6 SUMMARY OF FINDINGS

6.1 General

Piled-raft foundations were used to support many tall structures constructed in complex ground conditions. The behaviour of this type of foundation is very complex and still it is not fully understood. Present investigation was aimed at study of piled raft foundation using laboratory scaled model tests with few numerical study to know the behaviour and load sharing between pile group and raft, settlement characteristics in a sandy formation by varying relative density of sand, shape of raft, *L/d* ratio of piles, spacing between piles, configurations of piles, soil-pile friction characteristics and shape of piles. To predict the capacity of piled-raft some of the tests were also conducted on unpiled raft, single pile and only pile groups. From the result, analysis and discussion so presented in chapter 5 following are the findings summarized as below.

1. In absence of plate load test data of sand the theoretical relationship developed by Vesic and Selvadurai can be used to determine modulus of subgrade reaction by knowing modulus of elasticity of sand from triaxial test.
2. The ultimate bearing capacity of unpiled raft is maximum with square shape and minimum with circular shape considering equal contact area of the foundation with soil.
3. The secant stiffness of unpiled raft for square and circular shape is given by following equation

$$k_{sr} = 7300 B_r S_c e^{(0.028 I_d)} P^{(-0.55)}$$

where, $\boldsymbol{k_{sr}}$= secant stiffness of unpiled raft foundation in kN/m; $\boldsymbol{B_r}$= width/diameter of unpiled raft foundation in m; $\boldsymbol{S_c}$= shape factor (1 for square and 0.55 for circular shape of unpiled raft foundation); $\boldsymbol{I_d}$ = relative density of foundation soil (%); $\boldsymbol{P}$ = load applied on unpiled raft foundation in kN.

4. The initial tangent stiffness of pile group obtained from Fleming's equation is in good agreement with experimental results.

5. The load settlement characteristics of piled raft foundation in all most all the cases are tri-linear in nature.
6. The ultimate capacity of piled raft foundation (*FYL*) is more than the ultimate capacity of unpiled raft.
7. The *IYL* and *FYL* of piled raft increase with increase in relative density of sand bed.
8. The difference between *FYL* and *IYL* of piled raft foundation increases with increase in relative density of sand bed.
9. The contact pressure distribution in a piled raft foundation is greater in the space within the pile group as compared to outside the pile group.
10. At settlement corresponding to initial yield load of piled raft, the load shared by pile group is greater in PRF as compared to load taken by only pile group at that settlement whereas load shared by raft in PRF is less than that load carried by unpiled raft at same settlement in most of the cases.
11. The *FYL* of a piled raft is about 1.5 to 2.7 times the *IYL* of piled raft in the present study.
12. In most of the cases, the load shared by pile group in PRF at *FYL* is in the range of 1.4 to 5.7 times the ultimate load carrying capacity of only pile group and the load shared by raft in PRF at *FYL* is in the range of 0.4 to 0.9 times the ultimate capacity of unpiled raft foundation.
13. The range of efficiency of PRF at *IYL* (β_1) in PRF with different shape of raft was found to be 0.9 to 1.69 and at *FYL* (β_2) it was 0.89 to 1.47. The efficiency of PRF at *FYL* (β_2) was found to be increased with increase in spacing of piles from 3d to 7d. (β_1) and (β_2) was found to be lowest at 80% relative density of sand in most of the cases, this represents that in dense sand the efficiency of PRF is less than in medium dense sand.
14. In a piled raft foundation the 50% load sharing by pile group and 50% load sharing by raft occurs in the range of relative settlement 0.001 to 0.07 in majority of cases. In some of the cases, the pile group and raft did not reach the 50% -50% load sharing
15. In the early stages of load application, as the relative settlement (s/B_r) increases, piled raft coefficient (α_p) exhibits a rapid decrease from values close to 1 to ultimately falling within the range of 0.1 to 0.6. As the applied load continues to increase, α_p of

most of the PRF stabilizes in the range of the relative settlement (s/B_r) = 0.02 to 0.04. Further increments in load result in either a constant value or a slight increase in α_p.

16. Within the loading range of unpiled raft the settlement reduction ratio of piled raft with 3 × 3 pile group is 7% to 52% for circular raft, 1% to 74% for rectangular raft, 2% to 69% for trapezoidal raft and 30% to 86% for square raft.
17. Within the loading range of unpiled raft the settlement reduction ratio of piled raft with 5 × 5 pile group are increases with increase in *L/d* ratio of piles.
18. Within the loading range of unpiled raft, the settlement reduction ratio of piled raft with 3 × 3 pile group is found maximum with *3d* or *5d* spacing at 80% relative density, *5d* spacing at 60% relative density and *7d* spacing at 40% relative density of sand bed.
19. Within the loading range of unpiled raft the settlement reduction ratio of piled raft with 3 × 3 pile group is found maximum with H pile at 40 % relative density, H and hollow circular pile at 60% relative density and at 80% relative density of sand bed.
20. The load improvement ratio of piled raft foundation increases with increase in relative density of sand in circular shape of raft while it decreases in square and trapezoidal shape of raft with few exceptions.
21. The load improvement ratio of piled raft increases with increase in spacing of piles, number of piles, and *L/d* ratio of piles.
22. Considering effect of configuration of pile, the load improvement ratio of piled raft foundation is found maximum in PRF with all long piles and minimum with all short piles.
23. The load improvement ratio increases with increase in soil-pile friction angle at all relative density of sand bed.
24. Considering effect of shape of pile, the load improvement ratio of piled raft foundation is found maximum in PRF with H pile at 40% and 60% relative density while at 80% relative density it is highest with hollow circular pile.
25. The primary stiffness of piled raft increases with increase in relative density of sand. It is highest with square shape of raft and in decreasing order with trapezoidal, rectangular and circular shape of raft.
26. Load sharing of pile group is higher at lower settlements where as load sharing of raft increases with increase in settlement in most of the cases considered in this study.

27. In prototype piled raft foundation, maximum value *IYL* and *FYL* was obtained in case of all long piles with configuration *S9*, *C9* and at a configuration were longer piles were present in outer periphery *S1*, *C1*.
28. In prototype piled raft foundation, minimum value *IYL* and *FYL* was obtained in case of all short piles *S9*, *C9* and at a configuration were shorter piles are present in outer periphery *S2*, *C2*.
29. Configuration *C9* exhibited the highest settlement reduction ratio in prototype PRF, followed by *S1* and *C1*, while *C7* and *S7* showed the least reduction.
30. The load shared by the pile group in prototype piled raft foundation ranged from 60% to 93% at the initial yield load and from 47 % to 82 % at the final yield load, depending on the configuration.
31. Configurations with shorter piles in prototype piled raft foundation showed less load carried by piles i.e., 60% in *IYL* and 47% in *FYL* and a significant role of the raft in load sharing.
32. Load distribution analysis revealed variations in load sharing among individual piles within each configuration.
33. Longer piles generally carried a greater portion of the load, while shorter piles contributed less in prototype piled raft foundation.
34. The primary stiffness of prototype piled raft foundation obtained by the numerical analysis when compared was 32% to 60% nearer to those obtained with PDR method in all configurations. PRF with shorter pile was found more nearer to PDR method.
35. The primary stiffness of prototype piled raft foundation with all long piles agrees well with Clancy method.
36. The equations proposed for predicting *IYL*, *FYL*, $\left(k_{pr}\right)_p$ and $\left(k_{pr}\right)_s$ are listed as below and in most of the cases the predicted values were vary by less than 25% of the experimental values. The symbols used in the proposed equations are defined in Chapter 5.

$$IYL = C_1 * (P_r)_{s_i} + C_2 * \left(P_{pg}\right)_{s_i}$$

$$FYL = C_3 * Qur + C_4 * Qu, pg$$

$$\left(k_{pr}\right)_p = 54.6 I_d + 0.28 k_{ri} + 0.86\, (k_{pg})_i$$

$$\left(k_{pr}\right)_s = 15.13I_d + 0.018k_{ri}$$

where,

C_1 = Efficiency factor of raft in PRF at $IYL = (LSR)_{s_i}/(P_r)_{s_i}$

C_2 = Efficiency factor of pile group in PRFat $IYL = (LSPG)_{s_i}/\left(P_{pg}\right)_{s_i}$

$(P_r)_{s_i}$= Load taken by UPR at s_i in kN

$\left(P_{pg}\right)_{s_i}$= Load taken by only pile group at s_i in kN

s_i= Settlement of PRF at IYL in mm

IYL = Initial yield load of PRF in kN

$(LSR)_{s_i}$ = Load shared by raft in PRF at IYL in kN

$(LSPG)_{s_i}$ = Load shared by pile group in PRF at IYL in kN

B_r= Width of raft or least lateral dimension of raft in m

I_d =Relative density of sand bed in percentage

L = Length of pile in m

n = Number of piles

S = Spacing between piles in m

d = External diameter of pile in m

$\left(k_{pr}\right)_p$= Primary stiffness of PRF in kN/m

(k_{ri}) = Initial stiffness of UPR in kN/m

$(k_{pg})_i$ = Initial stiffness of pile group in kN/m

$(k_{pr})_s$ = Secondary stiffness of PRF in kN/m

6.2 Future Research Directions

This study provides valuable insights on initial yield load, final yield load, efficiency of raft and pile group in piled raft foundation at initial yield load and final yield load, primary stiffness of piled raft foundation, secondary stiffness of piled raft foundation, efficiency of piled raft foundation, and load sharing mechanism of piled raft foundations and sets the ground for future research directions in this area:

1. In this thesis, the aforementioned parameters of piled raft were studied on homogeneous sandy foundation soil. These parameters could be studied on layered sandy or clayey foundation soil.
2. In this thesis, the aforesaid parameters of piled raft were studied under vertical load at the center of raft; however, the effect of load eccentricity and load inclination or dynamic loading on these parameters is still an open area of research.
3. The effect of raising ground water table on the abovementioned parameters of piled raft could be studied by executing small scale tests.