

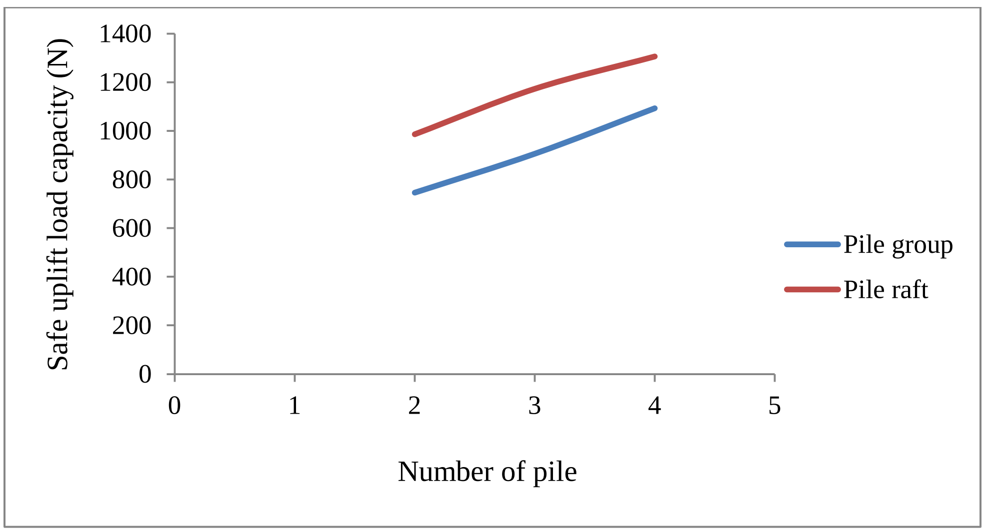

Figure 7 Safe uplift load capacity vs. Number of pile

As shown in figure 7, the safe uplift load capacity of pile raft is higher than the pile group in all configuration of the pile. In pile group, the skin friction of piles and lateral earth resistance of soil causes the resistance against the lateral load. In pile raft, these parameters as well as, the additional resistance were provided by the raft which is discussed in 4.1.3.

4.1 Load sharing parameters

4.1.1 Modulus of sub grade reaction

Winkler's hypothesis involves the concept of modulus of sub grade reaction. He assumed that the soil medium may be approximated by a series of closely spaced independent elastic springs. According to Vesic (1961), the laterally loaded pile is embedded in soil is closely related to the beam on an elastic foundation.

The lateral soil resistance for granular soils and consolidated clays can be given as per equation,

$$\frac{p}{y} = n_h z$$

Where, p = lateral soil reaction per unit length of pile at depth z below ground surface

y = lateral pile deflection

n_h = modulus of sub grade reaction.

For the piles embedded in sand and clays, the stiffness factor can be given by,

$$\text{Stiffness factor } T\,(m) = \sqrt[5]{\frac{EI}{n_h}}$$

Where, E = Young's modulus of material of pile in MN/m^3

I = Moment of inertia of pile cross section in m^4

n_h = modulus of sub grade reaction in MN/m^3

Table 6 Recommended value of modulus of sub grade reaction

Type of soil	N (blows/30cm)	Recommended values of n_h $(kN/m^3)*10^3$	
Very loose sand	0-4	<0.4	<0.2
Loose sand	4-10	0.4-2.5	0.2-1.4
Medium sand	10-35	2.5-7.5	1.4-5
Dense sand	>35	7.5-20	5-12

Broms (1964) provided solutions for both short and long piles installed in cohesive and cohesion less soils respectively. It is assumed that the deflection increases linearly with the applied load up to one half or one third of the ultimate lateral resistance of the pile. The lateral earth pressure distribution per unit length is given by

$$P = 3d\gamma z k_p$$

Where, d = diameter of pile,

γ = unit weight of soil,

z = embedment depth,

k_p = Passive earth pressure coefficient.

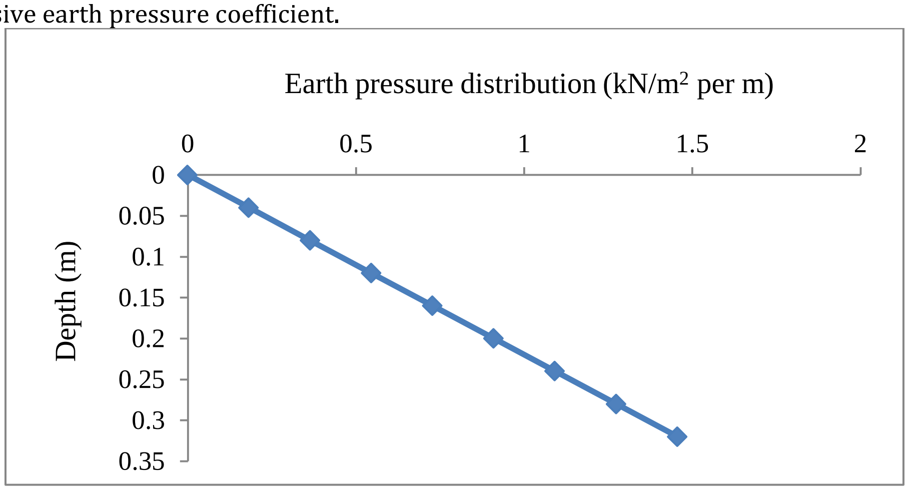

Figure 8 Earth pressure distribution

As shown figure 8, lateral earth pressure distribution is linearly varying with the depth of pile. At the depth of 0.32 m the lateral earth pressure 1.456 kN/m^2 per m was observed.

4.1.2 Skin resistance

According to Coyle and Castello (1981), the ultimate skin resistance (Q_f) in homogeneous soil is given by following equation:

$$Q_f = A_s\, q'\, K_s'\, \tan\delta \qquad (1)$$

Where, A_s = Surface area of pile

q' = Overburden pressure at pile base

K_s'= constant depend on depth of foundation

δ = Angle of wall friction

As per the equation, skin friction resistance is depending on the surface area, it is clear that it is also the function of pile diameter and pile length. For the long piles the skin friction resistance will be higher as compared to the short pile. Similarly the larger diameter of pile gives high skin friction resistance.
By using the equation 1 the skin resistance of pile is calculated and shown in figure 8.

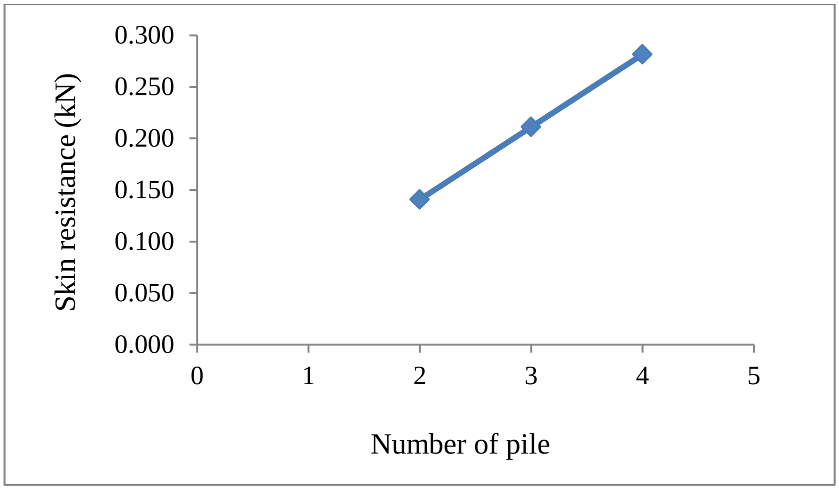

Figure 9 Skin resistance vs. Number of pile

From figure 9, it is observed that, when the number of pile increases, the skin resistance also increases. Mainly the skin resistance depends on pile diameter, pile length, number of piles in group and soil properties. Due to the increment of surface area, the skin friction resistance increased. The contribution of the skin resistance in pile group and pile raft is shown in figure 9.

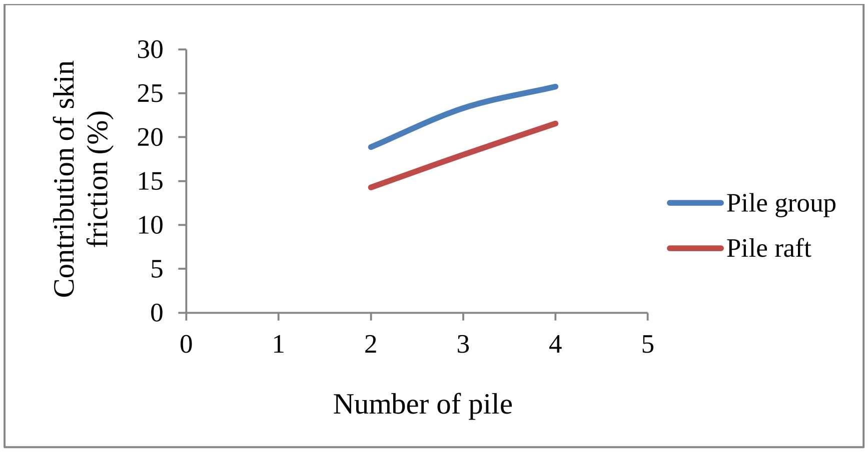

Figure 10 Contribution of skin friction resistance

From figure 10, the contribution of skin resistance in load sharing is less in case of pile raft as compared to the pile group system. In case of pile raft, the additional load resistance is provided by the lateral resistance of raft. The total capacity of pile raft is increased but the contribution of skin friction is less in pile raft system.

4.1.3 Lateral resistance in pile raft

The lateral resistance (L_R) of the pile raft in case of pile raft foundation is obtained using following equation:

$$L_R = \frac{(Pr - Pc)}{Pc} * 100\% \qquad (2)$$

Where, Pr = Load resistance by pile raft

Pc = Load resistance by pile cap

Table 7 Lateral resistance of raft

Foundation type	Pile raft lateral resistance
2 Pile raft	32.17%
3 Pile raft	29.5%
4 Pile raft	21%

4.2 Validation of experimental test result

The result obtained from the test is compared to the various theoretical models which are shown in figure 11.

- Uplift capacity of pile group (By Tomlinson, 1977):
  The uplift capacity of a pile group, when the vertical piles are arranged in closely spaced groups may not be equal to the sum of the uplift resistances of the individual piles. At the ultimate load conditions, the block of soil enclosed by the pile group gets lifted (Tomlinson, 1977). The equation for the total uplift capacity P_{gu} of the group may be expressed by:

$$P_{gu} = 2L\,(L' + B')\,Cu + W \qquad (3)$$

Where, L= Length of pile block
L' and B'= Overall length and width of the pile group
Cu= Average undrained shear strength of soil
W= Weight of block of soil enclosed by the pile group, piles and pile cap.

- Meyerhof's Model (1968):

$$P_{nu} = \frac{\pi}{2} K_u\, D\, \gamma\, L^2 \tan\delta \qquad (4)$$

Where, K_u= uplift coefficient,
D= Diameter of pile,
γ = Density of soil,
L= Length of pile,
δ= soil pile friction angle.

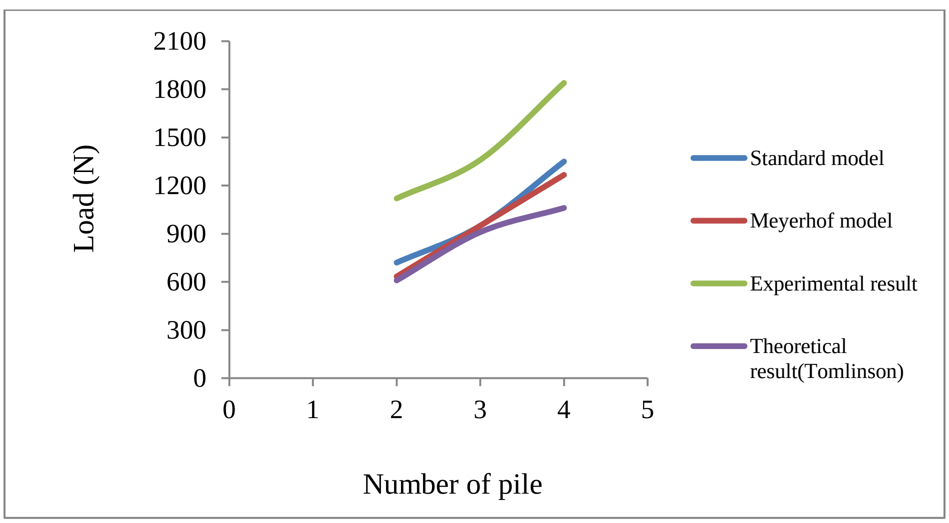

Figure 11 Comparison with theoretical models

The capacity obtained from theoretical model is less as compared to the experiment result. In the experimental result it is required to consider the factor of safety. If the factor of safety is considered than the results may be get closure to the theoretical capacity.

5. CONCLUSION

- As pile cap is placed above ground level and pile raft is placed on the ground as the top of the raft coincide ground surface, the resistance of pile raft against lateral loading and uplift effect is more as compared to the pile cap. The lateral resistance of raft occurred due to the passive pressure of surrounding soil. The raft is also sharing certain amount of load which is calculated from equation (2) and shown in table 7. It is observed that, as the number of pile increased in pile raft, the load sharing by the raft is decreased.
- It is observed that, in case of pile raft system, the lateral resistance provided by raft was more than the skin resistance of the pile.
- From figure 5, the settlement observed in each case is very less as compared to the uplift displacement for the same amount of load. So, the capacity of piles under tensile forces (forces inducing uplift) is significantly less than the piles under compressive forces (forces inducing settlement).
- The failure occurs before the full capacity of compression pile is mobilized.
- It is observed that, the uplift capacity of foundation increases with the number of piles increased in group and raft.

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