# Chapter 2

# Literature Review

## 2.1 Introduction

The selection of an efficient foundation type should not consider merely the transmission of upcoming load to the subsoil; it should rather be designed to satisfy the strength, stability and serviceability requirements, with a proper acknowledgement of the economic aspects.

A foundation is a structural element that transfers an impending load from a superstructure to the soil underneath it. It is the lowermost portion of any civil structure that is in direct contact with the supporting soil and connects the superstructure to the soil. So, it can be considered the most essential structural element as it provides structural safety and stability to the structure and ensures its serviceability throughout its design period. Figure 2.1 depicts the load transfer mechanism in a typical foundation. The upcoming load is transmitted through several super- and sub-structural elements such as slabs, beams, columns, and footings and finally dispersed over a large area of the supporting soil.

The bearing capacity of soil can vary significantly based on its profile at the construction site. Consequently, foundation design aims to limit structural settlement within permissible bounds and ensure that the anticipated loads remain within the subsoil's ultimate bearing capacity. Currently, foundation engineers have a diverse array of options to consider for different locations. Nevertheless, selecting the most suitable foundation type requires a comprehensive soil investigation report and a thorough understanding of the entire structural load, encompassing various load combinations that exert forces on the structure.

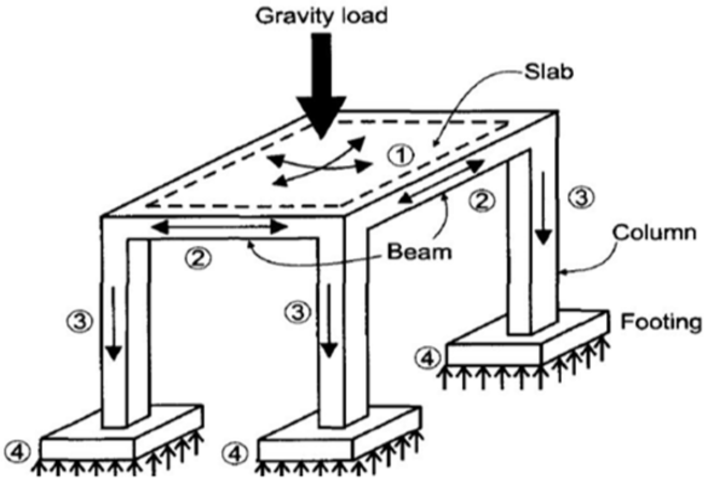


Figure 2.1: Load-transfer in a general foundation

## 2.2 Design Approaches of Piled Raft Foundation

The piled-raft foundations have now been recognised as an effective and economical substitute for conventional pile foundations. It is necessary to have an analysis and design approach that considers the interactions within the system and effectively utilises the benefits of piled rafts. The subsequent sections discuss the various design approaches for analysing piled-raft foundations that evolved over the years. The chapter also provides a comprehensive review of piled-raft analysis. The design approaches are grouped into categories such as simplified, approximate, numerical and experimental investigations in the sub-sections.

### 2.2.1 Simplified Approaches

The earliest evidence of the piled raft analysis may be ascribed to the simplified approaches that are based on established theories. These approaches include manual mathematical calculations. Over the years, researchers have strived to develop a mathematical model that can incorporate the majority of the design aspects discussed in previous sections. The following sections present an overview of such approaches.

### (i) Butterfield & Banerjee Approach

The first assessment of load-sharing in piled rafts with rigid caps was made by Butterfield and Banerjee (1971b). Prior to it, the lab and field analyses of group piles were made such that the pile cap made no contact with the soil. Hence, the studies neglected the interaction between the foundation elements and soil. Even in theoretical analyses, the only study that considered the interaction between a single pile and pile cap was presented by Poulos (1968a). Elastic analysis of the foundation, where the rigid pile cap was presumed to be resting on the ground, was first adopted by Butterfield and Banerjee (1971a). The analysis involved the Mindlin (1936) solution for a single concentrated load within a semi-infinite elastic medium. Such a load was distributed into several points throughout the interfaces near the cap ($C$) and those near shaft & base ($S$) (Figure 2.2). Vertical displacements of each point were represented into integral forms as a function of stress intensities ($\phi$). Moreover, the overall displacement due to the point load $P$ was given by

$$W(P) = W_1(P) + W_2(P) = \int_c \phi_c K(P, Q_c) dC + \int_s \phi_s K(P, Q_s) dS \tag{2.1}$$

$W_1(P)$ and $W_2(P)$ are the displacements at cap-soil and pile-soil interfaces, respectively. $K(P, Q_c)$ and $K(P, Q_s)$ are the Kernel functions derived from Mindlin's equation.

The attained results do not include radial displacement compatibility at the interface between piles and soil. Despite that, a change regarding displacements and load-sharing was found to be insignificant (Butterfield and Banerjee, 1971b). The approach was valid for a group of piles with a rigid cap, irrespective of its shape. However, an additional term for compressibility might be included in the case of compressible piles. Finally, the stresses could be found out using

$$\phi = \frac{W}{K} \tag{2.2}$$

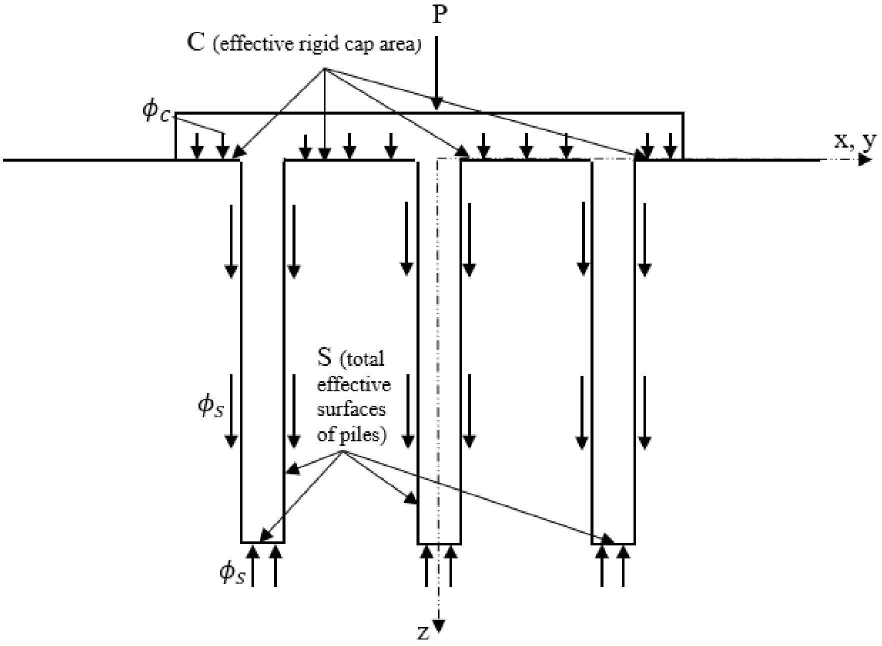


Figure 2.2: Typical Arrangement

Butterfield and Banerjee (1971a,b) reported the study on pile groups with a floating cap and later with the pile cap resting on the ground. Assuming the piles to be compressible, the piles were supposed to be completely bonded to the soil layer. Although it was found that the load distribution in piled rafts significantly differed from that in the pile group case, the load-displacement behaviour barely showed any variation.

The limitation of such an approach is that it solely determines the total settlement and neglects the interaction between the cap and piles. Besides, considering higher discrete elements in formulations leads to larger matrices, increasing the computational work.

### (ii) Davis & Poulos Approach

In the present approach by Davis and Poulos (1972), the pile cap attached with a single pile was considered to be supported on the soil instead of being contactless to the soil. For initial interaction analysis, the interaction among two identical units of pile cap was investigated. The same behaviour was assumed for units of the same area regardless of their shape, and hence, a circular one was used for simplicity. The elastic analysis in such an approach was confined only to rigid foundation elements. Such an interaction analysis is basically the analysis of a single unit and two floating piles (Poulos, 1968b) grouped together. Each pile was divided into $n$ parts along the length, the parts being subjected to shear $p$ over their surface and a uniform pressure $p_b$ at the base (Figure 2.3). Similarly, the pile cap was divided into $v$ number of annular rings, each being loaded by stress, $p_c$. Displacement at any element $i$ on pile 1

$$\rho_i = \frac{d}{E_s}\left(\sum_{j=1}^{n}({}_1I_{ij} +_2 I_{ij})p_j + p_b({}_1I_{ib} +_2 I_{ib}) + \sum_{k=1}^{v} p_{ck}({}_1I_{ik} +_2 I_{ik})\right) \tag{2.3}$$

where the influence factor $I_{ij}$ represents displacement at $i$ due to shear on element $j$, and the influence factors $I_{ib}, I_{ik}$ accounts for displacement at $i$ due to stress at base and on annulus $k$. $I_{ij}$ and $I_{ib}$ are calculated using Mindlin equation and $I_{ik}$ by Boussinesq equation.

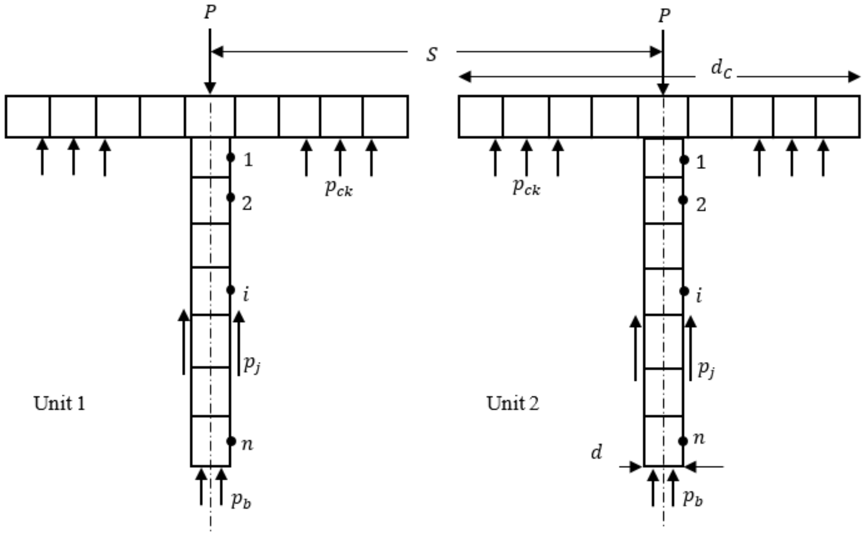


Figure 2.3: Stresses acting on pile-cap units (Davis and Poulos, 1972)

Since the piles and the cap are supposed to be rigid, the displacement of each elemental part is the same, and the same also reflects the soil displacement. The aforementioned formula was generalized for other pile layouts using another interaction factor given by

$$\alpha_r = \frac{Additional settlement due to adjacent unit}{Settlement of a single pile} \tag{2.4}$$

The superposition principle can be applied for a general piled-raft analysis of any configuration by considering the pile-cap units as several equivalent circular caps, each attached to a single pile. For the group piles in a square pattern, the equivalent diameter can be calculated as

$$\left(\frac{d_c}{d}\right) = \sqrt{\frac{4}{\pi}} \cdot \left(\frac{s}{d}\right) \tag{2.5}$$

where $d_c$ is the cap diameter, and d represents the pile diameter. The generalised equation for the settlement of any unit $i$ in a system comprising of $m$ units can then be determined as

$$\rho_i = \bar{\rho}_i \left( \sum_{j=1 j\neq 1}^{m} \bar{P}_j \alpha_{rij} + \bar{P}_i \right) \tag{2.6}$$

The overall settlement of the system can eventually be given by

$$S = R_G \cdot P_G \cdot \rho_1 \tag{2.7}$$

Here, $R_G$ is the measure of the system settlement with respect to the settlement of a single pile holding the same mean load, and $P_G$ is the summation of loads on unit $j$. $\rho_1$ signifies the settlement of a single pile cap unit per unit load. Further, this methodology was supported by an illustration (Poulos and Davis, 1980). The effect of Poisson's ratio, pile geometries and raft flexibility in piled rafts were also studied.

The initial step of such an approach is to determine the interaction curves of two adjacent pile-cap units and then predict the system's overall behaviour by superposition. Since the elastic superposition principle is applicable only if the piles are loaded equally and positioned circumferentially (Mendonca and de Paiva, 2000), generalising such an approach might not yield desirable results. Also, it overlooks the impact of shear distribution and bending moments adjacent to the equivalent cap, raising concerns about its accountability for the integrated system.

Davis and Poulos (1972) also presented a simplified method to present the load-settlement behaviour in piled rafts. It is based on the concept that elastic conditions endure till the failure point of piles in case no raft would have been present. Any further loading would be then carried solely by the raft. Figure 2.4 illustrates the load-settlement curve where OA represents the section where loading continues till the ultimate load of piles, while AB represents the load till the ultimate value of the overall system. It is also worth mentioning that this approach ignores the progressive yielding of soil below the raft and around the piles.

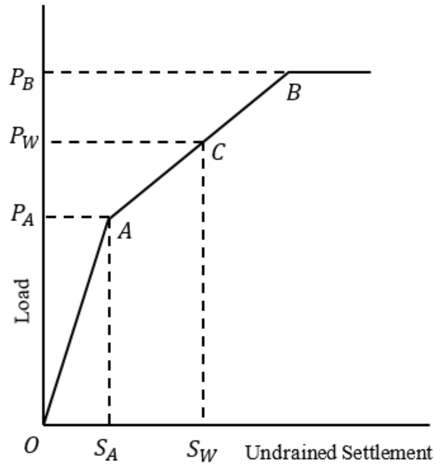


Figure 2.4: Simplified Approach (Poulos and Davis, 1980)

### (iii) Randolph Approach

Randolph (1983) presented a simplified method for analysing a single pile unit attached to a rigid pile cap. The floating pile unit was assumed to be supported over a semi-infinite soil medium. This approach was observed to be in good accord with the Butterfield & Banerjee Approach. The considered interactions among the foundation elements represented the settlement of the pile group and raft as

$$\begin{Bmatrix} w_p \\ w_r \end{Bmatrix} = \begin{bmatrix} 1/k_p & \alpha_{pr}/k_r \\ \alpha_{rp}/k_p & 1/k_r \end{bmatrix} \begin{Bmatrix} P_p \\ P_r \end{Bmatrix} \tag{2.8}$$

The reciprocal theorem gives

$$\frac{\alpha_{pr}}{k_r} = \frac{\alpha_{rp}}{k_p} \Rightarrow \alpha_{pr} = \alpha_{rp}\frac{k_r}{k_p} \tag{2.9}$$

The piled-raft stiffness and the load share of the raft were expressed by Randolph (1994) as

$$k_{pr} = \frac{k_p + k_r(1-2\alpha_{rp})}{1-\alpha_{rp}^2(1-2\alpha_{rp})} \tag{2.10}$$

$$\frac{P_r}{P_t} = \frac{P_r}{P_r + P_p} = \frac{k_r(1-\alpha_{rp})}{k_p + k_r(1-2\alpha_{rp})} \tag{2.11}$$

Here, $k$ represents the stiffness, while the subscripts $r$,$p$, and $pr$ represent the raft, pile-group and piled-raft, respectively. Similarly, $\alpha_{rp}$ and $\alpha_{pr}$ represent the raft-pile and pile-raft interaction factors. The two interaction factors $\alpha_{rp}$ and $\alpha_{pr}$ used in the equations can be defined as follows :

$$\alpha_{rp} = 1 - \frac{ln(r_c/r_0)}{\zeta} \tag{2.12}$$

$$\alpha_{pr} = \frac{r_c}{4L}\left[1 - \frac{1}{2(1-\nu)} + \left(2 + \frac{1}{1-\nu}\right)\cdot \sinh^{-1}\left(\frac{L}{r_c}\right)\right] \tag{2.13}$$

The parameter $\zeta$ signifies the effect of relative homogeneity and pile geometry. It can be expressed as $\zeta = \ln(r_m/r_0)$, with $r_m$ and $r_0$ being the radius of influence and diameter of the pile, respectively.

This approach was discussed for the load sharing and settlement estimation in a single pile-raft unit and becomes less precise with the increase in the size of the pile group (Randolph, 1983). The approach was discovered to be in conformity with the FEM results in the case of a single pile-raft unit. It may, however, be extended to any large pile group considering the equivalent raft area connected to the pile with little modification (Randolph and Clancy, 1993).

Clancy and Randolph (1996) investigated square piled rafts of different sizes and found that $\alpha_{rp}$ increases with pile numbers until it attains a maximum value of 0.85 (Figure 2.5). It was also discovered that it does not rely on the raft stiffness or slenderness ratio. The raft's load share and the total stiffness of the piled raft system can be re-written as

$$\frac{P_r}{P_t} = \frac{P_r}{P_r + P_p} = \frac{k_r(1-\alpha_{rp})}{k_p + k_r(1-2\alpha_{rp})} = \frac{\left(\frac{k_r}{k_p}\right)(1-\alpha_{rp})}{1 + \left(\frac{k_r}{k_p}\right)(1-2\alpha_{rp})} = \frac{0.15\left(\frac{k_r}{k_p}\right)}{1+0.7\left(\frac{k_r}{k_p}\right)} \tag{2.14}$$

$$k_{pr} = \frac{P_p + P_r}{w_{pr}} = \frac{\left[1-(\frac{k_r}{k_p})(1-2\alpha_{rp})\right]k_p}{\left[1-(\frac{k_r}{k_p})\alpha_{rp}^2\right]} = \frac{\left[1-0.7\left(\frac{k_r}{k_p}\right)\right]k_p}{\left[1-0.723\left(\frac{k_r}{k_p}\right)\right]} \tag{2.15}$$

Although this approach overlooked the interaction among the piles and considered those between raft and piles only, it is still quite simple and suitable for hand calculation. It is thus an extensively accepted approach due to the necessity of computing just one interaction factor, $\alpha_{rp}$ (Nguyen et al., 2014). However, further research should be required to identify more precise interaction factors.

Based on this approach, (Poulos, 2001b) proposed a simplified tri-linear load-settlement plot for piled raft foundations (Figure 2.6). The stiffness in such a case is determined using equation (22), which would remain applicable till the point ($A$) of full mobilisation of pile capacity and the corresponding load ($P_1$) at that point will be given by

$$P_1 = \frac{P_u}{(1-X)} \tag{2.16}$$

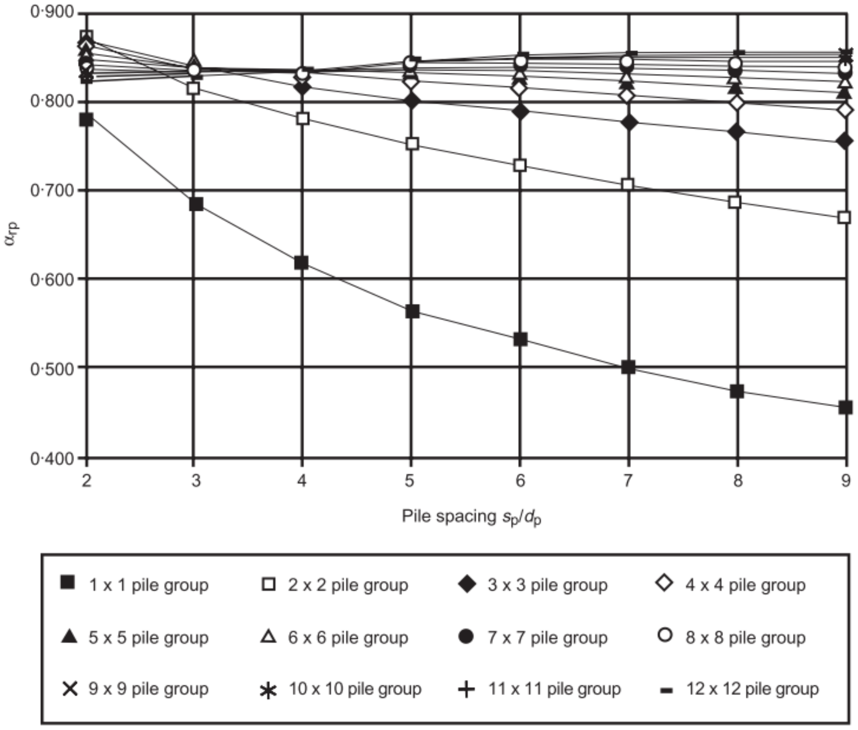


Figure 2.5: $\alpha_{rp}$ values $= s_p/d_p = 25, K_{ps} = 1000; K_{ps} = 1000$ (Clancy and Randolph, 1996)

where $X$ denotes the raft's share of the load and $P_u$ represents the ultimate load-bearing capacity of piles. The raft starts taking the entire load beyond point $A$. It continues till the point $B$, after which the curve becomes horizontal, and any additional load cannot be resisted by the system.

The Butterfield & Banerjee approach focuses on the total settlement of a pile group subjected to a single concentrated load. The other approaches, however, deal with a rigid pile coupled with a rigid circular raft. The impact of stresses near the raft could not be considered while analysing single pile-raft units in such approaches. Hence, utilising single units to anticipate the overall behaviour of the foundation system does not work well. Also, the aforementioned methods only address the total settlement in piled rafts, and nothing has been discussed about the differential settlement.

An approach that integrates the Poulos & Davis approach (1980) and the Randolph approach (1994) is often referred to as the Poulos-Davis-Randolph Approach. This approach also addresses the interaction among the piles along with that between

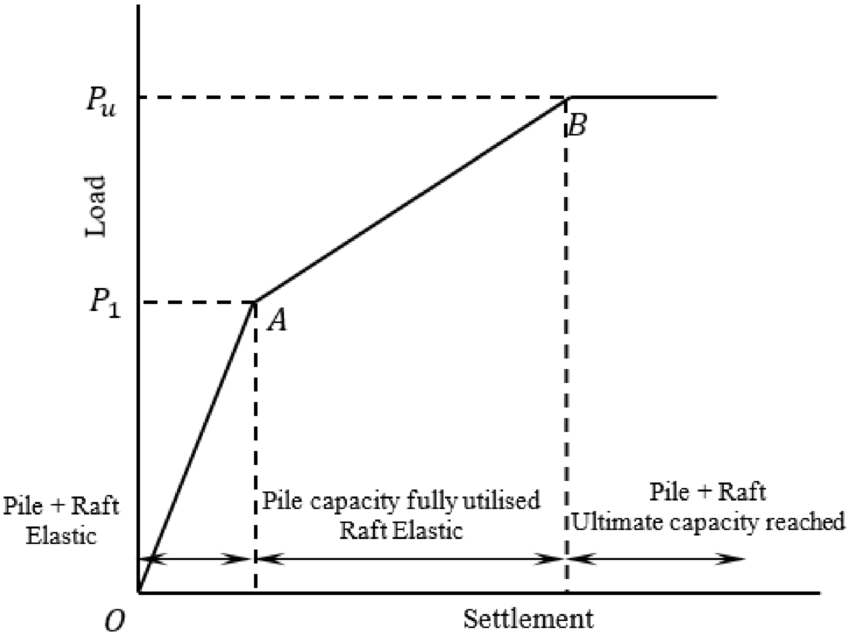


Figure 2.6: Simplified load-settlement curve (Poulos, 2001)

the raft and the piles. The raft stiffness in such cases is determined manually via elastic theory considering equivalent circular raft and pile stiffness. Moreover, the single pile stiffness is determined using closed-form solutions and multiplied by the group stiffness factor to further compute the group stiffness (Poulos, 2001b). This is the most commonly employed simplified approach for piled-raft foundations.

### (iv) Burland Approach

Another simplified approach was presented by Burland (1995), where the piles were assumed to be utilised as settlement reducers. The design steps initiate with plotting a load-settlement curve for raft (Figure 2.7), where a total settlement $w_0$ is indicated for the design load $P_0$. A safety factor is utilised to evaluate the designed settlement, $w_d$ and the corresponding load $P_1$. Piles are believed to carry the extra load $(P_0 - P_1)$, and a mobilisation factor of 0.9 was recommended for 'conservative best estimate' of the ultimate pile capacity $(P_{pu})$. Later, Poulos (2001a) suggested that no safety factor is applied in this stage as the pile resistance would reach its full mobilisation. For piles placed beneath the columns and bear loads greater than $P_{pu}$, the piled-raft system is treated as a raft subjected to reduced load $(Q')$ and moments in the raft are evaluated at such reduced load.

$$Q' = Q - 0.9P_{pu} \tag{2.17}$$

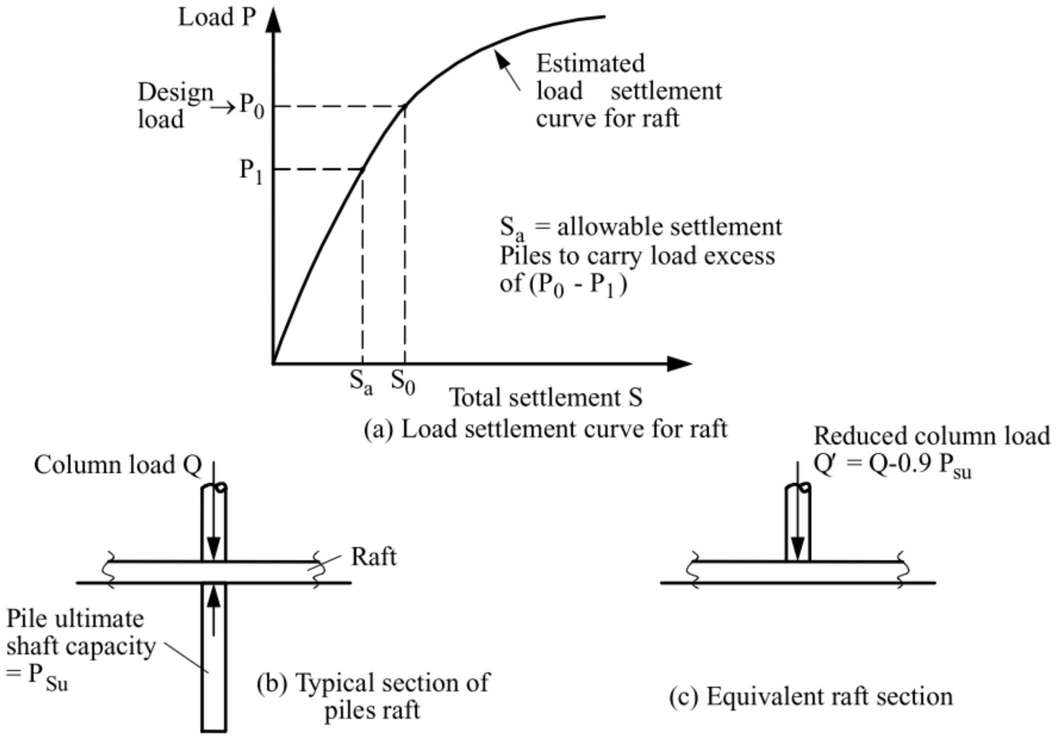


Figure 2.7: Burland Approach (1995)

Although this approach did not explicitly outline the settlement calculation, Poulos (2001a) recommended using the Randolph approach.

### 2.2.2 Approximate Approaches

Modelling a piled-raft foundation as a strip or a plate supported over springs is another design approach. This approach simplifies the rigorous numerical analysis through some approximation in its analytical solution. The reduction of equations in such cases lowers the processing cost of the computer and enhances productivity due to lesser memory allocation. Different literatures refer to such an approach as either an approximate method (Russo, 1998), a semi-analytical method, or a hybrid analytical method (Griffith et al., 1991; Kitiyodom and Matsumoto, 2003; Horikoshi and Randolph, 1998).

### (i) Strip on Spring Approach

Poulos (1991) proposed a method to analyse piled raft foundations using a computer code, GASP (Geotechnical Analysis of Strip with Piles). This method was based on the strip-superposition method (Brown and Wiesner, 1975), where solutions for several strip footings supported on piles are superimposed to get the overall settlement of the raft. The raft section was modelled as a strip foundation, consisting of several identical beams, whereas the piles were represented as springs of equivalent stiffness in soil continuum (Figure 2.8). The analysis used the Randolph approach for piles and the boundary element method for strips. Adjustments were provided for considering the different interactions among raft and pile elements. Soil settlement due to part outside the strip section was also included in the analysis. Finally, the moments and settlements on the strip due to applied loads were obtained.

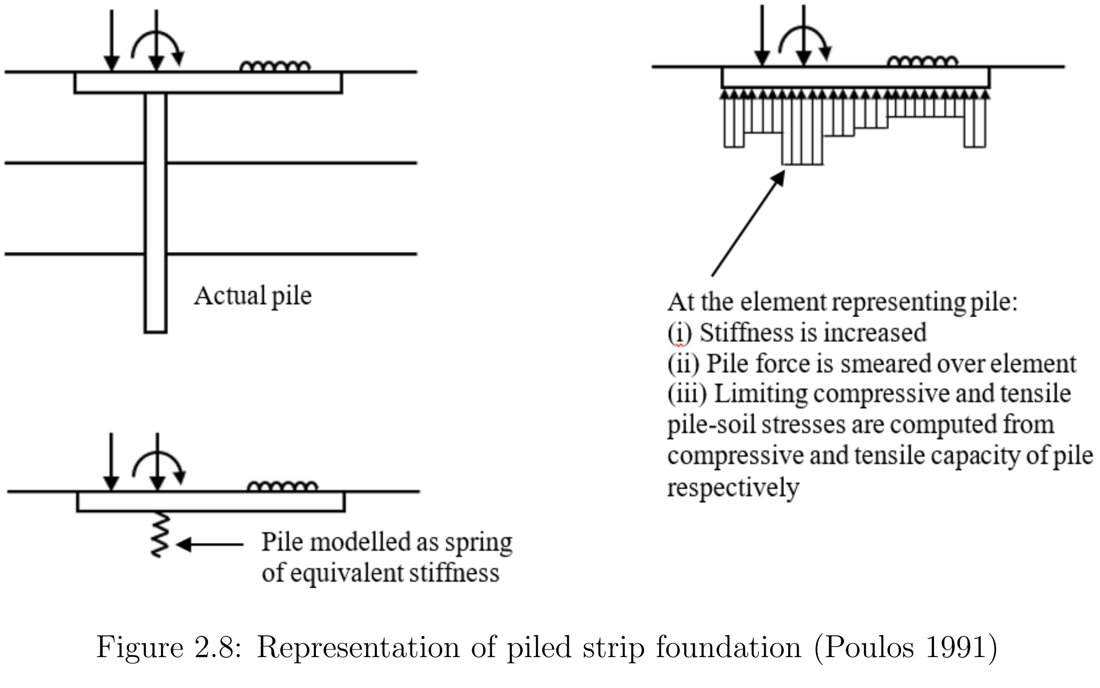


Figure 2.8: Representation of piled strip foundation (Poulos 1991)

However, this method neglects torsional moments in the raft. Since the beam width is ignored, there is possibility of inconsistency in settlements at a point where the strip is analysed through two directions. Also, the presented approach might produce unrealistic results due to variations in the performance of piles under discrete beams and pile groups under rafts. In the case of non-linearity in soil, it had been suggested to restrict the pile loads and strip-soil contact pressures to the bearing and uplift capacities of piles and rafts, respectively. In order to get realistic settlements under the strip, such an analysis recommends forbidding linearity in a longer direction only.

### (ii) Plate on Springs Approach

Another approach developed on the spring paradigm is the plate-on-springs approach. Although it is based on the elastic theory, it also accounts for the non-linearity in the foundation system. The piled raft foundation is modelled as a thin plate supported on springs in such an approach. Earlier, Hongladaromp et al. (1973) considered rafts as thin plates and piles as interacting springs but ignored interactions among the piles. Later on, Poulos (1994) used the finite difference method for raft analysis and implemented another computer program, GARP (Geotechnical Analysis of Raft with Piles). All the interactions among piles and rafts involved in the analysis were the same as those considered in GASP; hence, similar approximations were implicated. Such analysis also provided adjustments for the layered profile of soil, soil settlements and piles and rafts reaching the ultimate bearing capacity. The problem consisting of raft supported over piles and subjected to combined loadings can be demonstrated in Figure 2.9.

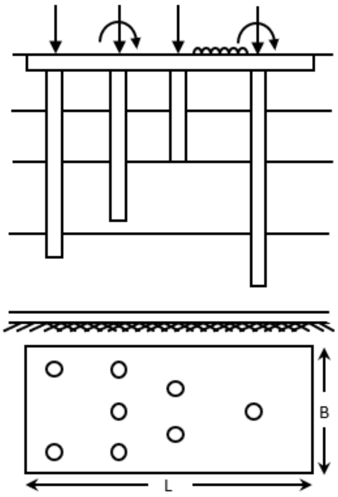


Figure 2.9: Piled-raft problem definition (Poulos, 1994)

An advantage of this approach is its ability to achieve stress distribution in rafts. However, the GARP program requires proper modelling and correct selection of soil parameters, or else pile behaviour could vary from reality, leading to inevitable errors in the resultant foundation settlement. Also, its applicability is quite limited since it is based on the elastic theory.

GARP program was modified by Sales (2000) where finite element method was used instead of finite difference method. Moreover, the modification was done to consider the bearing capacity of piles till their ultimate value.

Russo (1998) modelled piled raft using a similar approach with thin plate supported over vertical non-linear springs (Figure 2.10). Closed-form solutions of soil displacements were used to determine the springs' stiffness. Raft-soil interface used no-tension elements, and Steinbrenner approximation was employed for layered profiles. The Non-linear Analysis of Piled Rafts (NAPRA) program was employed for numerical analysis. Piles were considered as individual unit for the simplification, and their non-linearity were modelled using the curve fitting of Chin's hyperbolic curve. Further, the interaction factors were determined using BEM code. The model was validated with the existing centrifuge tests and proved reasonable in both linear and non-linear cases.

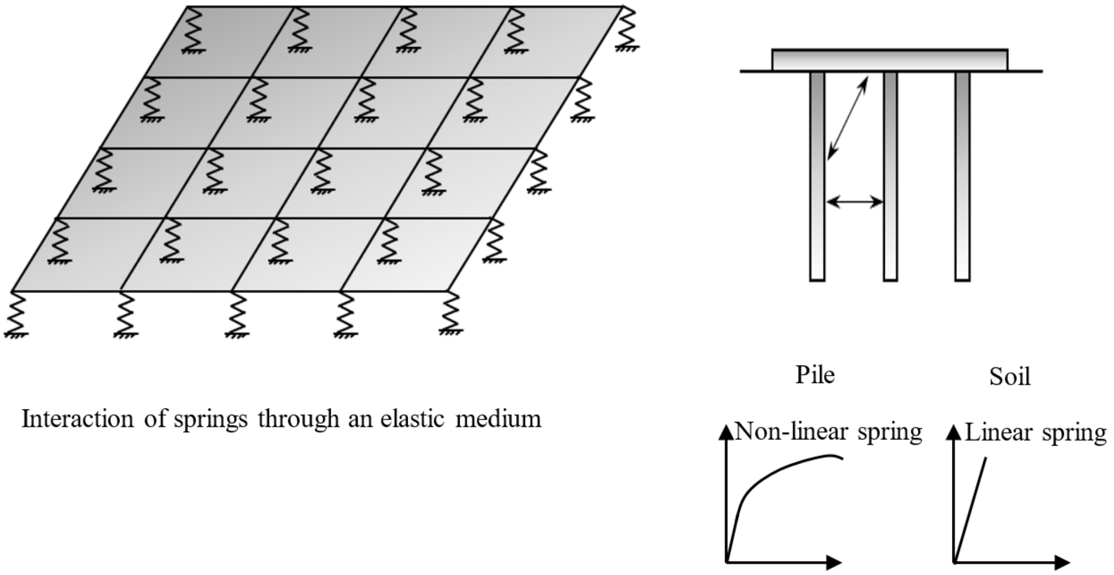


Figure 2.10: Basic features of a piled-raft model (Russo, 1998)

Clancy and Randolph (1993) described a hybrid model with comparatively lesser computations. The model associated finite element method for modelling piled raft foundation and an analytical method for representing soil. $2D$ plate bending elements and $1D$ rod elements were used for modelling raft and piles, respectively and were combined at the common nodes as presented in Figure 2.11. The interactions were calculated using Mindlin's equations. Load sharing between the structural components were proposed depending on their individual responses using interaction factor. Being an extension of the work by Griffith et al. (1991), this approach further considered shear modulus with hyperbolic variation. Still, the limitations regarding stiffness, verticality in loading and homogeneity in soil continued to be there. The approach focussed mainly on the average settlement and not differential settlement. However, differential settlements in limited cases could be determined by factoring raft displacements.

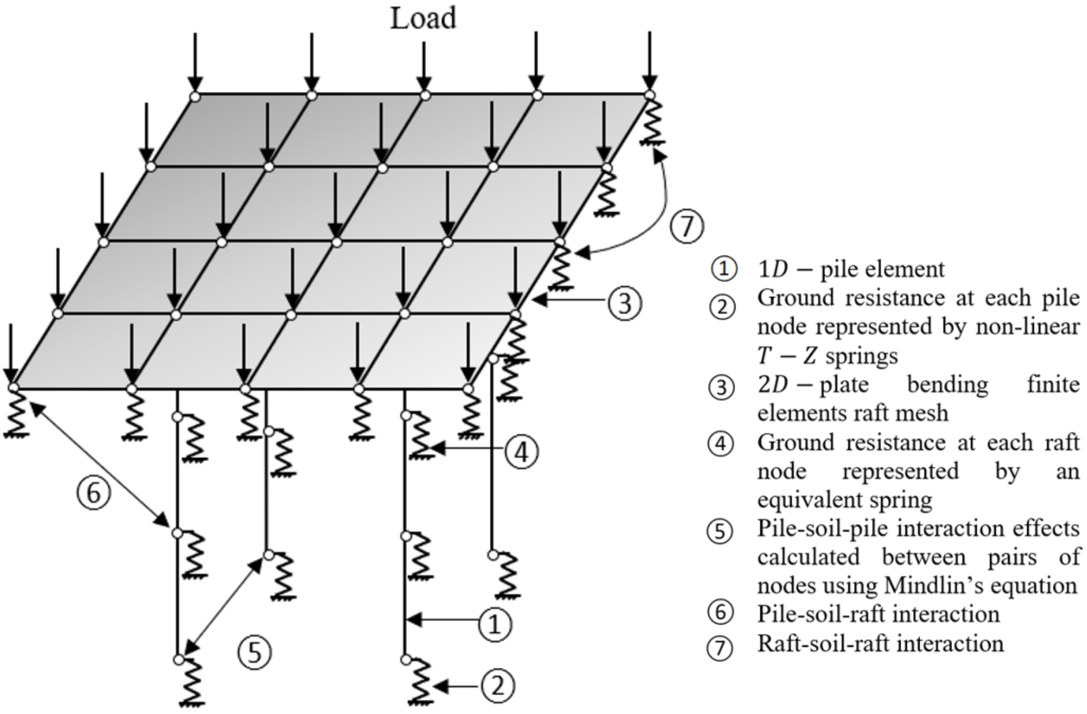


Figure 2.11: Numerical representation of piled raft (Clancy and Randolph, 1993)

Horikoshi and Randolph (1998) proposed a new methodology to reduce the differential settlement by attaching piles only below the central portion of a flexible raft. In order to consider the non-homogeneity in soil, they extended Clancy's hybrid model and considered the equivalent-pier concept given by Poulos and Davis (1980). In this concept, a single equivalent pier replaces a pile group, and the equivalent soil continuum's elastic modulus is calculated using the regional soil's average. They suggested the pile distribution within the central 16-25% area of the raft.

Due to the unavailability of any generally adopted interaction model for piled raft, Kim et al. (2001) assumed Winkler springs for pile-raft interaction and coupled spring approach Randolph and Wroth (1979) for pile-pile interaction (Figure 2.12). Finally, an optimization process was discussed to minimize the differential settlement, which could consider any further complicated interaction model.

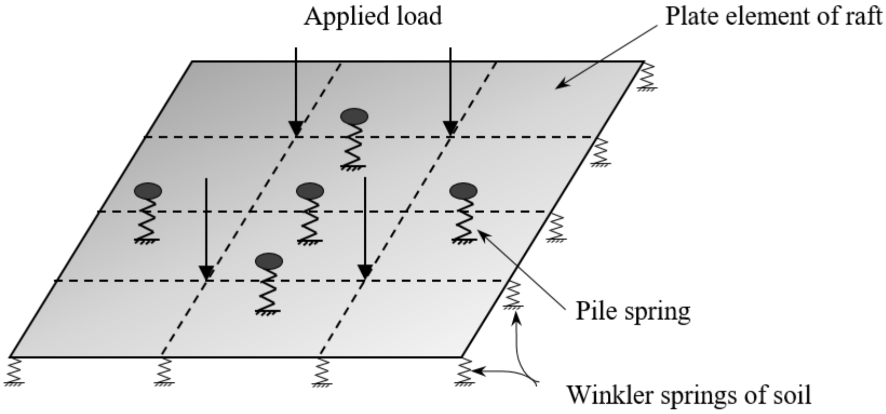


Figure 2.12: Finite element model of piled raft (Kim et al., 2001)

The isoparametric finite element is used to derive the following discretized stiffness equation of the piled raft.

$$f = k\Delta = (K^r + K^s + K^p)\Delta \qquad (2.18)$$

where $f$ and $\Delta$ represent the equivalent nodal force vector and nodal displacement vector, respectively. $K^r, K^p, K^s$ and $K$ are the stiffness matrices of raft, piles, soil and piled raft, respectively, and can be defined as follows:

$$K^r = \sum_e \int_{A^e} (B_b^T D_b B_b + B_v^T D_v B_v) dA$$

$$K^s = \sum_e \int_{A^e} \bar{N}^T k_s \hat{N} dA$$

$$K^s = \sum_i \sum_j \int_{A^e} \bar{N}_{e(i)}^T k_{ij}^p \hat{N}_{e(j)} dA$$

The equivalent force vector is given as

$$f = \sum_e \int_{A^e} N^T q dA \tag{2.19}$$

Kim et al. (2001) can be referred to for the description of the other notations. Since no interaction is assumed between raft and piles, it may result in an overestimation of the piled-raft stiffness.

Kitiyodom and Matsumoto (2003) developed a similar model of the thin plate on springs for piled rafts with piles represented as elastic beams. The model was subjected to axial and lateral loads, and the interactions considered were based on Mindlin's solutions. Resistance to axial and lateral loads by piles was represented by springs as shown in Figure 2.13.

Raft, represented as thin plates, is used in most of the cases. However, the piled rafts have been represented as thick plates on springs as well. Poulos (2001b) observed no variation in raft deflections, being it thin or thick rafts.

A rectangular raft subjected to uniform loading bends into a dish-like structure and hence carries bending moments. On the contrary, in plate-on-spring models, springs are assumed distinct and rafts settle uniformly with zero bending moments. Hence, Small (2001) suggested the discontinuation of the plate on spring models and preferred the use of continuum models over them.

Nguyen et al. (2013) proposed a similar approach in which the raft was represented by several plates and the piles by springs at their respective positions (Figure

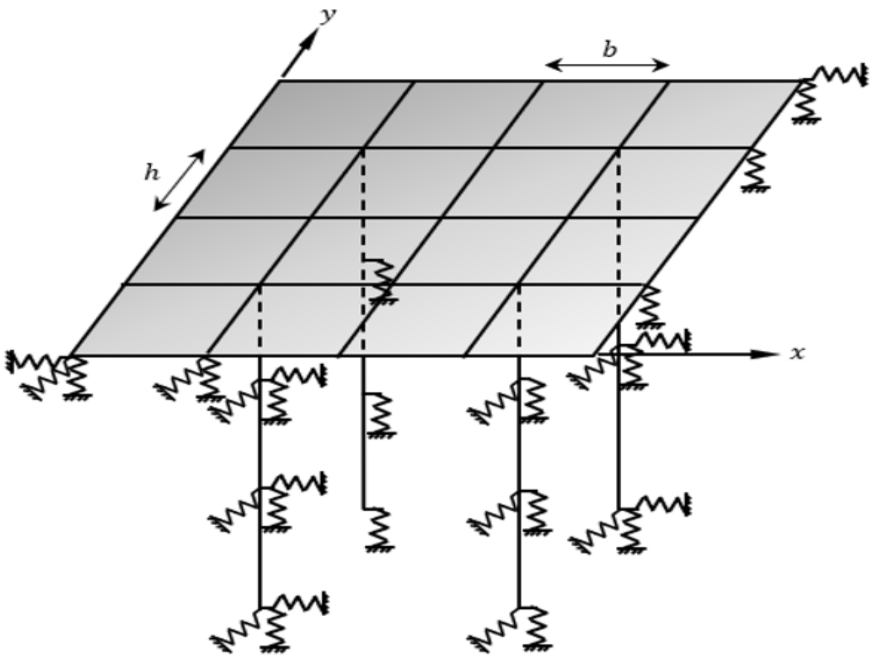


Figure 2.13: Plate-beam-spring modelling of a piled raft foundation (Kitiyodom and Matsumoto, 2002)

2.14). Since the lateral loads are comparatively much lesser than the vertical loads, lateral movements were ignored, and the corresponding stiffness of pile springs was determined. However, it was also suggested that lateral springs might be included in the case of heavy lateral stresses. The corresponding vertical displacements of any pile K and any raft spring M are thus defined as

$$w_{pK} = \sum_{J=1, J \neq K}^{n-1} (\delta_{1J} P_{pJ} \alpha_{KJ}) + \delta_{1K} P_{pK} \tag{2.20}$$

$$w_{rpM} = \sum_{K=1}^{n} (\rho_{1M} Q_M \beta_{KM}) + w_{rM} \tag{2.21}$$

where $\alpha_{KJ}$ and $\beta_{KM}$ represents the pile-soil-pile interaction factor of pile $J$ on pile $K$ and pile-soil-raft interaction factor of pile K on raft spring $M$, respectively. $P_{pJ}, P_{pK}$ and $Q_M$ denote the load on pile springs $J, K$ and raft spring $M$, respectively, while $\delta_1$ and $\rho_1$ denotes the displacement of the respective springs due to unit load. The interaction factors in this approach can be determined either using FEM or Randolph

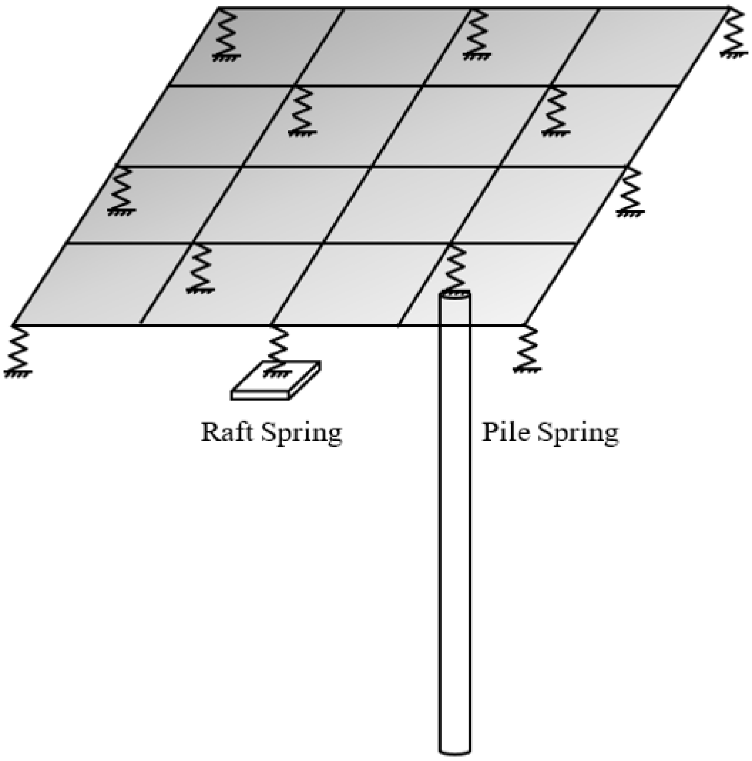


Figure 2.14: Plate on spring model of a piled raft foundation (Nguyen et al., 2013)

Approach, whichever is feasible. Consequently, it was validated with centrifuge results and was found that the stress distribution in the raft and settlement of the piled-raft system can be estimated efficiently. Also, it was confirmed using centrifuge results that the stress distribution in the raft and settling of the piled-raft system can be effectively computed in such an approach.

### 2.2.3 Numerical Approaches

In order to analyse the complex behaviour of piled raft foundations, numerical methods are widely employed nowadays. The common numerical methods used in such simulations are Finite Difference Method ($FDM$), Finite Layer Method ($FLM$), Boundary Element Method ($BEM$), Finite Element Method ($FEM$) and even the hybrid approaches that associate a few of these methods ($FEM + BEM, FEM + FLM$ etc.) together. Most of these methods can be applied using proper computer codes. While the majority of the complexities involved in the problem can be accounted for, performing such simulations demands high-processing computers and specialised expertise. The following sub-sections briefly discuss these methods and their relevance in piled-raft foundations.

### (i) Finite Difference Method

The application of the finite difference method in piled raft foundation analysis has been very limited. As discussed previously, Poulos (1994) adopted this method via *GARP* in analysing a piled raft. The assessment of raft (Figure 2.15) was done using the plate bending equation as an incremental finite difference equation, given by

$$[D_p]\{\Delta\rho_r\} = \frac{\{\Delta q\}}{D} - \frac{\{\Delta p\}}{D} \tag{2.22}$$

$[D_p]$ is the coefficient matrix; $D$ is the plate bending stiffness; $\{\Delta\rho_r\}, \{\Delta q\}$ and $\{\Delta p\}$ are the vectors of incremental raft displacements, incremental loadings and incremental contact pressures between soil and raft, respectively.

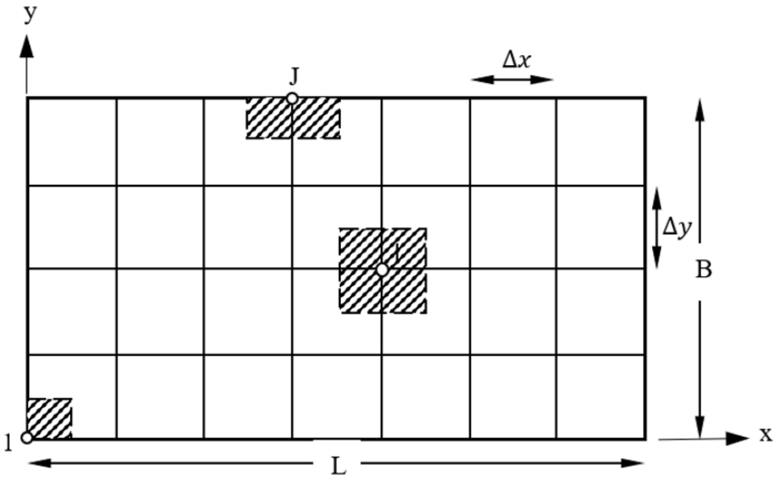


Figure 2.15: Raft Representation

Poulos also mentioned that the finite difference coefficients $[D_p]$ for raft corners and edges in previous publications dissatisfy the vertical equilibrium and hence are inconsistent. Consequently, he assumed free boundary conditions at all the edges and exemplified the applied moments and loadings into an equivalent uniform one.

The displacement under the elastic soil continuum was considered to be due to free-field movements such as consolidation or swelling and contact pressures between soil and raft. The expression for displacement increments was given by

$$\{\Delta\rho_s\} = [I_s]\{\Delta p\} + \{\Delta S_0\} \tag{2.23}$$

where $\{\Delta\rho_s\}, \{\Delta p\}$ and $\{\Delta S_0\}$ refer to vectors of incremental displacements, incremental contact pressures and incremental free-field movements, respectively. $[I_s]$ is the influence coefficient matrix obtained from elastic theories. Revised expression for incremental displacements was also derived for layered profiles. The results of the current model were verified with the centrifuge test results, and it also worked well for a full-scale model having a small number of piles.

The above method involves non-linearity and could consider external loading as well as free-field movements. Such analysis involves the matrix $[I_s]$, which can be modified to analyse different raft thicknesses and pile configurations. However, the analysis assumed several approximations and required decisions over the characteristic depth and reduction factor input values. Since a viable $FDM$ formulation has not been developed for the piled rafts, not much of the corresponding literature is available (Poulos, 1994).

### (ii) Finite Layer Method

The finite layer method can be employed in the case of soil containing several horizontal strata. Also, its versatility includes its application in considering the cross-isotropy and non-homogeneity in soil layers. It is sometimes believed to provide better performance than FEM due to its low data requirement and, consequently, better suitability to be used in computers.

Lee and Small (1991) applied the finite layer method for analysing a single pile in cross-anisotropic soil. The approach gave satisfactory performance when compared to other continuum approaches. Later, Ta and Small (1995) used the same to analyse the pile group in layered soil. In such an approach, exact solutions for individual layers could be obtained. Piles were modelled as 2-noded cylindrical solid elements. Loads transmitted from piles to soil were assumed as ring loads at the interfaces of each layer. Furthermore, this method was combined with FEM to analyse piled rafts in layered soil (Ta and Small, 1996), and hence discussed under the hybrid approach. Small (2001) compared the finite element results with those obtained from the finite layer program, *APRAF*. The finite layer approach produced satisfactory results for raft displacements and moments in piles, and consequently, its use was recommended for simple piled raft models rather than the analysis of complete $3D$ finite element models.

Chow (2007) analysed three cases in layered soil under lateral loading using Finite Layer program *APRILS* (Figure 2.16): (a) Freestanding pile group, (b) Piled raft where the raft is in contact with supporting soil from the bottom and (c) Piled raft where soil underlying and soil in front is considered. Poulos et al. (2011) used the same to compare the response of a pile group and a piled-raft having nine piles. It was observed that in piled rafts, rafts started carrying extra load after the mobilisation of the pile capacities.

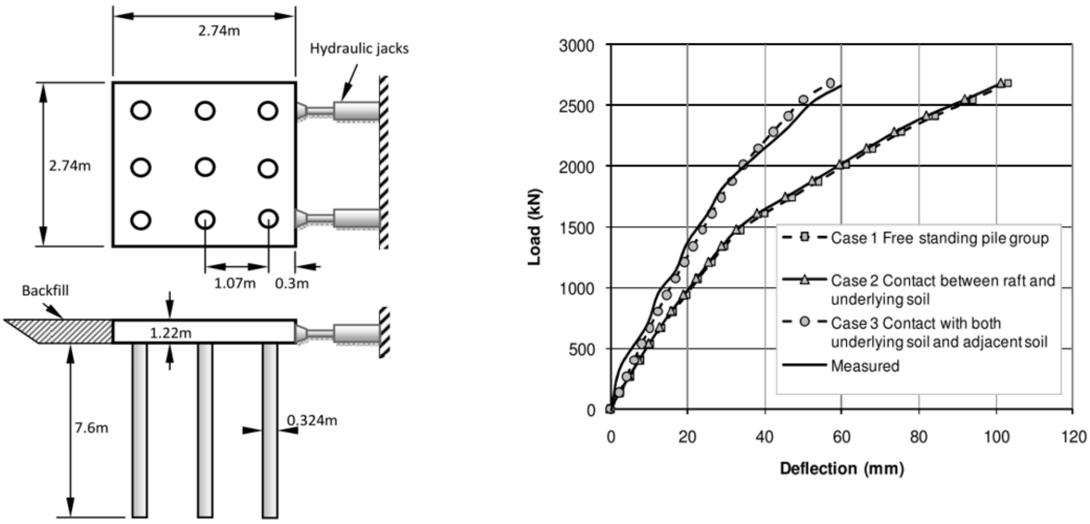


Figure 2.16: Layout and load-settlement curve

### (iii) Boundary Element Method

The versatility of the boundary element approach promotes its application in a variety of engineering domains. Since this approach deals only with the interface between soil and foundation elements, the number of unknowns to be solved is considerably reduced. Thus, it utilises less time and computer memory in addressing the problem as it only deals with boundary discretisation.

For piled-raft foundations, rafts and piles are discretised using elastic theory while the supporting soil is considered as an elastic homogenous medium (Butterfield and Banerjee, 1971a; Kuwabara, 1989). The model is meshed throughout the surface, and displacements at each location may be determined using the numerical solution of the given boundary integral equation. The boundary between the foundation elements and supporting soil is discretised into several elements. An approximate Green's function is finally employed to study the interaction among these elements. Other numerical methods are then utilized to develop equations based on the structural response and compute settlements. Kuwabara (1989) applied the boundary element method to piled rafts resting over the homogeneous soil surface and also to a free-standing pile group with the rigid raft having no contact with the surface. Piles were discretised into ten elements, and the raft was divided such that the element adjacent to the pile was twice the pile diameter and overhang elements were half the pile diameter. The load-settlement ratio was found to be a little higher in the case of piled raft due to the support of soil below the raft. Load resisted by raft was observed to be 20-40%. Only the upper portion of the piles experienced the raft benefit in load sharing. Moreover, the overhanging portion resisted about two-thirds of the total load carried by the raft, and the inner portion underwent uniform contact pressure. Moreover, Kuwabara (1989) applied the boundary element method on group piles subjected to negative friction.

Poulos (1993) analysed the piled raft through boundary element method subjected to externally imposed soil movements. In cases of upward or downward soil movements, additional loads were observed due to the action of expansive soil and negative friction, respectively. It was concluded that these movements were lesser for the equivalent pile group, and hence, piled raft needs to be avoided in such cases.

Russo (1998) compared the settlements due to BE method presented by Butterfield and Banerjee (1971a) and Kuwabara (1989). It was found that the settlements based on pile spacing and slenderness ratio ($L/d$) provided satisfactory results. However, the sharing of load between rafts and piles in these cases showed inconsistency with one another due to a variation approach and a few inaccurate parameters. A static analysis using the boundary element method was discussed by Mendonca and de Paiva (2000). The raft was modelled as a thin plate and pile as a single element. The elastic soil continuum was expressed using Mindlin's equation, and all the possible interactions were considered. The presented method was finally validated with the existing results of rigid as well as flexible piled rafts, and only a little variation was observed due to the different interaction approaches used in the analysis.

Basile (2015) used the non-linear boundary element method to determine the response of piled-raft foundation using the PGROUPN program. Rectangular components were employed to discretize the raft-soil contact, whereas cylindrical elements were used to discretize the pile-soil interface (Figure 2.17). It was suggested that the piled-raft concept can be effectively adapted to both 'small' and 'large' rigid piled-raft foundations using PGROUPN. Also, ignoring the effects of soil non-linearity might result in inaccurate speculations of load-sharing and deformations in the system.

Luo et al. (2018) adopted a similar discretisation using 3D BEM to analyse a rigid piled raft in clay subjected to vertical loading. The proposed method was validated with existing results and utilised for an extensive parametric study. Finally, a design chart was presented to examine the effect of soil rigidity on settlement variation under different safety factors

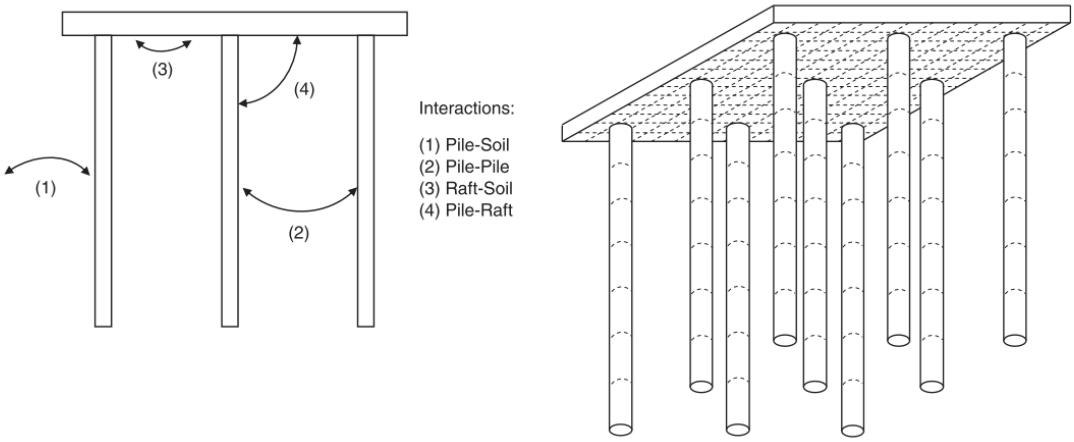


Figure 2.17: Interactions in piled-raft and boundary element mesh (Basile, 2015)

The limitations of the purely boundary element approach include its applicability only to linear homogeneous soil problems and require consideration of raft as 2D thin plate (Russo and Viggiaini, 1997). However, with new advancements and sophisticated computer codes, researchers have overcome these restraints and have widely embraced this approach.

### (iv) Finite Element Method

The finite element approach in piled-raft foundations has been widely used in recent years due to its diverse applicability and ability to consider the most complicated modelling. The researchers have utilised both two- and three-dimensional modelling for the same. For the FE analysis of piled rafts, both the soil and structure need to be discretised. Despite certain limitations, 2D modelling has not been overlooked for analysing such problems as it provides quick results. The 3D modelling provides the most appropriate simulation and can capture complex interactions; however, it needs specialist expertise and high computational cost. The following sub-sections discuss 2D- and 3D- finite element modelling available in the literature.

**Two-dimensional Finite Element Method** Hooper (1973) numerically investigated the piled raft foundation of a 90m high tower block over London clay. The previous numerical studies by Poulos and Butterfield and Banerjee could consider only the homogeneous soil and rigid raft over piles. These limitations restricted their application for the concerned problem. The axisymmetric model was adopted using the finite element method and 8-noded isoparametric quadrilateral elements as shown in Figure 2.18.

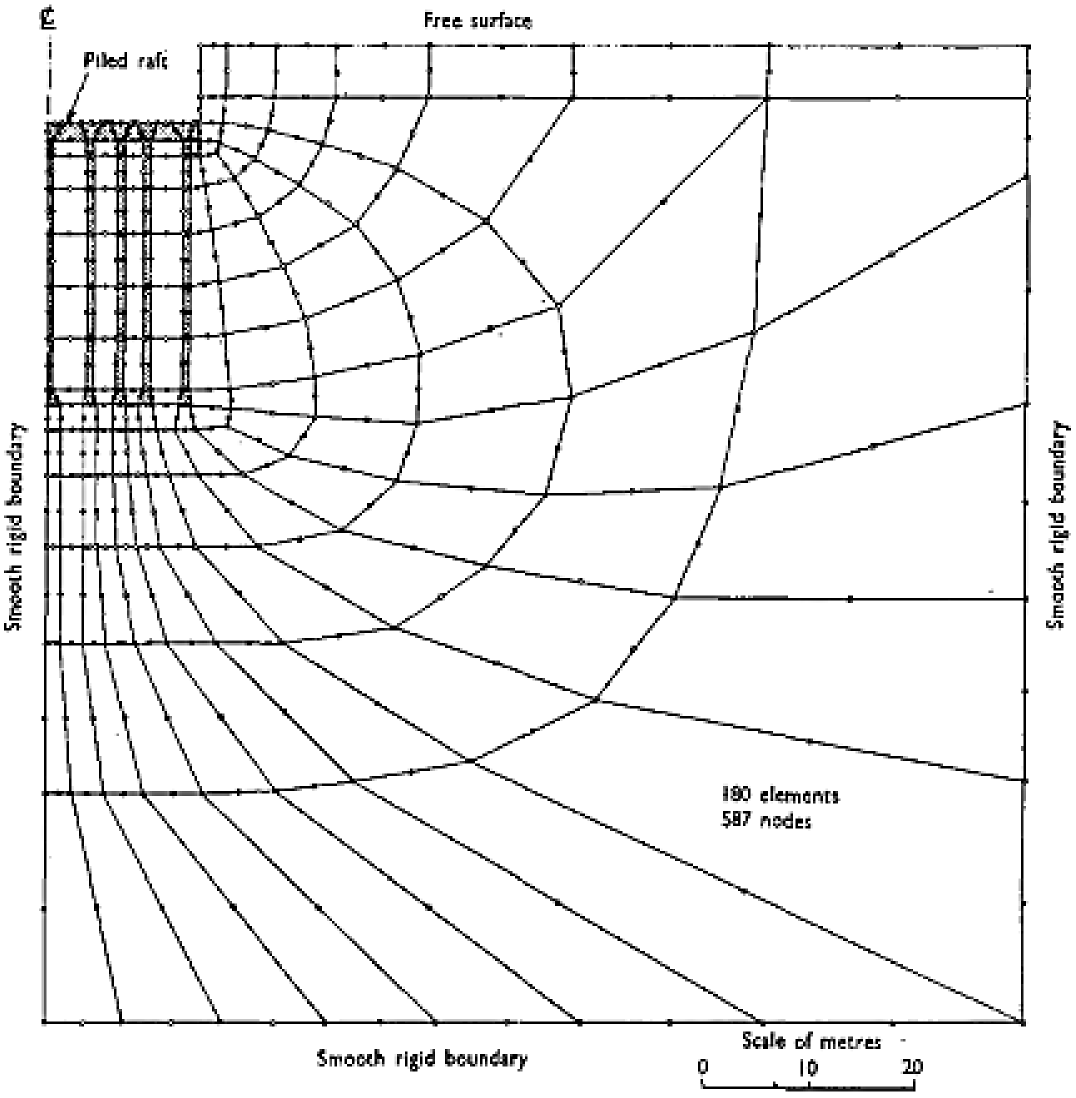


Figure 2.18: Axisymmetric model of piled-raft (Hooper, 1973)

The soil was considered linearly elastic, and its elastic modulus increased with depth. Total displacements were found to be increased with consolidation. Differential settlements were observed to increase during and even after construction, though they became constant in the long term. Consolidation in long-term transfers the load from the raft to piles, still a substantial amount of load would be resisted by the raft.

Hooper (1974) analysed piled rafts supported over homogeneous as well as heterogeneous layers. The foundation was subjected either to uniform or parabolic loading. The variation in elastic modulus with depth in the case of heterogeneous soil was given as $E_s(z) = E_s(0) + \lambda z$. The displacement finite element method was used to solve the adopted adhesive contact problems between soil and raft. It was observed that considering the adhesive interface lowers the differential settlement of the raft; however, interfacial slip restricts this lowering. After synthesising the findings based on the influence of the geometrical parameters and pile group compression capacity on various types of displacements and pile butt load ratio, Prakoso and Kulhawy (2001) evaluated the response of piled rafts on elastic as well as elastic-plastic soil and proposed a displacement-based approach.

**Three-dimensional Finite Element Method** The previous research based on 3D FEM had limited applications due to high computational cost and time. Hence, the researchers employed several assumptions for the simplification of the problems. In recent years, technological advancements have extended its use to address more complex problems, including non-linearity, non-elasticity, complicated loads and even complex boundary problems.

Ottaviani (1975) analysed an axisymmetric 3D model of pile groups over homogeneous soil to compute the settlements. Distribution of stresses in piles and soil was observed in the case of capped and uncapped piles. The system was rigid, as no interaction was considered between piles, cap, and soil. The assumption of symmetrical shear stress distribution in previous literature (Poulos, 1968b; Butterfield and Banerjee, 1971b) was not observed either in the case of the capped or uncapped pile group. The study supported the fact that the cap contact is an important factor as the cap in immediate contact with the soil modifies the load transfer mechanism while transferring the loads to the soil. Such a contact showed reduced shear stress around the upper soil portion and increased vertical stress in the soil below the piles. The study showed the utility of a 3D finite element model but was limited to elastic soil characteristics only.

de Sanctis and Mandolini (2006) presented an approach to evaluate the bearing capacity of piled raft foundations. Such an approach involved the individual bearing capacities of foundation elements with some load coefficients. The supporting clay was assumed elastoplastic, and numerical modelling of circular piled raft was done in ABAQUS.

### (v) Hybrid Methods

Hybrid methods are another class of analysis in which two or more numerical methods are integrated to capture the complicated behaviour of piled-rafts. The key objective of this integration is to assist in reducing the computational time and storage. The next sections cover the implementation of such approaches alongside their advantages. It is worth noting that the approximate approaches outlined earlier might also belong to this class but have limited applicability in terms of problem size.

**Finite Element Method + Boundary Element Method** The hybrid method involving the combination of the two-dimensional finite element method with the boundary element method may be observed in the works of (Hain and Lee, 1978; Russo, 1998) and others. The prime benefit of considering the BEM is its ability to capture the non-linearity using incremental technique.

Hain and Lee (1978) examined the effect of raft stiffness in the $2D$ piled raft analysis. The raft was modelled as rectangular plates using finite elements and pile-soil through boundary elements. The assumptions involved in determining stiffness equations to account for the interactions include that forces transferred to the pile head through the raft are vertical (raft-pile connection is assumed to be a sliding ball joint), and every pile takes up the entire ‘constant pressure’ region surrounding a certain node. For compatibility with the raft, the soil and pile elements were arranged as shown in Figure 2.19. With increasing pile length and stiffness, less settlement was observed. Moreover, due to the increase in flexibility of the raft, an increase in differential settlement and a decrease in the corresponding bending moment was observed.

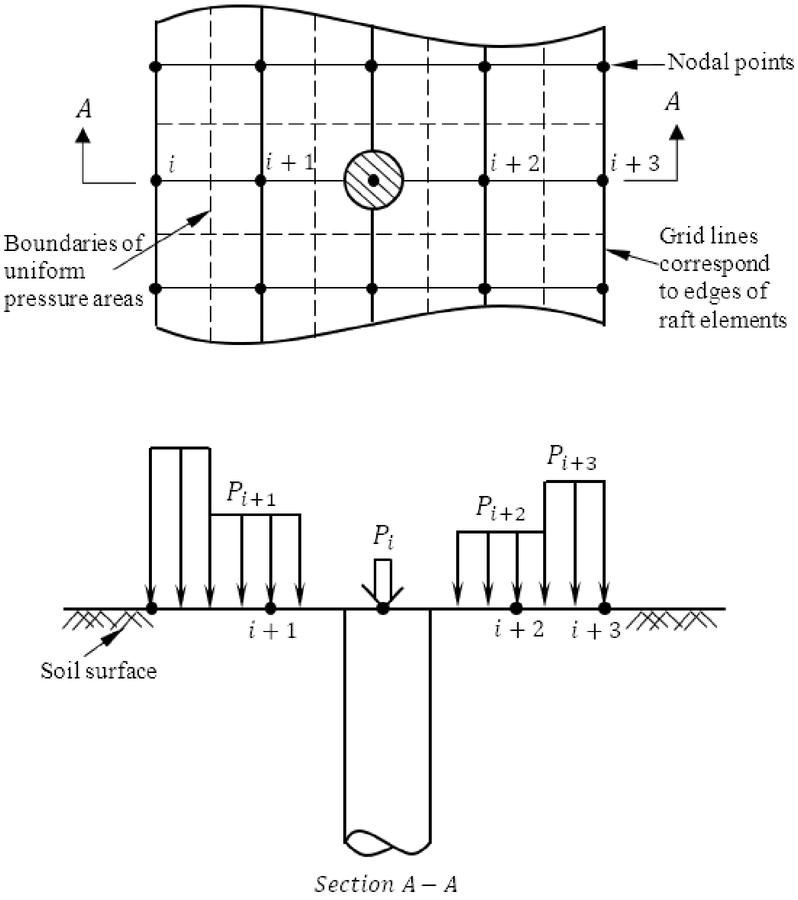


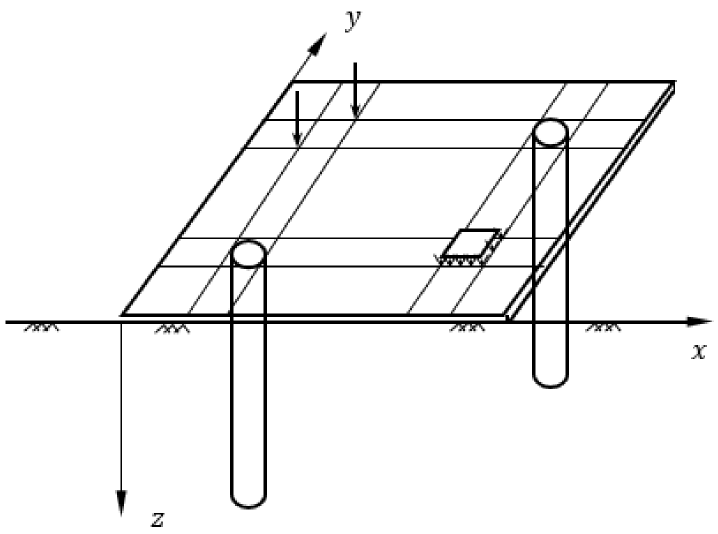
Figure 2.19: Representation of soil and pile elements for consistency with the raft (Hain and Lee, 1978)

Franke et al. (1994) employed a similar method, simulating the raft over pile and soil springs with $2D$ FEM and the non-linearity in the pile-soil interaction with BEM. This ‘mixed technique’ performed efficiently for lighter weights and shallow depths but not for greater values owing to the assumptions involved. Russo (1998) presented an approximate method to examine piled rafts exposed to forces and moments. It provided analysis to consider the raft of any configuration through the FE program NAPRA. Piles and soil as discussed in were represented as springs as discussed under the ‘plate on springs approach’. Interaction factors were calculated using BEM, and no-tension contact was modelled between the raft and soil. Russo and Viggiani (1998) utilised BE based GRUPPALO program and FE-based NAPRA program to determine the load-sharing and settlement of piles. Pertaining to the discussed case on soft and stiff clays, it was demonstrated that employing piles as settlement reducers and loading near to their bearing capacity can greatly reduce the number of piles while maintaining adequate foundation behaviour.

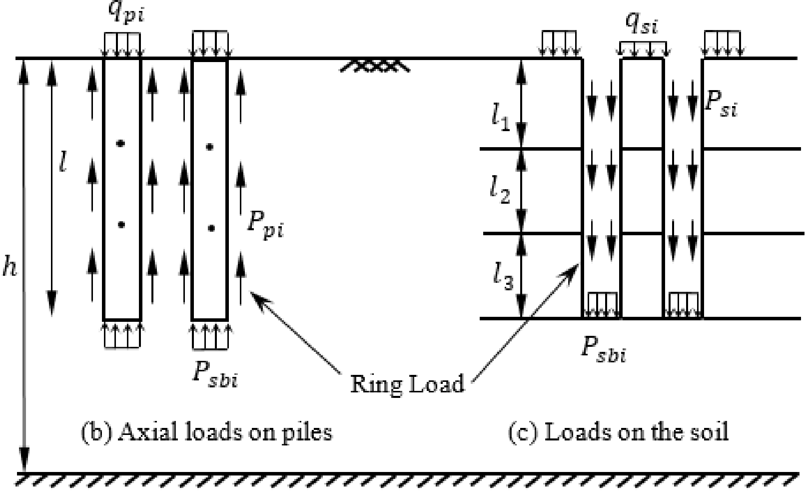
Mendonca and Paiva (2003) subsequently introduced a similar $BEM - FEM$ approach for static piled raft analysis in place of their previous work that used the $BE$ approach. Linearly varying subgrade modulus was considered, and the elastic half-space was assumed to be uninterrupted by piles. The plate was analysed using flat triangular elements through $FEM$. The coupling of $BEM$ and $FEM$ approach was done using matrix operations. Displacements due to such an approach were in confirmation with the previous results. However, variations in bending moment results were obtained due to stress concentrations, particularly in rigid rafts.

**Finite Element Method + Finite Layer Method** Another hybrid approach that combines the finite element and finite layer methods has also been utilised to analyse piled-raft foundations. Ta and Small (1996) extended the pile group analysis by Ta and Small (1995) to piled-raft and employed the hybrid method, which involved the combination of soil-pile analysis using FLM and raft analysis using FEM (Figure 2.20). The expression for displacements and stresses were expressed either in terms of Hankel or Fourier transforms.

The numerical methods involve discretising the structural components and producing fully populated matrices. Ta and Small (1997) realised the significant amount of time required in analysis specifically for the large-piled rafts and thus introduced an approximate method that accelerated the process over 100 times. Instead of estimating displacements due to a unit uniform pressure block on every identical square element, displacement was calculated using the pressure block on an equivalent circular area. Also, soil displacement at any point from the centre of such a loaded area was defined by a polynomial function. Hence, once the constants



(a) Piled-raft



(b) Axial loads on piles

(c) Loads on the soil

Figure 2.20: Forces presumed to be applied on the piles and soil (Ta and Small, 1996)

in the polynomial have been computed, evaluating the load effects on every element of piles and rafts would not be required.

Since the previous works were limited to vertical loadings, Zhang and Small (2000) also included the impact of horizontal loads, which might be due to wind, earth pressure or earthquakes. However, this approach was applied on pile groups with rigid raft/ pile-cap not in connection with the underlying layered soil. The contact forces between the cap and piles were supposed to be uniformly distributed on the cap and concentrated on pile heads. Certain simplifications were applied to field quantities and produced finite layer equations to attain a relation between transformed stresses and displacements. Horizontal shear and vertical ring loads were analysed using Hankel and double Fourier transformations. Influence matrices for cap and pile soil were produced using the method discussed by the authors previously. The group of piles exposed to horizontal loads was found to depend well on the pile-soil stiffness ratio. Also, lesser pile spacing ($s < 6d_p$) produced higher deformations and moments.

Further, Small and Zhang (2002) included the piled raft, with the cap rested over the soil. Contact forces were assumed as ring loads throughout the surface of the pile shaft and as circular loads at the base of piles (Figure 2.21). Uniform vertical pressure blocks were considered to be applied at the raft-soil interface. Moreover, the finite layer method was then used to determine displacements due to vertical as well as lateral loads. These analyses were done through the computer code APRAF (Analysis of Piled Raft Foundations) and finally validated with the finite element method.

Chow and Small (2005) extended the same approach to piled rafts with varying pile geometry and placed them under non-uniform vertical loading. In order to analyse using this hybrid method, the foundation was split up into isolated raft and pile groups, and the individual equations were finally combined to solve the required response. It was determined that the performance of piled rafts is dependent on the interactions, and employing long or thick piles below heavy loads reduces the total and differential settlements. The method provides a better and more efficient alternative to 3D FE analyses.

The estimation of the interaction factor is the major challenge in this approach. Since the factor is determined considering only two adjacent piles, the effect of the other piles is ignored. This approach is limited to elastic analysis and 2-D FE modelling for the raft analysis. Moreover, no analysis based on point loading has been explored and is limited to rectangular, circular and strip loadings.

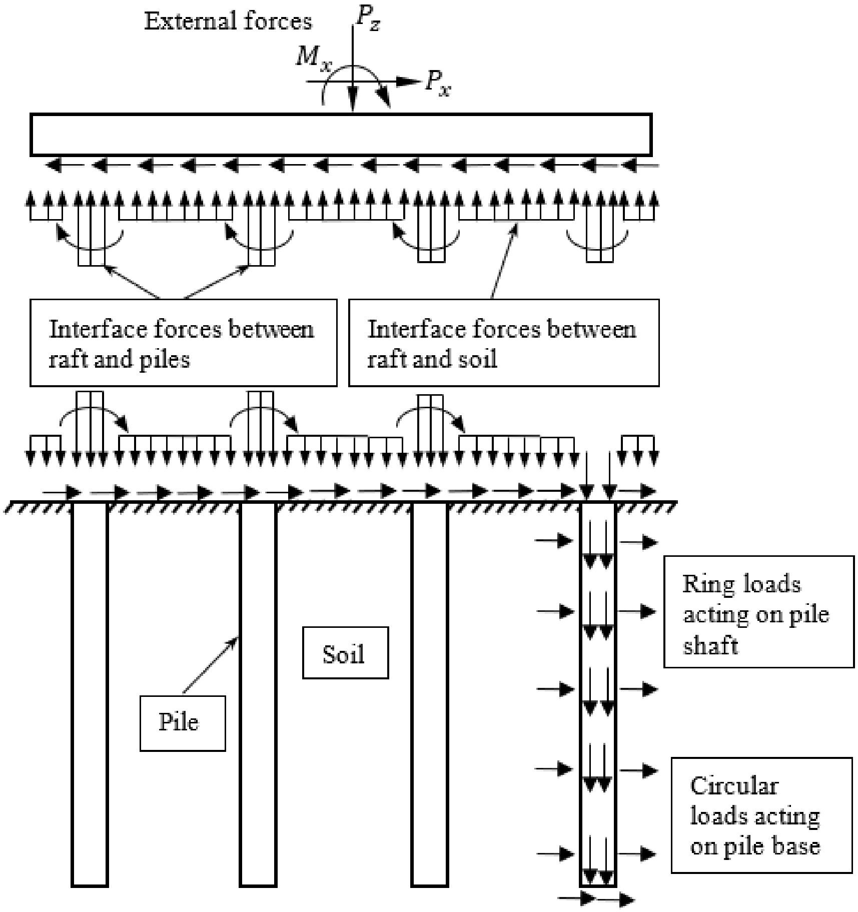


Figure 2.21: Raft and pile group exposed to internal and external forces (Small and Zhang, 2002)

### 2.2.4 Variational Approaches

Variational approaches have emerged out as an alternative approach to address the limitations of numerical approaches. In contrast to the numerical approaches, this approach minimizes the computational time and storage requirements and eliminates the discretisation associated with raft and pile shafts by adopting work energy principles.

Shen et al. (1999) popularized the application of a variational approach to analyse pile groups and raft foundations. They used Mindlin's solution to model the soil continuum. Later, Shen et al. (2000) and Chow et al. (2001) extended the formulation to rigid and flexible piled-raft foundations, respectively. In such an approach, raft and pile deformation were expressed in terms of finite series and the minimum potential energy theory was utilised to evaluate the raft and piled-raft response. This approach involved a two-step procedure, the first of which entailed determining a stiffness matrix for pile group soil at the raft-pile group-soil contact. In the second stage, the determined stiffness was integrated with the raft analysis to obtain a complete piled-raft analysis. The parametric simulations in the large pile group indicated no significant increase in settlements and moments due to lowering pile numbers and increasing the pile spacing from $3d_p$ to $6d_p$, $d_p$ denoting the pile diameter.

This approach was later modified by Liang and Chen (2004), in which the flexible raft was analysed separately in contrast to the previous approach that considered analysis of the piled-raft system as a whole (Figure 2.22).

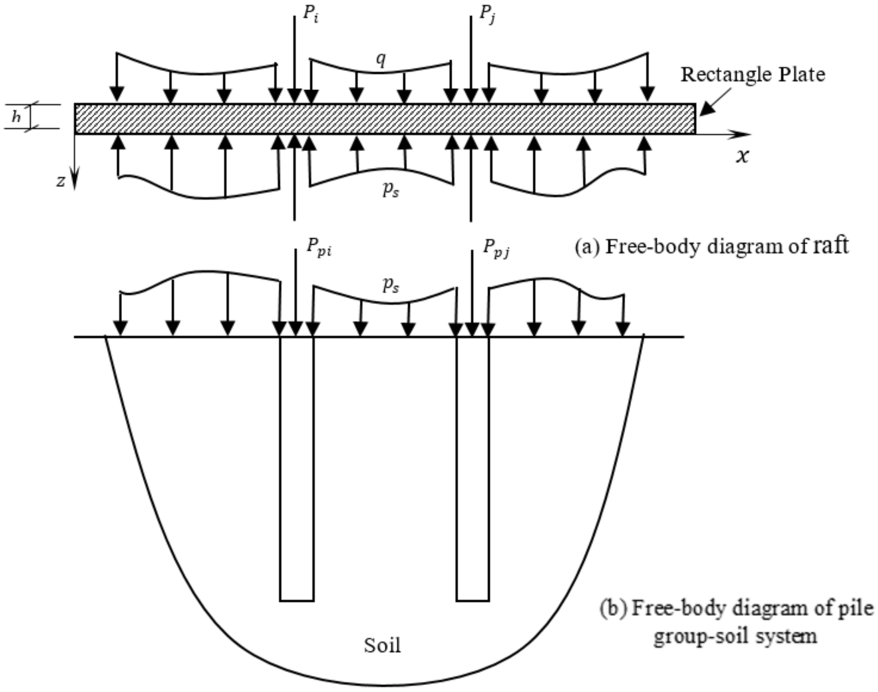


Figure 2.22: Modelling used in the Modified Variational Approach (Liang and Chen, 2004)

It simplified the analysis as the sole objective reduced to the evaluation of raft deflection and contact stress. Also, the utilisation of a simplified model for pile group-soil interaction eliminated the necessity for pile discretisation, making the approach efficient. The variational approaches proved to be consistent with the results of Butterfield and Banerjee (1971b) for rigid piled rafts and those of Clancy and Randolph (1993) for flexible piled rafts. However, these were checked only for small pile groups only.

Such an approach was limited to the consideration of soil as an isotropic and elastic continuum, neglecting any non-linearity. Moreover, any lateral impact caused due to vertical load was not included in the study. The torsional resistance in the raft analysis was also ignored since it was considered the thin plate theory.

Although the variational approach was incorporated into the laterally loaded pile groups by Shen and Teh (2002), the analysis was presumed linear. It was also reported that the responses are highly non-linear due to high strains around the soil surface and hence approximated using a soil modulus as a function of depth. It can thus offer an initial estimate of the group displacement.

### 2.2.5 Experimental Studies

The experimental research gives more realistic scenarios for anticipating the performance of piled-raft foundations as we get to know about real-world issues that could arise. However, in contrast to numerical analysis, there is comparatively limited information available about experimental studies on piled rafts, especially those supported over clayey soil. The literature makes it clear that experimental studies of piled rafts can be conducted either using small-scale model tests or centrifuge tests and have been reviewed briefly in the following sections.

#### (i) 1g tests

Kishida and Meyerhof (1965) conducted model tests on pile groups in sand under vertical and eccentric loads. The load-bearing capacity of group piles in loose sand was observed to be greater than the overall sum of individual piles due to the compaction of sand; conversely, the behaviour in dense sand showed the opposite relation due to the material dilatancy. It was also found that the higher eccentricities lower the pile group resistance, substantially lowering the capacity. The smaller eccentricities, however, have negligible influence. While analyzing the piled rafts, Akinmusuru (1980) experimentally revealed the overall bearing capacity to be greater than the sum of capacities of raft and group piles. The following expression was proposed for computing the capacity of a piled raft.

$$Q_{PR} = Q_R + \alpha' Q_{PG} \tag{2.24}$$

where $\alpha'$ indicates the pile sharing factor, which depicts the pile-soil-raft interaction on group pile capacity. Lee and Chung (2005) mentioned the raft contact with the soil as an important function of the pile configuration. It was also found that identical behaviour exists in load sharing for both the raft in piled-raft and the unpiled raft. Unsever et al. (2015) conducted experimental studies on a piled raft in the sand under combined loadings. Lateral and vertical tests were conducted on a piled-raft with three piles, and the results were later verified using PLAXIS 3D software. It was evident that the interaction between rafts and piles has a significant impact on how a piled raft behaves. Piled-raft behaviour in the sand was analyzed experimentally in the laboratory using small model foundations by Elwakil and Azzam (2016). It was discovered that the amount of load shared by the raft increased with a reduction in pile numbers and lengths. Moreover, the optimum performance of settlement-reducing piled-raft was achieved at a settlement ratio of 0.7%, and the percentage of load taken by raft was 39%. Kumar and Kumar (2018) experimentally examined the piled-raft behaviour in which the relative density of sand was varied. The differential settlement ratio was observed to decrease while the load improvement ratio increased with the number of piles. It was determined that the raft, in combination with piles, was observed to be quite successful in reducing the settlements.

Variations in relative density and number of piles were also investigated by Sosahab et al. (2019) through lab experiments on piled rafts. In contrast to the pile numbers, the former parameter proved to be more influential. Besides, the load improvement ratio was noticed to be more pronounced in the case of loose sands. A study on load eccentricity was conducted, and it was revealed that the ultimate bearing capacity of the piled raft gets reduced when the eccentricity of the load increases. The schematic diagram of the experimental setup is illustrated in Figure 2.23.

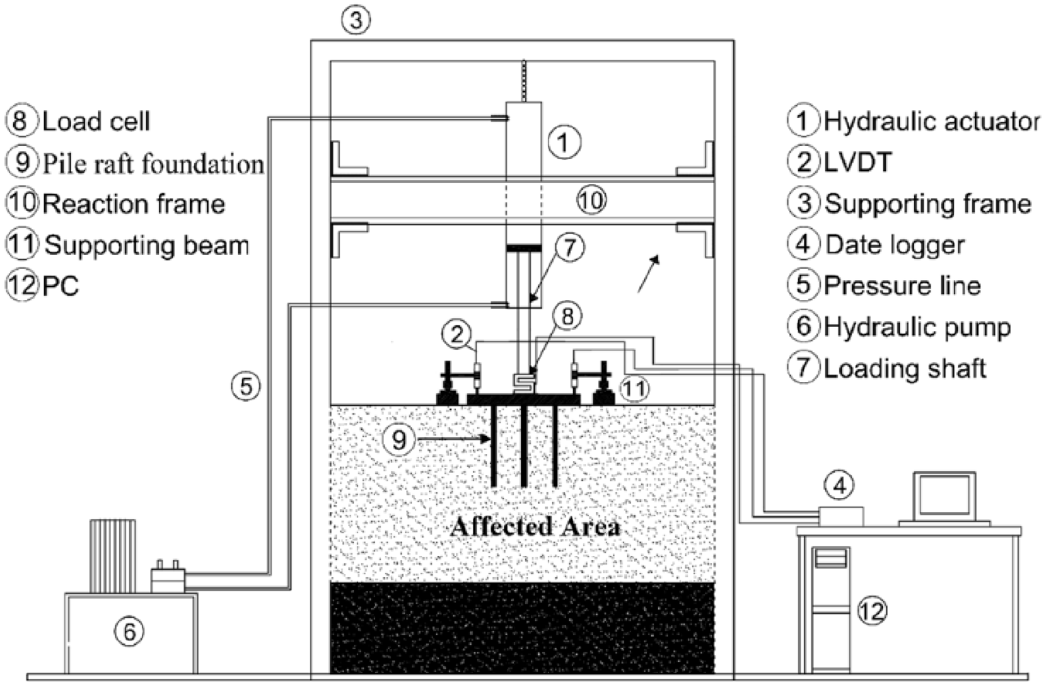


Figure 2.23: Schematic illustration of the laboratory setup Sosahab et al. (2019)

Bajad and Sahu (2008) performed 1g laboratory model tests to examine the influence of interaction among the raft and piles in a vertically loaded piled-raft supported on locally available soft clay. Mandal and Sengupta (2017) inspected the response of piled rafts on soft clay under eccentric loading. For the same e/B ratio, the average settlements for rafts with piles were lowered significantly when compared to unpiled rafts. Additionally, it was determined that piled rafts were quite beneficial in minimizing the differential settlement. Hoang and Matsumoto (2020) studied the long-term consolidation in clays. Although ground creep caused the foundation to continue settling, the load supported by the raft and piles remained steady.

### (ii) Centrifuge Tests

Centrifuge model testing offers a more reliable way than 1g-tests to explore the performance of piled rafts. The stress state of a 1g-scaled model might not idealize the realistic conditions due to a drastic reduction in upcoming stress. Utilizing centrifuge tests thus provides a more precise representation of the model even under larger accelerations (Rasouli et al., 2015). However, their applicability is limited due to the lack of access and high costs involved with such tests. Table 2.1 presents a few important scaling factors commonly used in centrifuge tests.

Table 2.1: Scaling factors for Centrifuge Modelling

| **Property** | **Dimension** | **Prototype** | **Model** |
|---|---|---|---|
| Acceleration | $m^2/s$ | 1 | $N$ |
| Length | $m$ | $N$ | 1 |
| Area | $m^2$ | $N^2$ | 1 |
| Volume | $m^3$ | $N^3$ | 1 |
| Mass Density | $kg/m^3$ | 1 | 1 |
| Force | $N$ | $N^2$ | 1 |
| Stress | $N/m^2$ | 1 | 1 |
| Strain | - | 1 | 1 |

A number of centrifuge tests were conducted by Park and Lee (2015) to explore several interaction effects of piled rafts over silica sand (Figure 2.24). Load-displacement curves demonstrated that the response of a piled raft first resembled that of piles, and with the later settlement, it became more comparable to those of rafts. According to the load response, raft-pile interaction was found to have a greater impact on the upper soil strata.

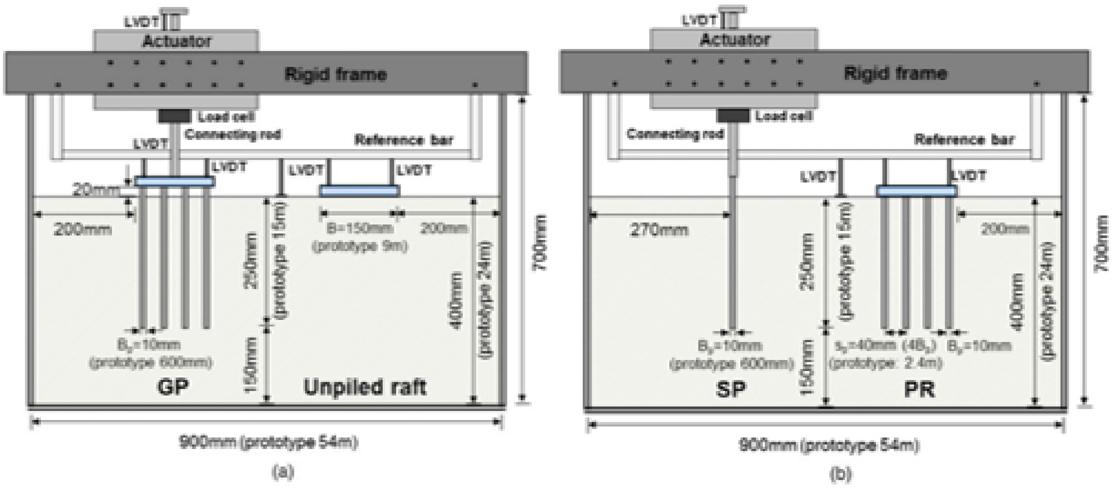


Figure 2.24: Schematic diagram of centrifuge test (Park and Lee, 2015)

Azizkandi et al. (2014) performed centrifuge tests in the sandy soil to examine the impact of relative density on the interaction between two piles. The findings showed that the relative density of soil has a substantial impact on the interaction coefficients. Consequently, the consideration of the relative density to modify the Randolph and Wroth equation proved to outperform the earlier approaches. A parametric study using a centrifuge test was also conducted on connected and non-connected piled-rafts by Rasouli et al. (2015). The parameters involved were pile spacing, pile numbers and granular layer thickness. Several such experiments were performed by Sahraeian et al. (2018) to analyze an oil tank over a piled-raft foundation on dry and saturated sand. It was observed that using piled rafts to support an oil tank can effectively lessen the tank settlement and rocking motion.

Horikoshi et al. (2003a) and Nakai et al. (2004) performed dynamic centrifuge model tests to examine the dynamic response of pile groups and piled rafts. Shake-table tests were performed by Matsumoto et al. (2004) to examine the response of piled-rafts beneath a superstructure. Using centrifuge tests, the effect of moments and lateral loads have also been observed on a piled-raft in the sand by Sawada and Takemura (2014). Due to the raft's contact with the supporting soil, the horizontal resistance of the piled raft was greater than group piles. Cyclic lateral loading tests were conducted by Hamada et al. (2015) to investigate the behaviour of vertical load during seismic activity. The findings demonstrated that the majority of the lateral forces were resisted due to the friction of the raft when there was significant earth pressure below it. Horikoshi et al. (2003a,b) examined load sharing in laterally loaded piled-rafts over loose sand while considering various pile head fixities.

## 2.3 Summary

Based on the present review, it was found that a significant amount of research has been conducted on piled-raft behaviour, and numerous methodologies have been devised accordingly. The present study offers a comprehensive review of the design approaches for piled-raft foundations that can aid design engineers and researchers in selecting the feasible approach that best suits their needs. Each approach is complemented by its applications available in the literature. The assumptions, benefits and drawbacks of these methods are also discussed to develop an understanding of their application. The review commences with an overview and then moves on to discuss the design considerations, classification and other aspects related to the piled rafts. It categorises the available design approaches for analysing piled-raft behaviour into simplified approaches, approximate approaches, variational approaches, numerical approaches, hybrid approaches and experimental studies. It was observed that the initial development was the analytical approaches that rely on the elastic approach and employ Mindlin's and Boussinesq's equations. These approaches do not acknowledge the influence of neighbouring pile movements and even neglect the pile caps' resistance towards settlement.

It was observed that although the two-dimensional analysis numerical are quick tool to analyse the preliminary behaviour, it lacks in addressing certain issues such as the torsional behaviour. Further, three-dimensional analysis has emerged as the most popular in recent times due to its wide range of applications. The capability to consider several aspects, such as non-linearity, inelasticity, complex loading and boundary conditions, supports the 3D analysis as the most efficient design approach. Several experts in this subject have identified the necessity for easy analysis and design models for piled raft foundations. Moreover, researchers have recently emphasised on the need for predictive models that might be used to decide load sharing and settlements during the early design stage.

Kulhawy and Prakoso (1999) organised the available conceptual understanding of the behavioural issues related to piled rafts as presented in Table 2.2. However, in the last decade, many of the issues that were not addressed till then have been worked upon but still require detailed investigation.

The following inferences can be drawn from the review regarding the analysis of piled raft foundations.

Table 2.2: Parameters related to piled raft foundation system

| Understanding | Issues |
|---|---|
| Conceptually understood, but more refinements are needed | System Geometry<br>Raft: thickness/ stiffness<br>Pile: depth, diameter, spacing, piled area<br>Non-linearity |
| Limited understanding | Non-homogeneity<br>Non-uniform loading<br>Non-uniform system geometry<br>Construction effects: Pile installation, deep excavation, raft concreting |
| Not explored to date | Soil consolidation<br>Non-vertical loading<br>Stress and property anisotropy |

- Piled raft foundations are efficient foundation systems for the soil that has limited load-bearing capacity, and the raft is incapable of meeting the design requirements on its own. They offer better settlement control compared to conventional pile foundations and shallow foundations.

- The ultimate bearing capacity of the piled raft is generally higher than the combined bearing capacities of the raft and pile foundation. This additional bearing capacity is due to its complex interaction mechanism.

- Load sharing is an exclusive and crucial characteristic of piled raft foundations. It is observed that the load-sharing ratio varies in a non-linear way in relation to the settlement ratio. As the settlement ratio increases, the percentage of load carried by the raft also increases.

- The behaviour of piled rafts varies on various parameters rather than being particular to any one parameter, including the geometry of foundation elements, soil characteristics, loading type, pile installation methods, etc. The geometry typically comprises of number, diameter, and length of piles as well as the size and raft thickness. The soil characteristics take into account all of the index properties, such as particle size distribution, cohesion value, angle of internal friction, specific gravity, relative density, and others.

- The research on piled raft foundations is mostly those that considered the total settlement into consideration, and less focus has been given to developing models based on differential settlement.

- The basic idea in any preliminary analysis is to maintain the model's simplicity. After comprehending the initial behaviour, complexities should be included, and the study might be expanded to include a thorough analysis. Further research might be done on the impact of varying pile lengths and non-uniform pile distribution in piled rafts.

- It can be observed from the literature that the studies are generally subjected to vertical loading at the raft's centre for analysis. The studies failed to explore the piled raft behaviour under eccentric and inclined loading, hence providing an opportunity for research.

- In a real scenario, soils are composed of multiple distinct layers with varying characteristics. The research on piled-raft behaviour in stratified soils is quite sparse and requires comprehensive investigation.

- The investigation of the impact of the water table on the behaviour of piled rafts is constrained mostly to two-dimensional modelling, allowing for the development of small-scale three-dimensional model tests.

- The studies available in the literature emphasise the immediate load sharing between the foundation elements. Hence, it might be useful to conduct experimental studies to explore load sharing under the influence of the long-term effects.

- The literature in recent years observes the development of several 3D numerical models to overcome the limitations associated with the other design approaches; still, minimal effort has been put into developing simplified analytical models based on these models.

- Owing to a lack of adequate and codified guidelines from authorities, designers are apprehensive towards the most recent innovations and instead utilise traditional design methods, resulting in over-conservative designs.

- Moreover, the literature lacks a proper and simplified step-by-step procedure for the design of piled-raft foundations. The review underlines the necessity for the design manuals and design methodologies for piled rafts. Further study in this area may assist in updating the design manuals for piled raft foundations, particularly for estimating settlement and load sharing.

Overall, the present study lays the foundation for further research in the field of piled raft foundation design and offers beneficial perspectives of its load-sharing mechanism.

## 2.4 Research Gap and Objectives

The literature review on design approaches for piled raft foundations has revealed several key findings and identified areas where further research is needed. While existing studies have provided valuable insights into the behavior and design of piled raft foundations, there remain significant research gaps:

- The literature has witnessed a growing adoption of advanced 3D numerical models to address design challenges. Nonetheless, due to constraints such as limited computational resources or time constraints, researchers frequently resort to simplified models that overlook non-linear soil behavior.

- Researchers frequently opt for square piles in lieu of circular ones, primarily for the sake of simplicity and time-efficiency. This choice is advantageous because it allows for a more straightforward and uniform meshing approach, whereas circular piles necessitate a more complex meshing technique.

- The lack of extensive experimental research on piled raft foundations in clayey soils, in contrast to sandy soils, necessitates addressing this gap to develop comprehensive, adaptable design approaches across diverse soil types and ensure structural safety and stability.

- Influence of interactions among the foundation elements: The interaction between piles and the raft is a critical aspect of piled raft foundation behavior. Current design methods often simplify or overlook this interaction, and further research is needed to better understand and quantify its effects on foundation performance.

- A noticeable research gap in the realm of piled raft analysis is the absence of comprehensive analytical models for determining interaction factors between the piles and the raft. This limitation hinders informed design decisions and increases reliance on resource-intensive numerical simulations, making the development of accurate analytical models essential for optimizing foundation systems and advancing foundation engineering.

- Exploring the response of piled raft foundations to prolonged cyclic loading, challenging soil conditions, dynamic forces like vibrations, and diverse scenarios including eccentric or inclined loading, stratified soil conditions, and load distribution is of paramount importance.

Based on the identified research gap, the following objectives are proposed for this study on design approaches for piled raft foundations:

- In the current study, significant emphasis has been placed on accounting for the inherent non-linearity within the soil continuum by employing the well-established elasto-plastic Mohr-Coulomb model.

- This study aims to investigate the behavior of piled raft foundations using circular piles instead of equivalent square piles, with the goal of accurately representing their actual performance. In order to enhance the precision of numerical simulations, this study intends to use an extensive meshing technique tailored for circular piles.

- In the pursuit of this research, the aim is to perform a parametric analysis on a 3D model of a piled raft foundation. The analysis will systematically vary geometric properties (pile length, diameter, number of piles, raft thickness) and soil characteristics (modulus of elasticity, Poisson's ratio, angle of internal friction) to comprehensively understand the foundation's response and enhance design and construction practices.
- This research endeavor aims to conduct small-scale model tests for piled raft analysis, encompassing diverse soil conditions, ranging from sandy to clayey substrates. The research aim involves conducting parametric analyses to evaluate certain design parameters. Ultimately, the study seeks to derive insights into the load improvement ratio and load sharing ratio in relation to settlement behavior.
- Nevertheless, there has been limited emphasis on creating simplified analytical models. This study fills this void by introducing settlement-based predictive models to determine the interaction factors in case of sandy and clayey soil.