CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Raft and pile are two independent foundation systems, which are used extensively to support variety of civil engineering structures. Understanding on the behaviour of these two foundations are established through extensive studies on physical models (lab models), analytical models and also through limited field studies. It is a common practice that the pile groups are provided with pile cap (or raft). The distinction between the pile groups with and without ground contacting cap has been brought out by few researchers (Poulos 1968; Butterfield and Banerjee 1971; Davis and Poulos 1972) while analysing pile group behaviour.

Though the foundation engineers have long recognized the use of piles along with raft, the contribution of raft towards load sharing and settlement is ignored in most of the design. It is only in the recent past the foundation engineers have realised that when competent soil is present beneath the raft the traditional design of pile group without ground contacting cap (or raft) is tend to become uneconomical. Even then many tall structures with basements and storage tanks supported on piled raft foundations are designed conventionally (i.e., without considering the ground contacting raft). This is due to three dimensional nature of the problem, which imposes complicated interaction between the elements of piled raft and soil. These interactions make the quantitative analysis very difficult and expensive. Despite the limitations, many conceptual design procedures have been developed and improved periodically.
Zeavert (1957) was one of the earliest to prepare the concept of using deep foundation elements particularly piles to reduce the raft settlement. Such a combination of raft with piles was termed as piled raft. A notable early example of the use of settlement-reducing piles in foundation design was given by Zeevaert (1957) for La Azteca office building in Mexico City constructed during 1954-57. The foundation comprised of 41m × 16m raft with 83 concrete piles of length of 24m and diameter 0.4m. Partially compensated friction-pile foundation was adopted in the design. The calculated immediate raft settlement was about 200mm, compatible with the observed settlement at the end of construction and the predicted differential settlement was about 30mm. A comparison of observed and computed settlements was given in an attempt to predict the future behavior of the foundation of the building.

Numerous researchers (Poulos 1994; Padfield and Sharrock 1983; Randolph 1983; Poulos et al 1997) have studied the behaviour of piled raft and evolved design procedures for piled raft system. Many tall structures have been designed and constructed based on these design procedures. A large number of field data related to performance of tall structures supported on piled raft have been published during the past few years. As the present study is focused on 1g model tests and based on the monitoring of real size piled raft of multi-storied structure, the literature on small scale model studies and studies on prototype foundations are discussed first and analytical model studies are discussed subsequently in the literature review. Finally the present level of understanding on the load settlement behaviour of the piled raft and the need for this study are outlined.

2.2 SMALL SCALE MODEL STUDIES

Even though the use of piles and raft either independently or in combination is extensive, experimental studies on piled raft appear to be limited. The limited studies reported in the literature based on the small scale
model studies relating to the behavior of piled raft are grouped under following heads and discussed:

(i) 1g model studies, and

(ii) Studies on centrifuge models

2.2.1 1g Model Studies

Tests on small scale (1g model test) models are popular in the field of Geotechnical Engineering. Results of model tests were effectively verified to understand complete behavior of soil-structure interaction problems and influence of various parameters on load sharing and settlement were also established. Some of the classical theories were also verified experimentally, through small scale tests. However small scale test on piled raft foundation is very limited. The limited tests reported in literature both in clay and sand are reviewed in this section.

Whitaker (1957 and 1961) conducted series of tests on 1g models of free standing pile groups and pile groups with rigid caps (piled raft) resting directly on a soil bed and examined the influence of number of piles, length of piles and spacing between piles on bearing capacity and settlement of pile group. The rigid cap of piled raft system showed block failure and efficiency of pile group was higher than 100% particularly for wider pile spacing. Since the failure was essentially block failure, a method was proposed for estimating bearing capacity of piled raft based on it. No differential settlement was reported since the raft used was relatively rigid.

Weisner and Brown (1978) performed tests on piled raft models installed in overconsolidated Kaolin clay bed and demonstrated the applicability of linear elastic continuum theory for predicting behaviour of piled raft with both rigid and flexible rafts. In these experiments settlement of raft and strains in the longitudinal and transverse directions of the raft were measured at selected points using displacement transducers and semi
conductor strain gauges. The settlements and moments thus measured for various vertical loads were compared. Satisfactory agreement were reported between the experimental results and results of elastic analyses extended from Hain (1975). Though the tests were conducted on rafts of two different shapes and different soil-raft stiffness (both flexible and rigid rafts), the role of pile group was not analyzed. Concentration was more on differential settlement and variation of moment in the raft rather than loadsharing between the raft and piles.

Cooke (1986) conducted elaborate model tests on rafts (unpiled), free standing pile groups and piled rafts on overconsolidated clay bed. The tests were conducted till the settlement was of the order of 1% of the width of the raft. Cooke established that very little advantage could be obtained by designing the piled raft with spacing lesser than 4d and also indicated that the block behaviour occurred at even much wider spacing (i.e. 6d to 8d) than what was being traditionally accepted for piled raft design. Hence fewer piles also could produce considerable settlement reduction. However this observation needs to be strengthened either through detailed model studies or observations on real structures supported on small number of piles. Cooke also established that the ratio of length of the pile to width of the raft influenced the behaviour. He indicated that the length of the pile must be such that the shaft friction should influence the settlement than the tip resistance, meaning that the settlement reducing piles must be friction piles.

Kim et al (2002) proposed a new approach for the optimum design of piled raft foundations. In this approach genetic algorithm without gradient requirements was used and the analysis of piled raft foundation were performed based on hybrid approach of Clancy (1993). In order to validate the method proposed, small scaled laboratory tests were conducted. Three series of tests were conducted in their study to bring out effects of stiffness of raft, spacing between the piles and arrangement of piles. All these tests were conducted on standard sand (Jumujin sand) with relative density of 68.3%. In
the first series of tests raft (180mm×180mm) with four piles (2×2) were tested to understand effect of raft thickness on load sharing between the piles and the raft. Tests were conducted for the raft thickness of 3mm and 8mm. It was reported that the load sharing ratio, $\alpha_{pr}$ ($= \sum R_{pile}/R_{tot}$ where $\sum R_{pile} =$ sum of loads carried by piles and $R_{pile} =$ total load applied) decreased gradually with settlement ratio, $\beta_{pr}$ ($=\frac{\delta_{pr}}{L_p}$, where $\delta_{pr} =$ settlement of piled raft and $L_p =$ length of the pile). However for the $\beta_{pr}$ higher than 0.5 in the case of raft thickness of 3mm and higher than 0.1 in the case of 8mm thick raft, the load sharing ratio ($\alpha_{pr}$) of the raft was greater than that of piles. The maximum load shared by the rafts were 71% and 55% for the raft thickness of 8mm and 3mm respectively and the corresponding $\beta_{pr}$ was more than 1%. In the second series of tests (2d, 3d and 4d where $d =$ diameter of the pile) influence of spacing between the piles was studied. Tests were conducted on 2×2 and 3×3 pile groups with raft thickness of 3mm and 6mm. From the analyses of test results, it was concluded that the total number of piles almost had no effect on the variation in the load sharing ratio. The load sharing ratio of the raft increased with thickness and size of the raft. The third series of tests were on pile configuration. Six different configurations were considered, which are as shown in Figure 2.1. Among the configurations tested, the second configuration (con-2) was the most efficient arrangement wherein average settlement was minimum and bearing capacity was maximum. Results of the experiments were utilized to validate the genetic algorithm based optimum design and both the results agreed well with each other.

![Figure 2.1 Configurations considered (Kim et al 2002)](image)
Turek and Katzenbach (2003) investigated the bearing behaviour of a combined pile-raft foundation on sand. A number of small scale model test at 1g level were performed. The geometric dimensions of the model was arrived based on typical dimensions of piled raft in Frankfurt am Main and a model scale of 1/50 was adopted. Tests were carried out not only with piled rafts but also with pile groups without raft-soil contact and raft foundations. A total of 12 tests were performed, two for each foundation on loose sand and two on dense sand. Comparison of test results of piled raft and plain raft showed a settlement reduction of 30% in loose sand and 50% in dense sand. However, much higher settlement was reported for the pile group. The load shared between the bearing elements (piles and raft) of piled raft was a function of settlement of piled raft as shown in Figure 2.2. It was also found that the central pile of the five pile group they had used behaved slightly stiffer than the outer piles.

![Figure 2.2 Load ratio vs settlement (after Turek and Katzenbach, 2003)](image)

The study showed that at a settlement level of 4mm the pile group mobilized its ultimate shaft resistance in the case of loose sand. The increase in the stress level below the raft influenced the shaft resistance of pile group more in the case of dense sand than in the case of loose sand. Also it was found that the piles of piled raft in loose sand did not reach the ultimate shaft resistance due to the increase in the stress level under the raft. Although the number of tests reported was limited, the study established that the
performance of piled raft in settlement reduction was better in dense sand than in loose sand.

As seen from the discussions the small scale model studies carried out on model piled rafts were mostly on overconsolidated clay bed. The concentration was mostly on the reduction of differential settlement and load carried by the piles. Even though Cooke’s study produced important conclusions on spacing of piles and length of piles, the effect of many other parameters appeared to have not been given adequate importance. The behaviour of piled raft on sand needs further study in detail to establish its effectiveness under various parameters of the constituting elements of piled raft.

2.2.2 Centrifuge Model

Centrifuge testing concerns the study of geotechnical events using small scale models subjected to acceleration fields of many times Earth’s gravity. With this technique, self weight measures and gravity dependent process are correctly reported and observations from small scale models can be related to the full scale prototype situation using well established scaling laws. Centrifuge model tests have proved to be useful in displaying mechanisms of deformation and collapse and in providing valuable data for validation of numerical analyses. However very limited centrifuge tests on piled raft foundation are reported in literature. The limited studies reported are reviewed here.

Thaher and Jessberger (1991) investigated the effect of pile length, pile number and pile diameter on the load bearing behaviour of piled rafts through centrifuge model tests conducted on 1/150 scale models. The models were tested in overconsolidated clay under centrifuge acceleration of 150g. In their study the raft used was 15mm thick aluminium alloy plate which represented the rigid behaviour of the raft. However the piles were placed only on the external periphery of the rigid raft. Besides the normal basic
models, the foundation of an actual tower building (Messe Turm) was also modelled in which longer piles were installed near the centre of the square raft and shorter in the edges as suggested by Padfield and Sharrock (1983).

The important conclusions drawn by Thaher and Jessberger (1991) were

1. The peak contact pressure under the piled raft with regularly spaced pile group was similar to that of conventional raft (unpiled raft).
2. The consolidation of clay equivalent to 13 years at proposed scale increased the total pile load up to 10% of the structural load.
3. The pile spacing and the number of piles influenced the load carried by the pile group. However the effect of length of the piles in the group was much less than the spacing of the piles and the number of piles.
4. The pile spacing ratio \((s/d, s\)-spacing and \(d\)-diameter of pile) played a key role in the behaviour.

Horikoshi and Randolph (1996) conducted a series of centrifuge model studies on piled raft supported on overconsolidated clay. A centrifuge acceleration of 100g was applied to 1/100 scale models. A small pile group was installed only beneath the central area of a flexible raft. The raft settlement and load transferred to the pile group were monitored. A fully piled raft designed by conventional method was also tested. The centrifuge model test set up used by them was as shown in Figure 2.3.

Tests were conducted to establish the fact that even a small pile group in the central area of flexible piled raft could reduce the differential settlement to a large extent and a cap of smaller size could increase the total bearing capacity also to a large extent, because of the load transferred through
the cap. An extensive parametric study was performed in order to develop a rational design method for piled rafts. In addition to fully elastic analyses, the centrifuge model tests were analysed using the hybrid method (HyPR), a numerical model developed by Clancy (1993) and compared the results. The applicability of equivalent pier theory in studying the load settlement behaviour of piled raft was also examined by generating nondimensional pier parameters. This study showed that piled rafts could be designed for negligible differential settlements by introducing a pile group over the central 16-25% area of the raft and the piles could share about 40-70% of the total load, depending on the pile group area ratio and Poisson’s ratio of the soil. The study established the effectiveness of a small centrally located pile group in reducing the differential settlement to a considerable extent. However the overall settlement reduction was not given much importance. Further it was established that the equivalent pier approach overestimated the stiffness (i.e.) underestimated the average settlement.

Figure 2.3  Centrifuge Package (Horikoshi 1995)
The degree of overestimation according to the study depended upon the depth of the layer compared to pile length, rigidity of the piles and spacing. The study was further extended to nonhomogeneous soil of increasing elastic modulus and showed that the variation in results was within 10% of the results produced by other approaches.

2.3 STUDY ON THE PROTOTYPE PILED RAFT

Even though 1g model studies provided very valuable data on the behaviour of piled raft, these are more appropriate under homogeneous soil conditions. Observational methods, even though are time consuming, they provide more factual results. The above facts made the engineers of those who have involved in the design of piled raft foundation to monitor the response of foundation during construction as well as for some period after construction. This has helped the geotechnical engineers to understand the mechanism of load sharing between the components of piled raft and in turn to improve the piled raft design. The data from field monitoring, thus obtained are published periodically. Some of them have been presented and discussed below.

Morton and Au (1975) presented and discussed the settlement data of eight structures in London monitored over a period of eight years. The settlement at the end of construction period was 60% of the anticipated maximum settlement irrespective of the type of foundation. Differential settlements were about 25% of the maximum settlements for all the structures examined. Finally the authors concluded that the maximum settlements of piled raft were \( \frac{1}{3} \) of the corresponding maximum settlements of rafts.

Burland et al (1977) was one of the earliest researchers to adopt the concept of settlement reducing pile. Figure 2.4 refers to the design concept of Burland. The foundation system comprised of 2.0m dia 16m long bored cast in situ piles placed under each column.
Figure 2.4   Burland’s Model (Burland, et al 1977)

It was proposed in the study that the behaviour of such piles should be ductile in their load-settlement response to take the raft settlement, meaning in general the settlement reducing piles should be, floating piles or mainly friction piles. Since the number of piles to reduce the raft settlement would be small, the spacing of such piles would be quite larger than the spacing used in the traditional design.

These piles were installed on 3m thick medium to dense sand with an individual capacity of 2850kN. In his concept the pile mobilized the ultimate shaft capacity, resulting in a reduced column load acting on the raft. The pile loads and the raft settlements were monitored and subsequently results of the study were further used by other designers and researchers like Yamashita et al (1994).

Hooper (1974) reported the behaviour of piled raft supporting a twin block for which the field measurements were taken for nearly 7 years from 1967 to 1973. The raft was 1.52m thick located at 8.8m below the average ground level. The piles were underreamed pile of 0.91m shaft dia and 2.44m bulb dia reinforced in the top 6m only. Even though the gross foundation load was 368kN/m², the net pressure was 196kN/m², due to the deep excavations involved. The tower was 90m tall having 31 floors. The maximum settlement observed was 21.2mm. The numerical analysis was
performed by adopting axisymmetric condition and treating each concentric row of piles as an annulus with an overall stiffness equal to the sum of stiffness of the individual piles. It was found that in the initial stages the applied load increased the contact pressure very slowly due to the fact that in the initial stages the excavation induced large uplift forces. At the final stages the ratio of distribution of load between raft and the pile was about 0.3. This computation indicates that the long term consolidation could reduce the raft contact pressure increasing the pile loads. The study further concluded that most of the settlement was taken place during the construction period itself.

The observed behaviour of a piled raft foundation of stone bridge park tower block, London was reported by Cooke et al (1981). The building is 43m high supported on 0.9m thick raft connected to 351 bored piles each 0.45m diameter and 13m long located on an almost square grid of 1.6m spacing. From the measurements using the borehole extensometers, the average raft settlement increased from about 10mm at the end of construction to around 18mm after a further period of four years and precise observations indicated that differential raft settlements were very small. Using the computer program NAPRA, Viggiani (1998) was able to obtain good agreement between the calculated and observed settlements. Viggiani also showed that the number and layout of piles were significant in terms of differential settlement. While reducing the number of piles tended to increase the differential settlement, concentrating the piles towards the centre of the foundation led to a marked reduction in the differential settlement. Almost similar conclusion was drawn through centrifuge model tests, which were conducted nearly 15 years later by Horikoshi and Randolph (1996).

Padfield and Sharrock (1983) analysed the piled raft system of an actual building which was constructed on London clay based on conventional design method. After confirming a good agreement between their elastic analysis and measured data, they proposed an alternative design to reduce the differential settlement and suggested that the shaft resistance of piles should
nearly be fully mobilized in the range of raft settlement. This would facilitate the role of settlement reducing piles. Even though the pile capacities would be nearly the maximum, the pile might not fail since the raft would have the capability of absorbing the additional load or any load shed from the pile. Padfield and Sharrock (1983) further proposed a stiff response in the central area of the raft and much softer response in the edges.

An extensive review of the settlements of actual structures was conducted by Cooke during 1986 with an intention to understand the factors affecting the overall and differential settlements under working condition and also to know how the structural loads were transferred to the supporting soil by the components of foundation. He concluded that, for unpiled rafts, the immediate settlements were found to be in the range of 0.2% to 0.3% of the equivalent breadth of the raft, when foundations were designed conventionally with a factor of safety 3. The settlement of structures on deep foundations was found to be ⅓ of those for comparable structures on shallow foundations. Almost similar observation was reported by Morton and Au (1975) based on their studies on prototype structures. The load shared by the raft was 30% of the structural loads even through the piles were designed to carry full structural loads. Finally Cooke (1986) concluded that the distribution of load between the piles of piled raft foundation was influenced by the stiffness of the structure-foundation system and the structural loading. However for highly rigid structures, the load distribution between the piles depends essentially on the number of piles and their spacing.

A coal silo of 11.6m supported on a circular piled raft was monitored to study the behaviour of piled raft embedded in a soft ground (Kulhawy et al 1987). The thickness of raft was 0.6m; it was supported by five pile group, with an annular ring beam of 1m wide and 1.3m thickness provided at the bottom of the raft. One pile was placed at the centre of the raft and the remaining four piles were located at a radial distance of 4.3m from the centre of the raft. From the observations reported, it was found that the safety
factor of piles against bearing failure found to vary between 1.6 and 1.8. Further good agreements between observed results and the results of elastic analysis were reported.

Franke (1991) from the review of the published results of three major buildings namely Torhause, Messe Turm and West End Street Tower I, provided certain guidelines for the design. A brief description of each structure and their performance are given below:

The Messe-Torhause (Figure 2.5a) building which is a 30 storied structure was supported on twin piled raft system measuring 17.5m×24.5m each (Figure 2.5b). The rafts were located at a depth of 3m and each one was supported on 42 piles of 20m long and 500mm dia each. The raft thickness was 2.5m. Each raft was loaded with an effective load of 200MN. Being the first building on the piled raft, this was designed conventionally.

The piles were assured to be utilized to its bearing capacity, while the remaining part of load would have to be taken by the raft and transmitted directly to the soil. The observed settlement was 150 mm over a period of 4 years and the load sharing ratio by the pile group, $\alpha_{pr}$ was 0.8 (Figure 2.5b). The maximum load shared by the raft was 20% of the total load. This piled raft is an example for first generation design.
Figure 2.5 (a) Messe-Torhaus, Frankfurt (Katzenbach, 2000)
Figure 2.5(b) Observed time-dependent load–settlement behaviour and load sharing for Messe-Torhaus, Frankfurt (Katzenbach, 2000)
The 256.5m tall Messeturm tower has a basement with two underground floors of each 58.8m² in plan and a 60 storey core shaft of size 41m×41m (Figure 2.6). The estimated total load was 1880MN. The raft was located at a depth of 14m below the ground level in a deposit of gravel and sand of 8m thick followed by Frankfurt clay of 100m thick or more. The raft was 6m thick at the centre and reduced to 3m at the edges. The bored cast in-situ piles were of 1.3m diameter arranged in 3 concentric circles below the raft. The length of piles in the outer middle and inner circles were 26.9m, 30.0m and 34.9m respectively.

![Figure 2.6 Instrumented foundation system for Messeturm tower (Katzenbach, 2000)](image)

The design was done by assuming a load sharing ratio. The piled raft was proportioned for the following two cases:

(a) Plan and cross-section
(b) location of instrumentation
(i) In the first case, the piles were assumed to carry only 30% of the structural load and the remaining load carried by the raft via contact pressure.

(ii) In the second case, the piles were assumed to carry 55% of the load and the remaining load on the raft

Further it was stated that the foundation system was instrumented elaborately (Figure 2.6) to measure settlements, contact pressures and load on piles. These instruments were monitored and measurements were made regularly over a period of about four years including the construction period of one and a half years.

The settlement of raft, load shared by the piles, and variation of contact pressure on raft with time are presented in Figures 2.7 and 2.8. The settlement of the raft at the end of construction was 85mm at the center and 48mm at the edges. The load shared by the piles at the end of construction was 55%. The average contact pressure was 160kN/m² and it was reported that the measured contact pressure at the centre of raft was about 20% higher than at the edges. Finally it was concluded that, the assumption made in the design was not complied with the field observation.

The West end tower is also known as DG bank building which was constructed during the period between 1990 and 1993. The structure is 53 storied 208m tall office building in L shaped form. The total structural load was 1420MN. This load was transferred to Frankfurt clay through a piled raft of raft thickness of 3 to 4.5m and 40 bored piles of 1.3m dia with a constant length of 30m. The raft was founded at a depth of 14.5m which is 9.5m below the water table. As stated in the earlier cases, this structure was also instrumented and monitored. The typical variation of load-settlement response was reported as presented in Figure 2.9. In this case the load was equally shared by the piles and raft.
Figure 2.7  Settlement of raft and load shared by piles for Messeturm Tower (After Katzenbach et al 2000)
Figure 2.8  Load shared by piles and contact pressure variation for Messeturm Tower, (Katzenbach et al 2000)
From the performance of piled raft foundation of three tall structures, Frank (1991) concluded that the raft contact pressure would increase only when the base resistance of the piles was relatively smaller when compared to the shaft friction and also suggested that a skill full layout of piles would reduce the raft bending moment and the internal stresses in the raft. The study further concluded that a balancing of load share must be done in such a way that the raft and piles share the load equally for a given settlement. This was achieved in the West end tower. This would warrant a repeated analyses to fix the length of the pile after selecting the diameter. Frank (1991) further gave more importance for the load shared by the raft and indicated that finite element and boundary element methods must take into account the bilinear elastic / plastic shaft resistance behaviour, and simple design calculation must be developed for the design office. Poulos (1991) used the computer program GASP (Geotechnical Analysis of Strip with Piles) and analysed various foundation options for the printing press building, Sydney. As a result of these analyses, it was decided to use a strip foundation
of 5m wide and 0.8m thick, with pairs of bored piles of 0.9m diameter, typically extending about 7.5m into moderately weathered shale.

Schwab et al (1991) used electronic devices for monitoring the performance of raft and measured raft contact pressure, settlement, pile head and tip loads. According to them the measurement of deformation below the raft has to be done for the assurance of structural safety and serve as the basis of design for future projects.

Yamashita et al (1994) instrumented and monitored a five storied structure support on piled raft in Urava, Japan and analyzed numerically. Here the piles were steel “H” piles embedded in predrilled holes and grouted. The raft was 300mm thick and located at 2.4m below the ground level. The foundation load was 47.5MN. The settlement was monitored for a period of 300 days and the magnitude of settlement was 12mm at the end of 300 days. The measured pile load in the corner piles was less than the peripheral piles contrary to the general opinion and also the view expressed by Cooke et al (1981). According to the study, this was due to a certain amount of load transferred through the edge beam of the raft to the soil directly, thus reducing the load carried by the pile. In the numerical model, the raft was modelled as plate and beam elements and the piles were idealized as springs. A portion of the load was applied as concentrated load on the column location and the balance load as uniformly distributed load on the tributary area of the raft. However no specific mention about the magnitude of the load ratio was specified. The results were in agreement when the load transfer through the sides of the foundation was considered.

The growing demand for office space in Frankfurt, Germany and the prevailing soil conditions of this area lead to the development of tall structures and cost saving foundation system. While the conventional design lead to choose deep piles, the concept of piled raft gained importance as an economical alternative foundation system for tall buildings. Numerous structures were built in Germany on piled raft foundations since 1983. The
first few German experiences with piled raft foundations started in the overconsolidated clay with the construction of high-rise Messe-Torhaus building. The second piled raft structure was the Messeturm building in Frankfurt, illustrated the advantages of this foundation and lead to the acceptance of the concept of piled raft foundation by geotechnical experts. Following this concept several other skyscrapers were built on piled raft and monitored. More recently for some of the high-rise buildings on loose sand in Berlin, piled raft foundation was adopted and monitored. It was referred that piled raft performed efficiently in sand and reduced the settlement of structures appreciably. The experience gained in each building was efficiently utilized to improve the design of piled raft. The improved design methods offer the possibility for an optimal design of piled raft foundations both in clay and sand.

In order to refine the design concept of piled raft keeping in mind its extensive use, Katzenbach and his team have been researching continuously on the piled raft foundation for more than 15 years (Katzenbach 1993; Katzenbach and Reul, 1997; Katzenbach and Moormann 1997; Katzenbach et al, 1998, 2000 & 2002 etc.) and validated their analyses results with the field performance data of piled raft foundations of several buildings in clay and sand. In all their works, the complex soil-structure interaction (soil-pile, pile-pile, soil-raft and pile-raft) was modelled numerically and the influence of each foundation element (i.e., soil, pile and raft) over the other was demonstrated and discussed. Finally, in the year 2000, they came out with recommendations for the design and construction of piled rafts wherein safety concept was also included. In book on “Design Application of Raft Foundation” edited by Helmsly (2000), Katzenbach and his research team contributed a chapter on piled raft foundation projects in Germany. In this chapter, the authors discussed about the concept of piled raft foundation, numerical analyses of piled raft foundation, design considerations of piled raft, safety concept of piled raft and piled rafts in Germany. In the chapter on piled rafts in Germany, the piled raft projects already built or in progress in
Frankfurt am Main during 1983 to 2001 were well documented. The authors classified them as first, second and third generation piled rafts. The first generation projects were Messe-Torhaus and Messeturm buildings for which conventional methods combined with engineering judgment were used. Piled raft foundations of the second third generation were designed using increasingly improved and verified calculation methods, based on analytical models or three dimensional finite element analysis with elasto - plastic constitutive laws for the soil. In Table 2.1 details of piled raft foundation of all the three generations including their performance are presented as reported by Katzenbach et al (2000).

From the table presented it can be seen that piled rafts provided for various structures composed of thick raft (maximum thickness 6m) with large diameter bored piles. Pile diameters were found to vary between 0.9m and 1.5m. These piles were normally spread at 3d (d-diameter of pile) distance. However maximum spacing adopted was 6d. Pile lengths provided were found to vary between 20m and 35m and ensured that the piles were sharing the load mostly through frictional resistance. The settlement and load sharing ratio, $a_{pr}$ of piled raft foundation were also reported. The settlement reported was found to vary between 32mm and 150mm and the minimum and maximum load sharing ratios reported were 0.3 and 0.8 respectively.
<table>
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<th>Messe-Torhaus</th>
<th>Messeturm</th>
<th>DG-Bank (Westendstrasse 1)</th>
<th>American Express</th>
<th>Taimuostor Japan-Centre</th>
<th>Forum (Kastor and Pollux)</th>
<th>Congress Centre Messe Frankfurt</th>
<th>Main Tower</th>
<th>Eurotheum</th>
<th>Frankfurter Welle</th>
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</tr>
<tr>
<td>Thickness of raft (m)</td>
<td>2.5</td>
<td>3.0–6.0</td>
<td>3.0–4.3</td>
<td>2.0</td>
<td>1.0–3.5</td>
<td>1.3–3.0</td>
<td>0.8–2.7</td>
<td>3.0–3.8</td>
<td>1.0–2.5</td>
<td>1.0–2.2</td>
</tr>
<tr>
<td>Number of piles</td>
<td>2 × 42</td>
<td>64</td>
<td>40</td>
<td>35</td>
<td>25</td>
<td>26/22</td>
<td>141</td>
<td>112</td>
<td>25</td>
<td>102</td>
</tr>
<tr>
<td>Average pile spacing (m)</td>
<td>3.0–3.5 D</td>
<td>3.5–6.0 D</td>
<td>3.8–6.0 D</td>
<td>3.5 D</td>
<td>3.0–6.0 D</td>
<td>4.0–6.0 D</td>
<td>3.0–6.0 D</td>
<td>3.0–6.0 D</td>
<td>1.6–6.0 D</td>
<td>3.5 D</td>
</tr>
<tr>
<td>Pile length l (m)</td>
<td>20.0</td>
<td>26.9–34.9</td>
<td>30.0</td>
<td>20.0</td>
<td>22.0</td>
<td>20.0–30.0</td>
<td>12.5–34.5</td>
<td>20.0</td>
<td>25.0</td>
<td>20.0 &amp; 25.0</td>
</tr>
<tr>
<td>Pile diameter D (m)</td>
<td>0.9</td>
<td>1.3</td>
<td>1.3</td>
<td>0.9</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
<td>1.5</td>
<td>1.5</td>
<td>0.9</td>
</tr>
<tr>
<td>Eccentricity of building load e (m)</td>
<td>0.8</td>
<td>0</td>
<td>&gt;0</td>
<td>&gt;0</td>
<td>7.5</td>
<td>e=0 for each tower</td>
<td>&gt;0</td>
<td>2.0</td>
<td>3.8</td>
<td>&gt;0</td>
</tr>
<tr>
<td>Slenderness ratio (H/B)*</td>
<td>5.4</td>
<td>4.3</td>
<td>4.7</td>
<td>1.8</td>
<td>3.6</td>
<td>3.0/4.1</td>
<td>3.0</td>
<td>4.5</td>
<td>9.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total load (G+P) (MN)</td>
<td>2 × 200</td>
<td>1880</td>
<td>1420</td>
<td>1200</td>
<td>1050</td>
<td>990 920</td>
<td>1800</td>
<td>2000</td>
<td>570</td>
<td>=1000</td>
</tr>
<tr>
<td>Buoyancy uplift force (MN)</td>
<td>–</td>
<td>430</td>
<td>280</td>
<td>400</td>
<td>180</td>
<td>160</td>
<td>360</td>
<td>530</td>
<td>120</td>
<td>=500</td>
</tr>
<tr>
<td>Instrumented piles</td>
<td>6</td>
<td>12</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>3/3</td>
<td>12</td>
<td>17 (+25)</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Earth pressure cells</td>
<td>11</td>
<td>11</td>
<td>13</td>
<td>9</td>
<td>3</td>
<td>6</td>
<td>12</td>
<td>30</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Piezometers</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Extensometers</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Observed pile raft coefficient α₀</td>
<td>0.8</td>
<td>0.55</td>
<td>0.5</td>
<td>0.4</td>
<td>0.5/0.4</td>
<td>0.4</td>
<td>0.85</td>
<td>0.3</td>
<td>under construction</td>
<td></td>
</tr>
<tr>
<td>Observed pile loads (MN)</td>
<td>1.7–6.9</td>
<td>5.8–20.1</td>
<td>9.2–14.9</td>
<td>2.7–5.1</td>
<td>7.9–13.8</td>
<td>7.4–11.7</td>
<td>4.2–6.5</td>
<td>1.4–8.0</td>
<td>1.8–6.1</td>
<td>–</td>
</tr>
<tr>
<td>Observed max. settlement w (mm)</td>
<td>150</td>
<td>144</td>
<td>110</td>
<td>55</td>
<td>60</td>
<td>80</td>
<td>40–60</td>
<td>25</td>
<td>32</td>
<td>–</td>
</tr>
</tbody>
</table>

* B = smallest side length of raft  
H = distance between foundation level and top of building (uppermost floor)  
G = dead load  
P = live load
The settlement and load-sharing ratio of piled raft foundation of Eurotheum tower of 110m tall with total load 500MN were 32mm and 0.3 respectively. This structure was constructed in 1997 in Frankfurt clay of Frankfurt am Main and it was known as structure on piled raft of third generation. In the same area a structure of 130m tall with 400MN (Messe-Torhaus building) was constructed in the year 1983. The settlement and $\alpha_{pr}$ values recorded on its piled raft foundation were 150mm and 0.8 respectively.

Despite the foundations of both the structures were on almost identical soil deposits and on piled raft, the structure with higher load recorded very less settlement, which was $1/5^{th}$ of the settlement of first generation piled raft. Further the raft of Eurotheum tower shared 70% of the total load while Torhaus raft resisted only 30% of its total load. This is a good example for the improvement on the design concept of piled raft foundation of first and third generation.

Katzenbach et al (1998) have reported the performance of some of the recent structures built on sand. For example in Berlin, the 121m tall Treptowers building was supported on piled raft foundation to transmit part of total building load of 670MN through the loose sand below the raft to dense sand at deeper depth. Thickness of the raft provided to the structure was found to vary between 2m and 3m. The raft of least thickness was provided in the area of elevator.

The raft was supported on 54 bored piles of 0.9m diameter each. The length of piles were varied between 12.5m and 16m to match with the founding level of the raft. However all the piles were terminated at the same level, which is as shown in Figure 2.10a.

In the Figure 2.10b the settlement of piled raft foundation measured over the construction period of three years was shown. The settlement reported was 65mm at the end of construction. Further the authors have reported the results of numerical analysis of piled raft foundation and
compared with results of field measurements. The measured and calculated load-settlement behaviour of piled raft was in good agreement. The calculated settlement of piled raft foundation was 57% of the settlement of shallow foundation arrived through numerical simulation.

Figure 2.10  Treptowers building (after Katzenbach, 1998)

The 103m high Sony - Centre building is a part of new construction at the Potsdamer Platz in Berlin. The plan area of building is 2600m². It was supported on a piled raft comprising of 44 bored piles of 1.5m diameter and lengths of piles of 20-25m and raft of 1.2 to 2.5m thick. The foundation
underwent a settlement of 20mm at the centre of the raft on construction of 18 of the 26 storey.

In 1998 the new office building for Deutche Messe AG was constructed in Hannover, where the deposit is multi-layered system consists of semi-stiff to stiff glacial drift of 12-15m thick followed by a 2-4m thick layer of fine sand which is underlain by dense sand and gravel with a thickness of 5-7m. Then stiff clay and till is encountered, which is underlain by marly clay rock at a depth of 30m. The structure constructed was 68m high office tower over an area of 24m×24m. The foundation for this structure was built as a piled raft with 32 bored piles, each 1.2m diameter and length 17.5m. The performance of the building was monitored over a period and the maximum settlement at the centre of raft was 14mm. The settlement at the corners of stair case towers was 10mm. From the performance of tower it was concluded that the concept of piled raft can also be applied successfully in multi-layered and non-homogeneous deposits in order to reduce total and differential settlements.

Reul and Randolph (2003) presented a comparison of in situ measurements and numerical analyses for three piled raft foundations on over-consolidated clay. Comparison of overall settlement, differential settlement and load carried by the piles showed reasonably good agreement even though numerical methods show higher pile loads than predicted from the field measurements. Three different structures studied were Westend, Messeturm and Torhaus. The features of the buildings are presented elsewhere (Table 2.1).

The design of Canary Wharf office tower, England was discussed briefly by Jones (1998) and in more detail by Bergmann and Campbell (1991). It is a building of 236m high 50 storey steel framed office tower supported on a 65m square raft of 4m thick connected to 222 concrete bored piles, each 1.5m in diameter. The piled raft had a substantial end bearing component, thus reduced the load shared by the raft.
Hong et al (1997) reported the behaviour of a piled cellular raft foundation of 24 storey office building constructed at Shanghai, China. The building is supported on 1.5m thick cellular raft. The raft is supported on 233 pre-cast concrete driven piles of 0.45m × 0.45m size. Building settlements were measured during the construction period of two years. At the end of construction, the average measured settlement of 31mm reflected the presence of end bearing piles.

A number of field data reported in literature on the performance of piled raft were on overconsolidated clays and surprisingly major part of the research was on the Frankfurt clay. In most of the cases, the rafts provided were 3m thick or more and seated at deeper depths (around 10m depth). Early days piled raft designs followed adhoc methods and data reported were not adequately validated. Very few cases only presented with detailed analytical interpretations.

There seems to be paucity of published data on moderately loaded and flexible piled raft. Performance of piled raft with flexible raft and slender piles (smaller diameter) is also scarce. Very little is discussed in the literature on pile arrangements in real field conditions.

2.4 ANALYTICAL AND NUMERICAL MODELING

The design of any three dimensional foundation systems including complicated interactions among the constituting elements can be done only through a powerful numerical model which will reasonably represent the field conditions. Piled raft foundation is one such complex soil structure interaction problem which requires rigorous analysis for understanding the mechanism of piled raft and for the reliable design. Moreover the use of this foundation for supporting high-rise buildings is in increasing recognition for the past few years, which has forced the geotechnical engineers to develop a suitable method for the optimal design of piled raft. This was recognized long back and the Technical committee (TC 18) of the International Society had focused
its attention since 1994 towards piled raft foundation and has collected considerable information on methods of analysis and design including case histories.


(i) Simplified analytical methods.
(ii) Simplified numerical methods.
(iii) Rigorous numerical methods

2.4.1 Simplified Analytical Methods

The simple analytical methods, though were not directly aimed to handle piled raft, they were aiming at solving the complicated pile group settlement analysis. In such cases certain approximations were done to make the computational procedure simpler. Subsequent development on computational facilities made the researchers to adopt alternate numerical modeling methods to solve the same problem. Equivalent pier and equivalent raft theory fall in the first category; whereas stiffness matrix method falls in the second category. However the equivalent raft method is meant only for pile group settlement where the raft would not be in contact with the ground.
2.4.1.1 Equivalent pier method

Poulos (1968) established that it might be useful to replace the pile group by an equivalent pier as shown in Figure 2.11 of the same gross area as in the group. The length \( L_e \) of the pier may be obtained by comparing the solutions for the settlement of pile group with the settlement of a single pier (Davies and Poulos 1972) and evaluating the required value of \( L_e \) in terms of \( L \) to give equal settlement of the pier and the group. He further established that the \( L_e / L \) is influenced more by pile spacing than by the number of piles and \( L/d \) ratio.

![Figure 2.11 Concept of Equivalent Pier (Poulos, 1968)](image)

Extending this, Poulos and Davis (1980) presented two methods; (i) An equivalent single pier of the same circumscribed plan area of the group (Figure 2.11) and of some equivalent length \( L_e \), and (ii) An equivalent single pier of same length \( L \) as the piles but having an equivalent diameter \( d_{eq} \). While the second method is good in computing the overall average settlement, this does not offer any solution for differential settlement. The equivalent pier approach of Poulos and Davis (1980) was further analysed by Poulos (1993).
In this approach Poulos (1993) replaced a portion of pile group by an equivalent pier and the stiffness of pier was predicted based on the elastic solution of single compressible pile proposed by Poulos and Davis (1980). The diameter of equivalent pier for friction and bearing piles was worked using following relations.

For friction piles

\[ d_{eq} = \frac{4}{\pi} \sqrt{A_g} \]  

(2.1)

For bearing piles

\[ d_{eq} = \frac{2}{\sqrt{\pi}} \sqrt{A_g} \]  

(2.2)

where \( A_g \) is the plan area of the pile group as a block. These two equations are derived using total peripheral length of the block and plan area of the block respectively. Randolph (1994) reported that Equation 2.1 might offer a more accurate stiffness even for a friction pile group.

### 2.4.1.2 Flexibility matrix approach

Randolph (1983) proposed an approximate method for the analysis of piled raft foundation. In the analysis two interaction parameters were introduced and related to settlement of pile group and raft as indicated in equation 2.3.

\[
\begin{bmatrix}
  1/k_p & \alpha_{rp}/k_r \\
  \alpha_{rp}/k_p & 1/k_r
\end{bmatrix}
\begin{bmatrix}
P_p \\
P_r
\end{bmatrix}
= \begin{bmatrix}
w_p \\
w_r
\end{bmatrix}
\]

(2.3)

where

- \( w_p \): Average settlement of pile group
- \( w_r \): Average settlement of raft
- \( P_p \): Total load carried by pile group
- \( P_r \): Total load carried by raft
- \( k_p \): Overall stiffness of pile group in isolation
- \( k_r \): Overall stiffness of raft in isolation
- \( \alpha_{rp} \): Interaction factor of pile group on raft
- \( \alpha_{pr} \): Interaction factor of raft on pile group
From the reciprocal theorem, the interaction factors were related as

$$\alpha_{pr} = \alpha_{rp} \frac{k_r}{k_p} \tag{2.4}$$

Since the average settlement of the piles and raft were assumed equal and from the above equations, the stiffness of the piled raft the proportion of the load taken by the raft were given by following expressions

$$\frac{P_r}{P_r + P_p} = \frac{k_r \left(1 - \alpha_{mr}\right)}{k_p \left(1 - 2\alpha_{mr}\right)} \tag{2.5}$$

$$k_{er} = \frac{(P_r + P_p)}{w_{pr}} = \frac{k_p + k_r \left(1 - 2\alpha_{mr}\right)}{1 - \left(k_r / k_p\right) \alpha_{mr}^2} \tag{2.6}$$

$$\alpha_{mr} = 1 - \frac{\ln \left(r/f_{rg}\right)}{\ln \left(r_m / r_y\right)} \tag{2.7}$$

where

- $r_r$ : Radius of raft / pile cap
- $r_p$ : Pile radius
- $r_m$ : Maximum radius of influence of each individual pile

Randolph compared these results with the results obtained by Poulos and Davis (1980) and found them to be in good agreement. Clancy and Randolph (1992) and Clancy (1993) found that the value of $\alpha_{mr}$ approached 0.8 as the number of piles increased. Clancy and Randolph (1993) introduced a parameter known as aspect ratio (R), which is expressed as $\sqrt{ns/L_p}$ where, $n$ is the number of piles in the group, $s$ is the spacing between the piles and $L_p$ is the length of the piles. This parameter is used to understand the behaviour of pile group. It was reported that for an aspect ratio greater than 4, the behaviour of pile group (group settlement pattern) was similar to that of a raft foundation. Therefore an equivalent raft approach is ideal choice for analysis. For values of R less than 2, it was recommended to adopt equivalent pier approach, at least for estimating average settlement of pile group.
2.4.2 Simplified Numerical Methods

In this method of analysis, the soil-structure interaction between the foundation element (raft or strip foundation) and the soil was accomplished by modeling soil continuum as a series of spring elements (Winkler model) and the foundation as plate or strip element. This also was known as simplified computer based analysis. It is an approximate method, because of inadequate representation of continuum response of soil. More over infinite extent of semi-infinite medium is also not represented by this model. Despite the limitations, this method is widely used in the design of raft and piled raft foundations. Based on the idealization of foundation element, this method has been identified as

(i) Strip on springs and
(ii) Plate on springs.

2.4.2.1 Strip on springs approach

A typical method in this group was that presented by Poulos (1991) in which a section of the raft was represented by a strip and the supporting piles by springs. Approximate allowance was made for all four components of interaction and the effect of the parts of the raft outside the section was accounted by computing free-field soil movements due to these parts. It has been shown that this method agreed reasonably with the results of more rigorous analysis. However this technique has following limitations:

(i) It cannot consider torsional resistance of the raft, and
(ii) Settlements at a point may not be consistent, if strip in two directions through that point are analyzed.

Brown and Wiesner (1975) and Wiesner and Brown (1976) have developed almost identical method of analysis as explained above for applied strip and suggested the way to extend this analysis to a piled raft.
2.4.2.2 **Plate on springs approach**

In this method, the raft is modelled as a plate, piles are modelled as interacting springs and the soil is represented by an elastic continuum (Poulos, 1994). In certain cases the soil is represented by springs and the pile as an one – dimensional element (Clancy and Randolph, 1993). Poulos (1994) presented an approximate analysis of piled raft in which the raft was modelled as a thin plate and the piles as interacting springs of appropriate stiffness. Allowance was made for the development of bearing failure below the raft, the piles reaching their ultimate capacity and free - field soil settlements. This method adopted boundary element approach as the basis and was similar to load cut off procedure explained by Hain and Lee (1978). Here, from the first set of analysis, in the nodes where the contact pressure exceeded the limiting value, the limiting value was applied on them; the analysis was repeated to obtain the constant value not exceeding the limiting value. The analysis was implemented through a package GARP and was compared with other published results. This method of numerical analysis involves a trial and error procedure and assumes limiting values of pile capacity and raft, hence has limitations for practical design.

O’Neill et al (1977) developed the so called the hybrid approach for the analysis of offshore pile group by modifying the boundary element approach. A load transfer analysis was used to compute the individual pile behaviour and Mindlin’s theory was used for the soil to consider the influence of the adjacent piles. Chow (1986) presented a hybrid analysis for linear and nonlinear response of the pile group subjected to vertical loads. The procedure employed the method developed by Randolph and Wroth (1978) to arrive at the nonlinear t-z relation with Mindlin solution for pile- soil and soil- pile interaction to be used for the formation of stiffness matrix. Chow (1987 b) further extended his work for the pile group with ground contacting cap. The soil non- homogeneity was considered by using finite element analysis.
Chow and Teh (1991) used Chow’s method to study the piled raft on non-homogeneous soil with a finite depth. Here the raft was assumed rigid raft and modelled as sub-elements and the piles were modelled as two noded one dimensional elements with an axial node of deformation. Finally they reported that the effect of rigid raft contacting the ground had a little influence on the stiffness of the group compared with the free standing pile group. The analysis based on the non-homogeneous soil condition resulted very low load on piles.

Clancy and Randolph (1993) extended the hybrid model generated by Chow (1986) and Chow and Teh (1991) in which the pile group and the interaction between piles and the raft element were based on Mindlin’s solution. But they have used the load transfer model of Randolph and Wroth (1979) for the single pile behaviour.

Figure 2.12 shows the model developed by Clancy (1993) wherein idealization of different elements of piled raft foundation is presented. The method allowed for slip along the pile shaft. The model was named as HyPR (Hybrid piled raft analysis).

Figure 2.12  HyPR Model (Clancy, 1993)

1. One dimensional pile element
2. Lumped soil response at each pile node: Load transfer springs
3. Two dimensional plate bending finite element raft mesh
4. Lumped soil response at each raft node: Direct solution
5. Lumped soil response at each rigid disc node
6. Pile-soil-pile interaction effects calculated between pairs of nodes - Mindlin’s Equation
7. Raft soil-raft-interaction
8. Rigid disc-soil-rigid disc interaction
9. Pile-soil-raft interaction
10. Pile-soil-rigid disc interaction
11. Raft-soil-rigid disc interaction
This model was further used by Yamashita et al (1998) in validating their observations made on a prototype piled raft of a five storied building. The only difference in their approach was both the soil and piles were represented by appropriate springs. Russo (1998) and Russo and Viggiani (1998) described a method wherein various interactions (soil-pile-raft) were obtained from elastic theory and non-linear response of piles was modelled using hyperbolic load settlement relation. Interaction between the piles was applied only to the elastic settlement of pile, while non-linear component of settlement of pile was assumed to arise only from the load of the particular pile. However this model can be used only for linear elastic analysis. Since the soil-pile interaction is represented through springs, the method becomes very sensitive to soil modulus (Es). Poulos (1994) formulated a numerical procedure for the analysis of piled raft wherein raft is modelled as a thin plate and piles are modelled as springs. The method permits the analysis to limit the base pressure of the raft and ultimate capacity. Poulos (1998) used GARP program for the analysis of piled raft and concluded that increasing the number of piles while generally benefit, did not always produce the best foundation performance. But no quantitative indication or limit was given for the number of piles to be used. The raft thickness influenced the bending moment and differential settlement of raft and not on load sharing or maximum settlement. Finally the author concluded that the piled raft designed by utilizing the full capacity of individual piles was economical.

Poulos et al (1997) reviewed a number of available methods for analyzing piled raft behaviour and applied few methods to analyse a hypothetical problem involving three different condition of piled raft viz., (i) a raft with 15 piles and a total load of 12MN, (ii) a raft with 15 piles and a total load of 15MN (iii) a raft with 9 piles and a total load of 12MN and an actual case history involving a tall building (Westend building) built in Frankfurt. The main objective of the analysis was to examine the capability of each method in predicting the behaviour of piled raft. Six different methods
have been used. They were Poulos and Davis (1980), Randolph (1983), strips on springs (GASP), plate on springs (GARP), finite element method of Ta and Small (1996) and finite element and boundary element of Sinha (1996).

The results of average settlement, differential settlement, maximum bending moment and proportion of load carried by piles obtained from the 6 methods for all the cases chosen for this study were compared independently. The results of analyses of Westend building from the six methods considered were compared in Figure 2.13.

Figure 2.13 Comparison of results from numerical methods (Poulos, 2001)

From the results compared, Poulos et al (1997) concluded the following:

(a) The differences in the results of analyses between six different methods were significant.

(b) At lower loads on the raft, the axial capacity of pile was not utilized fully thus the average settlement predicted by the six
methods was similar. When the pile capacity of a significant number of piles was fully mobilized, there was a significant variation in the predicted behaviour of the piled raft foundation.

(c) There was a considerable difference between the computed maximum bending moments of the raft depending on the method of analysis employed.

Further Poulos et al (1997) concluded that though the methods appear to provide reasonable basis for estimating overall behaviour of a piled raft foundations, there appears to be broad scope for a further study to improve the methods to predict the entire load settlement behaviour of piled raft reliably.

2.4.3 Rigorous Numerical Methods

The rapid developments in computing systems and powerful numerical methods have encouraged the researchers to develop various numerical methods to study the load-settlement and load sharing behaviour of piled raft. The various numerical approaches can be grouped as detailed below:

(a) Boundary element method (Butterfield and Banerjee 1971; Kuwabara 1989; Sinha 1997).

(b) Methods combining boundary element for the piles and finite element analysis for the raft (Hain and Lee 1978; Frank et al 1994; Ta and Small 1996).

(c) Simplified finite element analysis adopting a plane strain approach or axi symmetric idealization (Hooper 1974; Prokoso and Kulhawy 2001).
(d) Detailed finite element analysis involving three dimensional modeling (Zhang et al 1991; Lee, 1993; Gandhi and Maharaj (1996); Maharaj 1996; Katzenbach et al 1998; Reul 2000).

(e) Methods employing strip on spring approach with a series of strips representing the raft and springs of appropriate stiffness representing the piles (Poulos 1991).

(f) Plate on spring approach in which the raft is represented by a plate and piles by springs (Clancy and Randolph 1993; Poulos 1994; Russo and Viggiani 1998; Yamashita et al 1998).

2.4.3.1 Boundary element method

Butterfield and Banerjee (1971) studied two problems considering the interaction with the supporting ground of an arbitrarily spaced group of piles with a ground contacting pile cap. They studied the load-displacement behaviour and load sharing behaviour. In the analysis they adopted Mindlin’s solution for a point load in an elastic half space. The parameters considered in the analysis were lengths to diameter ratio of pile, pile cap size, compressibility of the pile and the soil medium. They found that the floating and ground contacting caps behave differently. The ground contacting cap exhibited 5 to 15% higher stiffness than the floating cap, which is the function of group size and spacing. The proportion of the load taken by the ground contacting cap varied from 20% to 60% depending on the group size and pile spacing. However no specific mention about the settlement behaviour or differential settlement was observed. This study was restricted only to small group of 2 and 4 piles.

Kuwabara (1989) performed boundary element analysis based on elastic theory to study the settlement and load transfer behaviour of piled raft. The soil was treated as homogeneous elastic and isotropic half space medium. The behaviour of the pile group of piled raft was compared with free standing pile group and termed the length beyond which there was no further decrease
in the settlement as critical length. Kuwabara’s analyses showed that 20% to 40% of the load was shared by the raft resting on the soil directly and concluded further that the critical length of the pile group was larger than the single pile when the dimensions were the same as the piles in the group. Accordingly the critical length would not get affected by the spacing of the pile so long as the spacing was restricted to 10 times the pile diameter. The author also found that the ratio of long term settlement to total settlement of pile group was higher than that of single piles but, the presence of raft did not alter the situation except for short pile groups. However, the study was restricted to smaller square pile groups.

Sinha and Poulos (1997) studied the effect of ground movement caused by the expansive soil on the behavior of piled raft considering two types of raft namely totally flexible and rigid. The raft was idealized as elastic plate, the pile as circular element each acted upon by shear stress and circular ring having uniform stress. From the study it was established that the movement caused redistribution of stresses and resulted higher load on piles. But swelling caused a reduction in the load taken by the piles.

### 2.4.3.2 Combined boundary element and finite element method

Hain and Lee (1976) in their study on raft pile system, considered the piled raft system as a flexible elastic plate supported on a group of compressible pile and the supporting soil was represented as an elastic homogeneous or non - homogeneous material. In order to consider the ultimate capacity of piles, Hain and Lee (1976) adopted a load cut off procedure, wherein the piles that were subjected to reactions more than their capacity were deleted from the compatibility equations and their loads were held constant in the equilibrium equations. Hence, any excess load on that pile got redistributed to the adjacent piles. This resulted in an analysis which took the finite load capacity of the pile into account.
Hain and Lee’s analysis incorporated two case studies (La Azatec and Cavalry Barracks buildings). In the analytical procedure applied to the building La Azatec, it was found that only 17% of the load was taken by the raft. Around 40% of the piles carried only 0.1MN against the design load of 0.26MN, 8% of the piles exceeded the ultimate load of 0.69MN. The measured differential settlement after 20 months was only 30mm, but the data available was insufficient to make a comparison of long term predicted and measured settlement. In the case of the second building namely Cavalry Barracks, it was shown that practically all the loads were carried by the piles because of the closer spacing. The paper however indicated the importance of the use of appropriate value for the modulus of variation of soil. It was predicted that the use of homogeneous soil model would overestimate the settlement by 50% whereas in the case of non-homogeneous model it was underestimated by more than 100%.

Ta and Small (1995, 1996, & 1998) performed a more rigorous analysis considering layered soil, adopting the finite layer theory in which the soil was treated as a series of horizontal isotropic or cross isotropic elastic layers of infinite extent in the lateral directions. For the case of load on circular area, Henckel transformations were applied to all field quantities namely loads and displacements. Solution was obtained for transformed quantities and these were finally converted to obtain actual field quantities. The study was done by Ta and Small for pile group by extending the method of Lee et al (1991) for settlement of single pile using finite layer theory. It was found that this method was advantageous in studying the behaviour in layered soil only; but a very limited number of layers only be considered to save computer time. They extended the study to piled raft. The raft was modelled as thin elastic plate and the soil was modelled using finite layer method. They could estimate the raft bending moment and pile head loads and found that the load distributions along the shaft of the pile in layered soils were affected by relative thickness and stiffness of the soil layers.
Combining the finite element method for raft and finite layer analysis for soil and pile group, Ta and Small (1998) analyzed the results of several case studies including the centrifuge models and prototype piled rafts and found that the results were in agreement. However under normal working load conditions which is mostly elastic in nature, the method proposed appears to predict the results with a reasonable accuracy even though this method did not include the contact forces and the material non-homogeneity.

Xu and Poulos (2002) developed a computer program GEPAN to study the behaviour of piles and pile groups and compared the results with the output of PIGLET and DEFPIG and found to be in agreement. In spite of the fact that was able to give various interaction factors and appear to be very versatile, no further application was developed mainly due to the mathematical complexity.

2.4.3.3 Finite element analysis

Prokoso and Kulhawy (2001) studied the effect of various parameters related to pile and raft on the normalized settlement of piled raft adopting two dimensional plane strain model (Figure 2.14).

Figure 2.14 Plane Strain idealisation of piled raft (Prokoso and Kulhawy, 2001)
The modulus of pile wall was computed from the term equivalent modulus which was a function of number of piles, width or dia of the pile and soil modulus. The study concluded that the ratio between the width of the raft and the length of the pile played an important role on settlement behaviour of piled raft. The piled raft with ratio equal to unity was very effective in reducing over all settlement, where as a ratio 0.5 was very effective in minimizing the differential settlement. Further it was concluded that a pile to raft area ratio of 5% to 6% was adequate to reduce the overall settlement. The results were mostly in the form of non-dimensional parameters. While the contribution was very useful as a parametric study, it has only a very limited application. The procedure would be ideal for a single group of large number of piles, in a row.

Three dimensional analyses were carried out by Reul (2000) and Katzenbach et al (1998) in analysing the observations made on the prototype piled raft supporting large structures on Frankfurt clay. In the analysis the long term behaviour of the soil was considered with the drained shear parameters c and ‘\( \phi \)’. The nonlinear material behaviour was considered by the elasto - plastic cap model. They developed a new design concept for piled raft foundations. This concept was developed based on the results of geotechnical measurements made on Frankfurt clay and numerical model that was developed at the Institute of Geotechnics, Darmstadt University of Technology, Germany. This numerical model consists of three parts: (i) the geotechnical model for continuum (i.e. 3 dimensional finite element mesh) (ii) elasto-plastic constitutive law to described the soil behaviour (i.e. constitutive relation), and (iii) numerical computer simulation in a step by step analysis. The constitutive law is based on a modified Drucker-Prager model taking into account inelastic soil behaviour depending upon the stress path and previous stress history. The ability of the model was verified by numerical simulation of in-situ pile load test and by the back analysis of existing piled raft. In the numerical analysis, single pile and a single pile-raft unit were used.
Figure 2.15 Influence of pile-raft interaction on contact pressure 
Frankfurt Clay model (Katzenbach et al 1994)

It was concluded that the frictional resistance of pile was not only a function of soil strength but was also a function of residual stress in the soil, besides relative movement between pile and soil. The influence of pile-raft interaction on the contact pressure has been brought out in Figure 2.15. This indicates that the pile leads to a significant reduction of contact stress in the raft next to the pile shaft.

Further, the load-settlement behaviour of piled raft in Frankfurt clay was examined by varying the number of piles and drawn the following conclusions:

Settlement of piled raft plays a significant role in sharing the load between the piles and the raft but the load sharing ratio ($\alpha_{pr}$) is not a linear function of settlement.
The load bearing behaviour of the pile in a piled raft is different from the behaviour of a comparable single free standing pile and it depends on the position of the pile in the group and its spacing.

Based on the observations made through detailed numerical analysis, the requirements for the safe and economical design of piled raft was suggested and the proposed concept was applied for the design of the foundations of Main Tower and Eurotheum building, which are founded on piled rafts in the Frankfurt clay.

Katzenbach et al (2006) compared the load bearing response between a conventional pile foundation and piled raft foundation through a three dimensional finite element analysis which was developed in the Darmstadt University. This three dimensional finite element model was validated further by analysing the high-rise buildings of Messeturm and Eurotheum towers in Frankfurt am main. The measured settlements of these two buildings were compared with numerically computed values. The close agreement between the measured and numerically computed settlements, emphasized the importance of rigorous finite element method for numerical modelling of complex structures.

Reul (2000) in his study, on the piled raft on overconsolidated clay incorporated the effect of consolidation by a coupled pore pressure and stress finite element analysis. It was shown that with every load, increase the piled raft coefficient increased with time. Further it was shown through the analysis that there was no difference in the results for both one phase model (without pore pressure) and two phase model (with pore pressure). The contact between the structure and the soil was taken as ideal contact meaning that no relative motion between the nodes of structure and the soil. Reul first established the constitutive model required for Frankfurt clay through a series of tests as Drucker – Prager cap model and this was further used for all the studies. The study also considered the effect of mesh refinement wherein it was shown that relatively coarser mesh also produced results within an
acceptable level of accuracy. The analytical model was calibrated by means of back analysis of the results of field measurements monitored in the following three buildings: Messe Tower, Westend and Torhaus (Figures 2.16 to 2.18). It was reported that a settlement reduction coefficient of 0.51 to 0.63 could be achieved. Further the author established that under normal load, the piles do not reach their ultimate bearing capacity.

Figure 2.16  FE mesh of the foundation – Messeturm (Ruel, 2000)
Figure 2.17  FE mesh of the foundation – Westend (Ruel, 2000)

(a) Plan of the foundation
(b) Finite element nodes for
(c) Finite element mesh for soil and combined piled raft
Figure 2.18 FE mesh of the foundation – Torhaus (Ruel, 2000)

(a) Plan of the foundation

(b) Finite element nodes for raft

(c) Finite element mesh for soil and combined piled raft
One of the very important conclusions drawn was, that stiffness of the raft or the stiffness of the super structures had no influence in the load share between the piles and the raft. But the depth of the soil layer below the pile tip influenced the settlement of the piled raft. Reul and Randolph (2003) further showed that the measured values and analytical values agree well for the cases analysed. It was shown that by changing the layout marginally, improved value of settlement reduction could be achieved. In this analysis the difference between the results of FEA and measured values ranged from 20% to 30%.

In their subsequent study (Reul and Randolf, 2004) on the effect of non-uniform loading, they showed that the length of piles rather than number of piles had more influence on the load taken by the piles. The overall stiffness of the piled raft decreased with increasing load level. But differential settlement was more sensitive to raft soil stiffness ratio. For uniform loading, a small central group was found to be efficient in reducing the differential settlement.

2.5 SUMMARY

The literature on piled raft foundation was reviewed under following heads: Laboratory model studies, studies on prototype piled rafts and analytical methods.

It appears that the laboratory model studies reported both on 1g and centrifuge models have aimed at to validate analytical models developed for soil-structure interaction. 1g model tests conducted are very limited and in the limited work, the concentration is on piled raft in overconsolidated clay. Though it is well known that model tests conducted in a geotechnical centrifuge provide more relevant information than 1g model tests, the research on piled raft foundation using centrifuge technique is also scarce, which is suppose to the best alternative method to field test on prototype foundation.
Field monitoring studies on piled raft foundation are more in number than laboratory studies on 1g models. Most of the studies are on deeply seated piled raft foundation in Frankfurt clay. The intention of providing piles below the raft is to reduce both total and different settlements of tall and heavy structures. The data are obtained by monitoring the performance of foundation during construction and some period after the completion of structure. These data are used improving design philosophy and validating analytical models. However, parametric analyses are almost nil and are nearly impossible to carry out such studies in prototype models. It is also true that its suitability for buildings of medium size and load with relatively smaller diameter piles and thinner raft is not been studied and validated. Further they are time consuming and expensive. Despite some of the limitations, the field data are considered highly valuable in the sense that they represent real behaviour, which will be very useful for improving design method and for validating the analytical methods.

A number of versatile analytical methods have been developed over the past two decades for analyzing complex behaviour of piled raft. Relative performance between various methods is also been discussed. Few analytical methods have been validated with limited experimental data. Some researchers have specifically concentrated on the analysis of piled raft and developed suitable constitutive model and validated with the limited field data. It is also true to certain extent that there are few field data to validate and is mostly on one soil type. Further no comparison has been made in the field between structures designed both by the conventional and the latest design philosophy such as Katzenbach et al (2000) and Clancy and Randolph (1993).

If piled raft is to be an automatic choice in locations where pile is required to reduce the settlement of raft, the existing design methods need to be improved by concentrating on minimizing the number of piles and pile locations. This may end to economy in piled raft design as well as meaningful
performance of piled raft. Further the design based on observational data that was validated by a suitable analytical method is considered more realistic. For example the results of observations made on the piled raft of Eurotheum tower has been used to design the piled raft of the Maxtower (Katzenbach et al 2002). This implies that adequate data based on the observations must be available along with analytical validation so that the results can be used as a base for the design. Therefore, it is felt essential that such data base must be available for different soil types. From the reasons presented above, it was decided to study the behavior of piled raft through 1g model tests, analysing the test results through numerical model and monitoring a real size piled raft foundation supporting a twelve storied building constructed in a deposit where the soil is dominantly sandy.