

Chapter 1

Introduction

The quest of shelter is some times overshadowed by the feeling of the conquest of sky by the human being who once fantasized to glide as birds and later flew in groups above clouds. Skyscrapers were probably less meant to meet accommodation requirements than to fulfill his desire to thrill at a cold breeze blowing through large stretch of azure seas and conquering palms that came on the way. Burj Khalifa is a consequence more of a spree than of a need. Such infrastructures symbolise how much developed a country is, how much affluent her citizens are, and also how much advanced her technology is. Yet, whatever be the reason, the requirement of a strong foundation of skyscrapers cannot be ruled out while an economic structure is required to actualise mass dreams. The underdeveloped world badly needs advanced technology to overcome shelter shortages.

The recent terrifying scenes of helplessly collapsing buildings in the states of Uttarakhand and Himachal Pradesh (India) reveal the weak foundations and lack of appropriate technology. Be it the low bearing capacity of the soil or avalanches or the mountain crevice or melting glaciers in the Himalayas, the lust for hill stations will continue, and even increase day by day. Therefore a solution to it is the need of the hour.

Clearly evident from the World Bank's statistical data is the remarkable surge of the urban population, which exceeded 56% in the year 2020 and continues with its upward trajectory (refer to Figure 1.1). This escalating trend toward urbanization highlights the necessity for tall buildings that can accommodate larger populations within constrained spatial confines. Consequently, the demand for effective and economical foundations for such structures has intensified. In this context, piled-

raft foundations have emerged as a viable solution, particularly in situations where the subsoil exhibits a limited bearing capacity and the potential settling of supported structures poses a significant challenge. Notably, the utility of piled raft foundations extends beyond high-rise buildings, including applications in diverse realms such as bridges, tunnels, and offshore oil industries.

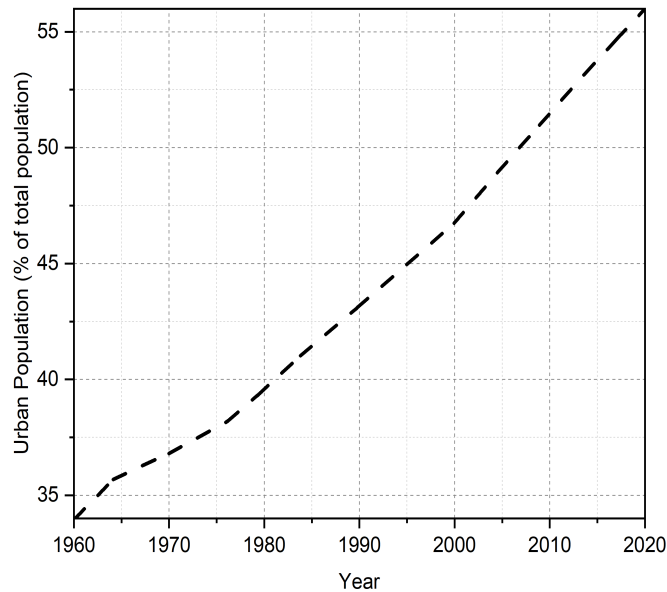


Figure 1.1: Urbanisation (%) (Source: data.worldbank.org)

The publication of ‘The Mechanics of Earth Construction Based on Soil Physics’ (in German) by Terzaghi (1925) paved the way for the evolution of modern soil mechanics. Following that, the concept of effective stress, consolidation, bearing capacity theories and other phenomena became more familiar. Later, the significance of foundation engineering attracted several researchers and academia, and eventually, it emerged as a more rational discipline.

A strong and effective foundation is vital for ensuring structural stability. Foundations provide a stable base for the superstructure, evenly distributing loads across the subsoil to prevent differential settlements and protect against soil movement from scouring, undermining, and natural events. They also control structure settlement within allowable limits and safeguard underlying soil from shear failure. Many factors guide foundation selection, as even excavation can affect nearby structures. Moreover, proper consideration of soil bearing capacity

is essential for foundation design to withstand potential failures.

The use of foundations dates back to the historical use of wooden and stone foundations. However, modern foundations are now constructed using steel or reinforced cement concrete (RCC). These foundations can be broadly classified as shallow and deep foundations. If the depth of the foundation is less than or equal to its width, it is referred to as a shallow foundation. Shallow foundations are the most basic type of foundation designed to evenly distribute the super-structural load to the supporting soil. They enable quick and straightforward construction. Additionally, due to their relatively shallow depth, the likelihood of encountering a high water table is usually low. Shallow foundations are commonly employed when there is a moderate load or when the soil has a higher bearing capacity. Various types of shallow foundations, including isolated footings, combined footings, strap footings, and raft foundations, are widely used today.

On the other hand, deep foundations have a depth greater than their width. Examples of deep foundations include well foundations and pile foundations. Deep foundations are used when the soil profile has a weak top layer and there is a need to transmit the structural load to deeper soil layers with higher bearing capacity. It is also recommended to use deep foundations to mitigate issues related to soil swelling and shrinking.

1.1 Evolution of Piled Raft Foundation

The foundations of high-rise structures often experience significant stresses, but a rigid layer of soil to support them might not always be available. Consequently, they are placed on soft soils, where settlement, particularly differential settlement, becomes a major concern. While raft foundations address bearing capacity issues, excessive differential settlement remains problematic. In contrast, traditional pile foundations transfer loads to deeper soil layers, effectively mitigating settlement. However, their design often overlooks raft contributions, leading to the need for

additional piles. Consequently, this approach might overestimate the response of both the superstructure and the substructure (Burland et al., 1977; Jeong and Cho, 2014).

A combination of pile and raft foundations has gained recent popularity as a rational and cost-effective foundation system. Such foundations have been referred to as piled-raft foundations, pile-raft systems, pile-cum-raft foundations, Combined Piled-Raft Foundations (CPRF), and commonly as piled-rafts. Piled-rafts are utilized when a single raft or pile foundation alone cannot counteract the imposed stresses. Generally, a piled-raft comprises three elements: piles, a raft, and subsoil. Piled-rafts harness interactions among these elements and have emerged as cost-effective alternatives to conventional foundations Poulos (2001b). Understanding load distribution behavior in piled-rafts is complex due to these interactions. Yet, technology advancements and high-speed computers enable numerical analysis of piled-rafts using commercial software. Despite progress, there remains limited understanding of how foundation elements interact as a whole. Thus, to achieve comprehensive comprehension, thorough investigations must be conducted from all conceivable perspectives.

Piled rafts are not explicitly mentioned in widely adopted design standard codes. However, some international design guidelines and codes offer recommendations for piled raft foundation design. Euro code 7 classifies piled raft foundations under geotechnical category 3, which covers complex geotechnical constructions (Katzenbach et al., 1998). Japan has developed a fundamental design methodology for piled raft foundations (AIJ, 2001). Conversely, Indian and American codes do not explicitly address piled rafts, leading to a prevalent over-conservative conventional approach due to the lack of proper guidelines in national and international codes.

The concept of combining rafts and piles was initially introduced a few decades ago by Leonardo Zeevaert (Poulos, 2005). Zeevaert (1957) implemented piled raft foundations in the volcanic clay of Mexico City. Initial attempts to simulate complex interactions in small piled rafts were made by Butterfield (1971a). Davis (1972)

subsequently proposed an approach to analyze piled rafts of any size. Subsequent years saw the development of various analytical techniques (Hooper, 1973; Burland et al., 1977; Sommer et al., 1985; Franke et al., 1994), with Randolph's approach (1994) being the most acknowledged.

Ongoing research has been dedicated to comprehending the behavior of piled-rafts through analytical, numerical, and experimental studies (Horikoshi and Randolph, 1996; Katzenbach et al., 2000; Poulos, 2000; de Sanctis and Mandolini, 2006; Lee et al., 2010, 2014; Park and Lee, 2015; Sinha and Hanna, 2016; Kumar and Choudhury, 2018; Deb and Pal, 2019; Conte et al., 2003). Certain design approaches have been adapted to incorporate interactions among the foundation elements (de Sanctis and Mandolini, 2006; Lee et al., 2015; Kumar and Choudhury, 2018; Deb and Pal, 2019). However, a standardized method to assess the intricate interaction mechanism is currently absent.

Analytical piled-raft approaches have emerged from established theories (Poulos and Davis, 1980; Clancy and Randolph, 1993; Randolph, 1994; Poulos, 1994; Burland, 1995; Viggiani, 1998). Given the limitations of conventional analysis methods, understanding the complex mechanisms across various subsoils is crucial. An alternative approach entails spring-based models for piled rafts (Griffith et al., 1991; Clancy and Randolph, 1993; Poulos, 1994; Horikoshi and Randolph, 1998; Russo, 1998; Kim et al., 2001; Kitiyodom and Matsumoto, 2002, 2003; Kitiyodom et al., 2005), wherein the raft is represented as a strip or plate, and the lower foundation components as springs.

Numerical piled-raft analysis was established in the 1970s (Hooper, 1973), employing Finite Element Method (FEM) and Boundary Element Method (BEM) (Butterfield and Banerjee, 1971a; Brown and Wiesner, 1975; Kuwabara, 1989). Hybrid methods combining finite and boundary element techniques have also been pursued (Hain and Lee, 1978; Ta and Small, 1996; Franke et al., 1994; Russo and Viggiani, 1998). Evolving computer processors enable these methods to solve complex problems more effectively. 3D computer modeling replicates real scenarios for more precise

outcomes. Simplified FE techniques employ equivalent models like axi-symmetric (Hooper, 1974) or plane-strain models (Desai et al., 1974). While 2D modeling is common for initial investigations due to fewer elements and quicker analysis, 3D modeling, considering interactions and complex configurations, is recommended for extensive analyses to ensure dependable results.

Since the piled-raft foundation is a combination of the raft and the piles, its load-bearing capacity (Q_{PR}) can also be expressed as the sum of the component capacities.

$$Q_{PR} = Q_R + Q_P \quad (1.1)$$

The piled-raft foundation stands out from conventional foundations due to its unique load-sharing behavior. Katzenbach et al. (2000) defined this behavior using the piled-raft coefficient, denoted as α_{pr} . This coefficient signifies load-sharing between the raft and piles and is sometimes referred to as the load-sharing ratio (LSR). In other words, it has also been represented as α_p (Lee 2015), defined as the ratio of load resisted by piles (Q_P) to that resisted by the piled raft (Q_{PR}).

$$\alpha_p = Q_P/Q_{PR} \quad (1.2)$$

The load-sharing ratio α_{pr} for a piled-raft foundation ranges between 0 and 1, thereby considering the raft and pile foundation as its extreme cases. This ratio relies on the piled-raft geometry and subsurface characteristics, influencing the effectiveness of piles in mitigating raft settlement. Figure 1.2 illustrates this relationship between load-sharing ratio and settlements for the same subsurface characteristics.

Figure 1.3 demonstrates a typical load-sharing mechanism, portraying interactions within a piled-raft system. These interactions among foundation elements are categorized as follows: (i) Pile-Soil interaction, (ii) Pile-Pile interaction, (iii) Raft-Soil interaction, and (iv) Raft-Pile interaction (Katzenbach et al., 2000; de Sanctis

and Russo, 2008). The subsequent chapter will delve into these interactions in greater detail.

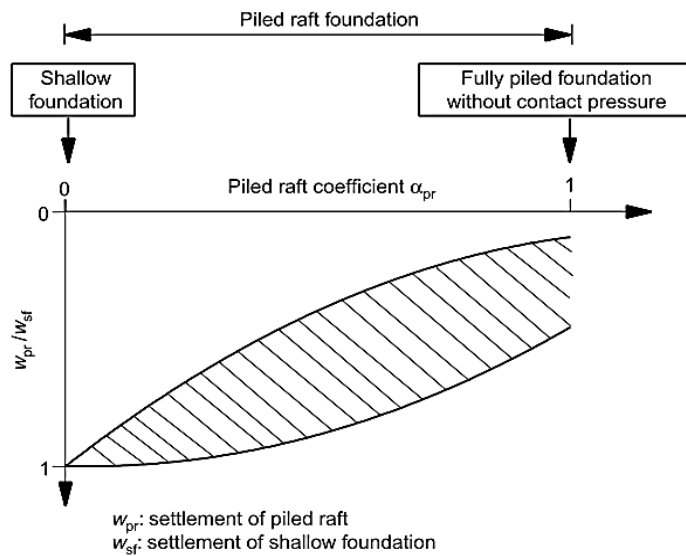


Figure 1.2: Piled-raft settlement as a function of load sharing ratio (Katzenbach, 2000)

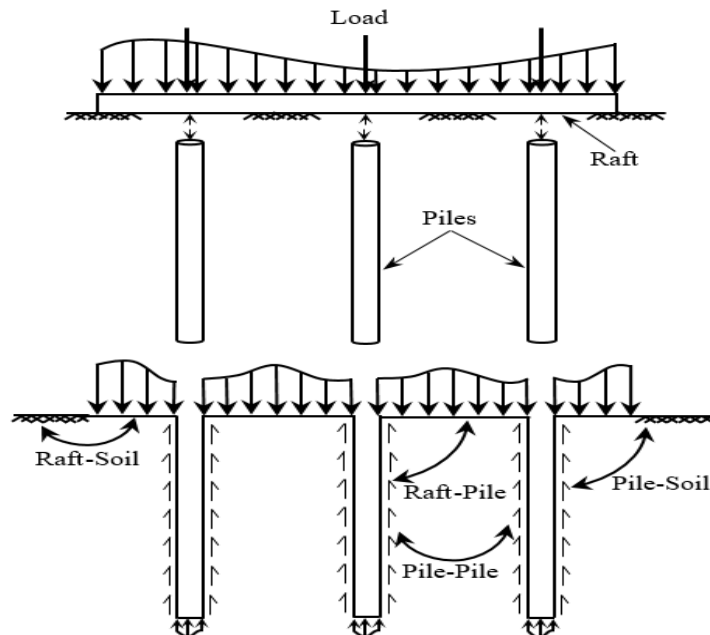


Figure 1.3: Interaction mechanism in piled-rafts

It is apparent that the design of piled-raft foundations is much more sophisticated and necessitates consideration of several factors, including foundation geometries, configurations, loading types, and geotechnical conditions. To achieve an optimal

foundation design, it is essential to have a clear understanding of the role played by the attached piles. Based on the purpose of the piles, Mandolini et al. (2013) categorized the design approaches as presented in Table 1.1. Utilizing a purpose-based approach will yield a reliable and economical design.

Table 1.1: Design approaches based on the purpose of piles (Mandolini et al., 2013)

Approach	Purpose
Settlement Based Design approach (SBD)	To reduce the average settlement
Differential Settlement Based Design approach (DSBD)	To reduce the differential settlement
Capacity and Settlement Based Design approach (CSBD)	To increase the stiffness and resistance of the raft
Raft Based Design approach (RBD)	Reduce the shear forces and bending moments in the raft
Earthquake Based Design approach (EBD)	To modify the foundation input motion underneath the structure

As the complex behaviour of piled-rafts has not been completely captured, it has led to numerous design techniques. Each of them adheres to certain presumptions and boundary conditions that are based on the soil conditions, loading types and structural requirements. The soil conditions encompass factors such as the type of soil, their properties, and the depth of the water table, while the structural requirements involve the type and configuration of the foundation. To assess the applicability of these developed models, they are tested against various soil conditions. The subsequent chapter reviews the advantages and disadvantages of different design strategies for piled-raft foundations. Furthermore, it aims to address several design-related issues, including design conditions, case histories, and the effects of parametric variations.

The three primary foundation options are raft foundations, pile foundations, and piled-raft foundations (Figure 1.4). Rafts are suitable where they cover over half the ground beneath the superstructure, effectively reducing settlement variations. They uniformly transmit loads over soft soils with a solid continuous slab, offering

better bearing capacity.

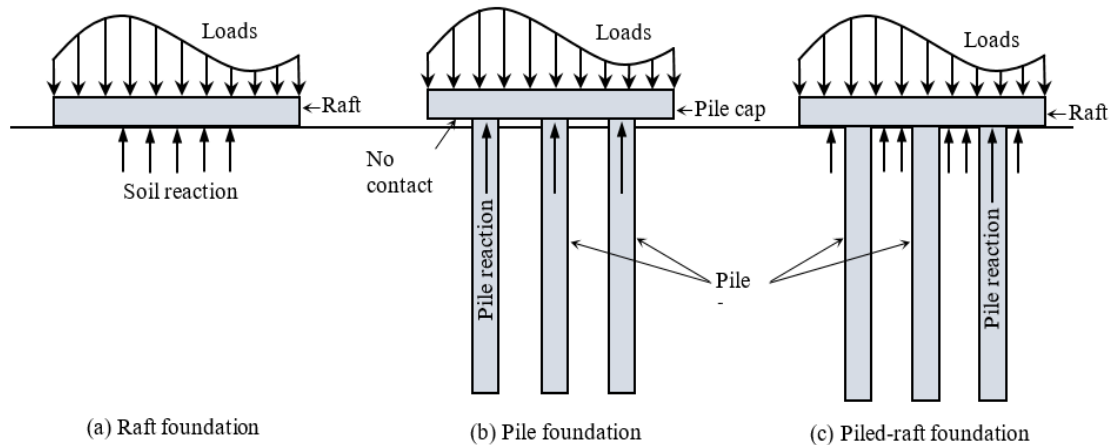


Figure 1.4: Different types of pile-raft system

In general, deep foundations are provided when the shallow foundations are insufficient to support the overall load. Moreover, there might be situations where a raft is safe against bearing capacity failure but the settlements are still excessive. In such cases, pile foundations are employed and a number of piles are affixed to the raft to limit the settlement. Pile foundations are employed in the absence of firm strata at shallow depths. Piles that are extended till a hard strata is reached are known as end-bearing piles. Moreover, friction piles are those in which the load is resisted by the friction between the piles and the surrounding soil.

In the conventional pile foundation design, pile numbers are selected to ensure sufficient safety against individual pile failure, and the piles are expected to resist the overall load. The pile design on the basis of ultimate load was referred ‘illogical’ by Davis and Poulos (1972) as they are solely employed to reduce the raft’s settlement. Also, the pile cap is presumed to connect the superstructure and piles and transmit the induced loads to lower components. It is anticipated not to withstand any load due to the absence of any contact with the subsoil. The majority of the standard codes mandate the adoption of a safety factor of 2 to 3 for pile foundations, which consequently leads to a higher number of piles. High-rise constructions are commonly constructed on pile foundations all over the world. Such foundations are also used for maritime projects since they offer stability against overturning and large

settlements. However, its complex design makes it comparatively uneconomical than rafts and should be utilised only when employing shallow foundation is not practical.

Notably, ignoring the pile cap/raft's load resistance in conventional pile design leads to over-conservative results. Realistically, the raft contributes significantly, prompting piled-raft foundations where rafts sit on subsoil, focusing on load sharing. Here, the raft partially carries the load via ground contact, and piles resist the rest through friction

Piled-raft foundations have been in existence since the 1970s (Hansbo et al., 1973; Burland et al., 1977). However, the piles were initially attached to the pile cap as settlement reducers and were not intended to bear any load. On the contrary, another approach is the conventional pile design approach, in which the entire loads are supposed to be withstood by the piles and the contribution of the raft is ignored. Hence, piled-raft foundations follow a mid-way approach where the load-bearing capacities of the raft and the pile foundations effectively utilised. This approach can be referred to as the load-sharing approach, as the upcoming load is shared among the raft and the piles.

1.2 Classification of Piled Raft Foundation

Russo and Viggiani (1998) classified the piled rafts in perspective of the design optimization into two classes: small piled-rafts and large piled-rafts. The small piled-rafts refer to those in which the raft lacks the necessary bearing capacity to withstand the overall load. Piles are hence affixed only to attain a reasonable level of safety. The raft width in such foundations extends only up to a few metres and is lesser in contrast to the pile length [$(B_r/L_p) < 1$]. Due to its high flexural stiffness, the differential settlement is not a serious issue in small piled-rafts and the only problem is to achieve enough bearing capacity. Alternatively, large piled-rafts are those in which the raft on its own carries the applied load satisfactorily and needs piles only for lowering the settlements. The raft width in such foundations is

substantially greater than the pile length [$(B_r/L_p) > 1$] (Figure 1.5). The differential settlement thereby plays a crucial function in the foundation design of such piled-rafts, and settlement reduction needs to be addressed properly. Viggiani et al. (2012) further recommended the use of the equivalent pier method for small piled-rafts and the equivalent raft method in case of large piled-rafts, discussed in the subsequent sections.

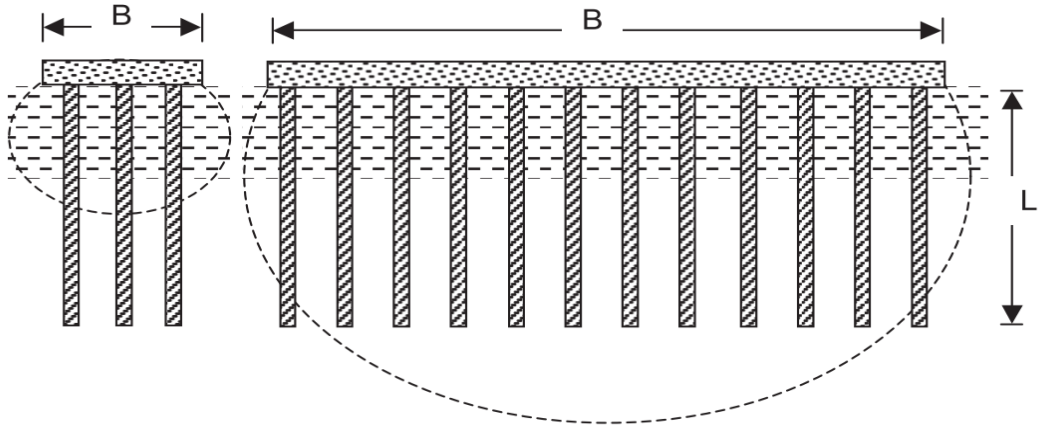


Figure 1.5: Small and Large piled-rafts (Viggiani et al., 2012)

In context with the existing literature, several aspects of the piled-raft foundations have been explored in the following sections of this chapter. The sections outline different design concerns, advantages, disadvantages and scenarios pertaining to the piled-rafts. The following sections discuss some significant design philosophies and the underlying assumptions. Ultimately, a comprehensive review of the different design approaches of piled-raft foundations has been conducted in the next chapter.

1.3 Design Aspects of Piled Raft Foundation

1.3.1 Design considerations

A typical piled-raft foundation may be subjected to complex loadings, high stresses and moments. The response of such foundations is indicated by several design factors (Poulos, 2001b; Katzenbach et al., 2005). The factors that need to be addressed while designing a piled raft foundation include (a) Maximum settlement (b) Angular

rotations and differential settlements (c) Ultimate load capacities under moments, lateral and vertical loads (d) Shear and moments in raft and piles for their structural design (e) Stiffness (or flexibility) of raft and piles (f) Soil characteristics (type, profile, index properties) (g) Raft and pile geometries (raft's dimensions, length and diameter of piles, configurations) (h) Load sharing between raft and piles (i) Interactions among the soil and foundation elements

1.3.2 Features of piled raft foundation

A piled-raft foundation offers numerous advantages (Katzenbach et al., 2000). Piled-rafts markedly reduce pile numbers and enhance stability compared to conventional pile foundations. They provide superior serviceability by effectively limiting total and differential settlements. Strategic placement of attached piles in such foundations decreases stresses and moments in the raft. The load sharing between foundation elements boosts the ultimate load-bearing capacity. Additionally, better stabilization against eccentric loads can be achieved by concentrating piles under the corresponding load regions.

However, limitations of piled rafts mainly stem from their complex interaction mechanisms among foundation elements. Precise examination is challenging due to limited understanding of these interactions. While modern high-processing computers can capture interactions, using available commercial codes requires skilled professionals. Moreover, a lack of regulations and standards from authorities restricts their widespread use.

1.3.3 Applicable scenarios for piled raft foundation

Poulos (1991) investigated several soil profiles and placed them into favourable and unfavourable conditions for piled-raft foundations (Table 1.2).

Piled rafts have been successfully employed so far in several contexts such as bridge foundations, offshore structures, power plants (Katzenbach et al., 1998) and tall

buildings (Hansbo, 1993; Katzenbach and Reul, 1997; Poulos et al., 2011)

Table 1.2: Favourable and unfavourable conditions for piled-raft foundations

S.No.	Soil Profile	Observations	Condition
1	Relatively stiff clays	Substantial amount of raft contribution in load carrying,	Favourable
2	Relatively dense sands	while piles are just performance booster and do not contribute in resisting load	Favourable
3	Soft clays near surface	Raft not being able to resist a substantial amount of load	Unfavourable
4	Loose sands near surface	Minimise the influence of raft on the foundation's long-term stiffness	Unfavourable
5	Soft compressible layers at shallower depths	Loss of contact between soil and raft	Unfavourable
6	Soils undergoing consolidation settlement	Significant increase in tensile stresses is observed	Unfavourable
7	Soils undergoing swelling movements		

1.3.4 Design philosophies

Most of the foundation designs are firmly based on the codal provisions and guidelines issued by the local authorities. Geotechnical experts for remedial guidance are generally not necessarily involved in such cases as the majority of the foundations show good responses. Nevertheless, the absence of such expertise might manifest an over-design of the foundation, hence making it uneconomical. Depending on the local ground conditions, an intimate investigation could provide better results. Such investigations have in fact proved more beneficial to a veteran engineer, rather than estimating the soil parameters precisely. This is due to the complexity involved in the latter due to several aspects of the structure and earth behaviour. Local observations also provide a 'back-analysis' viewpoint and can be calibrated to the design approaches. Consequently, for a safe and economical design, it can be inferred that a good design should have a proper balance between local experience and geotechnical expertise.

Several design philosophies have been evolved for the piled rafts. Randolph (1994) classified the piled raft design philosophies into the following categories:

(a) Conventional Approach: This approach considers of piles under the pile-cap to be distributed uniformly. In such an approach substantial amount of load is resisted by the pile group (60-75%) while relatively little of it is transferred directly to the subsoil by the pile-cap, resulting in a smaller number of piles. This approach was utilised by Cooke et al. (1981) that presented a case history with the foundation consisting of 350 piles. Later, it was suggested that these pile numbers could be reduced below 100 with a little more allowance to the settlement (Clancy and Randolph, 1993).

(b) Creep Piling Approach: Piles are intended to function at around 70-80% of the ultimate load-bearing capacity in this approach, which signifies the beginning of significant creep. This choice prevents high stresses from developing at the foundation edges. Hansbo and Kallstrom (1983) can be credited for proposing such an approach. Detailed case studies were described in their later works. Hansbo (1993) compared building settlements based on the conventional and creep piling approaches, and the latter showed a substantial reduction in piling costs (Figure 1.6).

(c) Differential Settlement Control Approach: It is a direct approach that is primarily focused on reducing the differential settlement in contrast to the other approaches where the objective was to reduce the average settlement through uniform distribution of piles under the raft. An unpiled raft subjected to uniform super-structural load forms a dish-shaped structure. The introduction of central piles limits the settlement at the central portion, leading to a reduction in differential settlement (Figure 1.7). Fewer settlement-reducing piles are required in this approach due to their strategic placement, thus proving it to be the most economical one (Poulos, 2001a). However, fewer piles result in stress concentration around the pile head and thus large flexural moments in the raft (Wong et al., 2000). Another approach is to utilise the full capacity of piles ($\sim 100\%$) and hence, can be indicated as an extreme version of the creep piling approach (Poulos, 2001a). This led to the development of an idea that prioritizes piles as ‘settlement reducers’

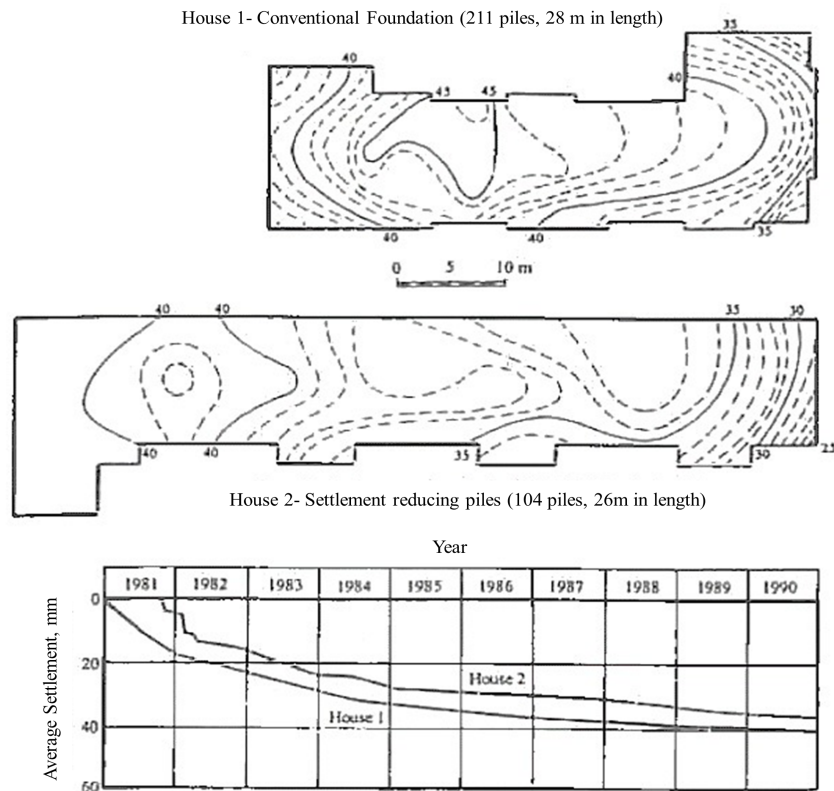


Figure 1.6: Settlement behaviour of buildings based on conventional and creep piling approach (Hansbo, 1993)

while also properly acknowledging their role in the entire load-bearing capacity of the foundation.

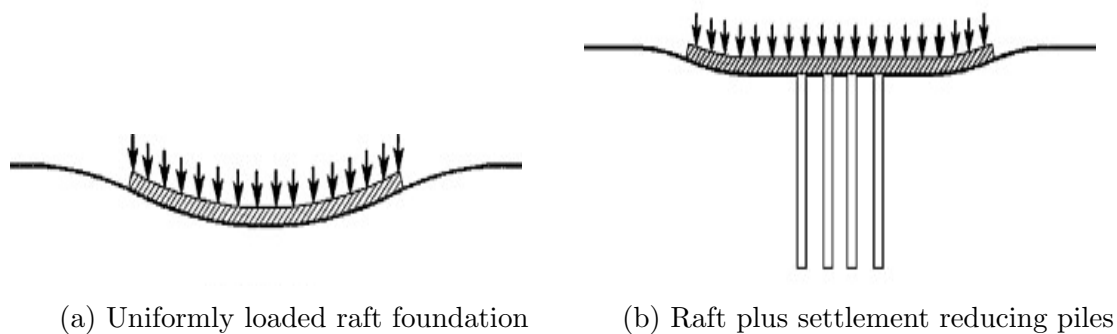


Figure 1.7: Piles acting as settlement reducers

Poulos (2001b) analysed the load-settlement behaviour of piled raft foundations using multiple design philosophies (Figure 1.8). Curve 0 indicates that the unpiled raft undergoes excessive settlement at the design load. Curve 1 illustrates the conventional approach, where the majority of the load is supported by piles. The creep piling approach (Curve 2) assumes a lower safety factor for piles and a

relatively higher load is resisted by the raft. Curve 3 represents the settlement-reducing approach. The foundation in such a case is sufficiently safe and meets the settlement criterion, making it more economically viable than other approaches.

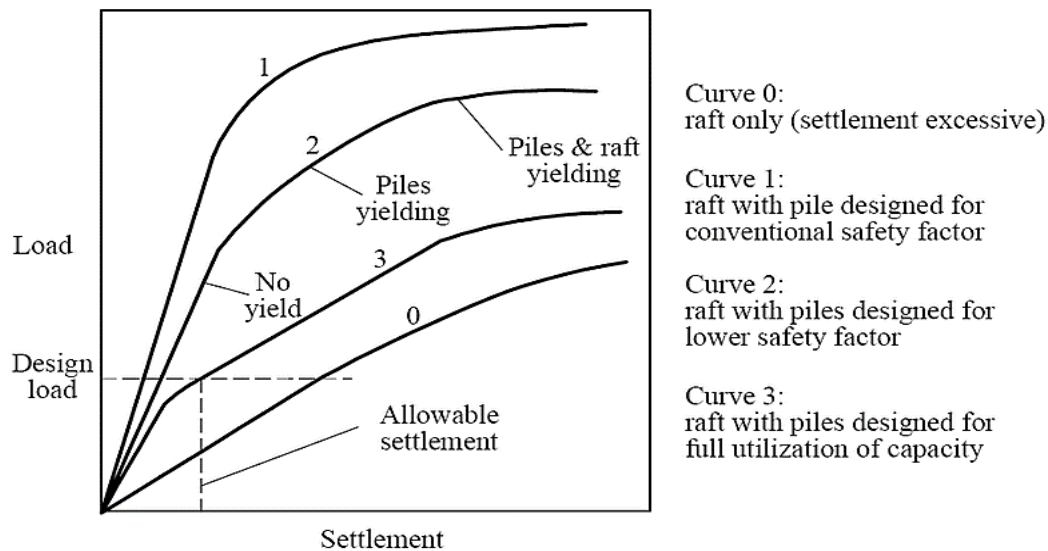


Figure 1.8: Load-settlement curves for piled raft foundations based on several design philosophies

1.3.5 Load-settlement behaviour

The advantage of settlement calculation in a shallow foundation or a single pile can be generalised to the pile groups by treating the group as an equivalent raft or an equivalent pier as discussed below. Moreover, the former approach is treated as the conventional one. The different suggestions in the literature (Viggiani, 1993; Randolph, 1994) provide alternatives to the designers, which may be based on their discretion.

(a) Equivalent raft approach: Interaction among the foundation elements can alternatively be treated by considering the foundation entirely (Randolph, 1994). The pile-group settlement is usually determined using the equivalent raft approach, in which a raft is considered to be situated either at the base of the pile (end-bearing piles) or at two-thirds length of the piles inserted into the main founding soil layer. The average settlement is then determined as

$$w_{avg} = w_{raft} + \Delta w \quad (1.3)$$

where w_{raft} represents the raft settlement and Δw denotes the elastic compression of the piles considered as free-standing piers and located above the corresponding raft level (Figure 1.9). Poulos (1993) suggested an expression for determination of the raft settlement given by

$$w_{raft} = F_D q \sum_{i=1}^{n_s} \left(\frac{I_\epsilon}{E_s} \right)_i h_i \quad (1.4)$$

where q represents the average pressure exerted on the raft. F_D and I_ϵ are the correction factor and influence factor, respectively. h_i denotes the thickness for i^{th} layer, while n_s denotes the number of soil layers. Thus, this approach has the advantage of considering the changes in soil stiffness underneath the raft and hence is particularly crucial in circumstances where a softer layer of soil exists at a certain depth beneath the piles (Randolph, 1994).

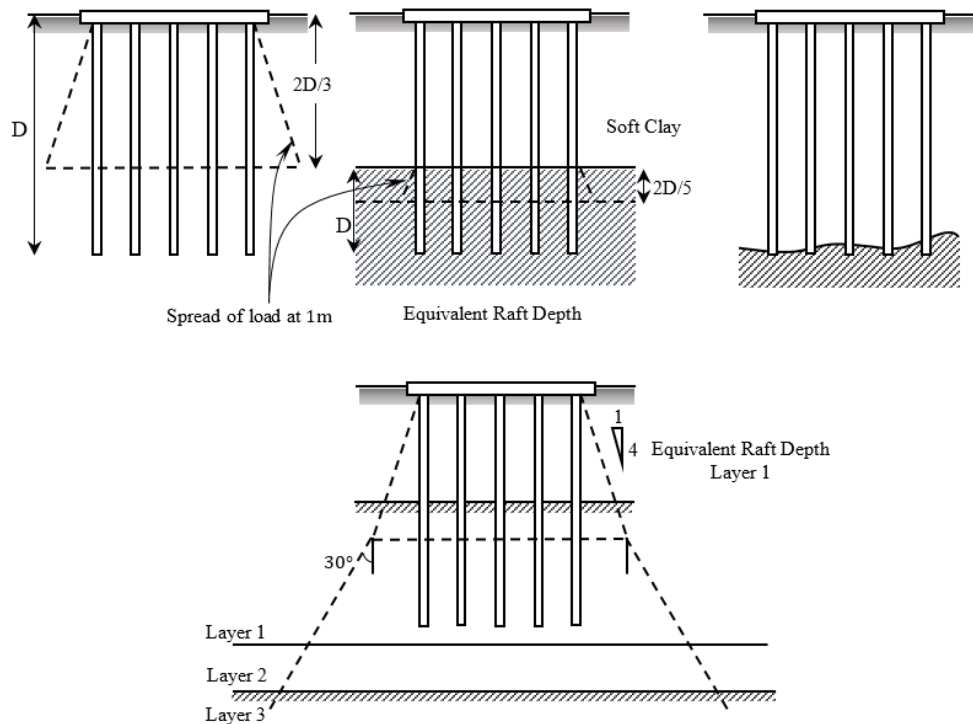


Figure 1.9: Equivalent Raft Approach

(b) Equivalent pier approach: Poulos and Davis (1980) suggested another approach wherein the pile group is substituted by a single equivalent pier affixed to a circular cap supported over soil (Figure 1.10). The corresponding diameter and modulus of elasticity of the pier may be computed as follows:

$$d_{eq} = \sqrt{\frac{4}{\pi} A_g} = 1.13 \sqrt{A_g} \quad (1.5)$$

$$E_{eq} = E_s + (E_p - E_s) \left(\frac{A_p}{A_g} \right) \quad (1.6)$$

A_g and A_p represent the gross area of the pile group and the total cross-sectional area of the piles, respectively. This approach has the benefit of exhibiting the group effect of piles and the soil in between, allowing the pier to be considered as a single pile.

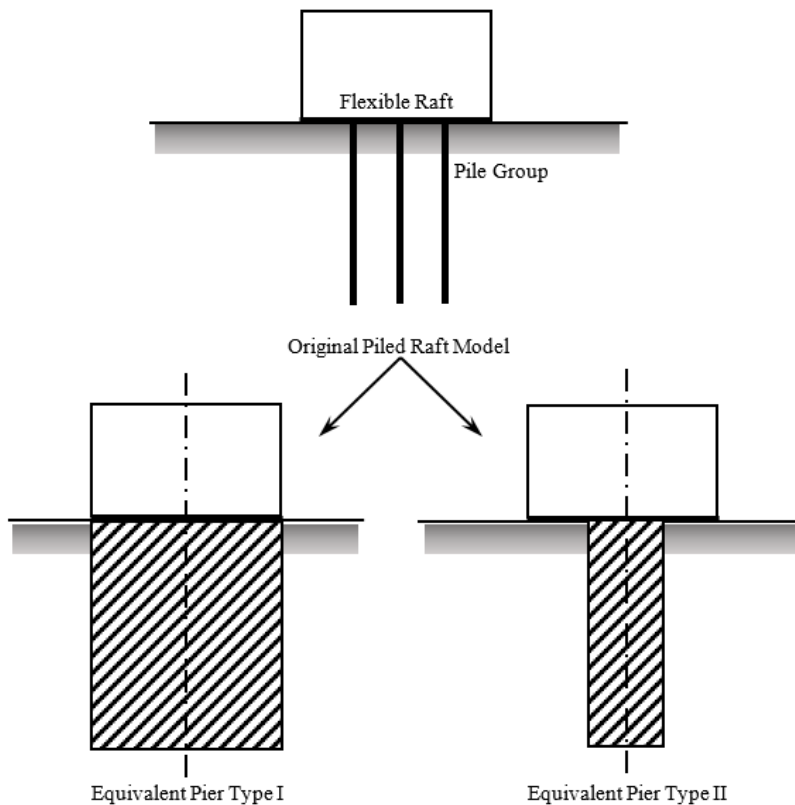


Figure 1.10: Equivalent Pier Approach

Randolph and Clancy (1993) introduced the aspect ratio (R) to signify the geometry of group piles. The aspect ratio can be expressed as

$$R = \sqrt{\frac{n \cdot s_p}{L_p}} \quad (1.7)$$

where n , s_p and L_p denote the number of piles, spacing, and length, respectively. Moreover, the equivalent raft method and equivalent pier method are preferred for the aspect ratio $R \geq 4$ and $R < 2$, respectively (Randolph, 1994). The method for intermediate values is based on judgment. Viggiani et al. (2012) further recommended the former approach for large pile groups and the latter for small pile groups.

Notably, neither of these approaches deals with the differential settlement of a pile group. Despite being a critical aspect in foundation design, comparatively little emphasis has been given to the differential settlement. The normalised differential settlement of a typical shallow foundation varies with only the relative raft-soil stiffness K_{rs} . Brown (1969) and Brown and Wiesner (1975) proposed the corresponding expressions for circular and rectangular rafts as given in equations 1.8 and 1.9, respectively,

$$K_{rc} = \frac{2(1 + \nu)E_r}{G} \left(\frac{t}{a}\right)^3 \quad (1.8)$$

$$K_{rs} = \frac{2(1 + \nu)E_r}{G} \frac{4B}{3\pi L} \left(\frac{t}{L}\right)^3 \quad (1.9)$$

Here, a signifies the radius of the circular raft, while L and B denote the length and breadth of the rectangular raft, respectively. The differential settlement in pile groups is more sophisticated due to its dependency upon the spacing, length and number of piles. Still, the normalised differential settlement can be described in terms of the aspect ratio, R (Clancy and Randolph, 1993). It was also advised

to employ the solution for an individual pile to predict the flexibility of such an equivalent pier (Randolph, 1994). Bajad and Sahu (2008) adopted this approach to estimate the influence of pile geometries on settlement reduction and load distribution between rafts and piles in piled-raft supported over soft clay.

In general, the design process of piled-raft foundations includes an initial preliminary phase and a detailed design phase. The initial phase involves the assessment of ultimate loads, geotechnical parameters, load-settlement behaviour, pile loads, moments and shears experienced by the raft. Minimal use of the computer is required in this phase. Further, the detailed design phase is utilised after the preliminary stage to ensure the feasibility of piled-raft foundation. The objective is to determine the optimal quantity, positioning and configuration of piles, as well as to estimate precise settlements, BM and SF in rafts and piles.

Poulos (2001a) proposed a three-stage design approach for piled raft foundations as follows:

(i) Preliminary Stage: In this stage, the response of unpiled raft on settlements and load capacities is inspected. The conventional pile design approach is used in such a case where the raft resists only a marginal amount of load. However, if a sufficient proportion of the load is carried by raft, the purpose of piles is to minimise the settlements. In such conditions, it is reasonable to use either the Settlement Control or the Creep Piling Method. The ultimate load-bearing capacity in the case of vertical loadings can be calculated as the smaller of: (a) Sum of ultimate capacities of raft and the piles; (b) The capacity of the block with piles and part of the raft above it along with the raft portion outside the pile group.

(ii) Second Stage: This stage gives emphasis on the locations of piles. Unlike in the preliminary stage where the uniform loadings are generally considered, location is strategically decided in this stage. In cases of column loadings, Poulos (2001a) suggested four conditions under which piles are needed below the columns. These four conditions individually allow for investigating the maximum column load and

are defined by the following criteria: (a) Maximum shear criterion, (b) Maximum moment criterion, (c) Maximum contact pressure criterion, and (d) Local settlement criterion. The minimum of these four maximum column loads can be considered as the critical load (P_{crit}), i.e., $P_{crit} = \min(P_{c1}, P_{c2}, P_{c3}, P_{c4})$. Consequently, the use of pile becomes necessary at such locations, where the actual column load (P_c) exceeds the critical load (P_{crit}).

(iii) Detailed Design Stage: After establishing the feasibility of piled rafts through initial assessment, the third stage requires a more detailed analysis, preferably through some complex computer program. The analysis involves calculations of BM , SF and settlement values for the foundation design. The important issues in the piled-raft design are the relative load capacities of rafts and piles and their effect on the total and differential settlements. These issues can be addressed by understanding the individual responses of raft and pile groups, along with the interactions between them.

1.4 Exploration of the Research Goals

Despite being the fifth largest economy with the largest population, India has a limited number of high-rise structures, mainly restricted to metropolitan cities. Even within these cities, the height of these structures is comparatively low compared to other countries. This is primarily due to strict regulations on floor area ratios imposed by authorities. One cause of the hesitancy is inadequate research on the suitable foundation for such structures in Indian conditions. Hence, it is necessary to explore the suitability of different foundation types and update the building code accordingly. In recent years, piled-raft foundations have gained attention from designers and researchers as an effective foundation solution for high-rise structures.

Prior to designing any such structure, it is important to consider local expertise and conduct a thorough soil investigation. It is recommended to perform model tests under controlled conditions to understand the behaviour before proceeding with

expensive field investigations. The main objective of this research is to investigate the interaction factors that reflect the complex interaction mechanism among the elements of piled-raft foundations. To achieve this objective, the current research involves determining the index properties of locally available soil. Subsequently, several small-scale model tests have been conducted on local soils to analyse the load-sharing behaviour of model piled-rafts under vertical loading.

However, conducting experimental studies for multiple parameters within the given time constraints is not feasible. Therefore, computational techniques can be utilized once they are validated. The use of such techniques requires a realistic simulation of the piled raft and its associated interactions. Proper justification should be provided for the selection of material properties and constitutive laws. In this research, the ABAQUS code has been employed to analyse the behaviour of different types of foundations. The results obtained have been used to present significant data that can be beneficial to design engineers. The recommendations provided aim to encourage researchers to explore other aspects of piled-raft behaviour and further enhance its applicability in various fields.

1.5 Organisation of the Thesis

The present thesis comprises the following chapters. Chapter 1 provides an introduction to the entire thesis, highlighting the significance of piled-raft foundations as an efficient and rational foundation system. This chapter also offers a comprehensive assessment of the available literature, aiming to enhance understanding of piled-raft behaviour. It covers the background of piled-raft foundations, their classification, and various other aspects for in-depth study

Following the introductory chapter, Chapter 2 explores different design approaches proposed for the analysis of piled-raft foundations, including analytical, numerical, and experimental methods. It also incorporates case histories, recent developments, and potential future research areas.

Chapter 3 focuses on the development of numerical codes capable of simulating complex non-linear problems. A three-dimensional numerical model of piled-raft foundations is discussed in detail. The chapter outlines the different modules and features of the ABAQUS software used for the analysis. A numerical model of the piled raft was validated from the literature. Thereafter, analysis of one-quarter of the 3D piled-raft model was conducted using the finite element-based program, ABAQUS. After verifying a model from the literature, an extensive parametric analysis of that model was performed to assess the response of the foundation.

In Chapter 4, a small-scale experimental study on model piled-raft foundations is presented. The index properties of the soils used were determined following the standard codes. The chapter provides a detailed discussion of the experimental procedure, including test models and soil characteristics. Load-settlement curves were analysed to assess the bearing capacities of rafts, piles, and piled-rafts, and parametric studies were conducted for piled-rafts supported over sand and clay. Additionally, the load-sharing between the raft and piles was investigated to understand the contribution of the raft in piled-rafts. The results were cross-verified against existing literature to ensure consistency.

Chapter 5 focuses on the development of analytical models for the complex behaviour of piled-raft foundations. It is acknowledged that the existing analytical methods have not completely captured the intricate behaviour of pile-raft foundations. Consequently, this chapter presents an analytical model that specifically addresses interaction factors. To develop the analytical model for maximum settlement, multiple regression analysis is conducted using data analysis software, Origin. The results of the analysis are used to formulate the analytical model, which is discussed in detail in this chapter.

Chapter 6 functions as the concluding chapter of the thesis, covering significant discussions, providing valuable recommendations, and identifying potential avenues for future research. It offers a comprehensive summary and analysis of the findings obtained throughout the study.