ORIGINAL RESEARCH

# Estimation of Equivalent Stiffness of Pile Groups in Piled Raft Foundations Using Numerical Methods and Introduction of a Transfer Approach to Structural Modeling in SAFE

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**Abstract:**

In the design of piled raft foundations, accurate analysis of the soil–pile–raft interaction is of particular importance, as the combined system utilizes the bearing capacity of both the raft and the piles, resulting in behavior different from isolated foundations. The main objective of this study is to develop a practical methodology for extracting the equivalent stiffness of pile groups using 3D numerical modeling and to implement these values in structural analysis software like SAFE, addressing a critical gap in conventional design approaches. While advanced geotechnical software such as PLAXIS 3D can simulate the nonlinear behavior of soil and the complex interaction between foundation components, structural software like SAFE typically lacks such capabilities and instead uses simplified spring elements to model soil behavior. The novelty of this research lies in integrating detailed numerical simulation results with practical structural modeling, enabling engineers to capture realistic soil–foundation interactions without conducting full-scale geotechnical experiments. In this study, the behavior of pile groups under static loading was analyzed in PLAXIS 3D considering different soil types and pile configurations, and equivalent stiffness values were derived. The proposed method was applied to a SAFE model, resulting in a 12–18% difference in predicted settlement compared to traditional simplified approaches, demonstrating both the accuracy and practical relevance of the method. These findings provide structural engineers with a reliable tool for incorporating precise stiffness data into foundation models, supporting safer and more economical designs.

**Keywords:**
Equivalent stiffness, Piled Raft Foundation, Numerical analysis, PLAXIS 3D, Structural modeling, SAFE software, Settlement, Soil–structure interaction.

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## 1.Introduction

With the rapid expansion of large-scale civil engineering and infrastructure projects in regions with weak or problematic soils, the use of piled raft foundations (PRFs) has emerged as one of the most practical and efficient foundation solutions [1]. PRFs combine the advantages of both raft and pile foundations by allowing part of the structural load to be distributed through the raft directly to the shallow soil, while the remainder is carried by piles to deeper, more competent layers. This load-sharing mechanism has been proven to significantly reduce total and differential settlement, increase overall bearing capacity, and in many cases, lower construction costs compared to conventional pile-only or raft-only systems [2].

In regions such as Kerman province in Iran, where fine-grained, low-strength silty-clayey soils dominate, these benefits are particularly valuable. In such ground conditions, conventional raft foundations alone often lead to excessive settlement and serviceability problems, while pile-only foundations are technically reliable but not cost-effective. By contrast, PRFs provide a balanced solution that optimizes both performance and cost-efficiency [3].

Early Developments and Limitations

The initial research on PRFs primarily relied on simplified analytical and empirical models to capture the soil–pile–raft interaction. Earlier contributions introduced concepts for estimating pile stiffness, interaction factors, and load-sharing ratios [4]. Although these methods were useful for preliminary design, they incorporated strong simplifications such as homogeneous soil profiles, linear elastic material assumptions, and neglect of three-dimensional group effects. Consequently, their predictive accuracy was limited when applied to complex soil conditions or large-scale structures.

Subsequent studies in the late 2000s and 2010s increasingly adopted finite element and boundary element methods to better represent the nonlinear, three-dimensional behavior of PRFs [5]. These studies showed that pile arrangement, pile length-to-diameter ratio, raft thickness, and stiffness ratios between raft and piles exert major influence on settlement distribution and bending moments in the raft. Despite these advances, a persistent gap remained between geotechnical numerical analysis (using tools such as PLAXIS 3D, ABAQUS, or FLAC3D) and structural analysis software commonly used in design practice (such as SAFE). Engineers in practice still struggle to transfer realistic stiffness and settlement parameters into simplified design models [6].

In structural software such as SAFE, the soil–foundation interaction is typically represented using discrete equivalent springs (Winkler foundation approach) assigned at multiple nodes. The accuracy of this representation depends entirely on how well the equivalent stiffness of the pile–soil–raft system is determined. In reality, however, PRF behavior is governed by a highly nonlinear, complex interaction influenced by soil stratification, stress-dependent soil properties, pile geometry, pile spacing, pile–pile group interaction, and raft flexibility [7].

Simplified spring models often neglect critical aspects such as:

- Group interaction between piles,
- Stress redistribution in heterogeneous soils,
- Raft bending and flexibility effects,
- Nonlinear soil constitutive behavior, and
- Dynamic or seismic load effects.

As a result, there is a significant mismatch between advanced geotechnical analyses and simplified structural modeling approaches, leading to uncertainties in predicting settlement and load transfer. These uncertainties may result in unsafe or overly conservative designs [8].

Over the last decade, particularly between 2018 and 2025, substantial research efforts have been devoted to addressing these shortcomings and improving the accuracy of

PRF analysis. Three main directions have been evident in the literature:

1. Advanced numerical modeling: Recent studies have utilized PLAXIS 3D, ABAQUS, and FLAC3D to simulate nonlinear soil–pile–raft interactions under static and dynamic loading [9]. Researchers have highlighted the importance of capturing soil nonlinearity, stress dependency, and three-dimensional effects. For example, advanced FEM studies showed that pile arrangement and stiffness ratio strongly influence settlement reduction efficiency and raft bending response [10].
2. Experimental investigations: Large-scale laboratory and centrifuge tests have been conducted to validate numerical predictions. These experiments confirmed that connecting pile heads rigidly to the raft significantly reduces differential settlement and improves performance under lateral or seismic loading [11]. Physical model studies also provided insights into the time-dependent and long-term performance of PRFs in clayey soils [12].
3. Dynamic and seismic performance: Since 2020, several works have emphasized seismic response analysis of PRFs, particularly in earthquake-prone regions. Studies showed that 3D nonlinear models are essential for accurately predicting system performance under seismic shaking, soil liquefaction, or lateral loading conditions [13]. Simplified 2D models were found to underestimate critical interaction mechanisms, leading to potentially unsafe design recommendations [14].

These contributions underline that while the state-of-the-art geotechnical modeling of PRFs has advanced significantly, the integration of such detailed outputs into practical design tools still remains underdeveloped [15].

Despite extensive progress, the following key challenges remain:

1. Absence of systematic frameworks for transferring geotechnical analysis outputs (e.g., stiffness matrices from PLAXIS 3D) into structural design environments such as SAFE.
2. Continued reliance on empirical or code-based stiffness values in practice, which are often oversimplified and fail to reflect the real soil–pile–raft behavior.
3. Insufficient bridging between 3D geotechnical analysis and simplified spring-based models, particularly for large-scale structures in weak soil regions.

As a result, practicing engineers frequently face a trade-off between advanced but computationally expensive geotechnical modeling and simplified but potentially inaccurate structural modeling [16].

To address these gaps, this study proposes a robust and practical framework for integrating advanced geotechnical outputs into structural modeling. The specific objectives are:

1. To conduct three-dimensional numerical simulations of PRFs under various soil conditions, pile configurations, and load cases using PLAXIS 3D [17].
2. To derive equivalent vertical stiffness values from load–settlement relationships and evaluate the impact of soil type, pile geometry, raft stiffness, and pile arrangement [18].
3. To develop a systematic methodology for converting geotechnical outputs into equivalent spring models compatible with SAFE, ensuring mechanical and numerical consistency [19].
4. To compare the accuracy and stability of the proposed method against traditional approaches (e.g., uniform stiffness assumption, code-based values) [20].

The novelty of this research can be summarized as follows:

- Bridging the gap between advanced geotechnical modeling and practical structural design tools, by introducing a structured framework for stiffness transfer.
- Providing a systematic methodology to convert 3D geotechnical outputs into simplified spring models while retaining essential soil–pile–raft interaction features.
- Enhancing prediction accuracy of settlement and load distribution compared with conventional uniform stiffness or empirical methods.
- Delivering a practical design tool suitable for large-scale projects in weak soils, with direct application to industrial foundations, high-rise buildings, and power plants in regions such as Kerman.
- Extending the applicability of the framework to both static and seismic loading conditions.

Through these contributions, this research not only advances the scientific understanding of PRF behavior but also provides a practical and implementable solution for engineers, enabling safer and more economical foundation designs in challenging ground conditions.

## 2.Geometrical and Mechanical Properties

The geometrical and mechanical parameters considered in this study are selected to accurately simulate the behavior of piled raft foundations (PRF) and the soil–pile–raft interaction. These parameters include pile characteristics, raft geometry, and soil properties, as detailed below:

### 2.1. Pile Length:

Pile lengths ranging from 10 to 20 meters were considered to investigate the influence of pile penetration in different soil layers. Longer piles transfer more load to deeper, stiffer layers, reducing overall settlement, while shorter piles transfer part of the load to shallower, softer layers, resulting in higher settlements.

### 2.2. Pile Diameter:

Pile diameters vary from 0.6 to 1 meter. Larger diameters increase the axial stiffness of piles and improve load distribution within the pile group, although they also raise construction costs.

### 2.3. Pile Arrangement:

Two main pile arrangements were examined: square and radial configurations, with spacings ranging from 2 to 4 meters. Arrangement and spacing significantly influence group effects and load transfer to the raft. Smaller spacings enhance pile–pile interaction and group stiffness, whereas larger spacings provide a more uniform load distribution.

### 2.4. Soil Elastic Modulus:

Soil elastic modulus was considered between 15 and 60 MPa to study the effect of soil stiffness on system behavior. Softer soils (lower modulus) lead to increased settlements, whereas stiffer soils enhance system stiffness and bearing capacity.
5. Soil Friction Angle and Cohesion:
The internal friction angle ranges from 25° to 35° and cohesion from 5 to 25 kPa. These parameters control soil shear strength and lateral resistance of piles. Higher friction angles and cohesion improve lateral resistance and help control raft settlements.

### 2.5. Modeling of Soil and Piles:

Soil: Modeled using the Mohr–Coulomb constitutive model to account for elastic and plastic behavior, including shear failure.

Piles: Assumed to behave linearly elastic to allow controlled and simplified load transfer analysis.

### 2.6. Boundary Conditions and Numerical Control:

Boundary conditions were carefully defined to prevent wave reflections and ensure that results were free from numerical artifacts. This ensures accurate and reliable predictions of settlements and stress distribution.

### 2.7.Effect of Parameters on PRF Performance:

Increasing pile length and diameter enhances bearing capacity and reduces settlements.
Pile arrangement and spacing affect group effects and load distribution.
Soil stiffness and strength dominate overall system behavior, particularly in soft or loose soils.
Proper pile–raft interaction and accurate mechanical properties are crucial for long-term performance.
Together, these geometrical and mechanical parameters provide a realistic simulation of the PRF system and form the basis for deriving equivalent pile stiffness for structural modeling in software like SAFE.

## 3. Loading and Analysis

A static loading condition was applied in the form of a concentrated vertical force at the center of the raft slab. The analysis was carried out until the system reached stabilized settlement. The system's response was evaluated in terms of vertical displacement (settlement) and axial forces within the piles.

### 3.1. Loading Protocol

The loading protocol for the piled raft foundation models was defined to simulate realistic service conditions. The protocol includes:

- **Type of load:** Vertical, lateral, or combined loads applied incrementally.
- **Load steps:** Gradual increase in load in several stages to capture nonlinear soil response.
- **Load duration:** Each stage maintained until settlement stabilization is observed.
- **Load application points:** Distributed across the raft or concentrated at pile locations depending on design scenario.
- **Monitoring:** Settlement, bending moments, and load-sharing between raft and piles recorded at each stage.

This protocol ensures accurate representation of structural behavior under service loads and facilitates extraction of equivalent stiffness values for structural analysis.

### 3.2. Sensitivity Analysis of Soil and Pile Parameters in Piled Raft Foundation Systems.

In the design of piled raft foundations, a precise understanding of the influence of soil parameters and pile characteristics on system behavior is of paramount importance. In this study, PLAXIS 3D FOUNDATION software was employed to perform a comprehensive sensitivity analysis, assessing the effects of key parameters on settlement, load distribution, and the equivalent stiffness of the pile group. The parameters investigated included the elastic modulus and Poisson’s ratio of clay and sand layers, pile dimensions and length, pile quantity and arrangement, groundwater table depth, and the type of loading applied to the raft.
The sensitivity analysis was conducted in a stepwise manner. Initially, variations in the elastic modulus of soil layers were applied within defined ranges, and their effects on overall system settlement and stress distribution at the raft level were evaluated.

Results indicated that increasing the elastic modulus of clay and sand significantly reduced settlement while enhancing system stiffness. Moreover, the load distribution on the piles and raft became more uniform with higher soil stiffness, reducing stress concentrations at critical points.
Subsequently, the effects of pile dimensions and arrangement were examined. Pile length directly influenced the load transfer from the raft to underlying layers; longer piles absorbed a greater portion of the applied load, resulting in reduced overall settlement. Additionally, increasing pile spacing and optimizing their arrangement demonstrated that uniform distribution of piles enhances the equivalent stiffness of the group, improving the foundation system's performance. The impact of pile diameter was also investigated; although increasing the diameter slightly enhanced axial capacity and reduced settlement, its effect was less significant compared to pile length and arrangement.
Furthermore, variations in groundwater table depth affected the behavior of the piled raft system. A shallower groundwater table reduced soil bearing capacity and increased settlement, whereas a deeper water table provided more stable conditions and higher system stiffness. Sensitivity results indicated that soil modulus and pile arrangement were the most influential factors on settlement and equivalent stiffness, while changes in pile diameter and loading type had relatively minor effects.
Based on these findings, the equivalent stiffness of the pile group was extracted and transferred to the structural model in SAFE. This approach enables more accurate modeling of piled raft behavior, reduces design risks, and provides optimized technical and economic solutions. The sensitivity analysis also allows designers to identify critical system parameters and manage variations in soil and pile characteristics to achieve optimal foundation performance under realistic loading conditions.
In conclusion, conducting a sensitivity analysis not only improves understanding of the piled raft system's behavior but also serves as an effective tool for enhancing design efficiency, reducing costs, and increasing structural safety against undesirable settlements and deformations.

### 3.3. Methods for Calculating the Equivalent Stiffness of Pile Groups

To determine the equivalent vertical stiffness of the pile groups, four different methods were employed:

**Method 1: Slope of the Initial Linear Portion of the Load–Displacement Curve**

In this method, the slope of the linear elastic region of the load–displacement curve obtained from the numerical output is considered as the equivalent stiffness:

$$K = \Delta P / \Delta \delta \qquad (1)$$

K = Equivalent stiffness (typically in kN/m)
ΔP = Change in load
Δδ= Corresponding change in displacement within the initial elastic range

**Method 2: Based on Allowable Design Settlement**

In this approach, a design settlement limit (e.g., 50 mm) is assumed. The corresponding load at this settlement is extracted from the load–displacement curve, and the stiffness is calculated as:

$$K = P_{allowable} / \delta_{allowabl} \qquad (2)$$

**Method 3: 40% of Ultimate Load**

Inspired by reinforced concrete design principles, 40% of the ultimate load applied in the numerical analysis is considered. The corresponding settlement from the load–displacement curve is used to compute the stiffness:

$$K = 0.4P_{MAX} / (\delta(.4P_{MAX})) \qquad (3)$$

**Method 4: Average of the Three Previous Methods**

To enhance accuracy and consistency, the final equivalent stiffness was selected as the average of the stiffness values obtained from the three preceding methods.

Transfer of Stiffness to SAFE Software

To implement the results into the structural model, the equivalent stiffness of each pile group was defined in SAFE as vertical springs with specific stiffness values. The spring locations were arranged according to the pile layout used in the numerical model. The global response of the system—including settlement and stress distribution—was then analyzed in the SAFE environment.

To account for variations in pile behavior based on position, the stiffness values were assigned separately for central, edge, and corner piles, reflecting the unique role and loading conditions of each.

This method enables accurate modeling of piled raft foundation behavior within structural analysis software, combining high precision with practical implementation.

## 4. Investigated Model in the Study

In this study, numerical modeling of the piled raft foundation system was carried out using PLAXIS 3D Foundation software. The finite element model was developed in three dimensions and includes piles, the raft, and the surrounding soil medium. To realistically simulate the soil behavior, the Hardening Soil constitutive model was employed, which provides superior capability in representing stress-dependent behavior, strain hardening, and the nonlinear response of clayey soils. An illustration of the modeled system within the software environment is shown in Figure 1.

The 3D model consists of a concrete raft with dimensions of 10 × 10 meters and a variable thickness ranging from 0.5 to 2 meters. The pile group comprises 9 piles with diameters varying from 0.6 to 1.2 meters and lengths of 6, 10, 14, and 18 meters, arranged in a square configuration. The center-to-center spacing of the piles was varied relatively from 2D to 6D to investigate the effect of pile spacing on settlement. The initial input parameters for the software were entered according to Table 1.

### 4.1. Finite Element Types in PLAXIS 3D Foundation

The table below presents the type and geometry of elements used in PLAXIS 3D Foundation for this study:

**Proposed Loading Protocol for Sensitivity Analysis of Piled Raft Foundation**

1. **Loading Type:**

- A quasi-static incremental loading is applied to accurately capture the effect of variations in soil properties and pile stiffness on the system response.

2. **Loading Steps:**

- The total design load on the raft and piles is divided into five equal stages.
- Each stage is applied as a linear increment from the previous stage.

**3. Load Magnitude and Increment:**

If the total design load is P_total, each stage corresponds to one-fifth of P_total. In the sensitivity analysis, soil parameters (E, φ, γ) and pile stiffness are varied by ±20%, while applying the same loading protocol for each scenario to enable direct comparison

**4.Stabilization and Iteration:**

- After each load stage, the model is maintained until settlements and stress distributions converge.
- This ensures that each stage independently reflects the effect of parameter variations.

### 5. Result Recording:

At the end of each stage, raft settlement, pile axial forces, and pile shear distribution are recorded.

- These results are used to plot sensitivity curves against changes in soil and pile parameters.

### 6. Rationale for the Protocol:

- Incremental loading better simulates nonlinear behavior of the soil-pile system.
- Stage-wise stabilization guarantees that sensitivity results are consistent and reliable.
- This protocol follows standard practices widely adopted in international studies on Piled Raft Foundations.

**Table 1. Types of Finite Elements in PLAXIS 3D Foundation**

| Element Type | Geometrical Shape | Description Features | Application and Advantage |
|---|---|---|---|
| **Soil Element** | Tetrahedral | 10-node second-order tetrahedral | Accurate 3D modeling of soil behavior in complex geometries |
| **Plate Element** | Triangular or Quadrilateral | 6-node shell or plate element | Modeling raft thickness and flexural stiffness |
| **Beam Element** | Rod (2-node or multi-node) | 3D beam element | Modeling bending and shear behavior of piles |
| **Interface Element** | Thin between surfaces | Interface with shear/friction properties | Simulating slip or adhesion between soil and structure |

## 4.2. Geometric Characteristics of the Model

The model consists of a concrete raft with defined dimensions and a set of piles arranged in a square configuration. To investigate the influence of geometric parameters, a parametric variation was applied to the pile diameter (0.6 to 1.2 meters), pile length (6 to 18 meters), pile spacing (2D to 6D), and raft thickness (0.5 to 2 meters).

Initially, a single pile and then a combined piled raft foundation system were modeled on the Kerman clayey soil, using laboratory-based geotechnical properties as reported in [17]. The range of these properties is presented in Table 1, with the listed values representing the average used in the analysis. For the overall design, the geotechnical properties of Kerman soil were input into the PLAXIS 3D Foundation software [23]. The settlement behavior of the pile was then compared under two different modeling conditions.

**Table 2. Soil Parameters of Kerman City**

| Parameter | Symbol | Value | Unit | Description |
|---|---|---|---|---|
| **Moist unit weight** | $\gamma$ | 18 | kN/m³ | Saturated Kerman clay |
| **Initial elastic modulus** | $E_{50}$ | 18,000 | kN/m² | From reliable geotechnical sources |
| **Unloading/reloading modulus** | $E_{ur}$ | 54,000 | kN/m² | $3\times E_{50}$ (PLAXIS default) |
| **Oedometer modulus** | $E^{oed}$ | 15,000 | kN/m² | Medium-stiff clay |
| **Internal friction angle** | $\varphi$ | 22 | ° | Based on regional data |
| **Cohesion** | c | 28 | kN/m² | Local data |
| **Poisson's ratio** | $\nu$ | 0.33 | — | Typical assumption for clay |
| **Initial shear modulus** | $G_0$ | 6,923 | kN/m² | Calculated from E and ν |
| **Initial horizontal stress ratio** | $K_0$ | 0.6 | — | Common assumption for natural clay |
| **Constitutive model** | — | Hardening Soil | — | Advanced nonlinear soil model |

## 4.3.Soil Constitutive Model

In this study, the Hardening Soil model was adopted under the assumption of undrained behavior. The parameters required for this model include the initial elastic modulus ($E_{50}$), unloading/reloading modulus ($E_{ur}$), internal friction angle ($\varphi$), cohesion (c), Poisson's ratio ($\nu$), and the initial shear modulus ($G_0$). These parameters were derived from experimental data and reliable geotechnical references for clayey soils in

Kerman.Table 1 presents the values used in the numerical analyses.

### 4.4. Boundary Conditions and Loading

The soil domain was modeled as a block with sufficient dimensions around the foundation to eliminate boundary effects; the minimum distance from the boundaries was set to five times the raft diameter. The lateral boundaries were constrained in the horizontal direction, and the bottom boundary was fixed in all directions. The mesh generation was performed automatically, with "Very Fine" mesh refinement applied around the piles and the raft-soil interface.

The lateral sides of the model were assigned horizontally constrained boundary conditions, and the bottom of the model was fully fixed in all directions. Loading was applied as a uniformly distributed vertical load on the raft surface, with the magnitude determined based on the design capacity.

The vertical load was applied centrally and uniformly over the raft. In different analyses, the magnitude of the load was varied from 2000 to 4000 kN to evaluate the system's behavior under both light and heavy loading conditions. Staged construction analysis was used to gradually apply the load, and the load was incrementally applied to the piles in accordance with PLAXIS 3D capabilities.

For the single pile, the same loading conditions and Kerman soil properties were considered, with varying pile lengths and diameters.

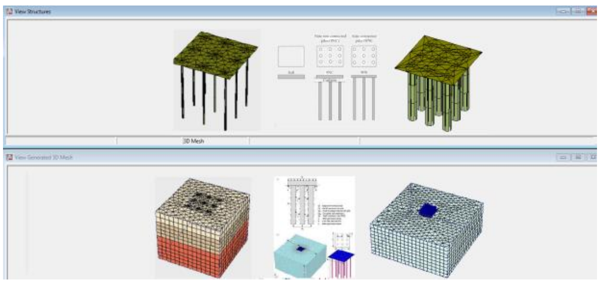

**Figure 1. 3D Model Considered in PLAXIS 3D Foundation Software**

Furthermore, for the combined foundation system, the software outputs are presented based on settlement–load diagrams, illustrating how the applied load influences settlement behavior. Subsequently, the influence of various pile parameters, including length, diameter, cross-section, number, and spacing, as well as different soil parameters, such as elastic modulus, cohesion, and grain size distribution, and also the raft thickness, are investigated with respect to their effects on settlement behavior in Kerman clay. The results are demonstrated using a series of graphs and diagrams.

It is noteworthy that, based on boundary effect considerations, the horizontal boundary of the soil domain was set to a distance of at least four times the size and length of the raft, and the vertical boundary (depth) was considered to be at least 30 meters. These boundary conditions were strictly maintained in all numerical simulations.

### 4.5. Soil and Material Behavior Model

For the clayey soil of Kerman, the Hardening Soil model was employed, which is capable of capturing stress–strain behavior dependent on the loading path and strain hardening effects. The required input parameters include $E_{50}$, $E_{ur}$, internal friction angle ($\varphi$), cohesion ($c$), Poisson's ratio ($\nu$), and initial shear modulus ($G_0$), all of which have been previously presented in Table 2.

The raft and piles were modeled as rigid concrete elements with an elastic modulus of 25 GPa. The interaction between pile–soil and raft–soil was defined using interface elements characterized by frictional contact behavior.

### 4.6. Numerical Modeling in PLAXIS 3D

In this study, the numerical analysis of the composite piled raft foundation system was conducted using the finite element software PLAXIS 3D Foundation. The objective of this modeling is to investigate the influence of geotechnical and geometrical parameters on settlement behavior, stress distribution, and the load-sharing contribution of the foundation components in clayey soil.

### 4.7. Validation of the Numerical Model

To evaluate the accuracy of the numerical model, the settlement results of a reference base model were compared with the results reported in the published study by Sinha and Hanna (2017) [2]. The similarity in overall behavior, settlement values, and stress distribution trends confirms that the PLAXIS-based modeling is sufficiently accurate and reliable for parametric analyses.

## 5. Numerical Analysis Results

This section presents the results of the numerical simulations performed in PLAXIS 3D, and analyzes the impact of various parameters on the behavior of the piled raft foundation system. The primary focus is on evaluating total settlement, differential settlement, stress distribution, and the load-sharing ratio between the raft and the piles under different conditions.

The numerical results, obtained from PLAXIS 3D outputs, include settlement at various points, stress distribution patterns, load-sharing diagrams for piles, and stress–strain behavior of the surrounding soil.

### Design Method

The total design load (P_total) is determined based on the combination of dead, live, and service loads according to relevant design codes. To ensure gradual settlement and stability of the piled raft system, the total load is applied in five equal stages, with each stage corresponding to one-fifth of P_total. In each stage, the load is increased incrementally and held until the system reaches equilibrium before proceeding to the next stage. This staged loading protocol is applied consistently across all sensitivity analysis scenarios, where soil parameters (E, φ, γ) and pile stiffness are varied by ±20%, allowing for direct comparison of the system response under different conditions.

### 5.1. Effect of Pile Length

With an increase in pile length from 6 meters to 18 meters, a significant reduction in total foundation settlement was observed. The most substantial decrease occurred in the range from 6 to 10 meters. Beyond this range, the rate of settlement reduction decreased, gradually approaching a saturation point, indicating a diminishing efficiency in increasing pile length further.

Increasing the pile length led to a rise in the vertical equivalent stiffness of the pile group, as both shaft resistance and end-bearing capacity increased, resulting in greater load participation by the piles.

### 5.2. Effect of Pile Spacing

Increasing the spacing between piles led to a decrease in pile density beneath the raft, which resulted in an increase in total foundation settlement. In the configuration with a spacing-to-diameter ratio (S/D) = 2, the settlement was more controlled, and the load-sharing contribution of the piles was higher.

In contrast, in the case of S/D = 6, a significant portion of the load was carried by the raft, and the piles played a minor role. This reduction in pile participation led to a decrease in the overall stiffness of the foundation system.

### 5.3. Differential Settlement Analysis

The analysis results indicated that the settlement at the center of the raft was greater than at the corners. In models with longer piles and denser arrangements, the settlement difference between various points was smaller. This suggests that the system performed well in controlling differential settlement and enhancing uniform stiffness across the foundation plan.

A well-distributed pile layout with uniform stiffness significantly contributed to reducing localized settlements.

### 5.4. Load-Sharing Between System Components

The load carried by the piles and the raft was calculated separately. In models with higher soil cohesion and shorter piles, a larger portion of the load was transferred through the raft. In contrast, with increased pile length and diameter, a greater percentage of the load was carried by the piles.

In the optimal case, approximately 65% of the load was supported by the piles, and 35% by the raft. Increasing the piles' load-sharing portion led to a significant increase in the vertical stiffness of the composite foundation system.

### 5.5. Effect of Cohesion and Friction Angle

An increase in soil cohesion from 10 to 30 kN/m² led to a reduction in total settlement. Similarly, the friction angle had a considerable effect on settlement reduction, especially in models with low cohesion.

Enhancing both parameters improved the shear strength of the soil and increased the lateral resistance capacity of the piles, ultimately resulting in an increase in the equivalent stiffness of the pile group in the numerical model.

## 6.Single Pile without Raft

In this section, various analyses were performed on a single pile model using PLAXIS 3D in Kerman clay, with different pile lengths and diameters. The remaining parameters and geometry were kept consistent with the previous sections.
As shown in Figure 2, which illustrates the load–displacement curve extracted from the PLAXIS 3D software, it is observed that increasing pile length and diameter leads to a decrease in settlement. The analysis was conducted for piles with lengths of 6, 8, 10, 12, 15, 18, 20, 25, and 30 meters, and for pile diameters of 1.0, 1.2, and 2.0 meters.

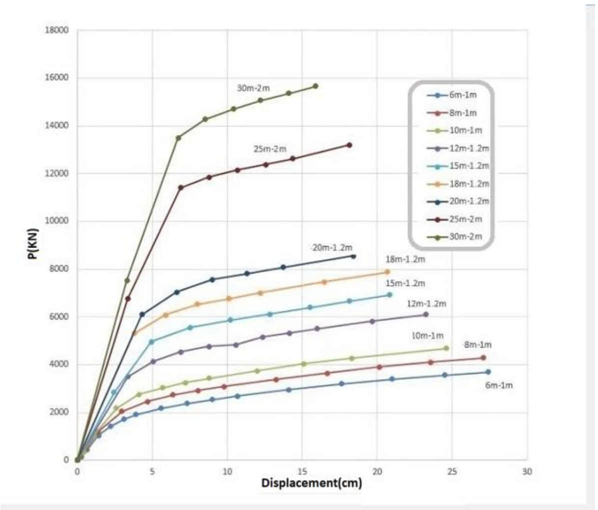


**Figure 2. Settlement in Single Pile for Various Lengths and Diameters**

## 7.Combined Piled Raft Foundation System

In this section, the settlement of a combined piled raft foundation system was analyzed using PLAXIS 3D for various length-to-diameter ratios of piles. The results indicate that as the L/D ratio decreases, the central settlement of the system increases.
The study also revealed that soil stiffness plays a critical role in controlling settlement. In conditions with low soil stiffness (such as the soft clayey soils of Kerman), a reduction in effective pile length has a more pronounced impact on increasing settlement. Therefore, in such analyses, it is crucial to consider the actual stiffness of the soil for achieving accurate results. The L/D ratios examined in this section were 6, 8, 10, 12, and 15, as shown in Figure 3.The soil properties used were the same average values defined in the previous sections.

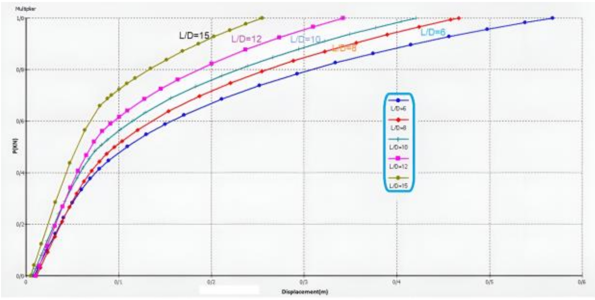


**Figure 3: Settlement at the Center of the Piled Raft Foundation for Soils with Different Length-to-Diameter Ratios**

## 8. Comparison of Single Pile vs. Piled Raft Systems

By comparing the single pile without raft system and the combined piled raft system (as discussed in Sections 3 and 4), it was observed that in the single pile model, not only does the load–displacement curve behave differently, but the settlement also exceeds the allowable limits, and the system can only resist a small portion of the applied load.Additionally, in single pile analysis, group effects are not considered, and it is evident that the overall stiffness is lower than that of the piled raft system in all configurations. As illustrated in Figure 4, the load–displacement curves for L/D ratios of 8 and 10 are presented for both cases: P (single pile) and PRF (piled raft foundation), as obtained from PLAXIS 3D.

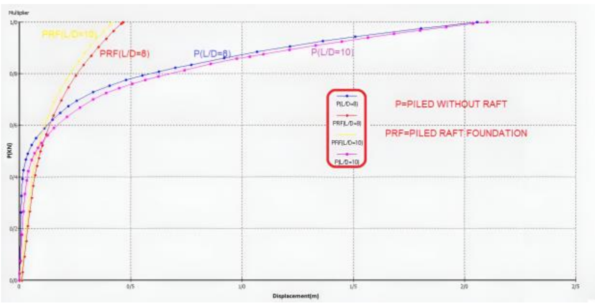


**Figure 4: Central Settlement of Piled Raft Foundation and Single Pile without Raft for Soils with Different Length-to-Diameter Ratios**

## 9. Effect of Soil Cohesion (c) in Combined Model

In this section, multiple numerical analyses were conducted using PLAXIS 3D on piled raft foundations in soils with varying cohesion values (c) of 20, 30, 40, and 50 kN/m². All other parameters and geometry were kept consistent with the previous sections.

According to Figure 5, which illustrates the displacement–load curve, it was found that increasing cohesion up to 40 kN/m² significantly reduced the central settlement of the combined foundation system. However, beyond that point, the rate of settlement reduction slowed down.

Since cohesion is a key factor influencing overall soil stiffness, it can be concluded that an increase in soil stiffness due to higher cohesion leads to further reductions in deformation and settlement. Therefore, there exists a direct relationship between increasing cohesion (and thus soil stiffness) and decreasing foundation settlement.

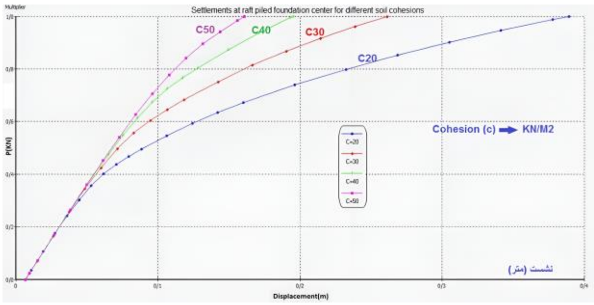


**Figure 5: Central Settlement of Piled Raft Foundation for Soils with Different Cohesion Values**

## 10. Effect of Soil Internal Friction Angle (φ)

This section presents a numerical analysis of the piled raft system using PLAXIS 3D on soils with different internal friction angles (φ): 10°, 15°, 20°, and 25°. Other parameters and geometrical features of the model remained unchanged, in line with the previous sections.

Based on Figure 6, which shows the load–settlement curve, it was observed that increasing φ up to 20° significantly reduced central settlement of the system. After this point, settlement reduction continued but at a diminished rate.

As the internal friction angle is one of the primary parameters affecting the stiffness of granular soils (e.g., sands), it can be concluded that increasing φ enhances soil stiffness, leading to reduced settlement in piled raft foundations. Thus, a direct correlation exists between increasing friction angle and decreasing structural settlement.

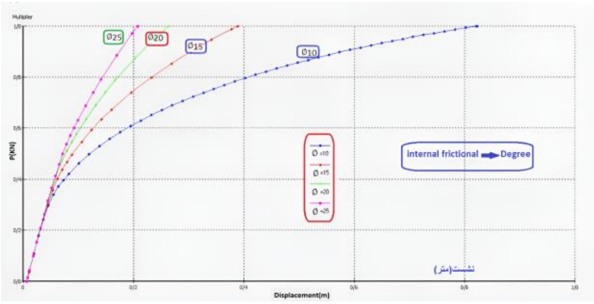


**Figure 6: Central Settlement of Piled Raft Foundation for Soils with Different Internal Friction Angles**

## 11. Effect of Pile Length

In this analysis, piles with lengths of 6, 8, 10, 12, and 15 meters were studied, while the pile spacing was kept constant at 4 times the pile diameter (4d). All other parameters and model geometry remained unchanged, with pile length being the only variable.

As shown in Figure 7, the central settlement of the piled raft system over Kerman clay is presented under incremental loading. The results clearly show that increasing pile length significantly reduces settlement.This behavior is attributed to the increase in vertical and lateral stiffness of the foundation system with longer piles, which penetrate deeper soil layers, thereby enhancing bearing capacity and resistance to settlement. Thus, increasing pile length is recognized as an effective strategy for settlement control in piled raft systems.

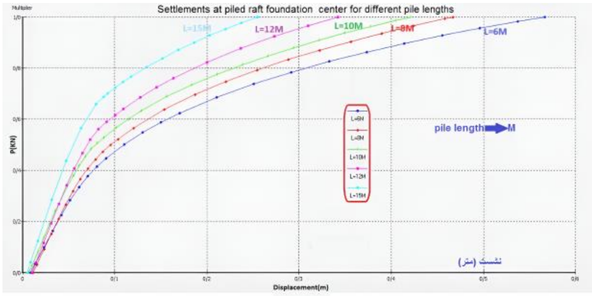


**Figure 7: Central settlement of piled raft foundation for different pile lengths**

## 12. Effect of Pile Cross-Section

In this section, two types of pile cross-sections were compared using PLAXIS 3D. The first type was a circular pile with a diameter of 1 meter (D = 1 m), and the second was a square pile with a 1-meter side length. All other parameters were kept constant as in previous sections.

The pile length was assumed to be 10 meters (L = 10 m) in both cases, and the central settlement of the combined piled raft system was evaluated and compared.

According to the results shown in Figure 8, the type of pile cross-section (circular or square) had no significant impact on the settlement. The system response in terms of settlement was approximately the same for both cases.

This finding indicates that, under similar geometrical and geotechnical conditions, the pile cross-sectional shape does not meaningfully influence the vertical stiffness or overall settlement of the system. Therefore, either shape can be selected based on construction or economic considerations.

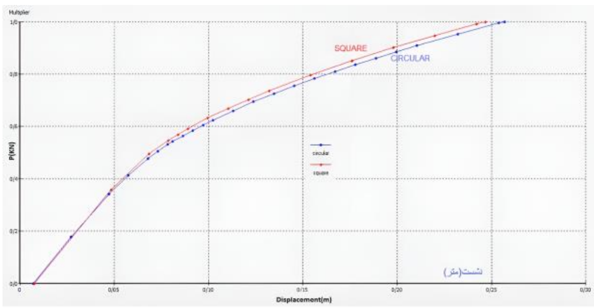


**Figure 8: Central settlement of piled raft foundation for piles with circular and square cross-sections**

## 13. Effect of Pile Diameter

In this section, three different pile diameters were considered: 0.8 m, 1.0 m, and 1.2 m, while the pile length was fixed at 10 meters (L = 10 m), and all other parameters remained consistent with the previous sections.
As shown in Figure 9, which compares the central settlement of the piled raft system under incremental loading using PLAXIS 3D Foundation, it is observed that the greatest settlement occurs for D = 0.8 m, and settlement decreases as the pile diameter increases.
Notably, the rate of settlement reduction is greater when the pile diameter increases from less than 1 meter, and although further increases beyond 1 meter continue to reduce settlement, the rate of reduction becomes more gradual.
Overall, there is a direct relationship between increasing pile diameter and decreasing settlement, although smaller diameters exhibit a steeper reduction curve.

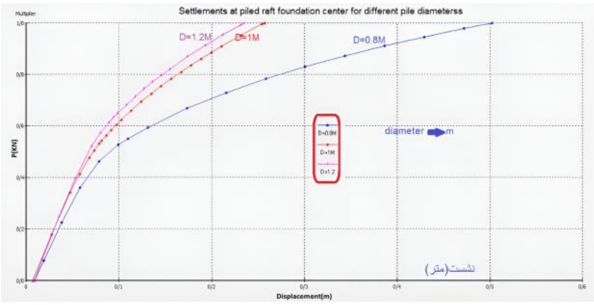


**Figure 9: Central settlement of piled raft foundation for piles with different diameters**

## 14. Effect of Soil Elastic Modulus

In this section, three different values of the soil elastic modulus ($E_{50}$) were considered to investigate its influence on the load–settlement behavior. According to Figure 10, it was observed that increasing the elastic modulus leads to a reduction in the central settlement of the piled raft foundation system.All other model parameters and boundary conditions were kept identical to those used in the previous sections.

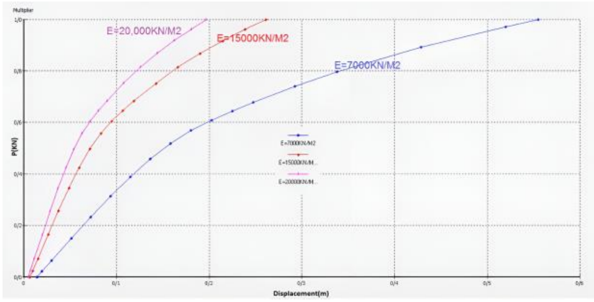


**Figure 10: Central settlement of piled raft foundation for soils with different elastic moduli**

## 15. Effect of Raft Thickness

This section examined a raft foundation with plan dimensions of 10 × 10 meters, and various thicknesses were analyzed, including: no raft, 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m. The soil properties used were based on average Kerman clay data from earlier sections.
According to the load–settlement curves shown in Figure 11, it was found that increasing the raft thickness led to a progressive reduction in settlement, following a consistent trend.

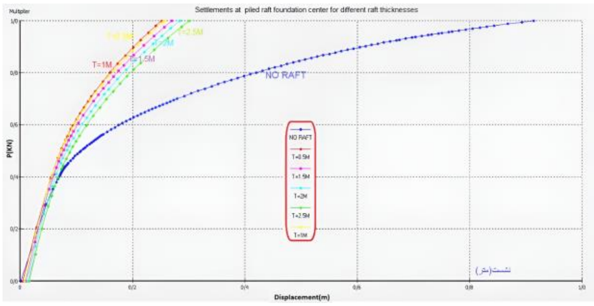


**Figure 11: Central settlement of piled raft foundation for different raft thicknesses and without raft**

## 16. Effect of Pile Spacing

In this section, a 16 × 16-meter raft foundation was analyzed, and the spacing between piles in a 3×3 configuration (9 piles) was varied from 3D to 6D, where D is the pile diameter (assumed to be 1 meter). The pile length was kept at 10 meters, and soil properties were based on Kerman data as before.As seen in Figure 12, increasing the pile spacing resulted in the piles reaching failure at lower loads, thereby reducing the overall system settlement.

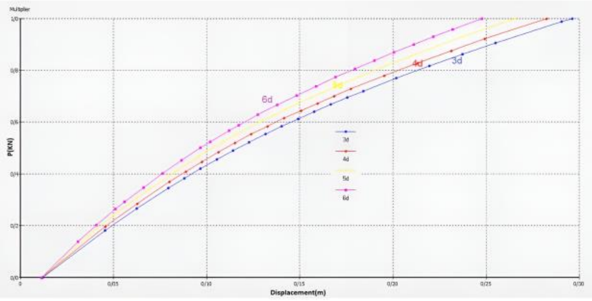


**Figure 12: Central settlement of piled raft foundation for different raft thicknesses and without raft**

## 17. Extraction and Application of Pile Stiffness from Numerical Analysis in PLAXIS 3D

In this study, pile stiffness values were extracted from the load–displacement curves generated by PLAXIS 3D Foundation simulations. These stiffness values serve two key purposes in the design and analysis of combined piled raft foundations:

**1. Implementation in SAFE Software:**

Given PLAXIS's high accuracy in simulating three-dimensional soil–pile interaction, the extracted stiffness values can be directly imported into SAFE. This significantly improves the accuracy of structural foundation design and reduces analytical errors in typical structural software.

**2. Nonlinear Material Analysis:**

The calculated stiffness values can also be used in nonlinear material analysis of the foundation system, offering deeper insight into the realistic behavior of the system under loading.
In this research, various methods within PLAXIS 3D were employed to estimate pile stiffness. The stiffness values were determined for central, edge, and corner piles, labeled as Ce (Center), Cd (Edge), and Co (Corner) respectively.

All piles were considered with a length of 10 meters, and the mechanical properties of the soil were defined based on the average laboratory data for Kerman clay (Table 1).

### 17.1. Three-Point Average Method

One of the common methods to determine the stiffness of piles from load–displacement curves in PLAXIS 3D Foundation is to use the slope of the initial linear portion of the curve, which represents the elastic behavior of the pile.
In this method, three points are selected in the linear region of the graph, ensuring that their displacement values do not exceed the allowable settlement (5 cm). The coordinates of these points are shown in Figure 13.
By moving the cursor over the curve in PLAXIS, the exact coordinates of each point can be obtained. It should be noted that the graph does not start from the origin (zero), since an initial preloading stage is automatically performed by the software. The initial displacement recorded is +0.0006774 m.
To correct for this, the displacement must be adjusted as follows:
If the initial displacement is positive, it should be subtracted from the plotted displacements.
If negative, it should be added to the displacements.
After making this adjustment, pile stiffness (K) is calculated using:

$$F=K/\Delta \tag{4}$$

Where:
K = Pile stiffness (kN/m)
F = Applied load
$\Delta$ = Corrected displacement (m)
The force
F is calculated by multiplying the Mstage-Sum value (from software output) by the 5000 kN load applied in the second phase of analysis.
The stiffness values for the selected points are provided in Table 2.

| point | Displasement (m) | Sum-Mstage |
|---|---|---|
| 1 | 0.0150 | 0.065 |
| 2 | 0.031 | 0.197 |
| 3 | 0.042 | 0.281 |

**Figure 13: Points considered in the average method from the displacement–force curve**

### 17.2. Allowable Settlement Method

In this method, pile stiffness is based on the allowable settlement defined by design codes. For this study, the allowable settlement was 5 cm.

By locating the corresponding load for this settlement on the load–displacement curve generated by PLAXIS 3D Foundation, stiffness can be computed as:

$$F = K/\Delta \quad (5)$$

In the Kerman clay model, when the pile settlement reached 5 cm, the corresponding Mstage-Sum value was 0.335. As the graph does not start from zero, the initial displacement (0.0006774 m) must be subtracted from the total displacement to obtain an accurate Δ.

Multiplying 0.335 × 5000 kN, the force F is obtained, and the stiffness for central (Ce), edge (Ed), and corner (Co) piles is then calculated using the above relation. Final values are shown in Table 2.

### 17.3. 40% of Ultimate Load Method

This method is inspired by concrete design principles, where 40% of the ultimate load is considered to represent elastic behavior.

Using the load–displacement curve from PLAXIS 3D, the point corresponding to 0.4 × Mstage-Sum is identified. In this analysis, the displacement at that point is 0.062 m.

After subtracting the initial displacement (0.006774 m), the corrected displacement is:

$\Delta = 0.062 - 0.006774 = 0.055226 m$

The stiffness is then computed as:

$$F = K/\Delta \quad (6)$$

Where:

F = 40% of the final applied load (kN)

The stiffness values for central, edge, and corner piles are shown in Table 2.

### 17.4. Average of the Three Methods

To obtain a reliable estimate of pile stiffness, an average of the three methods above is calculated:

1.Three-point linear slope method

2.Allowable settlement method

3.40% ultimate load method

This averaging approach helps minimize numerical uncertainties and modeling assumptions, providing a more realistic estimation of pile stiffness.

The final stiffness values for the center (Ce), edge (Ed), and corner (Co) piles, which can be used as input for combined piled raft foundation design, are presented in Table 2.

**Table 3. Approximate Pile Stiffness Using Different Methods (kN/m)**

| Pile Type | Three-Point Average Method (kN/m) | Allowable Settlement Method (kN/m) | 0.4 Ultimate Load Method (kN/m) | Average of Three Methods (kN/m) |
|---|---|---|---|---|
| Central Pile | 4000 | 33082 | 36215 | 39000 |
| Middle Pile | 47000 | 39483 | 36826 | 41000 |
| Corner Pile | 47000 | 39800 | 37469 | 41500 |

## 18. Application of Pile Stiffness in SAFE Software

This section discusses the implementation of the calculated pile stiffness values, obtained from PLAXIS 3D Foundation, in the SAFE software environment. The objective is to apply these stiffness values into the SAFE model to achieve a close agreement between the results of SAFE and PLAXIS 3D [19].

The input parameters in the SAFE model were synchronized with those used in

PLAXIS 3D, including the geotechnical properties of Kerman soil. In this model:
The allowable bearing pressure for Kerman clay was set to 100 kN/m².
The subgrade modulus was assumed to be 12,000 kN/m², which equals 120 times the allowable bearing pressure.
According to the results presented in Table 2, the stiffness values for different pile locations (center, edge, and corner) were extracted using various analytical methods in the combined piled raft foundation system. When these approximate stiffness values were input into SAFE, the resulting average settlement was found to be in good agreement with PLAXIS 3D results, particularly when the stiffness derived from the allowable settlement method was used.
It is important to note that to achieve full agreement between the analysis results of the two software platforms, the pile stiffness values from PLAXIS must be calculated in a manner that ensures matching average stresses and differential settlements in the SAFE model. This calibration approach may serve as a basis for future research aimed at improving the integration of numerical and structural design tools for combined foundation systems.

## 19.Approximate Estimation of Pile Stiffness in Kerman Soil

In this section, the approximate stiffness of piles at various locations in a 3×3 pile group (9 piles total) within a combined piled raft foundation has been evaluated using Kerman soil properties as provided in Table 1.
The pile stiffness values were calculated for:
-Pile lengths: 6, 8, 10, 12, 16, and 20 meters
-Pile diameters: 0.8, 1.0, and 1.2 meters
It is also noted that this process can be extended to larger pile groups, such as 4×4 (16 piles), 5×5 (25 piles), and beyond.
In Table 3, the approximate stiffness values are presented for three types of pile locations:
-Center pile (Ce)
-Edge pile (Ed)
-Corner pile (Co)

The results confirm that increasing both the length and diameter of the piles leads to higher stiffness values.
These findings are summarized and visually represented in Figure 14, where the stiffness trends across different pile configurations and dimensions are plotted.

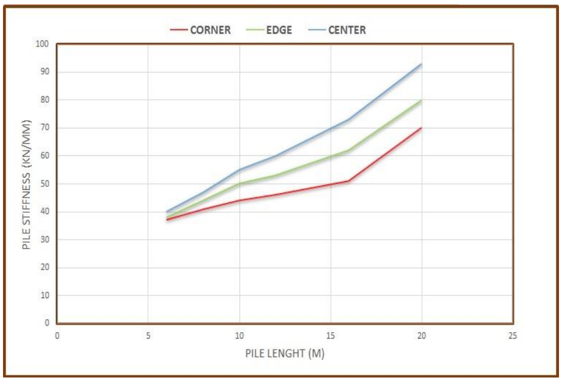


**Figure 14: Settlement at the center of the piled raft foundation for different piles in Kerman soil**

**Table 4. Approximate Pile Stiffness Using Different Methods (kN/m)**

| Pile Length (m) | Diameter (m) | Pile Position | Stiffness (kN/m) |
|---|---|---|---|
| 6 | 0.8 | Corner | 37000 |
| 6 | 0.8 | Edge | 37000 |
| 6 | 0.8 | Center | 36000 |
| 6 | 1.0 | Corner | 40000 |
| 6 | 1.0 | Edge | 38000 |
| 6 | 1.0 | Center | 37000 |
| 8 | 0.8 | Corner | 41000 |
| 8 | 0.8 | Edge | 36000 |
| 8 | 0.8 | Center | 36000 |
| 8 | 1.0 | Corner | 43000 |
| 8 | 1.0 | Edge | 40000 |
| 8 | 1.0 | Center | 37000 |
| 10 | 0.8 | Corner | 43000 |
| 10 | 0.8 | Edge | 40000 |
| 10 | 0.8 | Center | 37000 |
| 10 | 1.0 | Corner | 49000 |
| 10 | 1.0 | Edge | 47000 |
| 10 | 1.0 | Center | 42000 |
| 12 | 0.8 | Corner | 44000 |
| 12 | 0.8 | Edge | 40000 |
| 12 | 0.8 | Center | 39000 |
| 12 | 1.0 | Corner | 52000 |
| 12 | 1.0 | Edge | 48000 |
| 12 | 1.0 | Center | 44000 |
| 16 | 0.8 | Corner | 51000 |
| 16 | 0.8 | Edge | 47000 |
| 16 | 0.8 | Center | 45000 |
| 16 | 1.0 | Corner | 62000 |
| 16 | 1.0 | Edge | 58000 |
| 16 | 1.0 | Center | 55000 |
| 20 | 0.8 | Corner | 70000 |
| 20 | 0.8 | Edge | 63000 |
| 20 | 0.8 | Center | 59000 |
| 20 | 1.0 | Corner | 88000 |
| 20 | 1.0 | Edge | 80000 |
| 20 | 1.0 | Center | 75000 |
| 6 | 1.2 | Corner | 45000 |
| 6 | 1.2 | Edge | 41000 |
| 6 | 1.2 | Center | 39000 |
| 8 | 1.2 | Corner | 47000 |
| 8 | 1.2 | Edge | 43000 |
| 8 | 1.2 | Center | 41000 |
| 10 | 1.2 | Corner | 55000 |
| 10 | 1.2 | Edge | 52000 |
| 10 | 1.2 | Center | 48000 |
| 12 | 1.2 | Corner | 59000 |
| 12 | 1.2 | Edge | 53000 |
| 12 | 1.2 | Center | 49000 |
| 16 | 1.2 | Corner | 77000 |
| 16 | 1.2 | Edge | 68000 |
| 16 | 1.2 | Center | 64000 |
| 20 | 1.2 | Corner | 96000 |
| 20 | 1.2 | Edge | 95000 |
| 20 | 1.2 | Center | 88000 |

## 20. Summary and Conclusions

Based on the conducted study on the behavior of a combined piled raft foundation system on Kerman clay using the PLAXIS 3D Foundation software, the following conclusions are drawn:

1.The pile stiffness in PLAXIS can be obtained through several methods. Among these, the allowable settlement method showed the best compatibility when used in SAFE software, resulting in a close match between the average settlements obtained from both programs.

**2.** Increasing the soil cohesion up to approximately 40 kN/m² significantly improved the soil stiffness and reduced the central settlement of the combined system. This suggests that soil cohesion plays a decisive role in controlling settlement, particularly in clayey soils where cohesion governs shear resistance. Beyond this point, the reduction trend continued but at a slower rate,indicating that there is a threshold beyond which additional cohesion offers diminishing benefits for stiffness enhancement.

**3.** Increasing the internal friction angle up to 20 degrees led to a noticeable rise in lateral soil stiffness and a rapid decrease in settlement.This highlights the strong influence of frictional resistance in sandy and granular soils, where inter-particle interaction is crucial for load transfer. Although the rate of settlement reduction decreased beyond this angle, a direct relationship between friction angle and soil stiffness remained evident, confirming that soils with higher shear strength parameters generally provide more effective support for piled raft systems.

**4.** Increasing pile length led to higher overall stiffness of the combined foundation system, which in turn significantly reduced central settlement.This finding emphasizes the efficiency of longer piles in mobilizing deeper, stiffer soil layers, thereby improving load distribution and reducing differential settlement.

**5.** The pile cross-section shape (circular or square) had a negligible effect on the vertical stiffness of the system, resulting in nearly identical settlements for both shapes.This outcome suggests that, under vertical loading conditions, pile geometry is less critical than other parameters such as diameter and length. Therefore, designers may prioritize construction feasibility and cost rather than cross-sectional shape when selecting pile geometry.

**6.** Increasing the pile diameter enhanced both local and overall system stiffness. The highest settlement was observed for a diameter of 0.8 meters.The results indicate that increasing diameter is particularly effective in reducing settlement up to a certain limit, after which the improvement becomes marginal. The rate of stiffness increase and settlement reduction was greater for diameters below one meter and diminished as the diameter increased, showing that optimization of pile diameter is necessary to balance cost and performance.

**7.** Raft thickness and soil elastic modulus were identified as key influencing parameters: increasing raft thickness slightly increased settlement, while increasing soil modulus effectively reduced it.This somewhat counterintuitive behavior of raft thickness is due to increased self-weight, which partially offsets the benefits of added stiffness. On the other hand, soil modulus remains a dominant factor, highlighting the importance of accurate soil characterization in foundation design.

**8.** From the assessment of pile stiffness in a 3×3 pile group on Kerman soil with varying lengths and diameters (as shown in Table 1), it was observed that stiffness significantly increases with both pile length and diameter. This confirms that geometric scaling of piles has a strong impact on the overall stiffness of the group. It also reflects the local soil conditions of Kerman, where layered deposits of clay and sand require careful adjustment of pile geometry to achieve optimal stiffness.

**9.**The methodology for calculating pile stiffness can be extended to larger pile groups (e.g., 4×4, 5×5, etc.) to determine both local and global stiffness under varying geometric and mechanical conditions.This scalability provides a practical framework for engineers, enabling them to predict the performance of more complex piled raft systems without repeating the entire numerical modeling process.

**10.** The calculated pile stiffness values can be utilized in SAFE software for detailed analysis and optimal design of reinforced piled rafts.This integration bridges the gap between geotechnical analysis and structural design, ensuring that realistic soil–structure interaction effects are incorporated. Consequently, the proposed method enhances the reliability and efficiency of foundation design in engineering practice.

In this study, the behavior of a combined piled raft foundation system in clayey soils was investigated using the finite element method in PLAXIS 3D software, employing the advanced Hardening Soil constitutive model. A parametric analysis was performed to assess the influence of geometric and geotechnical parameters on foundation performance.

The results demonstrated that increasing pile length and diameter effectively reduces total settlement. However, the efficiency of length increase diminishes after reaching a certain threshold. Moreover, decreasing the pile spacing enhances pile contribution to load-bearing and reduces settlement.

A key finding was the analysis of load-sharing between raft and piles. A properly designed piled raft system can significantly reduce both total and differential settlement while improving bearing capacity. In optimal conditions, approximately 65% of the load was carried by the piles and 35% by the raft, which is highly favorable for safe and economical foundation design.

Another novel aspect of the research was the derivation of equivalent pile group stiffness for use in SAFE software. This approach enhances integration between geotechnical and structural modeling. The equivalent stiffness reflects the combined effects of geometric, mechanical, and soil parameters, providing a solid basis for more accurate modeling and optimal design of piled raft foundations.

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