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Numerical Evaluation of the Settlement Behavior of Shallow Foundations on Clayey Strata Reinforced with Piles

Sagar Thirmanpalli[1], Suresh Kommu[2], Srinivas Kadali[3], Asadi Sai Namratha Reddy[4]

[1]M. Tech Scholar, Department of Civil Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad-500090, Telangana, India.
[2]Sr. Assistant Professor, Department of Civil Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad-500090, Telangana, India.
[3]Associate Professor, Department of Civil Engineering, VNR Vignana Jyothi Institute of Engineering and Technology, Hyderabad-500090, Telangana, India.
[4]Student, Department of Civil Engineering, Koneru Lakshmaiah Education Foundation, (Deemed to be University) Vaddeswaram, Guntur (Dist.), Andhra Pradesh, India.

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KEYWORDS
Settlement Analysis, Shallow Foundations, Clayey Strata, Piles, PLAXIS 3D, Soil Profiles, Load Distribution, Soil Stabilization.

ABSTRACT:
This study investigates the settlement behavior of shallow foundations on clayey strata enhanced with pile inclusions under the raft foundation with two different pile diameters 1.0m, 1.2m and two different pile lengths 8m, 16m. Utilizing PLAXIS 3D software, it is conducted a comprehensive settlement analysis across three distinct soil profiles. Soil Profile 1 consists of clay having depth up to 6 m, underlain by 24 m of medium sand; Soil Profile 2 features clay up to 15 m with 15 m of medium sand below; and Soil Profile 3 consists of 30 m of clay from ground level. The analysis focuses on the variations in settlement of raft foundation with the application of pile inclusions, emphasizing their effectiveness in mitigating excessive settlement in clay-rich environments. Results revealed the significant differences in settlement response across the profiles, influenced by both the depth of the clay layer and the dimensions of the pile inclusions. The inclusion of piles substantially reduces settlement in all profiles, with larger and longer piles exhibiting greater efficiency in load distribution and soil stabilization. Detailed settlement plots illustrate the correlation between pile characteristics and soil stratification, providing insights into optimal design practices for shallow foundations on clayey soils. This research underscores the importance of installation of piles under the raft foundation, particularly in challenging soil conditions, thereby contributing to enhanced structural integrity and longevity in civil engineering applications.

1. Introduction:

The settlement behaviour of shallow foundations, particularly on clayey soils, is a critical consideration in geotechnical engineering. Clay-rich environments are known for their poor load-bearing capacity and high compressibility, often leading to excessive settlement and structural instability when subjected to significant loads. This poses a considerable challenge for civil engineers, particularly in the design of shallow foundations for large structures. In such contexts, foundation systems that effectively distribute load and mitigate settlement are essential for ensuring the long-term stability and integrity of structures.

Raft foundations, also known as mat foundations, are commonly employed in soft or weak soil conditions to spread loads over a large area, thus reducing the pressure on underlying soil. However, in highly compressible clay soils, raft foundations alone may not provide sufficient resistance to settlement, especially under heavy structural loads. As a result, enhancing raft foundations with pile inclusions has emerged as a practical solution for improving settlement performance. Pile foundations, designed to transfer loads to deeper, more stable soil strata, can significantly reduce settlement and improve load distribution when combined with raft foundations. This hybrid system, often referred to as a piled raft foundation, offers an effective strategy for optimizing foundation performance in challenging soil conditions.

Several studies have explored the behaviour of piled raft foundations, particularly on clayey soils, demonstrating the benefits of incorporating piles beneath the raft. Research has shown that the inclusion of piles enhances the stiffness of the foundation system, reduces differential settlement, and improves load transfer to deeper soil layers. However, the settlement response of such systems can vary significantly depending on factors such as pile dimensions, pile spacing, and the stratification of the underlying soil. Despite extensive research in this area, further investigation is needed to better understand the interaction between piles and soil, especially when considering different soil profiles and pile configurations.
This study aims to investigate the settlement behaviour of shallow foundations on clayey strata enhanced with pile inclusions beneath a raft foundation. Using PLAXIS 3D software, a comprehensive settlement analysis is conducted across three distinct soil profiles with varying depths of clay and sand layers. two different pile diameters1.0m and 1.2mand two different pile lengths8 m and 16m are examined to evaluate their influence on settlement reduction. The findings of this research provide valuable insights into the effectiveness of pile inclusions in mitigating settlement and improving foundation performance, particularly in clay-rich environments. The results contribute to the development of optimal design practices for shallow foundations in challenging soil conditions, thereby enhancing the structural integrity and longevity of civil engineering projects.

2. Objective:

To analyse the settlement for shallow foundations on Clayey Strata Reinforced with Piles

3. Methodology:

This study employs a systematic approach to investigate the settlement behavior of shallow foundations on clayey strata enhanced with pile inclusions, utilizing advanced numerical modeling techniques with PLAXIS 3D software(Geramian et al., 2022) [6]. The methodology consists of:
Three distinct soil profiles were established based on varying depths of clay and underlying medium sand. They are Soil Profile 1 has 6m of clay followed by 24m thickness of medium sand, while Soil Profile 2 has 15m of clay followed by 15m thick of medium sand beneath. Profile 3 consists solely of 30 m of clay. A shallow raft foundation measuring 12m by 10m was designed to support the loads applied in this study. (Cristovao et al., 2016)[4] The foundation's dimensions allow for a realistic assessment of settlement behavior across various soil profiles.
Pile inclusions were designed with two different pile diameters1.0m, 1.2mand two different pile lengths8m, 16m. Each combination of pile dimensions was analyzed to assess its impact on the settlement behavior of the shallow raft foundation.

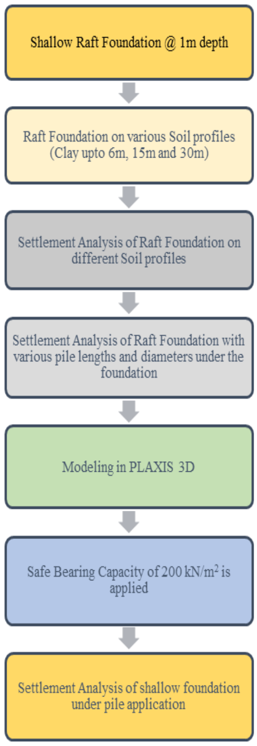

Figure 1: Step by step Processing of Methodology

The PLAXIS 3D software was utilized to create detailed finite element models of each soil profile with the corresponding pile configurations beneath the shallow raft foundation(Choobbasti et al., 2011)[2]. This software facilitates the simulation of complex soil-structure interactions under various loading conditions. The models were subjected to realistic loading scenarios that simulate the operational conditions of the shallow raft foundation. These conditions included uniform loads representing the weight of the structure supported by the foundation(Antonio et al., 2022)[3].
The primary focus of the analysis was on evaluating the settlement responses of the foundation across different soil profiles and pile configurations. The software output provided detailed settlement data, which were systematically analyzed(Kolay et al., 2013)[12].The settlement results from each scenario were compared to identify the effectiveness of pile inclusions in reducing settlement. Variations in settlement response were analyzed in relation to the depth of the clay layer and the dimensions of the pile inclusions. Detailed settlement plots were generated to visually represent the

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correlation between pile characteristics and soil stratification. These visualizations, along with statistical analyses, facilitated the derivation of optimal design practices for shallow foundations on clayey soils. This comprehensive methodology allows for a thorough understanding of the effects of pile inclusions on the settlement of shallow foundations, ultimately providing valuable insights for civil engineering applications.

4. Soil Profile thicknesses and Material properties

The analysis evaluates three distinct soil profile configurations that influence settlement behavior through variations in the thickness of the top layer. Each profile is characterized by field parameters that simulate actual conditions (Mohanty and Samanta, 2015) [13]. The soil profiles consist of two layers: a soft clay layer and a medium sand layer. The three configurations feature different thicknesses of the soft clay layer, specifically 6 m, 15 m, and 30 m. The following table outlines the details of the soil profiles and their respective thicknesses:

Table 1. Thicknesses of Soil profiles

Soil Profiles	Soft Clay (m)	Medium Sand (m)
Profile 1	0.0m - 6.0m	6.0m – 30.0 m
Profile 2	0.0m - 15.0m	15.0m – 30.0 m
Profile 3	0.0m - 30.0m	-

In the PLAXIS analysis, soil profiles and their characteristics are employed to assess the behavior of soft soils under raft footings. The material models for soils in PLAXIS are based on the Mohr-Coulomb failure criterion. The unit weights of the soil are evaluated under both dry and saturated conditions. Young's modulus and shear parameters are applied to analyze the internal behavior of the soft clay and medium sand layers. Soil behavior is examined under undrained conditions for soft clay and drained conditions for medium sand. (Hussein et al., 2020) [14] The properties of the soils are detailed in Table 2

Table 2. Soil Characteristics.

Medium Pattern	Mohr-Coulomb		
Criterion	**Medium Sand**	**Stiff Clay**	**Soft Clay**
Material Behavior	Drained	Undrained (A)	
Bulk Unit weight, γ (kN/m³)	16.67	19.20	15.41
Elastic modulus, E (kN/m²)	30000	10000	4000
Poisson'sRatio	0.3	0.35	0.4
Cohesion, C (kN/m²)	0.2	70	25
Internal Resistance angle, ϕ (º)	36	6	5
Angle of Distension, ψ (º)	6	0	0

The current analysis primarily focuses on the design of shallow foundations for deep clay soils.A raft footing with dimensions of 12 m by 10 m, exhibiting non-porous behavior, is modeled in PLAXIS using a linear elastic material model. The unit weight and Young's modulus are specified and can be found in Table 3, which provides comprehensive details of the raft footing for the 3D analysis.

Table 3. Footing Features

Criterion	Footing
Substance type	Concrete
Density, γ (kN/m³)	24
Medium Pattern	Linear elastic
Elastic Modulus, E* (kPa)	$23.5 x 10^6$

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Poisson'sRatio, ν	0.15
Substance Behavior	Non-porous

The comprehensive numerical analysis conducted in PLAXIS 3D incorporates specific design details. A surface Safe Bearing Capacity of 200 kN/m² is applied to the raft footing, which is positioned at a depth of 1 meter below ground level.

Table 4. Pile Features [1]

Criterion	**Pile**
Substance type	Concrete
Density, γ (kN/m³)	24
Medium Pattern	Linear elastic
Elastic Modulus, E* (kPa)	$30x10^6$
Poisson'sRatio, ν	0.10
Substance Behavior	Non-porous

These parameters are integrated into the 3D numerical analysis using PLAXIS software. The table below details the design properties relevant to the numerical analysis.

Table 5. Design Criterion considered for the evaluation in 3D using PLAXIS.

Proportions of Footing (m) (L x B)	**12.0 x 10.0**
Safe Bearing Capacity (kN/m^2)	200
Depth of Footing/Raft from NGL (m)	1.0

The properties of all materials considered in this study are outlined above(Thirmanpalli S et al., 2024)[15]. Using the specified input parameters, the numerical models are presented, along with the analyses conducted for the design of shallow foundations.

4.1. Numerical Analysis:

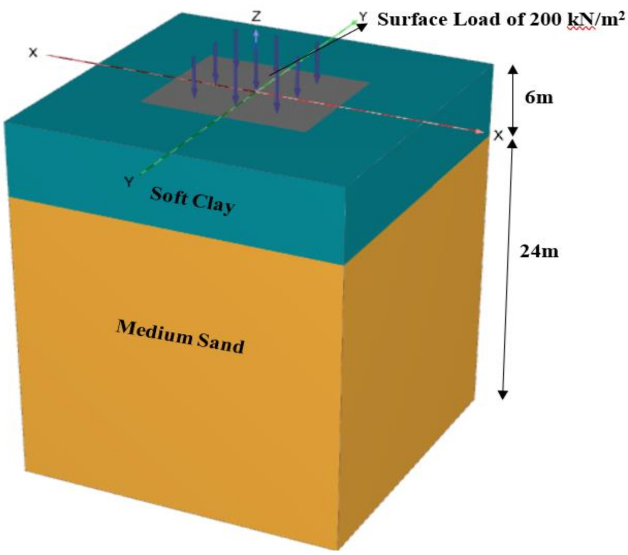

Figure 2: Profile View-Soil profile-1 (Clay up to 6.0m) with surface load of 200 kN/m^2

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The numerical models depicted in Figure 2 show scenarios with surface loading of 200 kN/m^{2}on the raft footing. (Ashraf et al., 2010)[5] The models feature varied Profiles with different lengths of pile inclusions, as detailed in Table 1. The raft footing, with dimensions of 10m x 12 m, is situated 1 meter below the ground surface. The pile length and diameters of 8m, 16m and 1.0m, 2.0m respectively and profiles used in the models are based on findings from literature studies(Jesus Fernandez et al., 2021)[7], and the models are designed to reflect these variations in 3 soil profiles.

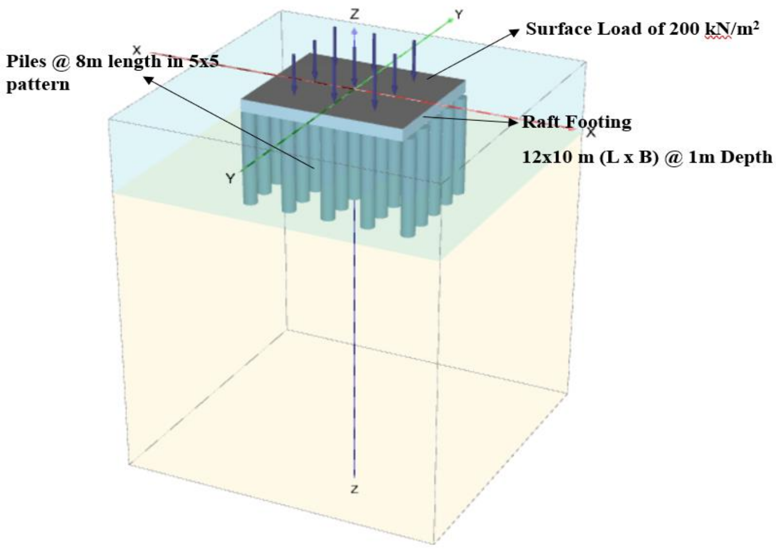
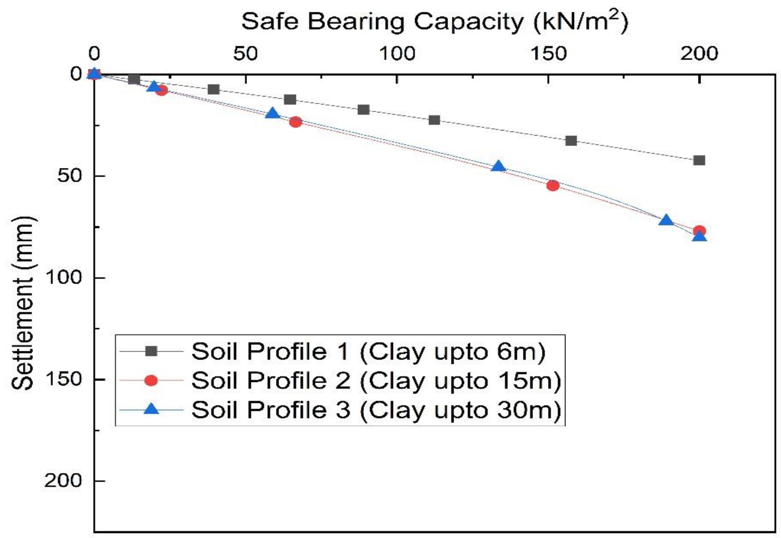


Figure 3: Structural View-3D Model of Soil profile-1 with Raft @ 10m depth with 8m length piles.

5. Results and Discussion:

The Piles of 5x5 pattern in group are applied under the raft foundation(kadali et al., 2022)[8]. The analysis in PLAXIS 3D with pile lengths of 8m and 16m are modelled with 1.0m and 1.2m diameters. Safe bearing capacity of 200 kN/m^2 is applied on foundation in the area of 10m x 12m. The foundation is placed at 1m depth from ground level. The analysis was performed in 3D to evaluate settlements with inclusion of piles.



Pile with 1.0m diameter

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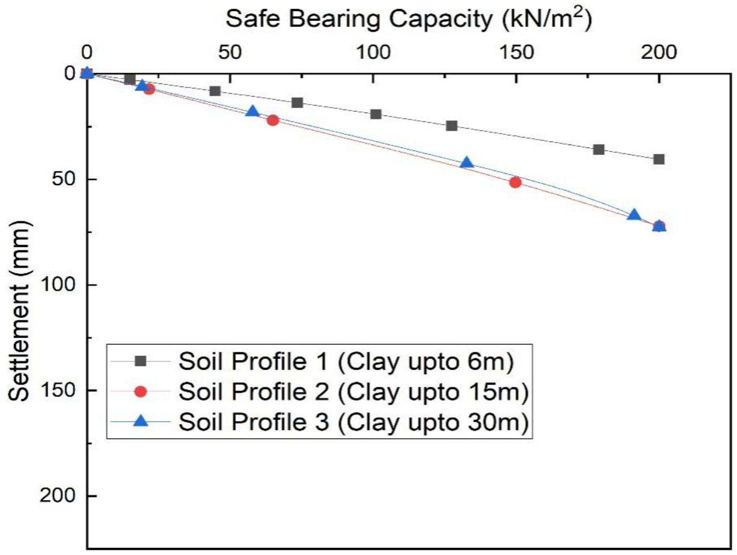
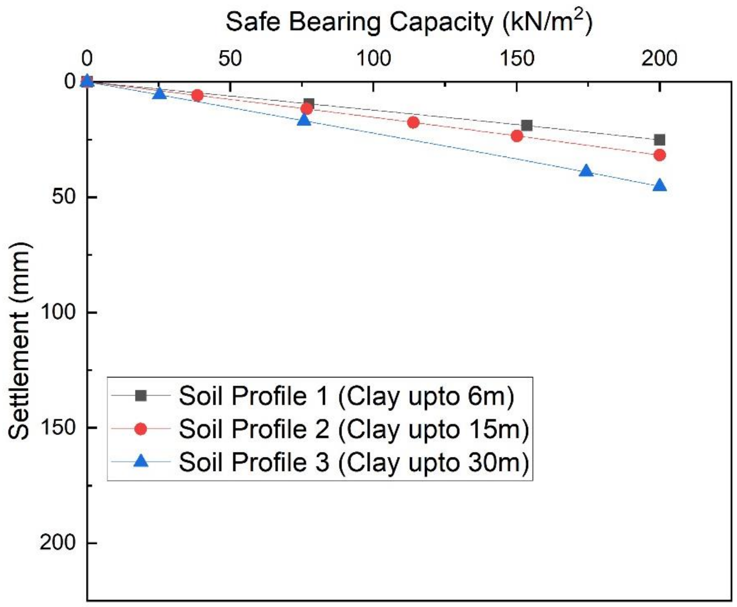


Pile with 1.2m diameter

Figure 4: Safe Bearing Capacity Vs Settlement in 3 soil profiles under pile inclusion of 8m length.

The figure 4 represents the settlement variation in Soil profiles 1, 2 and 3 where clay up to 6m, 15m and 30m respectively(Michael et al., 2014)[9]. The pile length of 8m with 1.0m and 1.2m diameters are considered. With the bearing capacity of 200 kN/m^2 settlements are evaluated in soil profiles 1 (clay up to 6m), 2 (clay up to 15m) and 3 (clay up to 30m) as 42.36mm, 77.0mm and 80.16mm in 1.0m diameter pile. With 1.2m diameter of piles settlements are evaluated in soil profiles 1 (clay up to 6m), 2 (clay up to 15m) and 3 (clay up to 30m) as 40.50mm, 72.18mm and 72.58mm.



Pile with 1.0m diameter

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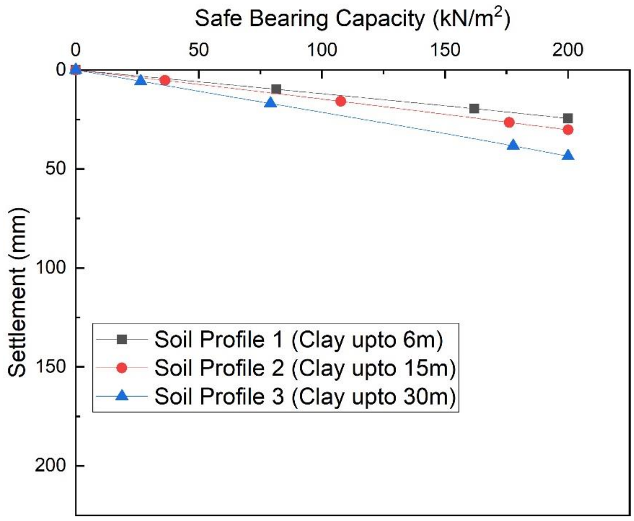

Pile with 1.0m diameter

Figure 5: Safe Bearing Capacity Vs Settlement in 3 soil profiles with 16m length piles under raft.

The figure 5 represents the settlement variation in Soil profiles 1, 2 and 3 where clay up to 6m, 15m and 30m respectively. (Fattah et al., 2017)[10] The pile length of 16m with 1.0m and 1.2m diameters are considered. With the bearing capacity of 200 kN/m^2 settlements are evaluated in soil profiles 1 (clay up to 6m), 2 (clay up to 15m) and 3 (clay up to 30m) as 25.15mm, 31.75mm and 45.32mm in 1.0m diameter pile. With 1.2m diameter of piles settlements are evaluated in soil profiles 1 (clay up to 6m), 2 (clay up to 15m) and 3 (clay up to 30m) as 24.43mm, 30.26mm and 43.53mm.

Table 6. Results of settlement analysis of pile 8m length and 1.0m diameter

Soil Profiles	**8m Length Pile**	
	1.0m Dia	
	SBC (kN/m^2)	**Settlement (mm)**
Soil Profile 1 (Clay up to 6m)	200	42.36
Soil Profile 2 (Clay up to 15m)		77.00
Soil Profile 3 (Clay up to 30m)		80.16

Table 7. Results of settlement analysis of pile 8m length and 1.2m diameter

Soil Profiles	**8m Length Pile**	
	1.2m Dia	
	SBC (kN/m^2)	**Settlement (mm)**
Soil Profile 1 (Clay up to 6m)	200	40.50
Soil Profile 2 (Clay up to 15m)		72.18
Soil Profile 3 (Clay up to 30m)		72.58

Table 8. Results of settlement analysis of pile 16m length and 1.0m diameter

Soil Profiles	**16m Length Pile**	
	1.0m Dia	
	SBC (kN/m^2)	**Settlement (mm)**
Soil Profile 1 (Clay up to 6m)	200	25.15
Soil Profile 2 (Clay up to 15m)		31.75
Soil Profile 3 (Clay up to 30m)		45.32

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Table 9. Results of settlement analysis of pile 16m length and 1.2m diameter

Soil Profiles	**16m Length Pile**	
	1.2m Dia	
	SBC (kN/m^2)	**Settlement (mm)**
Soil Profile 1 (Clay up to 6m)	200	24.43
Soil Profile 2 (Clay up to 15m)		30.26
Soil Profile 3 (Clay up to 30m)		43.53

(Paramita and Jayanth., 2017)[11] The settlements are in permissible limits with the application piles under the raft foundation in soil profile 1 (clay up to 6m) compare with soil profile 2 (clay up to 15m) and 3 (clay up to 30m) where the piles length @ 8m and 1.0m diameter. Other than this remaining in all 3 soil profiles at 1.0m and 1.2m diameters with 8m and 16m length of pile application results in permissible limits in settlement analysis.

6. Conclusions:

From the above study, conclusions are mentioned below:

The settlement analysis with pile inclusions in deep clay layers results with permissible settlement limits under the raft foundation.

The piles under the raft foundation of 1.0m diameter and 8m length, in soil profile 1 (having clay up to 6m) gives permissible settlement of 42.36mm and other 2 soil profiles (having clay up to 15m and clay up to 30m) exceeds the permissible limit of 75mm as 77.0mm and 80.16mm respectively.

The piles under the raft foundation of 1.2m diameter and 8m length, in soil profile 2 (having clay up to 15m), soil profile 3 (having clay up to 30m) gives within the permissible settlement of 72.18mm, 72mm respectively.

The piles under the raft foundation of 1.0m, 1.2m diameter and 16m length, in soil profile 2 (having clay up to 15m), soil profile 3 (having clay up to 30m) gives settlements within permissible settlement of 31.75mm, 45.32mm and 30.26mm, 43.53mm respectively.

In soil profile 1 (having clay up to 6m), under the raft foundation, having 8m length piles and increasing the pile diameter from 1m to 1.2m has reduced the settlement from 42.36mm to 40.50mm, but where as having 1.0m diameter piles and increasing the pile length from 8m to 16m has reduced the settlement from 42.36mm to 25.15mm. Increasing the pile length has greater impact on reduction of settlement than increasing pile diameter.

Based on the SBC and settlements observed from the study, 8m length piles of 1.0m diameter for soil profile 1 (having clay up to 6m) and 1.2m diameter for soil profile 2 (having clay up to 15m), soil profile 3 (having clay up to 30m) under the raft foundation are economical for the 200kN/m^2 SBC.

This analysis with the comparison of previous research papers on ground improvement with stone columns and soil replacement in deep clay layers, shallow foundation design is adoptable with inclusion of concrete piles in the deep clay soil profiles.

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