Review of stone columns, piled raft foundations, and combined stone columns and piles under raft as a ground improvement techniques for soft clay soils

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Abstract. This review paper aims to provide an in-depth analysis of three commonly used foundation systems: stone columns, piled raft foundations, and combined stone columns and piles under raft. These foundation techniques have gained significant attention due to their effectiveness in improving soil conditions and enhancing the load-bearing capacity of weak or problematic soils. The aim is to evaluate their effectiveness in addressing the challenges associated with building on soft clay. The review incorporates published research and case studies to compare the performance of each method in terms of enhancing bearing capacity, reducing settlement, and improving overall performance. The findings suggest that while each approach offers distinct advantages, the hybrid solution of combining stone columns and piles beneath a raft foundation offers the most comprehensive benefits for supporting structures on soft clay sites.

Introduction

The selection of appropriate foundation systems is crucial for ensuring the stability and performance of structures, particularly when dealing with weak or problematic soils. Among the various foundation techniques available, stone columns, piled raft foundations, and combined stone columns and piles under raft have emerged as effective solutions for improving soil conditions and enhancing load-bearing capacities.

Stone columns and pile foundations are commonly used foundation systems for weak and soft (compressible) soils. Pile foundations are employed when the existing soil has low bearing capacity and experiences high consolidation settlement. They transfer loads through soft soil to a more competent stratum through bearing and/or side friction. Pile foundations are typically utilized for structures with substantial loads, such as high-rise buildings, but their installation requires careful planning and heavy equipment. Stone columns, on the other hand, consist of compacted crushed coarse aggregates of various sizes installed in cylindrical holes in the ground. They improve the performance of soft soils and accelerate consolidation. When implemented, stone columns alter the properties of the original soil, creating a composite ground with reduced compressibility and increased shear strength. This cost-effective technique is well-suited for smaller structures, typically ranging from 1 to 4 stories in height. There is limited literature available regarding the utilization of a composite foundation system that combines stone columns and piles under a raft foundation in soft and compressible soils. However, this combined approach

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has the potential to be a more suitable foundation solution for medium-rise structures, typically ranging from 5 to 9 stories.

This review paper examines three ground improvement techniques (stone columns, piled rafts, and the combination of stone columns and piles under a raft foundation) and evaluates their performance in addressing the challenges. The review draws on published research and case studies to compare the effectiveness of each method in improving the performance of foundations in weak and problematic soil.

Stone Columns

Stone columns, also known as granular piles are a ground improvement technique where vertical columns of compacted granular material are installed in the soil. The stone columns serve to increase the bearing capacity, reduce settlement, and improve the overall stability of the soil. Several studies have demonstrated the effectiveness of stone columns in soft clay soils:

Hanna et al [1] conducted a numerical study to examine the behavior and failure modes of single stone columns and groups of stone columns installed in soft clay. Their research involved a parametric study considering factors such as modulus of elasticity, column diameter, spacing, and angle of shearing resistance. They identified two failure modes: bulging failure in individual columns and massive shear failure in groups of stone columns. The load ratio was found to increase significantly when the diameter of the stone column to foundation width ratio was less than 0.6, and the bearing capacity of the reinforced foundation improved with an increase in the angle of shearing resistance of the stone columns. Bulging failure occurred in the group of stone columns when the area replacement ratio was less than 10%, while massive shear failure occurred in the range of 10% to 35% as shown in Figure 1. The difference between bulging failure and massive shear failure in groups of stone columns can be attributed to the distinct failure modes and underlying mechanics involved. Bulging failure occurs when the soft clay exerts lateral pressure on the stone columns due to its low shear strength, causing them to deform laterally or bulge outwards. On the other hand, massive shear failure occurs when the shear strength of the clay is surpassed, resulting in sliding or collapse of the columns due to the clay's inability to resist the shear forces.

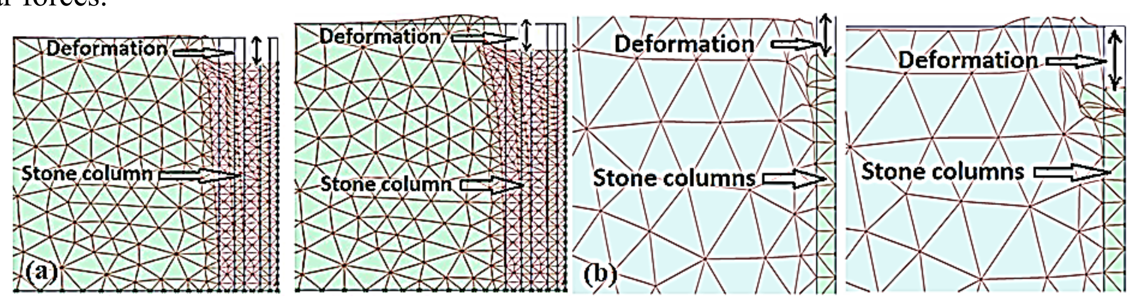

Figure 1 (a) Deformed shape of group of stone columns (b) Deformed shape of single stone column [1]

Nazari and Ghazavi [2] introduced a simple analytical method (given in Eq. 1) for the estimation of ultimate bearing capacity of stone column, the validity of the presented analytical method was verified by using finite element method including the effect of changes in parameters such as column size, spacing and angle of friction and it was reported that the bearing capacity of stone column increases with the friction angle and diameter of stone columns and bearing capacity decrease with the increase in center-to-center distance between stone columns, similar findings were reported in [3,4,5]. It was also observed that with smaller spacing between the stone columns have higher ultimate load carrying capacity and with higher spacing between stone columns the ultimate carrying capacity reduces and become steadier. This shows that there must be an optimal spacing range of stone columns, beyond which the benefit of increased spacing can diminish.

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Results shows that effect of internal friction angle of stone columns on the bearing capacity, with the increase in the angle of friction of stone columns the bearing capacity increases, similar conclusions were reported by Kouklanifar [6]. The angle of friction is a measure of the resistance to sliding between two surfaces in contact. When stone columns are stalled in the ground, they can interact with surrounding soil and can contribute to the overall load-baring capacity.

$$q_{ult} = C_c N_c + \bar{q} N_q + 12 W \gamma_c N_\gamma \quad (1)$$

Castro [7] studied the performance of groups of stone columns under rigid footing and investigated the effect of column configuration on the load-settlement curves by conducting the 2D and 3D finite element analysis. It was concluded that uniformly distributed columns are more beneficial, stone column length to diameter ratio has not much effect on settlement, column length more than the width of footing is more efficient, and higher area replacement ratio is less efficient for settlement reduction factor. Later authors [8] proposed that the critical length of columns can be range between 1.2-2.2*D* (*D* = width of footing). Figure 2 shows two sets of arrangement for stone columns under square raft one with stone columns at the corner of square raft and another with stone columns on the sides uniformly. These uniformly distributed stone columns under raft foundation can provide benefits due to the mechanism of load distribution and soil improvement. When stone columns are uniformly placed under a raft foundation, they can share the load from superstructure more evenly. This load sharing mechanism can help to reduce the stress concentration on individual stone columns, which can prevent localized failure. By distributing the load over a large number of stone columns, the overall load-bearing capacity of the foundation system can be increased.

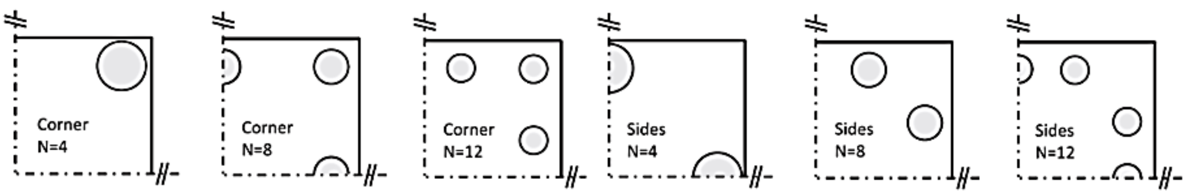


Figure 2 Stone columns configurations. [7]

Micheál and Bryan [9] conducted the 3-D finite element analysis using elastic-plastic soil model to study the influence of variation in the stone column configuration as presented in Figure 3. A simplified method to estimate the settlement was proposed. It was reported that the area ratio, column length and number of columns are related to each other. The number of columns near the footing edge has less effect on the settlement. The settlement improvement factor increases with the increase in column stiffness and strength as well as due to the lateral earth confinement *Ko*. Similar findings were reported by [10]. It has also been observed that the columns are more confined in the stiff crust and can bulge in the softer layer of soil. Stone columns near the edge of a raft foundation can have a reduced effect on the overall performance of the foundation compared to those located closer to the center. This is because the load distribution and settlement behaviour of the foundation can be influenced by the proximity of the stone columns to the load-bearing elements. When stone columns are placed near the center of a raft foundation, they can effectively distribute the load over a large area and can reduce the stress on the soil and minimize the settlement. However, when stone columns are located near the edge of raft, their ability to influence the load distribution and settlement patterns can diminished. The load from the superstructure can be directly transmitted to the surrounding soil through the edge of the raft, which can reduce the effectiveness of the stone columns in redistributing the load.

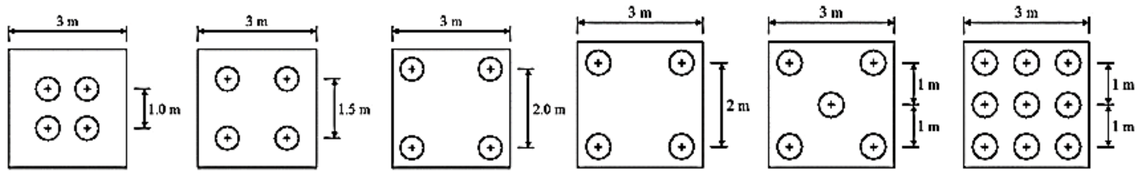


Figure 3 Different Stone Column configurations [9]

Elsawy and El-Garhy [11] have studied the behaviour of reinforcing the soft soil with granular pile (*GP*) under raft foundation using finite element program PLAXIS 3D. A parametric study was performed by changing spacing (*S*), diameter (*d*) and length (*L*) of granular piles (*GP*). In this study, in general they have concluded that the settlement and bending moment reduces with higher value of replacement area ratio and smaller value of spacing ratio, because with the higher replacement ratio the bearing capacity and settlement of the soil under the foundation can be improved [12,13,14,15].

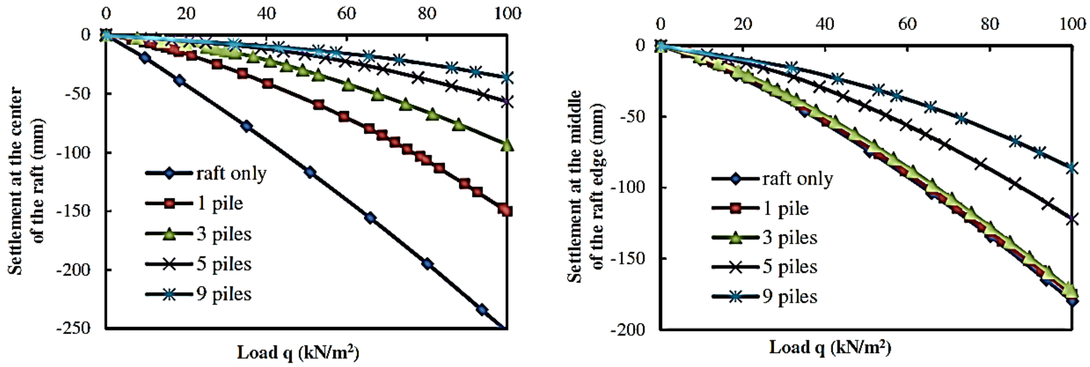
Grizi et al [16] carried out an 3D finite element parametric investigation using PLAXIS 3D in order to examine the influence of these parameters on the settlement of stone columns to support the shallow foundations. From this study it was concluded that using both drained and undrained analysis, the modelling of well-characterized soft soil profile can be used to predict the long-term settlements. It was also concluded that the presence of a stiff crust layer affect stone columns deformation in a significant way which is not captured by laboratory. A stiff layer can help to distribute the applied load more evenly, it can reduce the stress concentration at the column-soil interface by preventing excessive settlement and by improving load bearing capacity of the stone columns. Also, stiff crust layer can resist the downward movement of the stone columns which can minimize the settlement.

Mugahed et al [17] performed a numerical study on ordinary stone columns and encased stone columns in soft clay using PLAXIS 3D. Different set of parameters were selected to study the behaviour of stone columns. It was concluded that as the angle of internal friction for ordinary stone columns increased, the ultimate bearing capacity increased and settlement decreased [18]. Furthermore, it was found that the increase in BCR (Bearing capacity ratio) of the encased stone column over untreated soil for two diameters of columns (D = 0.4 m and 0.6 m) was 227% and 200%, respectively at 45° internal friction.

Piled Rafts

Piles are generally made of steel, concrete, or timber. Pile foundations are the long slender which are used to support the structure and heavy loads. In the piled raft foundation system, piles penetrate through the weak soil deposits to the stiff soil or bed rock to support the raft foundation. The main purpose of using pile foundations is to reduce the settlements and to increase the bearing capacity of raft foundation.

A parametric study has been carried out by Anhtuan et al [19] to study the behaviour of piled raft foundation using PLAXIS 3D and it was reported that the decrease in the settlement occurs when the number of pile and length is increased and increase in the settlement observed when the spacing of piles increase [20] as given in Figure 4. This shows the effect of number of piles on the settlement, it can be seen from the curves that the settlement of the foundation is decreasing with the increasing number of piles. This can be understood by the fact that when multiple piles are installed within a foundation system, they interact with each other which helps for load sharing. This load sharing mechanism helps to redistribute the applied load among the piles and reduces the stress and settlement on each pile [21].



Load-settlement curve at the centre of the raft

Load-settlement curve at the middle of the raft edge

Figure 4 Load-settlement curve [19]

Watcharasawe et al [22] performed the consolidation analysis on the piled raft foundation of 8 story and 25 story buildings when placed in clayey soil in Bangkok using 3D numerical modelling. Parametric study was conducted to study the effect on raft depth and load carried by piles, and it was concluded that the consolidation has strong impact on the load carried by piles, the percentage of load shared by the piles can increase up to 12 percent for low rise and 6 percent for high rise buildings. The load sharing behaviour of piles in piled raft foundation may undergo changes after consolidation of underlying soil. Consolidation settlement occurs when excess pore water pressure is dissipated over time. The influence of the consolidation on load sharing can vary depending on several factors, including soil properties, piles characteristics, and nature of the consolidation process. Consolidation settlement can lead to increased load sharing among the piles. This happens because the increased soil stiffness allows for better load transfer from the raft to the piles for this reason the piles that initially carried smaller portion of the loads may experience an increase in their load share after consolidation.

Nguyen et al. [23] investigated the use of piles under raft foundation using Plaxis 3D. The behaviour and performance of pile under raft was investigated using different parameters like pile length, pile arrangement, raft thickness and it was concluded in general that the increase in raft thickness, pile length, number of piles can reduce the total and differential settlement. Increasing the raft thickness can distribute the load over a larger area which can reduce the stress transferred to the underlying soil, longer piles can penetrate deeper into more competent soil layer which can provide enhanced load bearing capacity and reduced settlement, and increasing number of piles under the raft foundation can enhance the load distribution, more piles can help to evenly distribute the applied load which can help to reduce the load intensity on each individual pile and controls the settlement of the whole foundation [24,25,26,27,28].

Paravita and Daniel [29] have conducted the finite element analysis on raft foundation with and without piles using PLAXIS 2D to study the effect of the number of piles on the settlement. It was concluded that by increasing the number of piles the settlement of piled raft foundation can reduce, and the optimum number of piles should be calculated in pile raft foundation system to control the foundation settlement effectively and economically. The results also show that settlement reduces with the increasing number of piles [30,31].

Abdel-Azim et al [32] performed a 3D finite element analysis on a piled raft foundation of Messeturm building in Germany using Plaxis 3D to investigate the performance of foundation in Frankfurt over-consolidated clay. Piled raft foundation was evaluated based on total settlement, differential settlement and pile skin friction and it was concluded that the piled raft foundation is the optimized foundation solution for high rise buildings.

Elsawwaf et al [33] conducted a numerical investigation to study the effect of length of pile, diameter of pile, and number of piles in soft clay using PLAXIS 3D. It was reported that settlement and differential settlement of foundation decreased with the increase in pile length and number. It was also reported that the load sharing ratio of piles increases by 13.7, 36, and 58% with the range of pile length to diameter ratio from 10 to 30 and number of piles 4, 9, and 16 respectively.

Amornfa et al [34] compares monitoring data from real world with 3D numerical simulations using PLAXIS 3D, a parametric study of piled raft was conducted on the Ho Chi Minh sub soil. According to the results, total and differential settlement decreased with increased pile length, pile number and embedding raft depth. Moreover, it was also reported that the raft could share 66% of building's load by being located in the second layer of stiff clay.

Combined Stone Columns and Piles under Raft

The combination of stone columns and piles under a raft foundation can provide the benefits of both ground improvement techniques, resulting in a more comprehensive solution for soft clay soils. The stone columns improve the overall soil conditions, while the piles provide additional bearing capacity and reduce settlement. So far very few works have been reported in the literature on the use of combined stone column and pile under the raft.

Liang et al 35] proposed the concept of combining two types of pile system under raft such as short pile made of flexible materials and long piles made of rigid material. ANSYS program was used for finite element analysis to study the behaviour of seven-story building foundation with different parameter including ratio of length to diameter, elastic moduli of piles, thickness and elastic modulus of cushion. It was reported that the elastic modulus of piles is more effective in long piles to control the settlement than the short piles, thickness of cushion has significant effect on the load sharing ratio of piles to subsoils and decrease in modulus of elasticity of cushion can decrease the stress concentration of long piles.

Samanta and Bhowmik [36] conducted the numerical analysis of the piled raft foundation in soft soil improved with stone columns. PLAXIS 3D was used to study the influence of parameters on the total and differential settlements of the foundation. It was concluded that the increase in the length of the pile increases the percentage of load shared by piles whereas by increasing the diameter of stone columns results in higher portion of load shared by stone columns which played a significant role in reducing the settlement of foundation. The length of stone columns helps to control the settlement, but it has no effect in sharing the load percentage. Increase in angle of friction of stone columns and thickness of raft foundation increases the percentage of load shared by stone columns and help to reduce the foundation settlement. It was also reported that using pile slenderness equal to 40 and area replacement ratio equal to 25% results in balanced share of loads between stone columns and piles.

Recently, an extensive numerical investigation has been conducted and presented by Ahmed et al [37,38], and Ahmed [39,40,41,42] to study the behaviour (i.e., modes of failure) of this new combined foundation system (Stone Columns, Piles and Rigid Raft Foundation in Soft Soils) in order to optimize the configuration of stone columns/piles to get optimum soil improvement. For this reason, parametric study was conducted to examine the effect of the configuration and arrangement of the combined foundation system on the performance of this type of foundation system on soft soils. Also, an optimization study was conducted aiming to display the geometrical layout of stone columns/pile foundations exhibiting the superlative improvement of the performance of soil foundation. It was observed from the parametric study that combining stone columns and piles in one foundation system, improve the carrying capacity of the system, modify the soil foundation to a new upgraded composite ground, and certainly can reduce the cost of the geotechnical works. Overall, 680 combinations were investigated for this parametric study and based on the optimization study, chief leading sets were selected to get optimum soil improvement. It was noticed that these chief leading sets can increase the bearing capacity of the raft foundation by almost 50% to 90% compared to that of raft foundation resting on stone columns only. Based on the results of the optimization study, the behaviour (i.e., modes of failure) of such combined foundation system under loading was examined and it was observed that the combined foundation system fails by shear in the stone columns and soft soil, and by bearing and shear failure of pile's tip under the rigid raft. In light of the observed behavior and failure modes, an analytical model was developed to predict the ultimate carrying capacity of the combined foundation system in soft soil. Unfortunately, due to space constraints, only the master equation for the ultimate carrying capacity of the combined foundation system can be provided below:

$$Q_u = \left(BL - n_1 \frac{\pi D_1^2}{4}\right)\left[C_{comp}\overline{N_c} + q_1\overline{N_q} + \frac{1}{2}B\gamma_{comp}\overline{N_\gamma}\right] + q_2\overline{\overline{N_q}} + C_1\overline{\overline{N_c}}$$

Conclusion

This review paper has examined three ground improvement techniques - stone columns, piled rafts, and the combination of stone columns and piles under a raft foundation - and their performance in addressing the challenges of constructing on soft clay soils.

Most of the research work has been carried out to investigate the effect of parameters on the load-bearing performance and settlement of foundations. So far what has been discussed, it can be concluded that the change in parameters for any type of foundation system (stone under raft, pile under raft, stone, and pile under raft in soft soil) can make the notable effect on the load-bearing performance and settlement of foundations. The key parameters that can affect the performance of the foundation with stone columns mostly include, spacing, diameter, angle of friction of stone columns and length of stone columns. These parameters play important roles in the load-bearing performance of a foundation. Each parameter influences the load distribution, bearing capacity improvement, settlement control, and overall stability of the foundation system.

Similarly, the performance of a piled raft can be influenced by several factors, including pile length, pile diameter, aspect ratio, number of piles, pile spacing and raft foundation thickness. These factors play important roles in distributing loads, improving bearing capacity, controlling settlement, and ensuring overall stability. In general, the notable effect of stone columns can only be seen in shallow foundations whereas the pile foundation can be used to support the excessive load by resting on the stiff and hard soil layers, and the use of pile foundations are not economical.

There is a limited amount of research available in the literature regarding combined foundation systems that incorporate both stone columns and piles. Such a system can pose additional complexities compared to using either technique separately. Several factors need can affect the load-bearing performance of combine foundation system, including number of piles, diameter ratio of piles and columns, angle of friction of stone columns, modulus of elasticity of soil, the length ration of stone columns and piles. The combination of stone columns and piles in a single foundation system has the potential to significantly enhance the overall carrying capacity of the structure. It can effectively transform the soil foundation into a new and improved composite ground. Additionally, this approach can lead to cost savings in geotechnical works, making it an attractive option. Combining stone columns and piles under a raft can provide the most comprehensive benefits, including improved bearing capacity, reduced settlement, and cost-effectiveness. The review of published research and case studies highlights the potential of this combined approach for successful construction on soft clay sites.

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